The Simulation and Assimilation of Doppler Wind Lidar Observations in Support of Future Instruments

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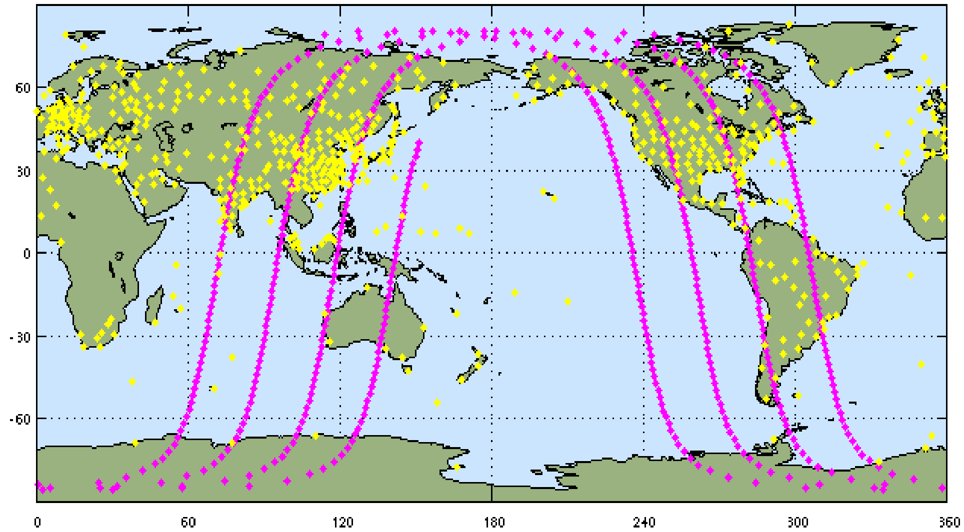
Introduction

- Importance of Wind Measurements
  - Global wind profiles are "essential for operational weather forecasting on all scales and at all latitudes"
    - World Meteorological Organization (1996)
- Atmospheric Winds from the ground
  - Global Rawinsonde Record
  - Ground-based, remotely sensed wind observations
  - Mainly in data rich regions
- Atmospheric Winds from Space
  - Atmospheric Motion Vectors (AMVs) and Scatterometers

Introduction to Doppler Wind Lidar

- The Doppler Wind Lidar Concept
  - Lidar backscatter is Doppler shifted by a scattering agent
  - Improved accuracy in height assignment
- Spaceborne Doppler Wind Lidar
  - Global, 3D measurements of wind
  - NASA **3D-Winds** (NRC Decadal Survey recommendation)
    - Full horizontal wind
  - ESA **ADM-Aeolus** (2012)
    - single horizontal wind component



Radiosonde	ADM

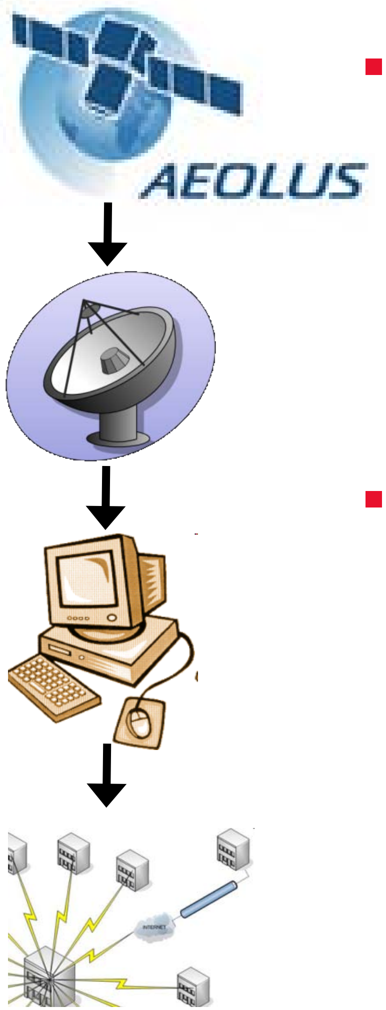
Observation Locations

ADM-Aeolus

- Direct-Detection technique (355 nm)
  - Vertical single-component profiles in clear sky (Rayleigh)
  - Higher quality measurements in presence of scattering agent (Mie)
- Orbit Characteristics
  - 408 km
  - Dawn-dusk
  - Sun-synchronous

- Viewing Geometry/Sampling
  - 90 off-track (away from sun)
  - 7 second measurements (~50 km)
  - One measurement every 200 km

ADM-Aeolus Pre-Assimilation Data Flow Chart



- Downlink
  - Location: Svalbard
  - Latency
    - Near-Realtime: 3 hr
    - Quasi-Realtime: 30 min
- Processing & Distribution
  - L1B distributed in NRT by ESA via GTS
  - L2B product will be produced by ECMWF (IFS)
    - NRT modeling centers will have to run L2B processing independently
      - Best scientific methodology due to first-guess dependency

ADM-Aeolus Pre-Launch Data Flow Chart

- Prior to launch, realistic data for system preparedness
  - Establish a realistic dataset for data assimilation system development
    - Local Proxy Data
    - Generated using OSSE framework
      - Purpose of this effort is not to "sell" instrument (already sold)
  - Establish a realistic end-to-end flow to test mechanics of system
    - NRT Proxy Data
    - To be considered closer to launch

Data Assimilation

- Variational Cost Function:

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}-H[\mathbf{x}])^T\mathbf{R}^{-1}(\mathbf{y}-H[\mathbf{x}])$$

- When minimized,

$$\mathbf{x} = \mathbf{x}_a \text{ (analysis state)}$$

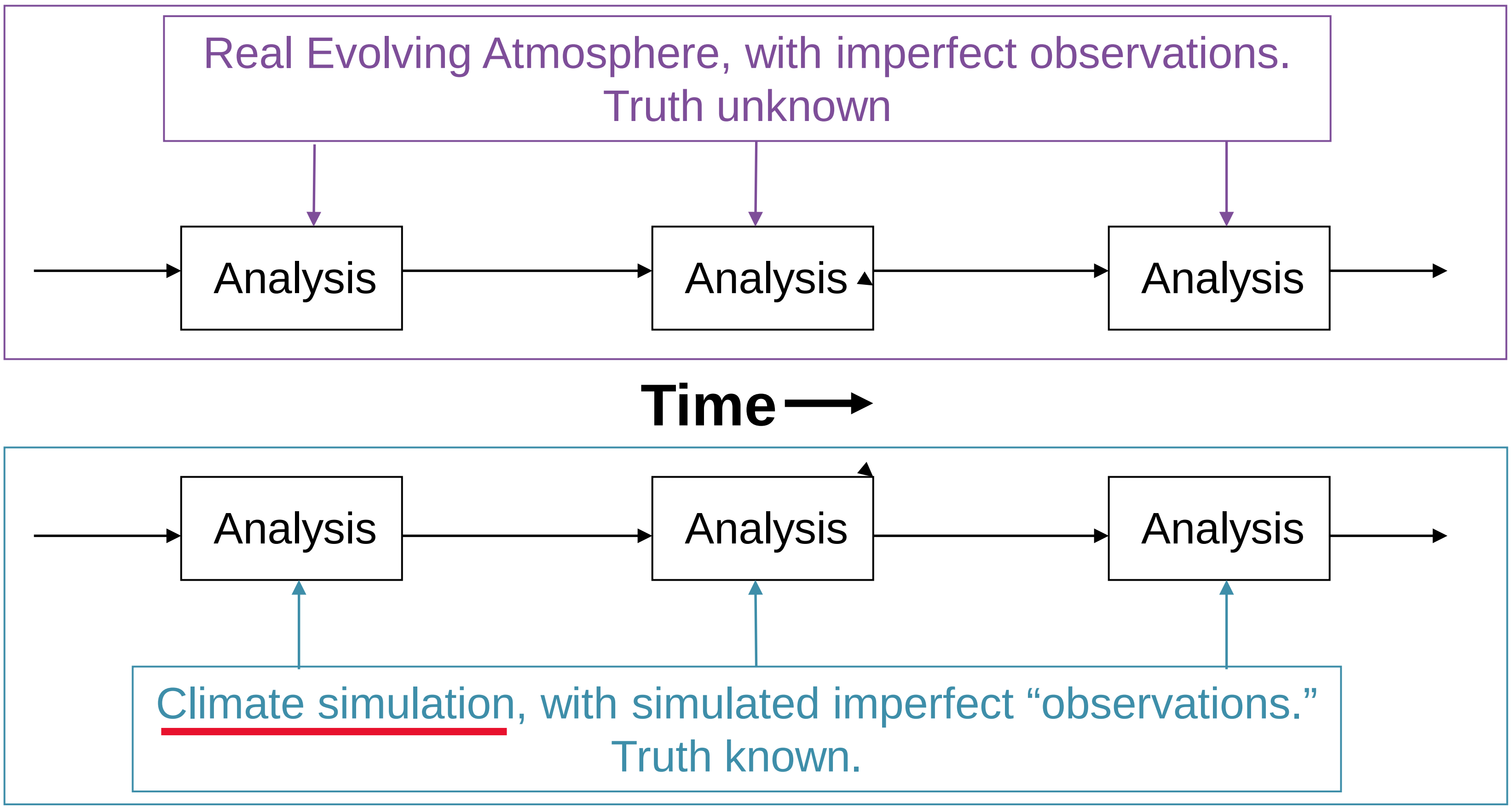
- *H*[**x**] transforms the atmospheric state to observation space
  - Currently, *H*[**x**] is a projection of the winds to line-of-sight space
  - Upon launch, *H*[**x**] will include L2B processing

OSSE for ADM Preparedness

- There is no predecessor for spaceborne DWL
- Sources of proxy data
  - Ground-based instruments
    - Inadequate spatial sampling
  - Adapt existing spaceborne measurements
    - Completely different in nature than spaceborne DWL
  - Simulated Observations
    - Can be simulated anywhere
    - If done properly, they can contain all of the necessary characteristics to best emulate real data:
      - Spatial and vertical sampling
      - Yield
      - Error characteristics

What is an OSSE

Assimilation of Real Data

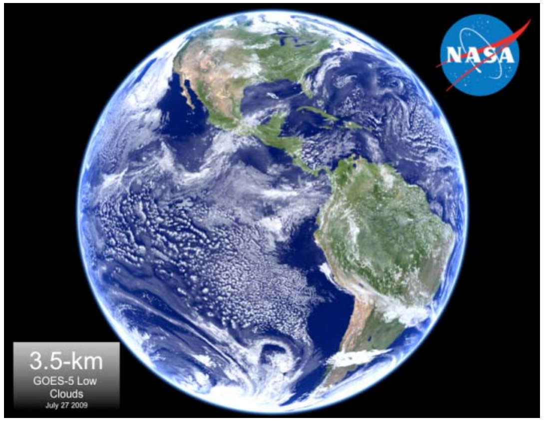


Observing System Simulation Experiment (OSSE)

(R. Errico)

The “Real” Atmosphere

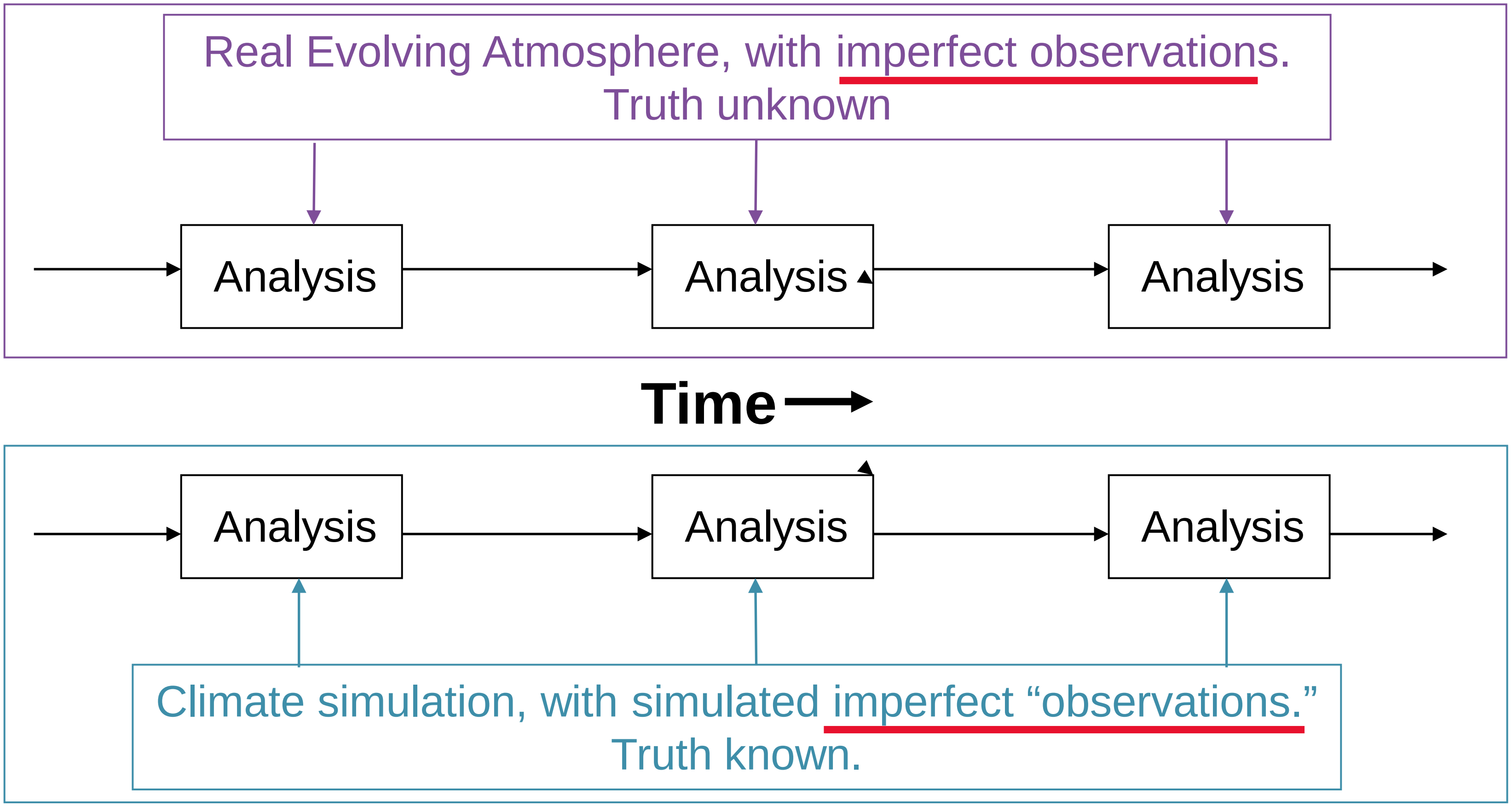
- In an OSSE, an atmospheric model is run in a climate (free-running) mode
  - This is the Nature Run (NR)
- The behavior of this atmosphere is essential to the process
  - Though artificial, it needs to be realistically chaotic
  - It is the truth
- Current Nature Run – Joint OSSE Nature Run
  - T511 ECMWF 13 month model run spawned in May 2005
- Future Nature Run – GMAO/GEOS-5 Hi-res Nature Run



3.5 km GEOS-5 Climate Simulation

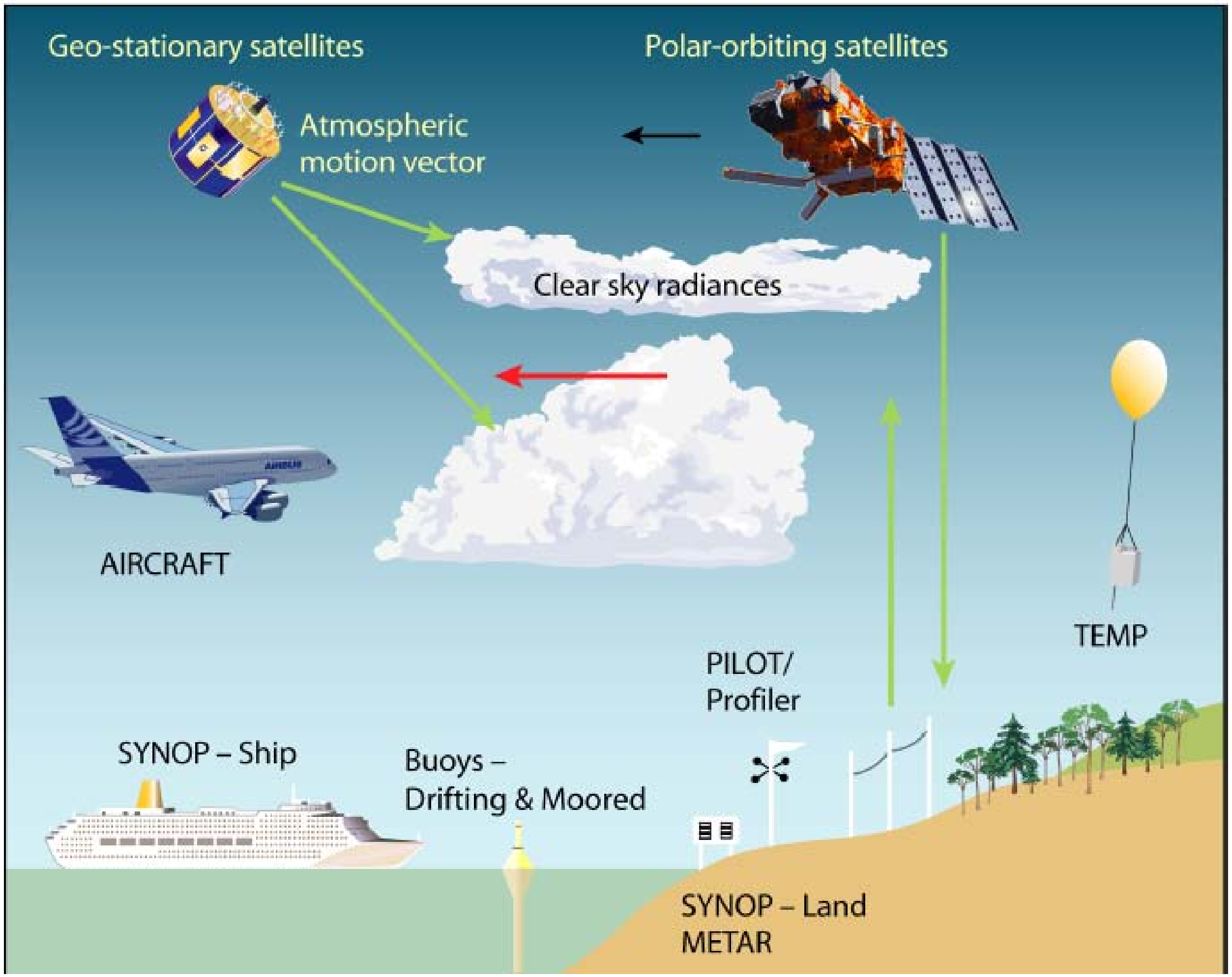
What is an OSSE

Assimilation of Real Data



Observing System Simulation Experiment (OSSE) (R. Errico)

Simulating Observations



- Six million+ observations are assimilated globally, daily
  - Most observations are from satellites
- A successful OSSE requires realistic fake observations

Figure via ECMWF

Simulating a Realistic Observing System

- The analysis solution (minimized cost function) can be written as

$$\mathbf{x} = \mathbf{x_b} + \mathbf{K}\left[\mathbf{y} - H(\mathbf{x}_b)\right]$$

- In an OSSE, your observations are

$$\mathbf{y} = H_z(\mathbf{z}) + \mathbf{e}$$

- The validity of a simulated observation network is dependent on the errors
  - Simulated observation errors (**e**) need to account for
    - Instrument noise
    - Observation contamination (data yield, i.e. clouds, precipitation)
    - Representativeness (sub-gridscale variability)

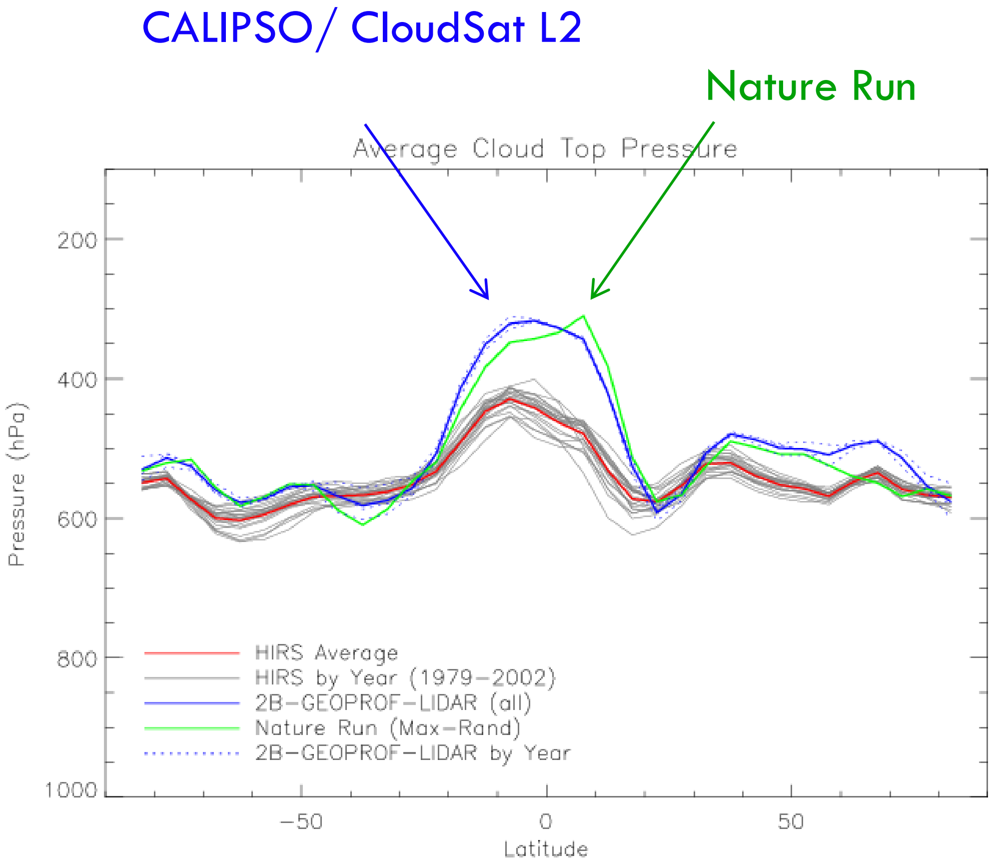
Simulating Doppler Wind Lidar Observations

- Simulation of ADM is dependent on key fields
  - Backscatter & extinction from the atmosphere, clouds, and aerosols
  - 3D wind field
- Only the wind field is inherent to the nature run
  - Molecular/Rayleigh backscatter – f(T,p)
  - Cloud backscatter/extinction – f(Cloud Fraction, CLWC, CIWC)
  - Aerosol backscatter/extinction
    - Not inherent to NR
- ADM measures at a scale finer than that of the NR
  - Need to account for sub-gridscale variability
- The DJF season of the NR is compared to the seasonally corresponding CloudSat/CALIPSO (CS/CAL) record

Comparing NR Clouds to CloudSat/CALIPSO

- Only cloud fraction is considered
- CS/CAL
  - Level 2B GEOPROF-LIDAR product
  - 1 km resolution along-track, reports up to five cloud layers
  - Only consider highest vertical cloud
- NR
  - A maximum-random overlap scheme implemented for sub-gridscale variability
    - Adjoining model levels to have maximum overlap
    - If two clouds exist in a vertical column with clear-sky between them, random overlap is assumed
    - Sampling the same as one season of the CS/CAL data
- Comparisons are made in 5   bins

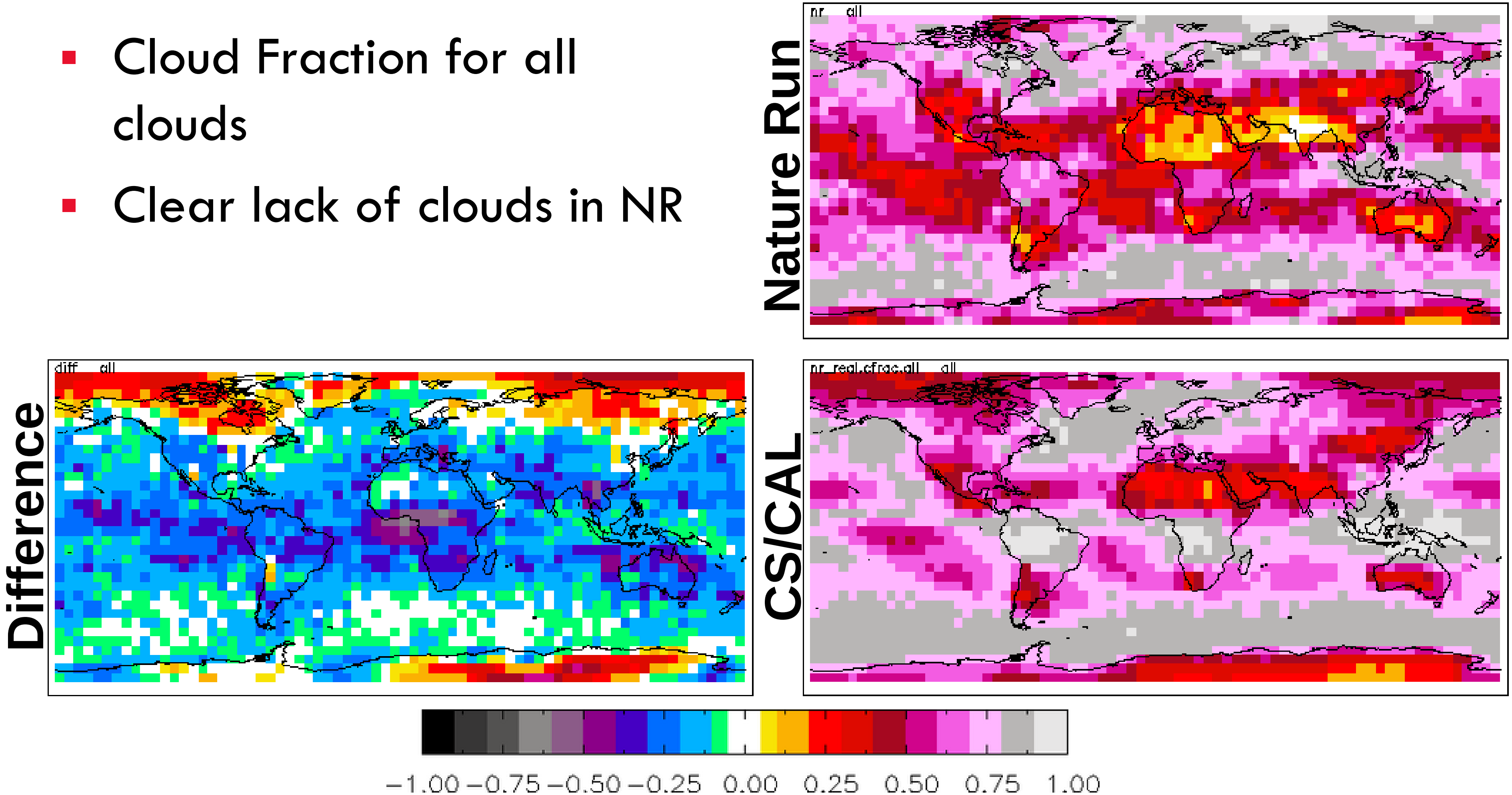
Clouds in the Joint OSSE Nature Run



- Importance of clouds
  - The top of a cloud can act as a scattering agent
  - Optically thick clouds limit wind retrievals
- Placement of clouds
  - Realistic vertical placement of clouds
  - NR underestimates cloud amount
    - ~12% globally
    - Related to measurement yield

Clouds in the Joint OSSE Nature Run

- Cloud Fraction for all clouds
- Clear lack of clouds in NR



Aerosols in the Joint OSSE Nature Run

- Importance of aerosols
  - Aerosols act as a scattering agent
- Placement of aerosols
  - Not available in the NR
  - Traditionally taken from a climatological background
    - Inconsistent with atmospheric state
  - Dynamically consistent aerosol fields
    - Unique GSFC effort
    - GOCART aerosol transport model embedded in the GEOS-5 model
      - Aerosol fields forced by the meteorology of the Nature Run

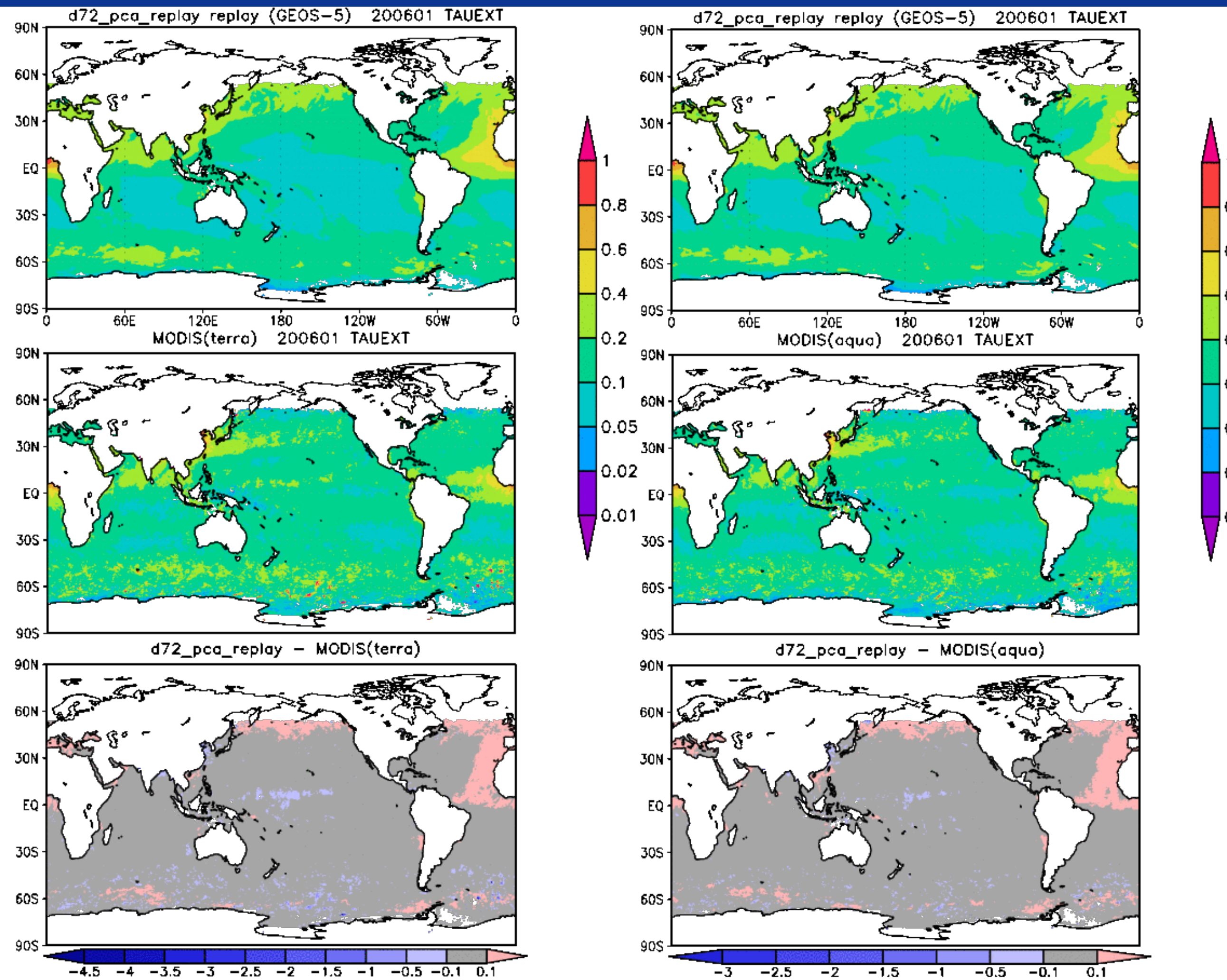
Aerosol Validation

- Replay aerosols compared to MODIS (Aqua and Terra, separately) and MISR
  - NR sampled at MODIS/MISR retrievals for consistency
    - Clear sky, daytime only
- Showing January of the Nature Run versus real January 2006

Aerosol Validation

- Terra (left)
- Aqua (right)

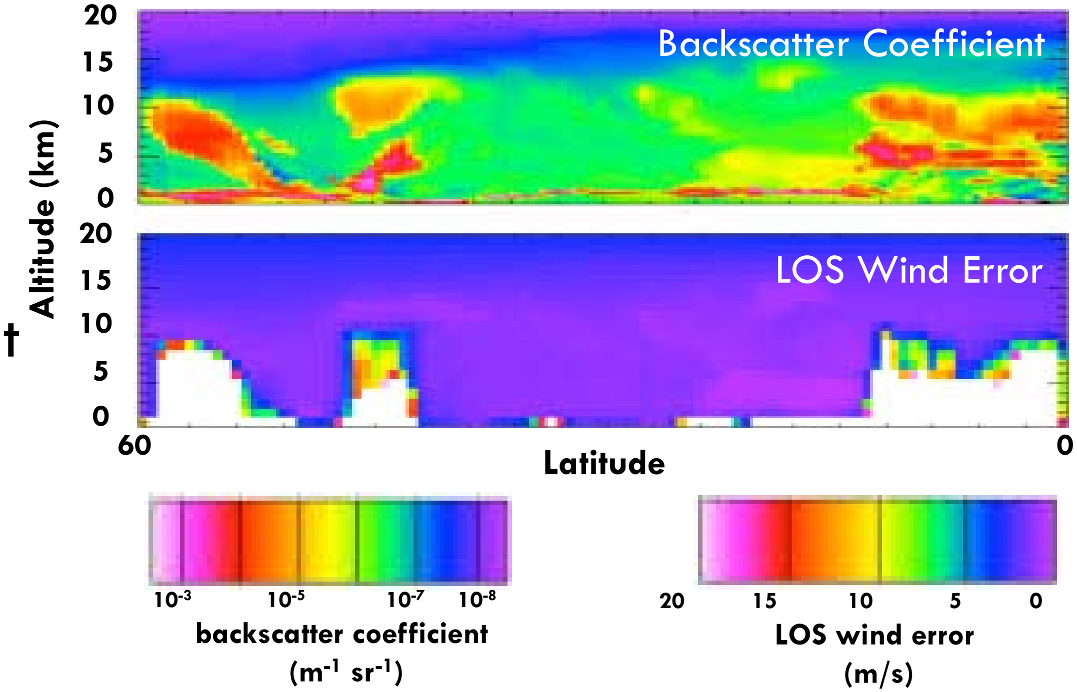
- NR (top)
- MODIS (middle)
- NR – MODIS (bottom)



(R. Govindaraju)

Simulated Doppler Wind Lidar Observations

- Simulated from a modeled atmospheric state
- Errors increase with height
- Clear-Sky backscatter coefficient and line-of-sight wind error are inversely proportionate
- Clouds degrade measurement quality



(M. McGill, S. Palm)

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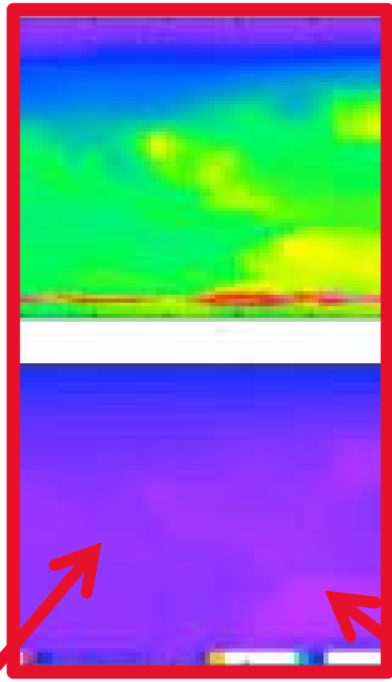
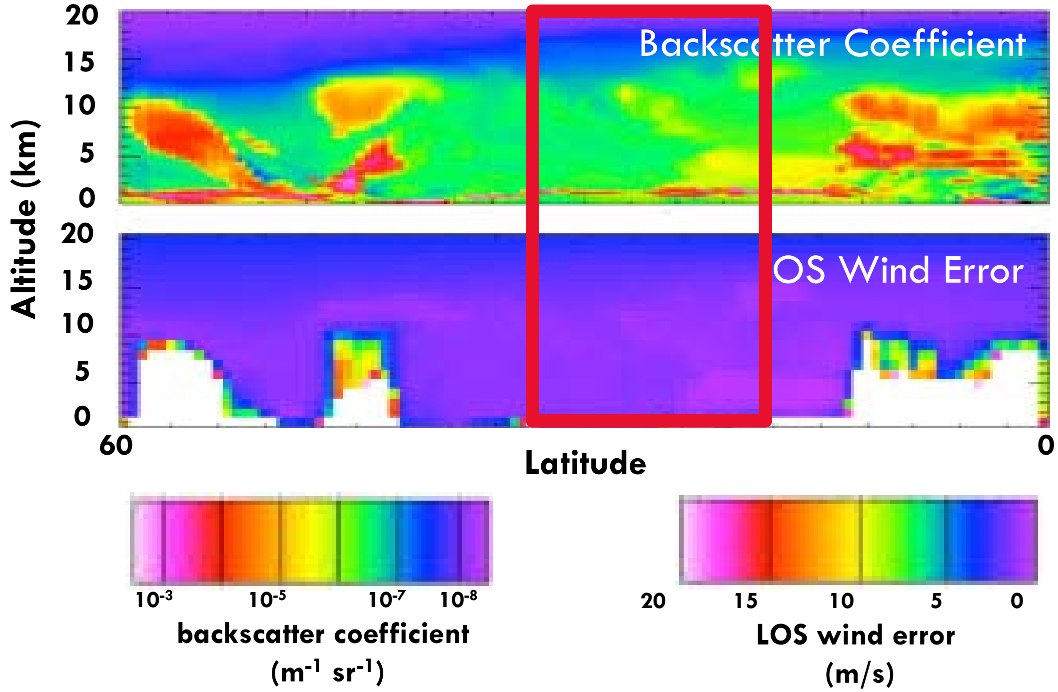


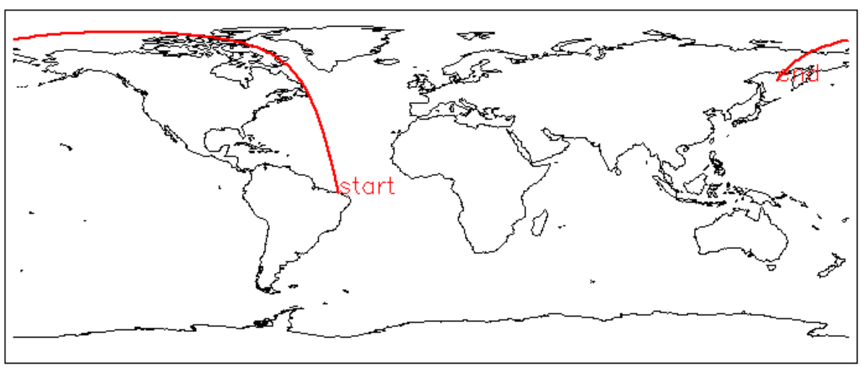


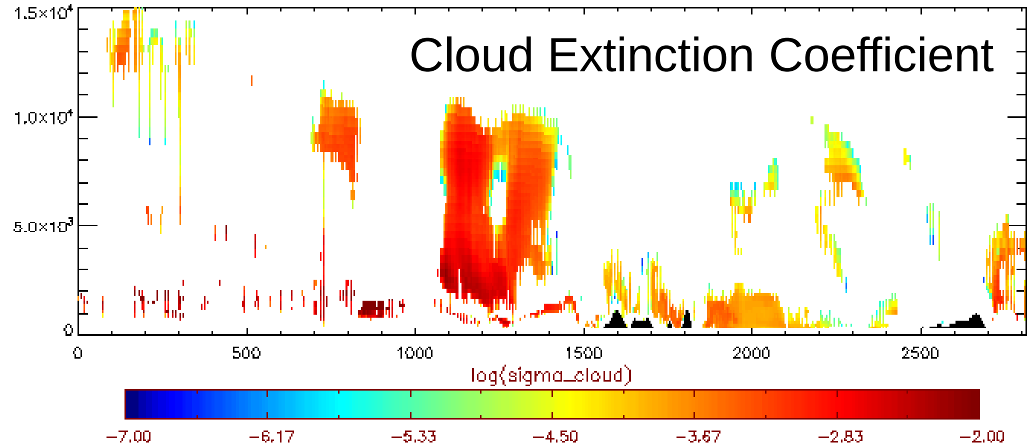
- Molecular detection full wind profiles vertically
- Aerosol detection has reduced error

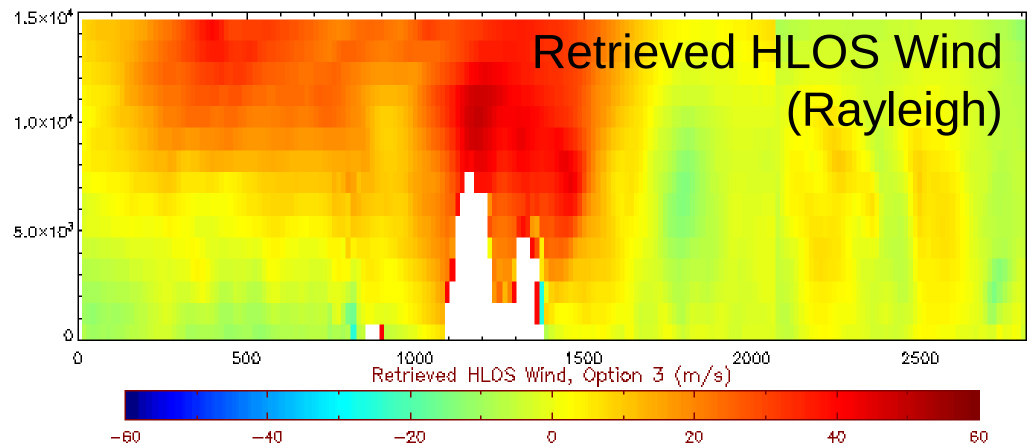
(M. McGill, S. Palm)

Simulated Doppler Wind Lidar Observations

- Simulated ADM measurements
  - Nature Run
  - LIPAS
    - ADM Simulator developed at KNMI
  - Not run in “Burst Mode”







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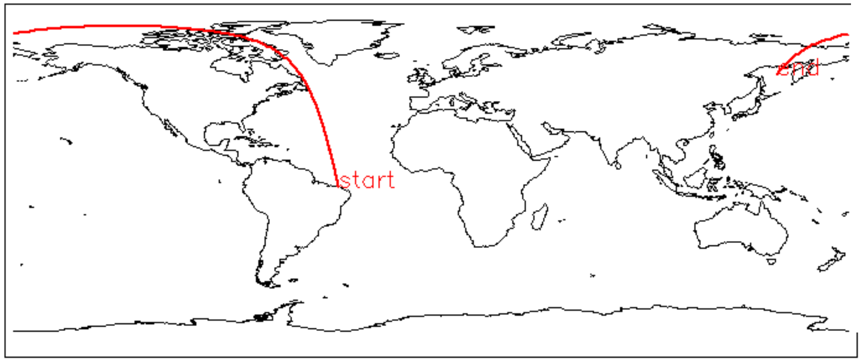

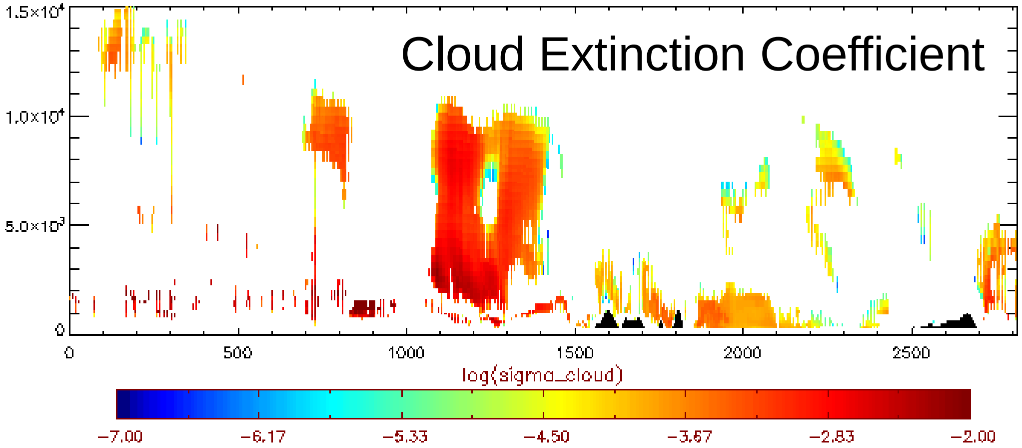

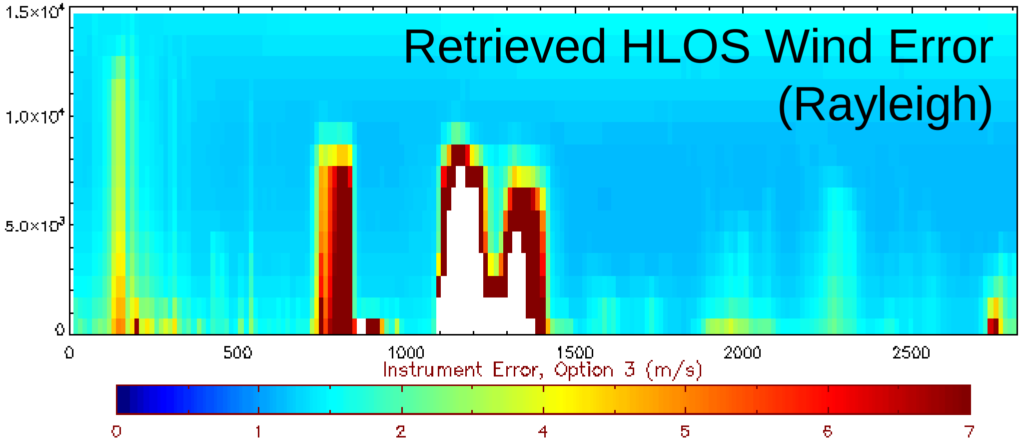

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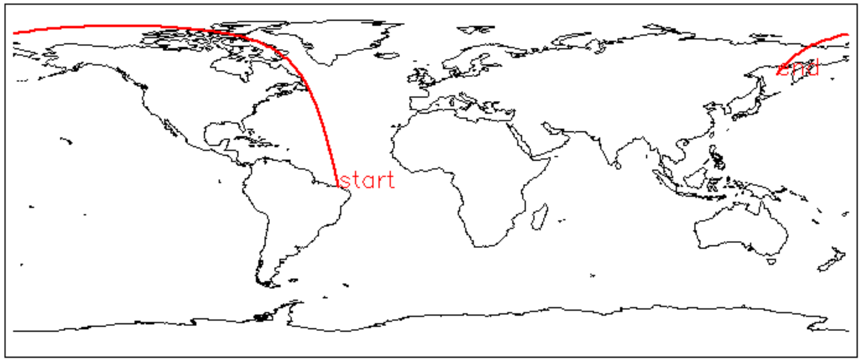
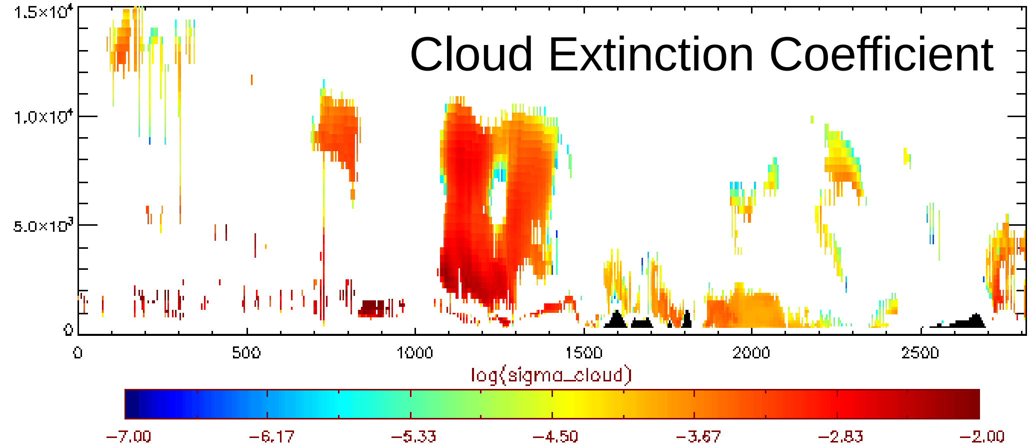
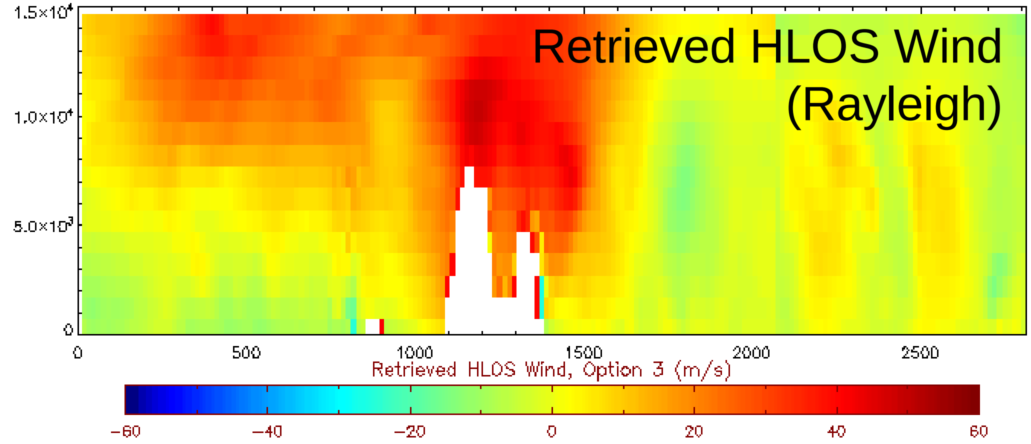
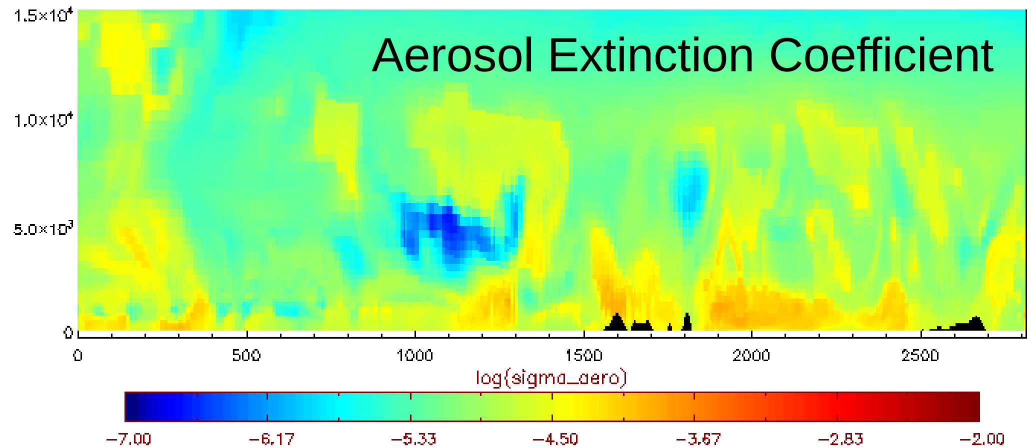


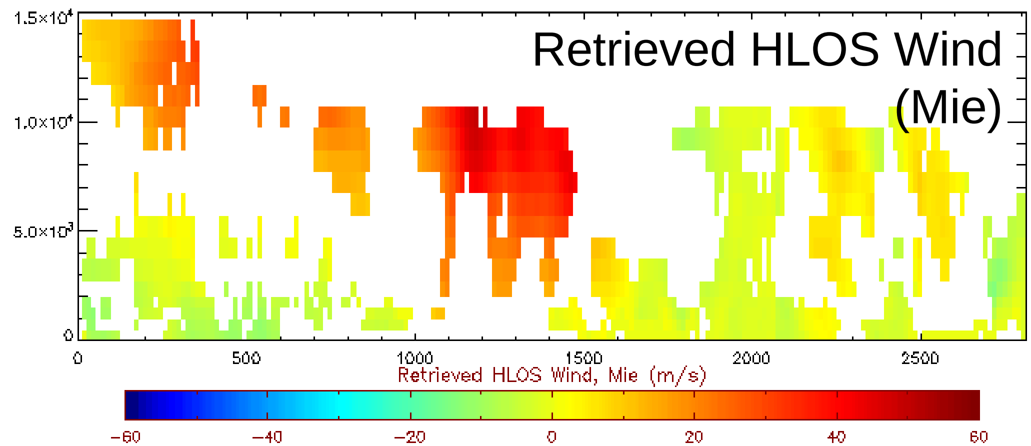


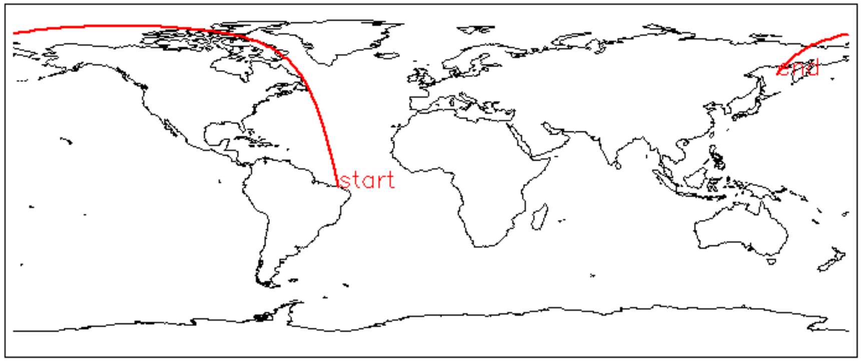


Simulated Doppler Wind Lidar Observations

- ADM Obs (cont'd)
  - cloud and aerosol fields consistent
  - Mie channel sampling illustrated





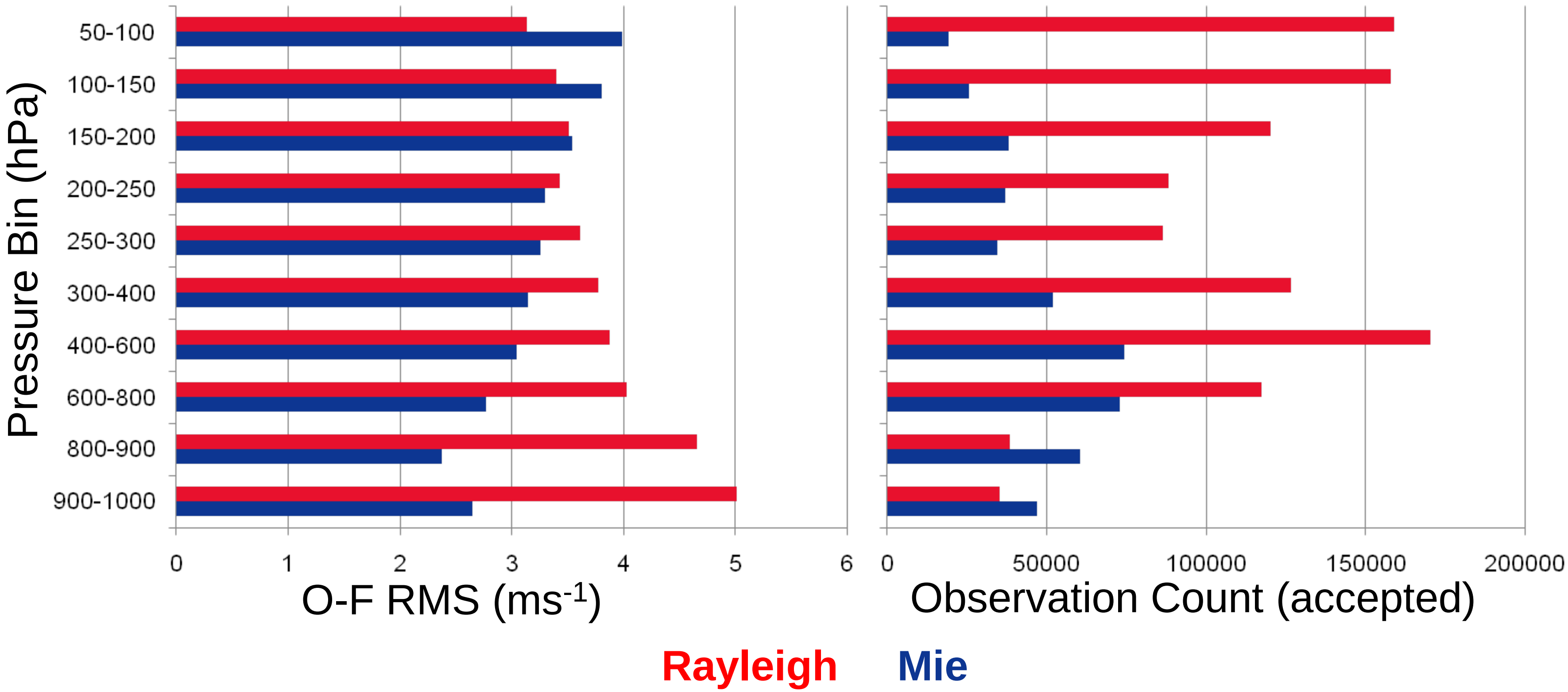


Assimilation and Forecast Impacts

- The results shown are applicable to January of the nature run period
  - DAS Runs every 6 hr with a +/- 3 hr observation window
- Analyses are considered 2x/day (00/12 UTC)
- Forecasts are considered 1x/day (00 UTC)
- Observations included in Control
  - Based on operational data for Jan. 2006
  - Conventional (incl. RAOB & Satellite Winds), TOVS (MSU, AMSU A/B, HIRS), AIRS
- Observations for DWL Experiment
  - Control + ADM

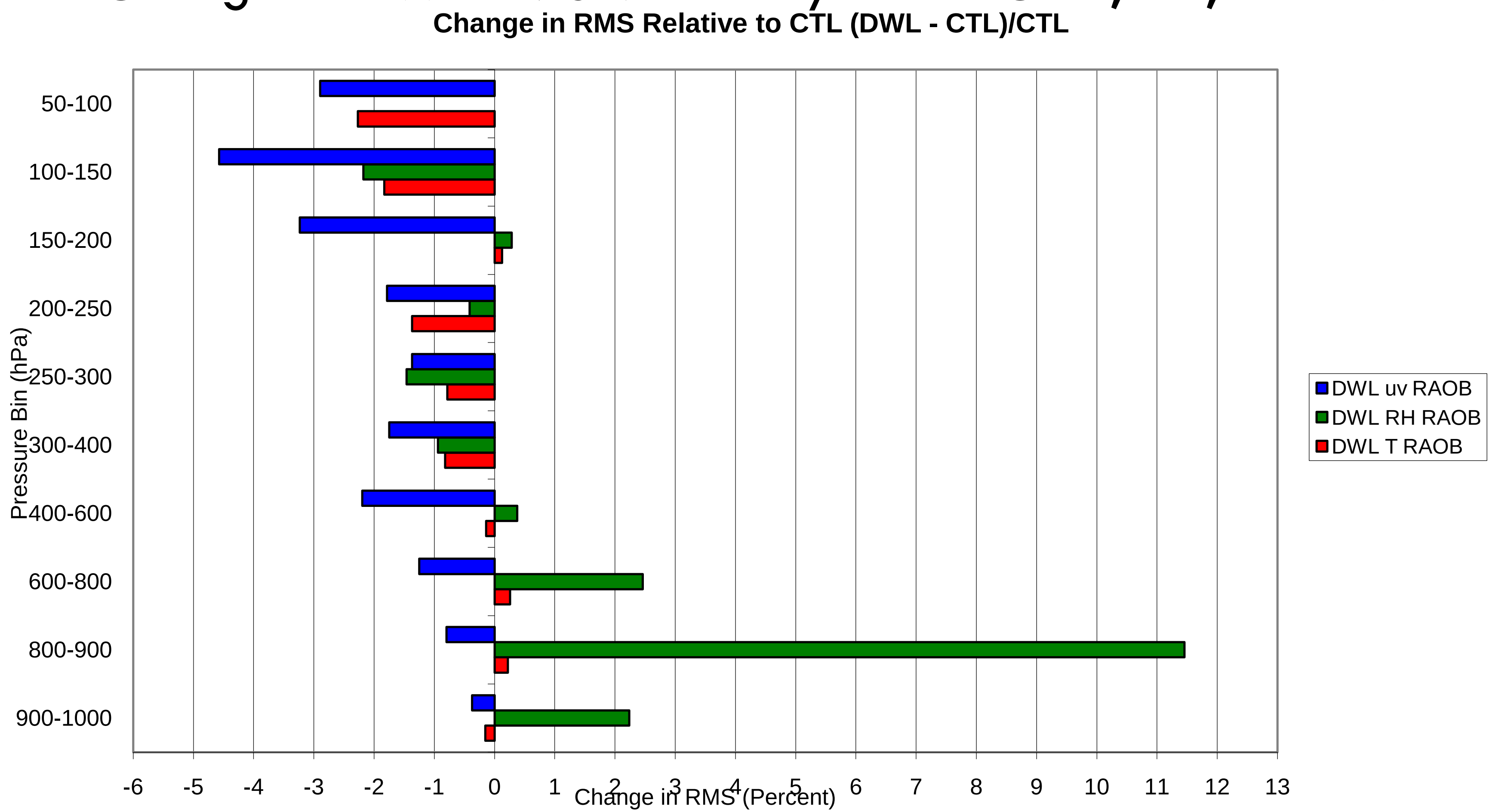
Assimilation Results

- Doppler Wind Lidar O-F RMS & Counts vertically
  - Full Month, All Cycles (00, 06, 12, 18 UTC)



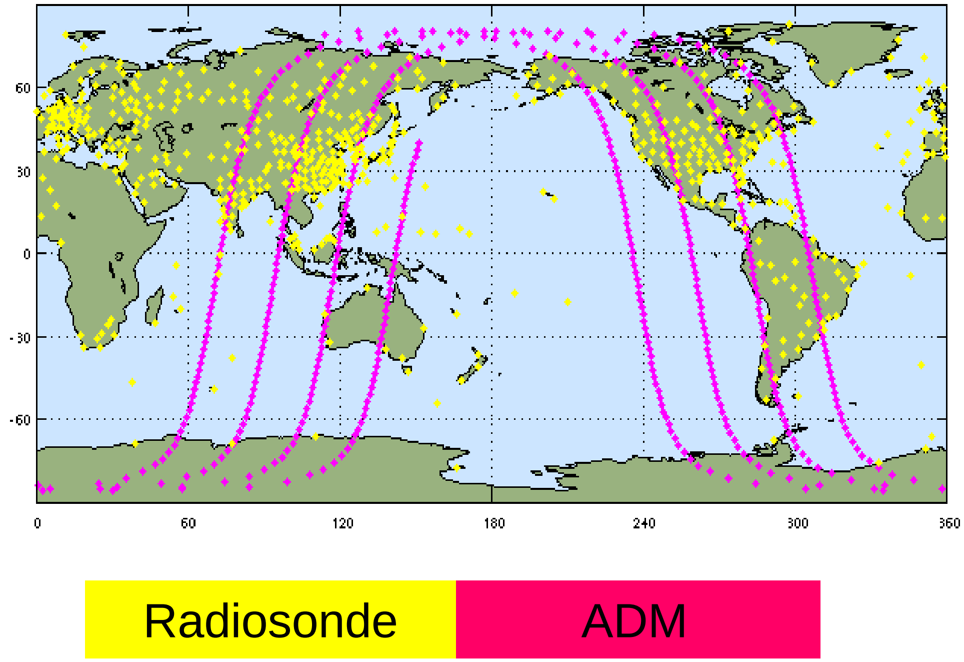
Assimilation Results

- Change in DWL RMS Vertically for RAOB T, RH, and uv



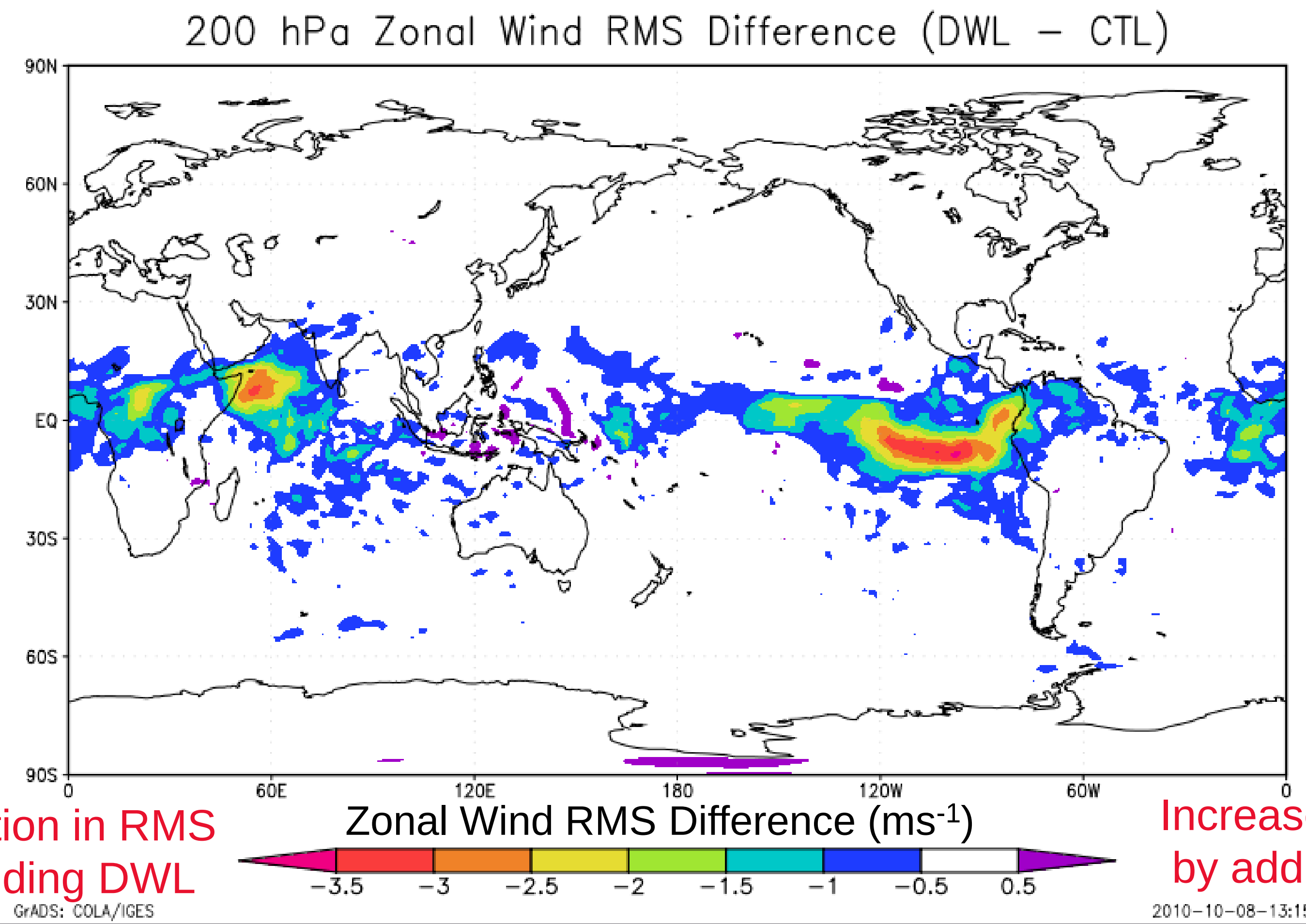
Assimilation Results

- RAOB observations biased towards Northern Hemisphere midlatitudes
- OSSE framework allows comparison between the analysis and a known truth in analysis space



Observation Locations

Assimilation Results



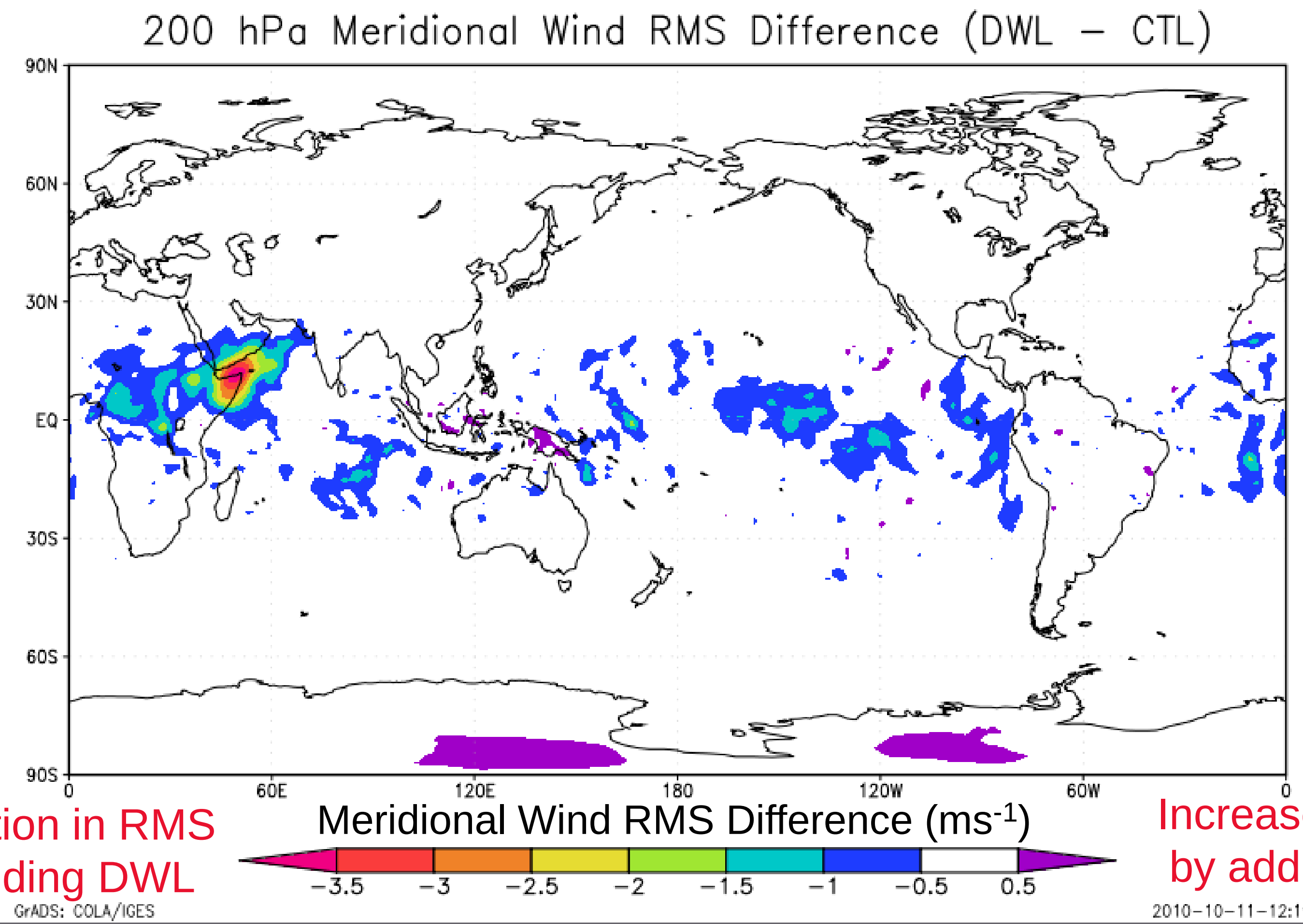
Reduction in RMS by adding DWL

Increase in RMS by adding DWL

RMS calculated for exp ANL versus NR Truth

Difference of RMS for DWL and CTL presented

Assimilation Results



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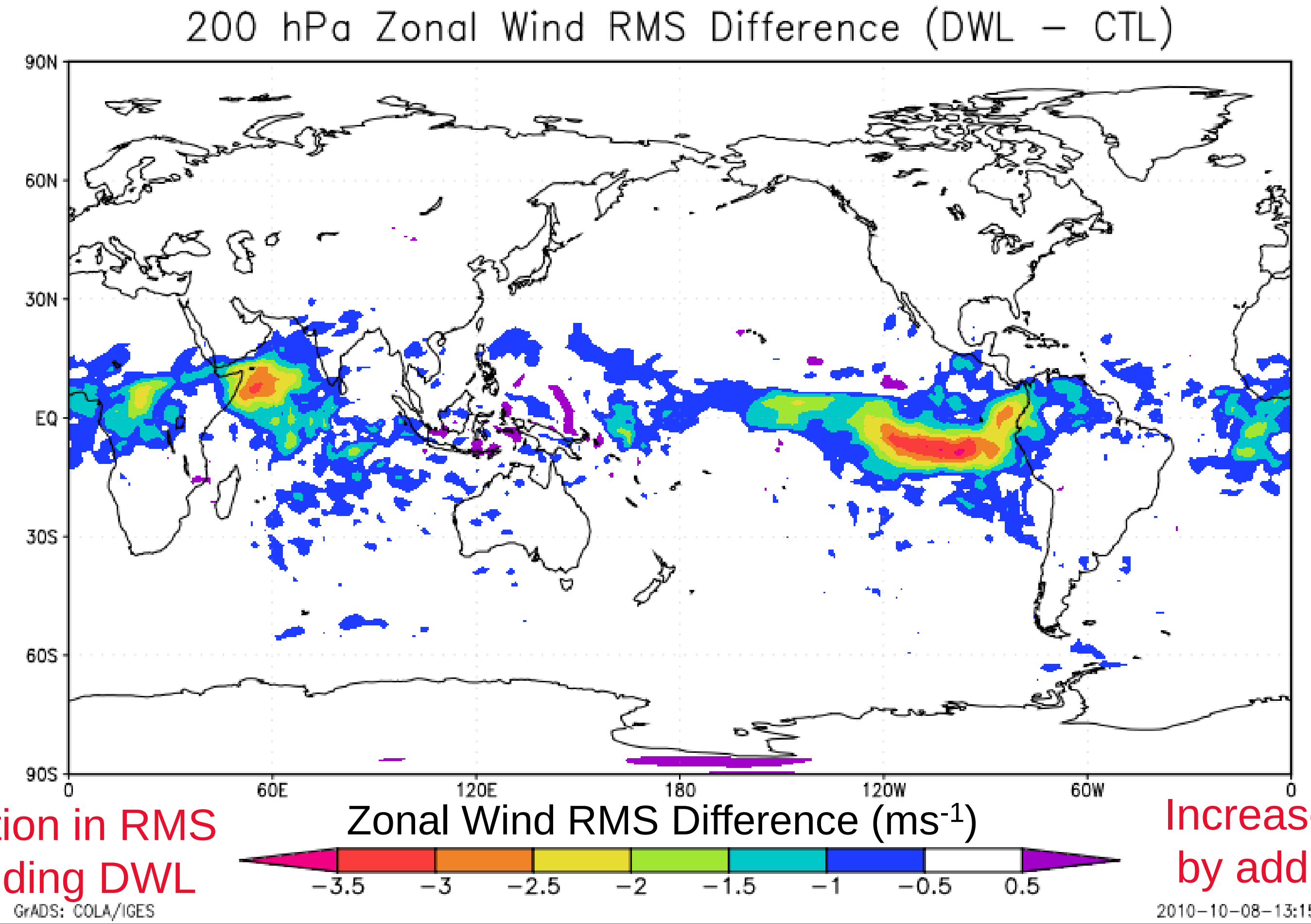

Reduction in RMS by adding DWL

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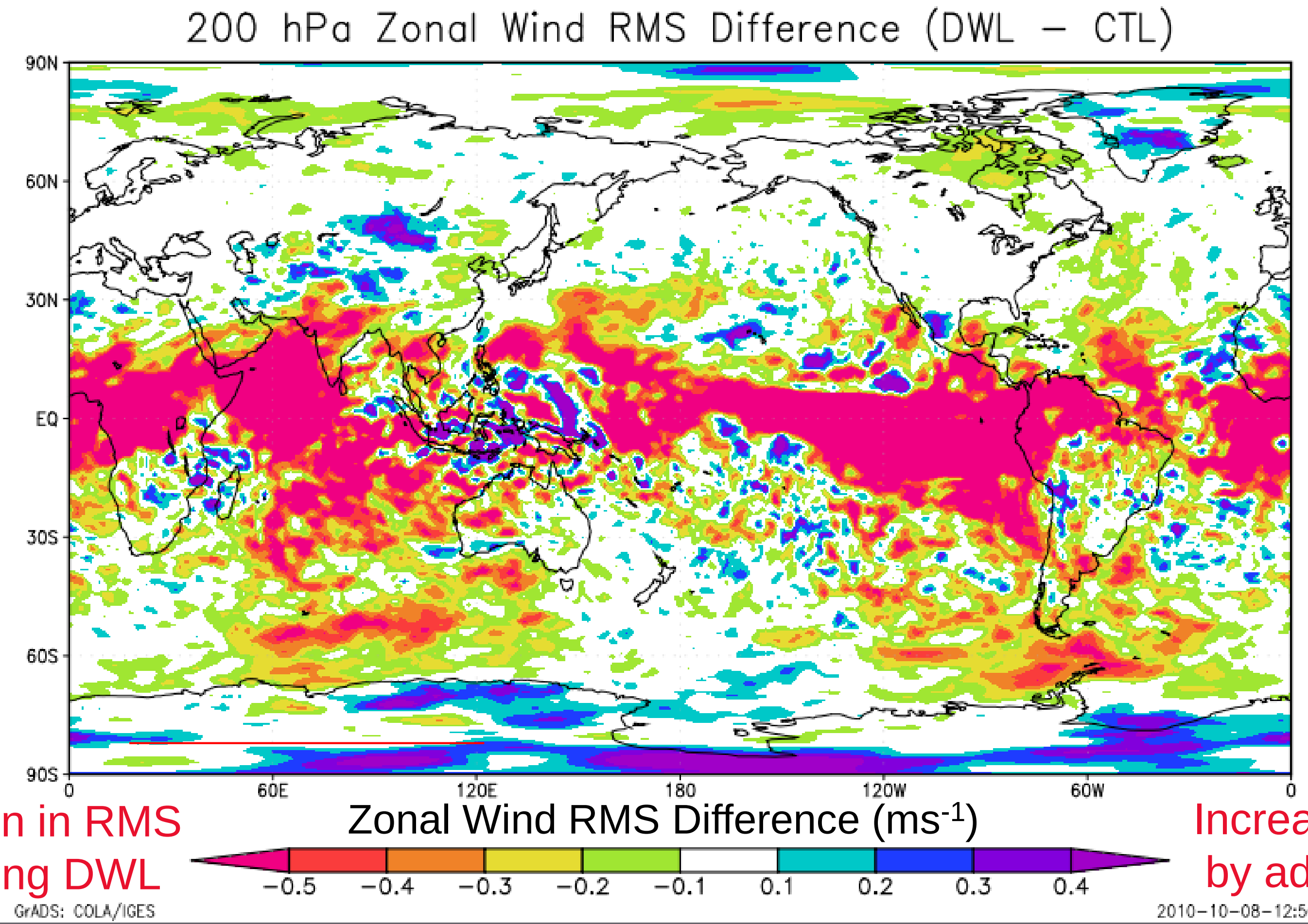

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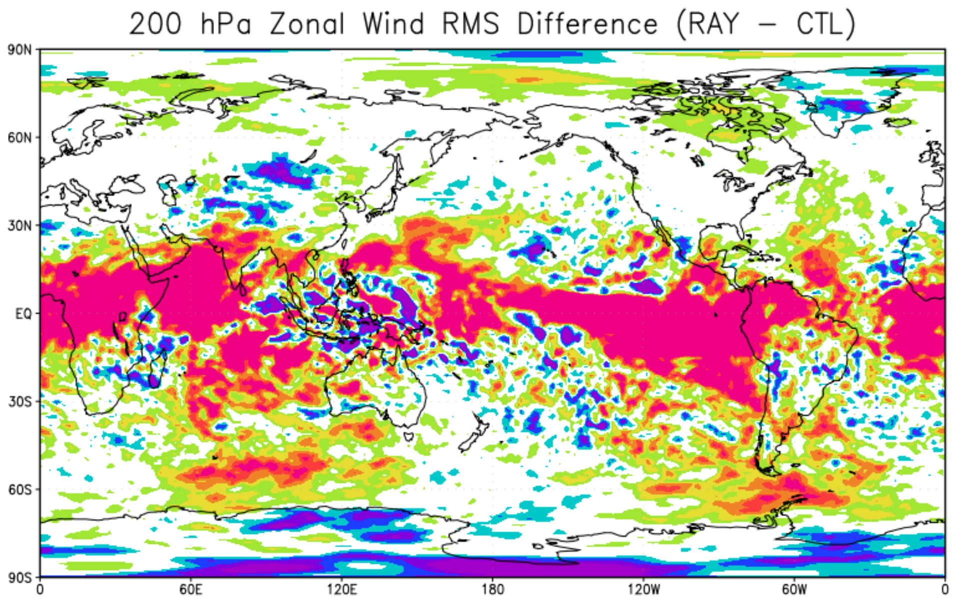
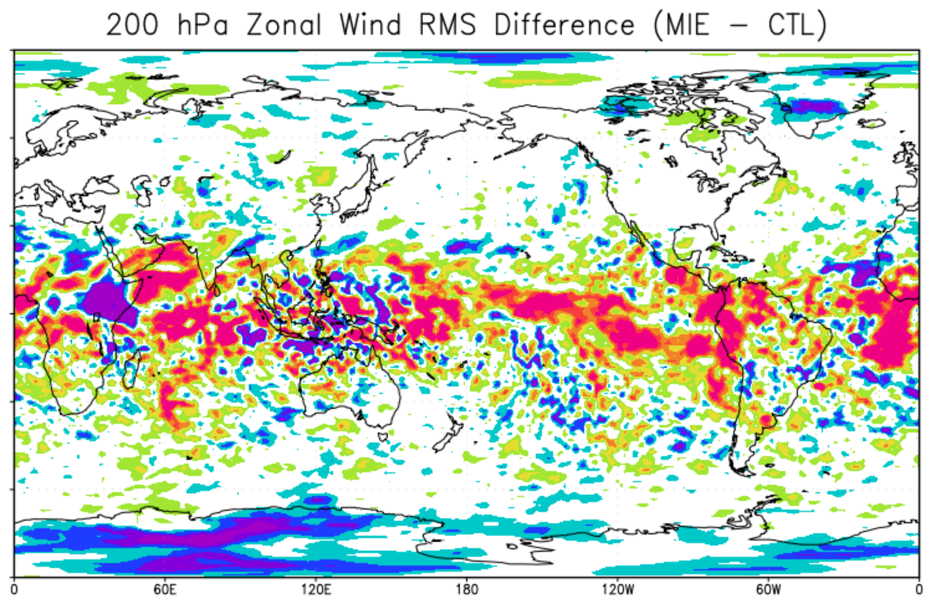


Rayleigh Only



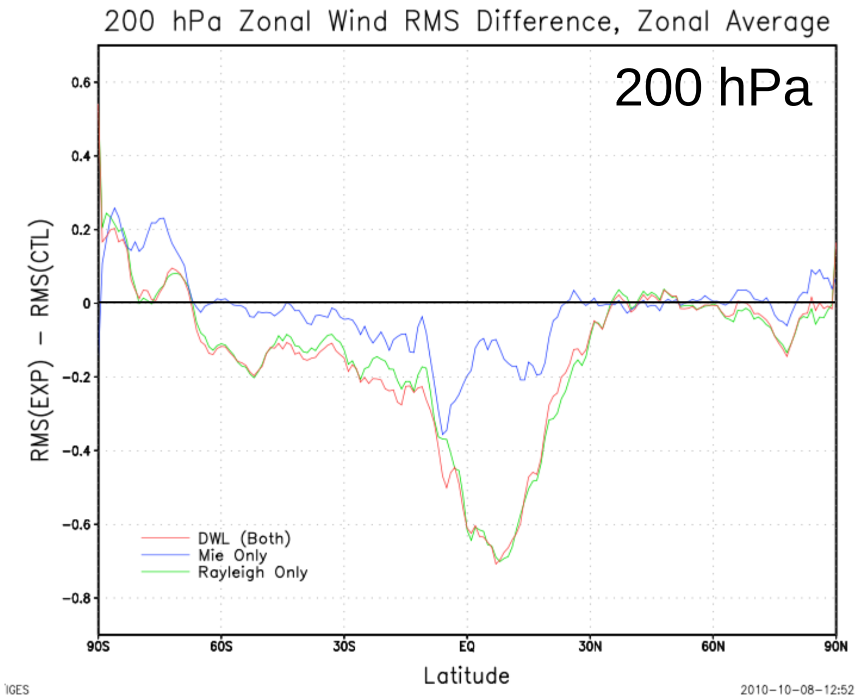
Mie Only

Reduction in RMS by adding DWL

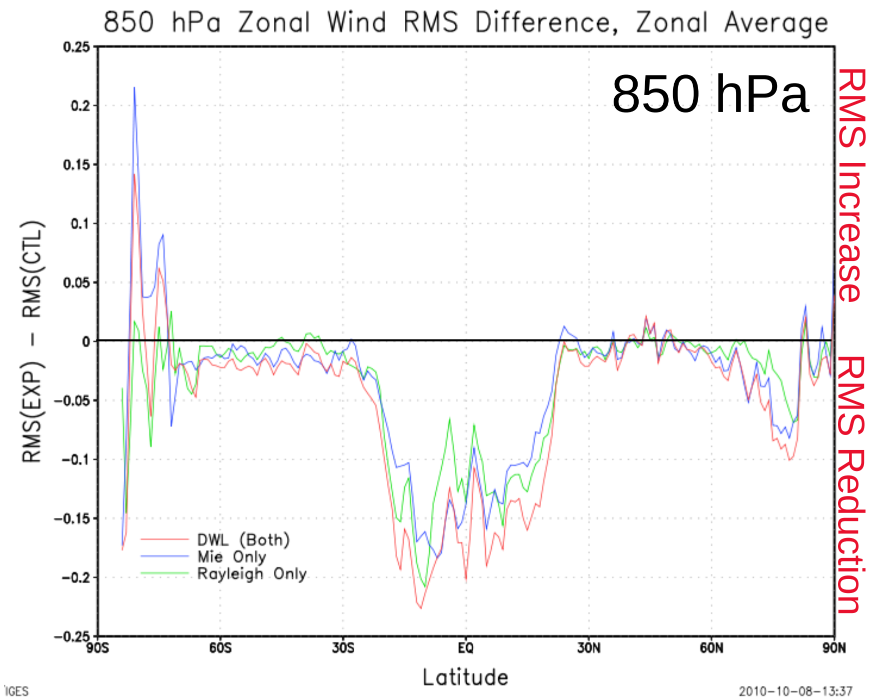
Increase in RMS by adding DWL

Zonal Wind RMS Difference (ms^{-1})

Assimilation Results



- Aloft, largest impact from Rayleigh measurements
- Below, comparable, but not additive, impact seen from both



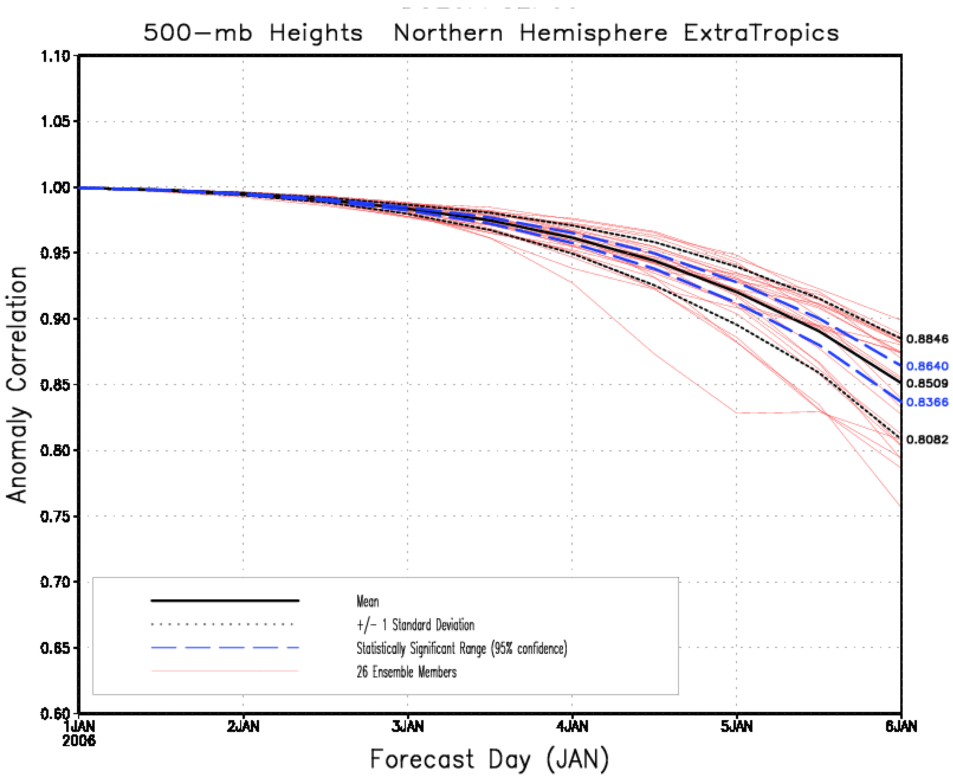
Experiments:

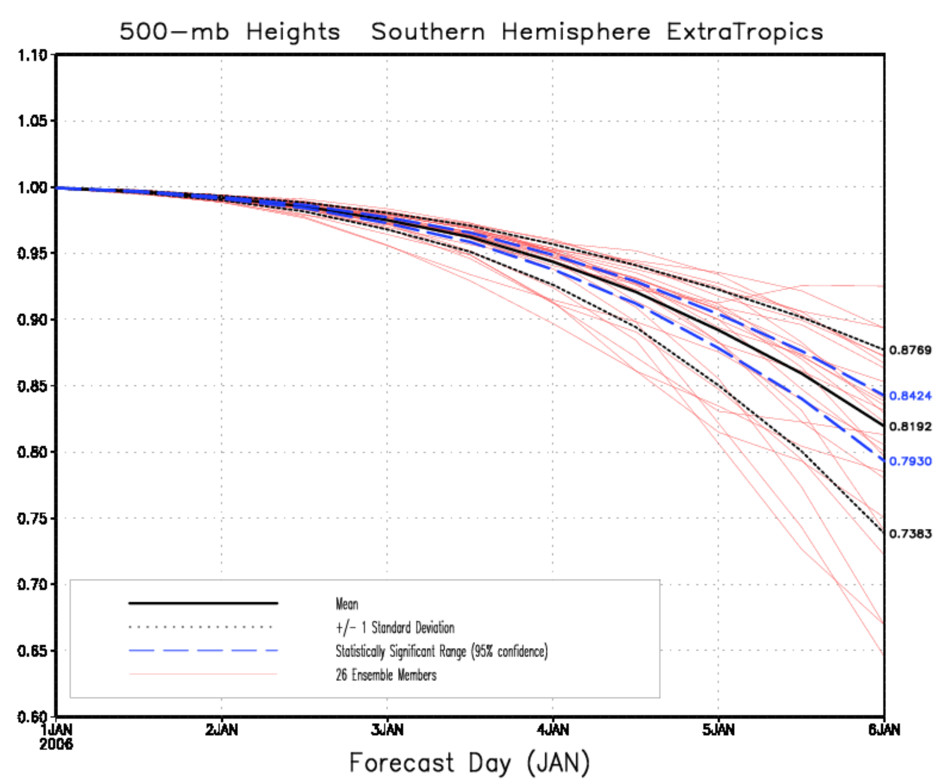
DWL (Rayleigh + Mie)

Rayleigh

Mie

Impact on Forecast



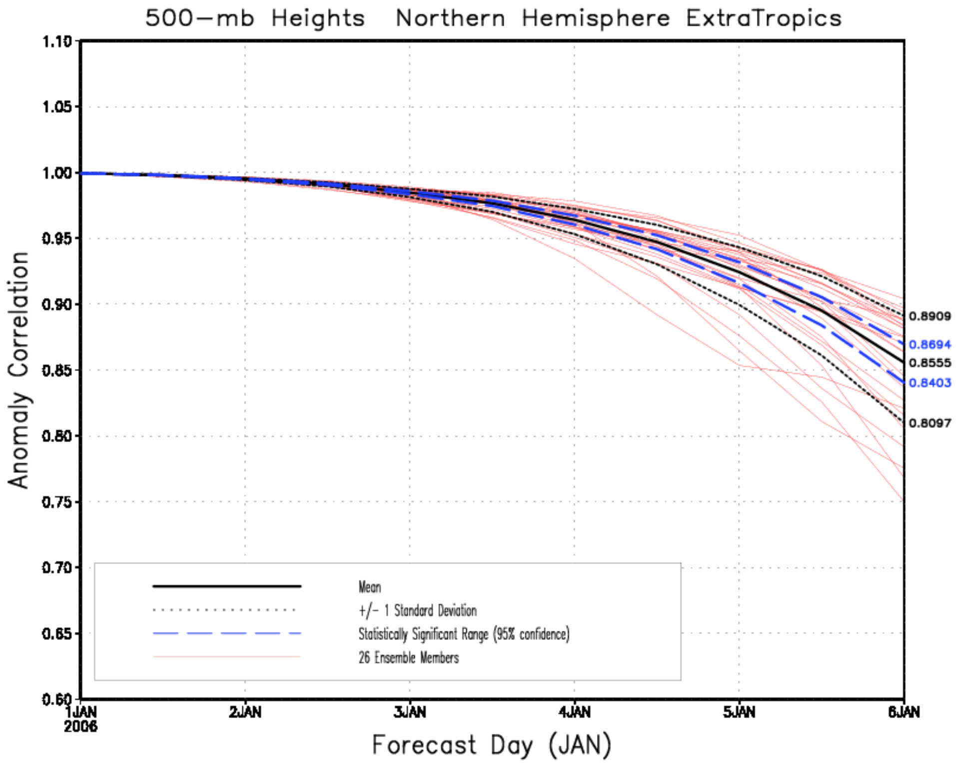


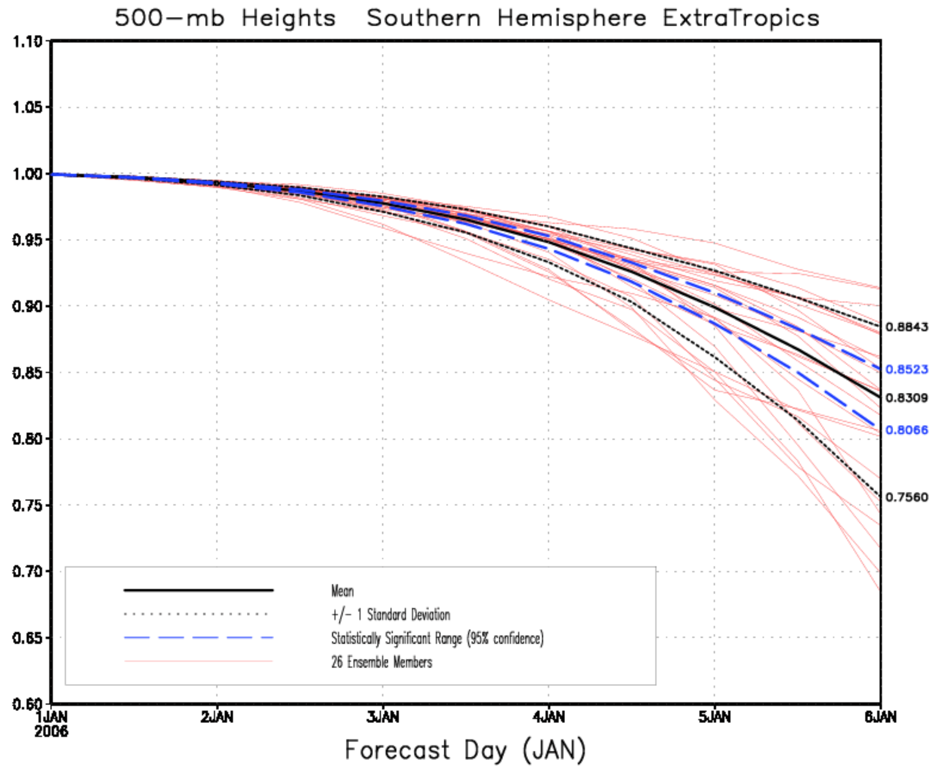
500 hPa Height Anomaly Correlation (CTL)

NH – 0.8509

SH – 0.8192

Impact on Forecast





500 hPa Height Anomaly Correlation (DWL)

NH – 0.8555

SH – 0.8301

Conclusions and Future Efforts

- There are known flaws with the current use of ADM data in the OSSE experiment
  - Observations are too ideal (quality & quantity)
  - Representativeness errors are underspecified
- Expand experiment to increase statistical robustness
- ADM Effort readily translates to studies for 3D-Winds decadal survey mission
- Incorporate L2B processing into GSI system
  - Accelerate ADM/future DWL observation usage into operations
  - Joint Center for Satellite Data Assimilation task

Aerosol Validation

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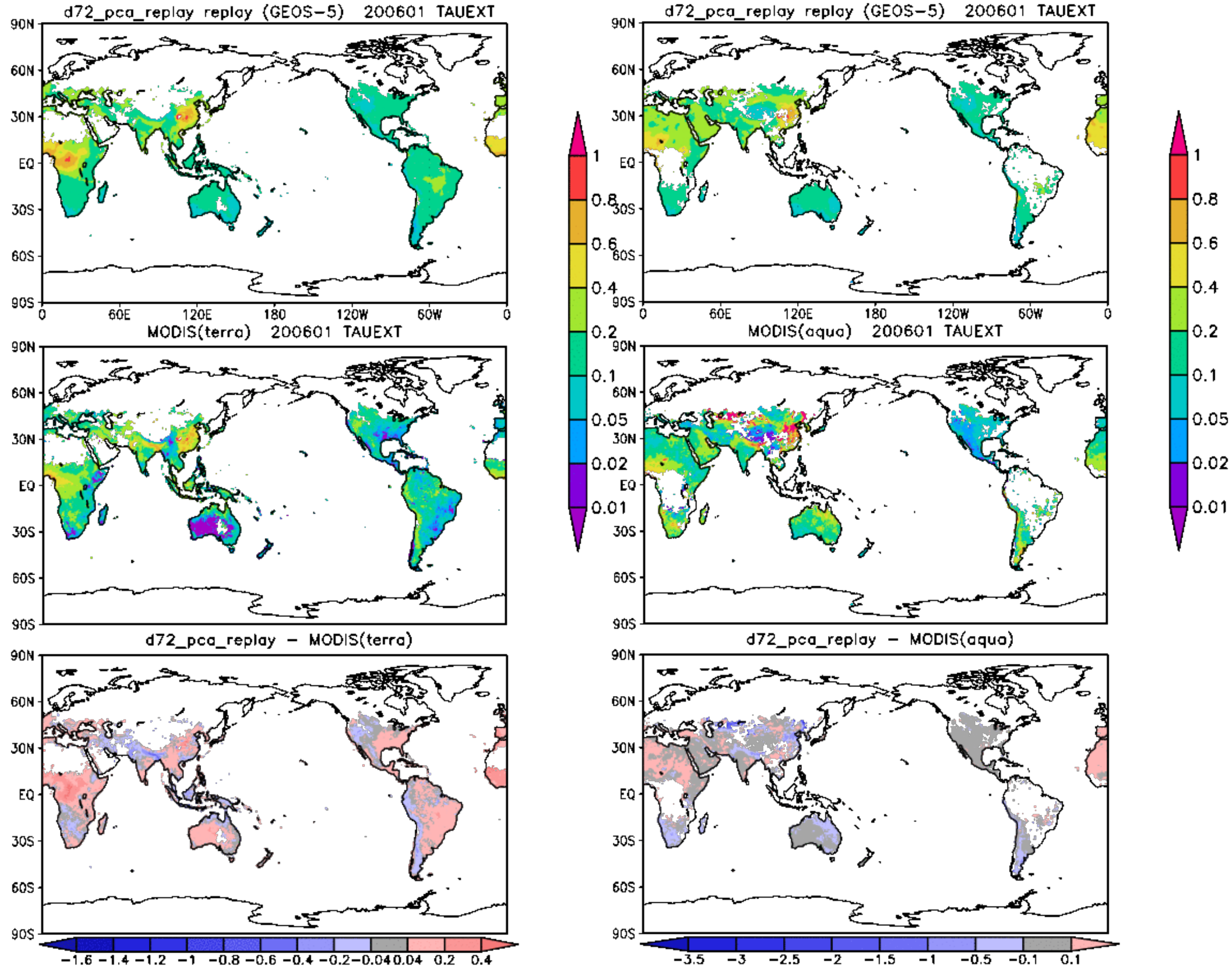
- MODIS (middle)
- NR – MODIS (bottom)



(R. Govindaraju)

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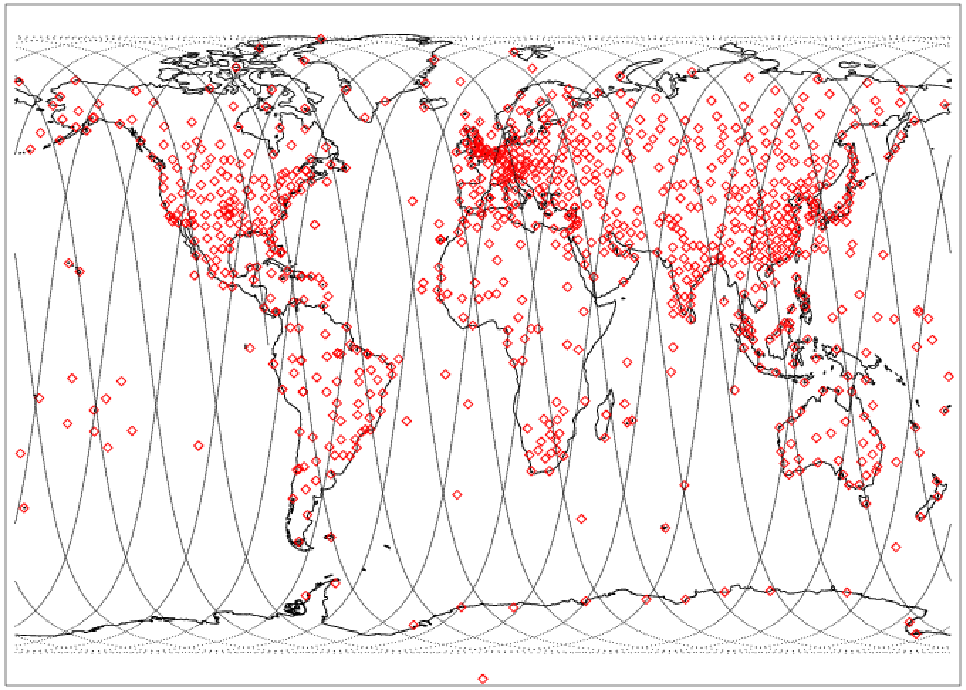
  - NASA **3D-Winds** (NRC Decadal Survey recommendation)
    - Full horizontal wind



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  - Location: Svalbard
  - Latency
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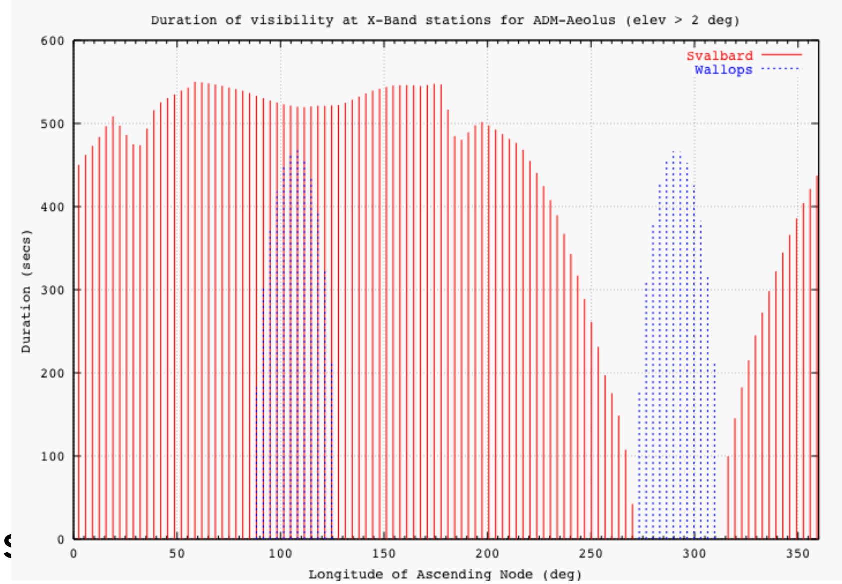
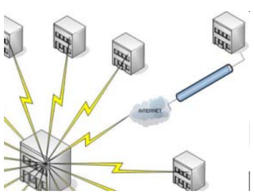
  - Coverage Gaps
    - N. America in NRT
    - N. America and S. Hemis in QRT
    - Wallops Ground Station solution for data gaps being considered



ADM Pass Duration at Svalbard (red) and Wallops (blue)
(L. P. Riishojgaard)

ADM-Aeolus Pre-Assimilation Data Flow Chart



- Near-Realtime Processing & Distribution
  - L1B distributed in NRT by ESA
  - BUFR table description not finalized
    - BUFR is a WMO standard for data distribution
  - L2B will be produced by ECMWF as part of integrated forecast system (IFS)
    - Unavailable to other operational systems (timeliness)
    - All major DA centers will have to run L2B processing independently
      - Best scientific methodology due to first-guess dependence of the processing

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}-H[\mathbf{x}])^T\mathbf{R}^{-1}(\mathbf{y}-H[\mathbf{x}])$$

$$\mathbf{y} - H[\mathbf{x}] = \mathbf{y} - (H[\mathbf{x}_b] + \mathbf{H}\delta\mathbf{x})$$

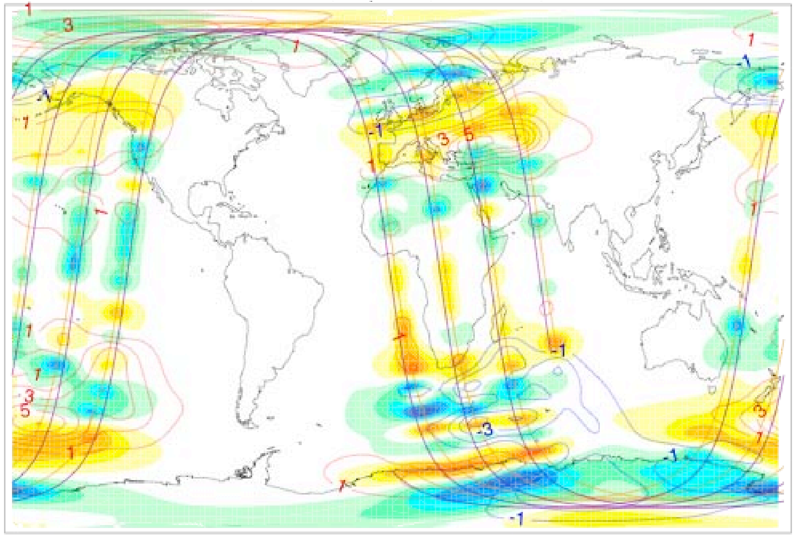
- $H[\mathbf{x}]$ transforms the background/guess state to observation space
  - If in the same space, as simple as an interpolation
  - If in different space, H can be radiative transfer (radiances), a projection of the winds (DWL LOS or radial winds)
- To solve the minimization, the H operator is linearized about the background state to form $\mathbf{H}$
  - To compensate for nonlinearities, multiple linearizations, or outer loops, are performed in the analysis solution

Doppler Wind Lidar and Data Assimilation

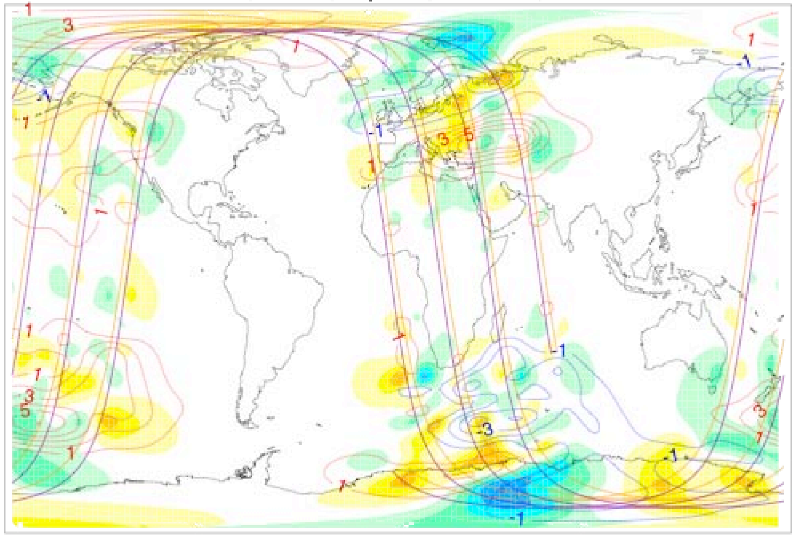
- Dynamics and Thermodynamics statistically coupled via the B matrix
  - Works fairly well for the extratropics and synoptic situations
- So why busts?
  - Ageostrophy = a more complicated forecast
  - Primary global measurements are passive sounders (MW & Thermal IR)
  - Global wind measurements (Scatterometers & GEO winds)
    - Poor vertical sampling
    - Poor vertical height assignment
    - Spatial sampling dependent on presence of a feature to track (i.e. cloud edge, WV gradient)
    - Necessary to constrain the statistical balance coupling
    - Poor error characterization

Assimilation of Simulated Doppler Wind Lidar Measurements in Preparation for 3D-Winds and ADM

Analysis Inc 200 hPa **u-comp** (shaded), T_v



Analysis Inc 200 hPa **v-comp** (shaded), T_v



- Infrastructure in development to simulate line-of-sight measurements from Joint OSSE Nature Run
- 1st step: ADM-like orbit, no addition of error, crude account of cloud structure (no aerosol considerations)
- Our data assimilation system (GSI) updated to assimilate these Level-2 measurements

Ongoing and Future Efforts

- NR cloud verification journal article (in progress)
- Aerosol verification (in progress)
- NR cloud tuning – need to compensate for apparent lack of clouds in NR
- ADM simulation (in progress)
  - Use existing DA infrastructure for verification of simulations
- DA studies (future)
  - Full observation system development (in progress)
  - Refine DA methodologies for ADM, (QC and error handling)
- OSSE studies (future)
  - Consider use and utility of new GMAO 3.5 km NR
  - Perform "classic" OSSE for 3D-Winds proposal

Aerosols from Nature Run

- Aerosol fields generated for entire duration of the Joint OSSE Nature Run
- Meteorology of the nature run is converted from ECMWF native (reduced Gaussian) grid to GEOS-5 native (finite volume square) grid
- Using real sources from the 2005-06 period, the aerosols are transported in a "replay" mode using GOCART scheme embedded in the GEOS-5 model.
  - The model is re-initialized every three hours using the converted NR fields\

Aerosols from Nature Run (cont'd)

- Aerosols/chemical species considered:
  - Dust, sea salt, dimethylsulphide, SO_2, Sulphates, Methanesulphonic acid, hydrophobic/hydrophilic black carbon, hydrophobic/hydrophilic organic carbon
- Mixing ratios are converted to backscatter and extinction using locally developed calculator
  - Lookup table-centric, point-by-point (in all 3 dimensions) and species-by-species (function of wavelength: 355 nm, 532 nm, 1064 nm have been tested)
  - Then combined to produce three dimensional fields of backscatter and extinction (and others: SSA, layer AOT, attenuated BS/EX from sfc/toa)
  - Admittedly, a black box

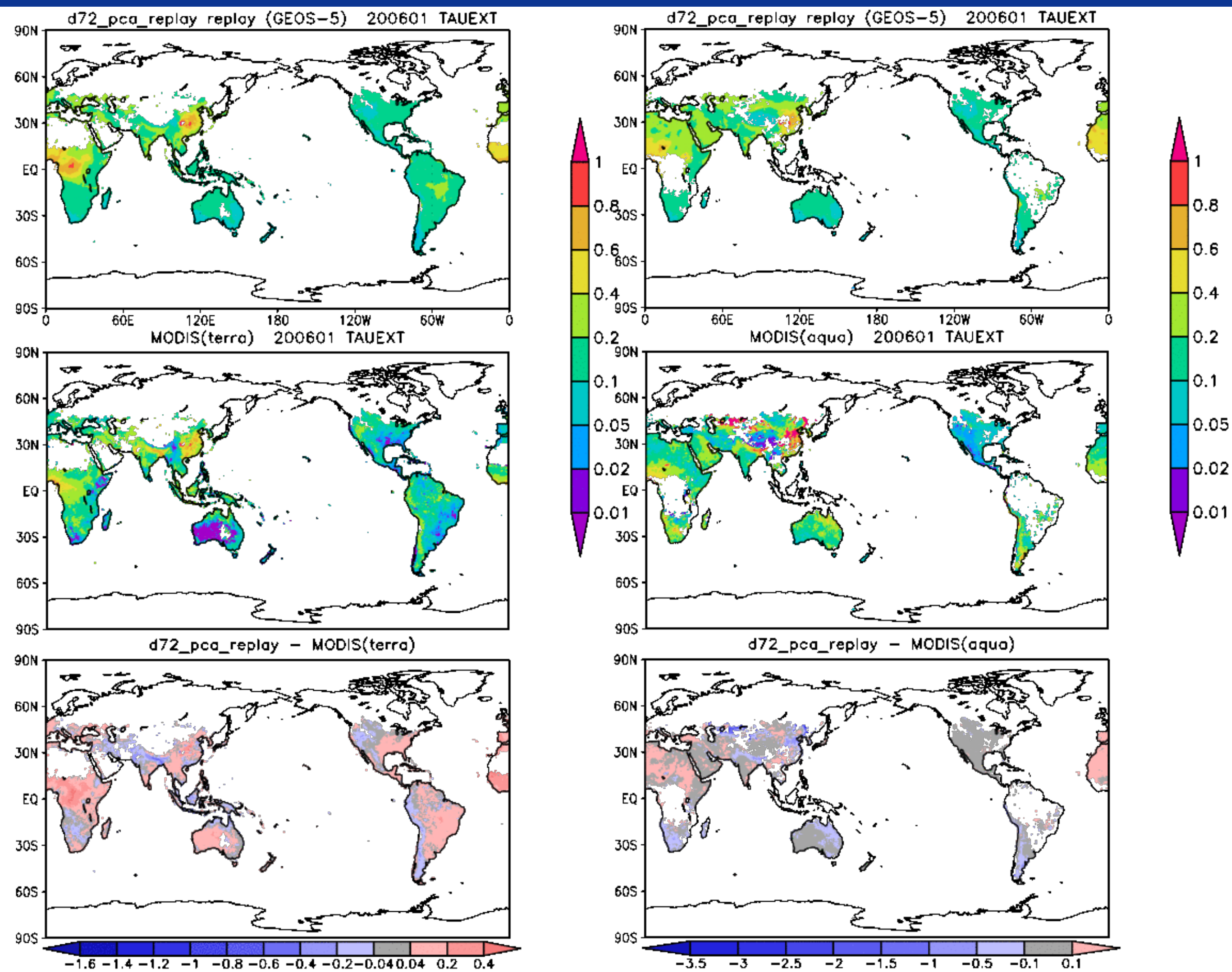
Aerosol Validation

- In validation, the replay aerosols were compared over land and sea for MODIS (Aqua and Terra, separately) and MISR
  - Only points corresponding to successfully retrieved AOT were considered
    - Consistent sampling
    - Daytime only
- Showing January "2006" of Nature Run versus real January 2006

Aerosol Validation

- Terra (left)
- Aqua (right)

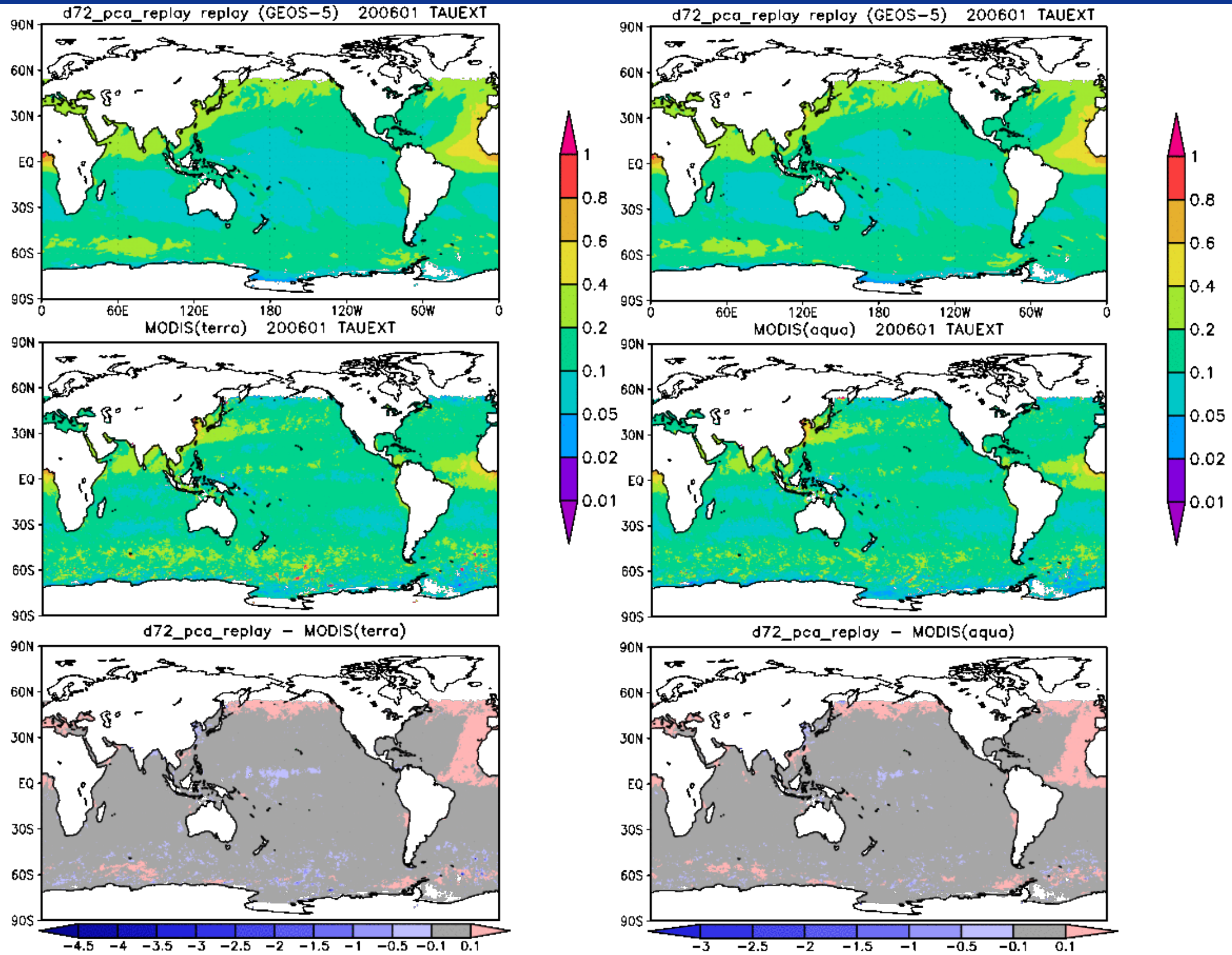
- NR (top)
- MODIS (middle)
- NR – MODIS (bottom)



Aerosol Validation

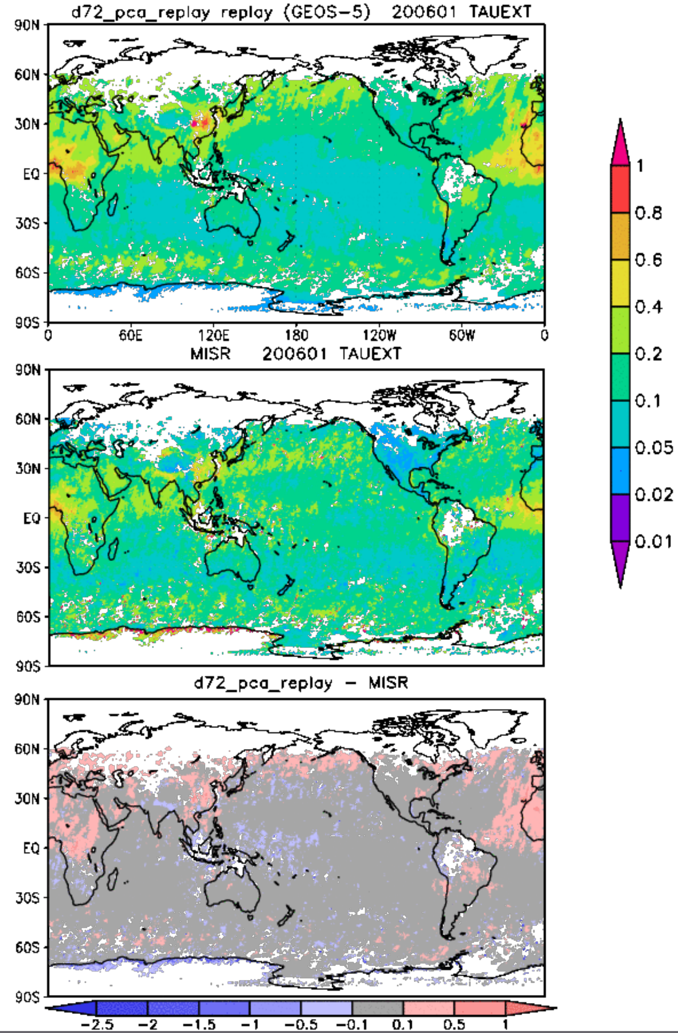
- Terra (left)
- Aqua (right)

- NR (top)
- MODIS (middle)
- NR – MODIS (bottom)



Aerosol Validation

- NR (top)
- MISR(middle)
- NR – MISR (bottom)



Final Thought on NR Aerosol Fields

- Willing to distribute
- They (those who generated them) feel comfortable with results
- They want to produce quick write-up for citing purposes
- Some issues (i.e. how, exactly, to distribute) can be pushed forward if needed
  - I don't know all the answers, but those who do occasionally need to be told if it is a priority
- Format: square geometric grid (540x361x91), hdf4
- What would be preferred? Backscatter/Extinction? Species mixing ratios? Both?

Assimilation Results

- Experiments:
  - CTL: Control
    - "Existing" observing system by Ron Errico and Runhua Yang
    - Conventional observations (from "PREPBUFR" stream)
      - Includes satwinds and scatterometer
    - Satellite Observations
      - AMSU-A/B, MSU, HIRS, AIRS
  - DWL
    - CTL + LIPAS Simulated Retrieved HLOS winds
  - DPERF
    - CTL + LIPAS Input HLOS winds
    - Error values same as retrieved HLOS winds

Assimilation Results

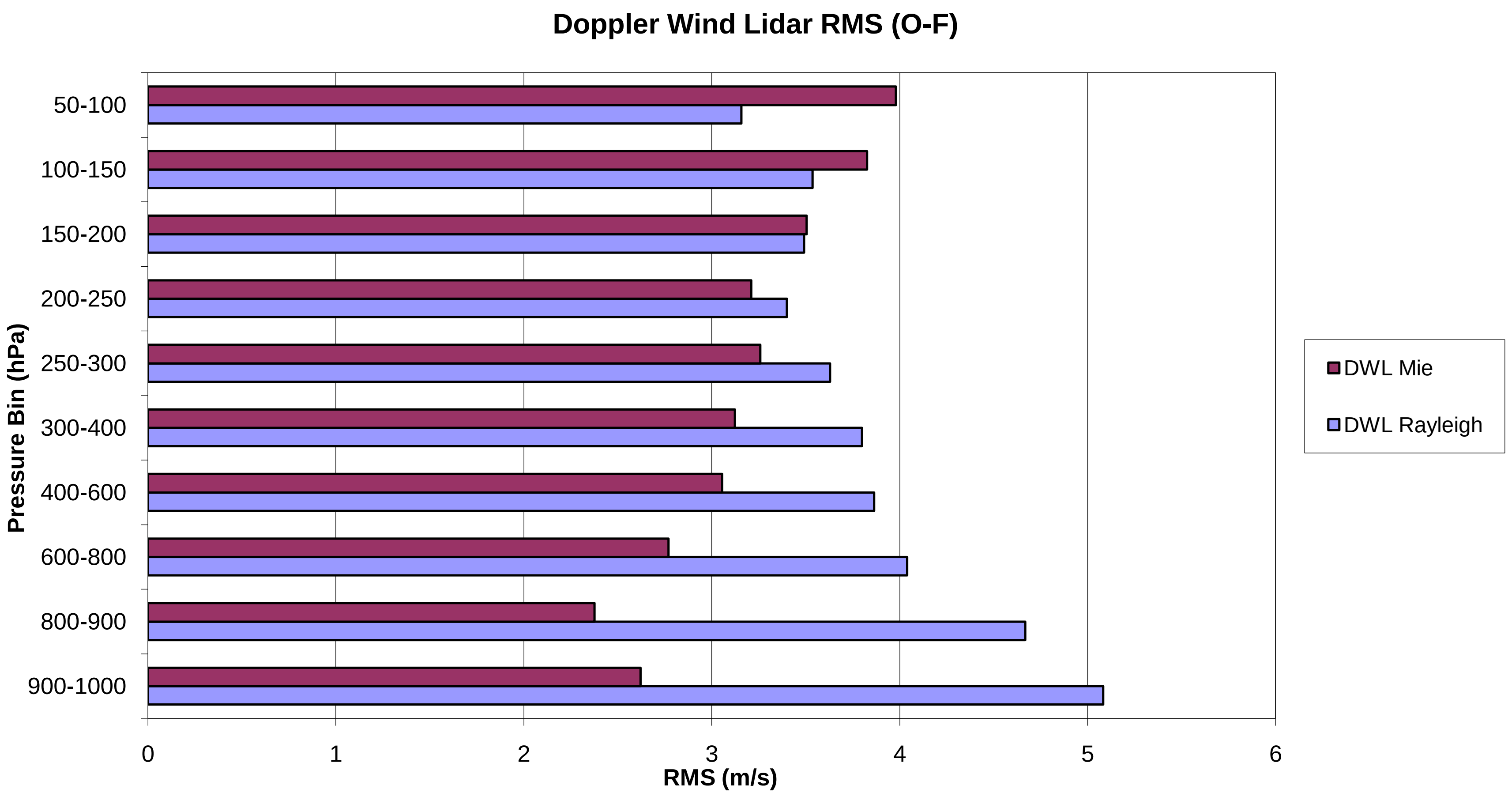
- Two weeks of assimilation after 8 day spin-up
- Results shown are for all analysis cycles (4x/day)

- Doppler Wind Lidar O-F RMS

	DWL	DPERF
Mie	3.09 ms^{-1}	2.34 ms^{-1}
Rayleigh	3.72 ms^{-1}	2.46 ms^{-1}

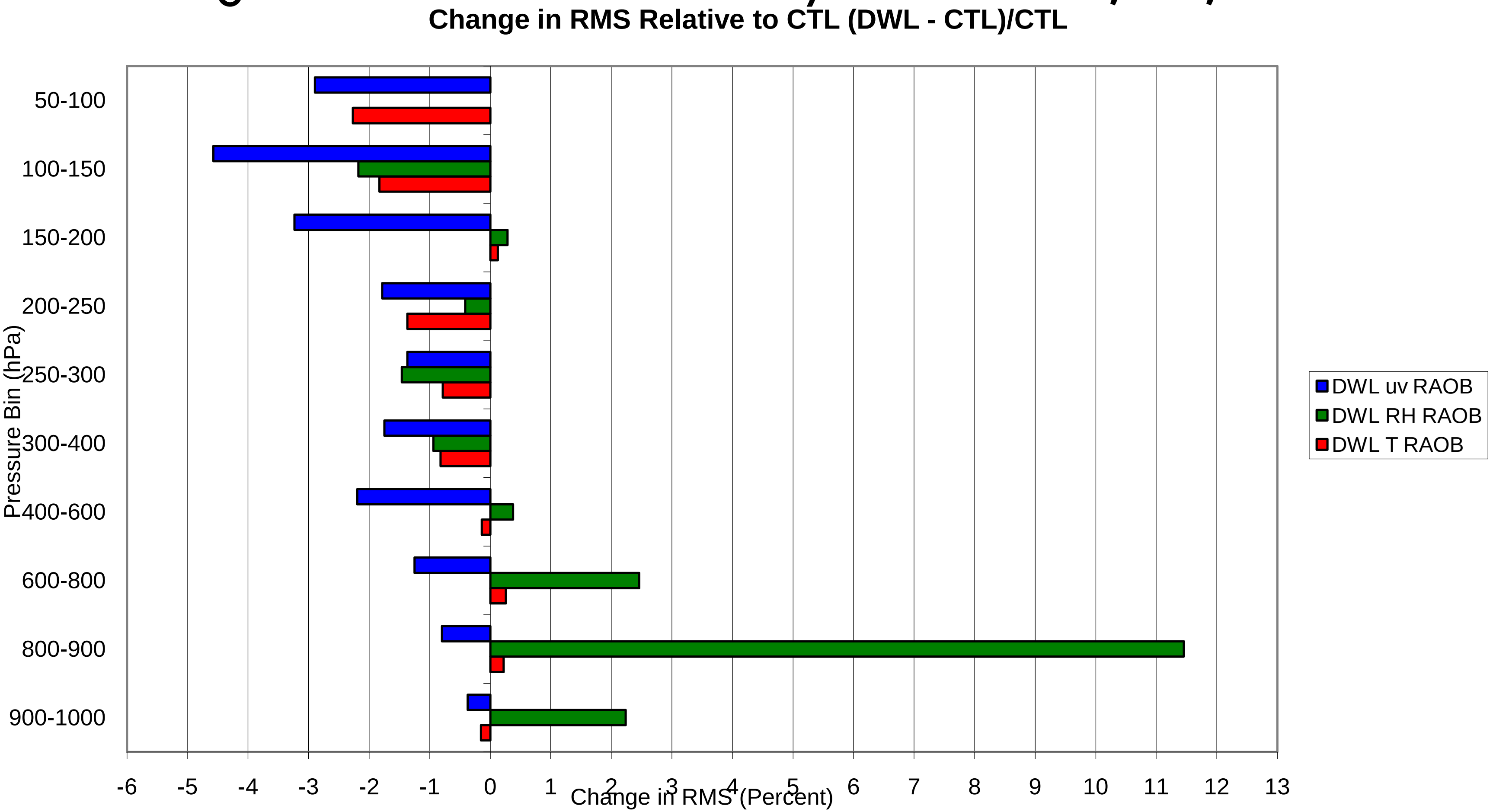
Assimilation Results

- Doppler Wind Lidar O-F RMS vertically

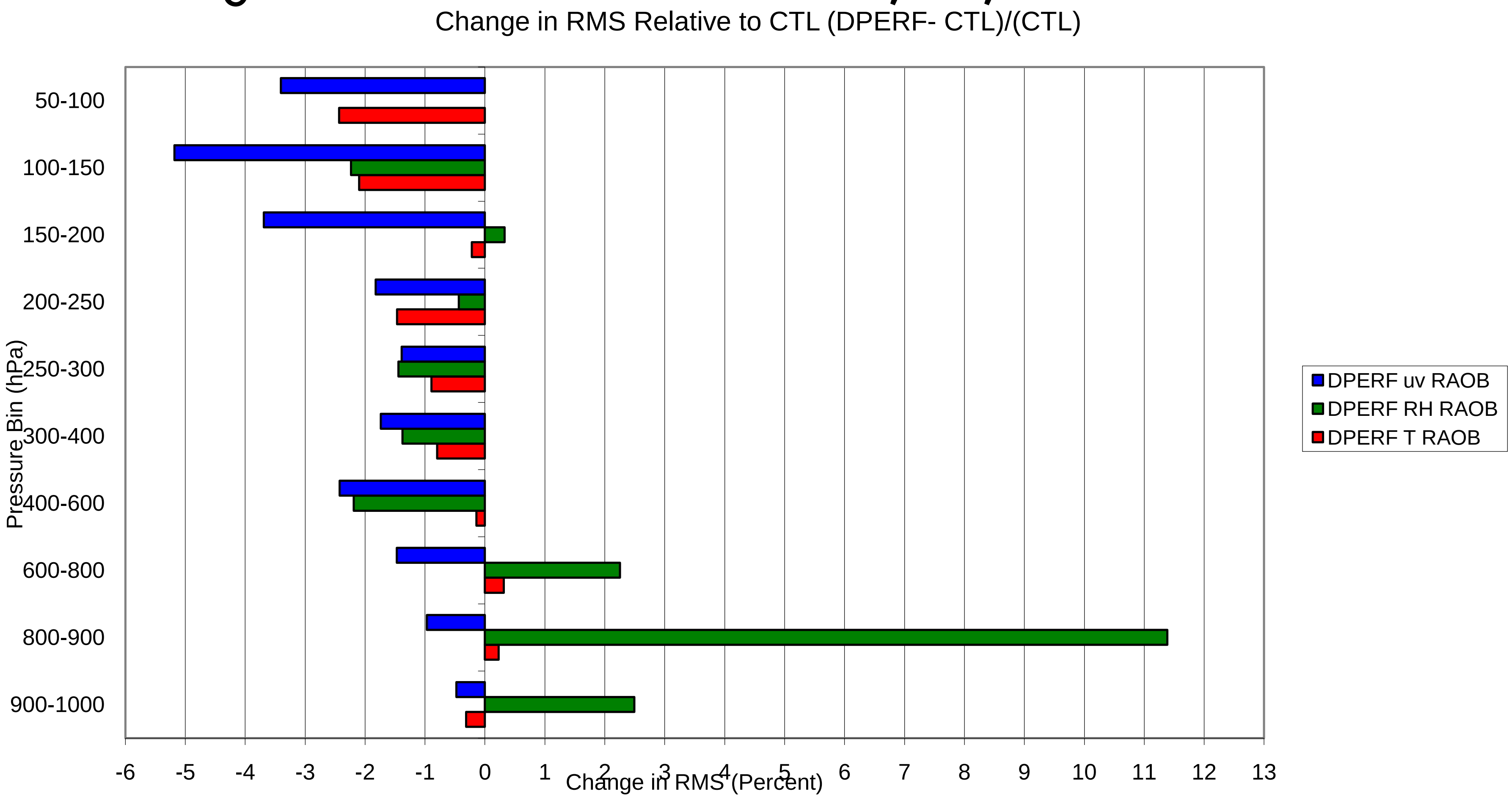


Assimilation Results

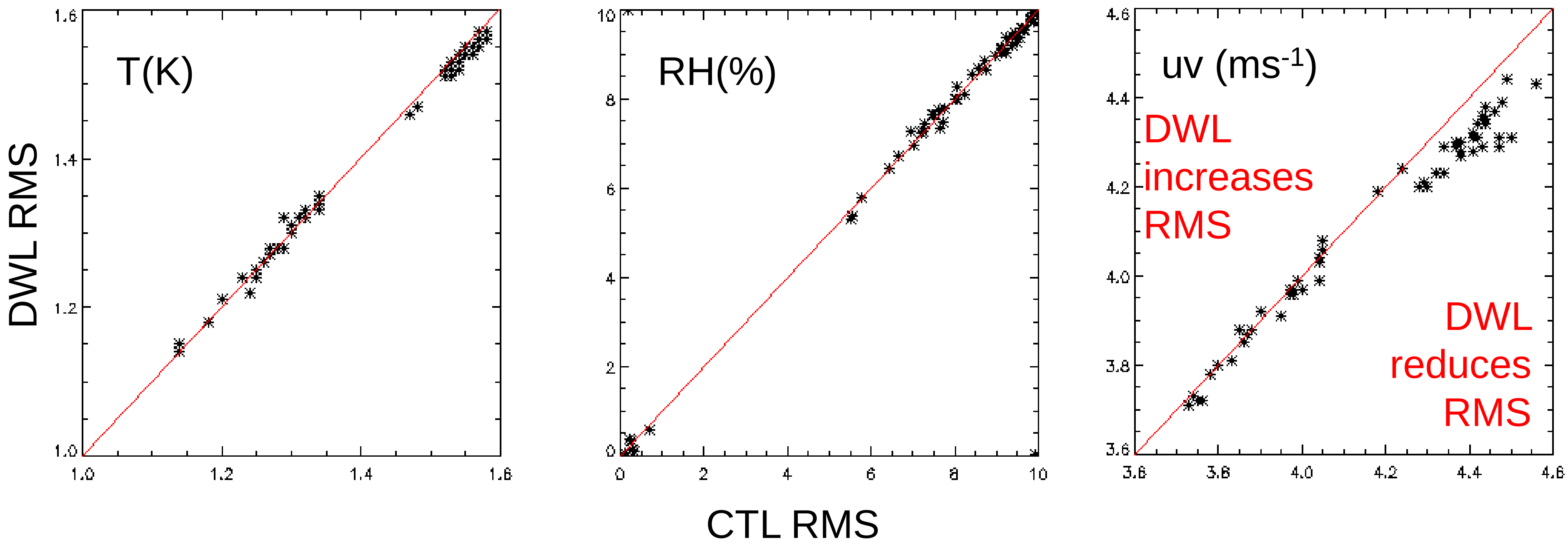
- Change in DWL RMS Vertically for RAOB T, RH, and uv



- Change in DPERF RMS for RAOB T, RH, and uv

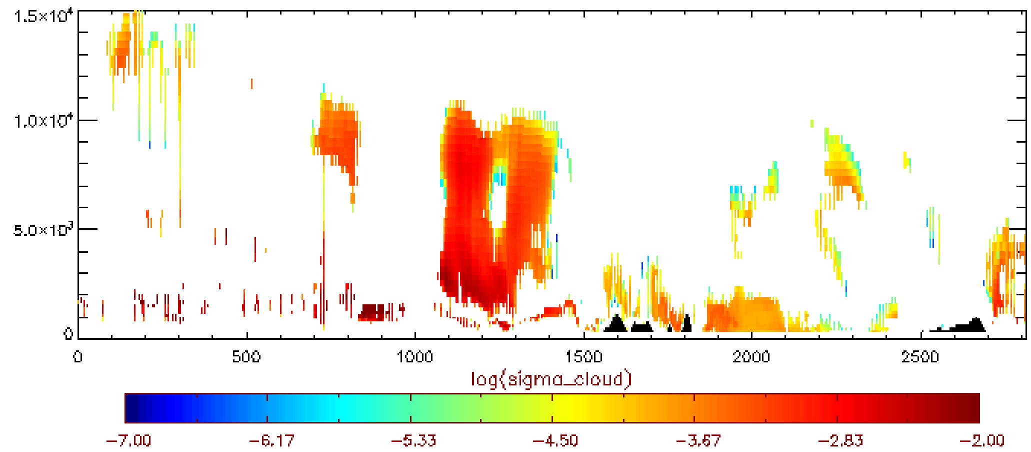


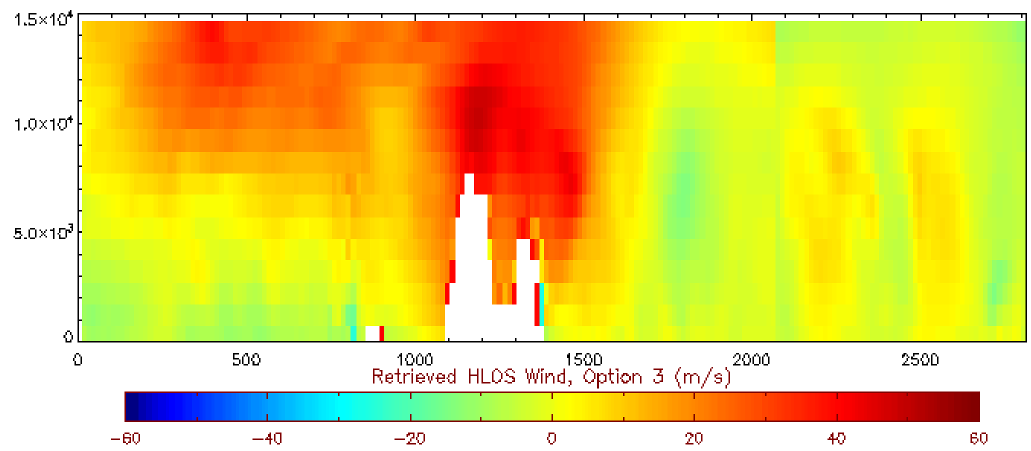
Assimilation Results

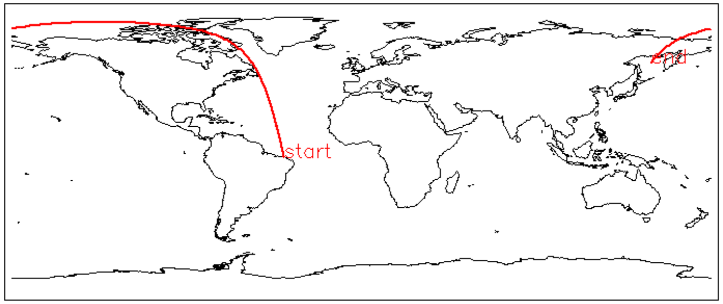


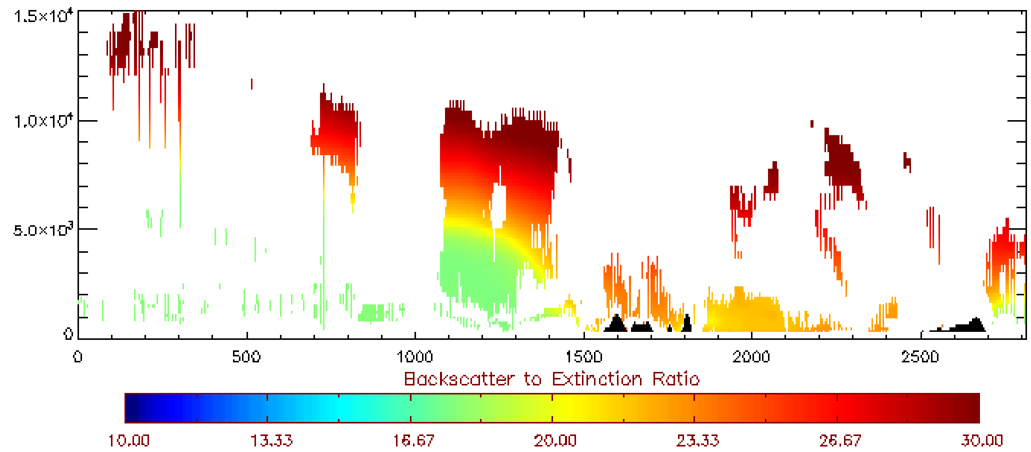
LIPAS Example

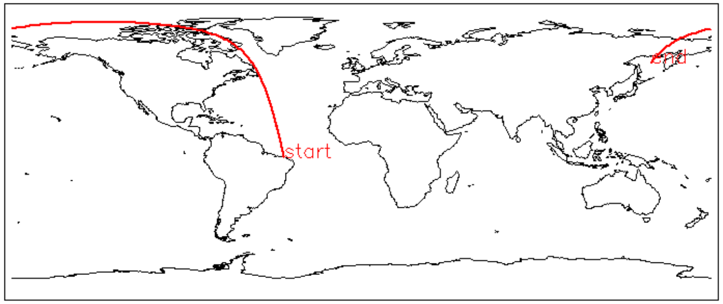
- Executed for continuous observations
- Burst most implemented in post-processing (BUFR generation)

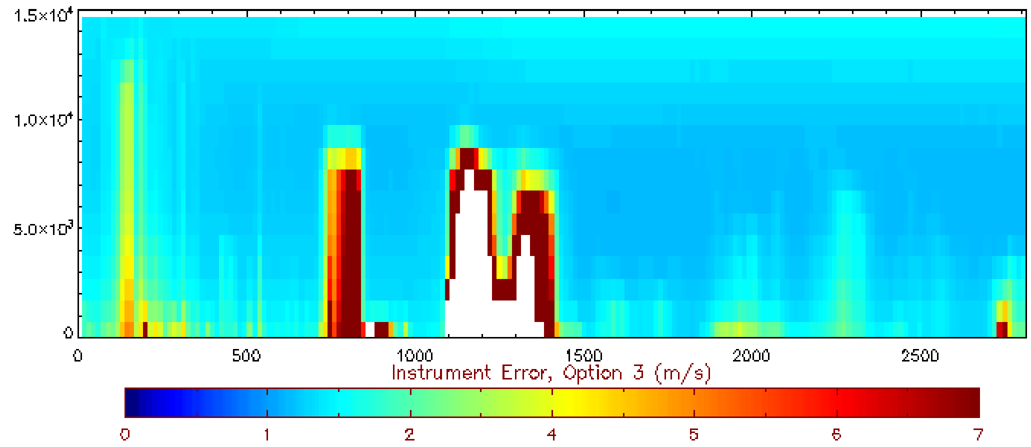

1.5×10⁴
1.0×10⁴
5.0×10³
0
0
500
1000
1500
2000
2500
log(sigma_cloud)
−7.00
−6.17
−5.33
−4.50
−3.67
−2.83
−2.00

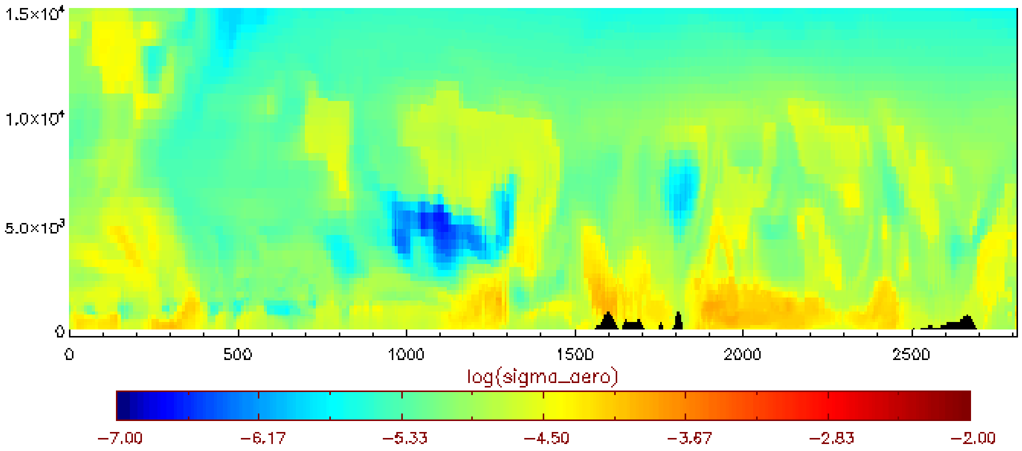

1.5×10⁴
1.0×10⁴
5.0×10³
0
0
500
1000
1500
2000
2500
Retrieved HLOS Wind, Option 3 (m/s)
−60
−40
−20
0
20
40
60

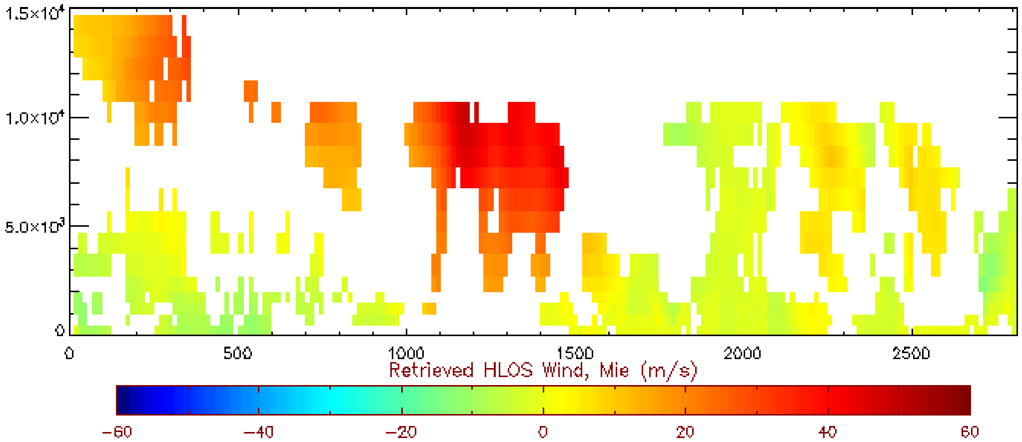

start
end

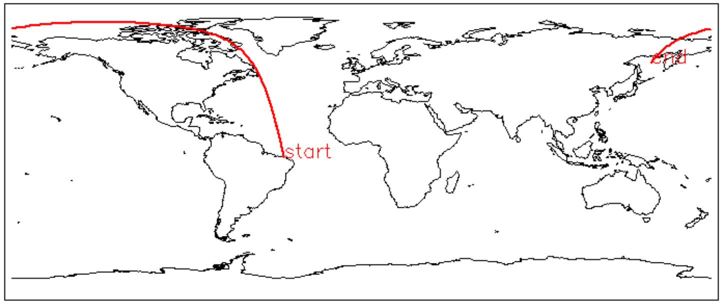

1.5×10⁴
1.0×10⁴
5.0×10³
0
500
1000
1500
2000
2500
Backscatter to Extinction Ratio
10.00
13.33
16.67
20.00
23.33
26.67
30.00


start
end


1.5×10⁴
1.0×10⁴
5.0×10³
0
500
1000
1500
2000
2500
Instrument Error, Option 3 (m/s)
0
1
2
4
5
6
7


1.5×10⁴
1.0×10⁴
5.0×10³
0
0
500
1000
1500
2000
2500
log(sigma_aero)
−7.00
−6.17
−5.33
−4.50
−3.67
−2.83
−2.00


1.5×10⁴
1.0×10⁴
5.0×10³
0
0
500
1000
1500
2000
2500
Retrieved HLOS Wind, Mie (m/s)
−60
−40
−20
0
20
40
60


start
end