NASA impact on Numerical Weather Prediction: Past, Present and Future

Eugenia Kalnay

University of Maryland

with deep gratitude to NASA for the many opportunities it provided me

Past

- The beginnings of use of satellite data in numerical weather prediction
- Jule Charney's vision
- (Also his desertification theory for the Sahel)
- Controversy with NMC (now NCEP)
- Bob Atlas will talk more about this…
- Satellite data helped in SH but had little impact in NH until radiances were used

Jule Charney was the NWP super hero…

Use of Incomplete Historical Data to Infer the Present State of the Atmosphere

J. CHARNEY, M. HALEM[1] AND R. JASTROW[1]

Dept. of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass.

22 August 1969

Charney et al. (1969) showed that inserting satellite temperatures would provide information on winds and sea level pressure

(but not of winds in the tropics!)

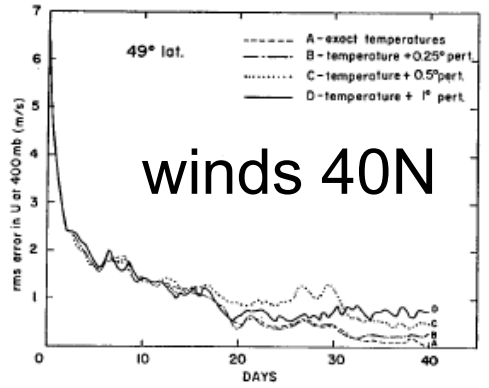


FIG. 1. The rms error in zonal wind (m sec^{-1}) at 400 mb at 49° latitude, in cases where temperatures with random error perturbations of 0, 0.25, 0.5 and 1C are inserted every 12 hr at all grid points.

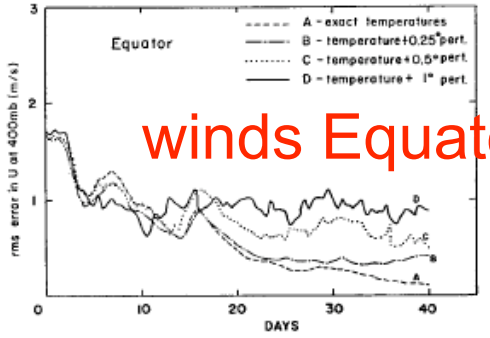


FIG. 2. Same as Fig. 1 for the equator.

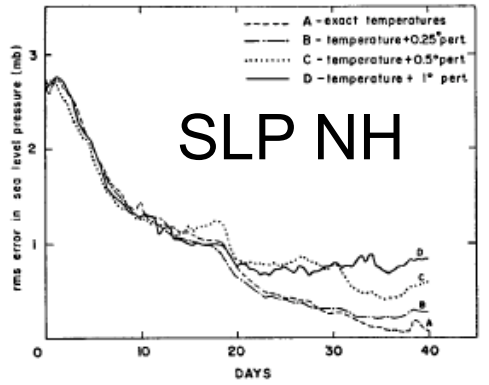


FIG. 3. The rms error in sea level pressure anomaly (mb) for the Northern Hemisphere, in cases where temperature with 0, 0.25, 0.5 and 1C random error perturbations are inserted every 12 hr at all grid points.

Nimbus 2/3 provides first annual net radiation budget: Raschke , Bandeen and Van Der Haar

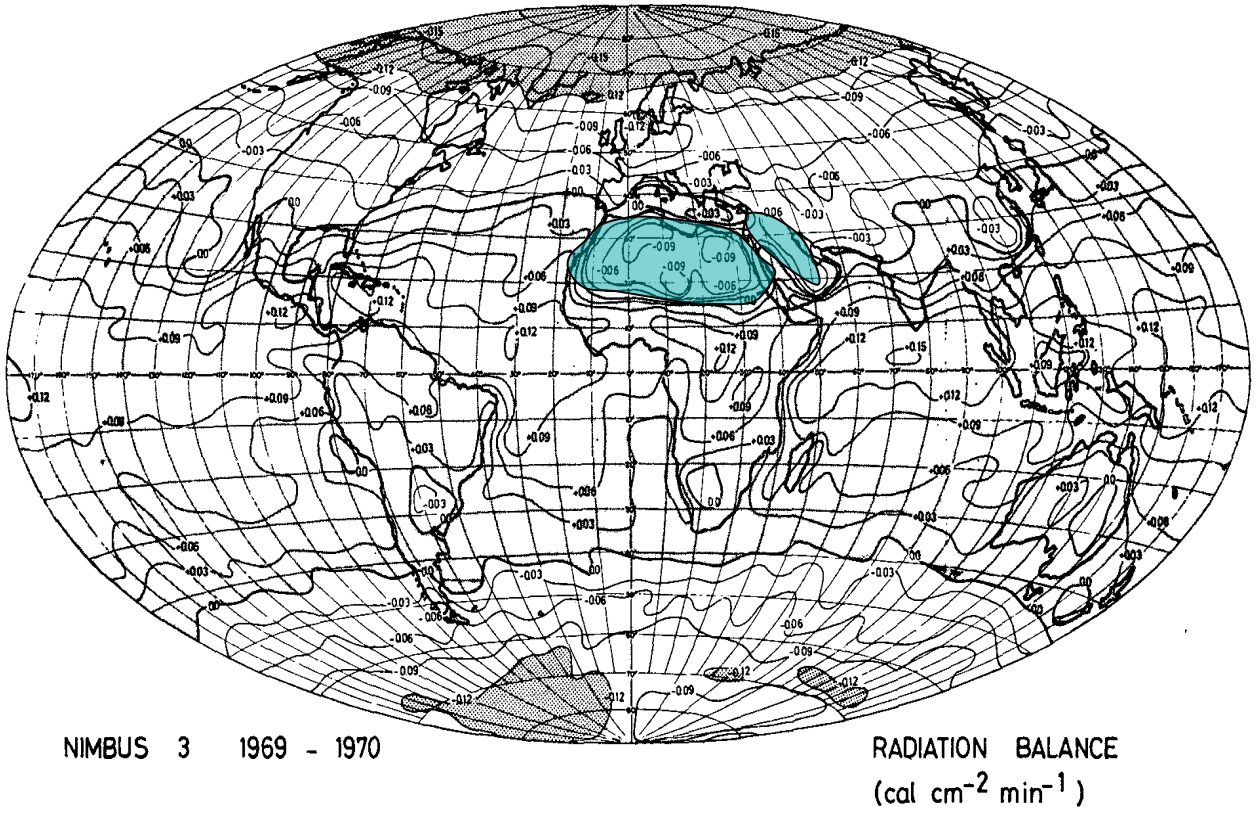
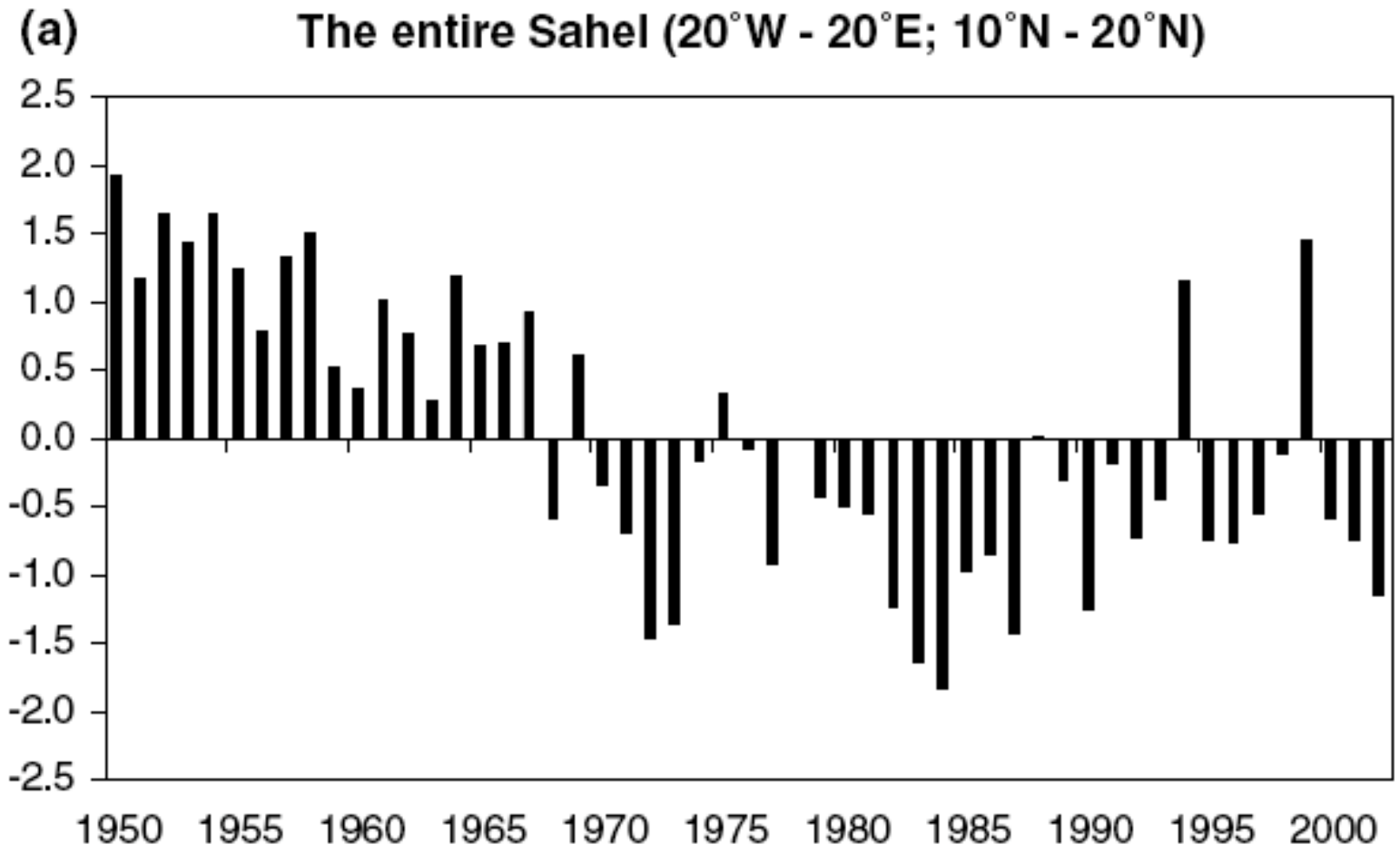
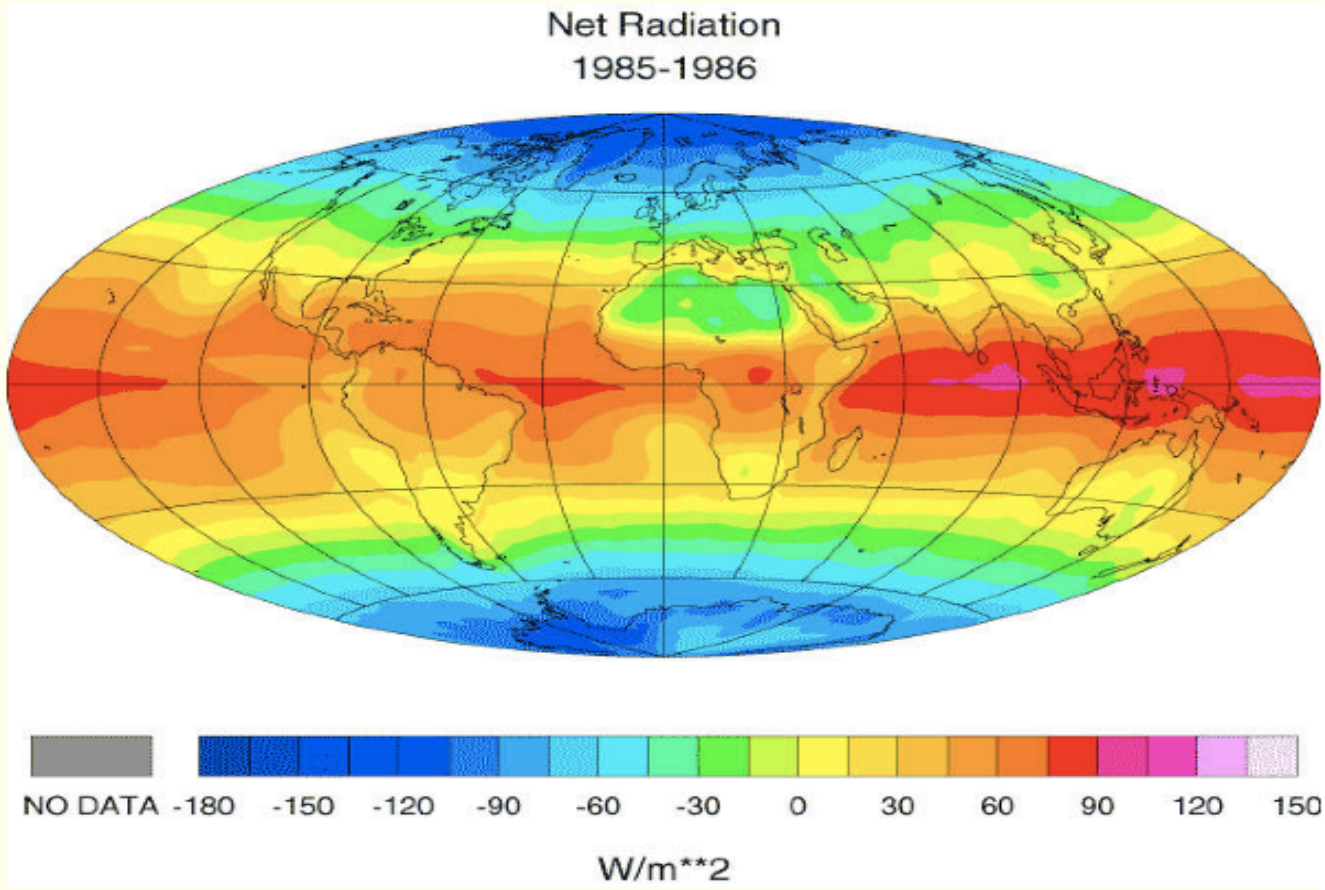


FIG. 17. Annual radiation balance of the earth-atmosphere system.

Charney saw that subtropical deserts were a radiative sink anomaly, and came up with the idea of albedo-feedback

The Sahel had suffered a long-term reduction in precipitation





Charney: Deserts have a net loss of energy because of high albedo, which in turn increases subsidence and reduces rain.
=> In the Sahel, overgrazing increased albedo and Charney's albedo-rain positive feedback increases desertification!

NWS, Tracton et al., 1980: a devastating paper (but see Atlas)

Satellite data impacts with the Data System Tests of 1975 and 76:

- "Overall the impact of the remote soundings in the NH was negligible,

- but the amplitude of weather systems in SAT were consistently weaker than in NOSAT".

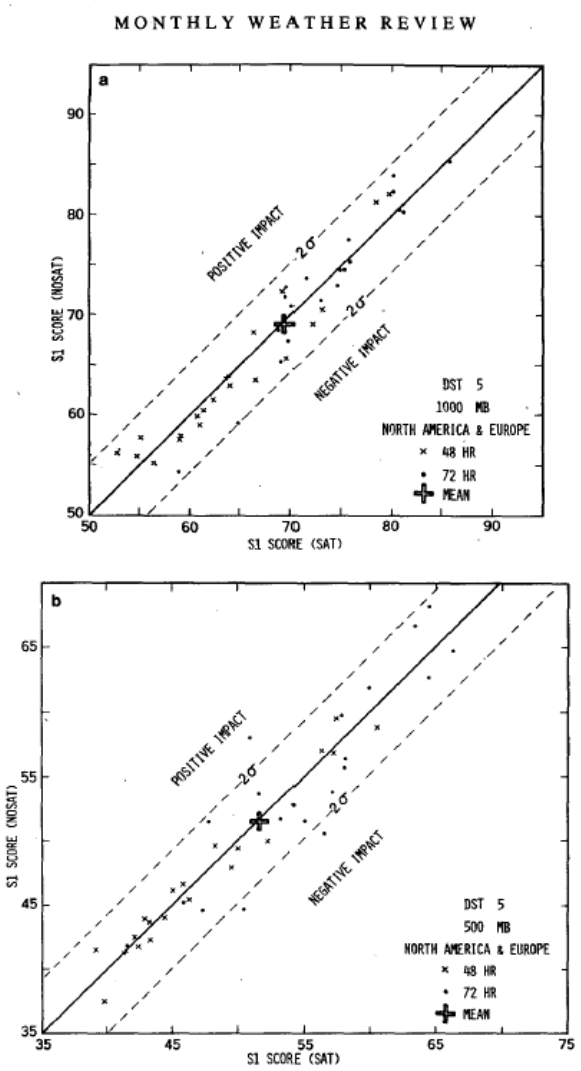


FIG. 18. Collective results of 48 and 72 h DST-5 forecast verification against analyses over North America and Europe at the 1000 (a), 500 (b) and 300 (c) mb levels in terms of plots of the SAT versus NOSAT *S*1 scores. The sigma (σ) of the 2σ lines is the standard deviation of the set of differences between SAT and NOSAT scores.

Halem, Kalnay, Baker and Atlas, 1982: first FGGE satellite data impact study.

GARP TOPICS

No. 72 April 1982

An occasional series reporting on U.S. and international GARP scientific, technical, and planning activities, developments, and programs, presented as a public service to the meteorological community by the American Meteorological Society through arrangements with the U.S. Committee on the Global Atmospheric Research Program of the National Academy of Sciences–National Research Council. Opinions expressed in "GARP Topics" do not necessarily reflect the point of view of the U.S. Committee.

An Assessment of the FGGE Satellite Observing System during SOP-1

M. Halem, E. Kalnay, W. E. Baker, and R. Atlas

Goddard Laboratory for Atmospheric Sciences (GLAS)

NASA Goddard Space Flight Center, Greenbelt, Md. 20771

Abstract

This study investigates the degree to which data from the space-borne FGGE observing systems are able to determine the complete state of the atmosphere when incorporated into a global objective analysis cycle. Three data assimilation experiments are performed with the Goddard Laboratory for Atmospheric Sciences (GLAS) analysis/forecast system, using different combinations of the FGGE

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curred in periods of atmospheric blocking situations also

Halem, Kalnay, Baker and Atlas, 1982: first FGGE satellite data impact study.

It was controversial after Tracton et al (1980)!

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A figure that saved satellite data impact!

The figure shows the analysis correction to the 6 hour forecast for SAT and NOSAT
Large corrections in west coast in NOSAT, smaller in SAT.
Over the oceans, no corrections in NOSAT, small corrections in SAT

This result impressed Norm Phillips very much and convinced him and others of the utility of satellite data!

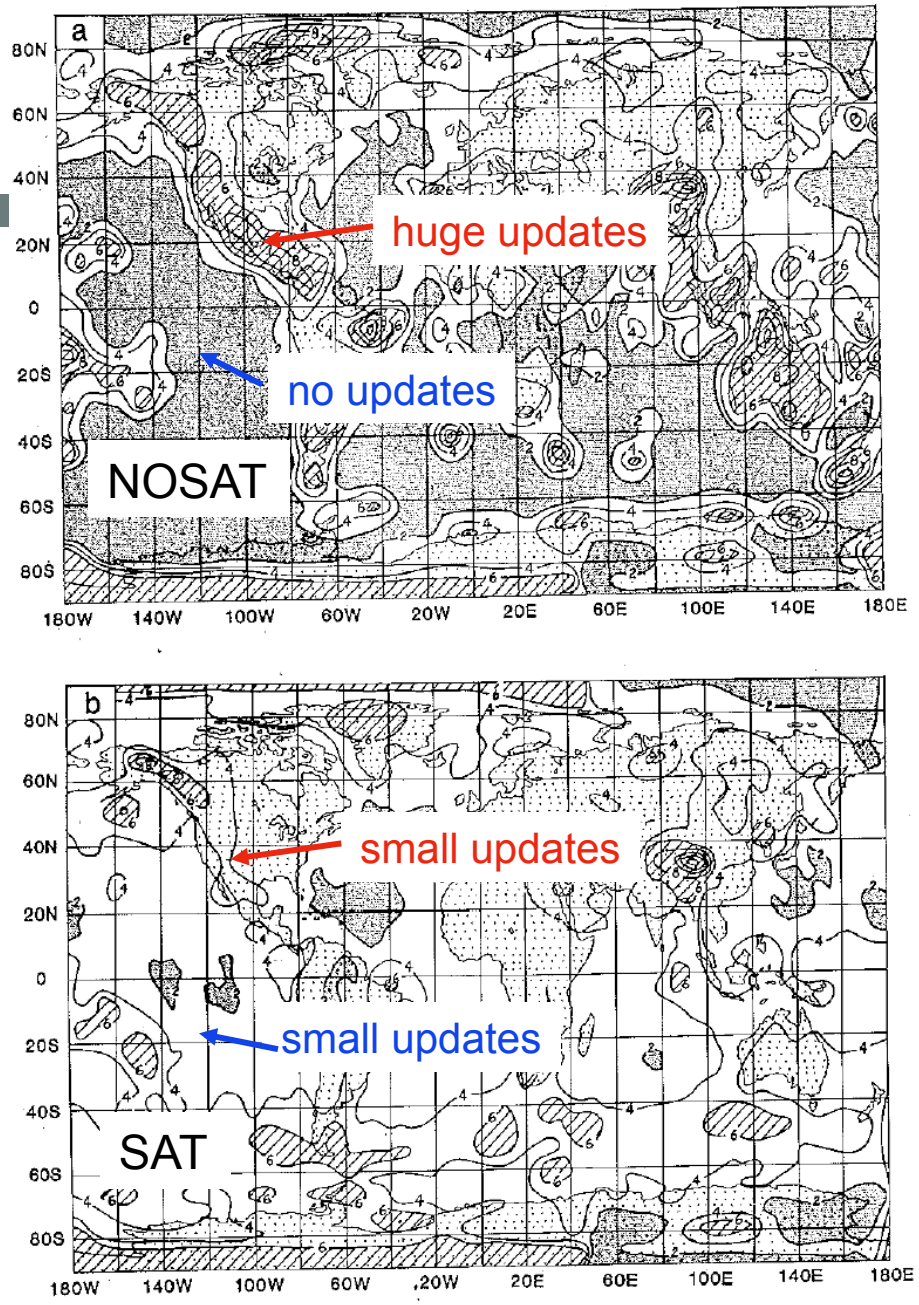


FIG. 5. The rms difference between the 6 h forecast of the 300 mb geopotential height field and the analysis for the period 5–21 January 1979. Contour interval is 20 m. a) Rms difference between the NOSAT analysis and forecast. b) Rms difference between the FGGE analysis and forecast.

The forecast impact in the NH was mixed, slightly positive. In the SH it was very clearly positive

North America

Europe

Australia

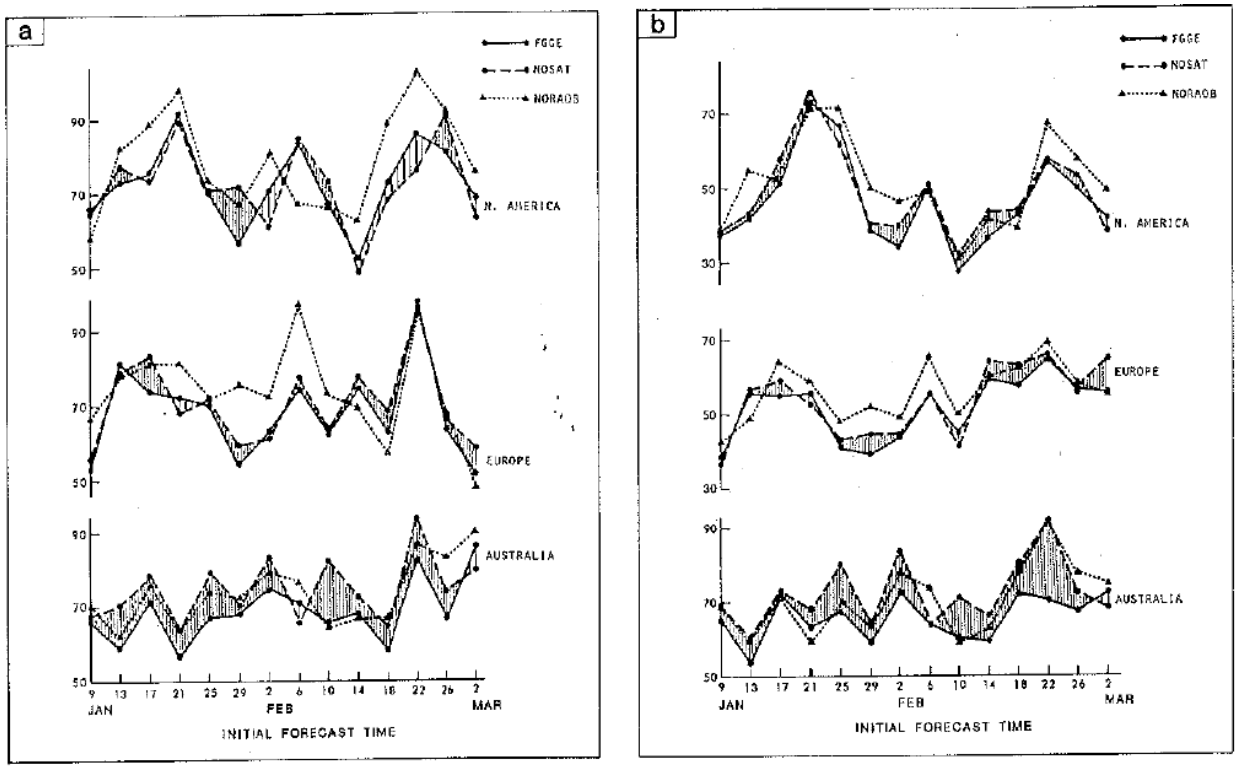


FIG. 11. S_1 skill scores for 72 h forecasts from the FGGE, NOSAT, and NORAOB systems over North America, Europe, and Australia from 0000 GMT of the indicated initial days during SOP–1. All forecasts verified against the NMC analysis. a) Sea level pressure forecasts. b) 500 mb forecasts.

Why the small impact in the NH with retrievals? TOVS and MSU have only ~4-5 “pieces of information”, the rest came from climatology!

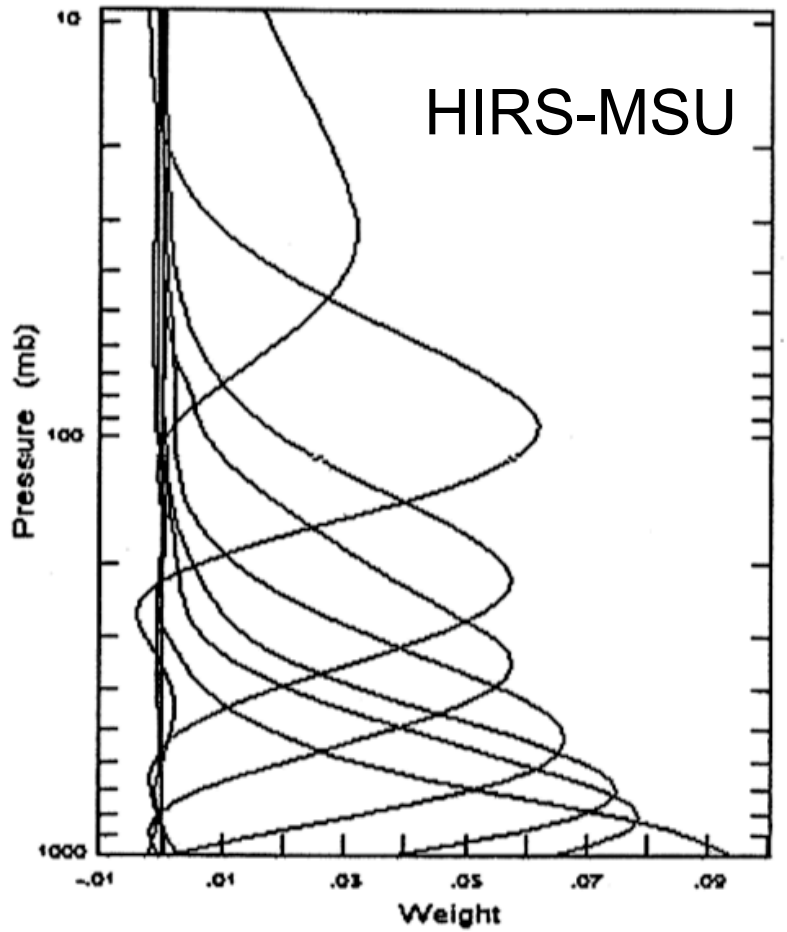
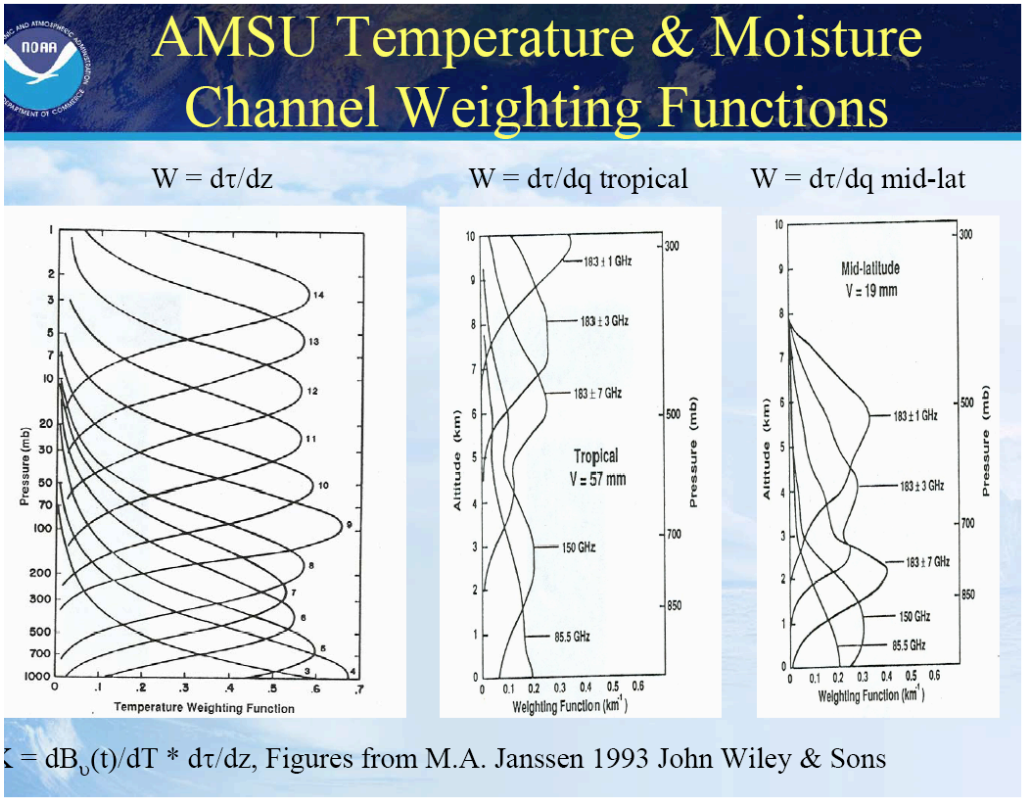


Fig. 6. HIRS–MSU deep-layer meantemperature averaging kernels.

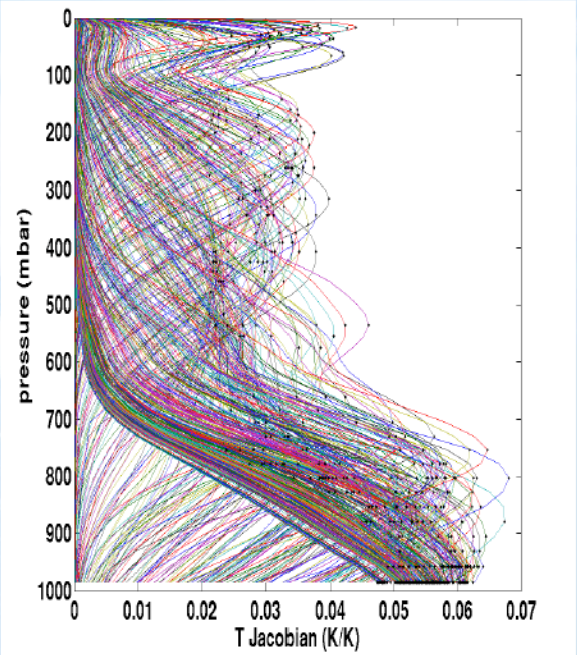


(With AIRS we don't need additional information!)

Example Channel Kernel Functions, $K_{n,j}$ for Temperature and Moisture

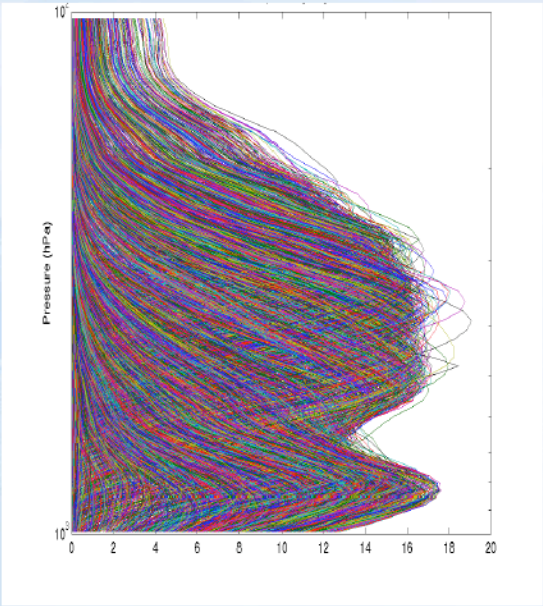
AIRS 15 μm (650-800 cm-1) band

K = dR/dT



AIRS 6.7 μm (1200-1600 cm^{-1}) band

K = dR/dq



Derber and Wu (1998) (almost two decades later!)
Impact of using TOVS radiances compared with retrievals:
It doubled the large positive impact in the SH

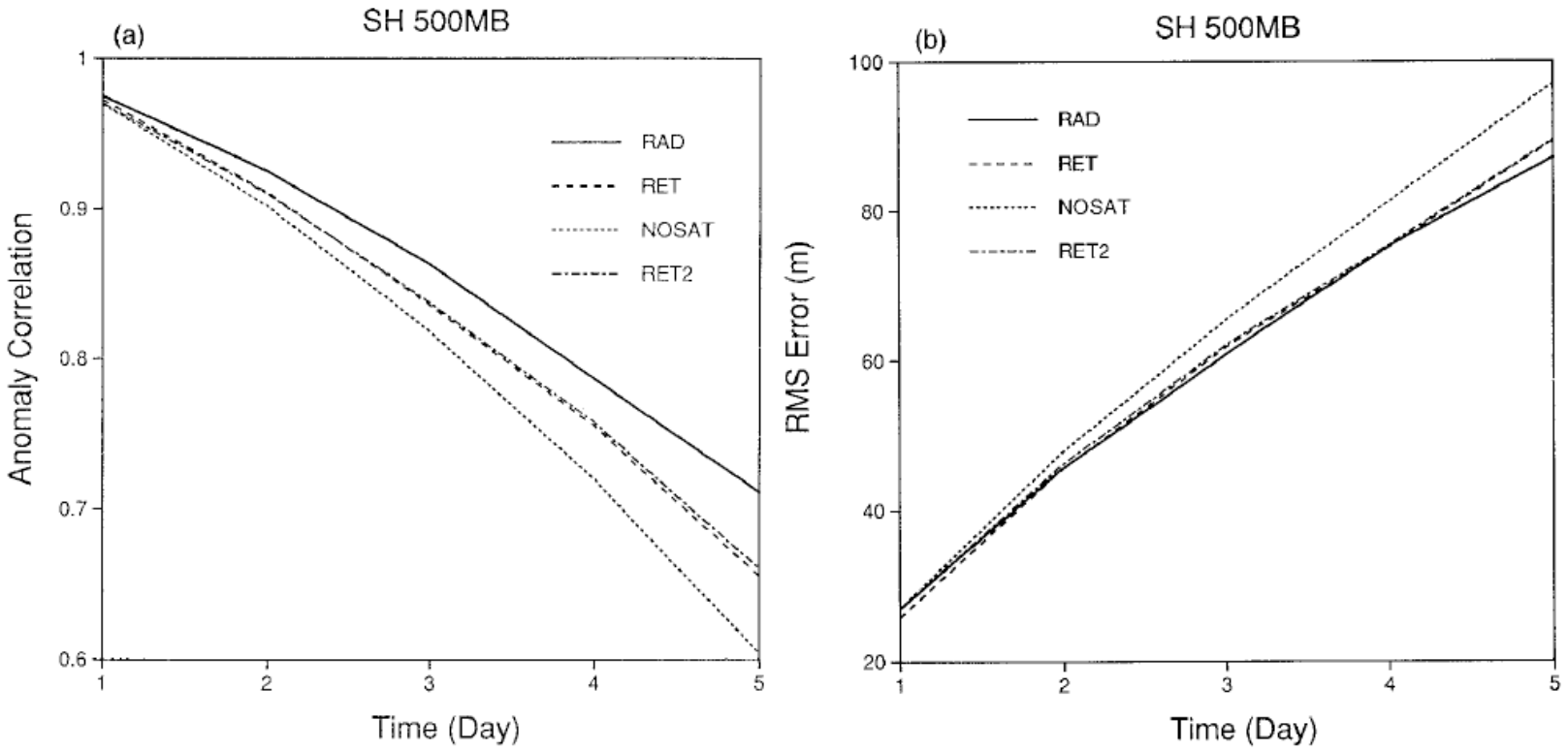


FIG. 9. Same as in Fig. 8 except for Southern Hemisphere.

Derber and Wu (1998): TOVS radiances gave for the first time a clear positive impact in the NH!!!

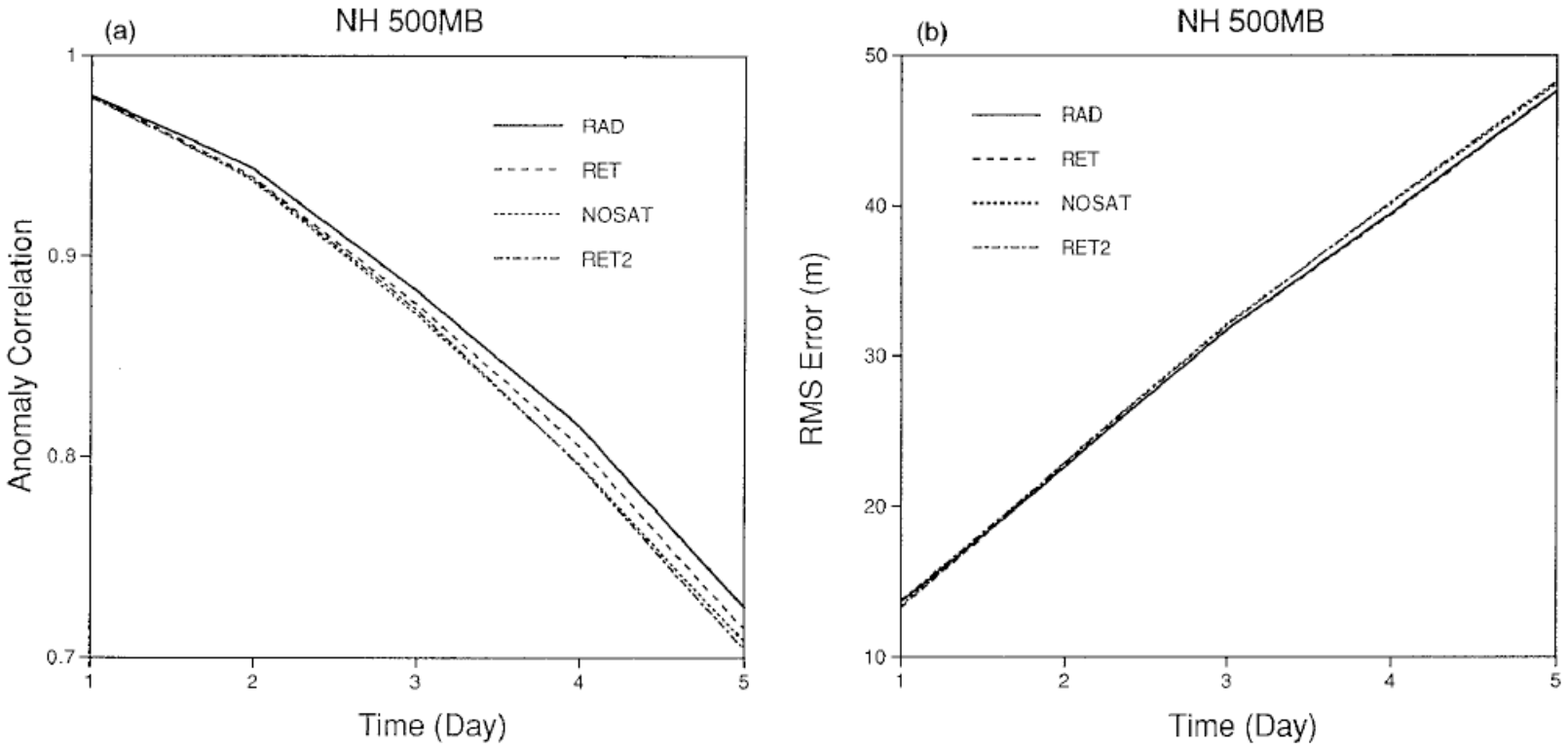
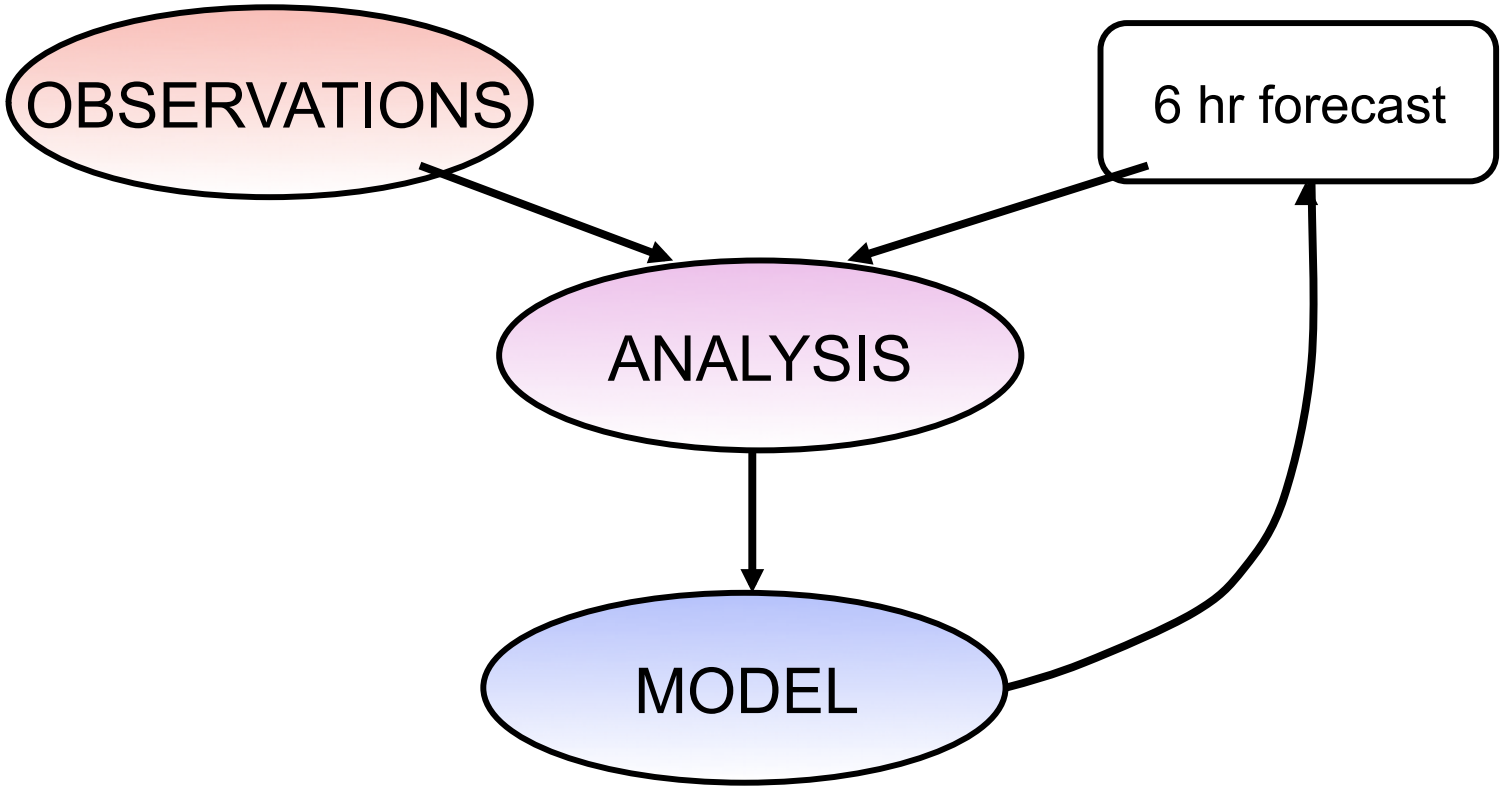


FIG. 8. Northern Hemisphere anomaly correlations (a) and rms errors (b) for 5-day forecasts from NOSAT, RAD, RET, and RET2 experiments. Results are averages over 21 forecasts (29 July 1995~18 August 1995).

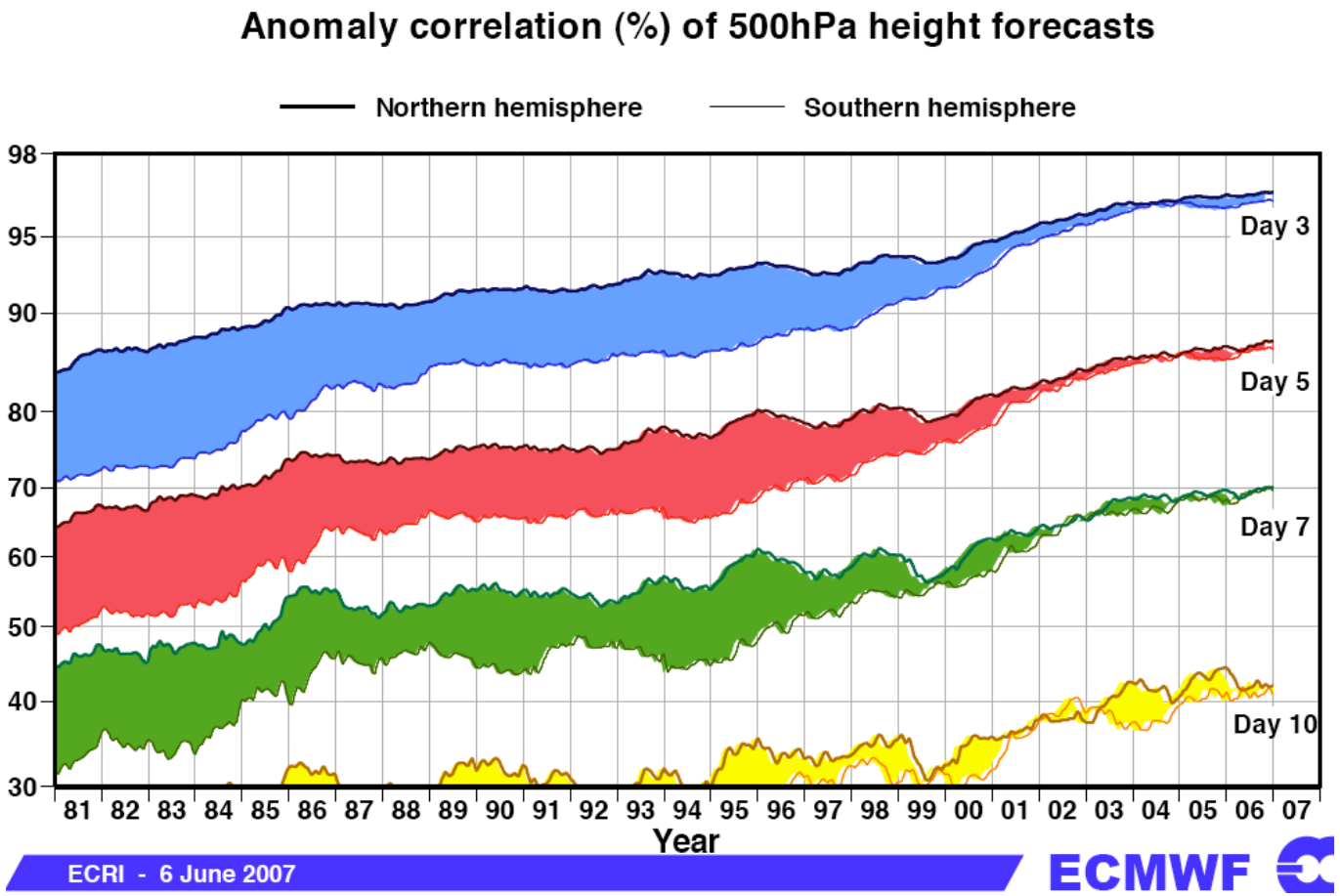
Present

- Satellite data use in numerical weather prediction is mature
- SH skill is similar now to NH
- Wonderful impact of AIRS
- What has brought these impressive improvements?

Data Assimilation: We need to improve observations, analysis scheme and model

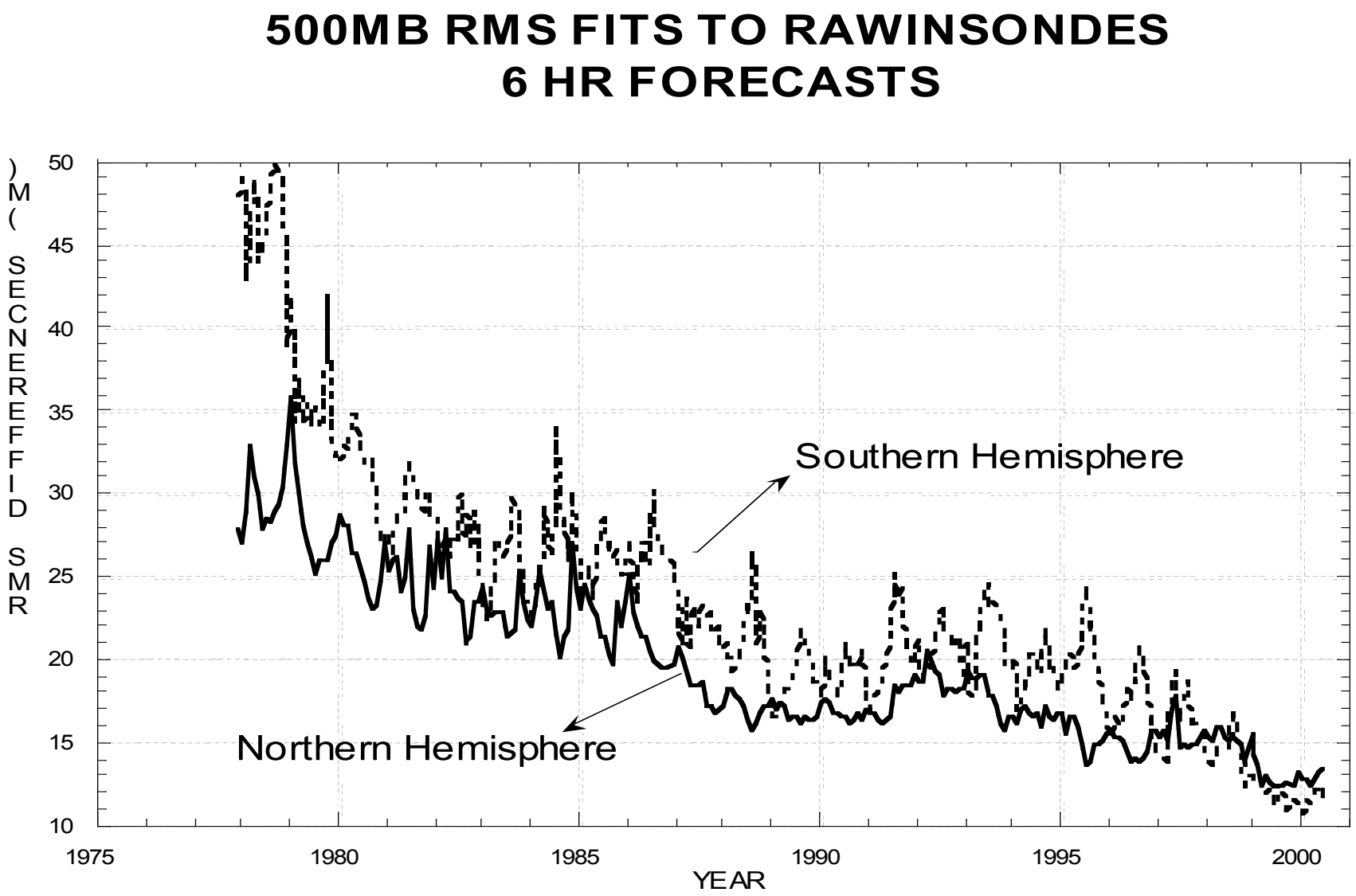


Comparisons of Northern and Southern Hemispheres



Thanks to satellite data the SH has improved even faster than the NH!

We are getting better… (NCEP observational increments)



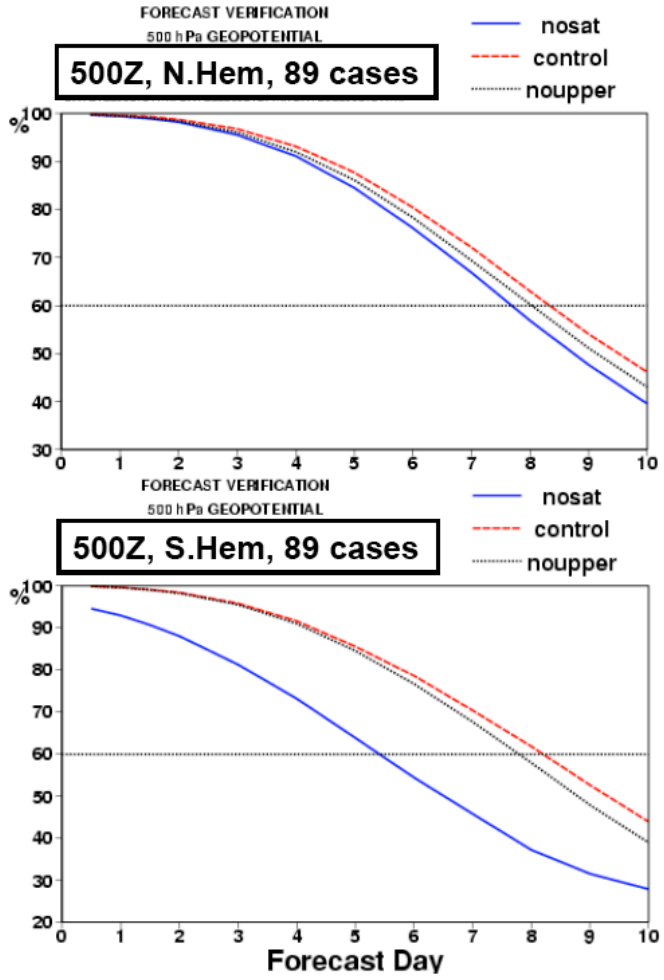
Current results: Satellite radiances are essential in the SH, more important than rawinsondes in the NH!

Observing System Experiments (ECMWF - G. Kelly et al.)

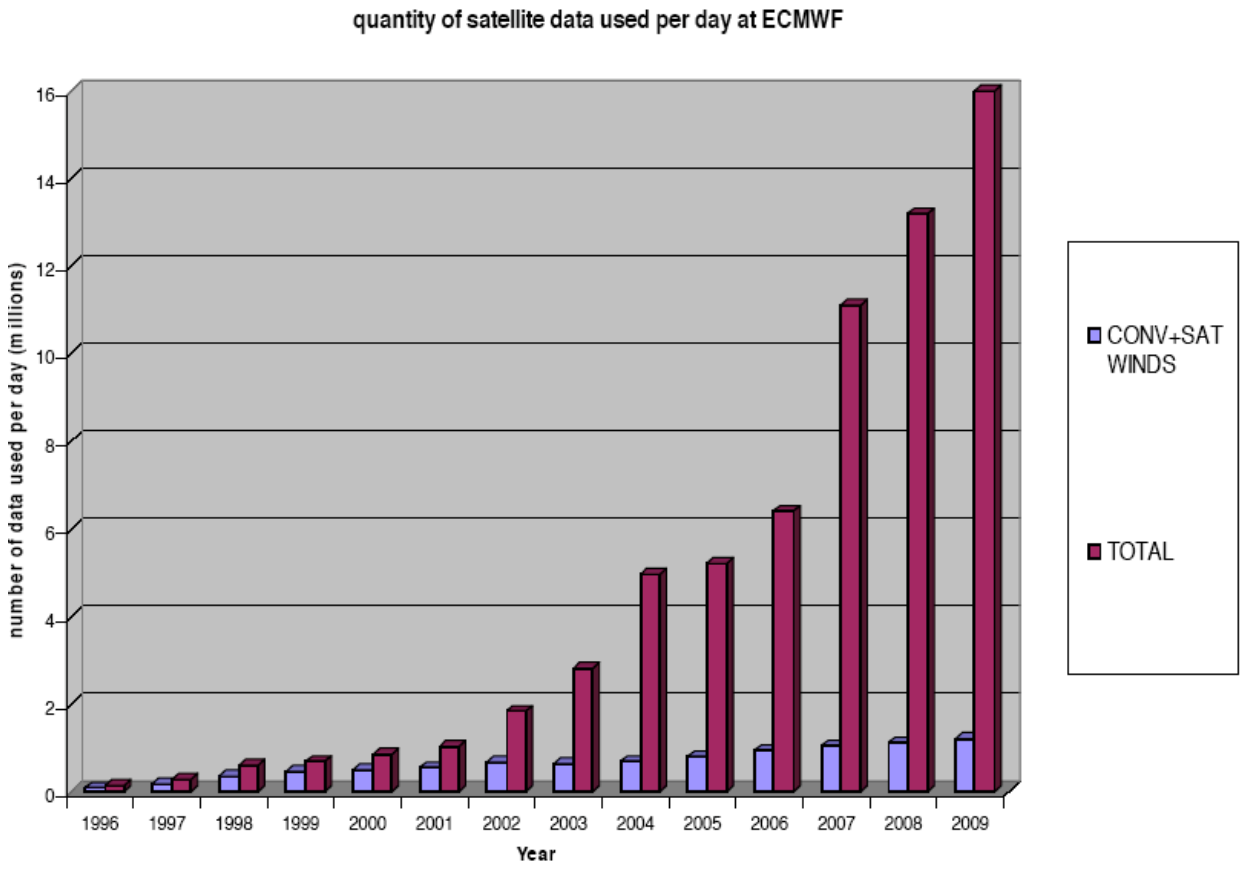
NoSAT= no satellite radiances or winds

Control= like operations

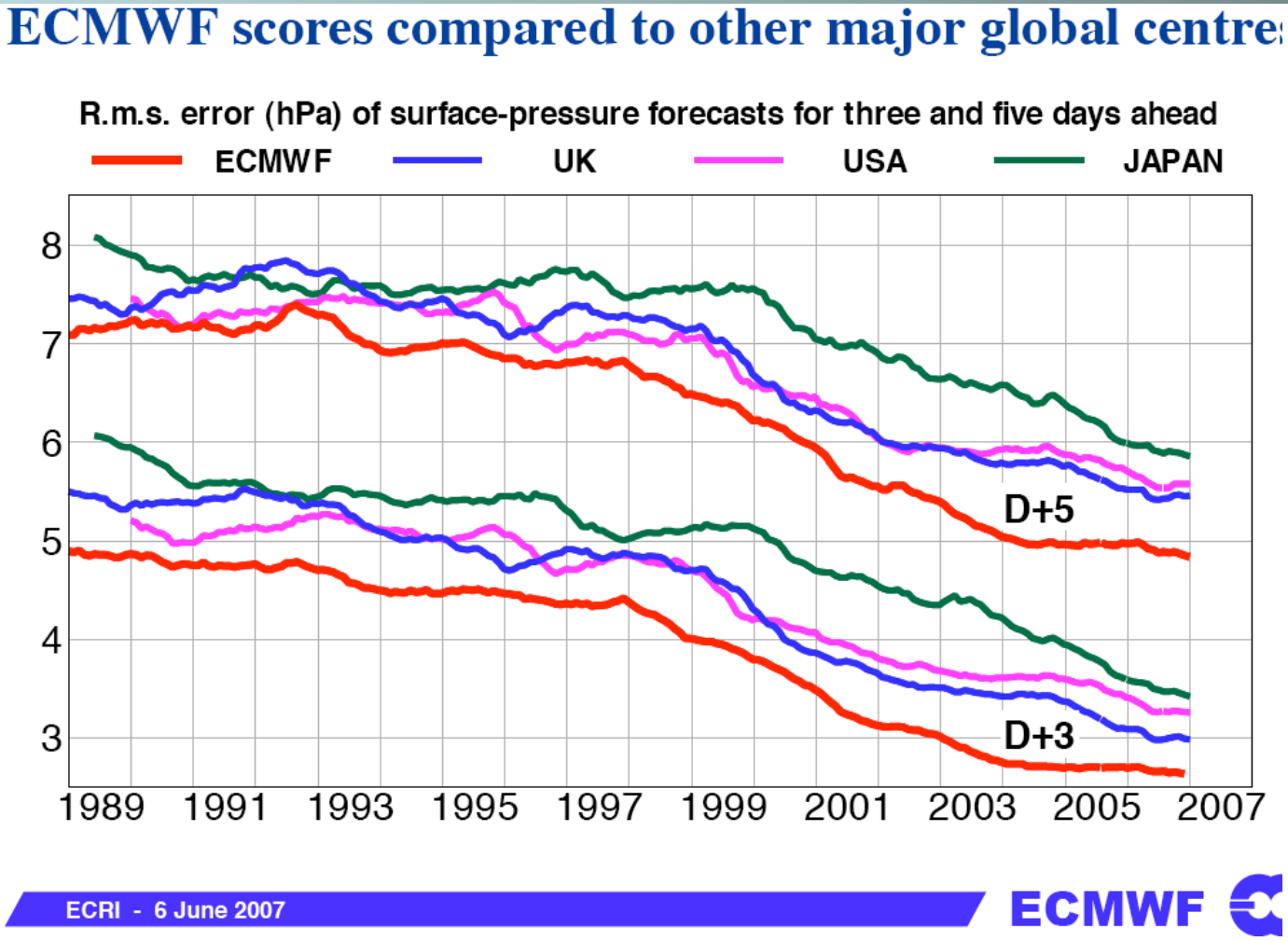
NoUpper=no radiosondes, no pilot winds, no wind profilers



More and more satellite radiances…

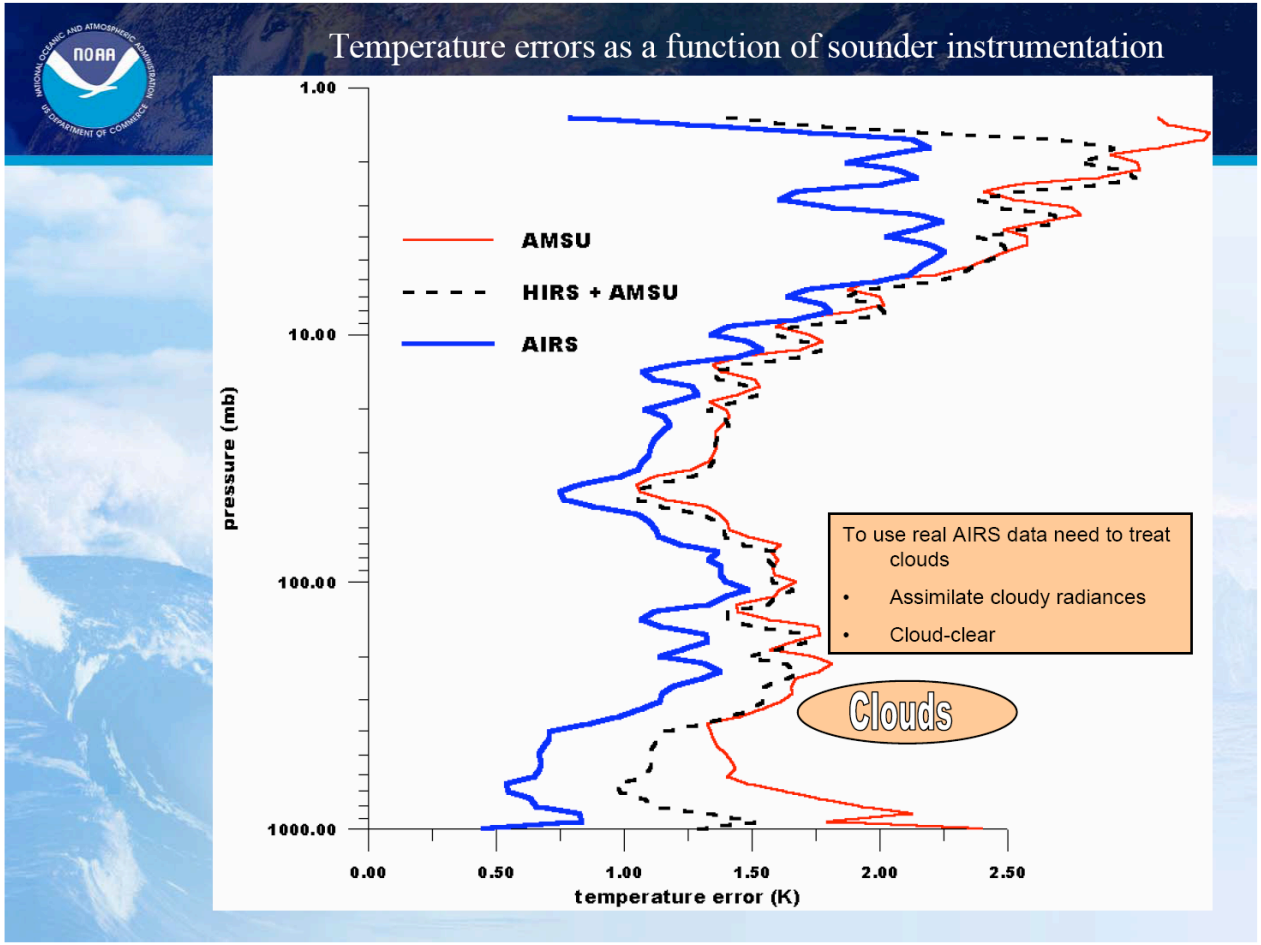


Some comparisons…



The largest improvements have come from AMSU and 4D-Var

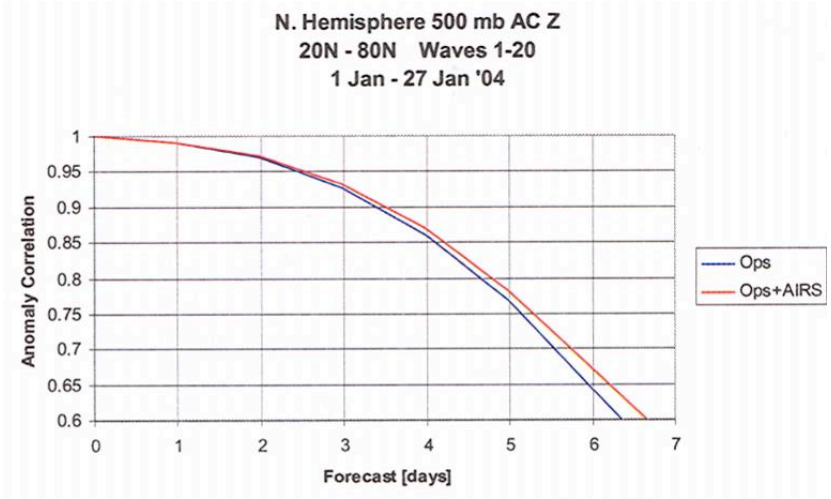
AIRS



Goldberg, 2007

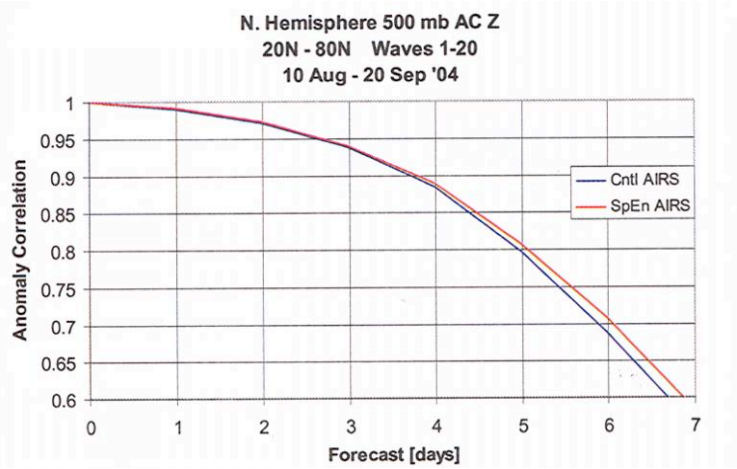
AIRS Data Significantly Improves NCEP Operational Forecast

Initial inclusion of AIRS data



6 Hours in 6 Days (1 in 18 Footprints)
Operational: October 2004

Utilizing All AIRS Footprints



Additional 5 Hours in 6 Days
Experimental (LeMarshall)

Le Marshall, J., J. Jung, J. Derber, M. Chahine, R. Treadon, S. J. Lord, M. Goldberg, W. Wolf, H. C. Liu, J. Joiner, J. Woollen, R. Todling, P. van Delst, and Y. Tahara (2006), "Improving Global Analysis and Forecasting with AIRS", Bulletin of the American Meteorological Society, 87, 891-894, doi: 10.1175/BAMS-87-7-891

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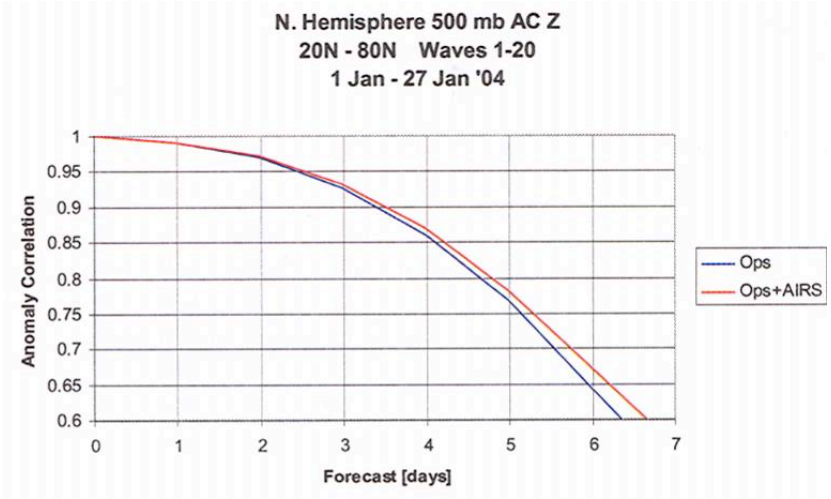

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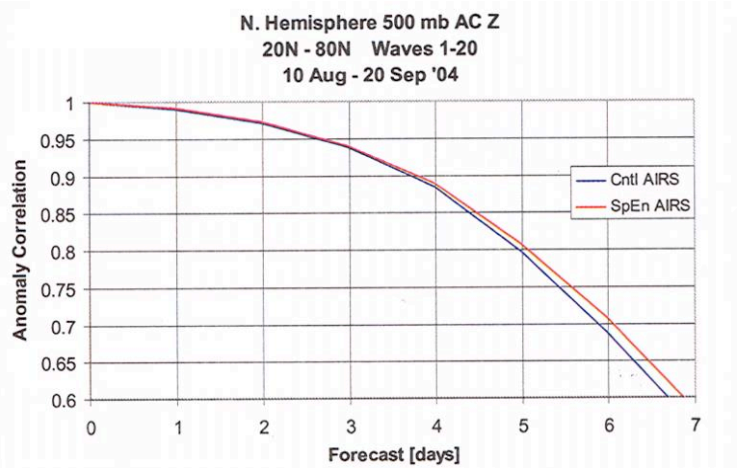


Additional 5 Hours in 6 Days
Experimental (LeMarshall)

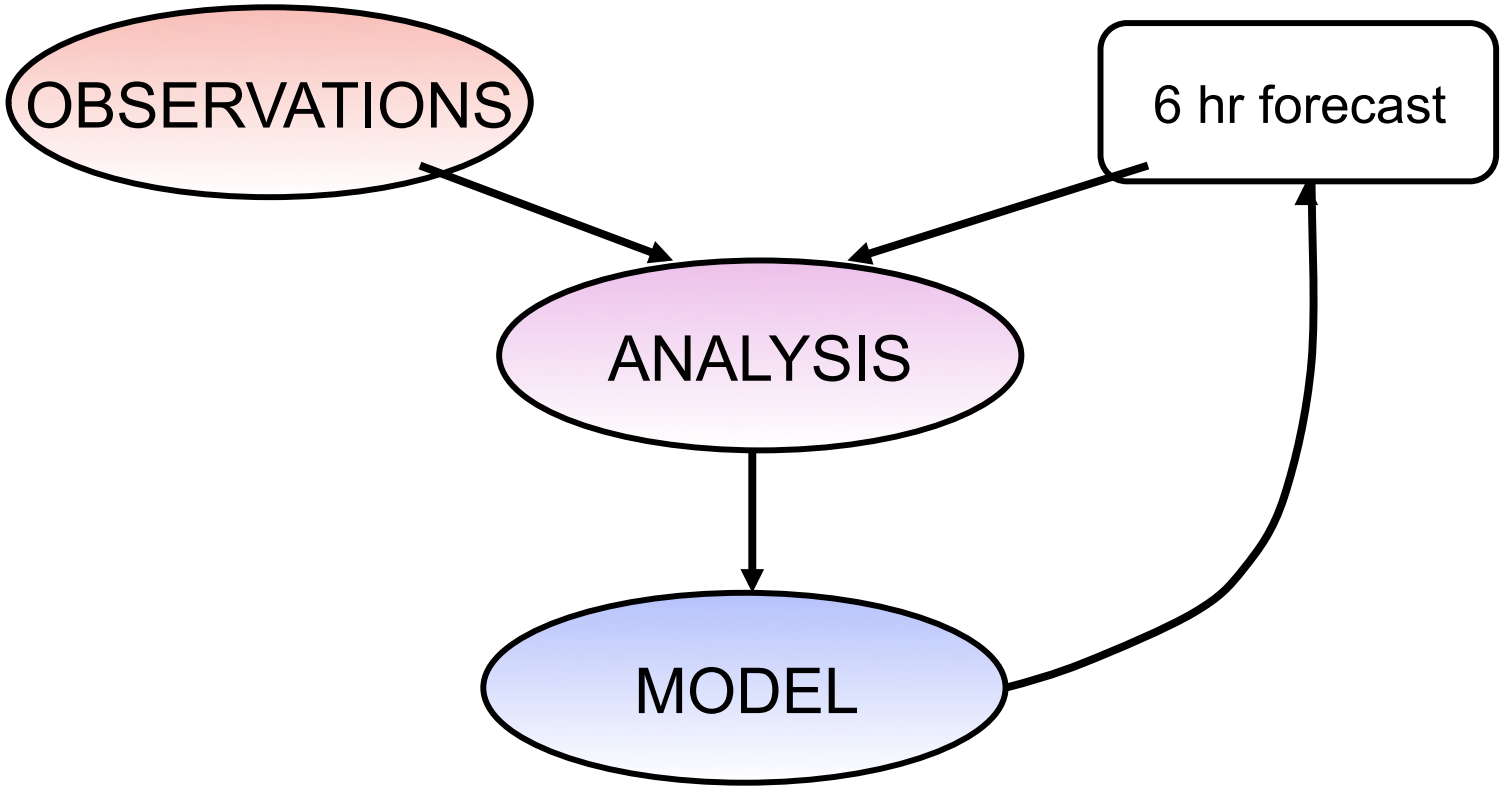
"The forecast improvement accomplishment alone makes the AIRS project well worth the American taxpayers' investment" (Mary Cleave, associate administrator for NASA's Science Mission Directorate).

"This AIRS instrument has provided the most significant increase in forecast improvement in this time range of any other single instrument," (Conrad Lautenbacher, NOAA administrator).

The future

- New data assimilation approach: Ensemble Kalman Filter
- Faster, cheaper, better…
- Whitaker results: it beats operational GSI
- Ability to find observations that are not helping
- Estimating forecast errors

Data Assimilation: We need to improve observations, analysis scheme and model



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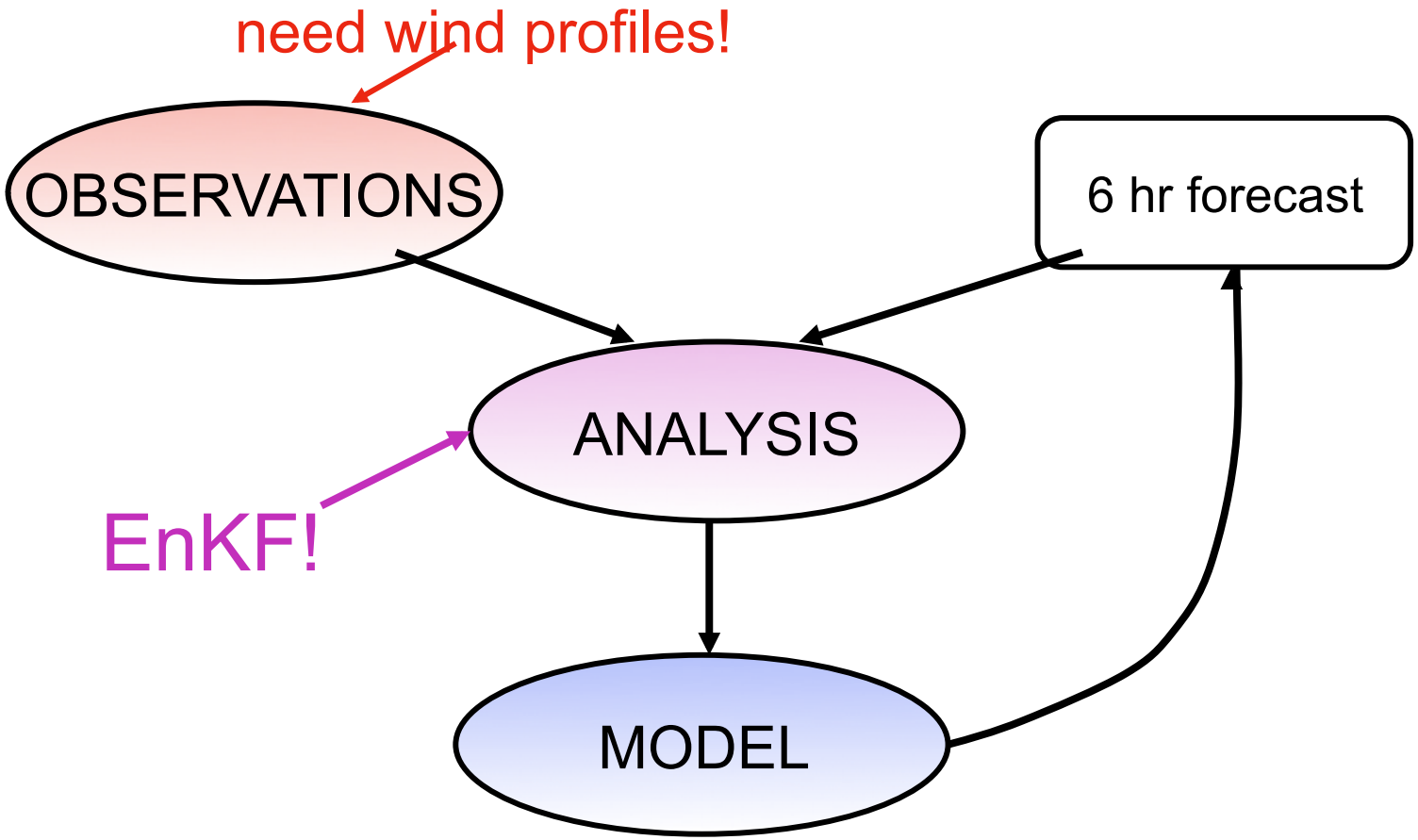
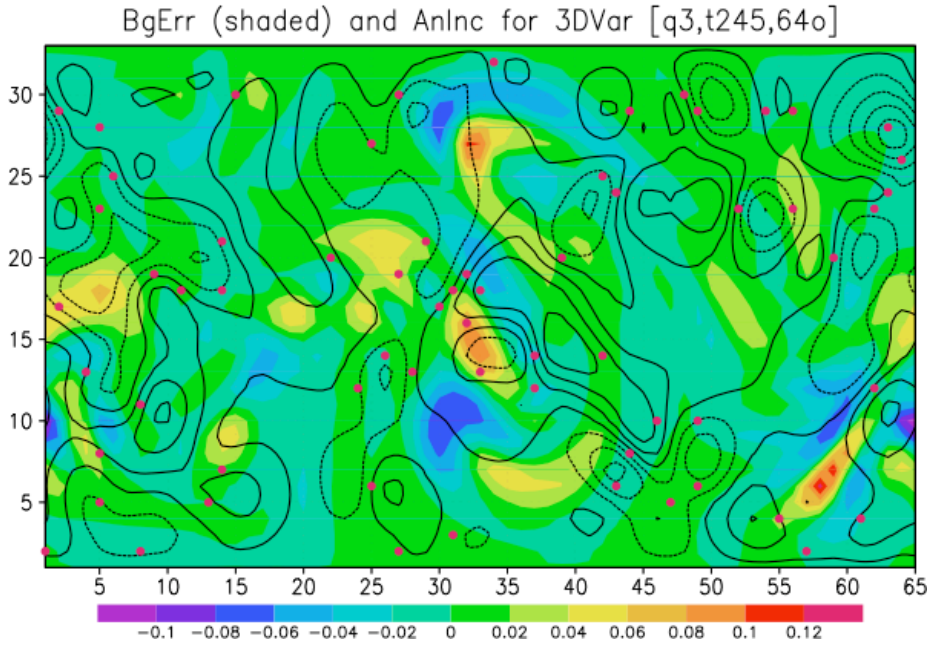
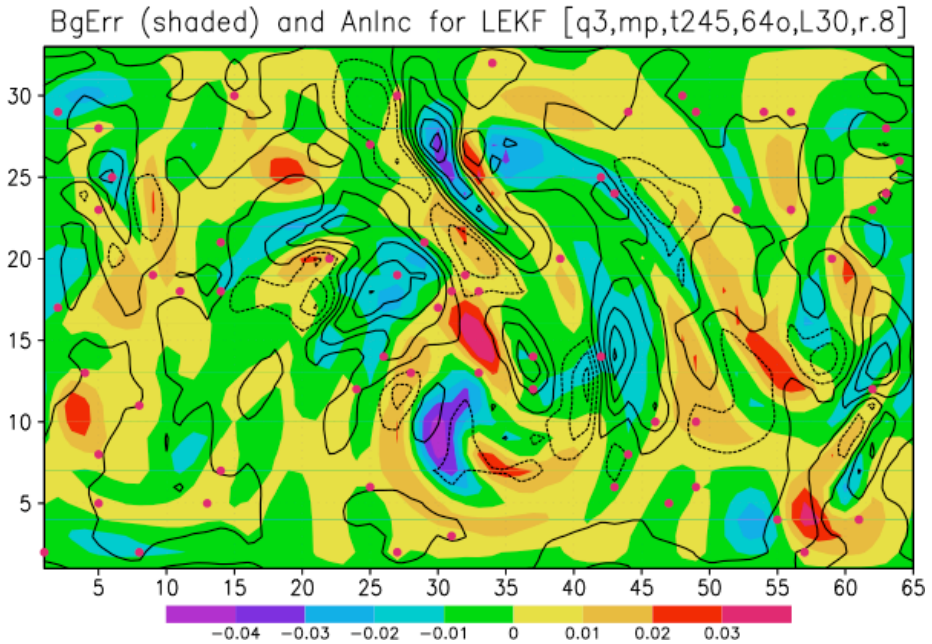


Ensemble Kalman Filter uses obs more efficiently

3D-Var



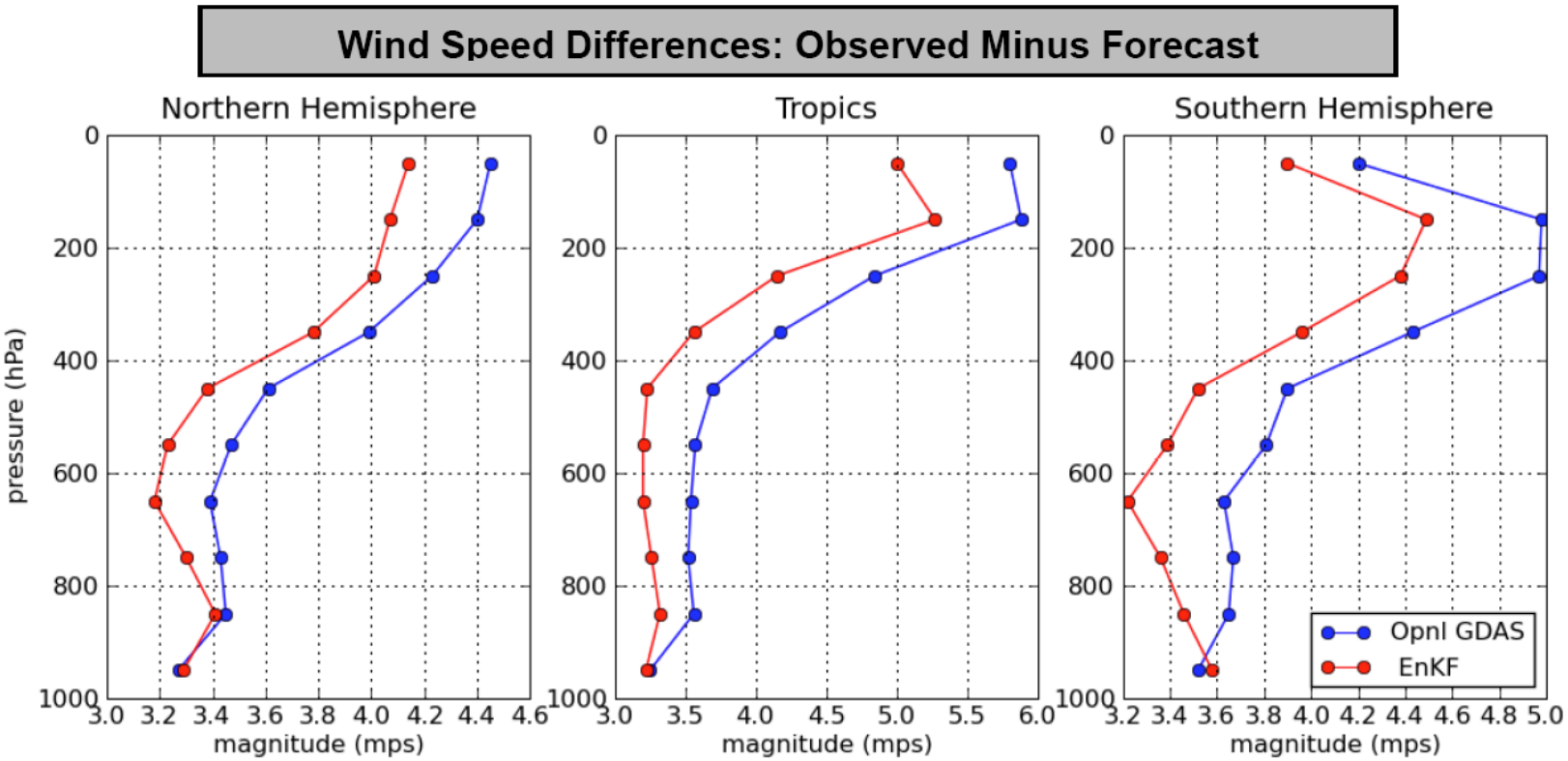
LETKF



The colors show the 12 hour forecast errors (background error), the contours the analysis corrections. The LETKF (an Ensemble Kalman Filter) knows about “the errors of the day” As a result the corrections are stretched like the errors and extract information from the observations much more efficiently

Corazza et al., 2007

Whitaker: Comparison of T190, 64 members EnKF with NCEP T382 operational GSI, same observations

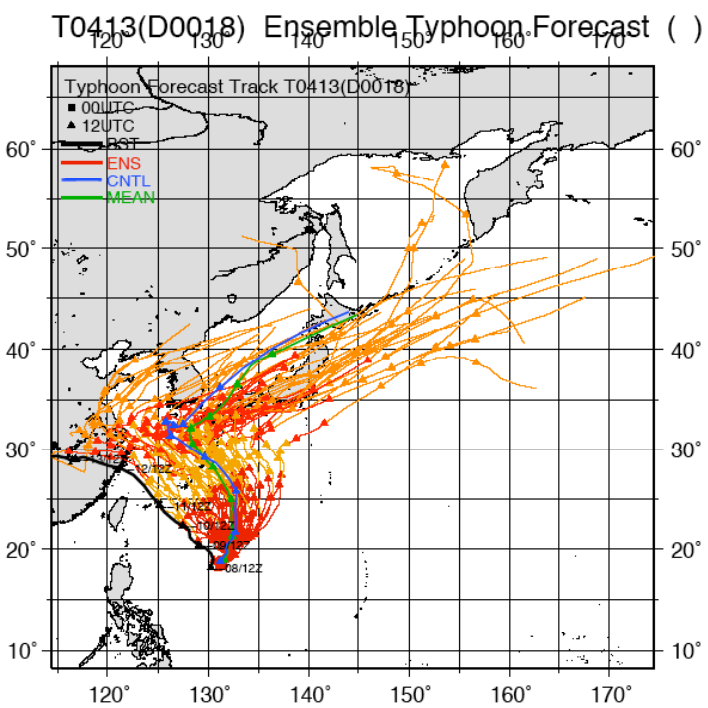


Vertical profiles of the RMS difference between six hour forecasts and in-situ observations for the period 2007120700 – 2008010718. Observations are aggregated in 100 hPa layers. The red curve is for the ensemble mean of the experimental 64-member T190 EnKF system, and the blue curve is for the T382 GSI-based GDAS system operational in December 2007.

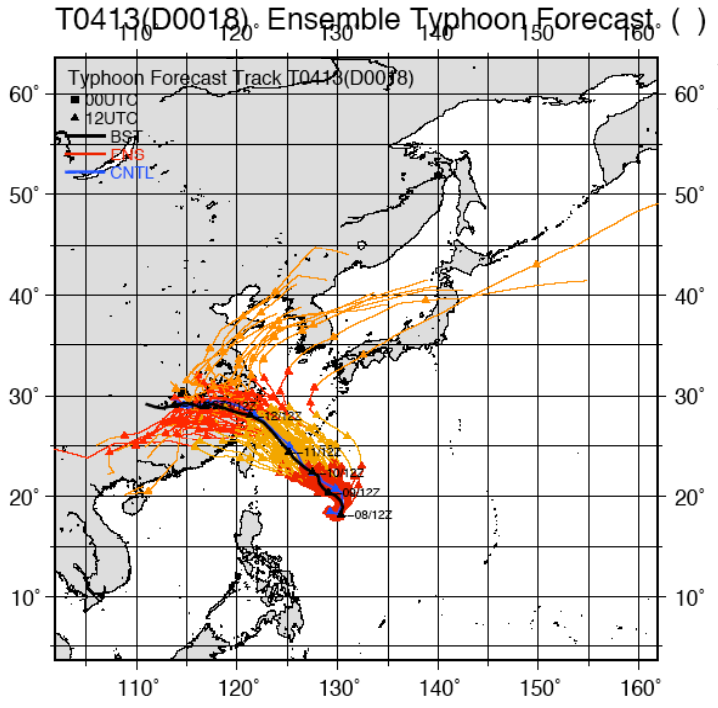
Comparison of 4-D Var and LETKF at JMA

18th typhoon in 2004, IC 12Z 8 August 2004

T. Miyoshi and Y. Sato



Operational 4D-Var



LETKF

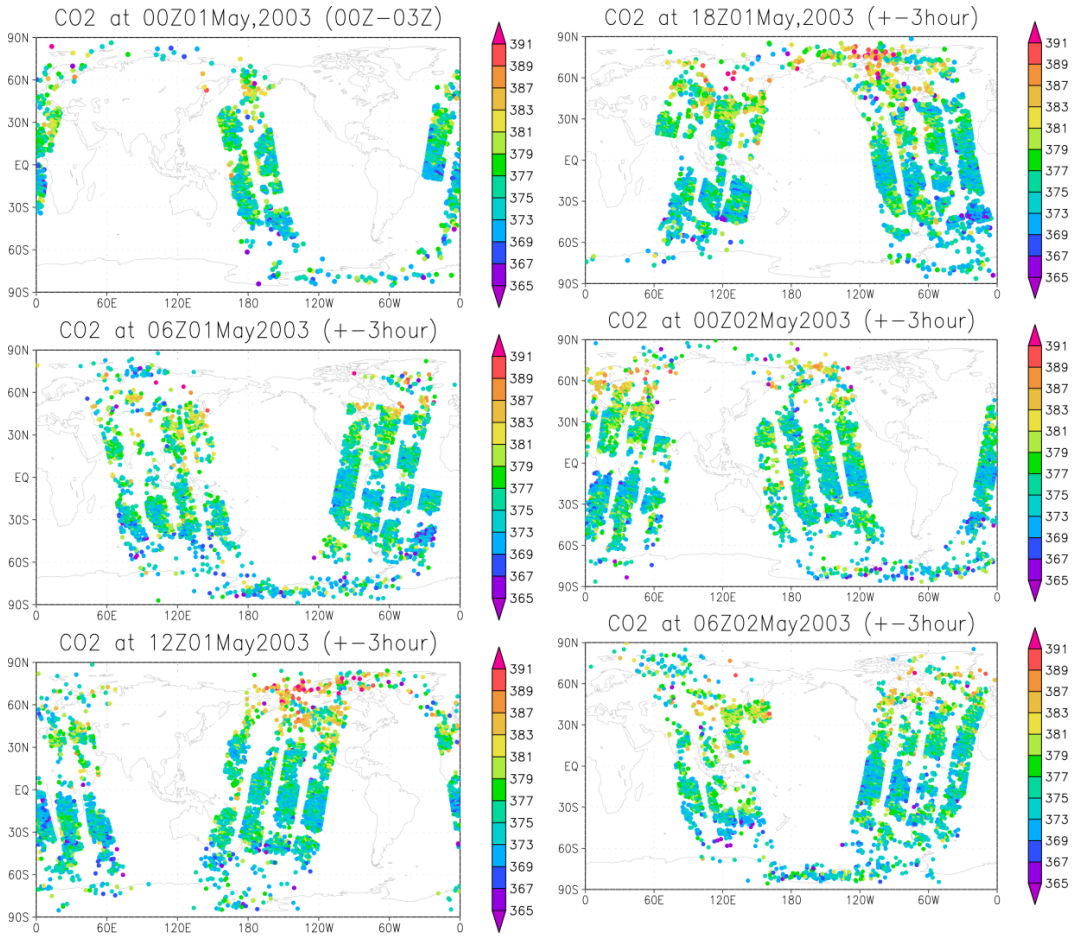
New applications: Assimilate AIRS Level 2 CO_2 with Ensemble Kalman Filter into CAM 3.5

Motivation:

Accurate carbon flux estimation from inversion needs far more CO_2 observations than current surface observations can provide.

Goals:

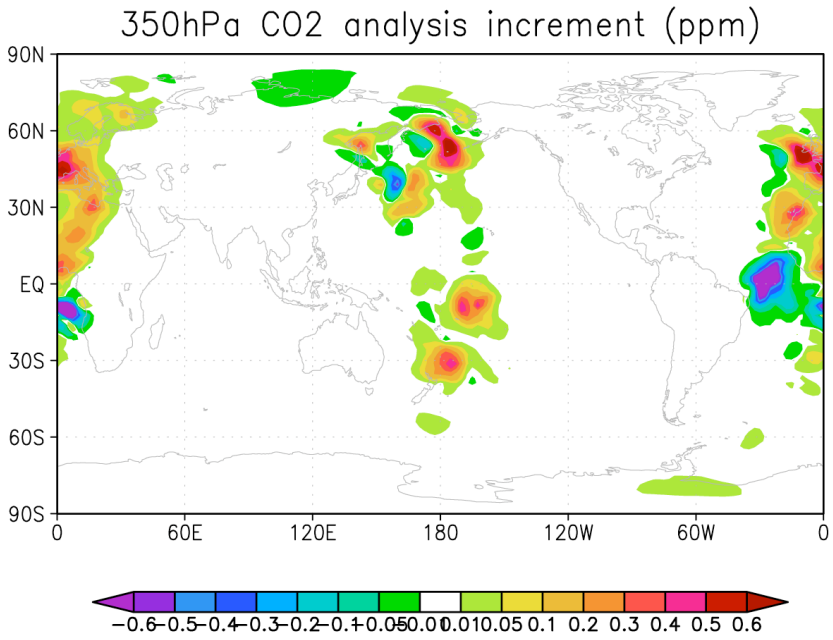
Propagate AIRS CO_2 in both horizontal and vertical directions through data assimilation and transport model



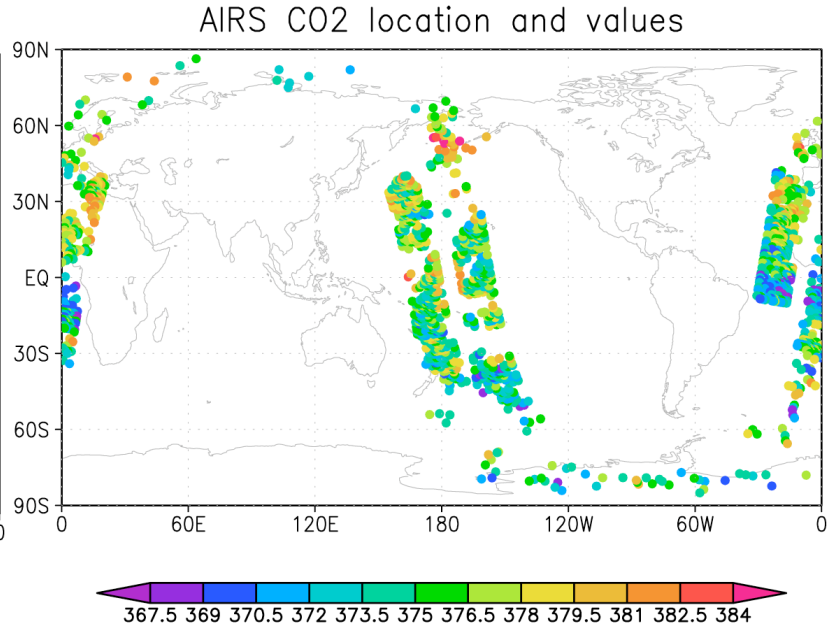
Junjie Liu and Inez Fung (UC Berkeley), Eugenia Kalnay (UMCP)

Single CO_2 Analysis Step
May 2003

350 hPa CO_2 analysis increment (ppm)



CO_2 at 00Z01May2003 (+3hour) after QC

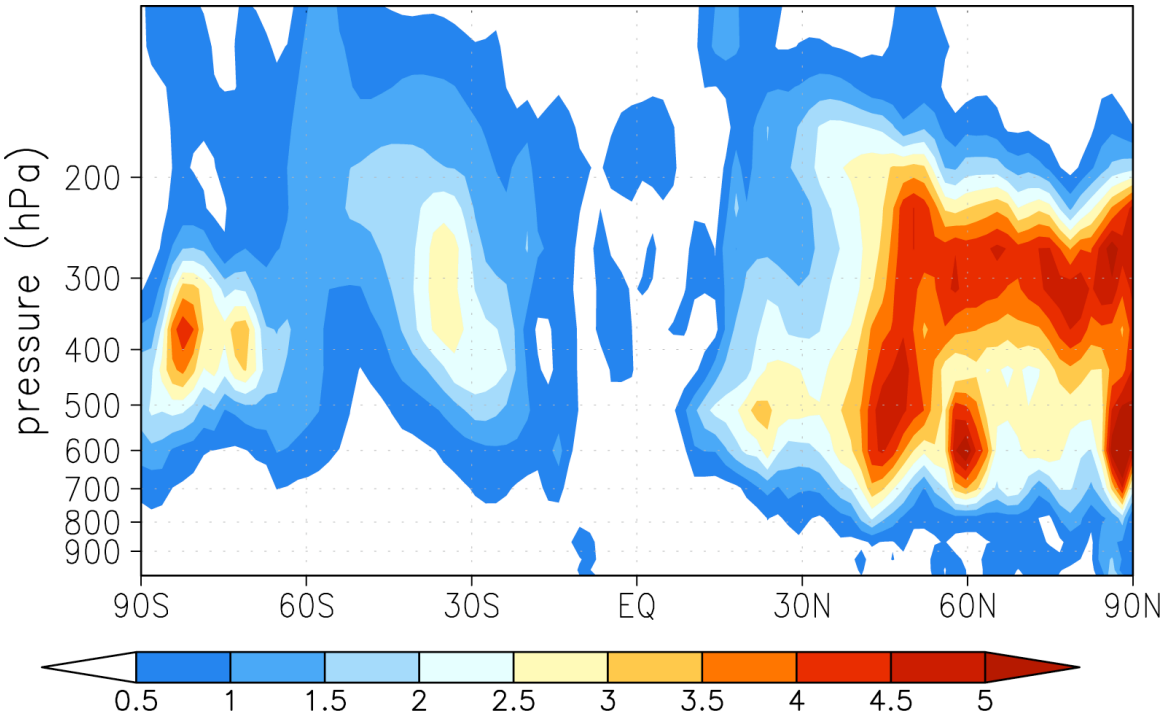


- Analysis increment= analysis - background forecast
- Spatial pattern of analysis increment follows the observation coverage.
- Propagates observation information horizontally knowing “errors of the day”.

Junjie Liu and Inez Fung (UC Berkeley), Eugenia Kalnay (UMCP)

CO_2 Difference between CO_2 Assimilation Run and Meteorological (Control) Run

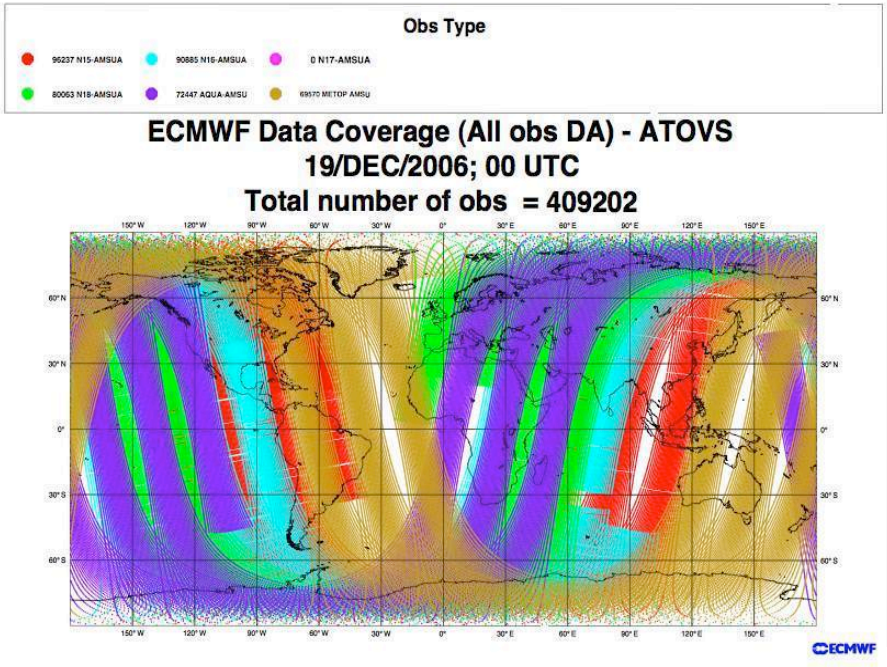
May 2003



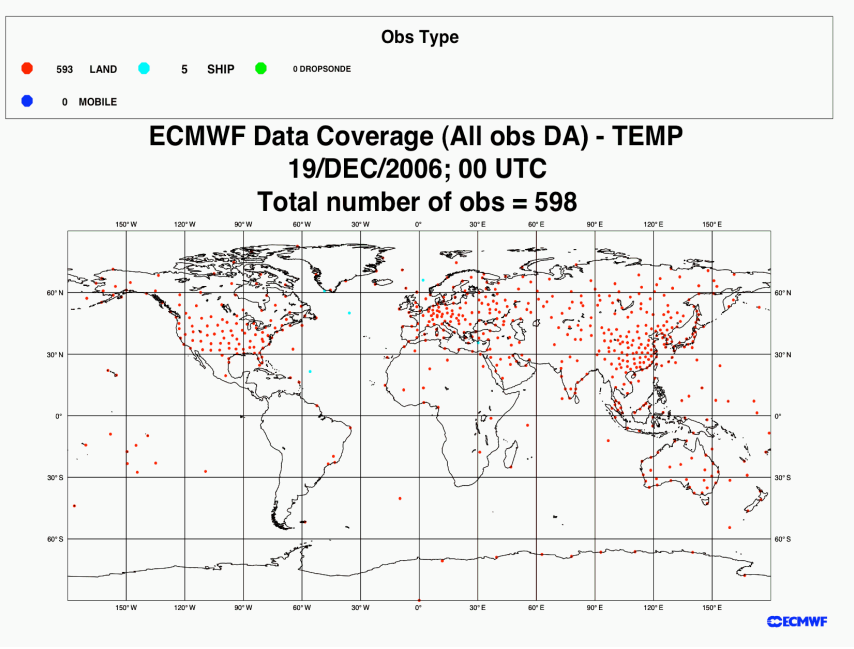
1. Adjustment by AIRS CO_2 spans from 800hPa to 100hPa
2. The adjustment is larger in the NH

Junjie Liu and Inez Fung (UC Berkeley), Eugenia Kalnay (UMCP)

Current Upper Air Mass & Wind Data Coverage



Upper Air Mass Observations



Upper Air Wind Observations

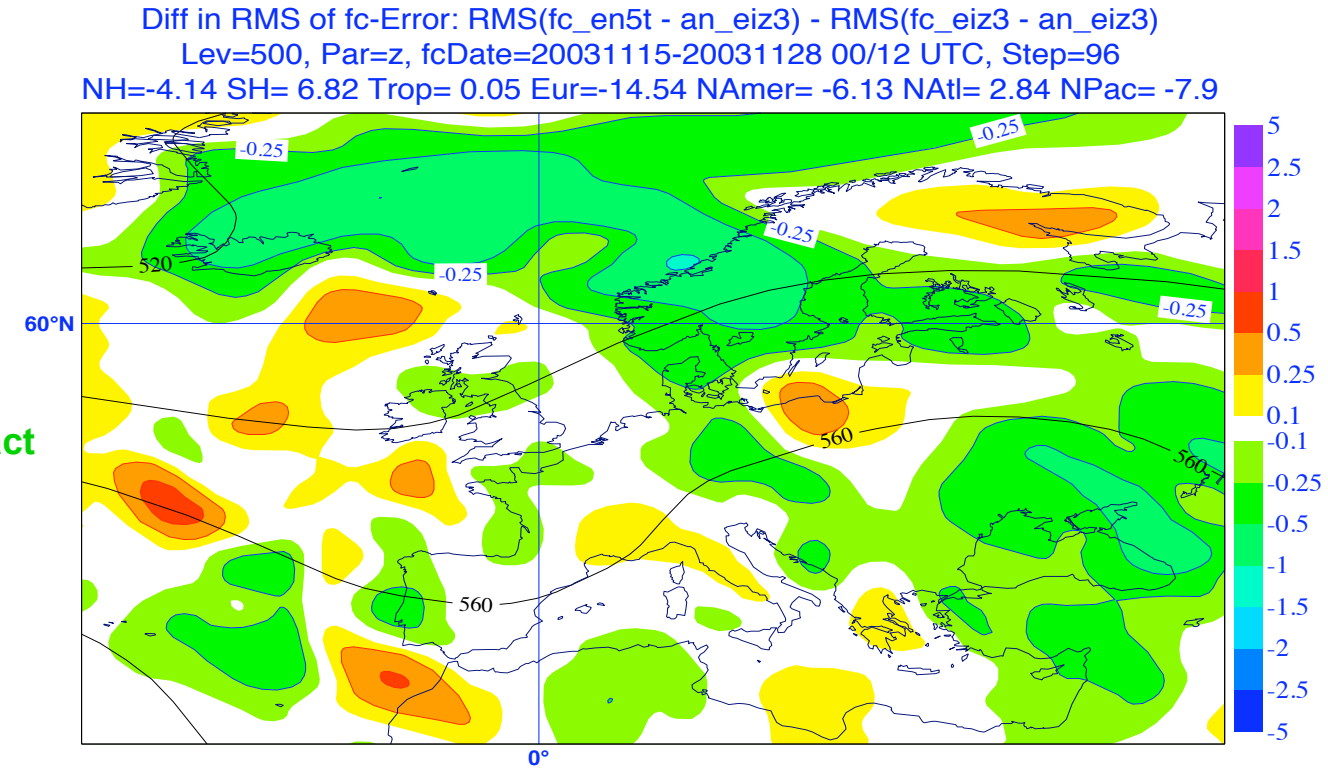
We need wind profiles, especially for the tropics!!!

ECMWF

Forecast Impact Using Actual Aircraft Lidar Winds in ECMWF Global Model (Weissmann & Cardinali, 2007)

- **DWL measurements reduced the 72-hour forecast error by ~3.5%**
- **This amount is ~10% of that realized at the oper. NWP centers worldwide in the past 10 years from *all* the improvements in modelling, observing systems, and computing power**
- **Total information content of the lidar winds was 3 times higher than for dropsondes**

Green denotes a positive impact



Mean (29 cases) 96 h 500 hPa height forecast error difference (Lidar Exper minus Control Exper) for 15 - 28 November 2003 with actual airborne DWL data. The green shading means a reduction in the error with the Lidar data compared to the Control. The forecast impact test was performed with the ECMWF global model.

Summary

- NASA's contribution to NWP has been huge!
- We need to improve data, models and data assimilation
- The most obvious missing obs are wind profiles
- Ensemble Kalman Filter is a very promising, efficient and simple approach that is already better than 3D-Var and competitive with 4D-Var.