Assessing the impact of observations in the NASA GEOS-5 atmospheric data assimilation system

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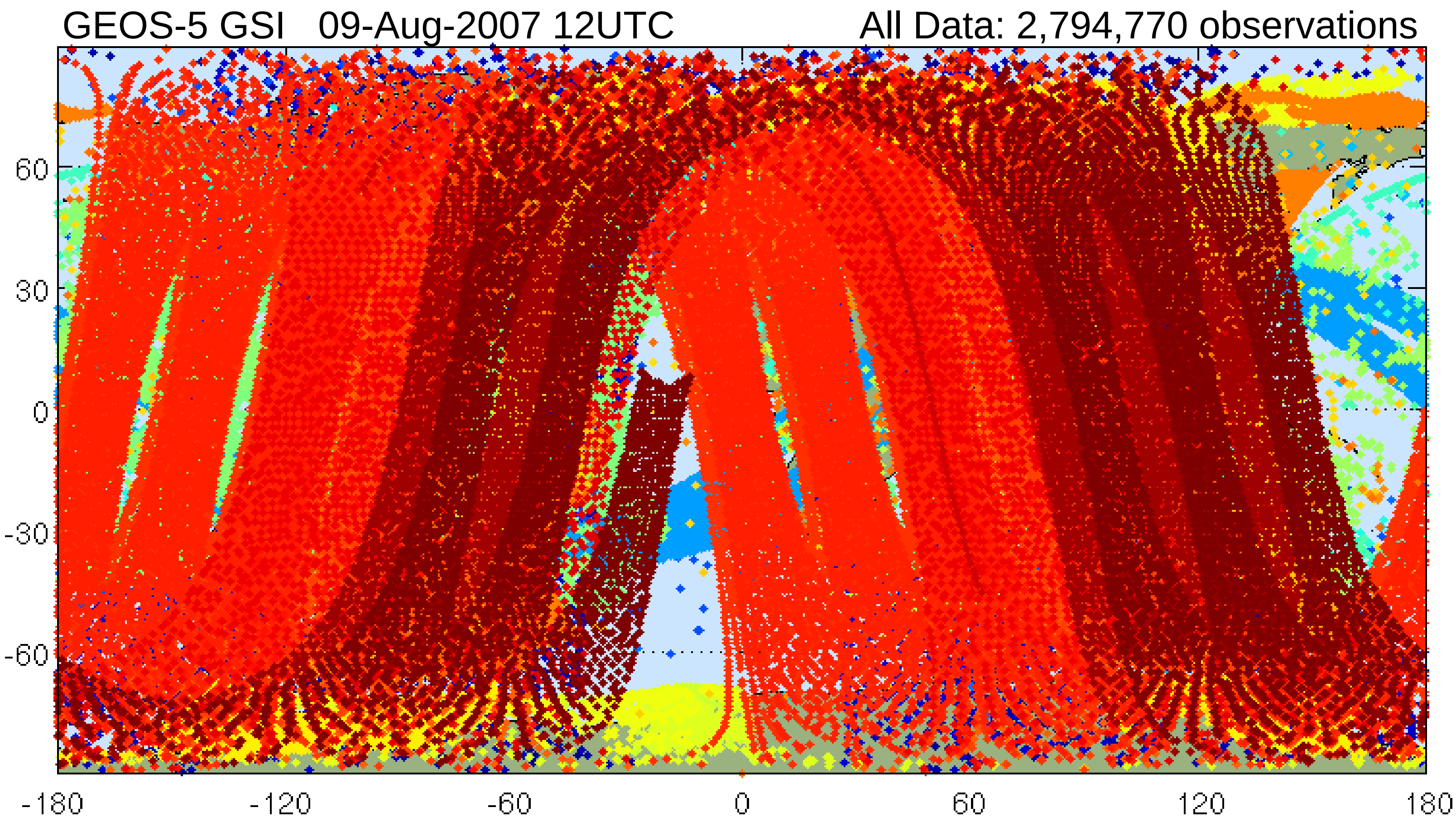
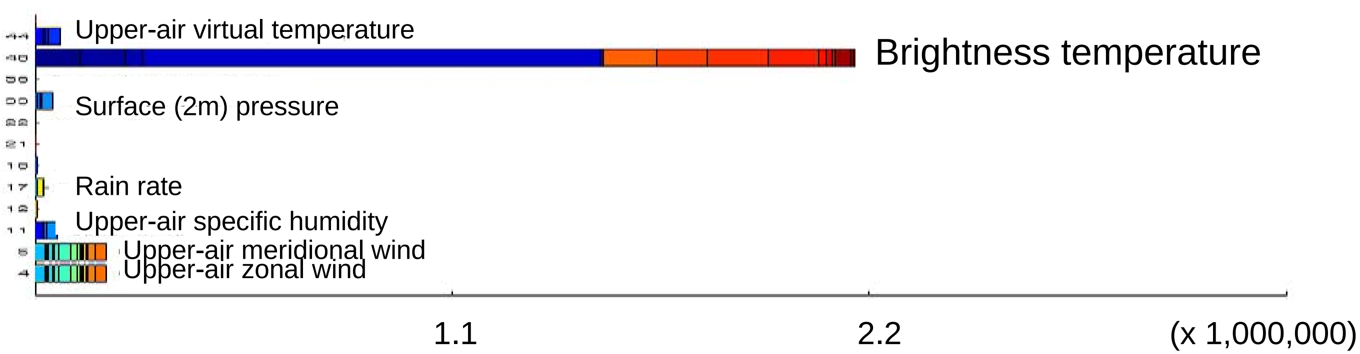
The observing system…today



Data Types



Observing System Experiments (OSEs)

The traditional method of assessing the impact of observations on forecast skill…

- Subsets of observations are **removed** from the assimilation system and forecasts are compared against a 'control' system that includes all observations

- Performed intermittently at operational centers but, because of their expense, usually involve a relatively small number of independent experiments, each considering relatively large subsets of observations

But what if one wants to investigate, for example, the impact of *all individual channels* on a given satellite…and *over arbitrary periods of time, or even routinely*…?

Outline of Talk

- Estimation of observation impact – adjoint (ADJ) method
- GEOS-5 observation impact results (‘old’ GSI)
- Comparison of ADJ and OSE results
- Looking ahead: 3/4-DVAR results with ‘new’ GSI
- Concluding remarks

Data Assimilation-Forecast System

- Atmospheric forecast model:

$$\mathbf{x}^f = \mathbf{m}(\mathbf{x}_0)$$

- Atmospheric analysis (best estimate of $\mathbf{x}_0$) :

$$\delta\mathbf{x}_0 = \mathbf{K}\delta\mathbf{y}$$

where: $\delta\mathbf{x}_0 = \mathbf{x}_\mathrm{a} - \mathbf{x}_\mathrm{b}$ (increment, correction vector)

$\delta\mathbf{y} = \mathbf{y} - \mathbf{h}(\mathbf{x}_\mathrm{b})$ (innovation vector ~10^6)

$\mathbf{K}$ determines the scalar weight (gain) given to each observation

Note that $\delta\mathbf{x}_0 = \mathbf{K}\delta\mathbf{y}$ may be viewed as a transformation between a perturbation in state space and a perturbation in observation space

Estimating Observation Impact

Forecast error measure (**dry energy**, sfc–130 hPa):

$$e = (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})^\mathrm{T} \mathbf{C} (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})$$

Taylor expansion of change in e due to change in $\mathbf{x}_0$:

$$\delta e = \delta \mathbf{x}_0 \left(\frac{\partial e}{\partial \mathbf{x}_0} + \frac{1}{2} \frac{\partial^2 e}{\partial \mathbf{x}_0^2} \delta \mathbf{x}_0 + \frac{1}{6} \frac{\partial^3 e}{\partial \mathbf{x}_0^3} \delta \mathbf{x}_0^2 + \ldots \right) = (\delta \mathbf{x}_0)^\mathrm{T} \mathbf{g}$$

Transformation to **observation-space**:

$$\delta \mathbf{x}_0 = \mathbf{x}_\mathrm{a} - \mathbf{x}_\mathrm{b} = \mathbf{K} \delta \mathbf{y}$$

3rd order approximation of δe in **observation space**:

$$\delta e \approx (\delta \mathbf{y})^\mathrm{T} \mathbf{K}^\mathrm{T} [\boxed{\mathbf{M}_\mathrm{b}^\mathrm{T} \mathbf{C} (\mathbf{x}_\mathrm{b}^f - \mathbf{x}_\mathrm{v})} + \boxed{\mathbf{M}_\mathrm{a}^\mathrm{T} \mathbf{C} (\mathbf{x}_\mathrm{a}^f - \mathbf{x}_\mathrm{v})}] = (\delta \mathbf{y})^\mathrm{T} \tilde{\mathbf{g}}_3$$

analysis adjoint

model adjoint

…summed observation impact

Properties of the Impact Estimate

$$\delta e \approx (\delta \mathbf{y})^{\mathrm{T}} \tilde{\mathbf{g}}_3$$

- The impact of arbitrary subsets of observations (e.g. instrument type, channel, location) can be easily quantified by summing only the terms involving the desired elements of $\delta \mathbf{y}$.

- The "weight" vector $\tilde{\mathbf{g}}_3$ is computed only once, and involves the *entire* set of observations; removing or changing the properties of one observation changes the scalar measure of all other observations.

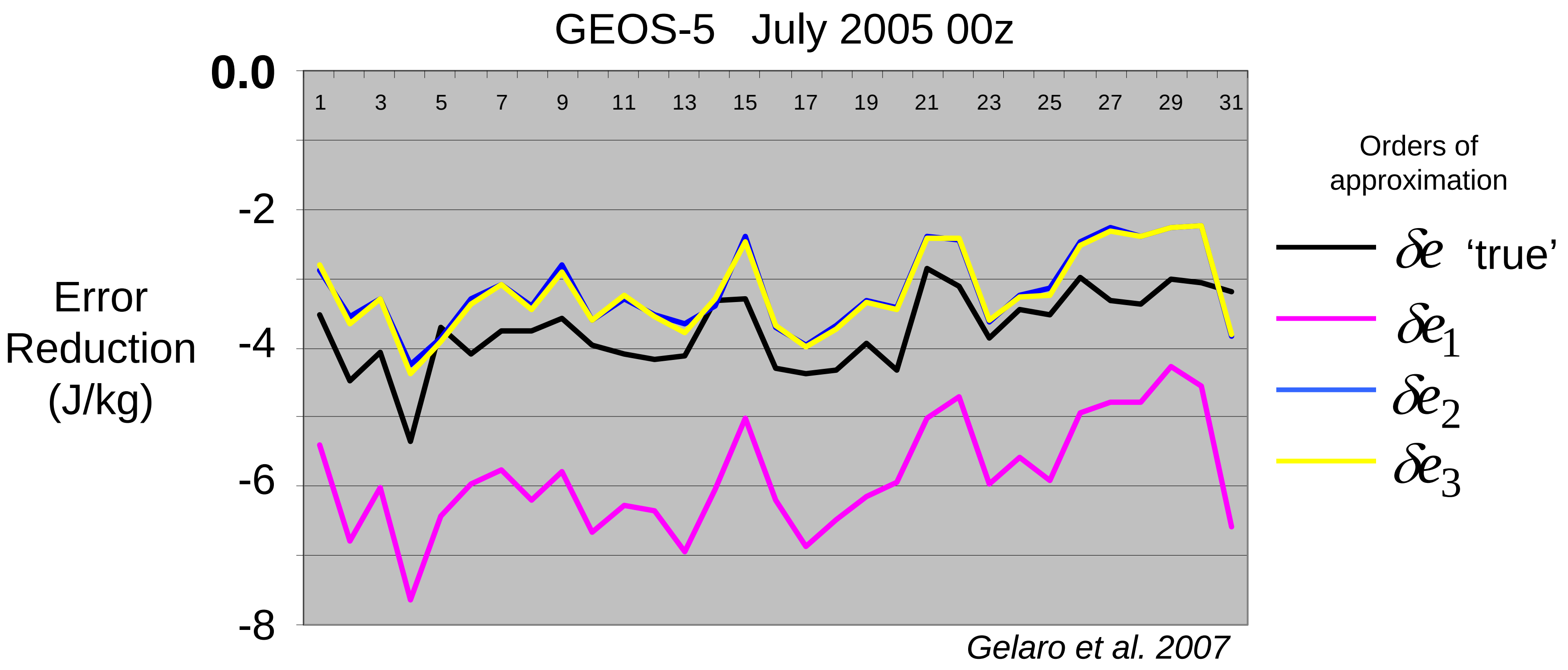
- Valid forecast range limited by tangent linear assumption for $\mathbf{M}^{\mathrm{T}}$

$\delta e < 0$ …the observation **improves** the forecast

$\delta e > 0$ …the observation **degrades** the forecast

…see Langland and Baker (2004), Errico (2007), Gelaro et al. (2007)

Accuracy of Observation Impact Estimate



- All values negative…observations provide benefit overall

- 2nd and 3rd order approximations recover ~85% of 'actual' impact computed from model fields directly

- Accuracy of observation space estimate allows meaningful aggregation by observation type, location, channel, etc.

Nonlinearity Considerations

$$\delta e \approx (\delta \mathbf{y})^{\mathrm{T}} \underbrace{\mathbf{K}^{\mathrm{T}}[\mathbf{M}_{\mathrm{b}}^{\mathrm{T}}\mathbf{C}(\mathbf{x}_{\mathrm{b}}^{f} - \mathbf{x}_{\mathrm{v}}) + \mathbf{M}_{\mathrm{a}}^{\mathrm{T}}\mathbf{C}(\mathbf{x}_{\mathrm{a}}^{f} - \mathbf{x}_{\mathrm{v}})]}_{\tilde{\mathbf{g}}_3}$$

*Gelaro et al. (2007) examined the effects of nonlinearity on the interpretation of the **partial sums** used to estimate observation impact by platform, station, channel, etc.*

- $\tilde{\mathbf{g}}_3$ depends nonlinearly on **all** innovations due to dependence on $\mathbf{x}_{\mathrm{a}}$ *…partial sums of* δe *involve cross terms with other observations* $\Rightarrow$ *possible ambiguities*

- No obvious detrimental effects (cross terms appear small) for estimating impacts of the major observing systems…smaller subsets?...

- Higher than first-order accuracy is required to capture adequately the observation impact

- The dominant nonlinearity arises from the quadratic nature of the error measure e …not from higher-order terms in the model

GEOS-5 Observation Impact Experiments

Analysis System

- 3DVAR Gridpoint Statistical Interpolation (GSI)
- 0.5º resolution, 72 levels
- **Adjoint:** Exact line-by-line (Zhu and Gelaro 2008)

Forecast Model

- GEOS-5: FV-core + full physics
- 0.5º resolution, 72 levels
- **Adjoint:** FV-core **1º resolution + simple dry physics**

Experimentation

- 6h data assimilation cycle, July 2005 and January 2006
- **24h forecasts from 00UTC** to assess observation impact
- **Separate error response functions** for the globe, NH, SH and tropics

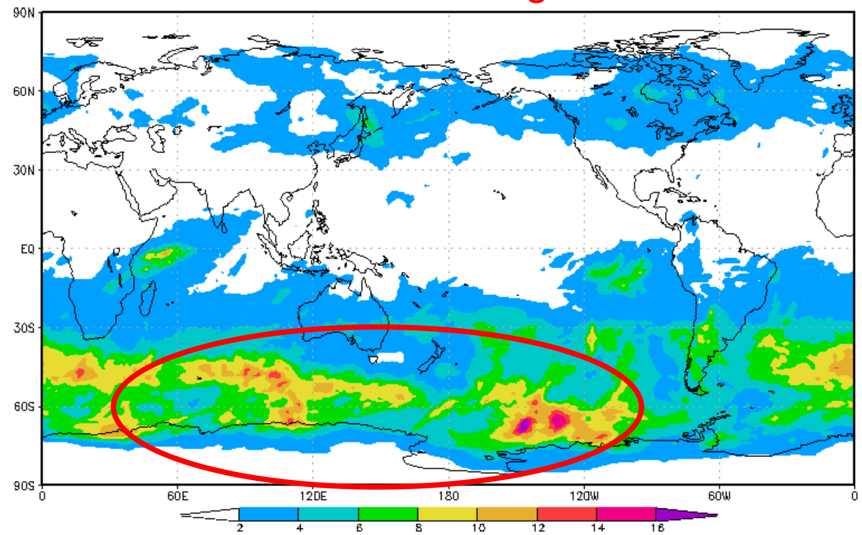
24h Forecast Error Sensitivity to Initial Conditions

GEOS-5 July 2005

Vertically integrated energy (u,v,T,ps)

Valid 00z from 18z Background States

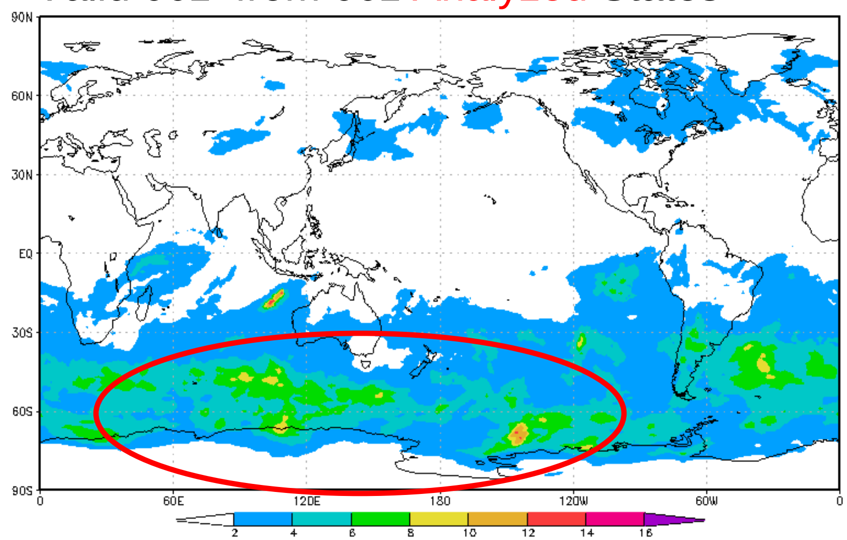
$$\mathbf{M}_b^T \mathbf{C}(\mathbf{x}_b^f - \mathbf{x}_v)$$



July 2005 Control Background

Valid 00z from 00z Analyzed States

$$\mathbf{M}_a^T \mathbf{C}(\mathbf{x}_a^f - \mathbf{x}_v)$$

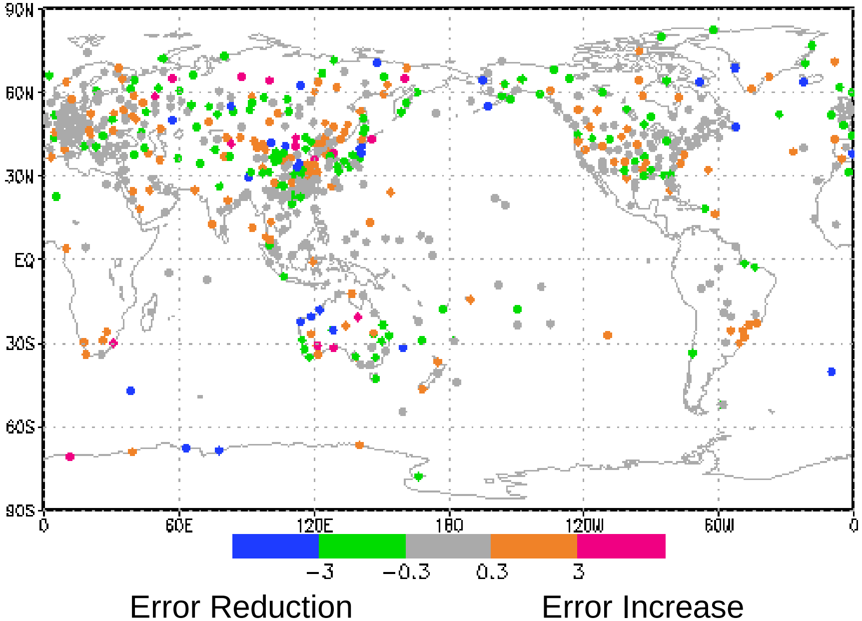


Large impact of observations over southern oceans during winter

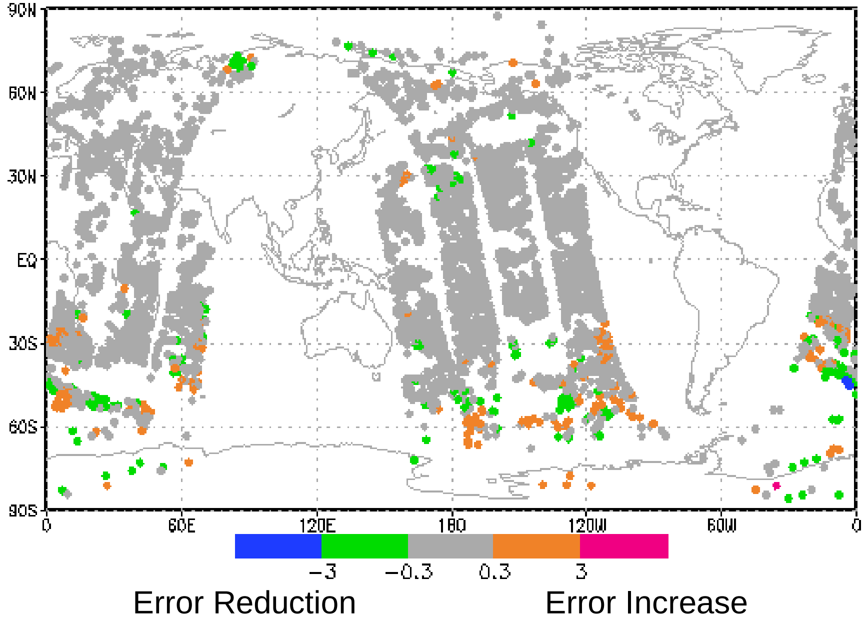
Observation Impact on GEOS-5 24h Forecast Error

10 July 2005 00Z

Impact of 500mb RAOB Temps



Impact of AIRS Ch.221 Radiances



●● Observations that reduced the 24h forecast error: $\delta e < 0$

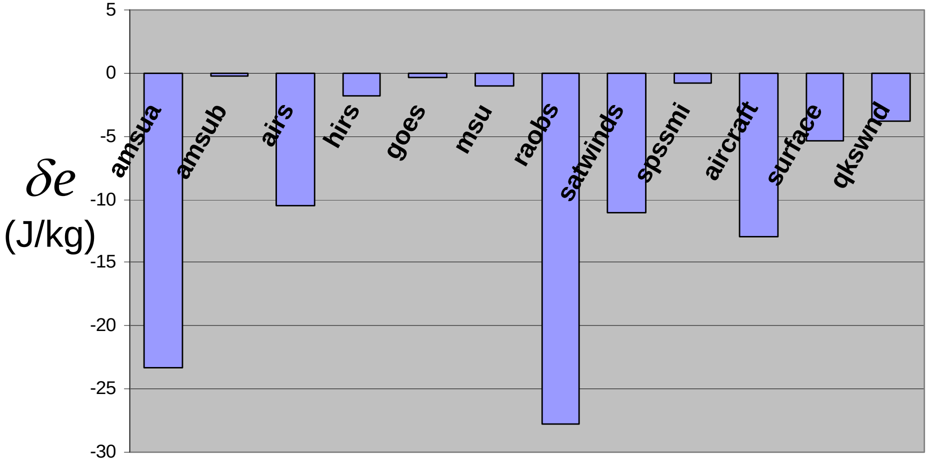
●● Observations that increased the 24h forecast error: $\delta e > 0$

●● Observations that had small impact on 24h forecast error

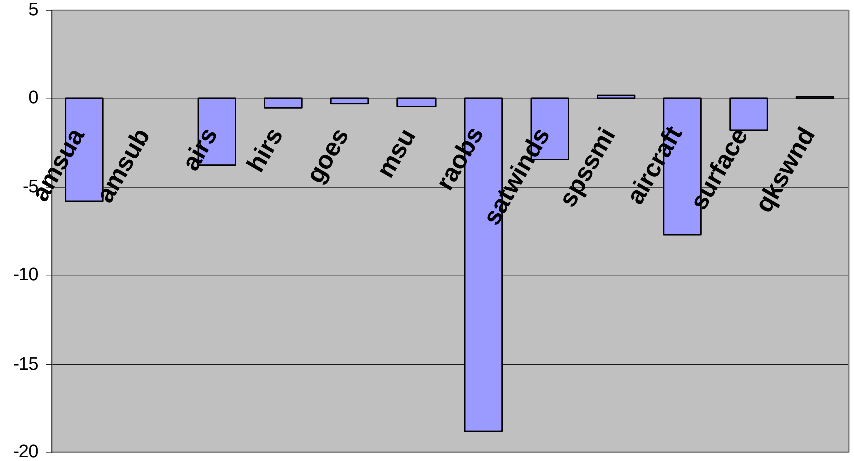
Total 24hr Forecast Error Reduction due to Observations

January 2006 00UTC

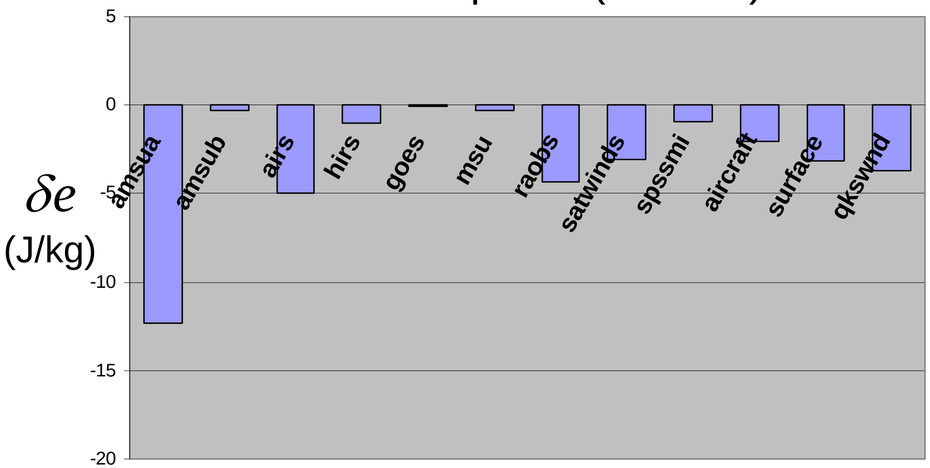
Global



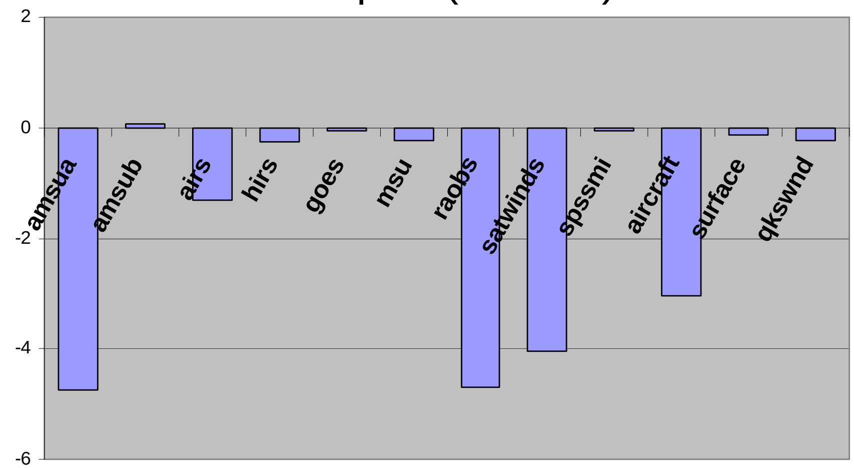
N. Hemisphere (20º-80º)



S. Hemisphere (20º-80º)



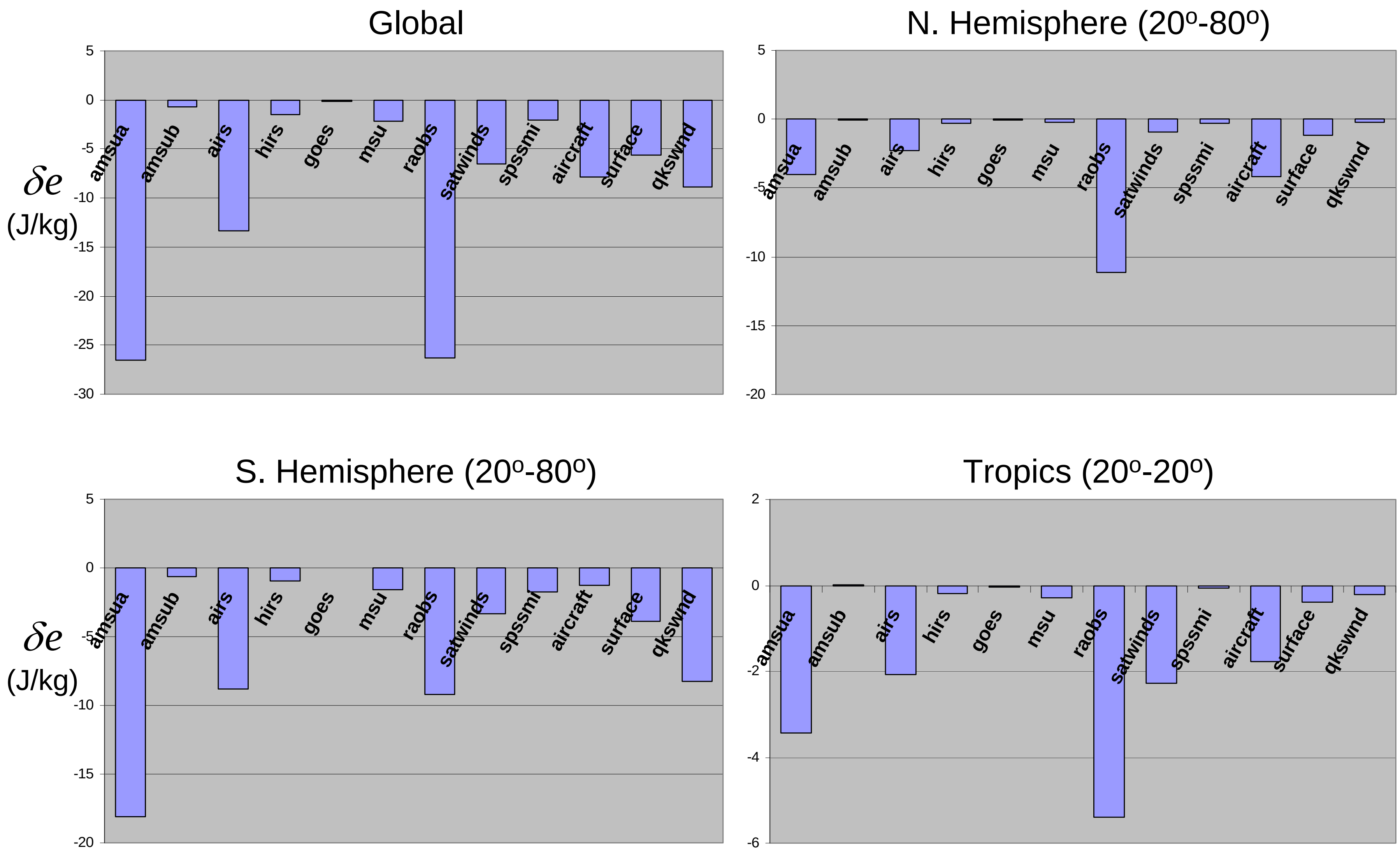
Tropics (20º-20º)



GEOS-5 Adjoint Data Assimilation System

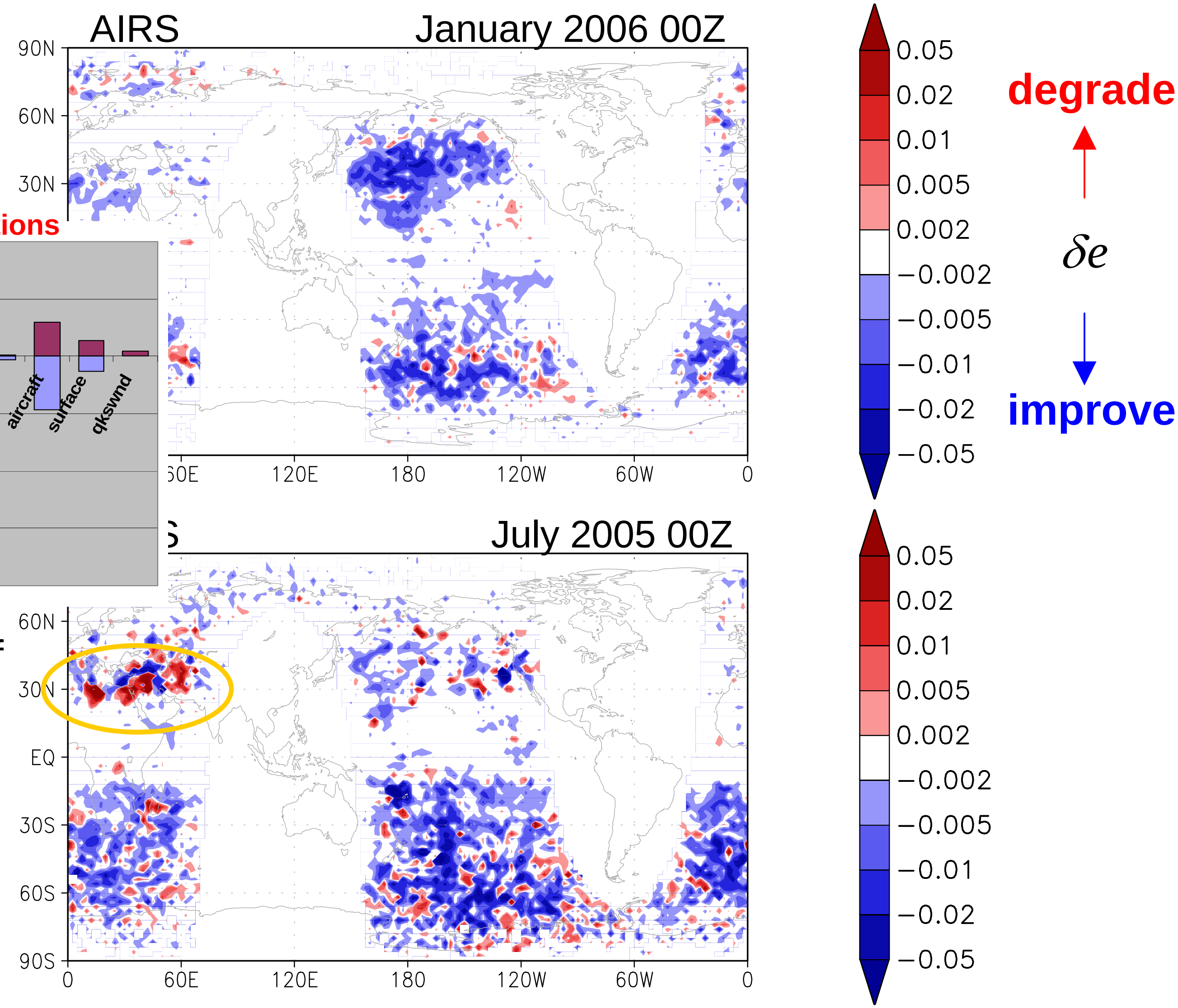
Total 24hr Forecast Error Reduction due to Observations

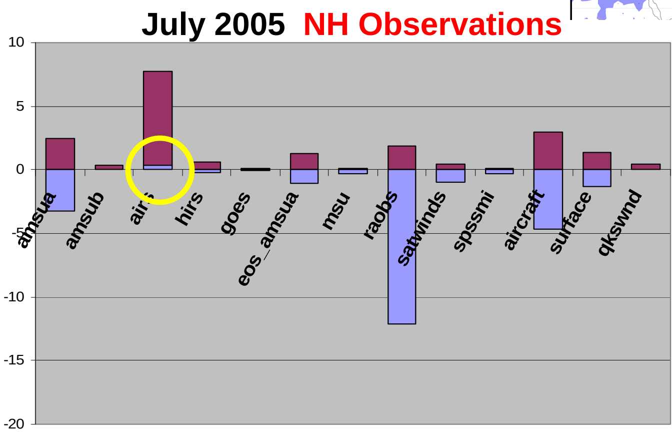
July 2005 00UTC



GEOS-5 Adjoint Data Assimilation System

Accumulated Observation Impact - AIRS

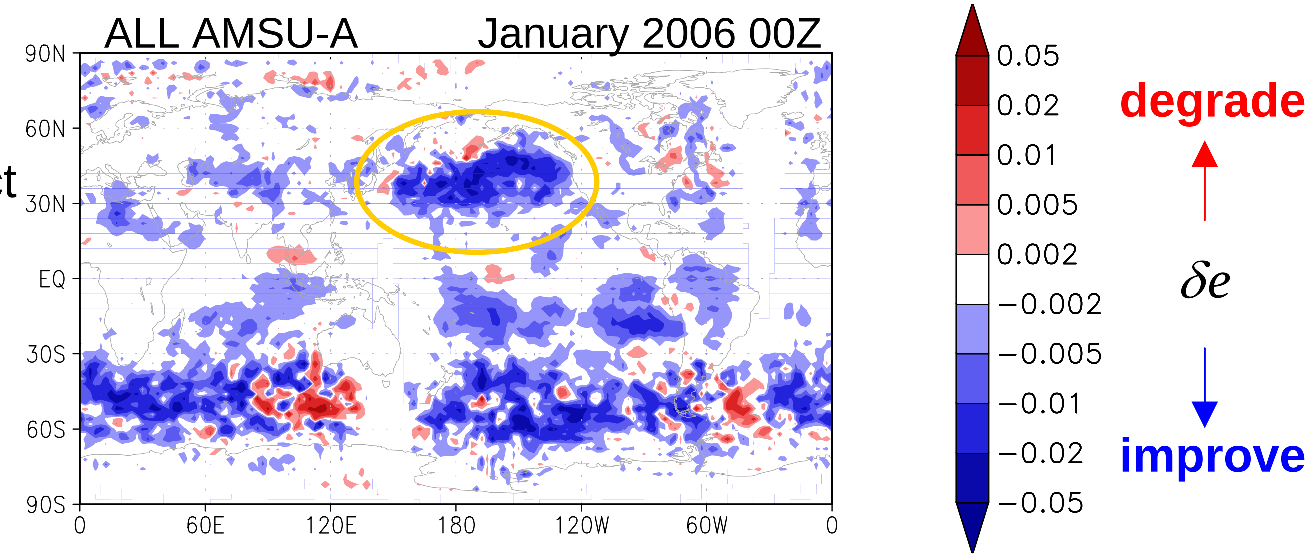




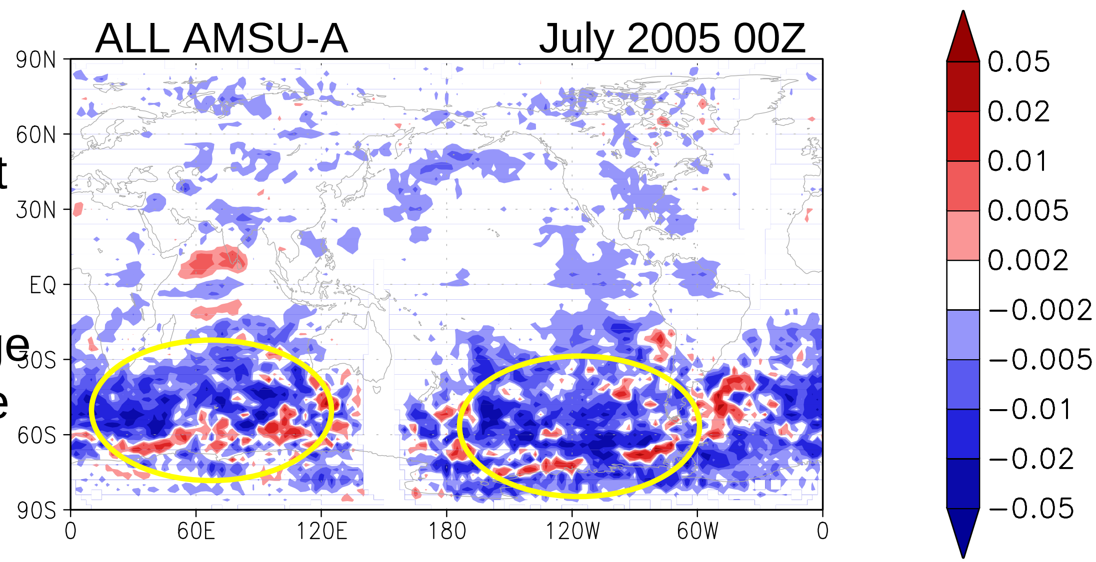
- Negative impact of AIRS observations over land…

Accumulated Observation Impact – ALL AMSU-A

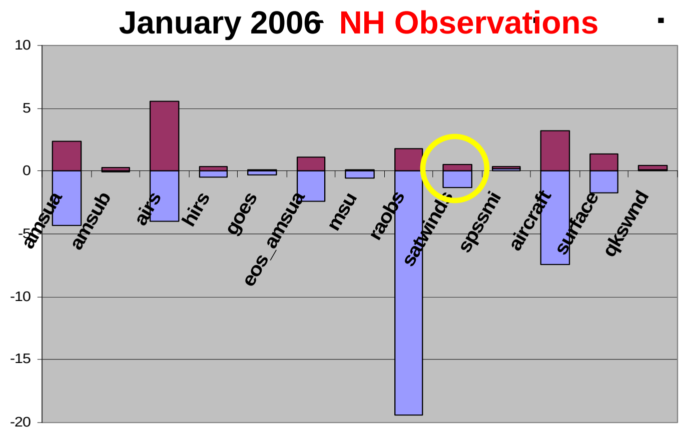
- Large positive impact over N.Pacific; region of large forecast error sensitivity

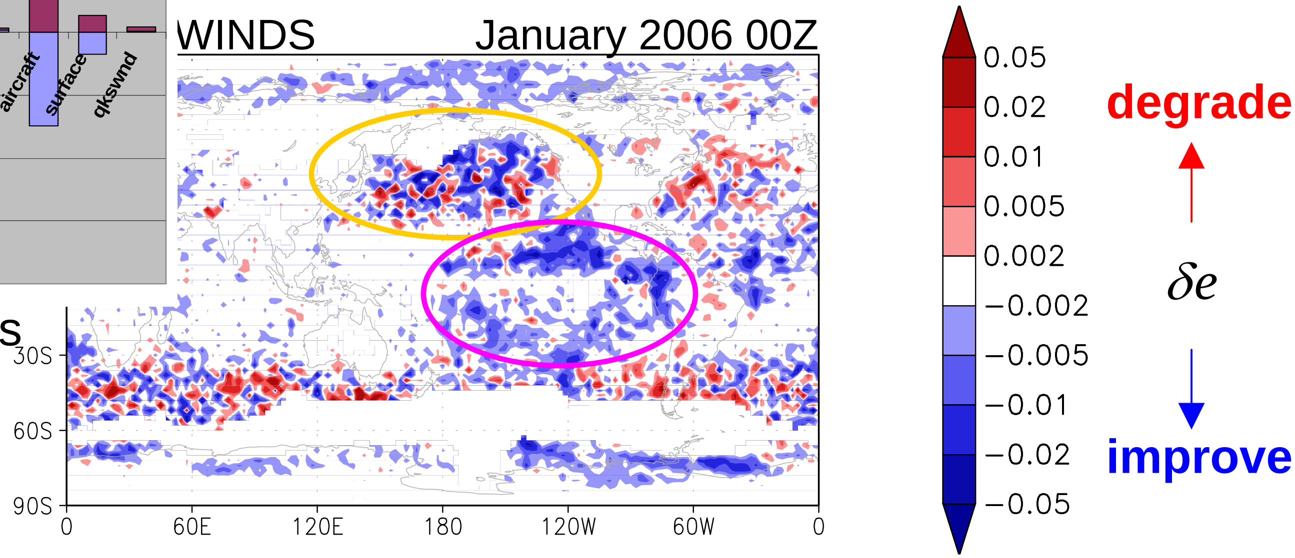


- Large positive impact over southern oceans, but negative impacts along Antarctic ice edge …problem with surface type/emissivity…?

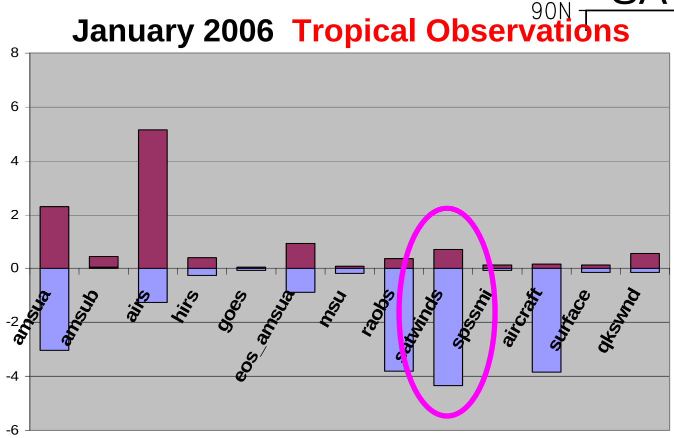


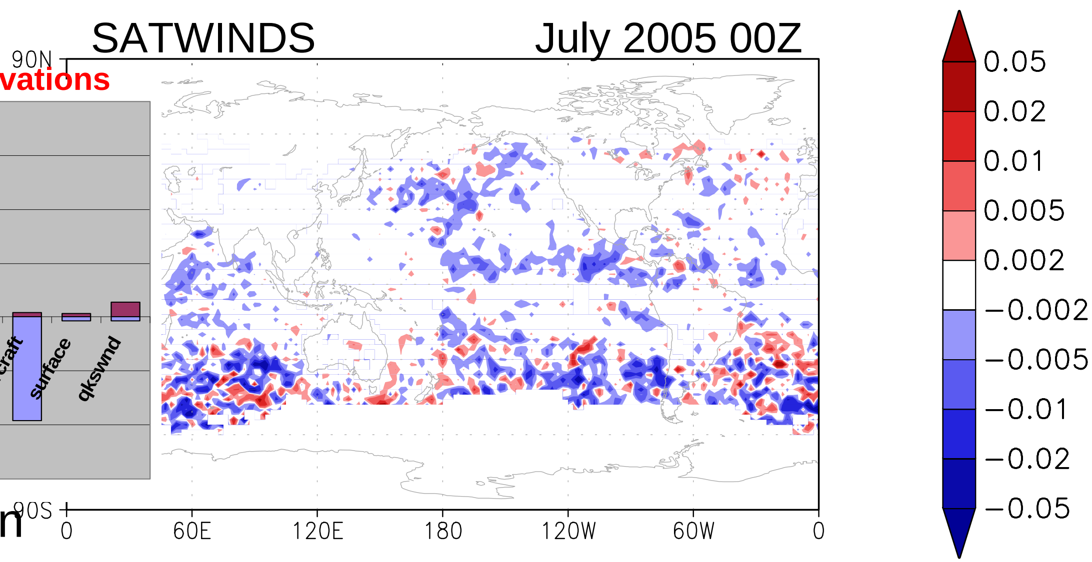
Observation Impact – Satwinds





- SATWIND impact is ‘mixed’ in the extra-tropics…



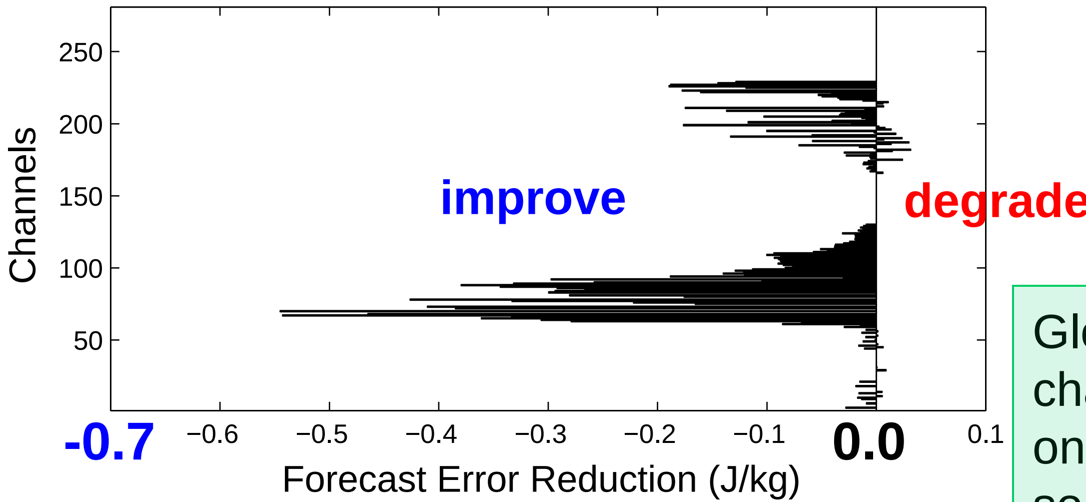


…but clearly positive in the tropics, (and polar regions)

Impact of satellite observations by channel

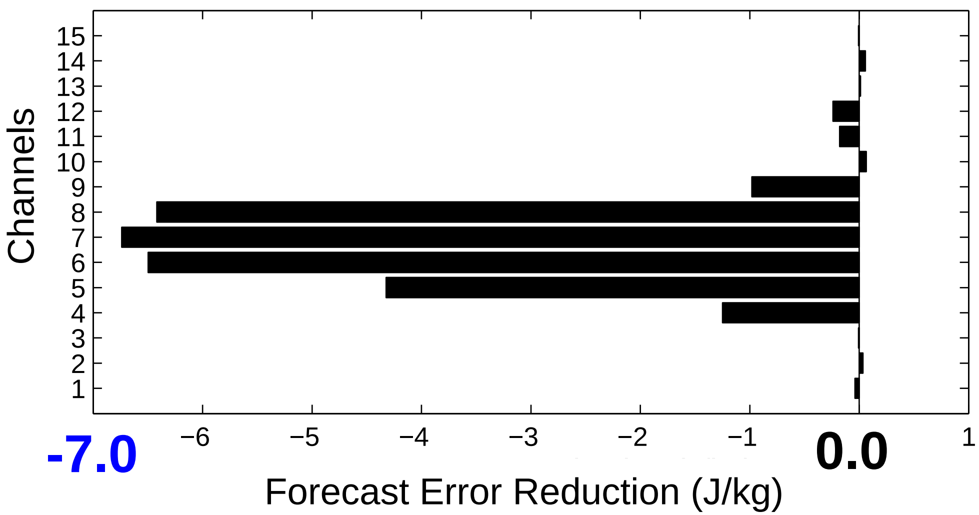
July 2005 00UTC

AIRS



Global impact of most channels is beneficial on average…with some exceptions

AMSU-A



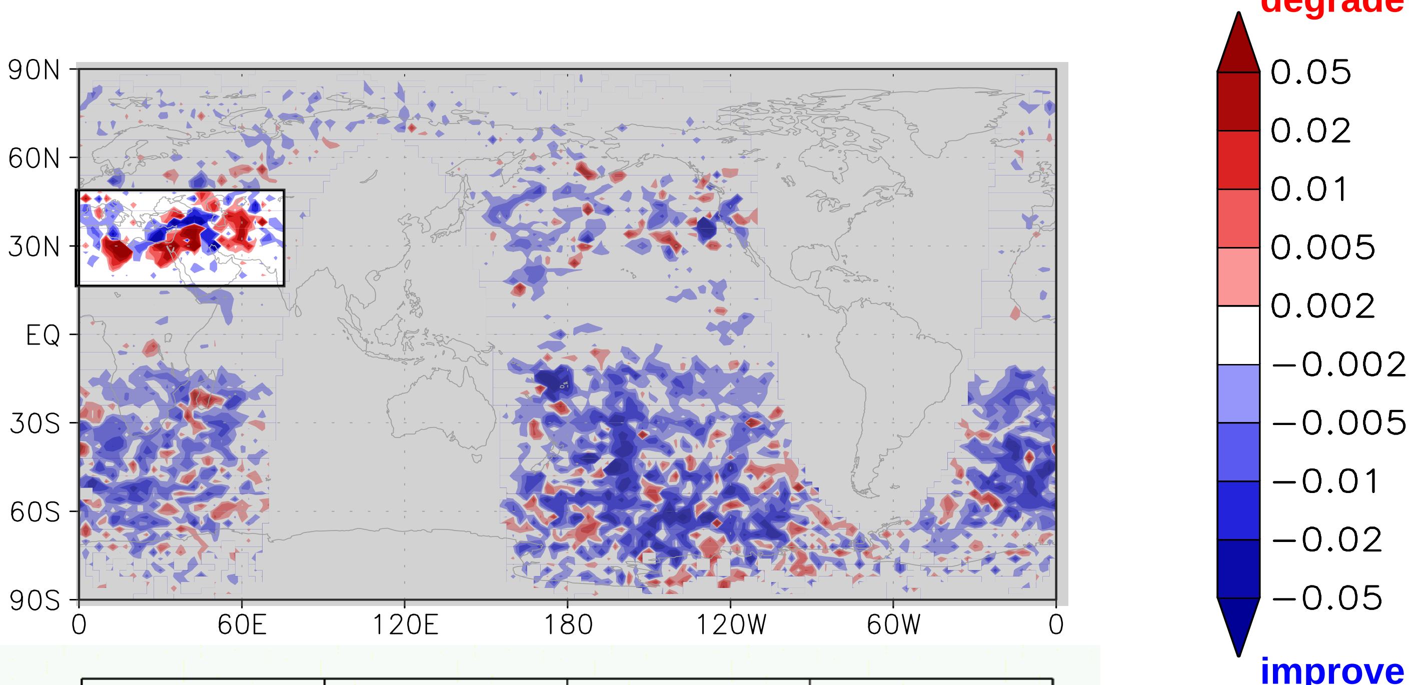
GEOS-5 Adjoint Data Assimilation System

Localized examination of AIRS impacts

July 2005 00UTC

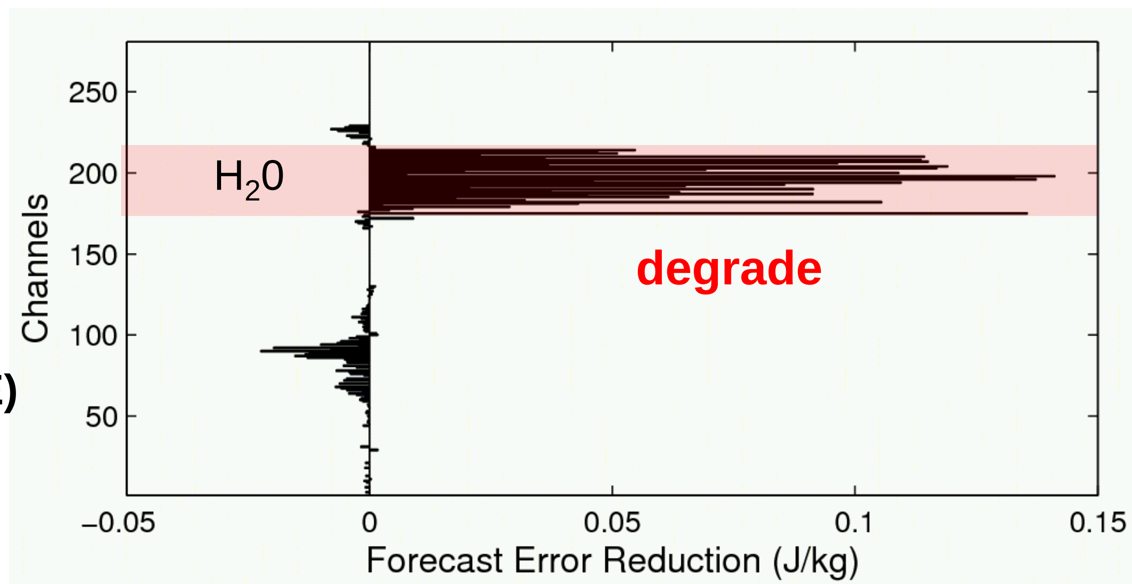
AIRS impact map

(All Channels)



AIRS impact by channel

(20-50N, 0-80E)

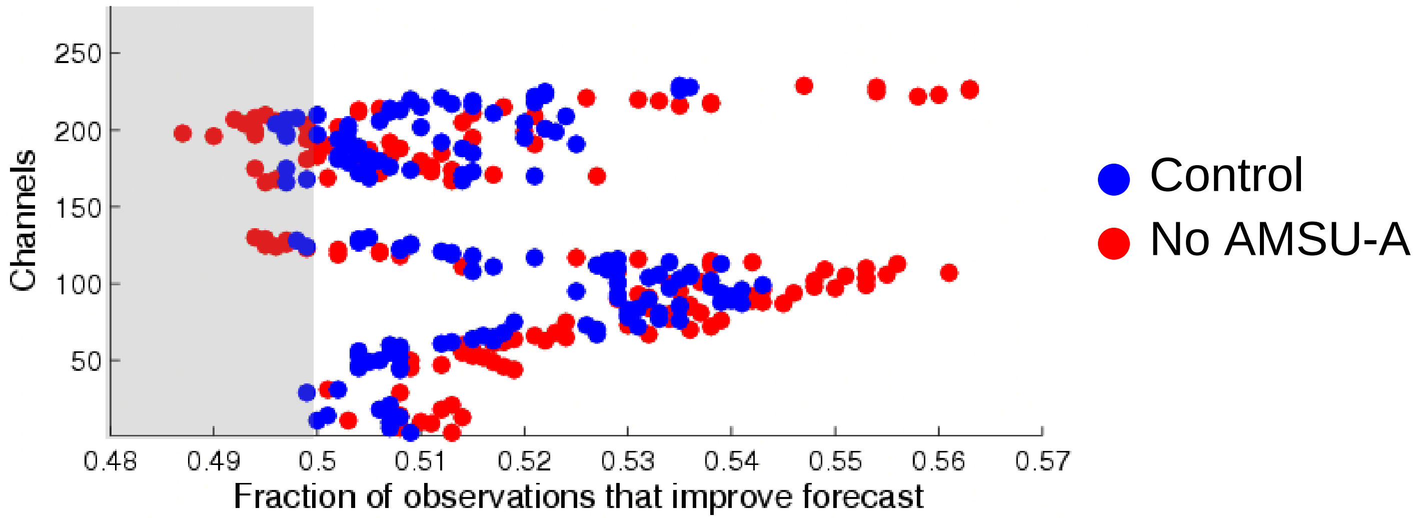


Removal of AIRS **water vapor channels** improved the forecast scores

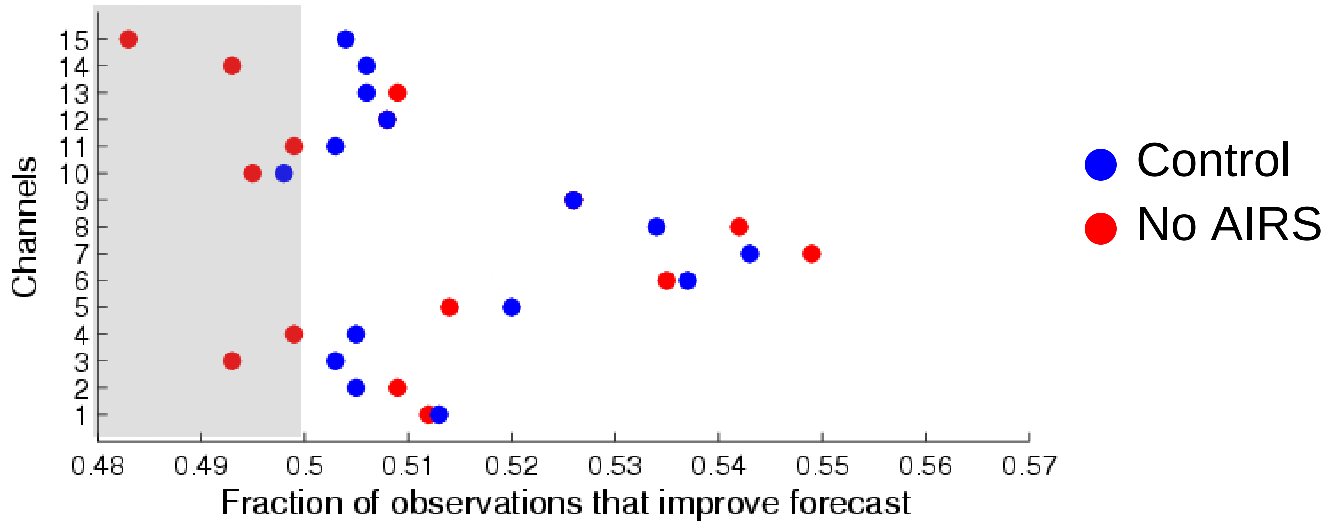
Fraction of Observations that Improve the Forecast

GEOS-5 July 2005 00z

AIRS



AMSU-A



Only a small majority of the observations improve the forecast!

How can 'good observations' have a negative impact?

The fact that data assimilation relies on <u>statistics</u> of background and observation errors implies a distribution of beneficial and non-beneficial impacts…

…the fact that we don't know these error statistics accurately increases the likelihood of there being non-beneficial impacts

- Single-ob, scalar analysis: $x^a = x^b + k\left(y - x^b\right)$ where $k = \sigma_b^2 / \left(\sigma_b^2 + \sigma_o^2\right)$
- Expected impact is positive: $E\left(\varepsilon_a^2 - \varepsilon_b^2\right) = -k\sigma_b^2 < 0$
- **But sometimes, the impact is negative:**

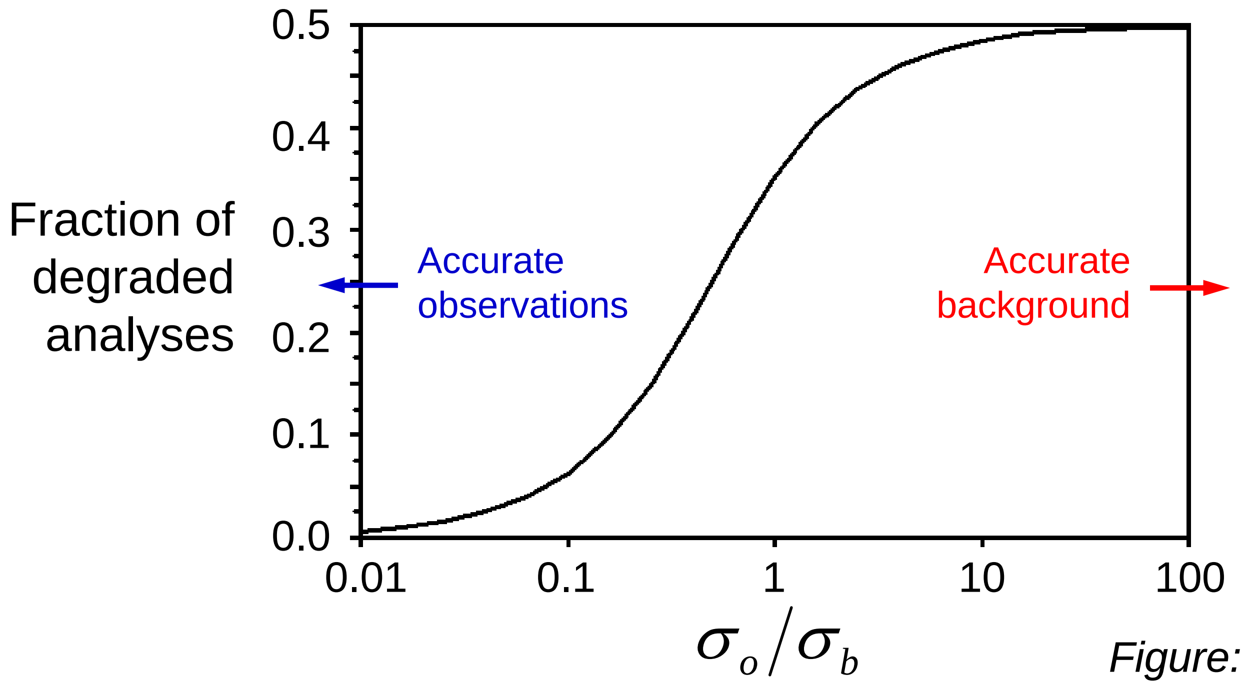
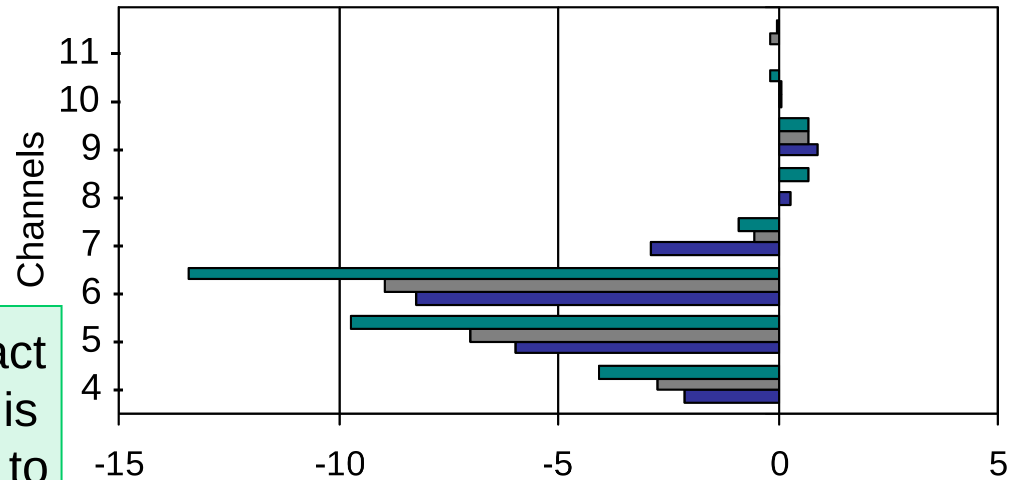


Figure: Mike Fisher, ECMWF

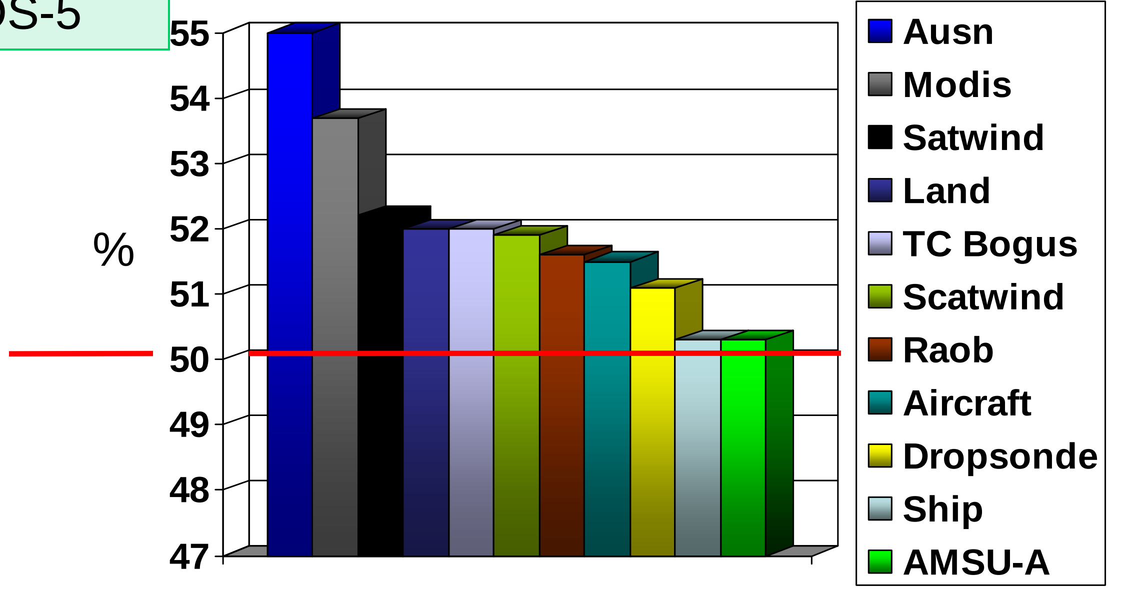
Observation Impact in NRL/NAVDAS

24h Forecasts from 00z Jan-Feb 2006



Summed Impact by channel for AMSU-A 15,16,18

Observation impact in NRL/NAVDAS is similar in general to GMAO/GEOS-5



Fraction of observations that improve the forecast

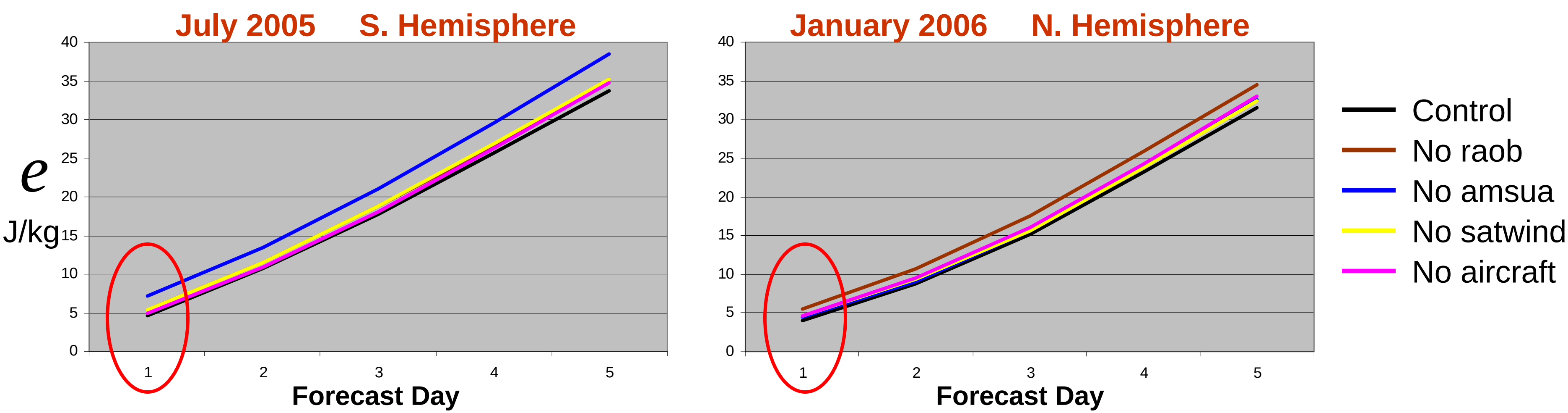
Rolf Langland, Nancy Baker, NRL

Comparison of ADJ results with OSEs

How do observation impact results based on the ADJ method compare with traditional observing system experiments…OSEs?

Can the two approaches be meaningfully compared?

- **GEOS-5 OSEs** were conducted for July 2005 and January 2006 00UTC forecasts at 1^{o} horizontal resolution



- Skill (impact) measured using same energy-based error metrics for the globe, NH, SH and tropics as in ADJ experiments

Comparison and Interpretation of ADJ and OSE Results

…a few things to keep in mind…

- The ADJ measures the impacts of observations in the context of all other observations present in the assimilation system, while the OSE changes/degrades the system (i.e., $\mathbf{K}$ differs for each OSE member)

- The ADJ measures the impact of observations in each analysis cycle separately and against the control background, while the OSE measures the impact of removing observational information from both the background and analysis in a cumulative manner

- The ADJ measures the response of a single forecast metric to all perturbations of the observing system, while the OSE measures the effect of a single perturbation on all forecast metrics

- The ADJ is restricted by the tangent linear assumption (valid ~1-3 days), while the OSE is not

‘Direct’ quantitative comparison of ADJ and OSEs

$$e = (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})^\mathrm{T} \mathbf{C} (\mathbf{x}_0^f - \mathbf{x}_\mathrm{v})$$

$$\delta e = (\delta \mathbf{y})^\mathrm{T} \mathbf{K}^\mathrm{T} [\mathbf{M}_\mathrm{b}^\mathrm{T} \mathbf{C} (\mathbf{x}_\mathrm{b}^f - \mathbf{x}_\mathrm{v}) + \mathbf{M}_\mathrm{a}^\mathrm{T} \mathbf{C} (\mathbf{x}_\mathrm{a}^f - \mathbf{x}_\mathrm{v})]$$

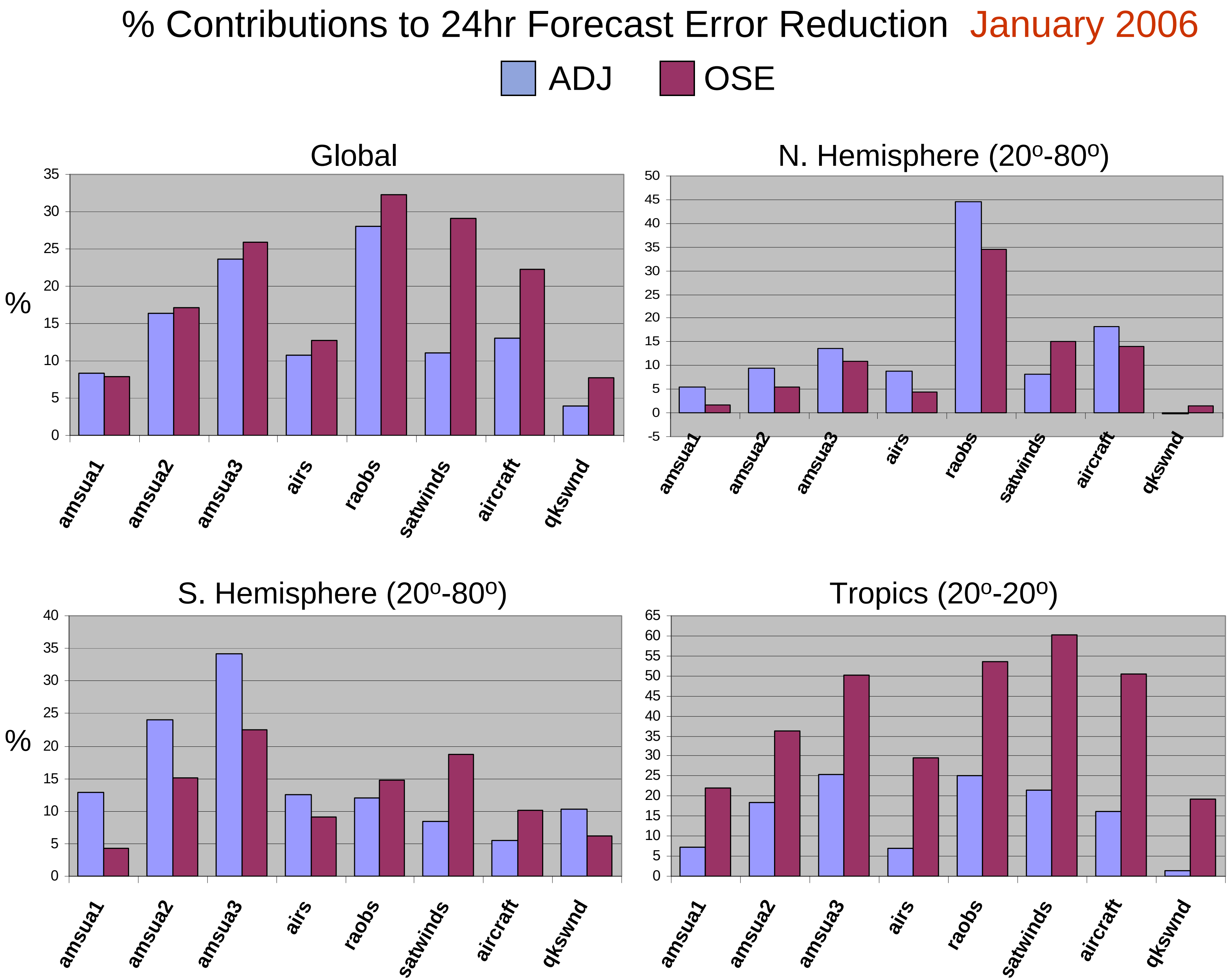
Define the fractional impact F_j of observing system j for each approach:

$$F_j(\mathrm{ADJ}) = \delta e_j / \delta e$$

- Measures the % **decrease** in error due to the **presence** of observing system j with respect to the **background** forecast
- $\sum_j F_j(\mathrm{ADJ}) = 1$

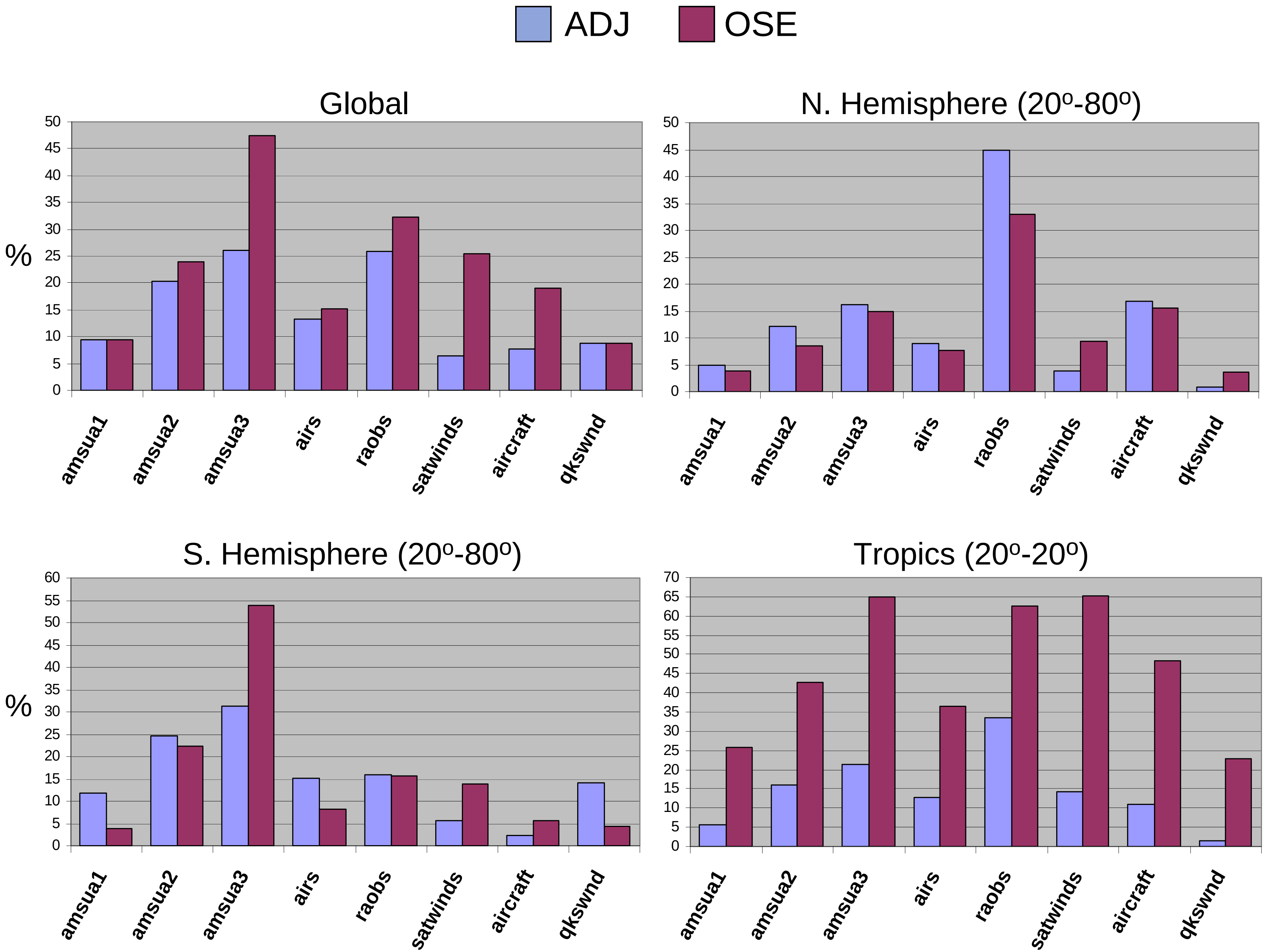
$$F_j(\mathrm{OSE}) = (e_{\mathrm{no}\,j} - e_\mathrm{ctl}) / e_\mathrm{ctl}$$

- Measures the % **increase** in error due to the **removal** of observing system j with respect to the **control** forecast
- $\sum_j F_j(\mathrm{OSE}) \neq 1$

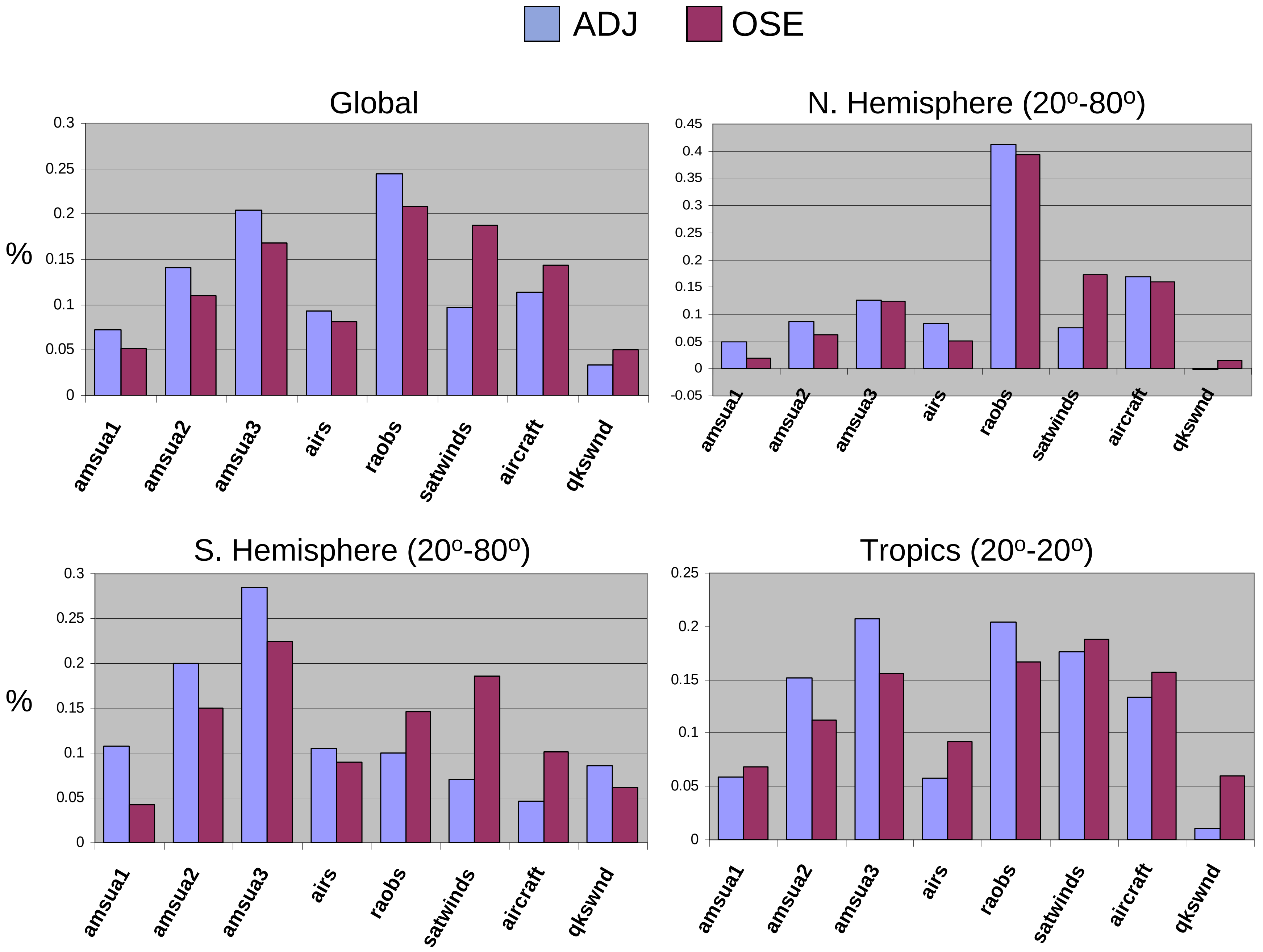


% Contributions to 24hr Forecast Error Reduction January 2006
ADJ
OSE
Global
N. Hemisphere (20º-80º)
S. Hemisphere (20º-80º)
Tropics (20º-20º)
%
amsua1
amsua2
amsua3
airs
raobs
satwinds
aircraft
qkswnd

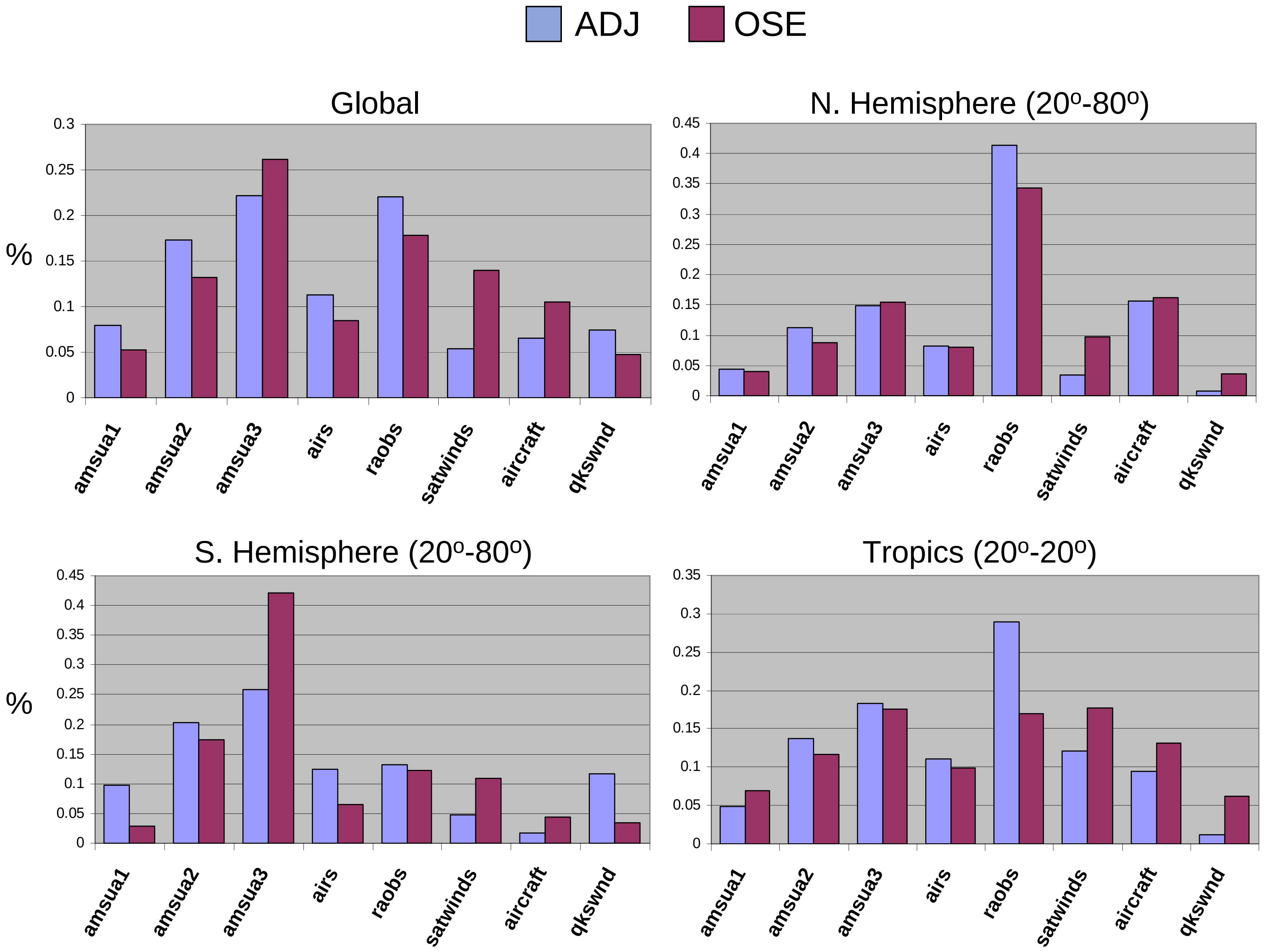
% Contributions to 24hr Forecast Error Reduction July 2005



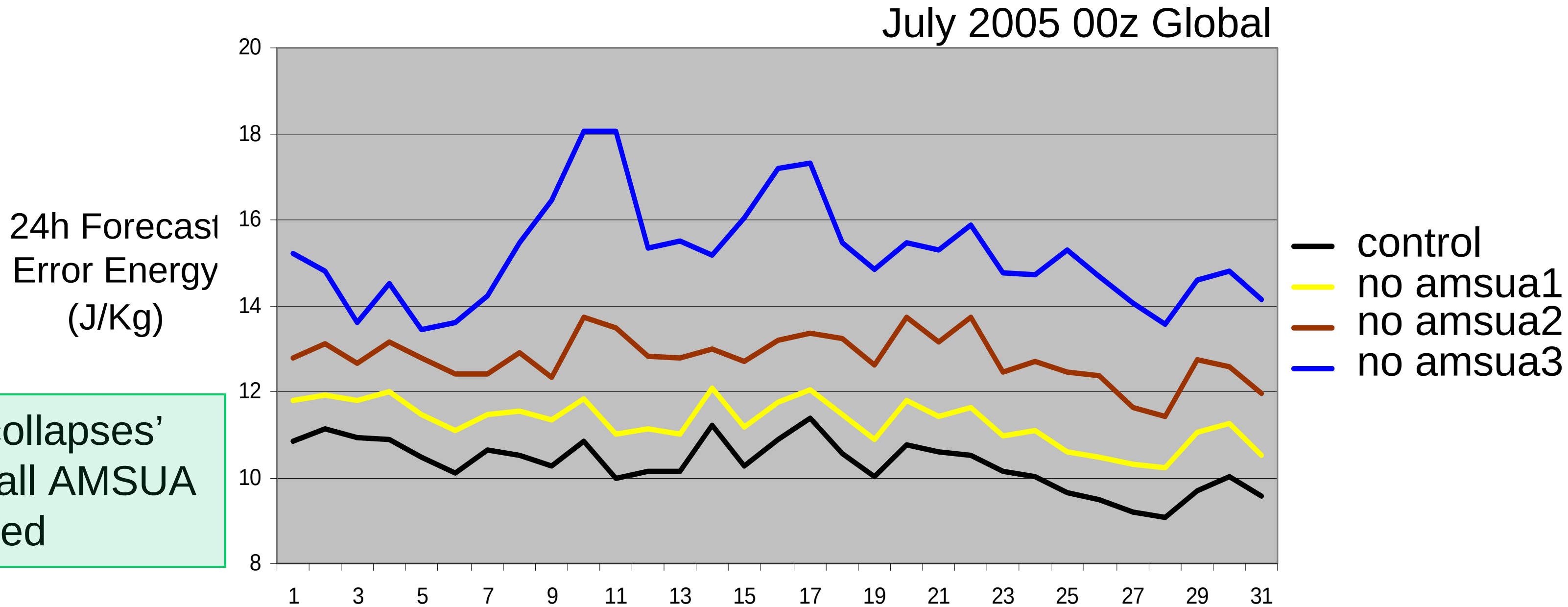
Normalized % Contributions to 24hr Fcst Error Reduction January 2006



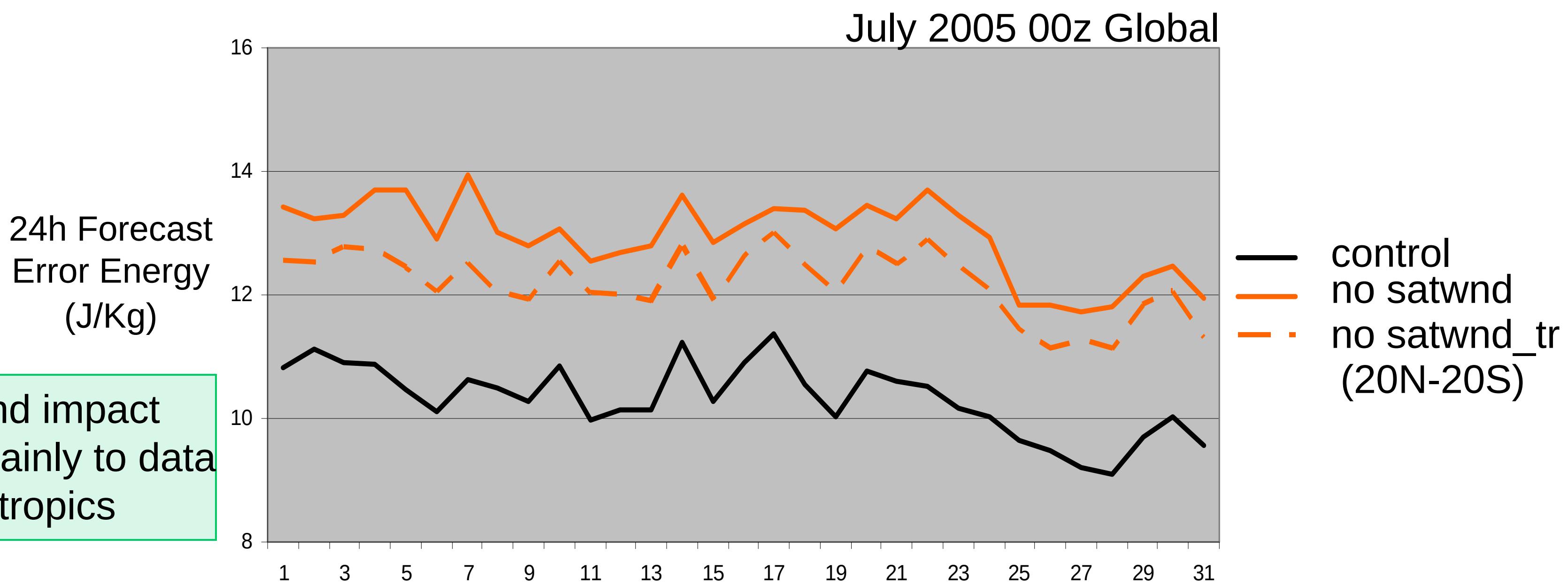
Normalized % Contributions to 24hr Fcst Error Reduction July 2005



GEOS-5 Observing System Experiments (OSE)

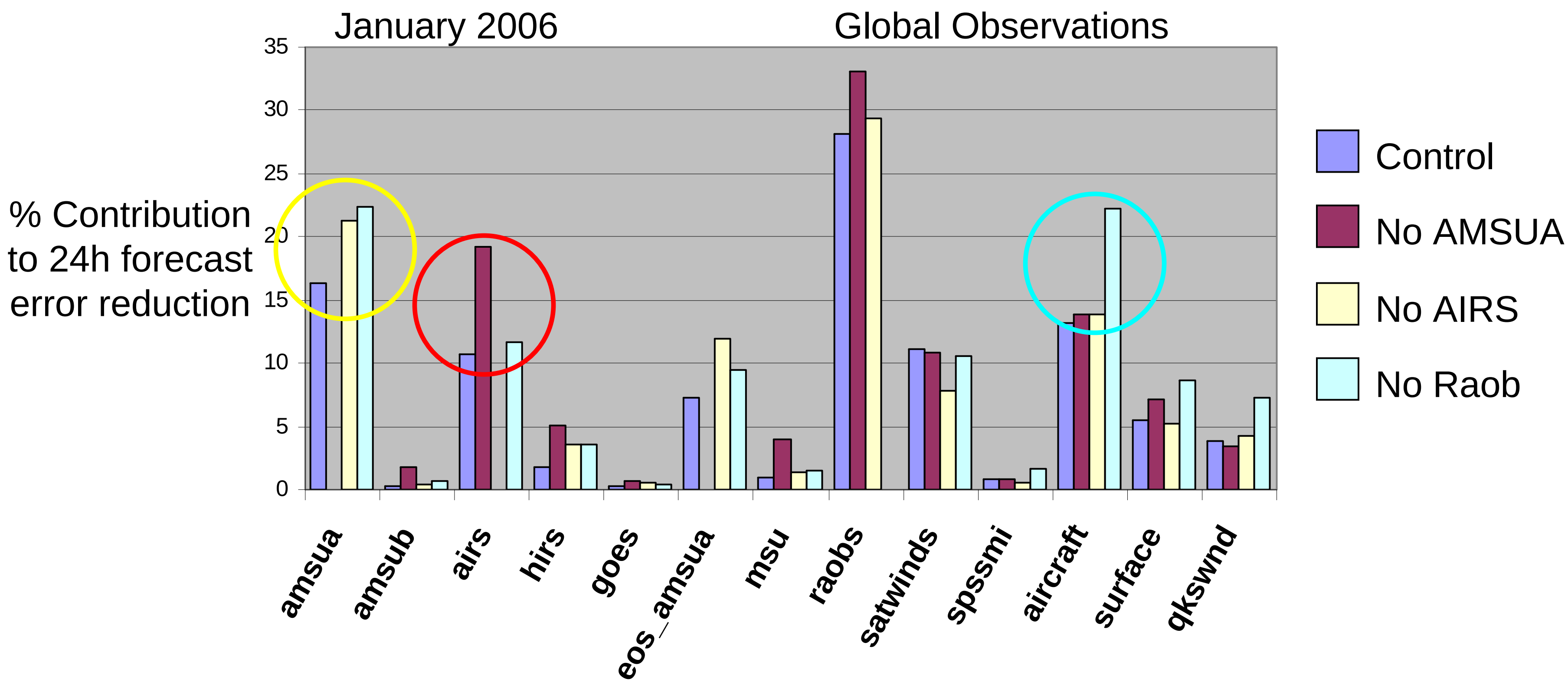


Skill 'collapses' when all AMSUA removed



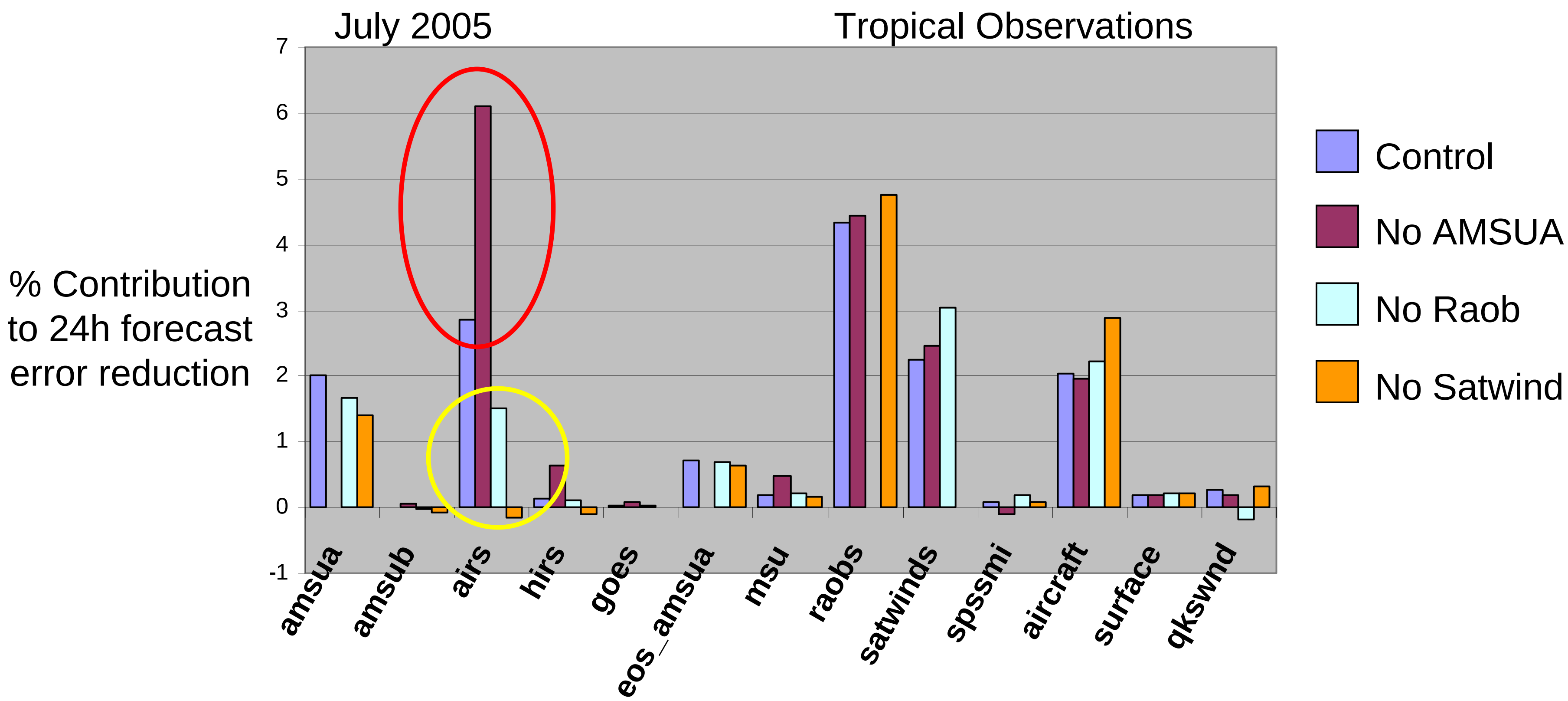
Satwind impact due mainly to data in the tropics

ADJ applied to OSEs



- Removal of AMSUA results in large increase in AIRS (and other) impacts
- Removal of AIRS results in significant increase in AMSUA impact
- Removal of Raobs results in significant increase in impact of several obs types, with AIRS and Satwinds being a notable exceptions

ADJ applied to OSEs



- Removal of AMSUA results in large increase in AIRS impact in tropics
- **Removal of wind observations** results in significant **decrease** in AIRS impact in tropics (in fact, AIRS degrades forecast without Satwinds!)

Looking ahead…new methods for computing the adjoint of GSI for 3DVAR and 4DVAR

Features recently added to GSI as part of 4DVAR development allow 'maintenance free' adjoint capability for both 3DVAR and 4DVAR…

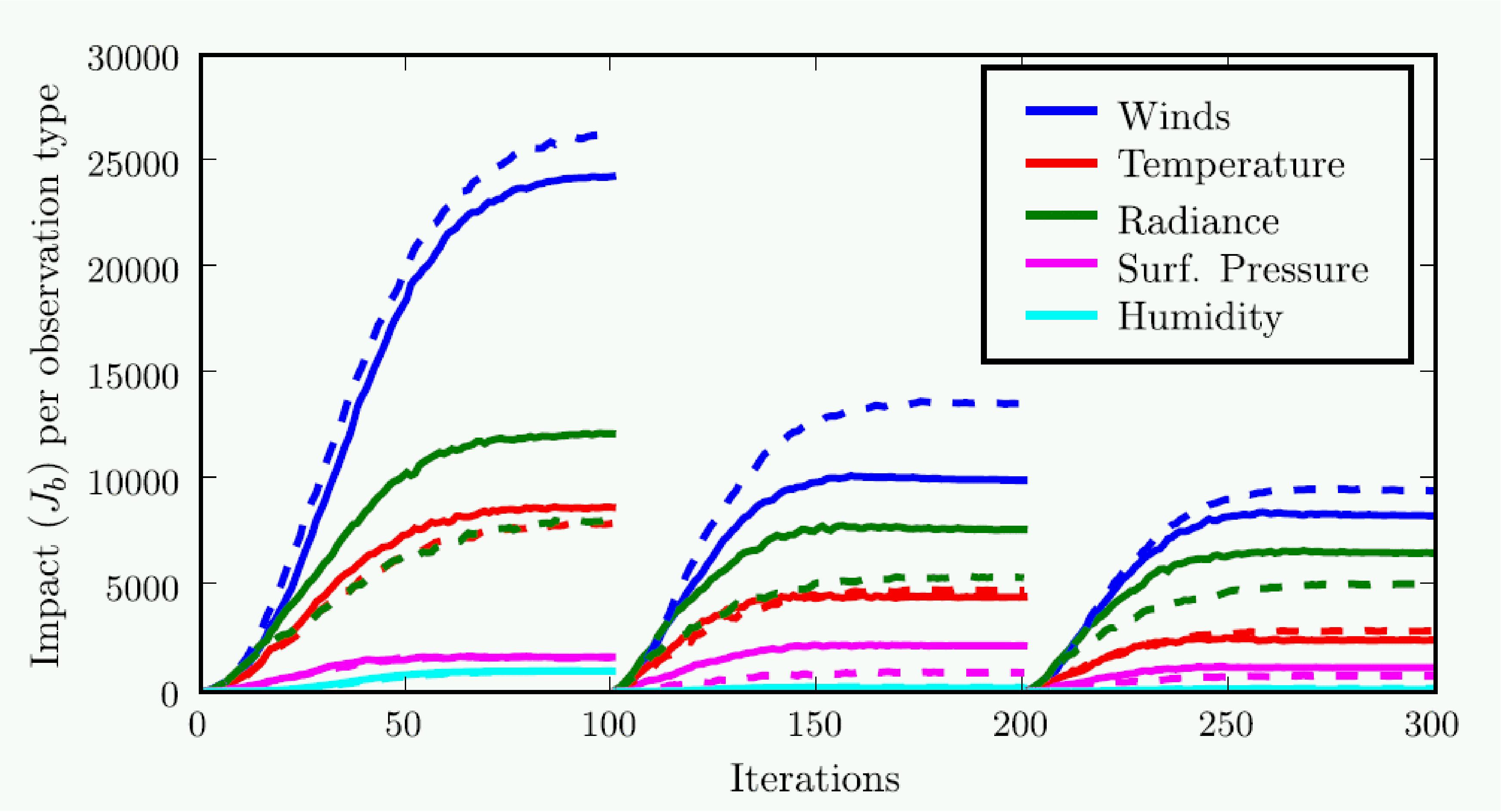
Method 1: *Use GSI minimization (CG or quasi-Newton) to solve modified linear system (input sensitivity vector instead of* $\delta\mathbf{y}$ *)*

- Adjoint costs the same as the analysis
- Minimal extra storage requirements (outer loops)
- Adjoint valid only at convergence

Method 2: *Use transposed Lanczos vectors (Lanczos minimization)*

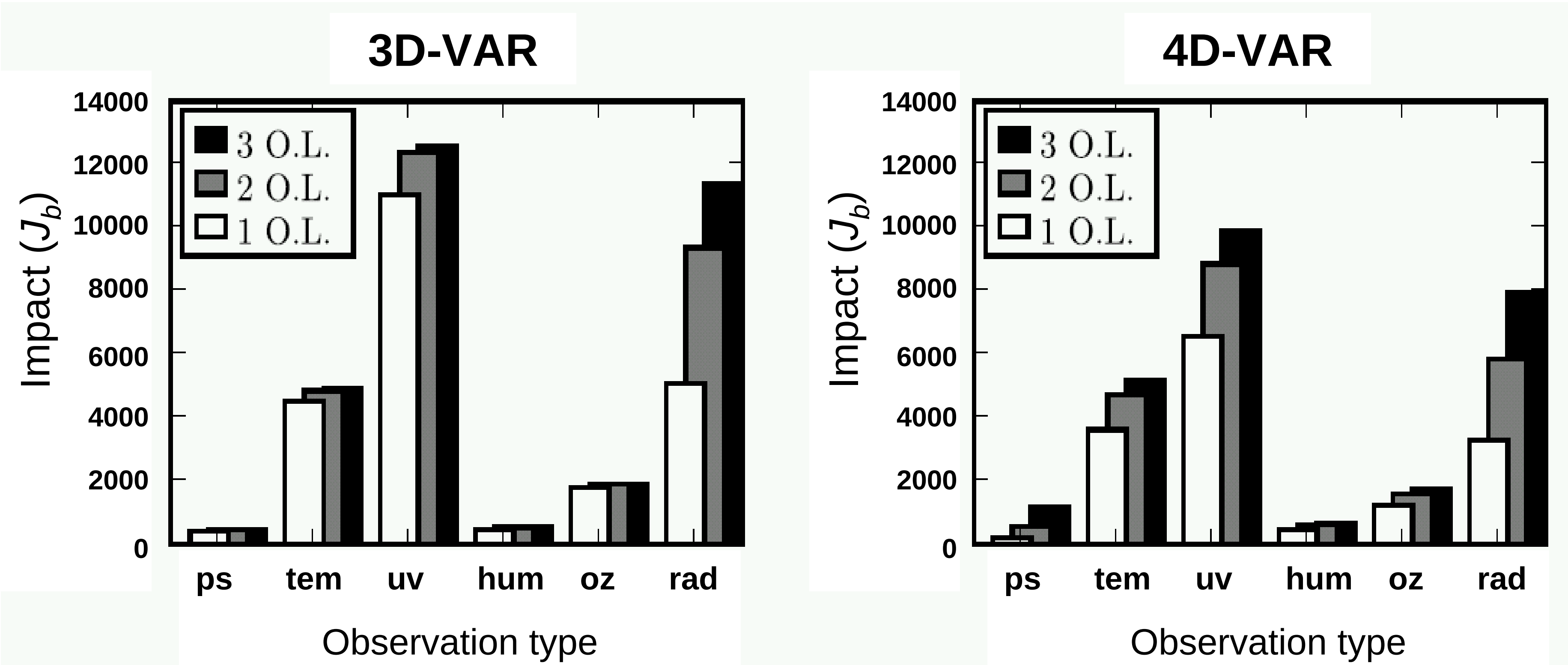
- Adjoint is essentially free…big savings in 4DVAR
- Need to store Lanczos vectors
- Adjoint valid regardless of convergence…good diagnostic tool

Observation impact during the minimization



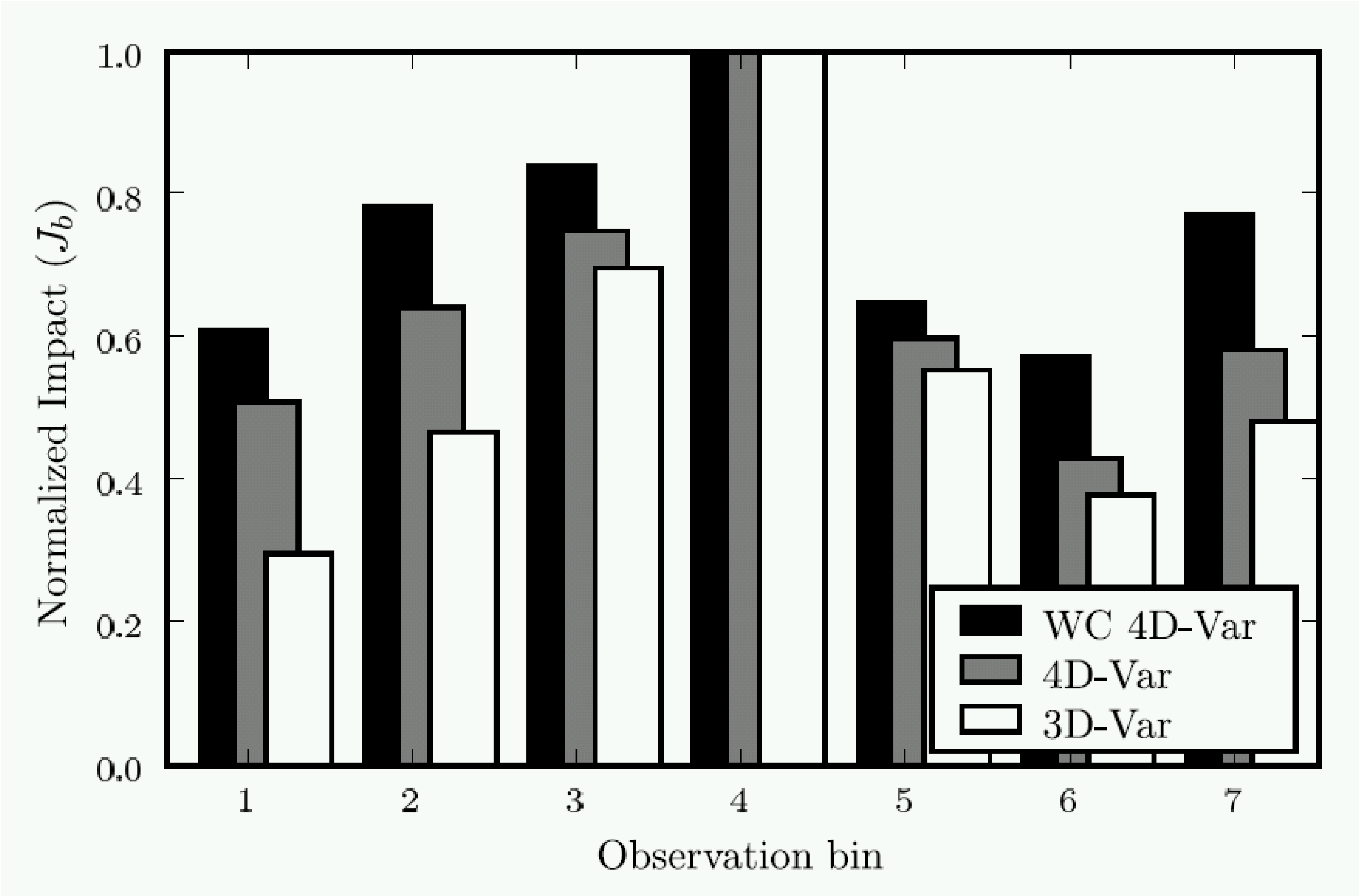
Partial impact of observations during the inner-loop iterations of **4DVAR (solid)** and **3DVAR (dashed)**

Observation impact and outer loops



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

Observation impact vs. time in the assimilation window



Average normalized impact per observation for each bin within the 6-hr assimilation window

Conclusions - 1

- Adjoint data assimilation system provides an accurate and efficient tool for estimating 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.

- Applicable to data quality assessment and selection, understanding DAS behavior, identifying redundancies in the observing system

- Excellently suited for real-time monitoring of observation impact:
  …see NRL page: http://www.nrlmry.navy.mil/ob_sens/

- Complement and extend, but not replace, traditional OSEs as tools for assessing observation impact…metrics, interpretations differ

Conclusions - 2

- Despite fundamental differences in how impact is measured, ADJ and OSE methods provide comparable estimates of the overall ‘importance’ of <u>most</u> observing systems tested

- Comparisons of impacts in different forecast systems should help clarify deficiencies in data quality vs. assimilation methodology, and hopefully provide useful feedback to data producers.

Used together, ADJ and OSEs illuminate the complex, complementary nature of how observations are used by the assimilation system

Observation impact activities in the NWP community

- The adjoint method for assessing observation impact is either in regular use or active development at NRL, GMAO, MSC, ECMWF and Météo France

- These organizations have agreed to participate in an inter-comparison of results for the period Jan-Feb 2007

    ✓ preparation for THORPEX Pacific Asian Regional Campaign (T-PARC) scheduled for Fall 2008-Winter 2009

    ✓ first results to be presented at workshop: Impact of Various Observing Systems on NWP, WMO HQ Geneva, May 2008

- NRL and GMAO have JCSDA-sponsored inter-comparison effort; plan includes implementation of online, real-time monitoring already in place at NRL (shared display software developed at NRL)