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

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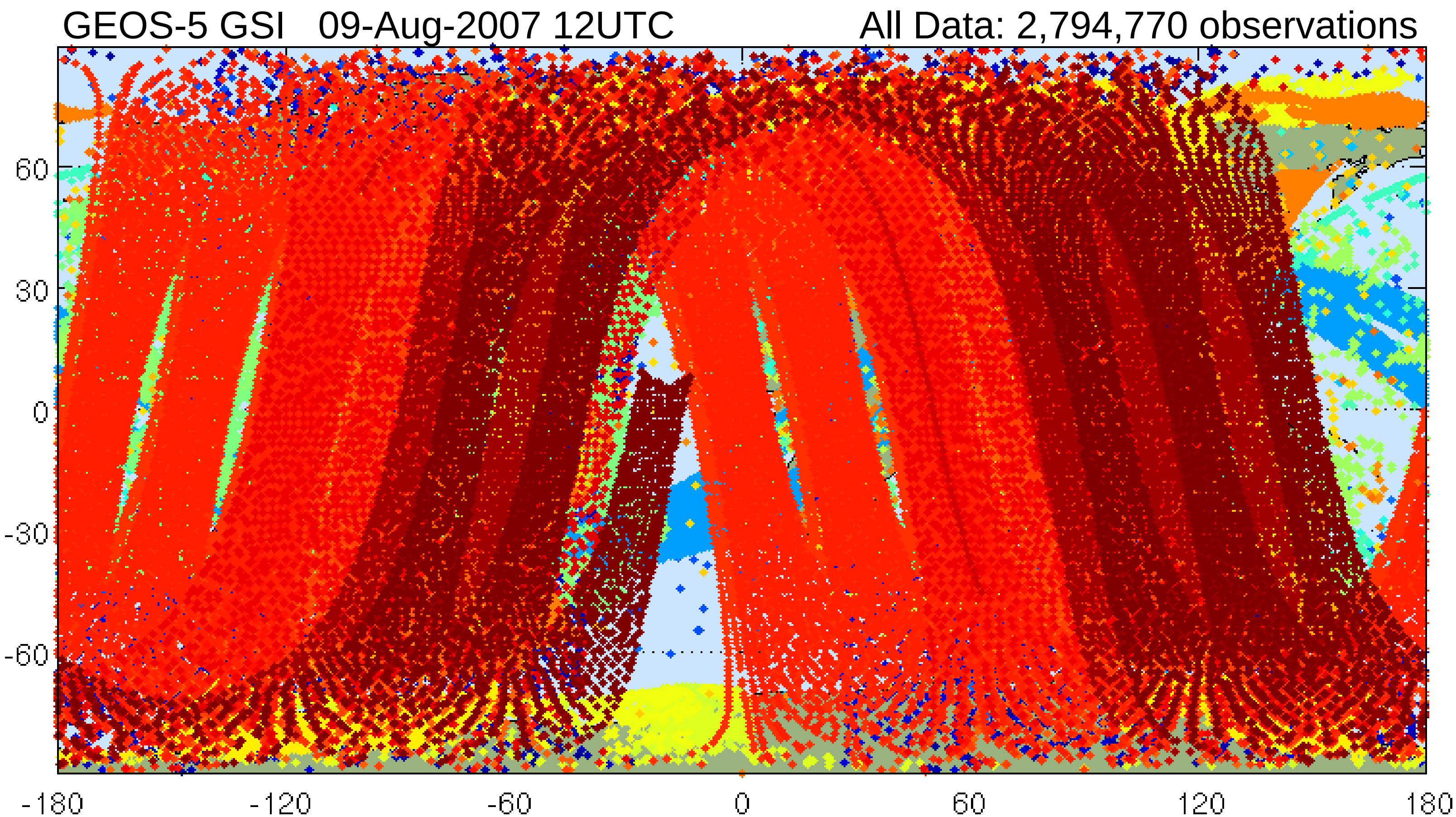
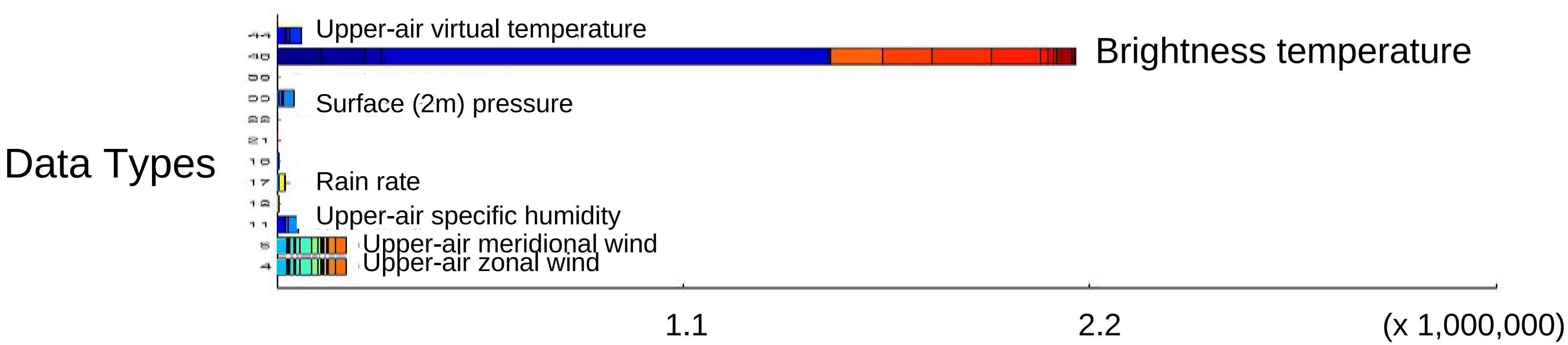
The observing system…today





Observing System Experiments (OSEs)

The traditional, tried and true, 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

- Intermittently performed 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…*over arbitrary periods of time, or even routinely*…?

Outline of Talk

- Methodology: Adjoint-based estimation of observation impact
- GEOS-5 observation impact results (‘old’ GSI)
- Comparison with OSEs
- Future development: Early results with 4DVAR (‘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 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 (**global 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

Usage and 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., separate satellites, channels or locations) can be easily quantified

- Computation always involves the *entire* set of observations; changing the properties of one observation changes the scalar measure of all other observations (i.e., $\tilde{\mathbf{g}}_3$ depends on $\mathbf{K}$)

- 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)

Orders of Approximation of δe

(Errico 2007)

Forecast error measure (energy):

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

Taylor series expansion of δe about $\mathbf{x}_{\mathrm{b}}$:

1st order:

$$\delta e_1 = 2\delta \mathbf{y}^{\mathrm{T}} \underbrace{\mathbf{K}^{\mathrm{T}} \mathbf{M}_{\mathrm{b}}^{\mathrm{T}} \mathbf{C} (\mathbf{x}_{\mathrm{b}}^f - \mathbf{x}_v)}_{\tilde{\mathbf{g}}_1}$$

2nd order:

$$\delta e_2 = \delta \mathbf{y}^{\mathrm{T}} \underbrace{\mathbf{K}^{\mathrm{T}} [\mathbf{M}_{\mathrm{b}}^{\mathrm{T}} \mathbf{C} (\mathbf{x}_{\mathrm{a}}^f - \mathbf{x}_v) + \mathbf{M}_{\mathrm{a}}^{\mathrm{T}} \mathbf{C} (\mathbf{x}_{\mathrm{b}}^f - \mathbf{x}_v)]}_{\tilde{\mathbf{g}}_2}$$

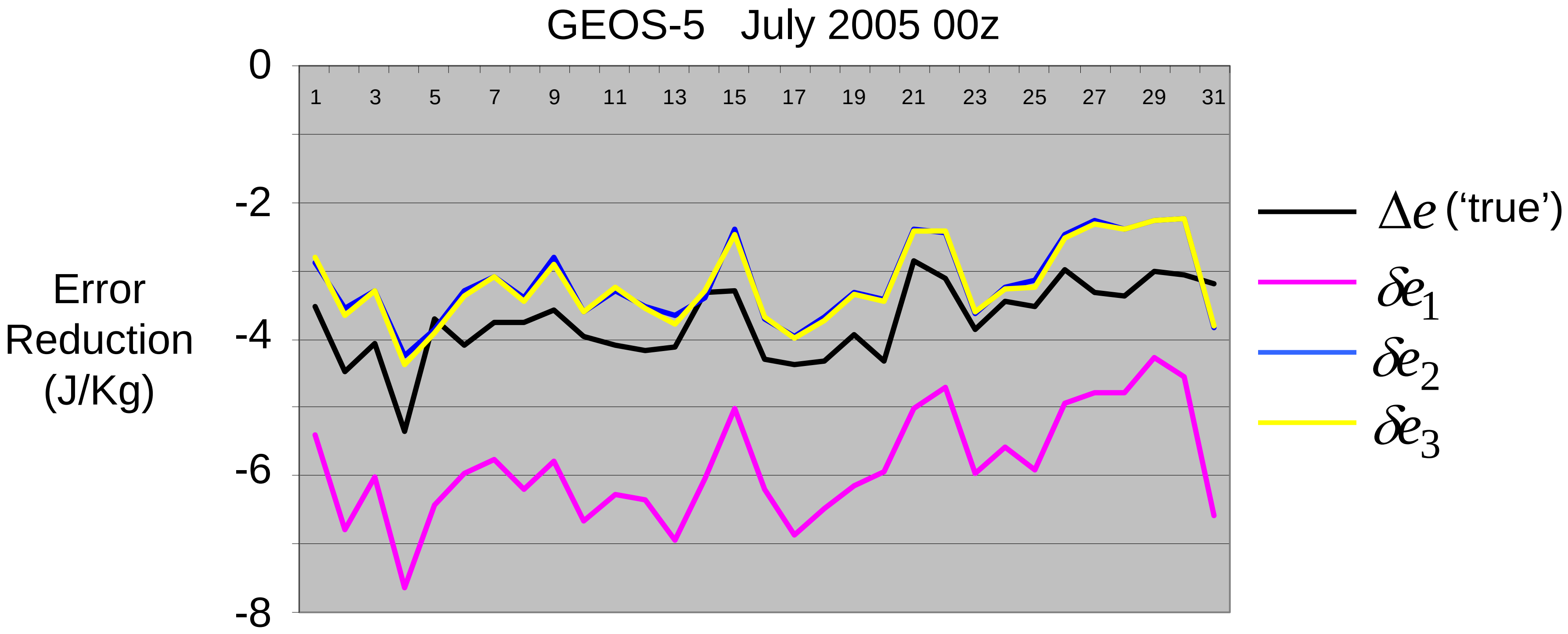
3rd order:

$$\delta e_3 = \delta \mathbf{y}^{\mathrm{T}} \underbrace{\mathbf{K}^{\mathrm{T}} [\mathbf{M}_{\mathrm{b}}^{\mathrm{T}} \mathbf{C} (\mathbf{x}_{\mathrm{b}}^f - \mathbf{x}_v) + \mathbf{M}_{\mathrm{a}}^{\mathrm{T}} \mathbf{C} (\mathbf{x}_{\mathrm{a}}^f - \mathbf{x}_v)]}_{\tilde{\mathbf{g}}_3}$$

Note that $\tilde{\mathbf{g}}_1$ is a *gradient*, but $\tilde{\mathbf{g}}_2$ and $\tilde{\mathbf{g}}_3$ are *weights that depend on all* δy…

Accuracy of Observation Impact Estimate

(*Gelaro et al. 2007)*



- 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 2007)

Forecast Model

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

Experimentation

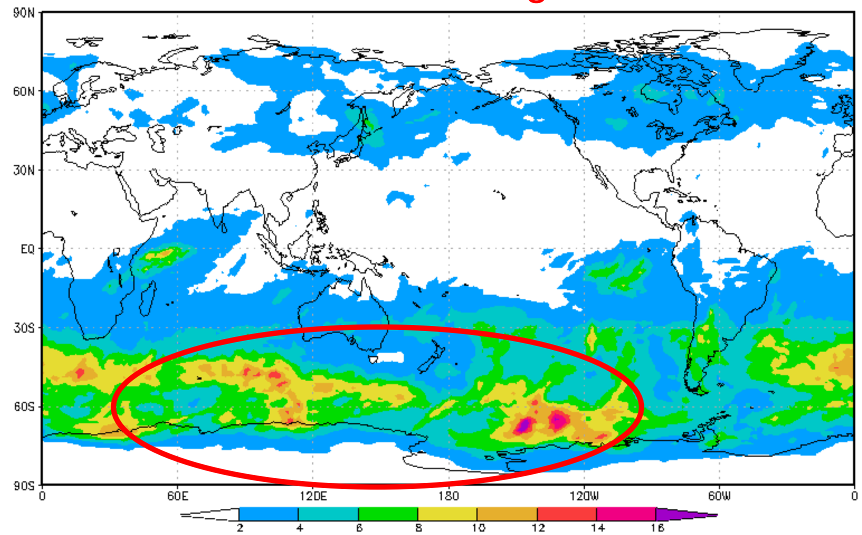
- 6h data assimilation cycle, July 2005 and January 2006
- **24h forecasts** from 00z to assess **observation impact**

24h Forecast Error Sensitivity to Initial Conditions

GEOS-5 July 2005

Valid 00z from 18z Background States

$$\mathbf{M}_{\mathrm{b}}^{\mathrm{T}}\mathbf{C}(\mathbf{x}_{\mathrm{b}}^{f} - \mathbf{x}_{\mathrm{v}})$$

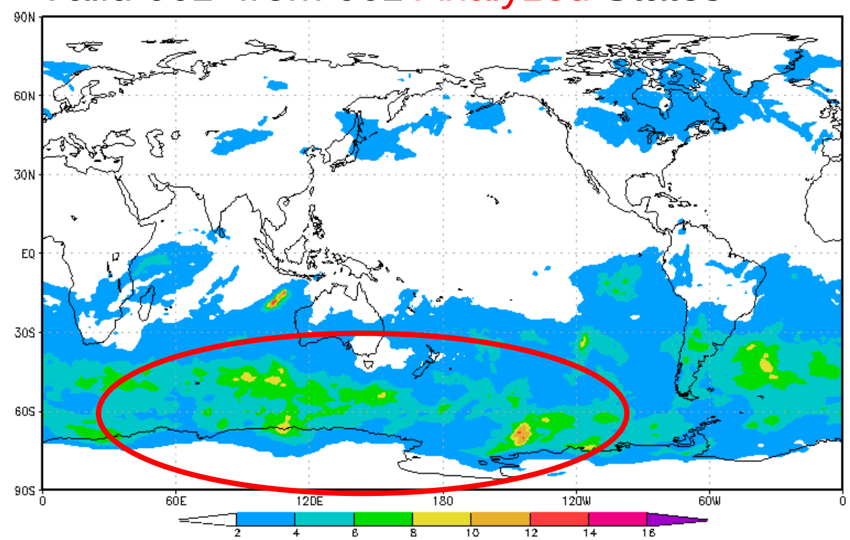


July 2005 Control Background

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

Valid 00z from 00z Analyzed States

$$\mathbf{M}_{\mathrm{a}}^{\mathrm{T}}\mathbf{C}(\mathbf{x}_{\mathrm{a}}^{f} - \mathbf{x}_{\mathrm{v}})$$

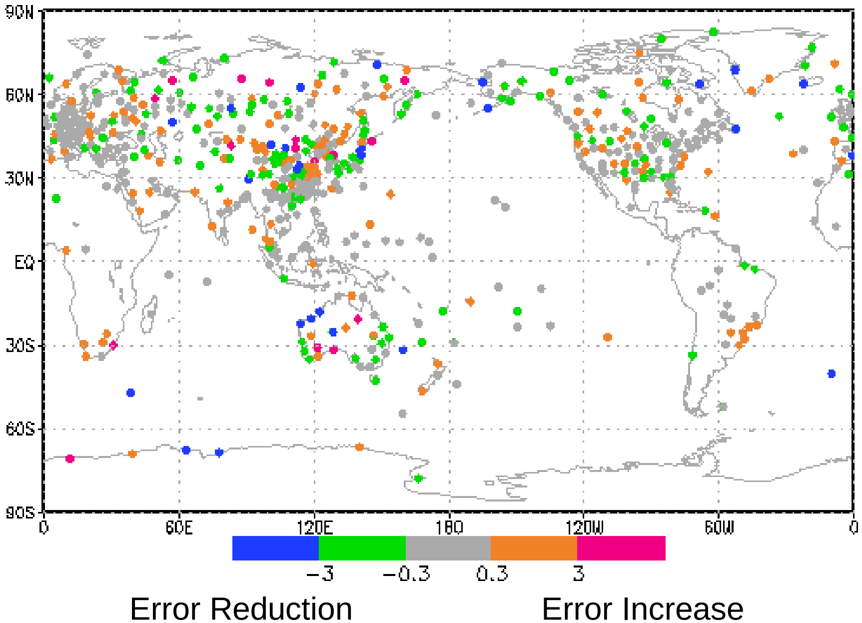


Large impact of observations over southern oceans, especially during winter

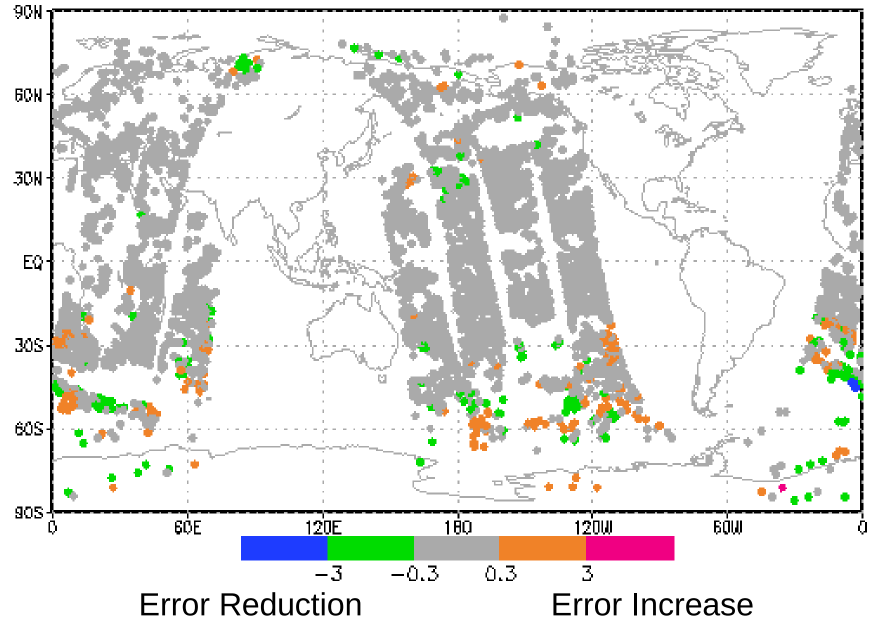
Observation Impact on GEOS-5 24h Forecast Error

10 July 2005 00Z

Impact of 500mb RAOB Temps



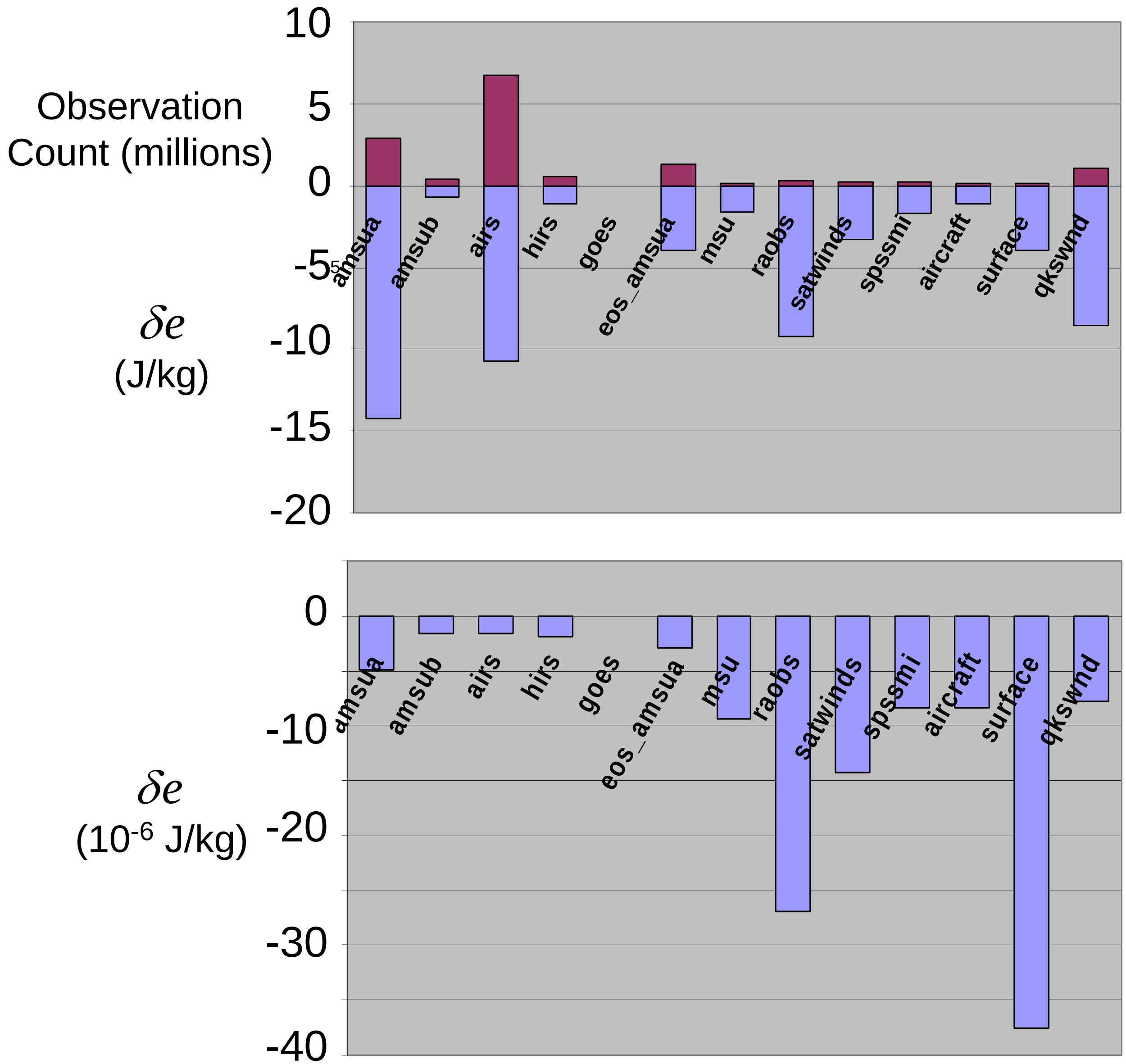
Impact of AIRS Ch.221 Radiances



- 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

Observation Impact by Instrument

July 2005 SH Observations 20S-80S



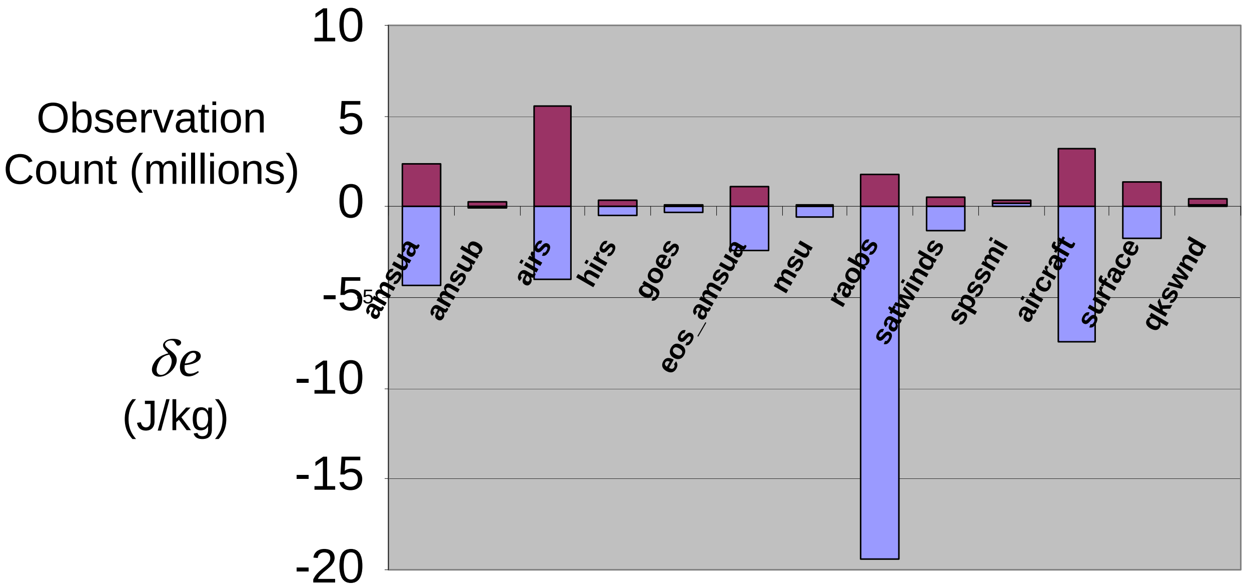
Summed observation impact and data count

All data types provide benefit in this case... $\delta e < 0$

Average impact per observation

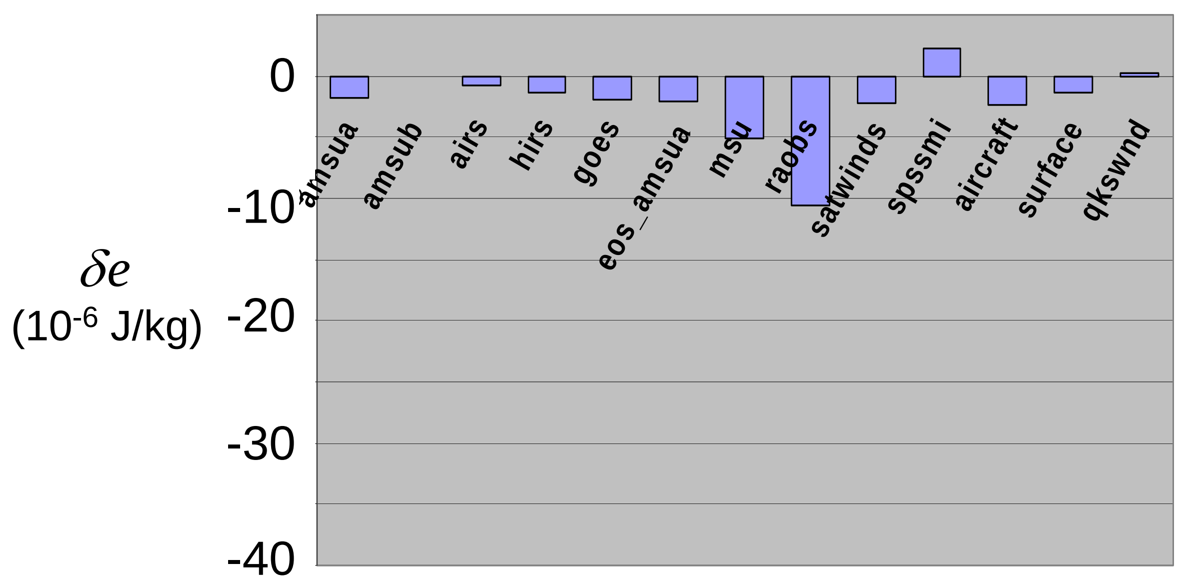
Observation Impact by Instrument

January 2006 NH Observations 20N-80N



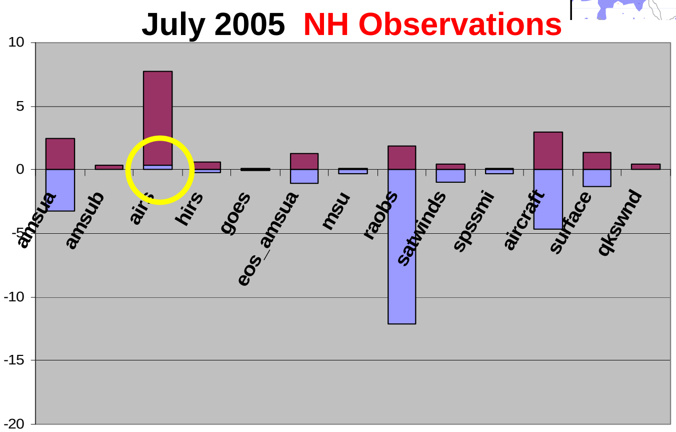
Summed observation impact and data count

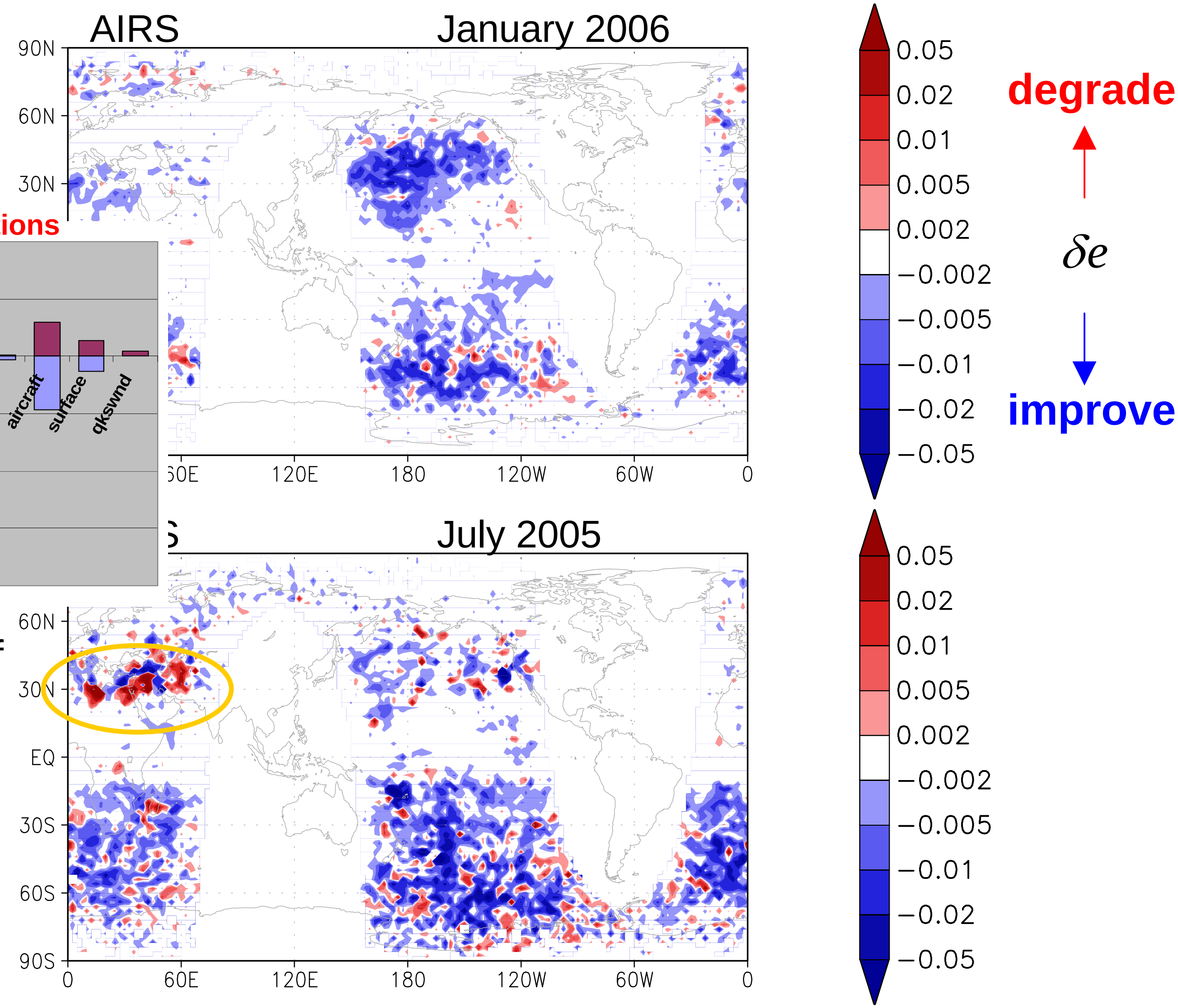
Some data types degrade the forecast in this case...



Average impact per observation

Accumulated Observation Impact - AIRS



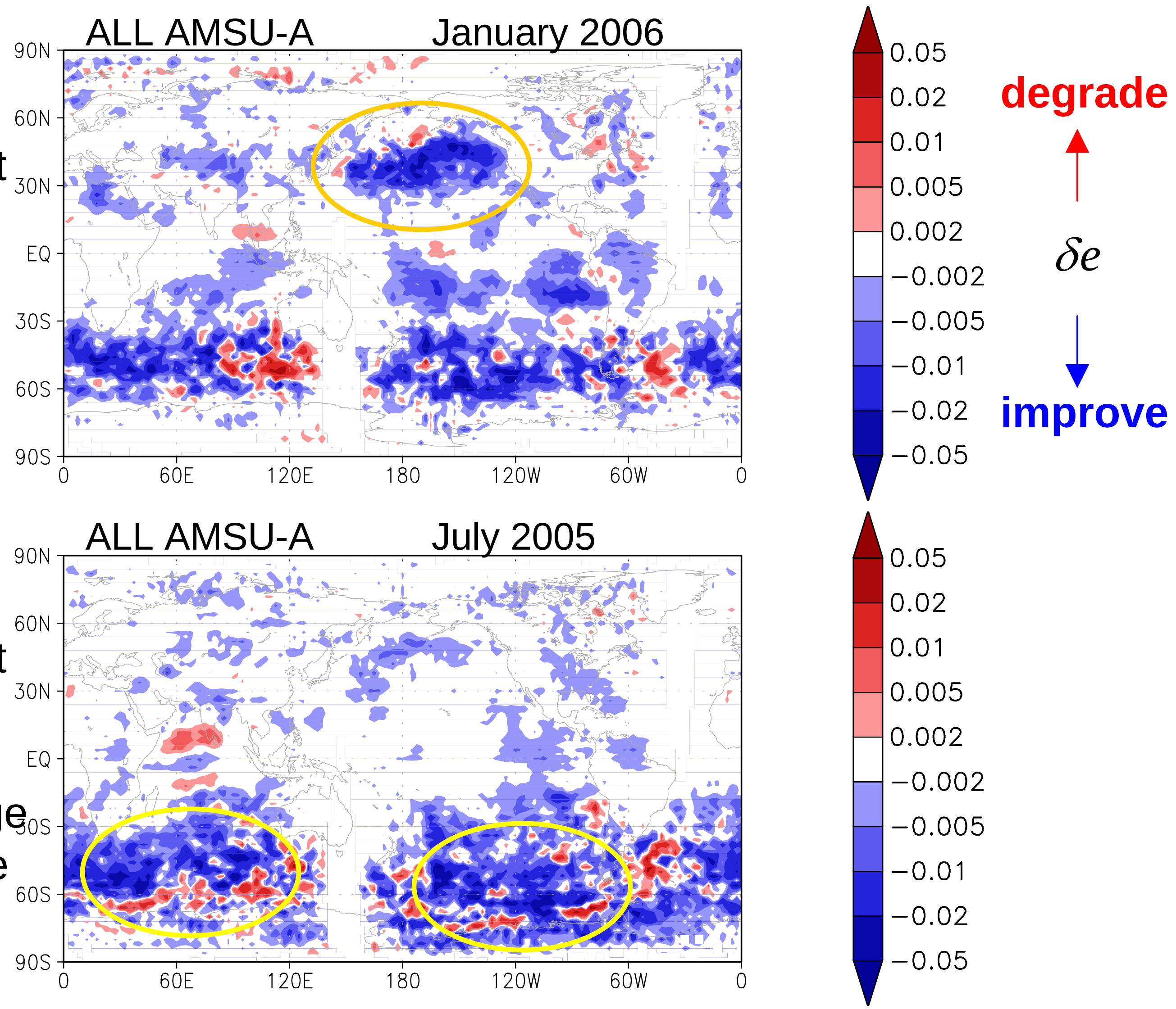


- Negative impact of AIRS observations over land…

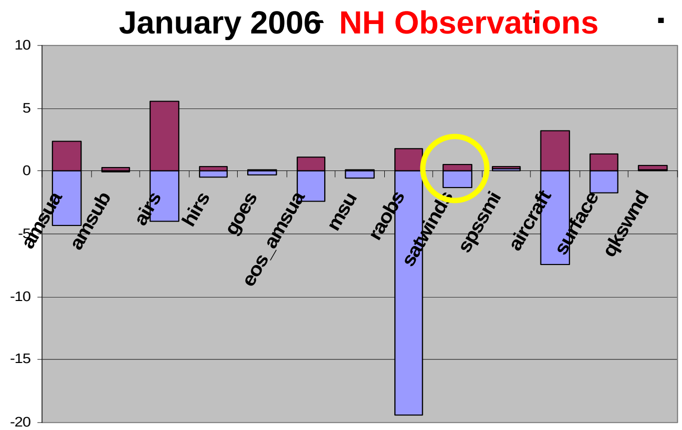
Accumulated Observation Impact – ALL AMSU-A

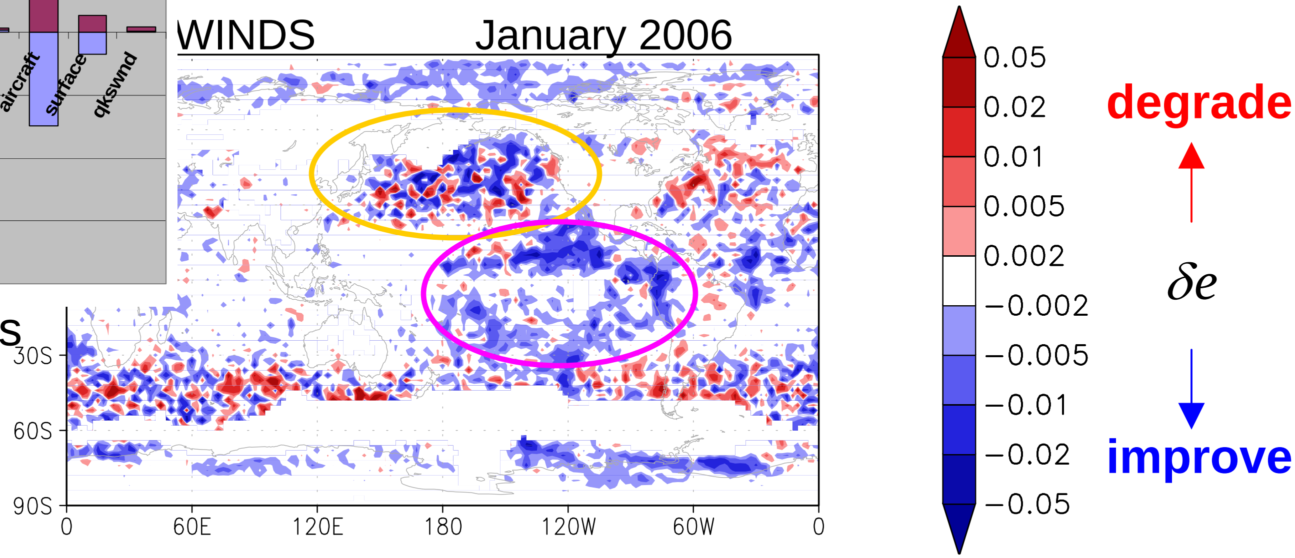
• Large positive impact over N.Pacific; region of large forecast error sensitivity

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

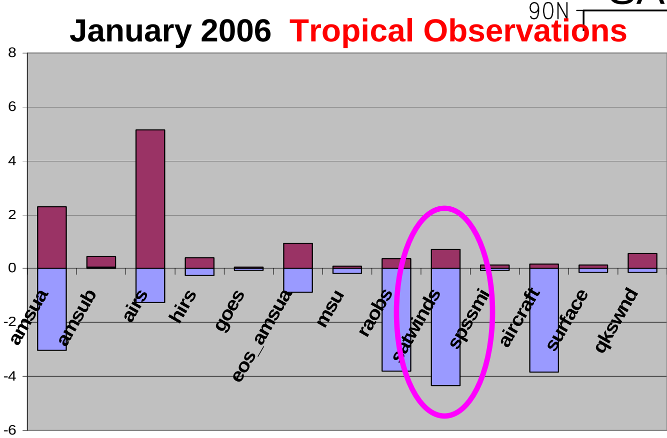


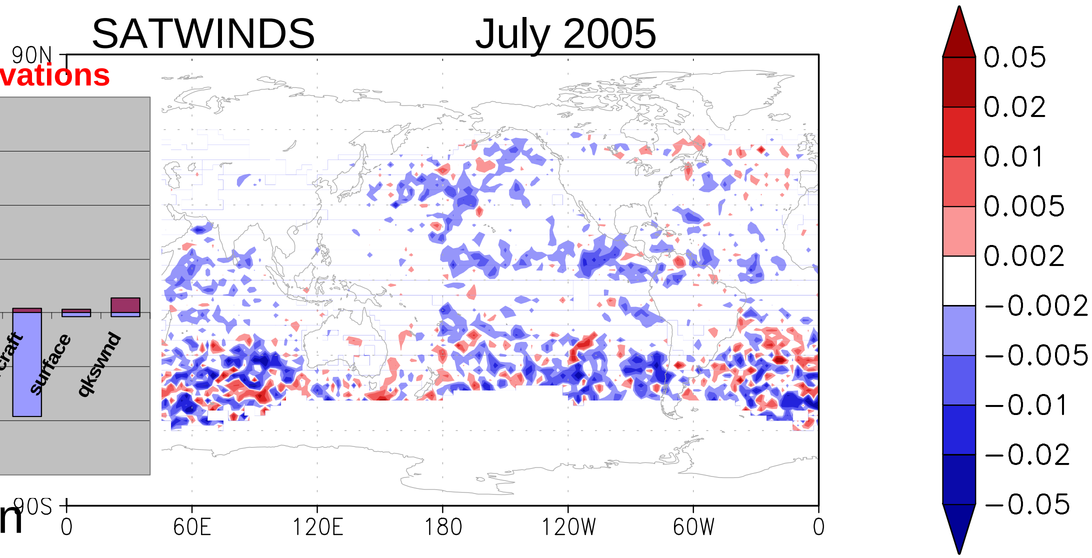
Observation Impact – Satwinds





- SATWIND impact is 'mixed' in the extra-tropics…

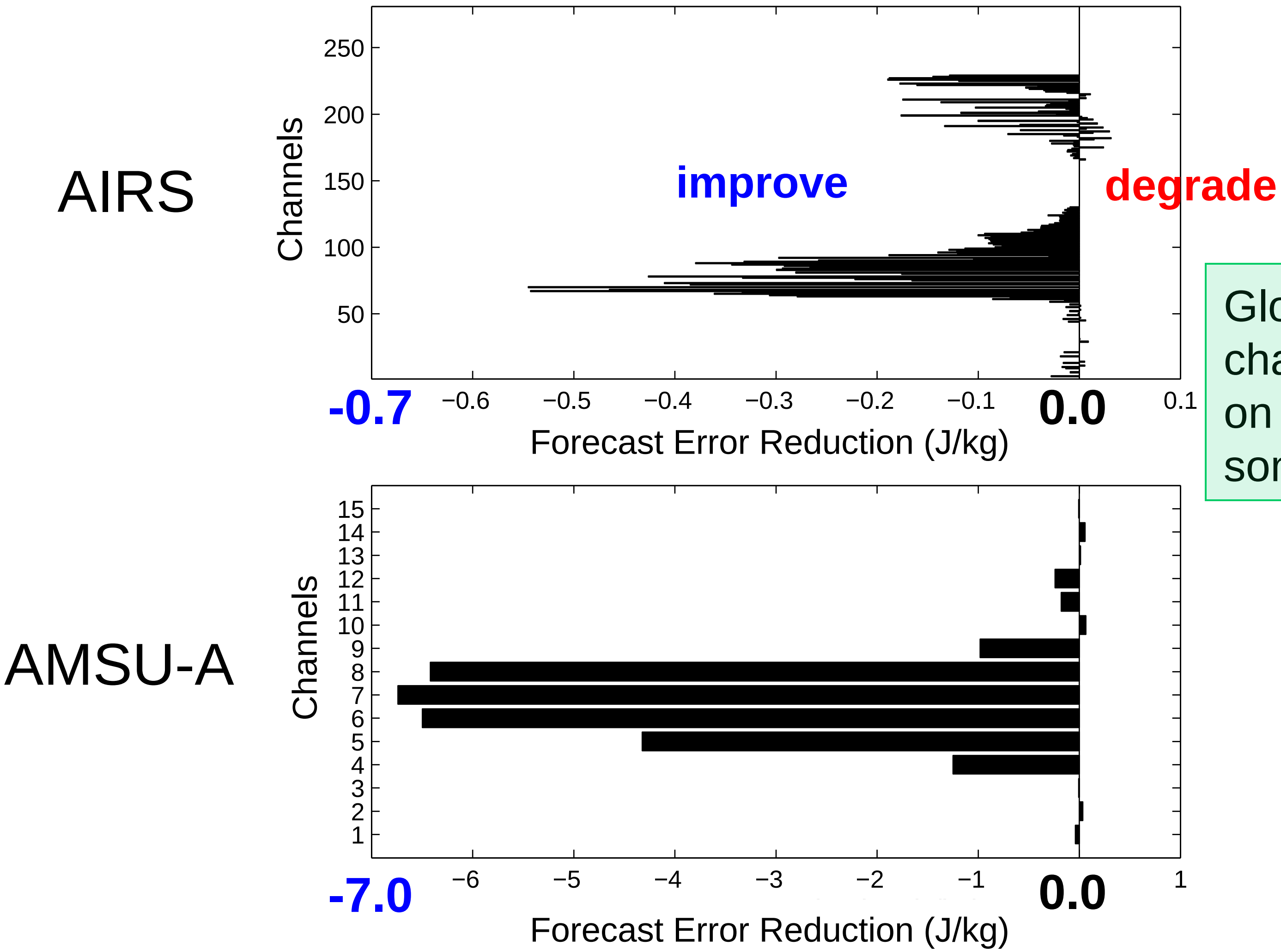




…but clearly positive in the tropics, (and polar regions)

Impact of satellite observations by channel

GEOS-5 July 2005 00z

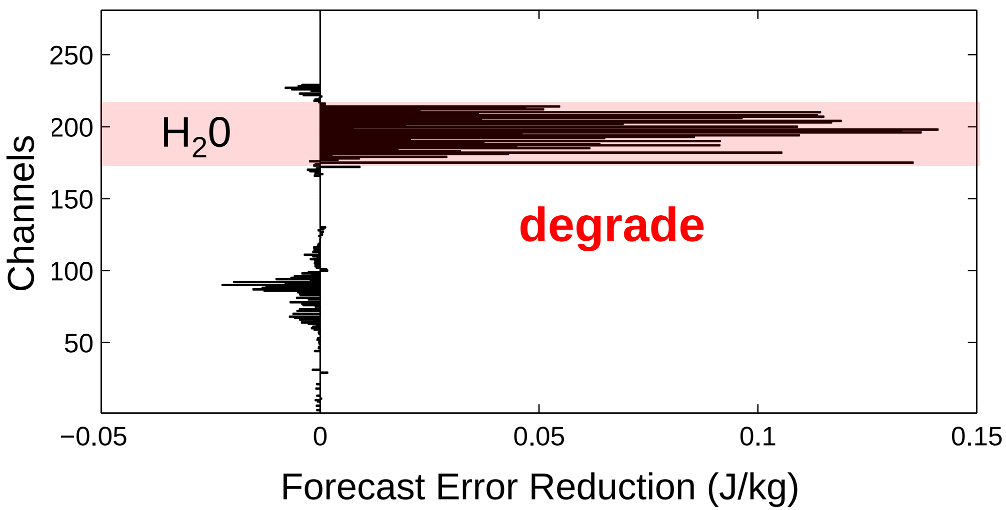


Global impact of most channels is beneficial on average…with some exceptions

Localized examination of AIRS negative impact

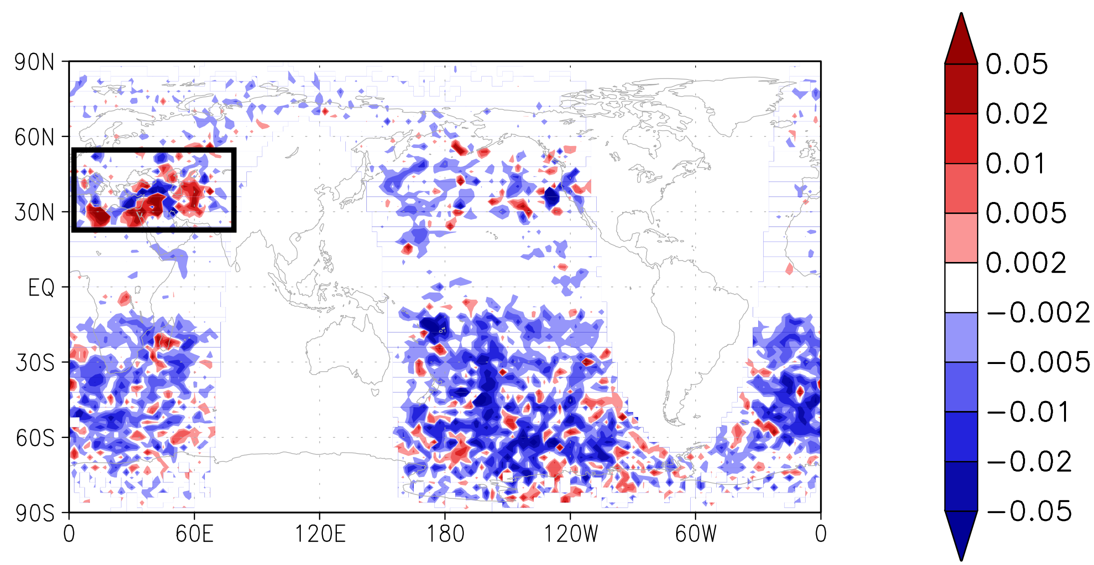
July 2005 00z (20-50N, 0-80E)

AIRS impact by channel



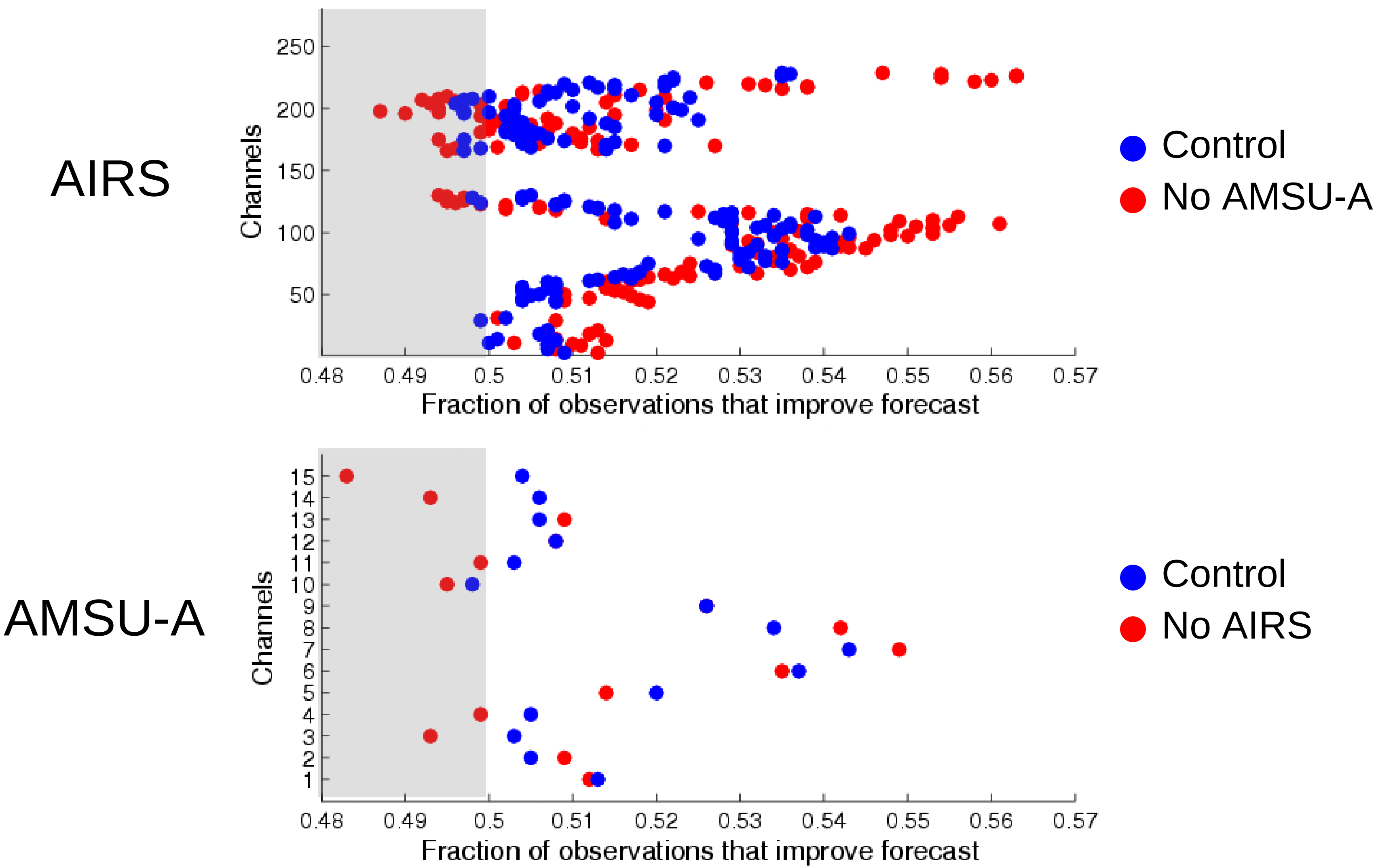
Subsequent removal of AIRS **water vapor channels** improved the forecast scores

AIRS impact map



Fraction of Observations that Improve the Forecast

GEOS-5 July 2005 00z

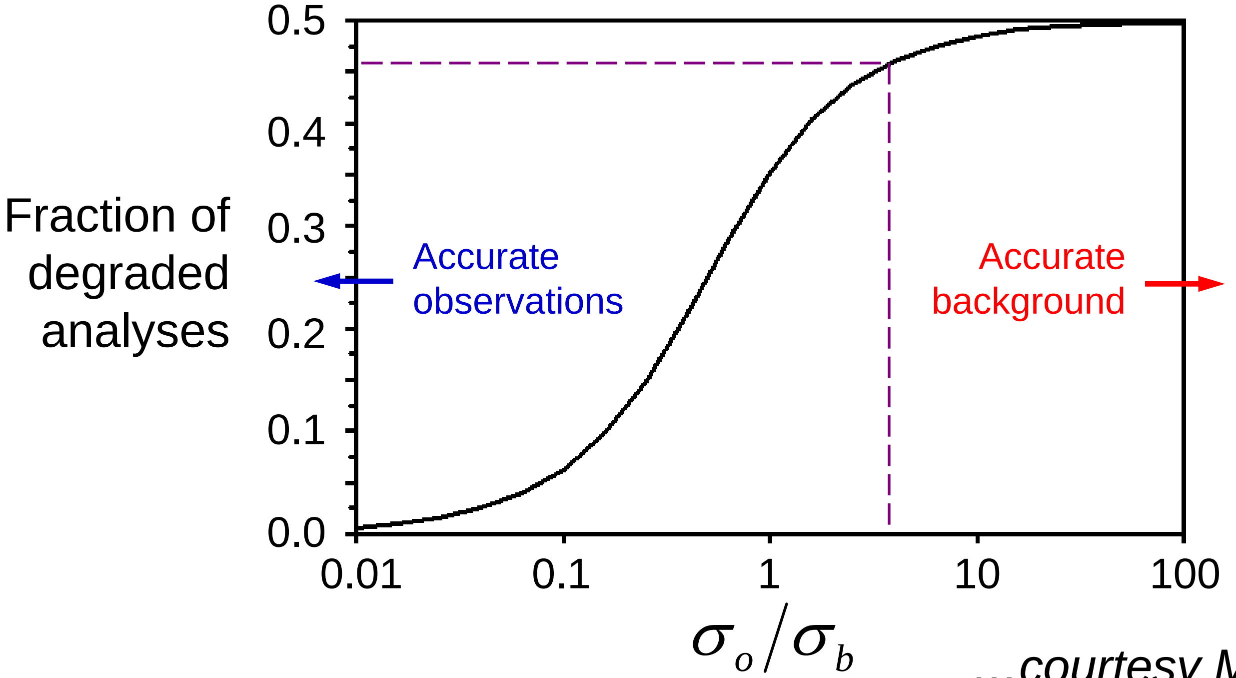


Only a small majority of the observations improve the forecast!

How can ‘good observations’ have a negative impact...?

The fact that observation and background error statistics for data assimilation cannot be specified precisely implies a statistical distribution of beneficial and non-beneficial observation impacts

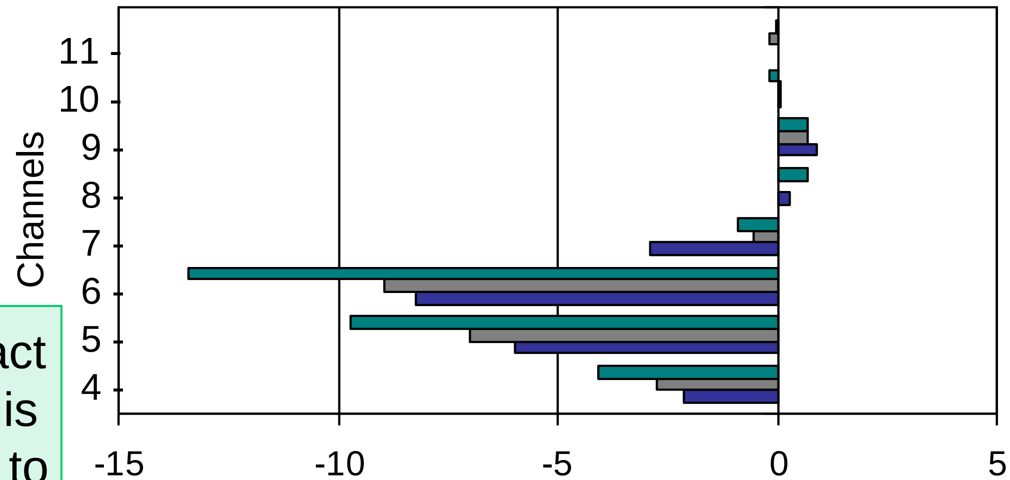
- Single-ob, scalar analysis: $x^a = x^b + k\left(y - x^b\right) \quad \text{where } k = \sigma_b^2 / \left(\sigma_b^2 + \sigma_o^2\right)$
- Expected impact is positive: $E\left(\varepsilon_a^2 - \varepsilon_b^2\right) = -k\sigma_b^2 < 0$
- **But sometimes, the impact is negative:**



…courtesy Mike Fisher, ECMWF

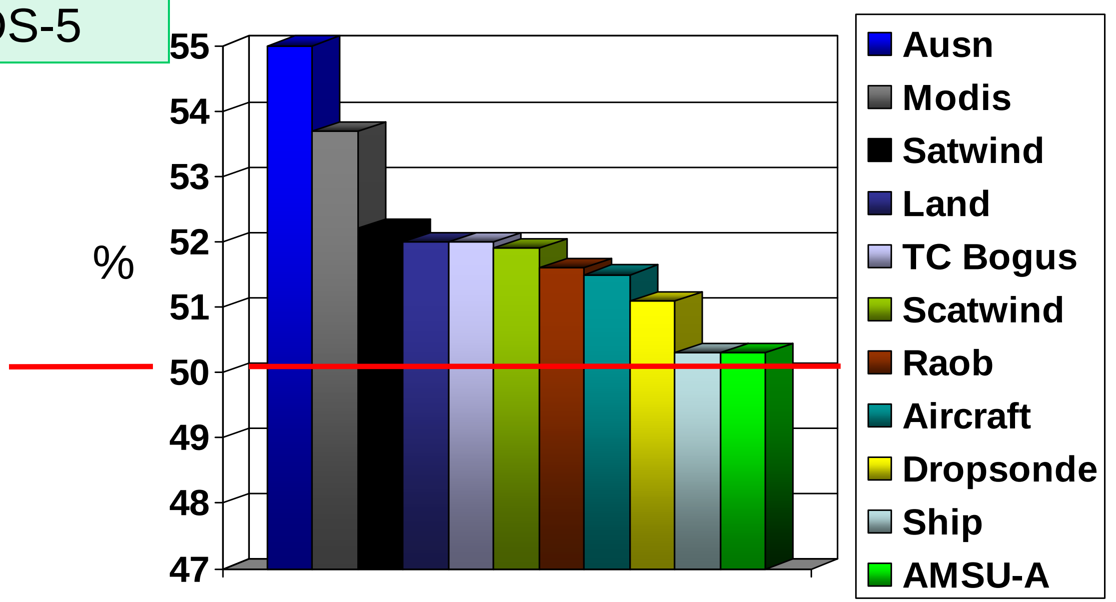
Observation Impact in NRL/NAVDAS

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

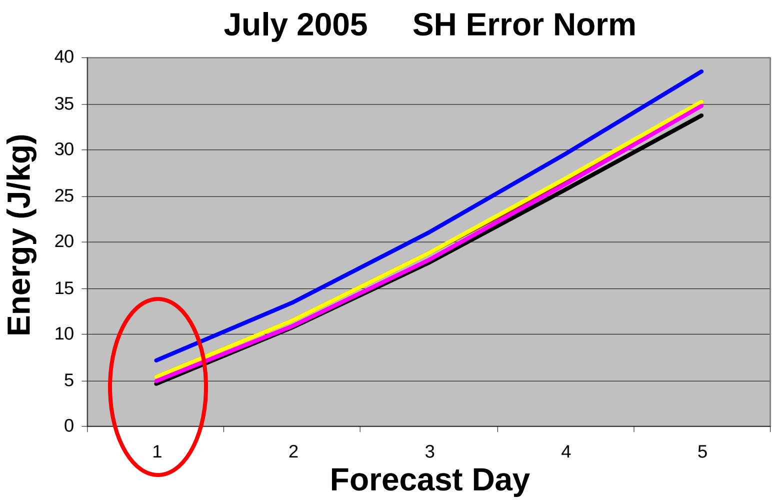
Rolf Langland, Nancy Baker, NRL

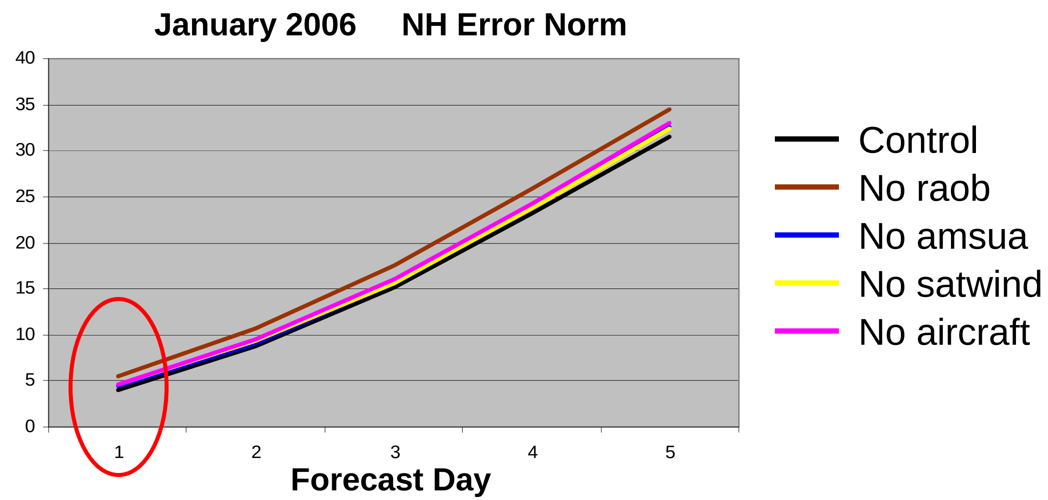
Comparison (Validation?) of ADJ results with OSEs

How do observation impact results based on the ADJ method compare with more traditional observing system (data-withholding) experiments…OSEs?

Can the two approaches be meaningfully compared?

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





- **GEOS-5 ADJ** impacts were computed using <u>separate 24h error norms for the globe, NH, SH and Tropics</u>

Comparison / Interpretation of ADJ and OSE Results

…a few things to keep in mind…

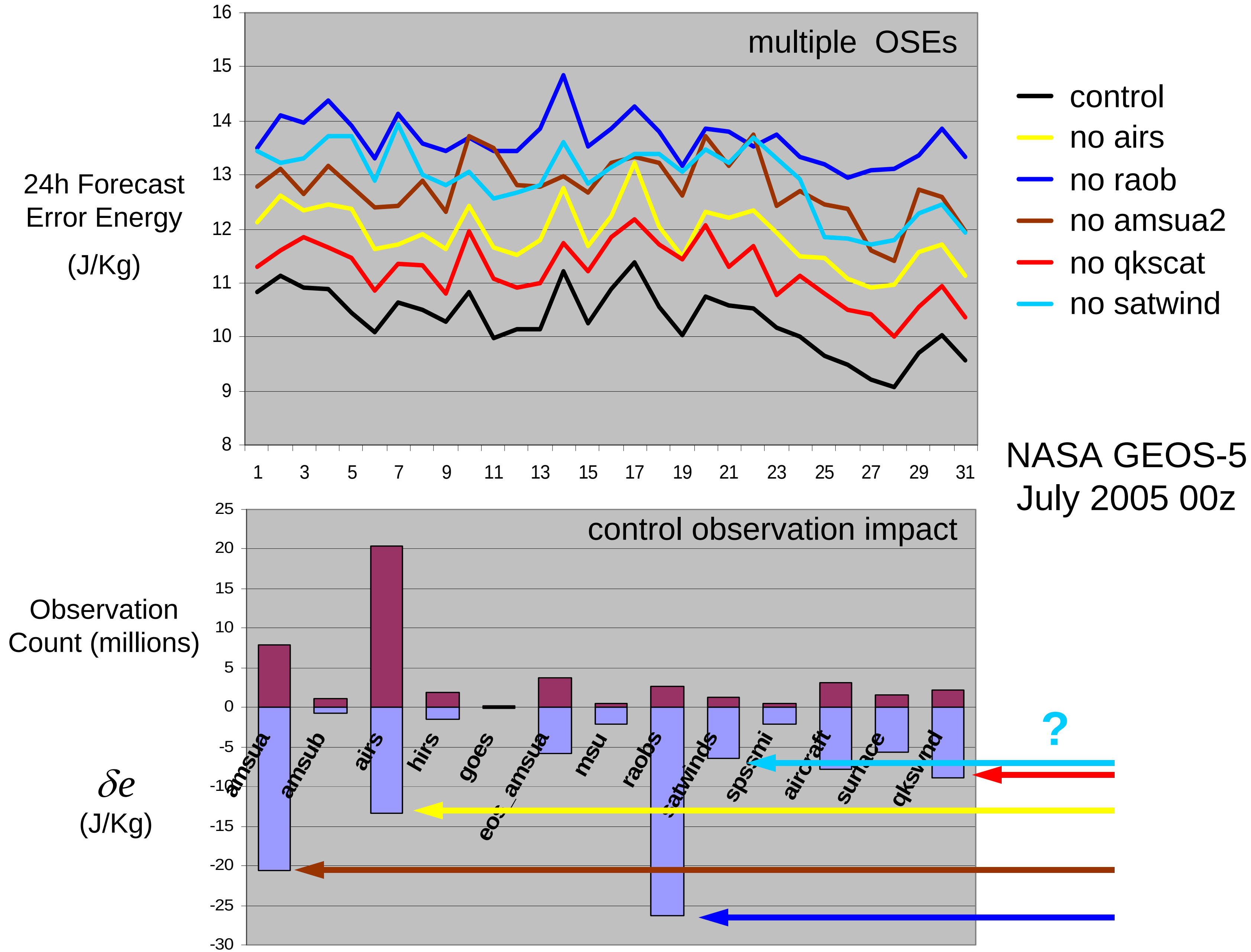
- The ADJ measures the impacts of observations in the context of all other observations present in the assimilation system, while the OSE changes/degrades the system (i.e., $\mathbf{K}$ differs for each OSE member)

- The ADJ measures the impact of observations on the analysis (increment) alone, while the OSE measures the impact of removing information accumulated in the background as well

- 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

How to compare observation impact in ADJ and OSEs?



‘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:

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

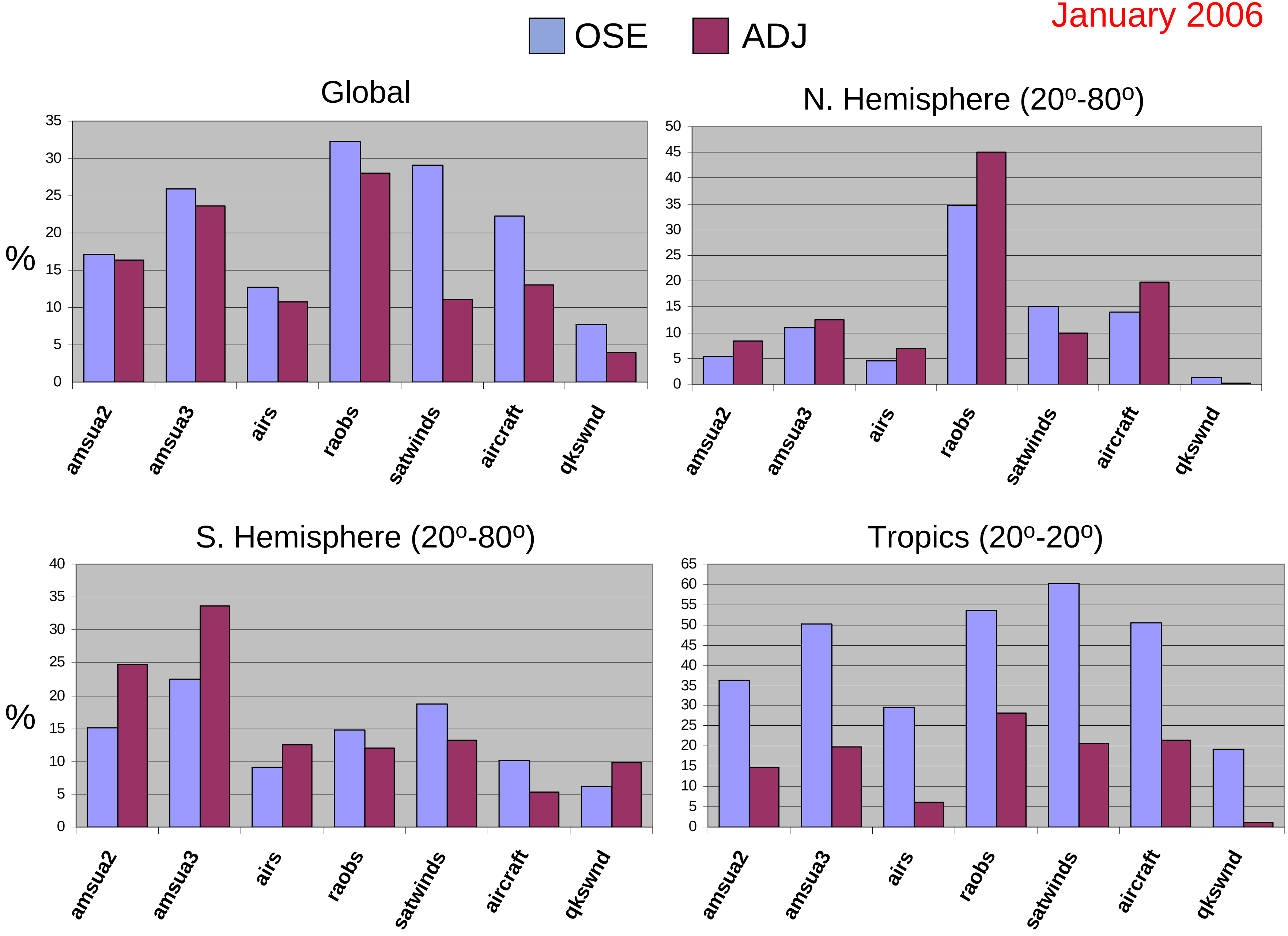
- Measures the % decrease in error due to the presence of observing system j with respect to the **background** forecast
- $\sum_j F_j(\mathrm{ADJ}) = 1$

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

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

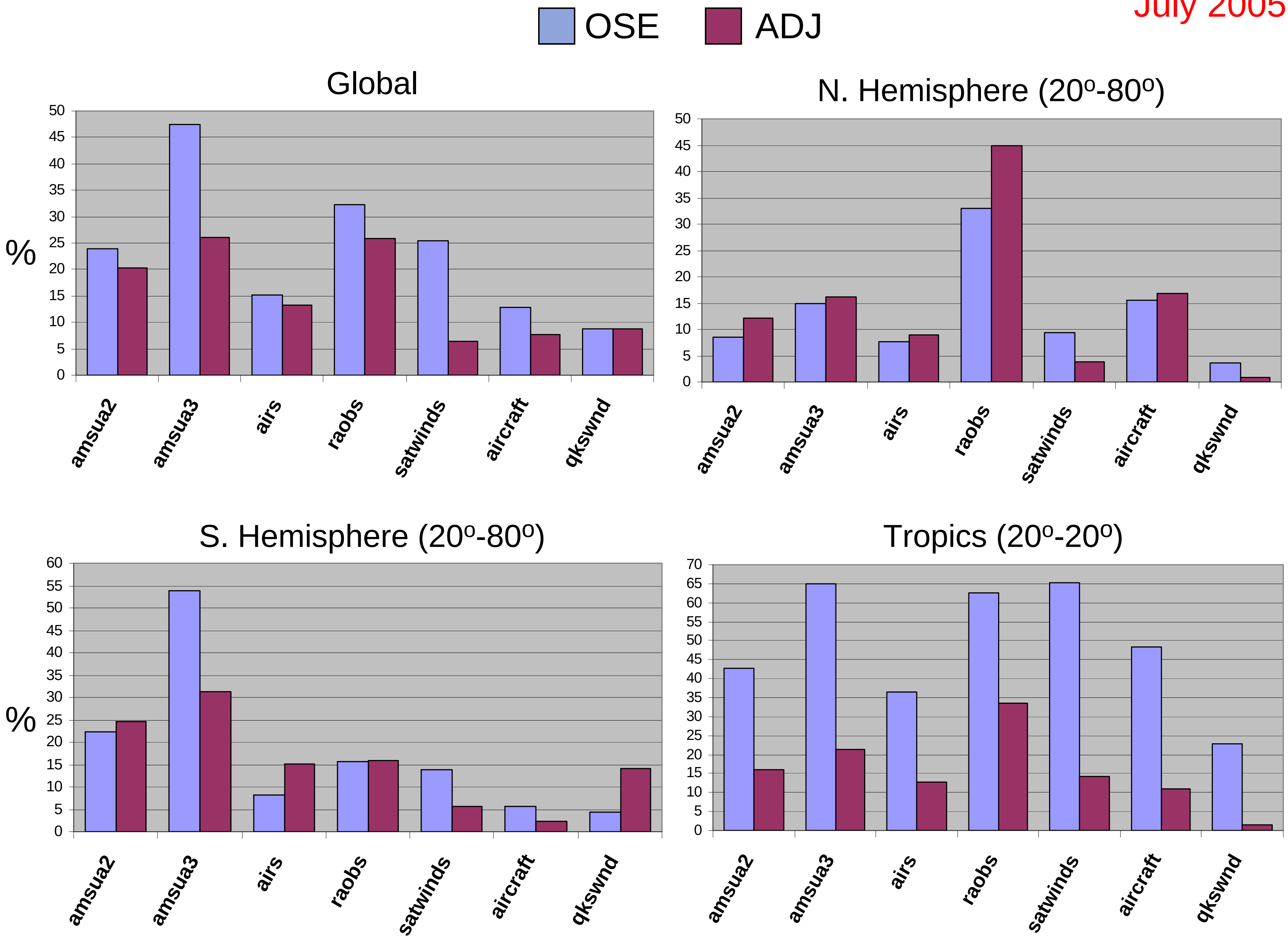
OSE vs ADJ Estimated Contributions to 24hr Fcst Error Reduction

January 2006



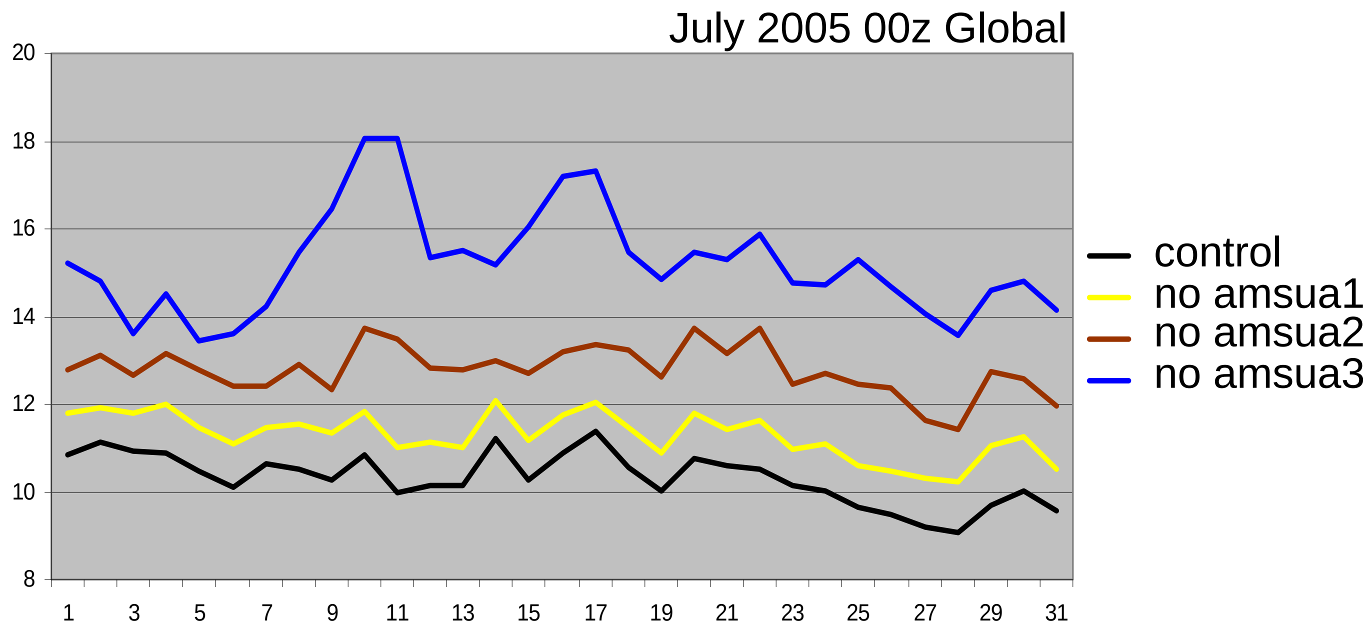
OSE vs ADJ Estimated Contributions to 24hr Fcst Error Reduction

July 2005



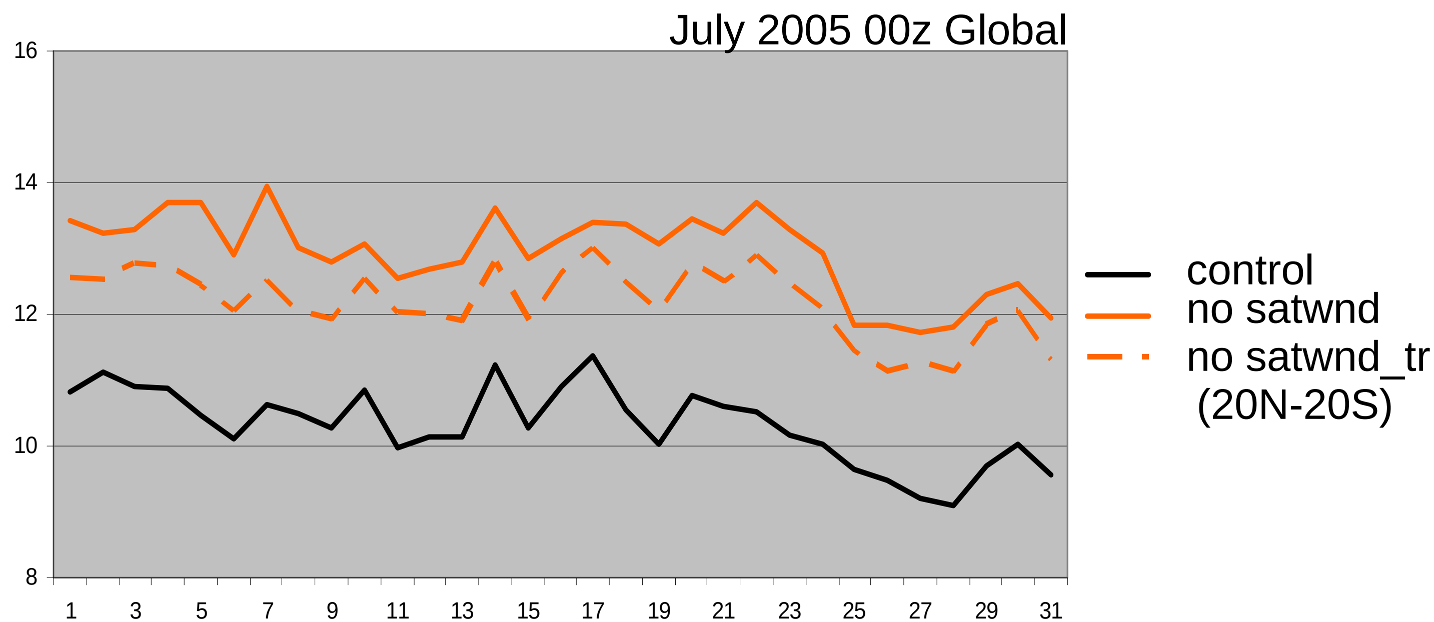
GEOS-5 Observing System Experiments (OSE)

24h Forecast Error Energy (J/Kg)



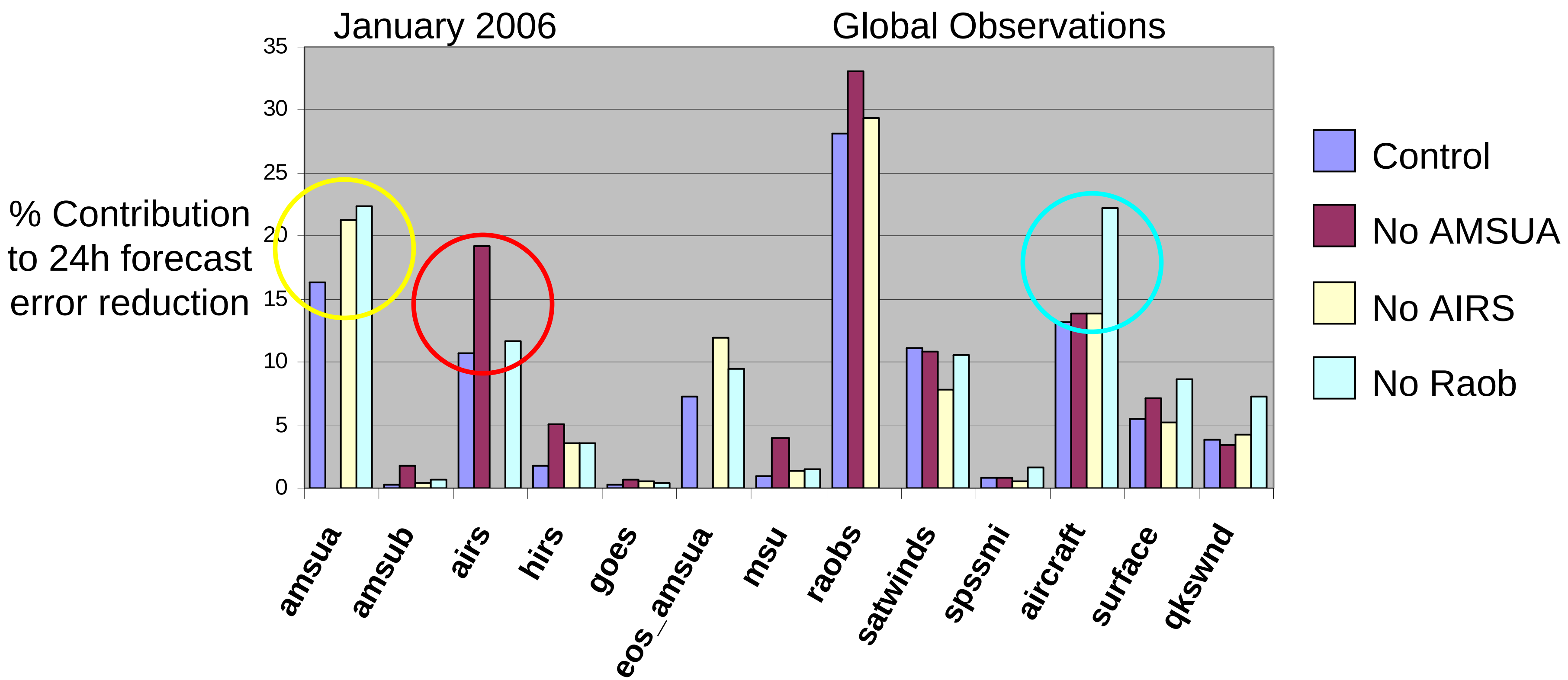
Skill ‘collapses’ when all AMSUA removed

24h Forecast Error Energy (J/Kg)



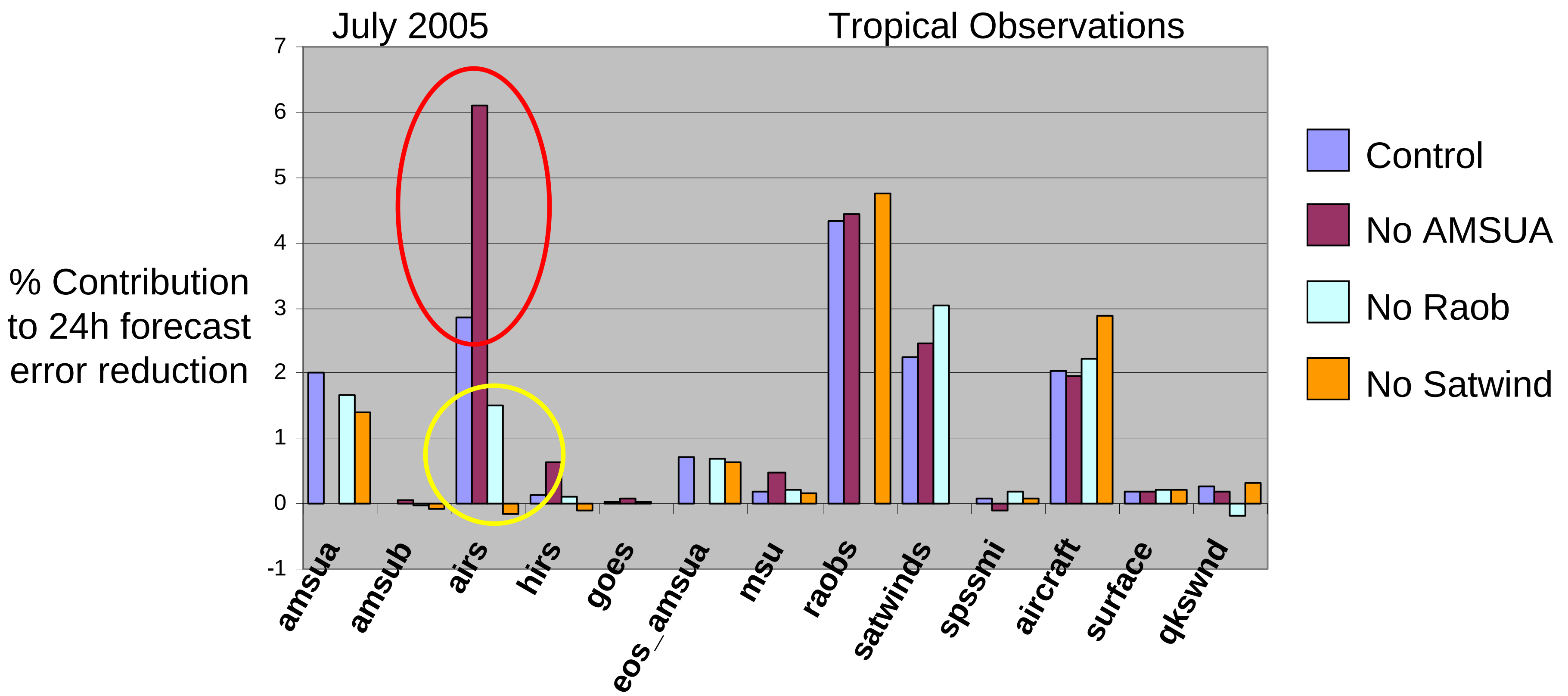
Satwind impact due mainly to data in the tropics

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!)

Summary of ADJ-OSE Comparison

- Despite fundamental differences in how impact is measured, ADJ and OSE methods provide comparable estimates of the overall ‘importance’ of most observing systems tested, especially in the extra-tropics

- Notable exceptions:

  ✓ % tropical impact of all observing systems underestimated in ADJ compared to OSE…missing physics in ADJ one factor, but not necessarily most important

  ✓ impact of satwinds underestimated in ADJ compared to OSE, most likely due to large contribution from tropics

  ✓ impact of removing all 3 AMSU-A underestimated by ADJ in southern winter (only)…OSE skill collapses with all AMSU-A gone

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

Looking ahead…a new method 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* $\partial \mathrm{J} / \partial \mathbf{x}$ *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)*

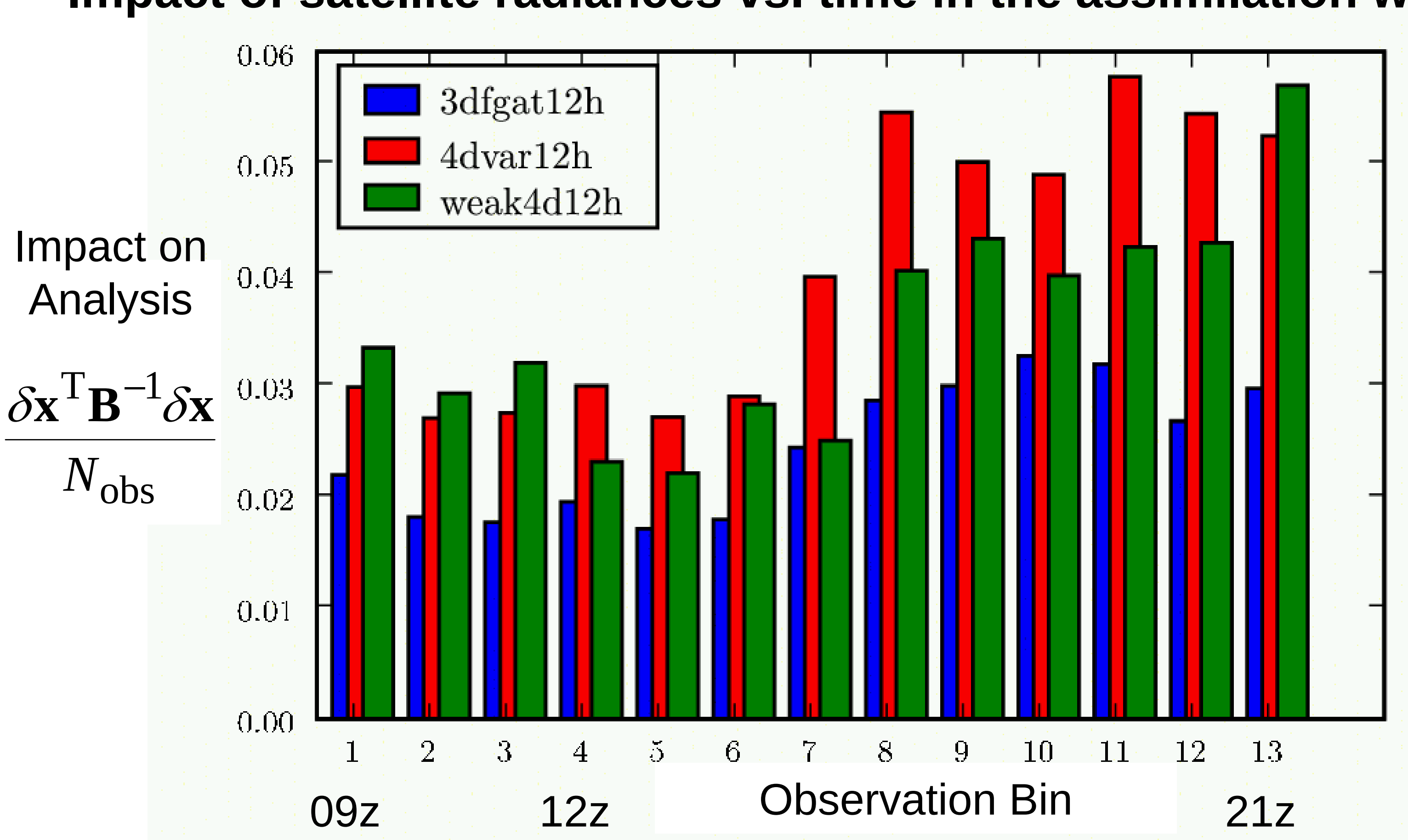
- Lanczos costs more than CG, but adjoint is ‘free’ $\Rightarrow$ 4DVAR
- Need to store Lanczos vectors
- Adjoint valid regardless of convergence (good diagnostic tool)

…look for Tremolet (2008)

Observation Impact in GEOS 4DVAR: Preliminary Results

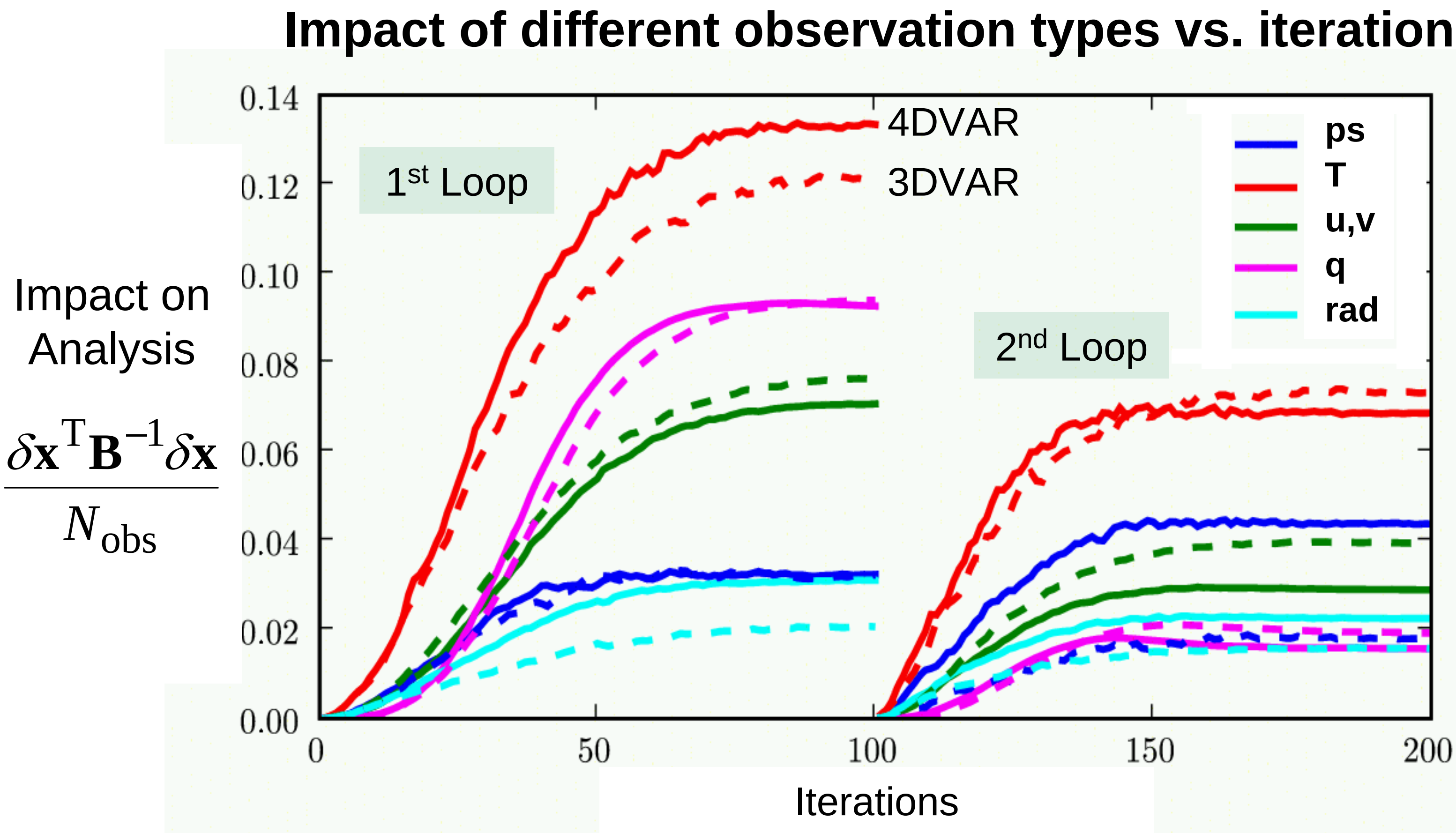
(Very low resolution, single analysis cycle…)

Impact of satellite radiances vs. time in the assimilation window



12hr Assimilation Window

Observation Impact in GEOS 4DVAR: Preliminary Results



- Benefit of 4DVAR differs by observation type
- Saturation of impact to examine convergence/stopping
- Erroneous increase in **ps** impact in 2nd outer loop of 4DVAR…
  …subsequently fixed by digital filter Jc term

Conclusions

- Data assimilation system adjoint provides an accurate and efficient tool for estimating observation impact on analyses and forecasts
  - ✓ computed with respect to <u>all observations simultaneously</u>
  - ✓ permits arbitrary aggregation of results by data type, channel, location, etc.

- Applications to data quality assessment and selection, understanding assimilation system behavior, identifying redundancies (and gaps?) in the observing system

- Excellently suited for real-time monitoring of assimilation system

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

- 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.

Observation impact activities in the community

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

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

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

    ✓ first results to be presented at WMO Geneva, March 2008 Workshop on Observation Impact

- 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)

    ✓ NRL Real-time Observation Impact Monitor page: http://www.nrlmry.navy.mil/ob_sens/