GMAO's Atmospheric Data Assimilation Contributions to the JCSDA and future plans

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NASA/Goddard Space Flight Center

JCSDA Seminar
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Global Modeling & Assimilation Office

http://gmao.gsfc.nasa.gov

Outline

- GEOS-5 DAS
- AIRS
- Cloud-cleared radiances
- MLS Ozone
- 4dVAR
- OSSE capability
- Land assimilation

GEOS-5 Atmospheric Data Assimilation System

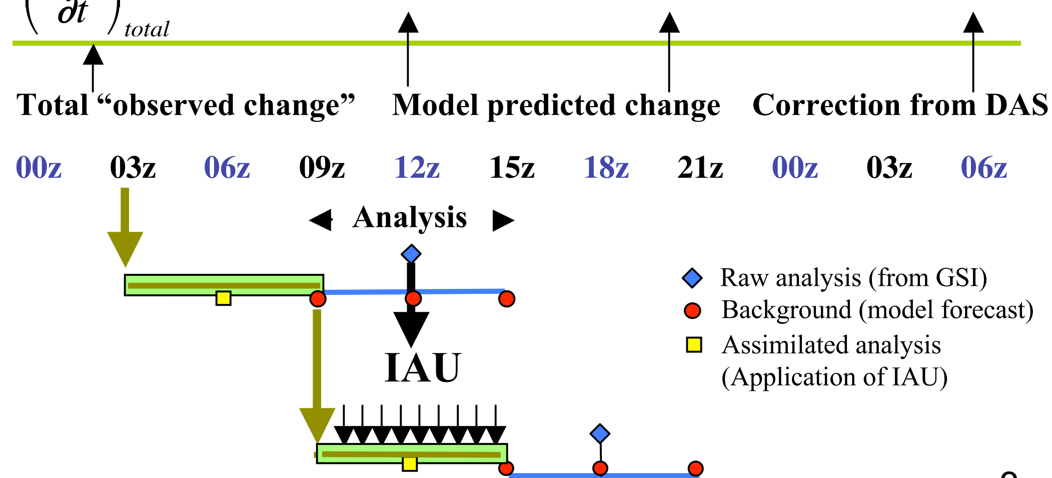
Ricardo Todling, Max Suarez, Larry Takacs, Emily Liu

- **AGCM**
  - Finite-volume dynamic core
  - Bacmeister moist physics
  - Integrated under the Earth System Modeling Framework (ESMF)
  - Catchment land surface model
  - Prescribed aerosols
  - Interactive ozone
  - Prescribed SSTs

- **Assimilation**
  - Apply Incremental Analysis Increments (IAU) to reduce shock of data insertion
  - IAU gradually forces the model integration throughout the 6 hour period

- **Analysis**
  - Grid Point Statistical Interpolation (GSI)
  - Direct assimilation of satellite radiance data
  - JCSDA Community Radiative Transfer Model (CRTM) for most current instruments in space
  - GLATOVS for SSU
  - Variational bias correction for radiances

$$\left(\frac{\partial q^n}{\partial t}\right)_{total} = dynamics(adiabatic) + physics(diabatic) + \Delta q$$



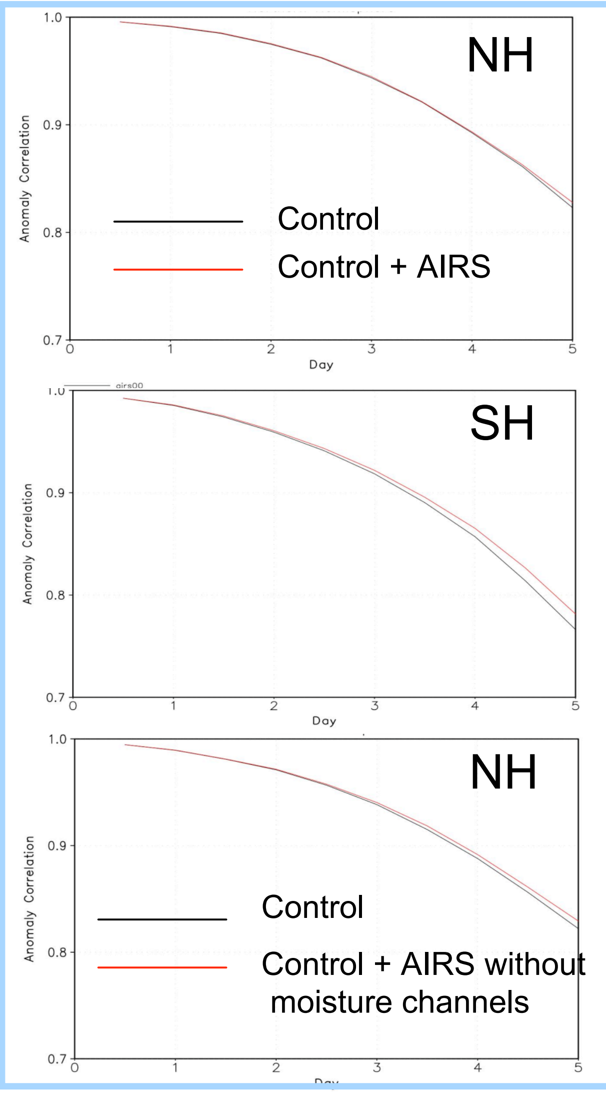
AIRS impacts

Observing System Experiments - Emily Liu
Impacts from Adjoint Tools - Ron Gelaro & Yanqiu Zhu
Cloud Cleared Radiances - Emily Liu

GEOS-5 used to Evaluate Impact of AIRS in NWP

Emily Liu

Forecast Skill vs. Time



- GEOS-5 resolution: 1° x 1.25° x 72L
- Period: January 2003
- Control: baseline with AIRS
  - Thinned AIRS data set
  - 152 AIRS channels
- Perturbed run: control with AIRS moisture channels turned off
  - 108 AIRS channels

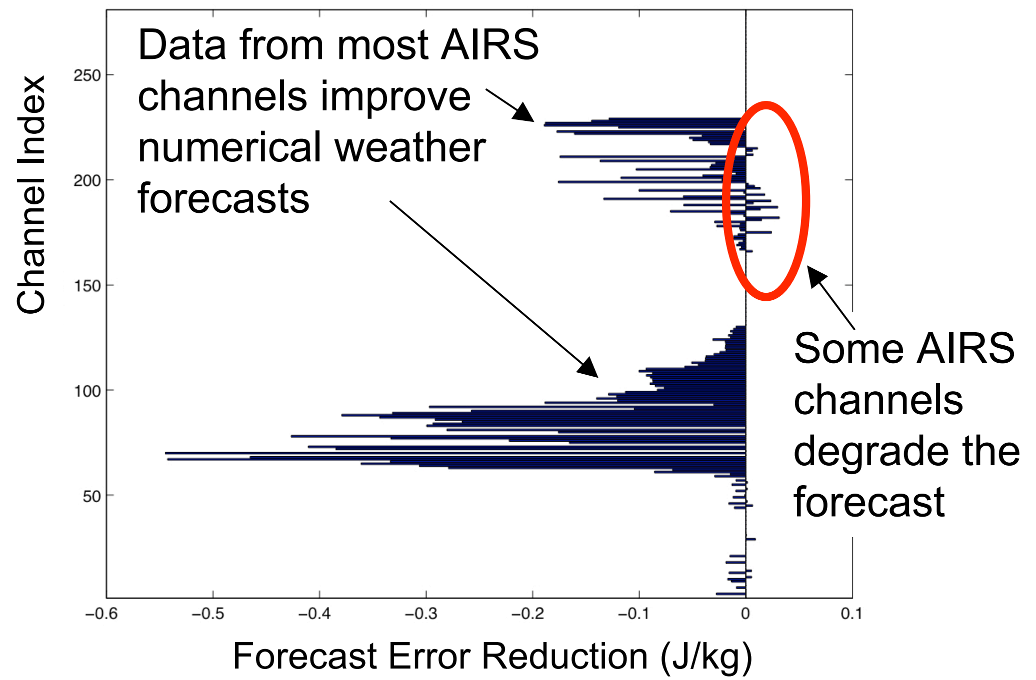
- Other satellite radiance data used: SSMI, MSU, HIRS-2, HIRS-3, AMSU-A, and AMSU-B, and MHS

AIRS brings slightly positive impact on forecast skill in Northern Hemisphere; clear positive impact in Southern Hemisphere. But forecast skills are increased when moisture channels from AIRS are not included

Adjoint tools provide additional detail

Ron Gelaro, Yanqiu Zhu

- GEOS-5 resolution: 1° x 1.25° x 72L
- Period: July 2005
- Other satellite radiance data used: SSMI, MSU, HIRS-2, HIRS-3, AMSU-A, and AMSU-B, and MHS

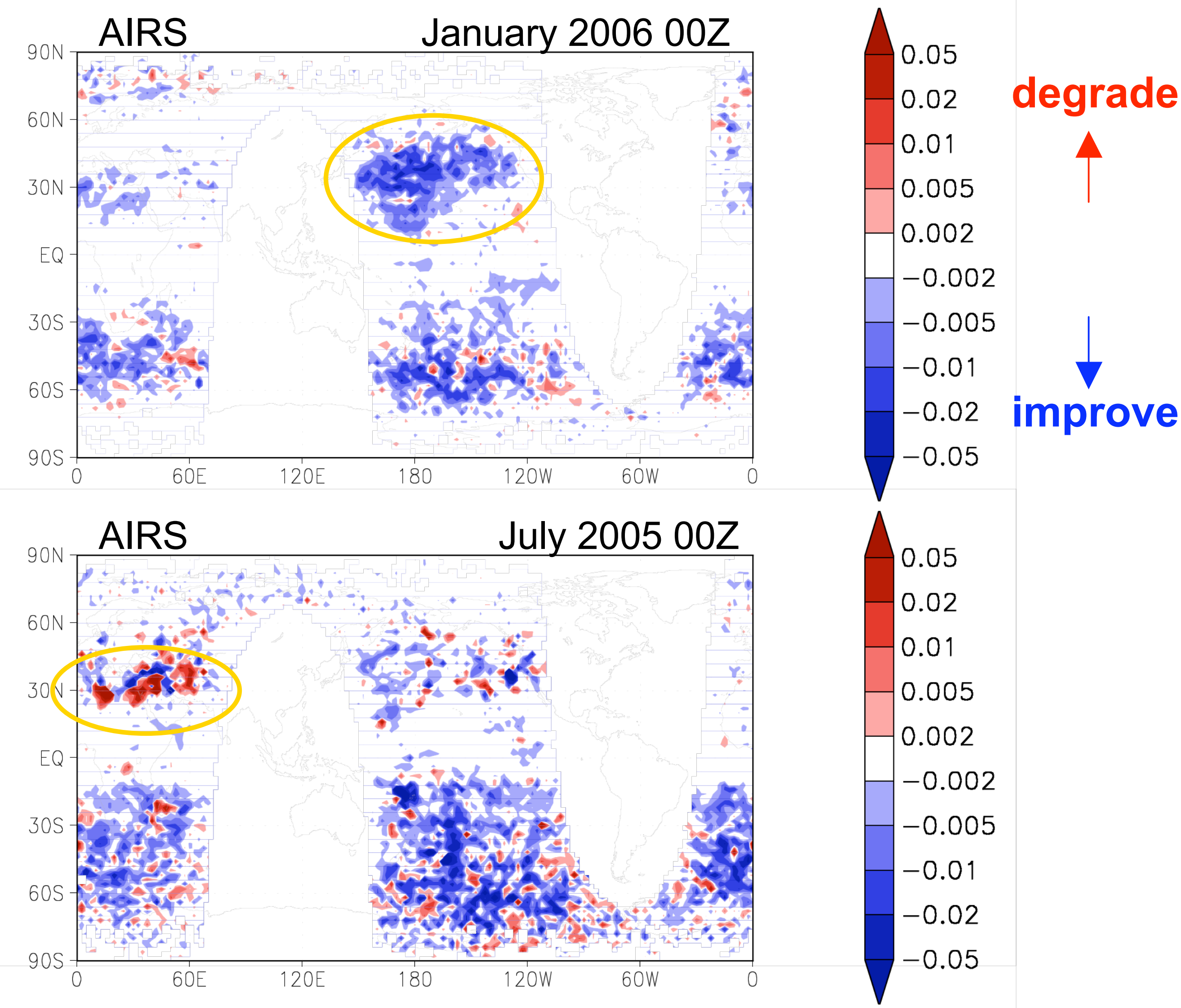


The Adjoint data assimilation system estimates observation impact on analyses/short-term forecasts

- *computed with respect to <u>all observations simultaneously</u>*
- *permits arbitrary aggregation of results by data type, channel, location, etc*

Accumulated Observation Impact - AIRS

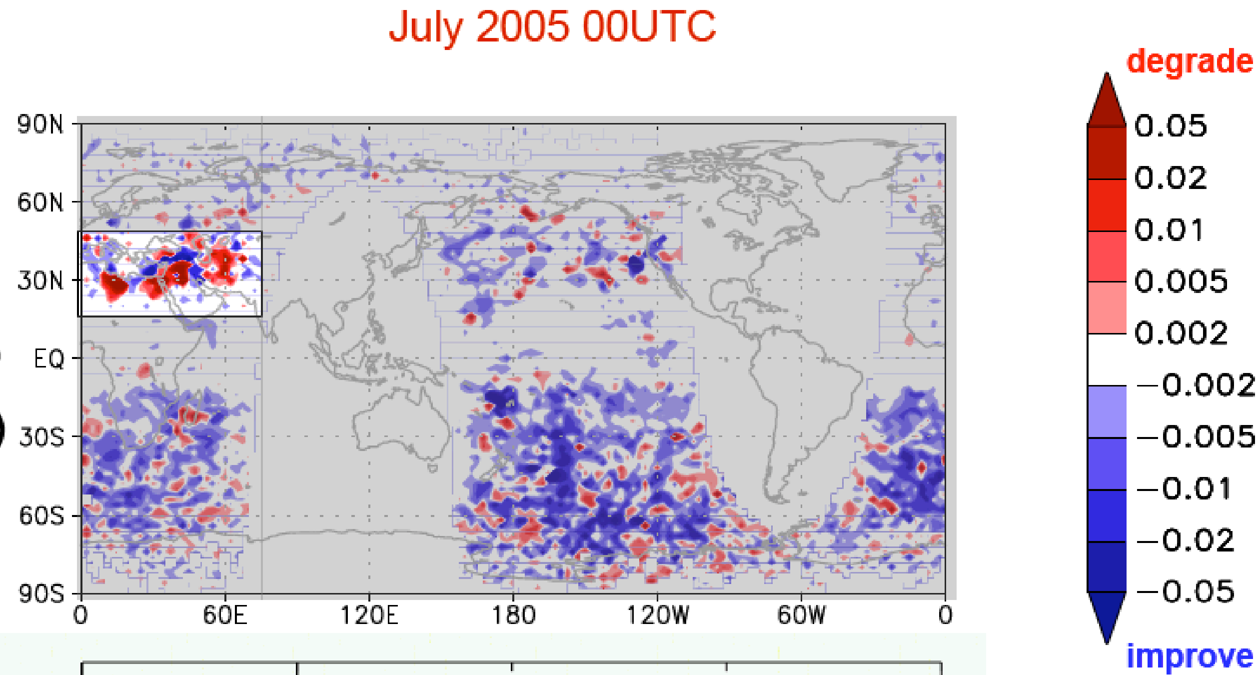
- Substantial positive impact over N.Pacific winter storm track
- Negative impact over land…



Localized examination of AIRS impacts

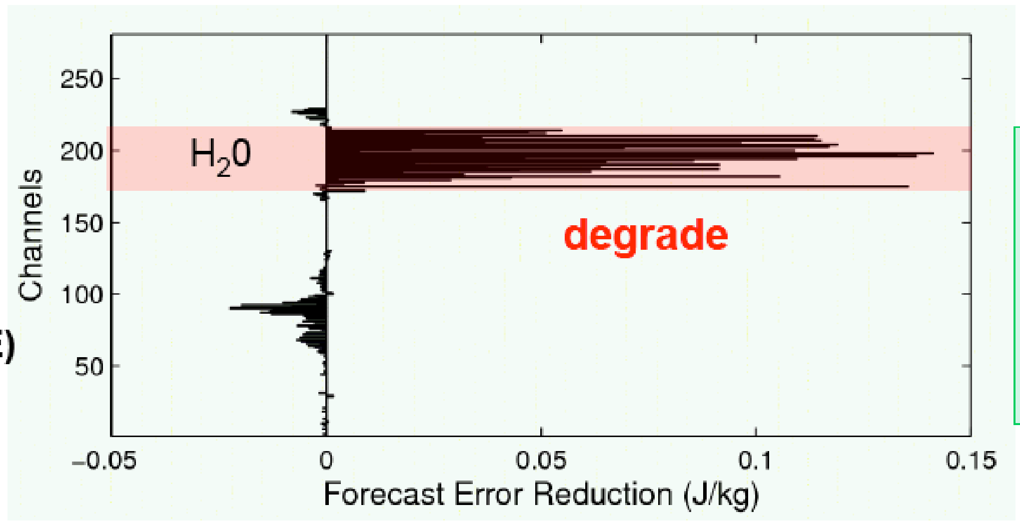
AIRS impact map

(All Channels)



AIRS impact by channel

(20-50N, 0-80E)



Removal of AIRS **water vapor channels** improved the forecast scores

Additional OSE

Eliminate moisture channels over land

1 case study

No discernible impact on extratropical 500 mb height anomaly skill ☹

However, this was a January experiment - still need to do July experiment

Comparison of Adjoint tools and OSEs - see Ron Gelaro's JCSDA seminar (Nov 15 2007)

The Use of Cloud-Cleared Radiances in GEOS-5

Emily Liu

Cloud-Cleared AIRS Radiances

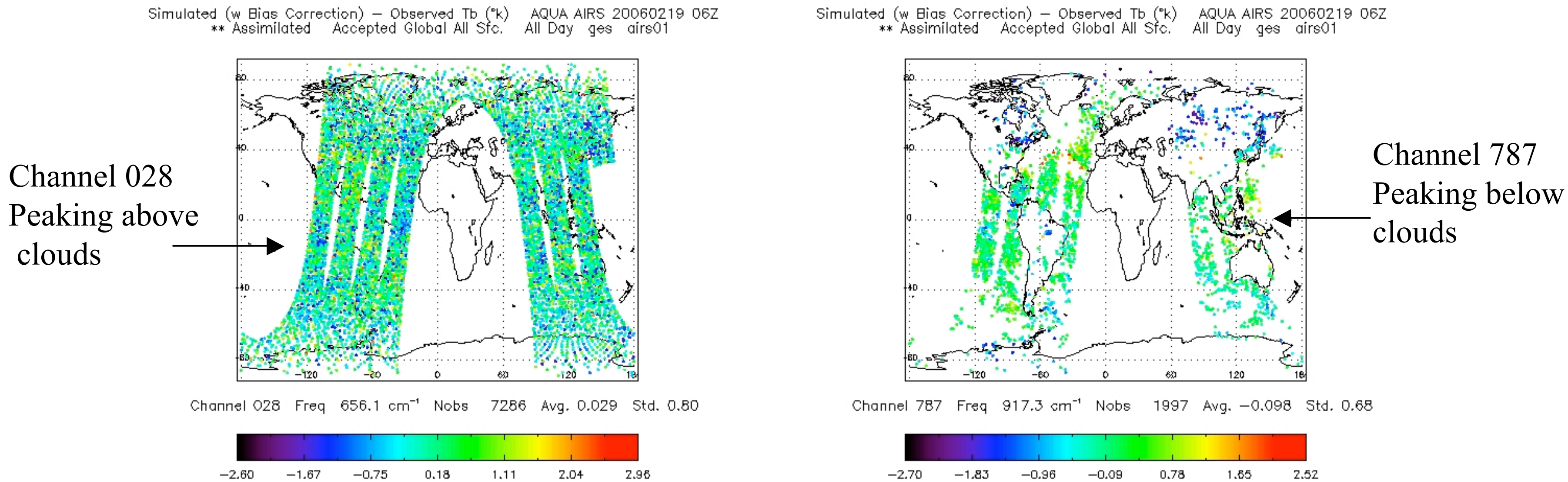
Motivation

– Currently, only clear IR channels (not affected by clouds) are used in most of data assimilation systems.

– Cloud contaminated and surface-sensitive channels have not been used effectively due to difficulties in modeling clouds and surface conditions in both forecast and radiative transfer models.

– Initial tests - Cloud-cleared AIRS radiances provide useful sounding information beneath clouds and improve forecast skill in the troposphere.

Assimilated Data Coverage

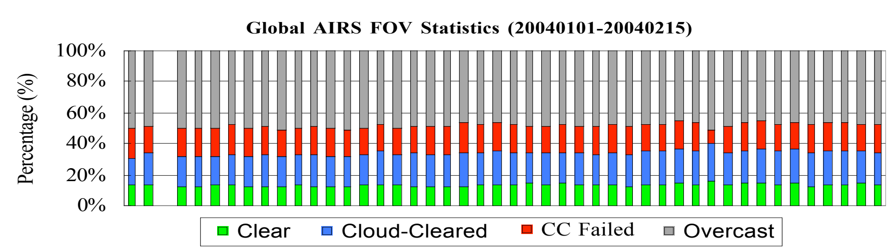


Background Information

- The model resolution: 1°x1.25°x72L
- Time frame - Jan 01 to Feb 15 2004
- Radiance data included in the Observing System for the baseline experiment:
  - HIRS-2/HIRS3 (clear channels)
  - AMSU-A/EOS-AMSU-A
  - AMSU-B/MHS
  - SSM-I
  - GOES Sounders

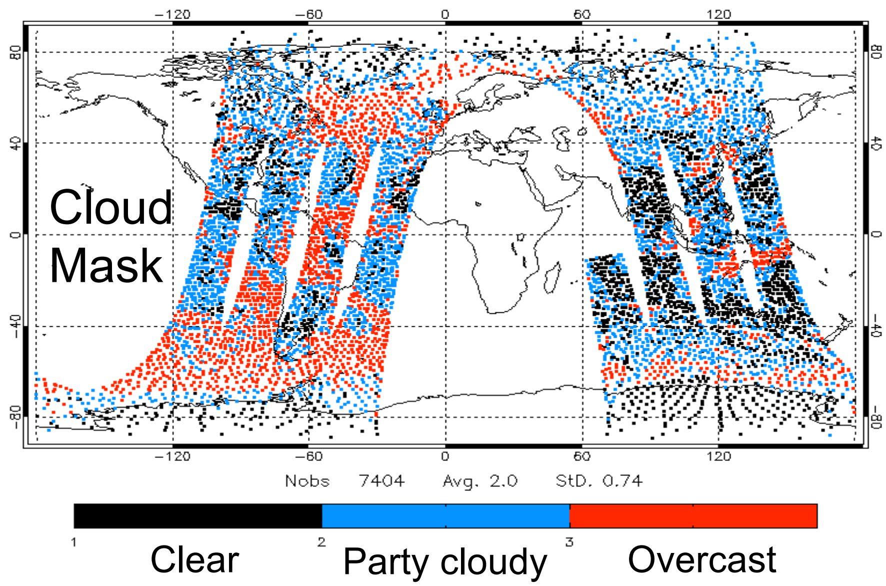
Satellite Data in Focus

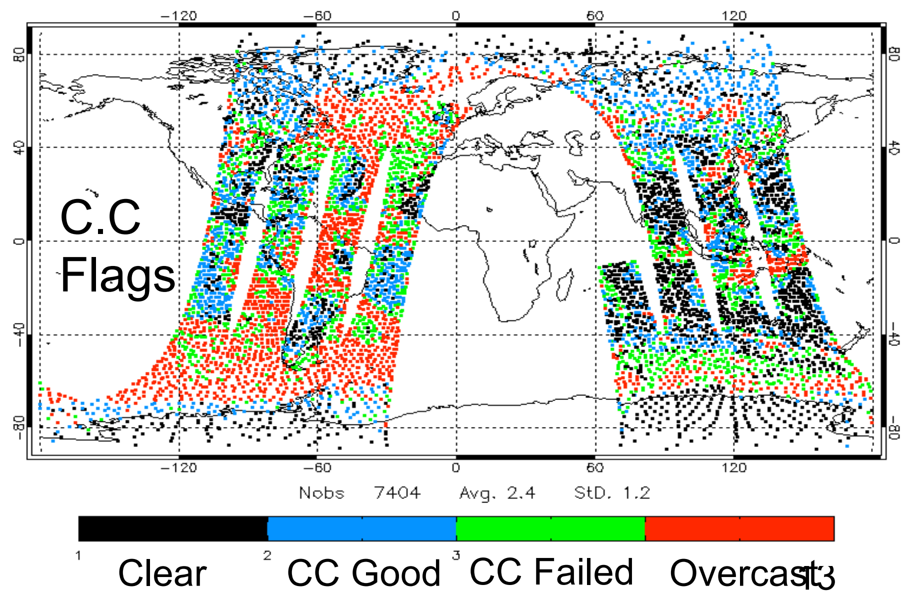
- MODIS/AIRS Synergistic Cloud Cleared Radiances (Li et al. 2005)
  - Optimal cloud clearing procedures to retrieve clear column radiances: combining collocated multi-band MODIS IR clear radiances and the AIRS cloudy radiances.
- AIRS cloud mask was also generated by collocated MODIS cloud mask data.
- No background information is needed.
- ~ 13% of the AIRS footprints are clear
- additional 21% of the AIRS footprints can be cloud cleared successfully.



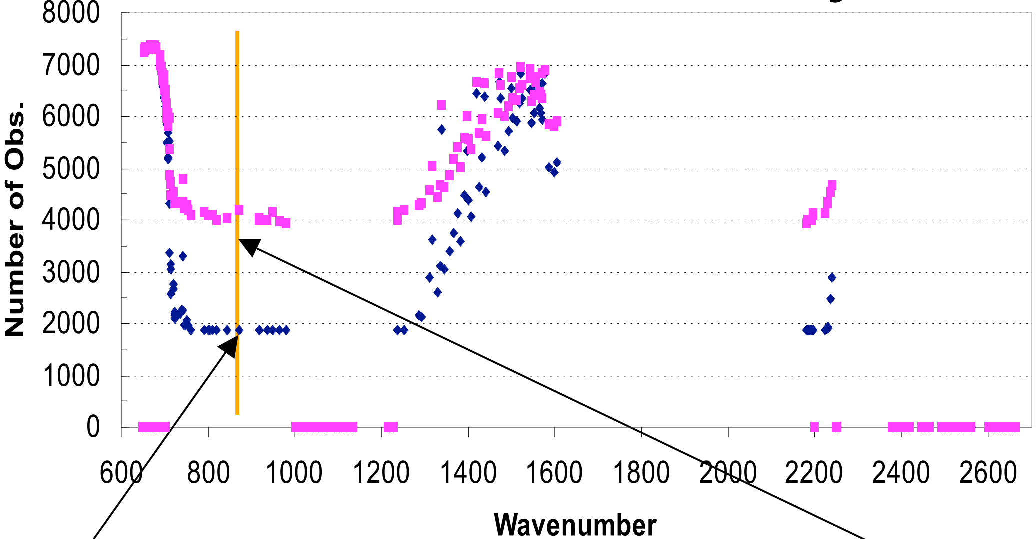
Case Study

- Level-1b data and cloud cleared AIRS in 6 hourly data bins
- AIRS data were thinned to a 180km box, and set to *passive mode* to calculate departure statistics - bias and standard deviation of the departures (OMF).
- *Channel selection and observation errors stay the same as the clear channel case.*
- Both AIRS cloud mask and cloud clearing flags for each AIRS footprint were considered in the data thinning and quality control procedures. AIRS footprints with clear and cloud-cleared successful flags were selected over the overcast footprints.



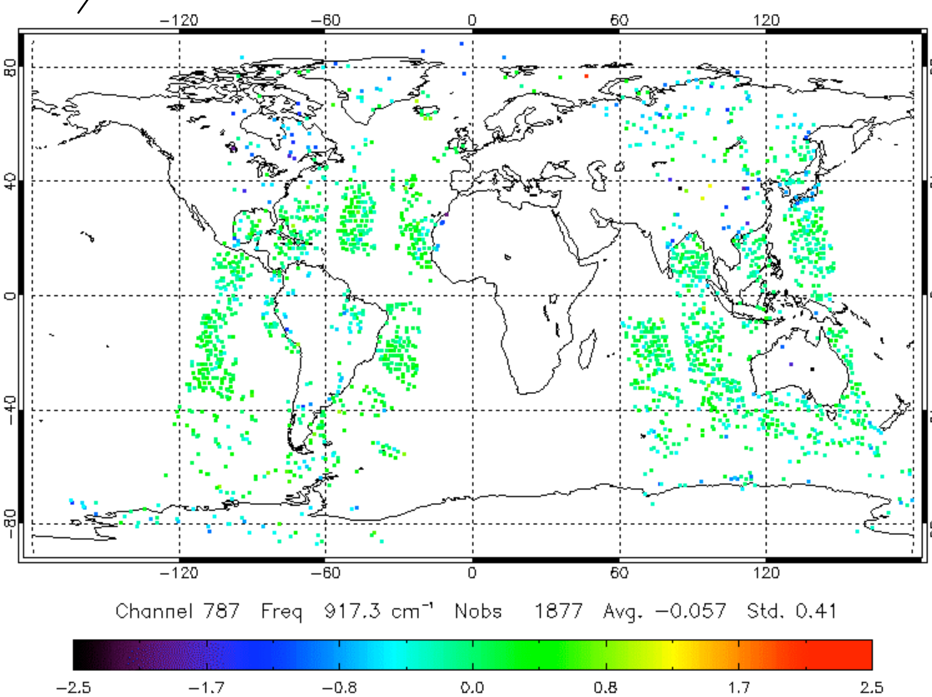


Preliminary Assimilation

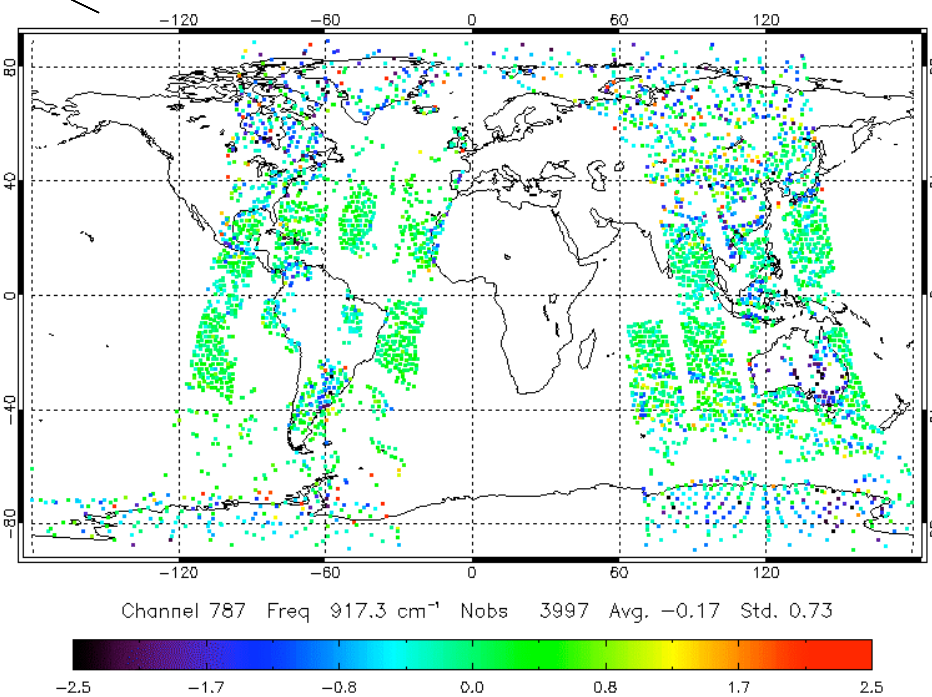


Preliminary assimilation showed that more data from AIRS can be used in the analysis, giving information in the troposphere.

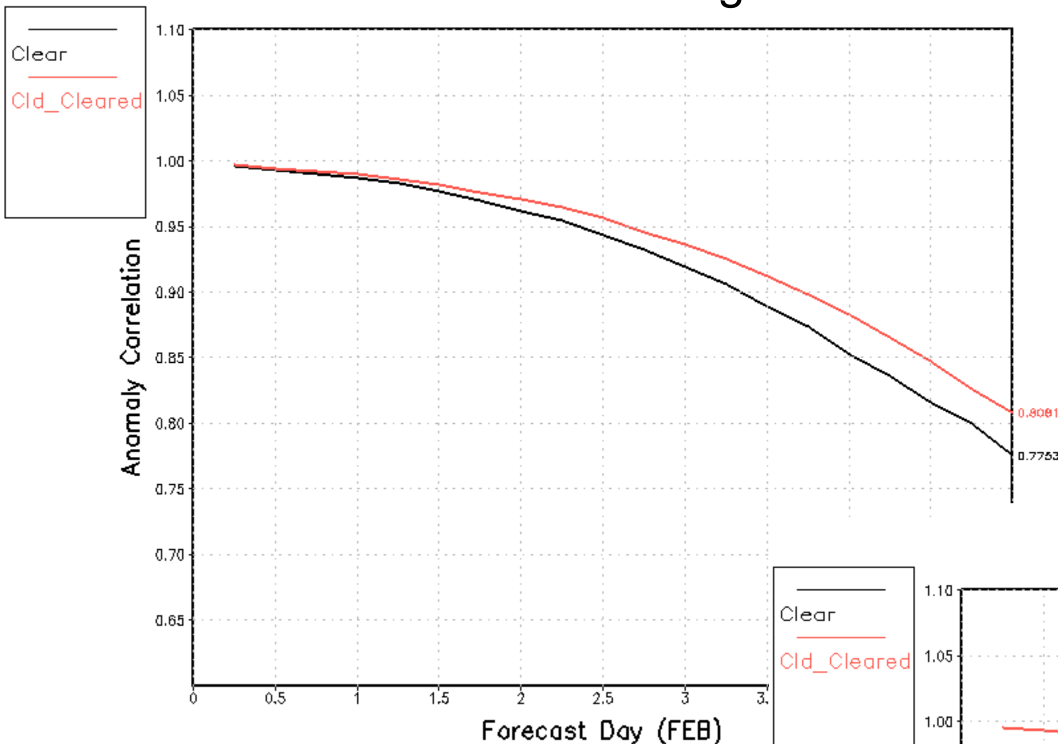
Clear Channel Radiance Assimilation



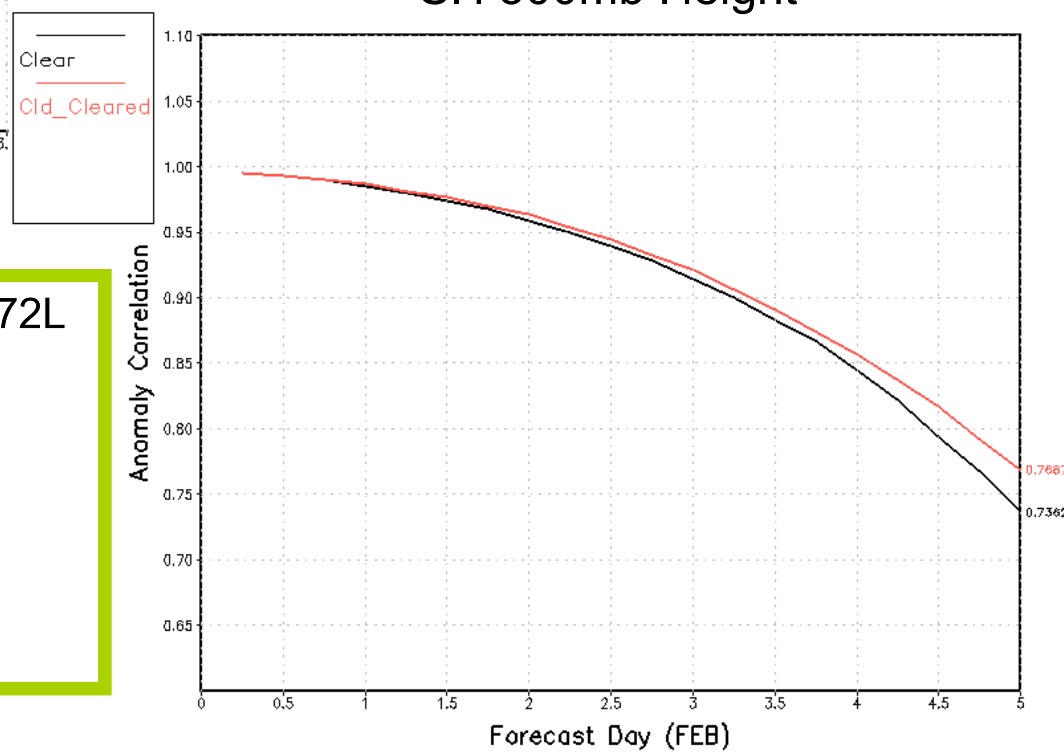
Cloud-Cleared Radiance Assimilation



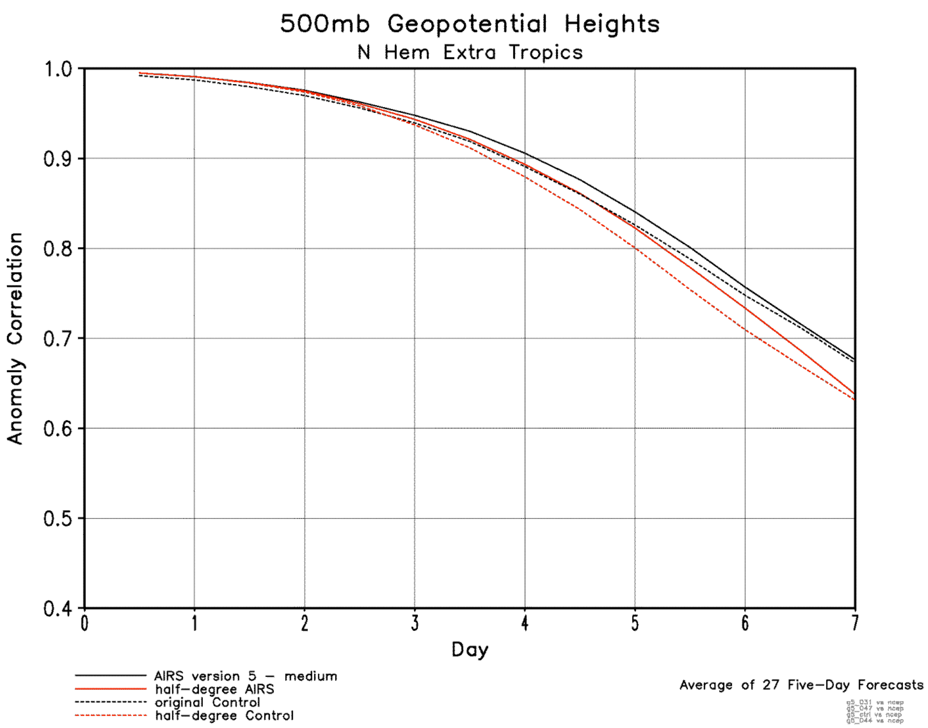
NH 500mb Height



SH 500mb Height



- GEOS-5 model resolution: 1°x1.25°x72L
- Time frame: Jan 01 to Feb 15 2004
- Other Radiance data:
  - HIRS-2/HIRS3 (clear channels)
  - AMSU-A/EOS-AMSU-A
  - AMSU-B/MHS
  - SSM-I
  - GOES Sounders



Oreste Reale's experiments with AIRS retrievals

- GEOS-5 model resolutions: 1° and 1/2° experiments
- Different model versions
- Time frame: January 2003
- Other Results:
  - Smaller +ve impact in S.H.
  - Newer system more sensitive to satellite radiances, no impact in S.H.
  - Boreal summer experiment (8/10/06 - 9/15/06) showed +ve impact N.H., no impact S.H.

Summary and Next Steps

- More AIRS data can be used in the cloud affected areas.
- The impacts of AIRS cloud-cleared radiances on forecast skills were positive for both hemispheres.
- Impact is comparable to those seen with retrievals.
- Next steps:
    - Different channel selection
    - Observation errors for cloud-cleared AIRS radiances (with Joel Susskind, NASA/GSFC)
- GEOS-5 adjoint tools will be used to examine the impact of cloud-cleared radiances.

Ozone Assimilation

Ivanka Stajner, Meta Sienkiewicz, Kris Wargan

Ozone in GEOS-5 DAS

Data:

- **SBUV** and **OMI** ozone
- **TOVS** and **AIRS** radiances
- **MLS** retrieved stratospheric ozone profiles

Model:

- Parameterized chemistry (production and loss rates)

Prognostic ozone used in:

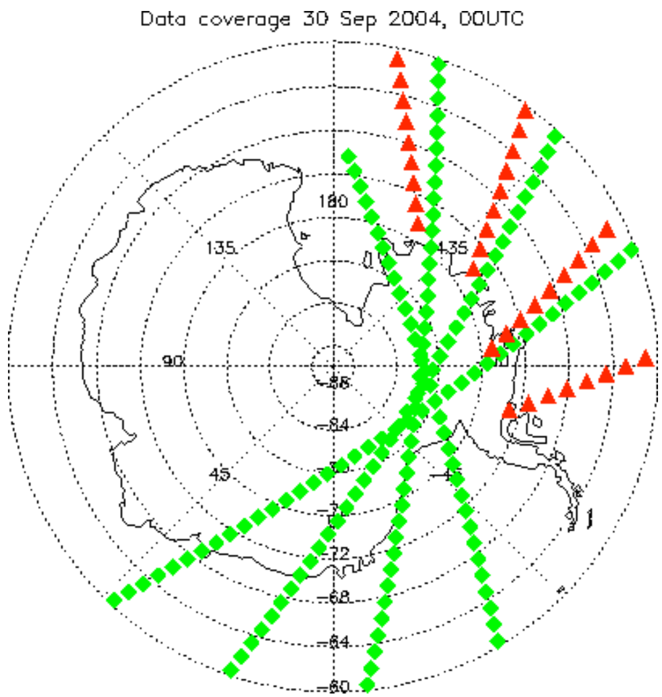
- Radiative heating computations in AGCM
- Assimilation of IR radiances

Assimilating AURA/MLS ozone

Meta Sienkiewicz and Ivanka Stajner

SBUV daytime only – no data near South Pole due to high solar zenith angle

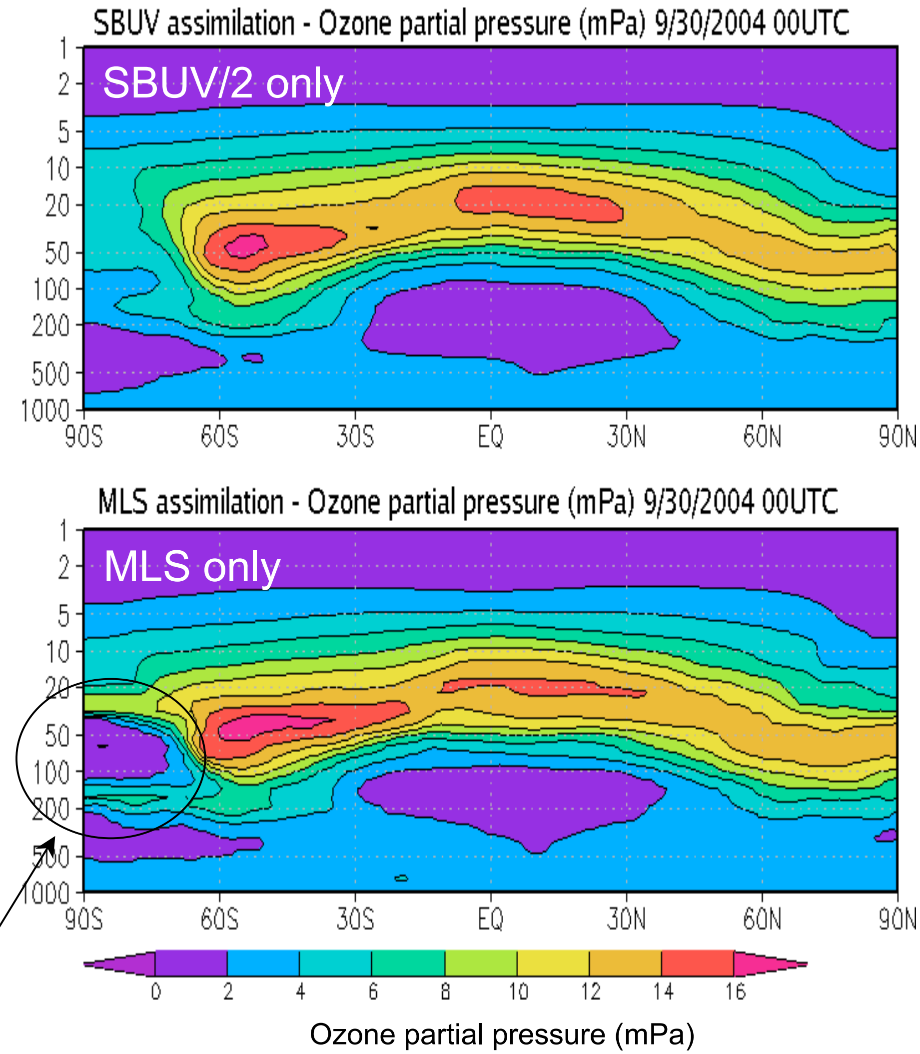
MLS orbital limit ±82º



▲ NOAA 16 SBUV

◆ MLS

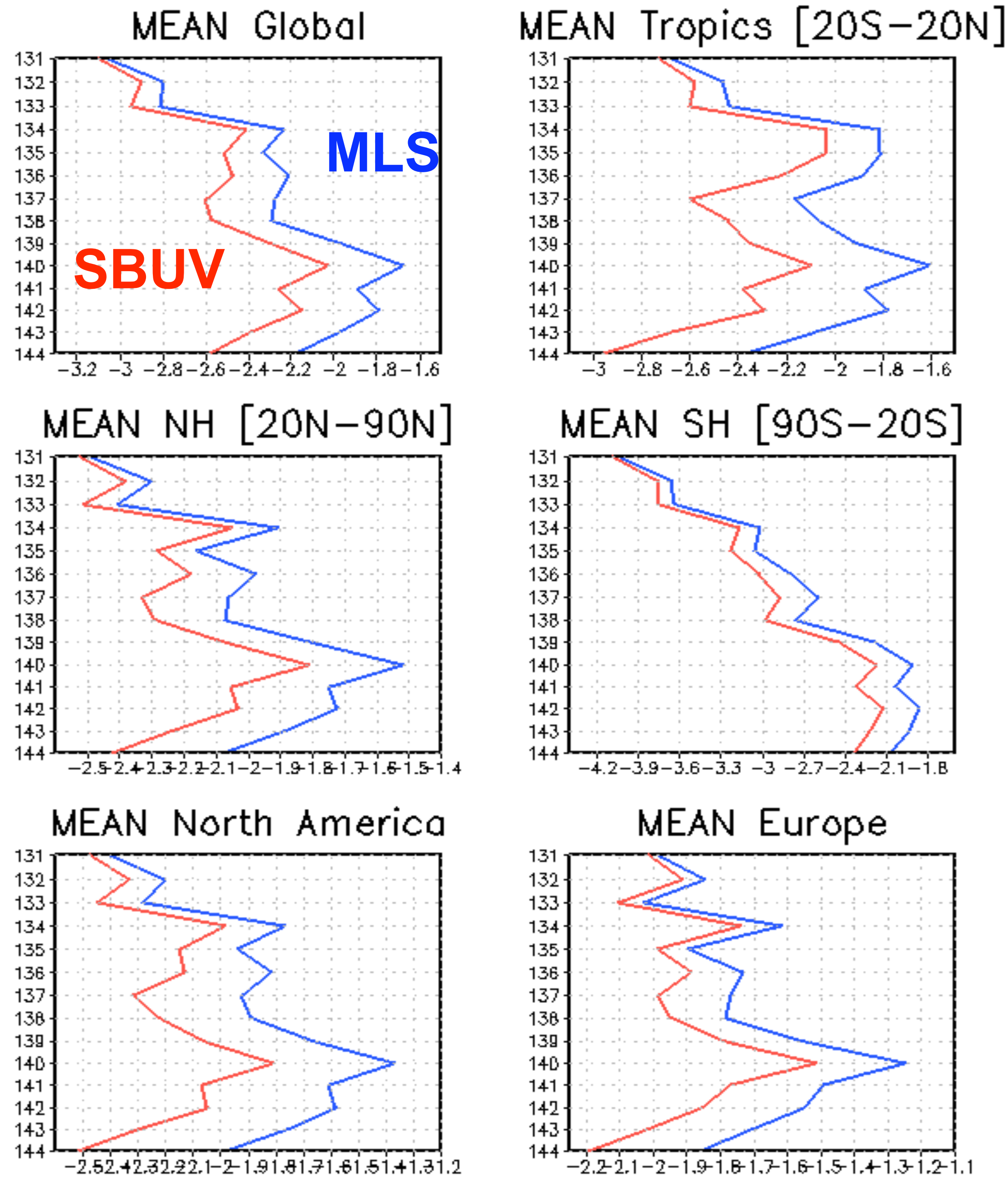
Zonal mean ozone 9/30/2004 00UTC



Ozone hole develops in MLS assimilation

AIRS
mean O-A

- AIRS observation-minus-analysis (O-A) residuals for September 2004
- Mean for ozone channels 131-144 (1001.4 - 1041.1 cm^{-1})
- Smaller bias with MLS, especially in channels more sensitive to ozone (e.g. 144)



GEOS-5 4dVAR and Adjoint Tools

Ricardo Todling and Yannick Tremolet

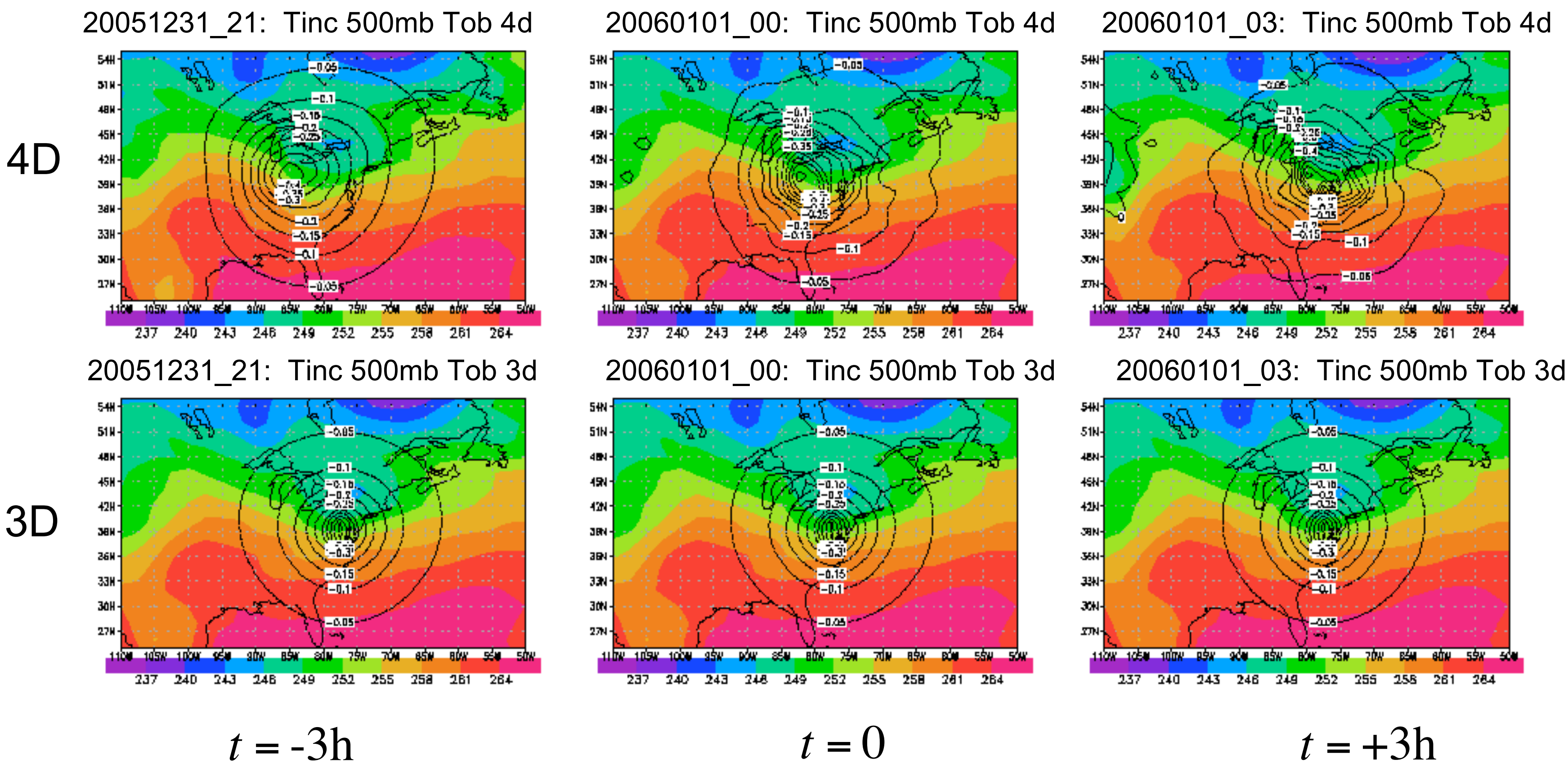
GSI extensions
Early 4dvar results
Observation sensitivity results

Progress in 4D-VAR Development in GEOS-5

1. **Trajectory Model: GEOS-5 with full physics**
2. **Model Adjoint: FV core with simple physics**
3. **Additions to GSI**
   - Observer capability
     - windowing flexibility
     - higher temporal-resolution bins
     - computation of time-dependent departures (OmF's)
   - SQRT(B) preconditioning
   - Options for minimization algorithm (QNewton, L-BFGS, Lanczos CG)
   - Adjoint for GSI
   - ESMF Coupler interface
4. **Additions to overall DAS**
   - TL/AD Dynamical Models (Forecast Sensitivity, Singular Vectors)
   - Observation Impact
   - FGAT
   - 4DVAR

Preliminary 4dVAR tests

Single observation experiment



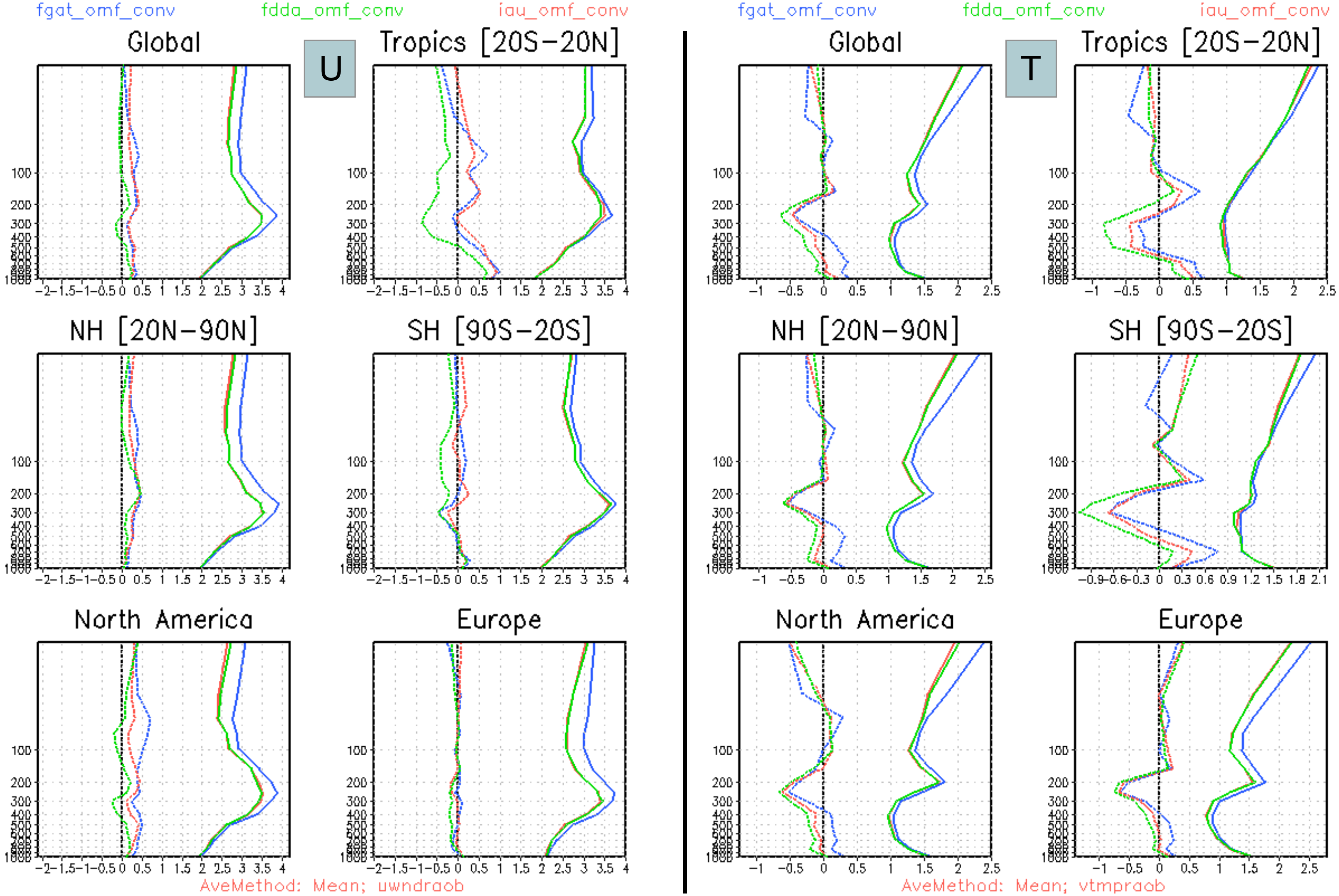
Observation at the **end** of the 6-hr assimilation window

Some initial tests
3dVAR, 3d-FGAT and 4dVAR in GEOS-5

- 2°x2.5°x72L resolution
- Early version ACGM
- Period: January 2006
- Comparison: Monthly Means and Residual Statistics
- Lanczos CG: 2 outer loops, 50/30 iterations

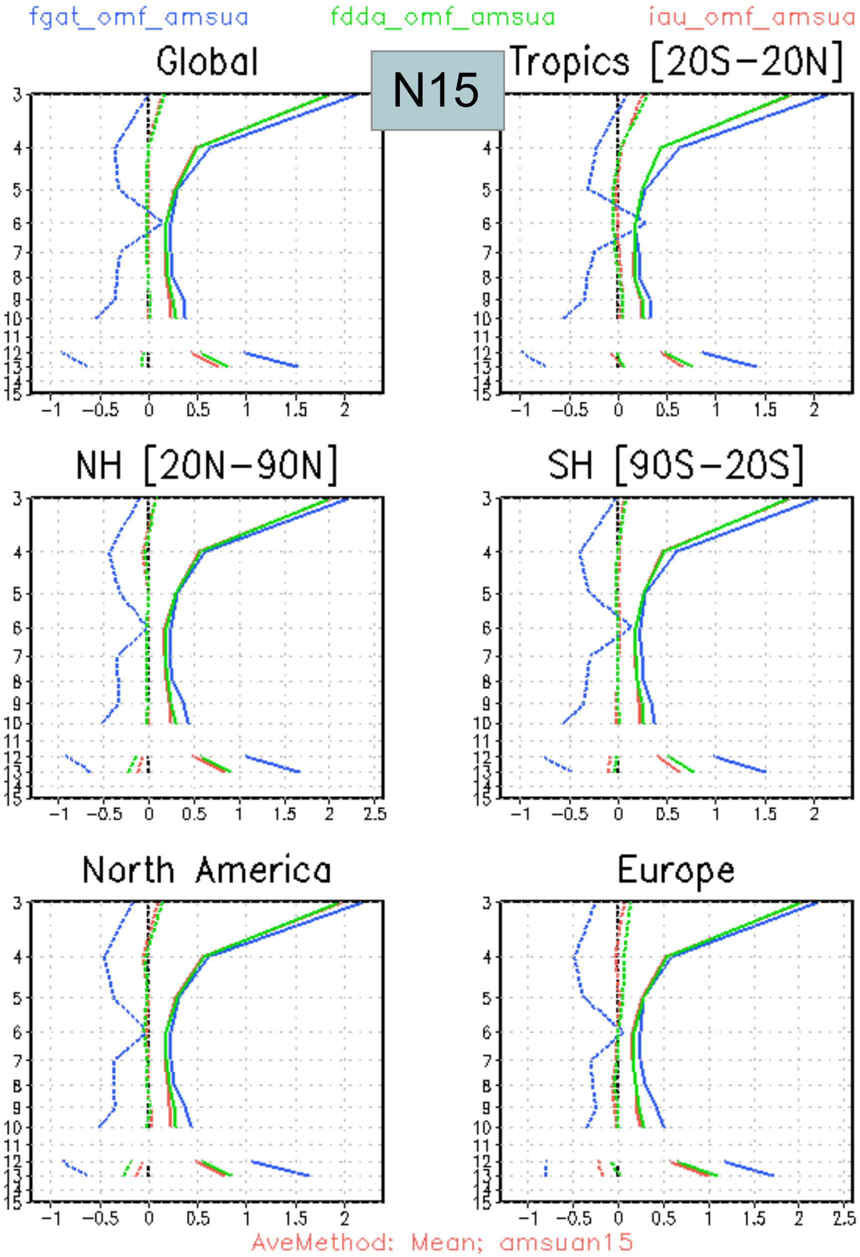
DAS Comparison: IAU vs FGAT vs 4DVAR

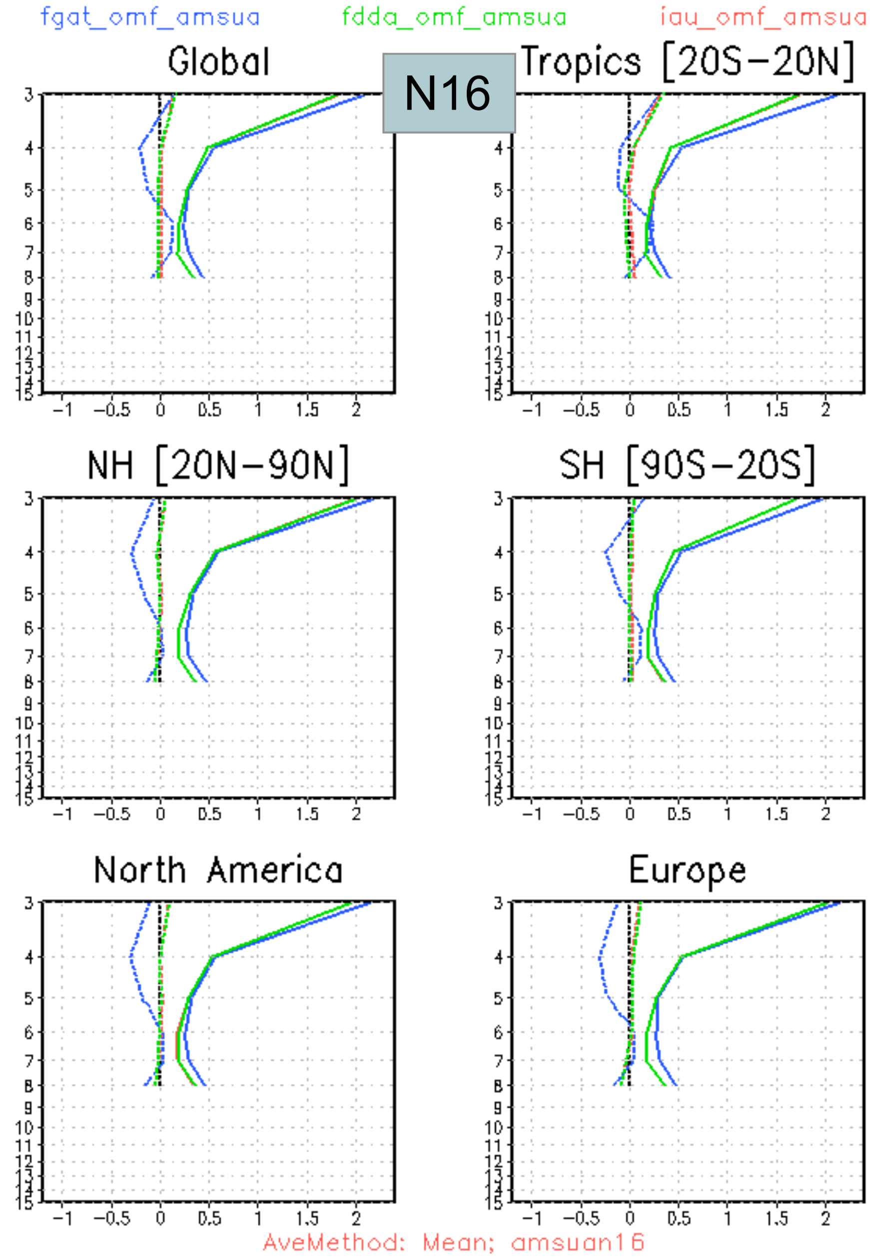
Mean (dashed) & Std Dev for **Raob** O-F



DAS Comparison: IAU vs FGAT vs 4DVAR

Mean (dashed) & Std Dev for **AMSUA** O-F





Zonal Ave Monthly Mean Temperature (K): GEOS-5 vs ECMWF

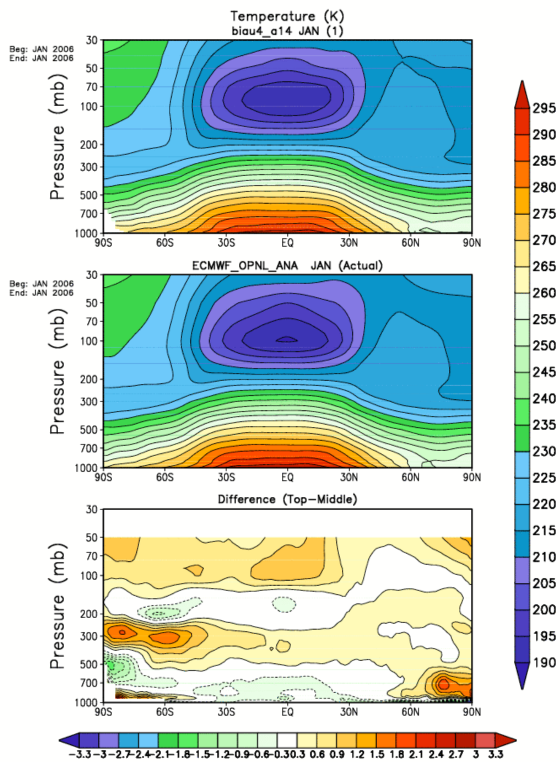
3dvar

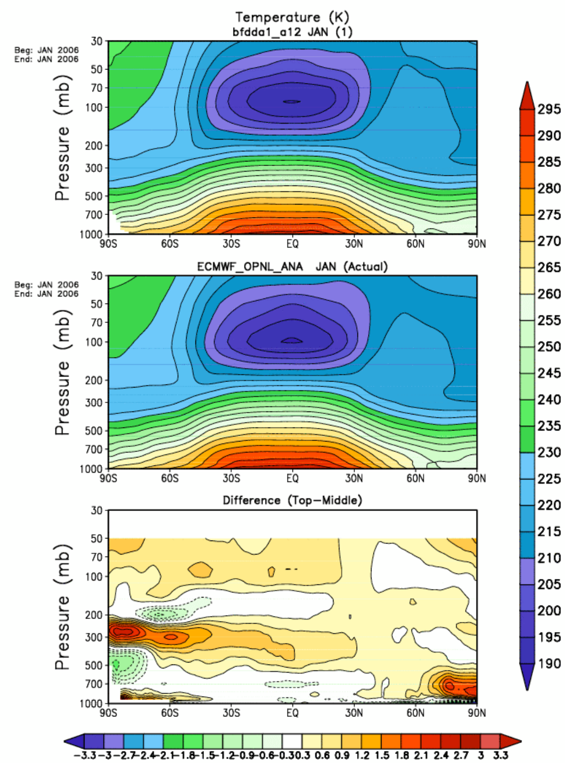
4dvar

GEOS-5

ECMWF

Δ
Top-middle





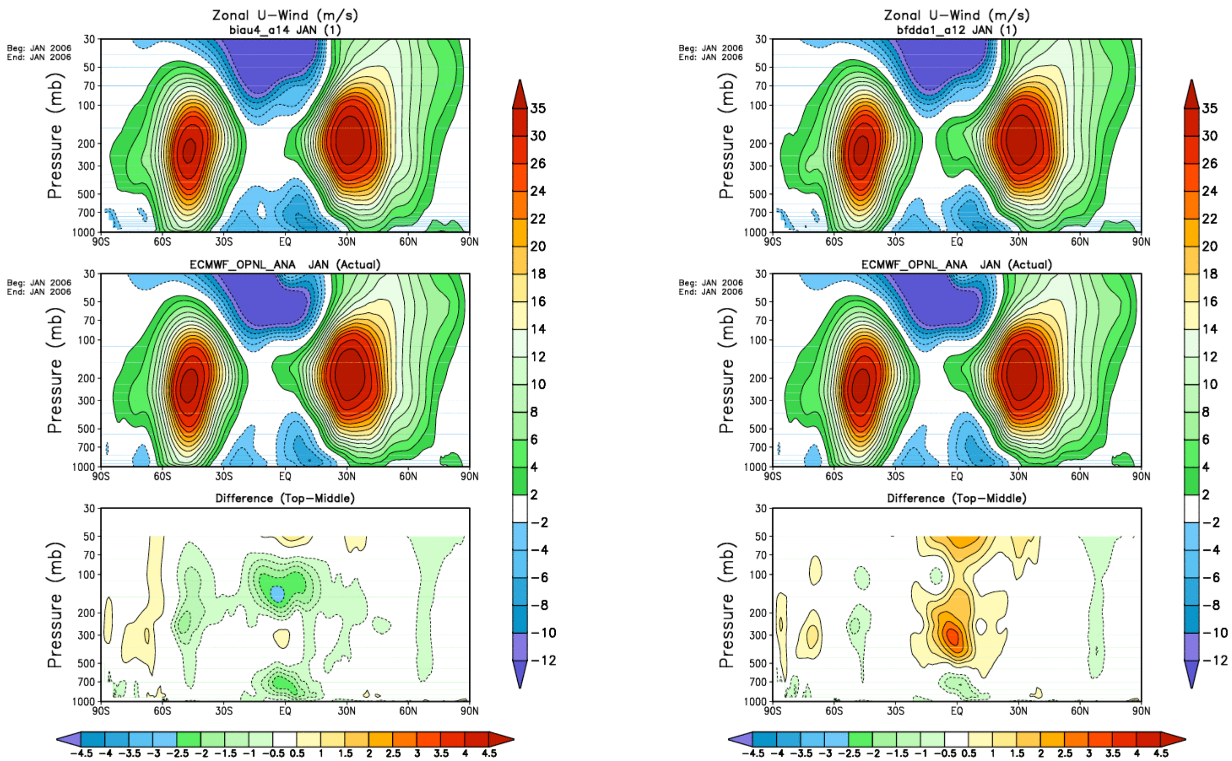
Zonal Ave Monthly Mean Zonal Wind (m/s): GEOS-5 vs ECMWF

3dvar | 4dvar

GEOS-5

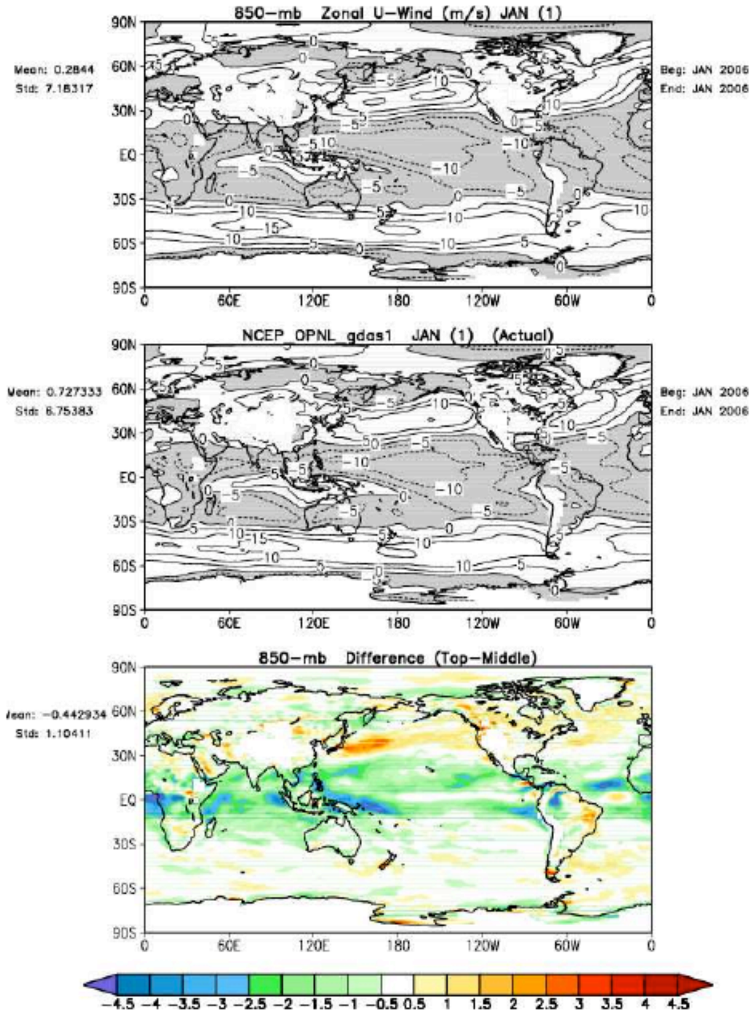
ECMWF

Δ
Top-middle

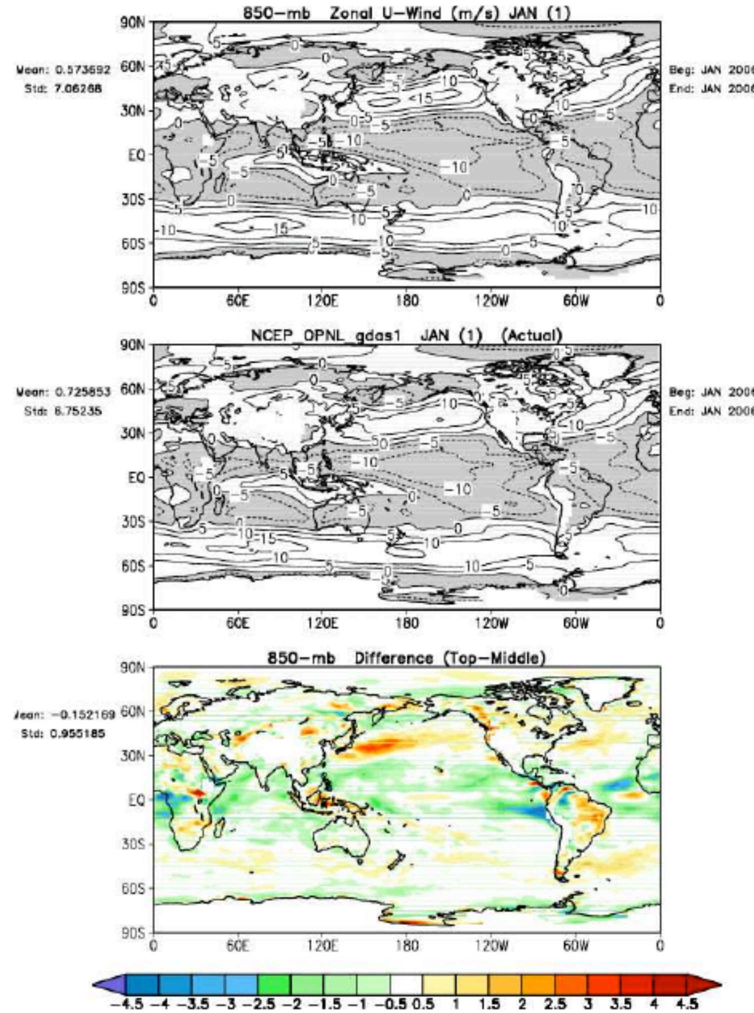


4D-Var Preliminary Results

3D-Var



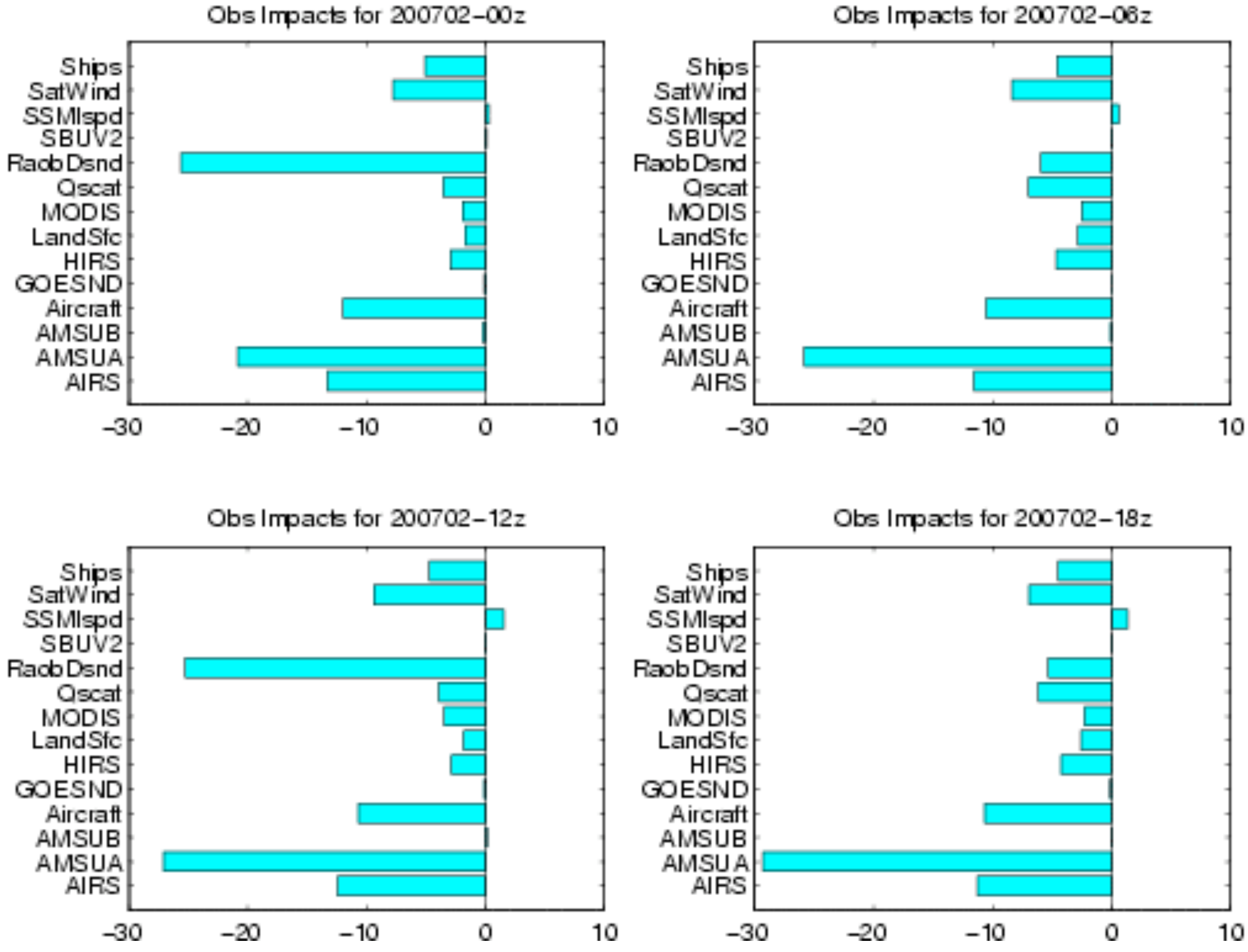
4D-Var



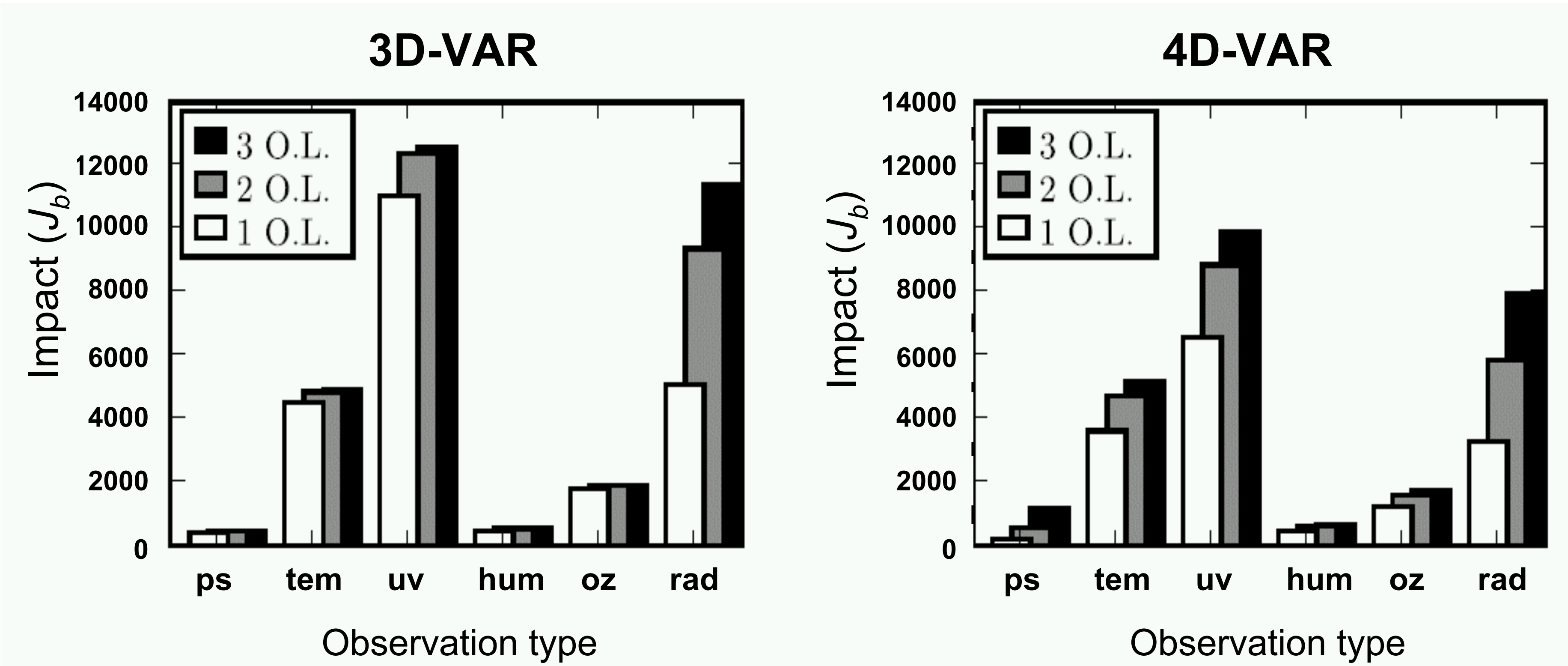
January 2006 850mb u-wind comparison with NCEP Ops

Observation impact: 3dVar DAS & Forecasts

Accumulated forecast error reduction due to various observing instruments for the 24-forecasts for February 2007 - 1/2degree system



Observation impact and outer loops



Impact per observation type with 1, 2 and 3 outer loop iterations

Summary

- GEOS-5 DAS now has a 4D-option, though still some details to be finished
- Various adjoint tools, capable of performing studies in forecast sensitivities, singular vectors, analysis sensitivity and observations impact
- First exercise of these tools is the Observations Impact Intercomparison Study (NASA, NRL, ECMWF, and Env. Canada)
- Weak constraint option is in place in GSI and soon will be in place in the GEOS-5 AGCM, but need model error covariances!
- Work is underway to update the GCM TLM/ADM with cube-sphere f.v. core
- Soon: compare 4DVAR with NCEP's approximate 4D-scheme - First Order Time-interpolation to Observations (FOTO)

The implementations thus far have benefited greatly from the incredible infrastructure of GSI.

Developing an OSSE capability

Ron Errico, Runhua Yang
Emily Liu, Joanna Joiner

Design of an Observation System Simulation Experiment Capability at the GMAO

Goals:

1. Estimate the effect of proposed instruments on analysis and forecast skill by “flying” them in a simulated environment.

2. Evaluate present and proposed data assimilation techniques in a simulation where “truth” is known perfectly.

Requirements:

1. A self-consistent and realistic simulation of nature - provided to the community by ECMWF through NCEP.

2. Simulation of all presently-utilized observations, derived from the “nature run” and having simulated instrument plus representativeness errors characteristic of real observations.

3. A validated baseline assimilation of the simulated data that, for various relevant statistics, produces values similar to corresponding ones in a real DAS.

The OSSE Design Plan at the GMAO

A phased approach:

1. Phase one: use a simple approach to produce a significantly more realistic baseline than has been done to date using all observation types currently demonstrated to have significant impacts (rather than attempting to simulate all observations as realistically as possible).

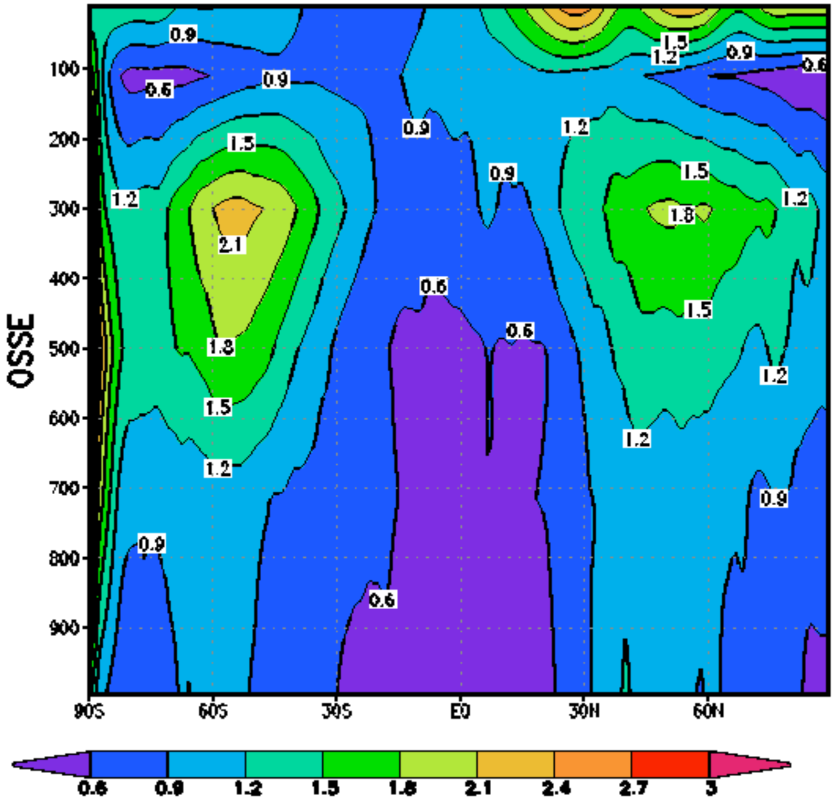
2. Use the adjoint of the GEOS-5 DAS to determine separate impacts of all the simulated observation types for comparison with corresponding impacts in a real DAS.

3. Later phases: add more instruments to the baseline and attempt to provide more realism to the simulated characteristics of observation and representativeness errors.

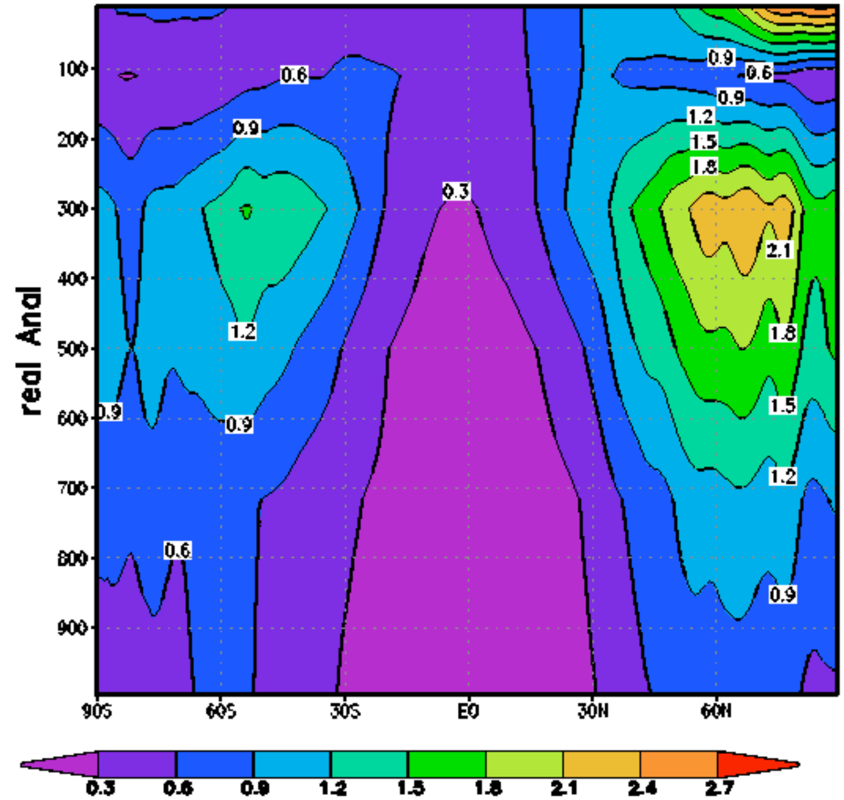
This is currently a small effort within the GMAO that we hope to grow.

Calibrating an OSSE example - validating statistics
Square root of zonally-average variance of δu^a

NCEP OSSE



Operational analysis

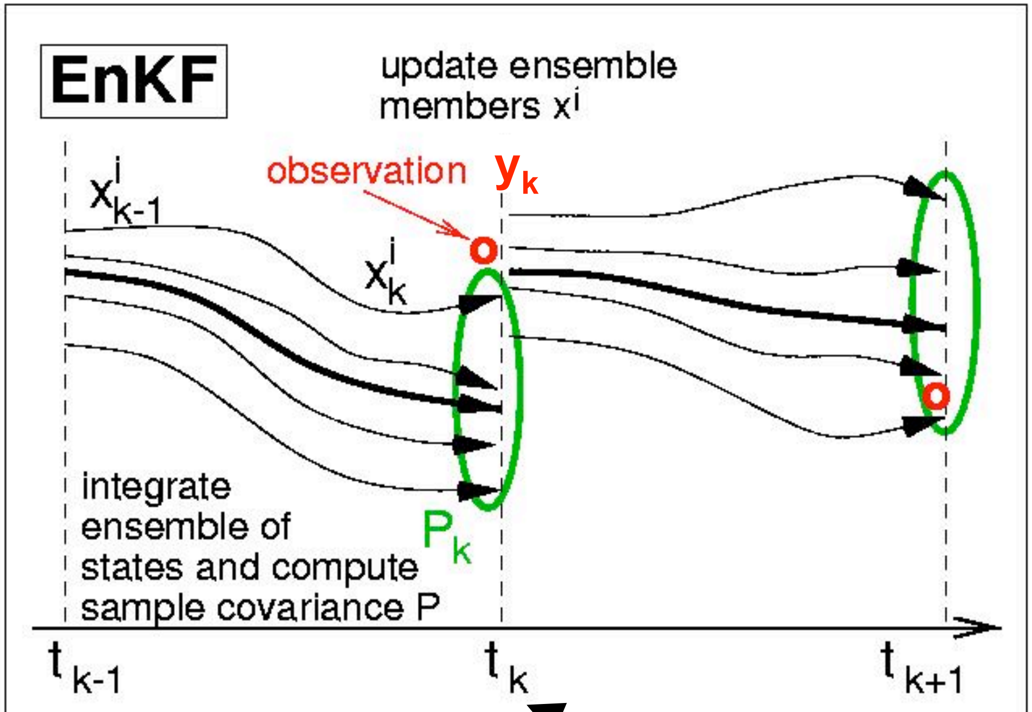


Based on data-denial experiments, the disagreement appears to be mostly due to inadequate simulation of satellite observations. From Errico et al. (2007).

Land Data Assimilation System

Rolf Reichle

GMAO's Land Data Assimilation System



$\mathbf{x_k^i}$ state vector (eg soil moisture)

$\mathbf{P_k}$ state error covariance

$\mathbf{R_k}$ observation error covariance

Propagation $\mathbf{t_{k-1}}$ to $\mathbf{t_k}$:

$$\mathbf{x_k^{i-} = f(x_{k-1}^{i+}) + w_k^i}$$

w = model error

Update at $\mathbf{t_k}$:

$$\mathbf{x_k^{i+} = x_k^{i-} + K_k(y_k^i - x_k^{i-})}$$

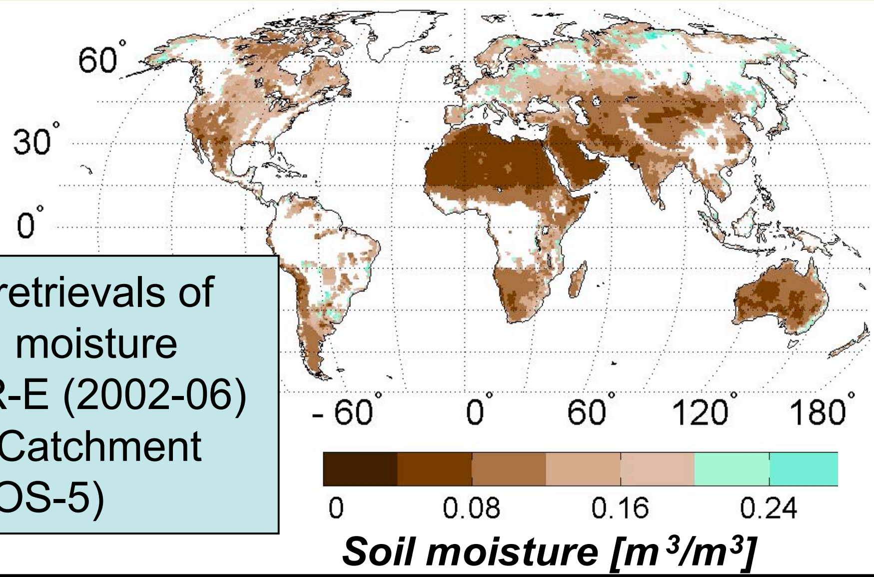
for each ensemble member i=1…N

$$\mathbf{K_k = P_k (P_k + R_k)^{-1}}$$

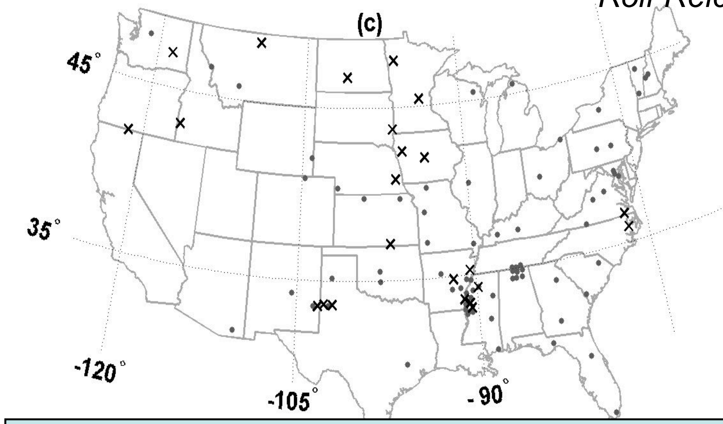
with $\mathbf{P_k}$ computed from ensemble spread

Global assimilation of AMSR-E soil moisture retrievals

Rolf Reichle



Assimilate retrievals of surface soil moisture from AMSR-E (2002-06) into NASA Catchment model (GEOS-5)



Validate with USDA SCAN stations (only 23 of 103 suitable for validation)

Reichle et al. *JGR*, **2007**		Anomaly time series correlation coeff. with in situ data [-] (with 95% confidence interval)			Confidence levels: Improvement of assimilation over	
	N	**Satellite**	**Model**	**Assim.**	**Satellite**	**Model**
Surface soil moisture	23	**.38±.02**	**.43±.02**	**.50±.02**	**>99.99%**	**>99.99%**
Root zone soil moisture	22	**n/a**	**.40±.02**	**.46±.02**	**n/a**	**>99.99%**

Assimilation product agrees better with ground data than satellite or model alone.

Modest increase may be close to maximum possible with *imperfect* in situ data.

Summary

- AIRS moisture channels not used effectively - still examining this in more detail
- Cloud-cleared AIRS radiances can be used effectively
- Positive impacts of AIRS cloud-cleared radiances on forecast skill in both hemispheres.
- Data assimilation system adjoint provides an accurate and efficient tool for estimating observation impact on analyses and forecasts
    - Complement and extend, but not necessarily replace, traditional OSEs as tools for assessing observation impact
    - Comparisons of impacts in different forecast systems should help clarify deficiencies in data quality vs. assimilation methodology, and provide valuable feedback to data producers (GMAO and NRL collaboration)
- Enhanced GSI system incorporates analysis adjoint - easy for updates and maintenance
- Observation impacts to be contributed to Observations Impact Intercomparison Study
- 4dVAR development maturing
- OSSE capability progressing - ready for calibration and tuning
- Land Data Assimilation System being integrated with ADAS

Acknowledgements

- Collaborations with NCEP on the GSI - John Derber and Russ Treadon
- Yannick Tremolet, ECMWF - for many developments associated with 4dVAR
- CRTM - the essential tool - especially helpful for our atmospheric reanalysis (MERRA)
- Allen Huang and Hong Zhang, CIMSS - for cloud-cleared radiances
- Many people in GMAO