Satellite Assimilation Activities At NRL

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Space Sciences Division
NRL, DC

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Stennis, MS

May 1, 2007

Overview

- Use of adjoint methods to assess forecast improvement/degradation due to satellite observations
- Evaluation of DMSP SSMI/S
- Development of NAVDAS-AR (Weak Constraint 4D-Var)
- Satellite assimilation upgrades and development
- Observing System Experiments: assessing the relative contributions of forecast model, data assimilation improvements over the past 10-15 years.
- Aerosol assimilation
- Ocean data assimilation

Naval Research Laboratory (NRL)

- ***Monterey – Marine Meteorology Division***
  - **research and development of global, mesoscale and shipboard atmospheric analysis and prediction systems**
- ***Washington, D.C. – Remote Sensing and Space Sciences Divisions***
  - **Upper atmosphere assimilation and modeling**
  - **Designed and built POAM and WindSat**
  - **Ozone Chemistry (NOGAPS and GFS)**
- ***Stennis Space Center, MS – Ocean Division***
  - **Ocean data assimilation and modeling**

Primary customer is Fleet Numerical Meteorology and Oceanography Command (FNMOC)

- Provides weather support for Navy and Marine Corps, Air Force and other DoD activities
- Produces and distributes products from numerical prediction models of the ocean and atmosphere

Approved for public release

NRL/FNMOC Forecast Suite

- NOGAPS - Navy Operational Global Atmospheric Prediction System
  - Spectral T239, L30 with effective model top at 4 hPa
  - Provides input/boundary conditions for
    - mesoscale, ocean, wave and ice prediction models,
    - ensemble forecasting system
    - Aircraft and ship routing programs
    - tropical cyclone forecast model (GFDN)
  - Used for basic research predictability studies, adjoint sensitivity studies, adaptive observation-targeting

- COAMPS®* - Coupled Ocean/ Atmosphere Mesoscale Prediction System
  - nonhydrostatic; globally relocatable, nested grids; explicit prediction of moisture variables
  - 5-10 different operational areas

* COAMPS® is a registered trademark of the Naval Research Laboratory, Monterey CA

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NRL/FNMOC Analysis Systems

- NAVDAS – NRL Atmospheric Variational Data Assimilation System
  - 3dvar observation space algorithm
  - Designed to be precursor for NAVDAS-AR, our 4d accelerated representer assimilation system
  - Unified code for both global and mesoscale NWP systems
    - Operational for NOGAPS on October 1, 2003
    - Operational for COAMPS® October, 2006
  - Adjoint of NAVDAS is used for observation impact studies

- NAVDAS-AR is under development
  - Observation space 4D-Var using cycling representer method
  - “AR” stands for accelerated representer
  - Targeting late 2008 for implementation into NOGAPS

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Assessing observation value with adjoints

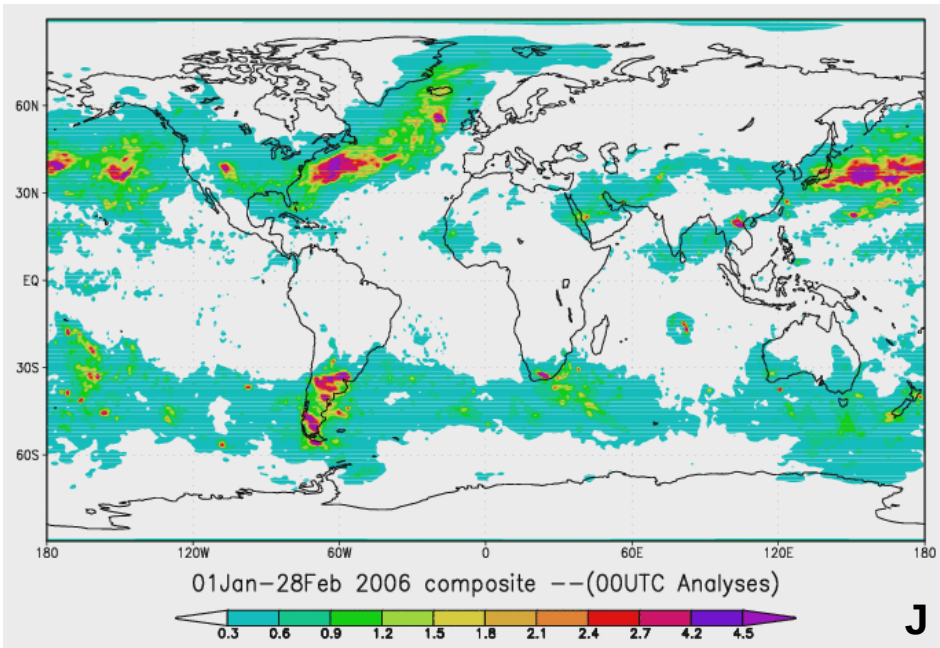
- Use NAVDAS and NOGAPS adjoint models
- Observation impact is routinely generated once per day at 00 UTC
  - Operational analysis fields and operational innovation vectors from NAVDAS / NOGAPS are used
  - Also computed for FNMOC parallel OPS system
- Observation impact generated for specific Observing System Experiments (AIRS, SSMIS)
- Results are used to
  - evaluate observation quality
  - tune observation reject lists
  - guidance for modifying assimilation procedures
  - Select AIRS channels for assimilation

Baker and Daley (QJRMS, 2000)
Langland and Baker (Tellus, 2004)

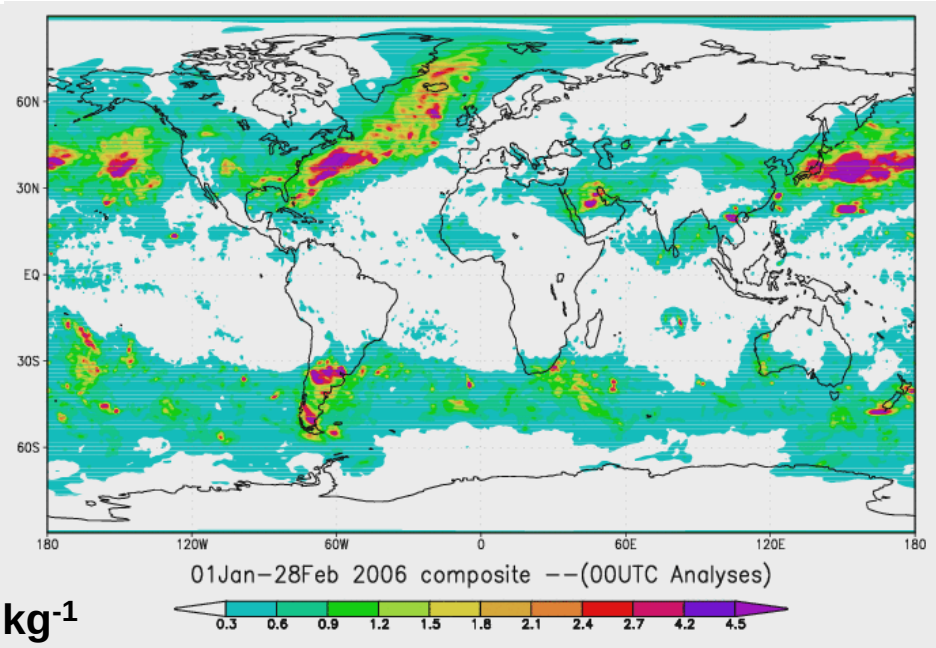
NOGAPS: Sensitivity of Forecast Error to Initial Conditions

1 Jan – 28 Feb 2006

Energy-weighted sensitivity of e_{24} to x_a 00UTC

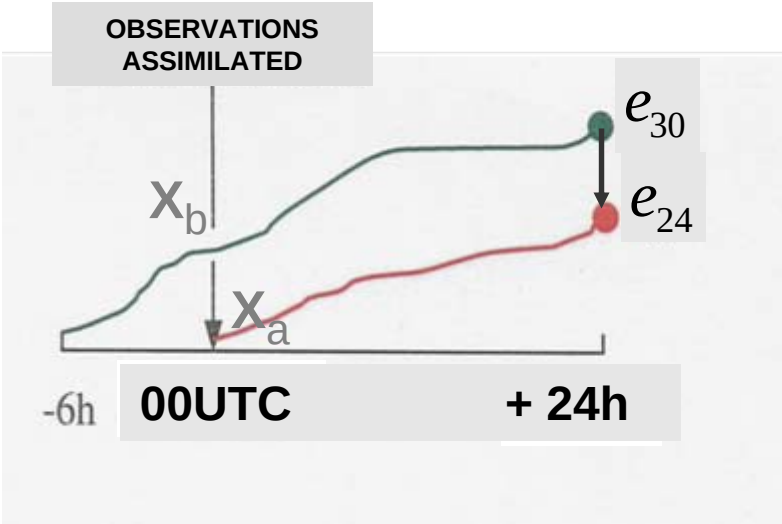


Energy-weighted sensitivity of e_{30} to x_b 18UTC



J kg^{-1}

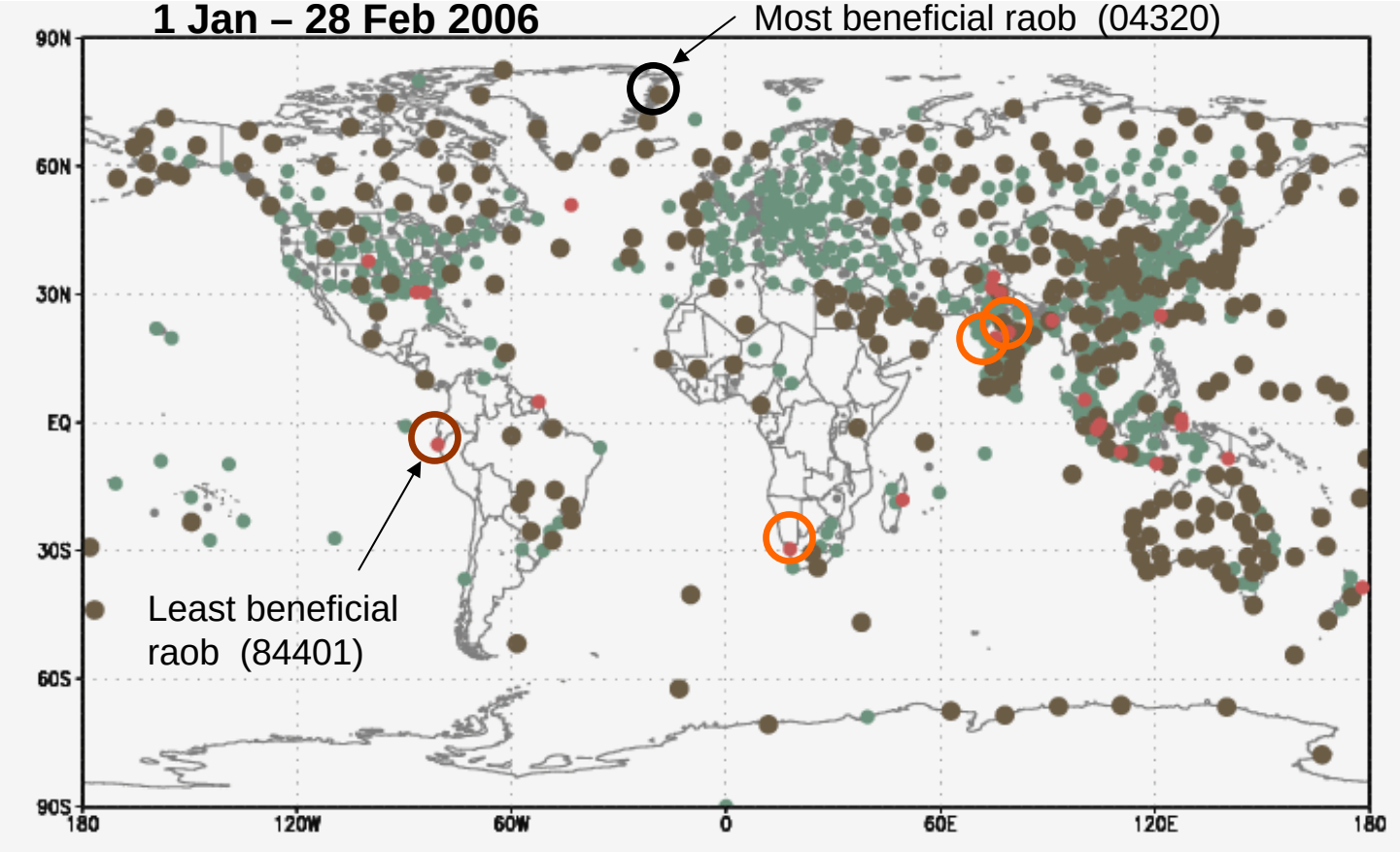
Observations, model trajectories and forecast error



Observations move the model state from the "**background**" trajectory to the new "**analysis**" trajectory

The forecast error difference, $e_{24} - e_{30}$, is due to the combined impact of all observations assimilated at 00UTC

Radiosonde profile observation impact



On recent UKMO blacklist

- Most beneficial (< - 0.1 J kg^{-1})
- Beneficial (-0.01 to -0.1 J kg^{-1})
- Non-beneficial (0.01 to 0.1 J kg^{-1})

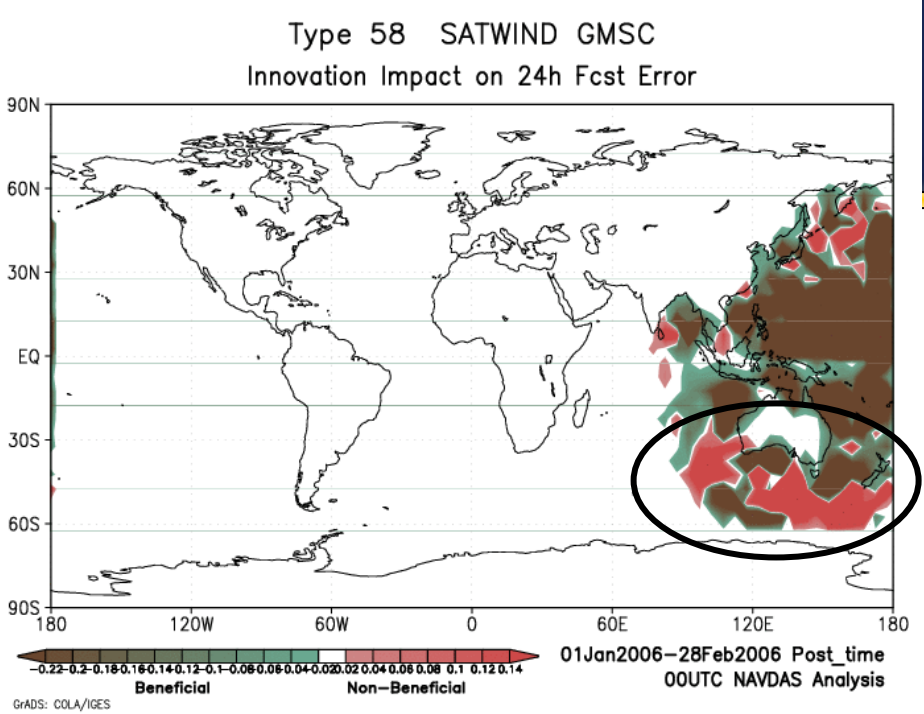
Combines all separate temperature, wind, moisture, and height impacts at all levels of radiosonde profile

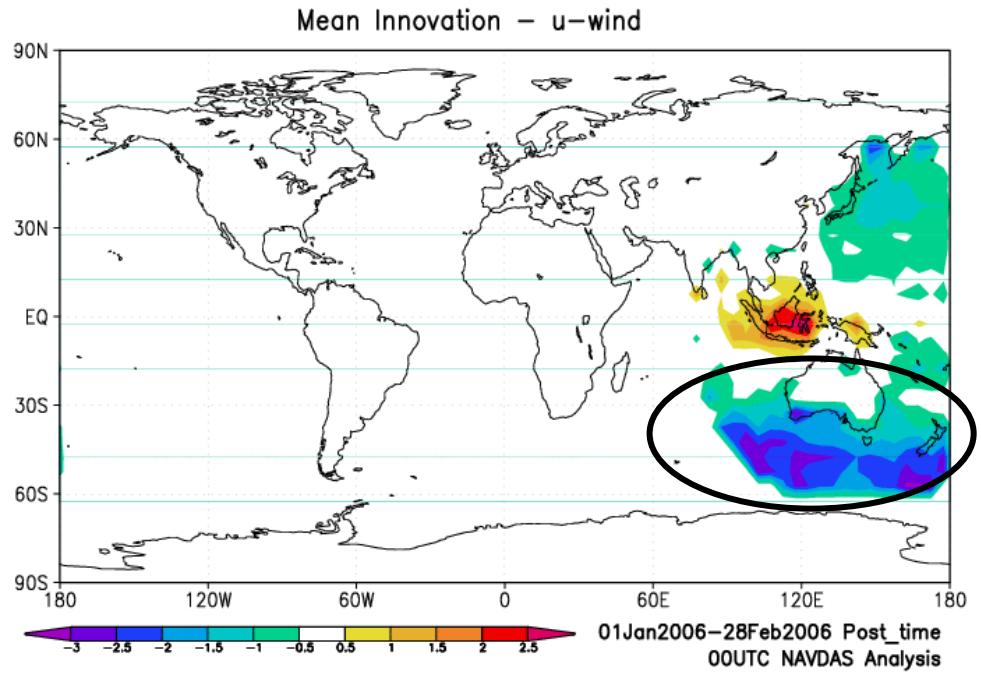
SATWIND data denial experiment

Date: Jan-Feb 2006

Issue: Large innovations and non-beneficial impact from satwinds at edge of coverage areas

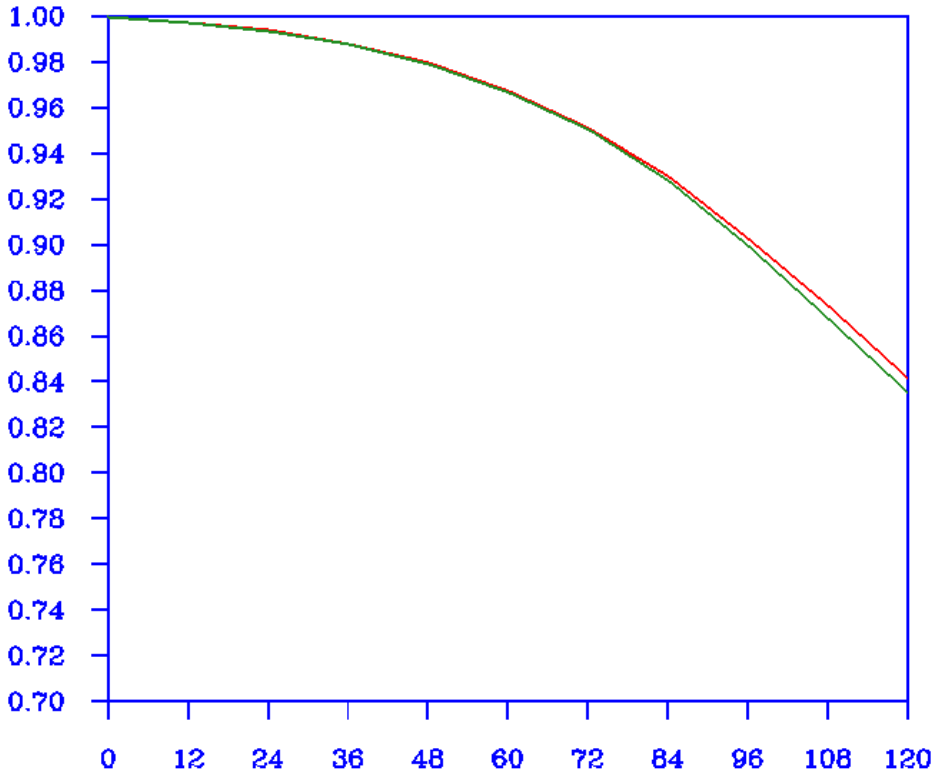
Action Taken: Ob data removed if > 39° from satellite sub-point – gave 3-hr improvement in SHEM NOGAPS forecast skill



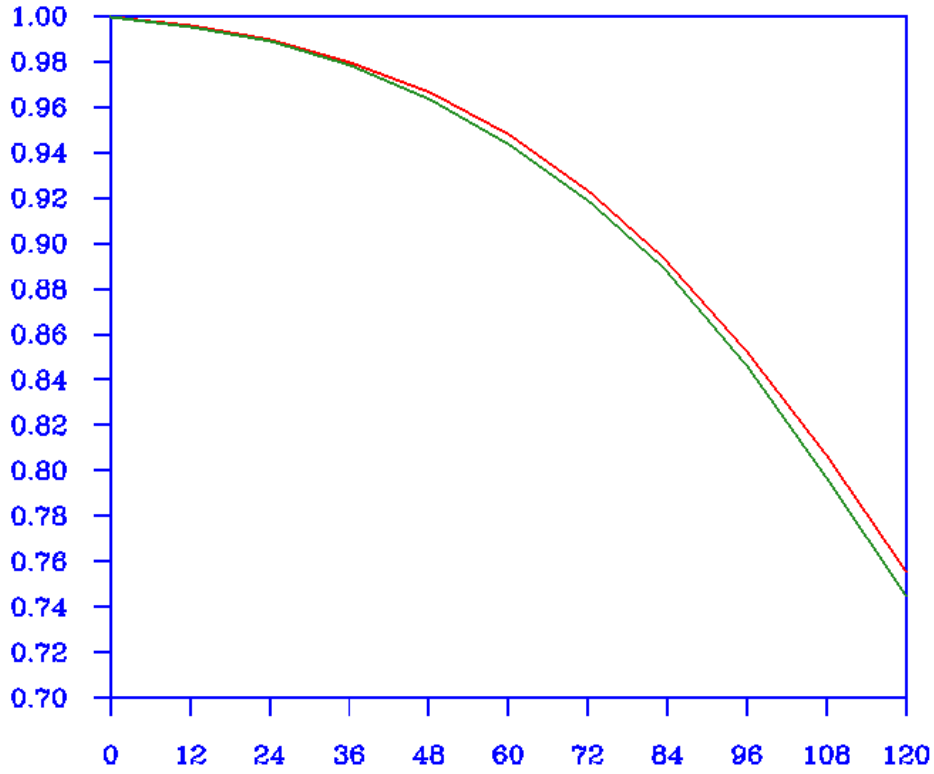


Restricting SSEC MTSAT Winds
500 mb Height Anomaly Correlation

Northern Hemisphere



Southern Hemisphere

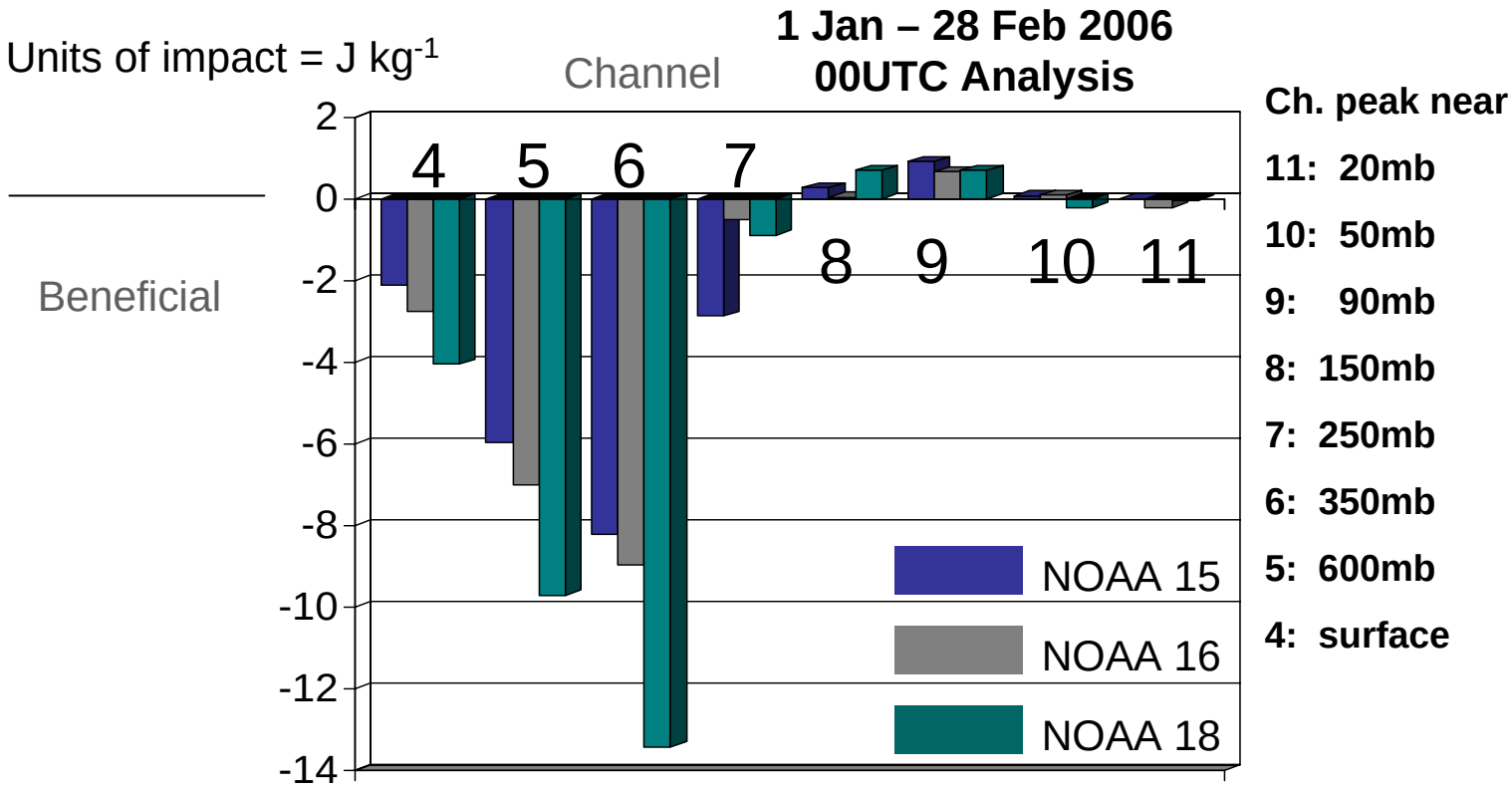


Restricted Winds

Control

February 16 – March 27, 2006

Impact for AMSU-A channels



Results suggest a problem with assimilation of ch 8 and 9
Likely sources are the operational bias correction and insufficient model and analysis resolution

Data Assimilation

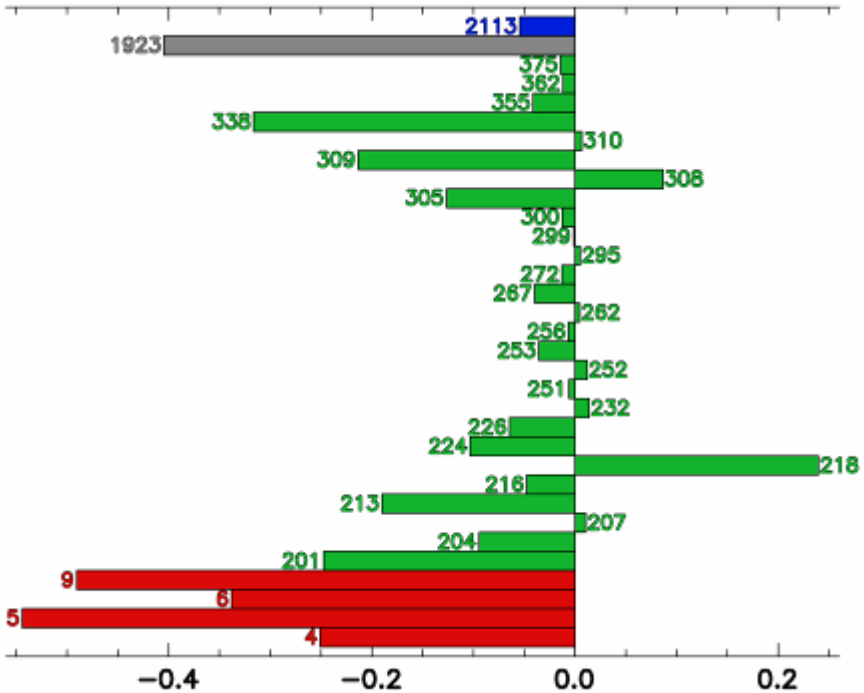
Use of NAVDAS Adjoint

Assessment of AQUA sensors

AMSU/A, AIRS longwave 14-13μm,

AIRS shortwave 4.474μm, AIRS shortwave 4.180μm

AQUA sensitivity specified by channel number: Aug 15-26, 2006



Beneficial **Non-beneficial**

SSMIS Radiance Preprocessor

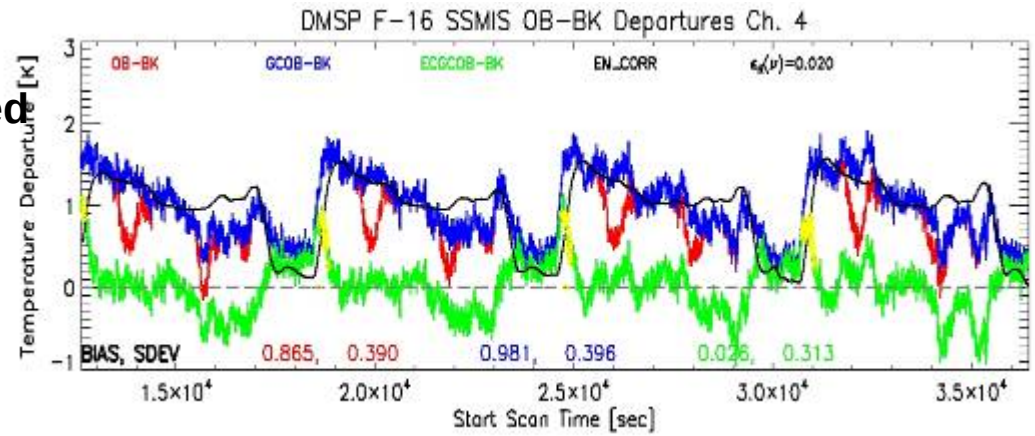
Unified SSMIS Radiance Preprocessor for NWP

Why is it Important ?

- Significant SSMIS Calibration Anomalies uncovered during Cal/Val
- Calibration errors exceed accuracy thresholds for NWP (~0.25K for temperature sounding channels)
- Objective is to develop a unified radiance preprocessor for NWP/JCSDA users to correct for calibration anomalies
- Implementation of unified SSMIS Preprocessor at FNMOC for F-16 planned for late summer 2007
- Data will be distributed via Shared Processing Network

NRL Collaborations

- SSMIS Cal/Val Team – Determined physical mechanisms responsible for SSMIS Calibration Anomalies
- Met Office – SSMIS BUFR Based Preprocessor
- JCSDA – Discussions about alternative NESDIS preprocessor algorithms
- ECMWF – Provides Analyses of T(p) to 0.01 hPa ~ 80 km



SSMIS Upper Atmosphere Capabilities

NRL Middle Atmosphere (40 – 80 km) Data Assimilation

Why is it Important ?

- **Extend NWP predictability**
- **Analyze and Forecast Stratospheric O_3 and related constituents and their role in Global Warming**
- **Provide correlative measurements for new satellite systems**
- **DoD Specific Interests – high altitude vehicles, communications, missile defense, intel**
- **SSMIS pre-processor will provide calibration anomaly corrected radiances**

NRL Collaborations

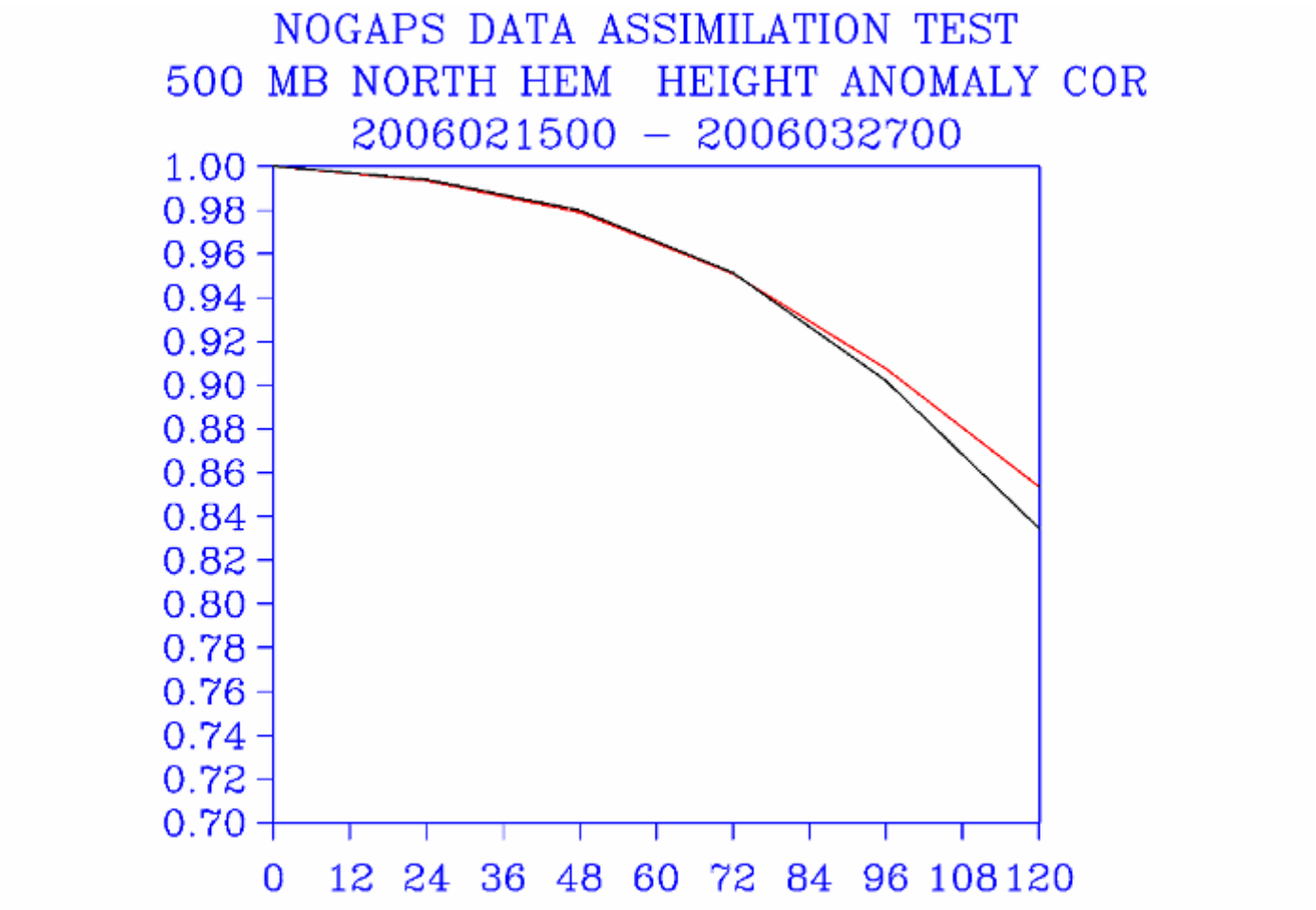
- **JCSDA – Fast Upper Atmosphere Radiative Transfer Model with Zeeman Effects – CRTM-Z**
- **ECMWF – Provides Analyses of T(p) to 0.01 hPa ~ 80 km**
- **Met Office – SSMIS Anomaly Mitigation efforts**
- **NASA JPL – Lidar Temperature Profiles for verification**

NAVDAS-AR*

- NRL developed NAVDAS-AR, an observation space, weak-constraint four-dimensional data assimilation system
- We plan to transition to FNMOC for operational implementation at the end of FY08
- The adjoint of NAVDAS-AR is readily developed, allowing for an assessment of the impact of observations on forecast accuracy to be evaluated
- NASA is considering adapting NAVDAS-AR

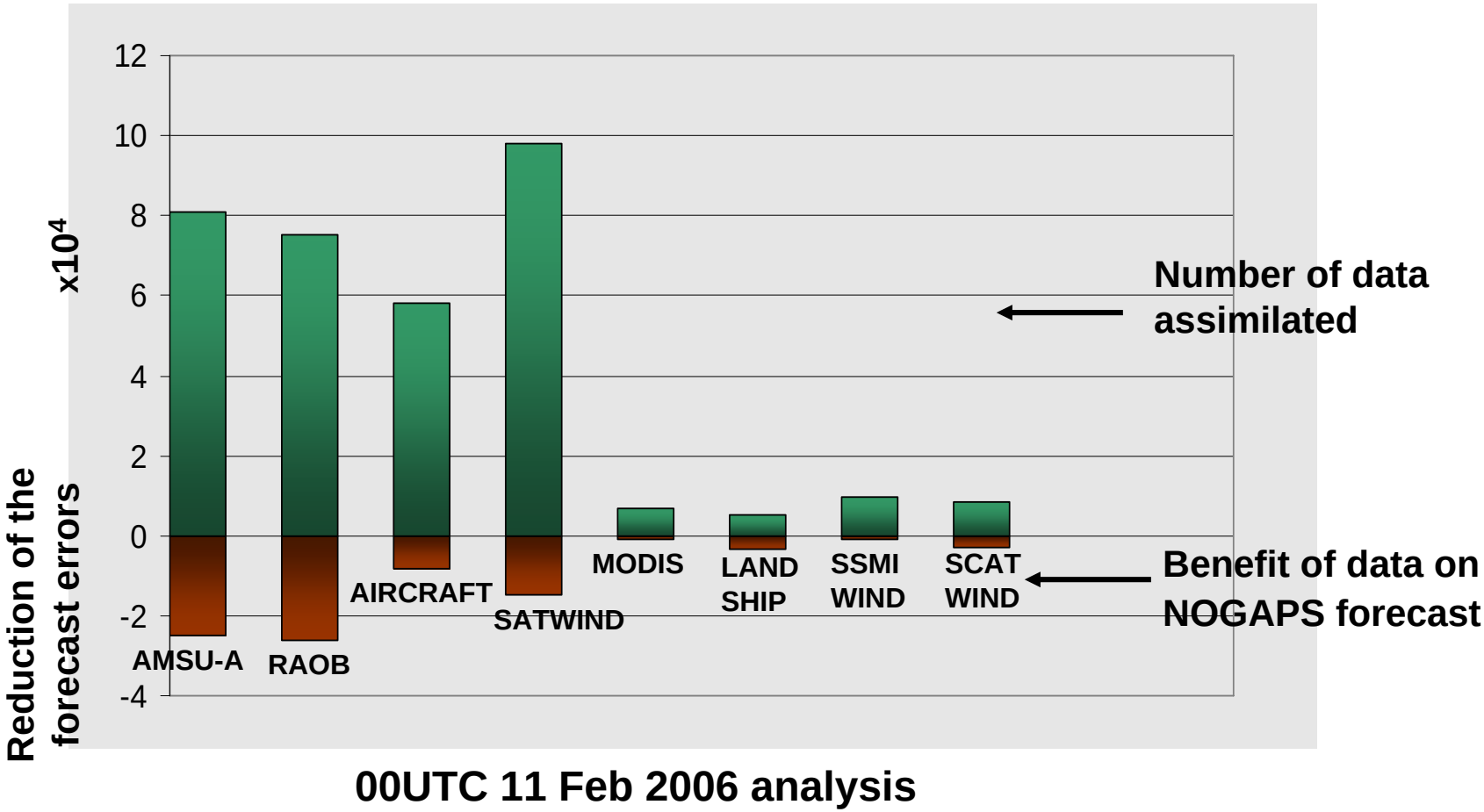
* Accelerated Representer

Preliminary Results for 06 Winter 'AR' vs. OPS



Forecasts produced with NAVDAS-AR are better than the ones produced with the FNMOC OPS for the winter of 2006.

Observation Impact in NAVDAS-AR / NOGAPS



00UTC 11 Feb 2006 analysis

The new adjoint of "AR" provides an unique capability to examine the temporal aspect of observation sensitivities.

Satellite Assimilation Status

- **Operational**
  - AMSU-A operational (3 NOAA satellites)
  - Geostationary satellite winds – vis, IR and WV
  - MODIS polar winds (including direct broadcast winds)
  - WindSat vector winds and TPW
  - DMSP SSMI and SSMIS wind speed and TPW
  - QuikScat and ERS scatterometer wind vectors
- **Awaiting transition to OPS**
  - CRTM, new bias correction, AMSU from AQUA and METOP
  - AQUA AIRS
  - SSMIS
  - Assimilation of MW and IR radiances over land
  - NOAA AMSU-B and MHS
  - HIRS
- **Research assimilation**
  - Upper atmosphere channels of SSMIS
  - MLS temperature, water vapor and ozone
  - CHAMP and COSMIC GPS
  - METOP IASI, MHS

Data Assimilation

1dvar Preprocessor

Land surface emissivity retrieval

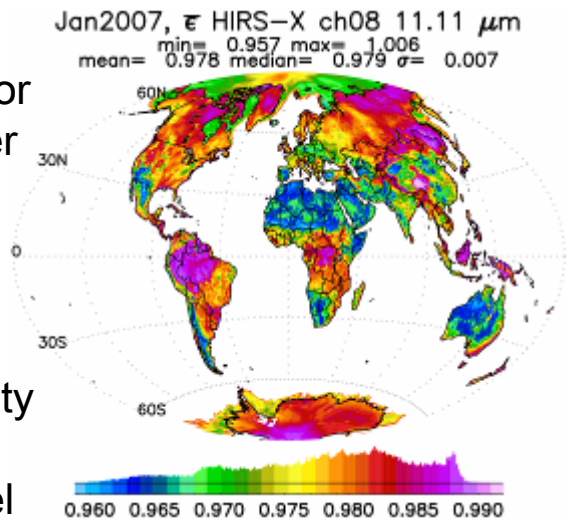
- NRL developed a combined microwave and IR 1dvar preprocessor to retrieve MW and IR emissivity over land

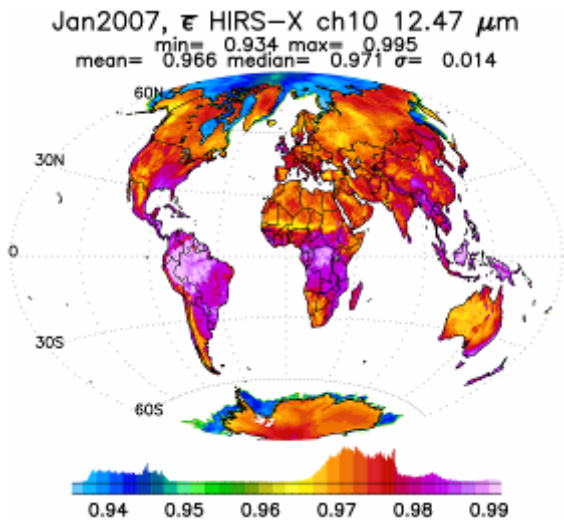
- One year climatology

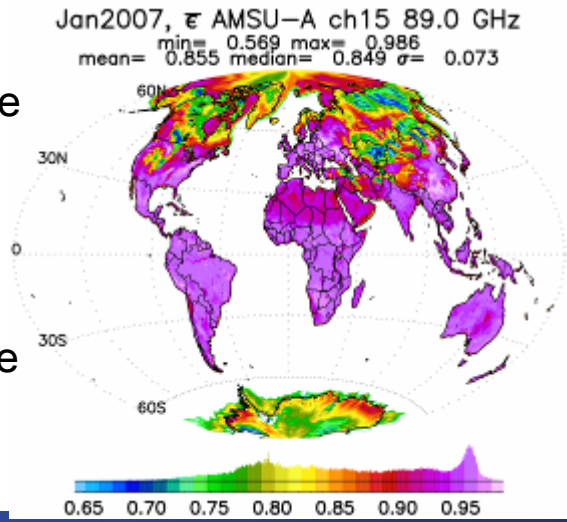
- Used to access Microwave Emissivity Model (MEM) included in JCSDA Community Radiative Transfer Model (CRTM)

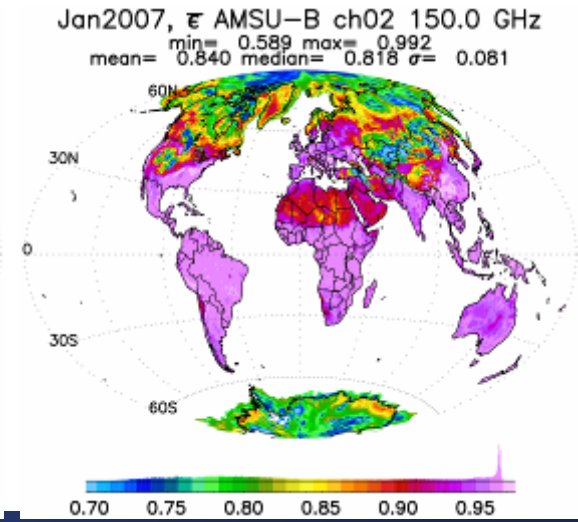
- Ability to assimilate surface-sensitive sounding & imaging channels over land

- Improved description of boundary layer (LST, temperature and moisture at 2m), land-sea breezes, and convective initiation

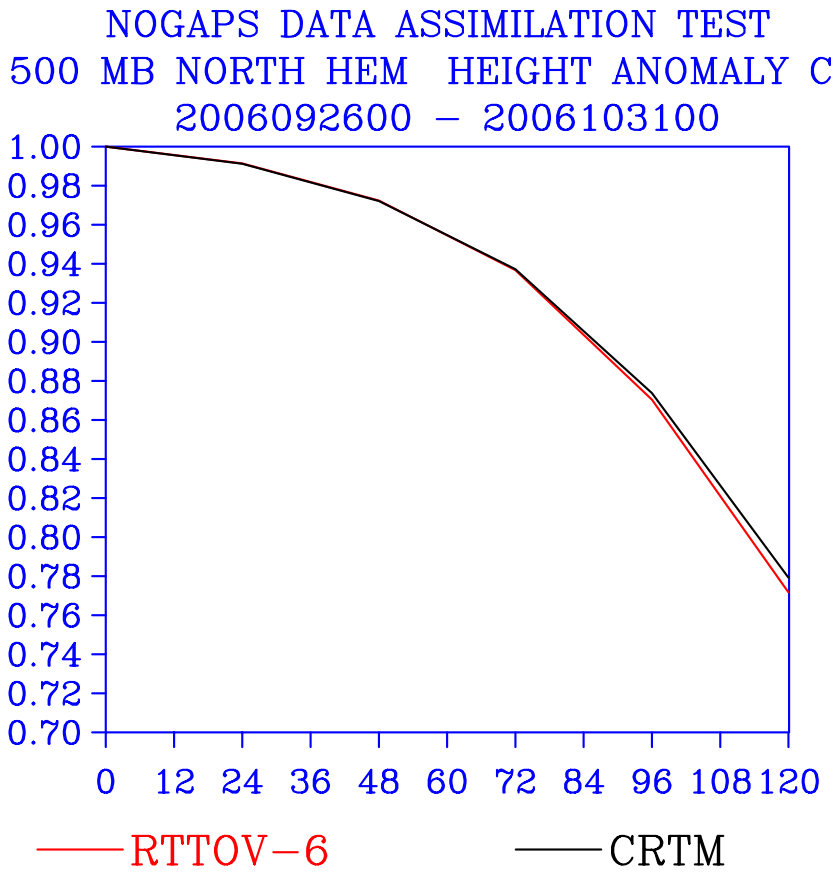




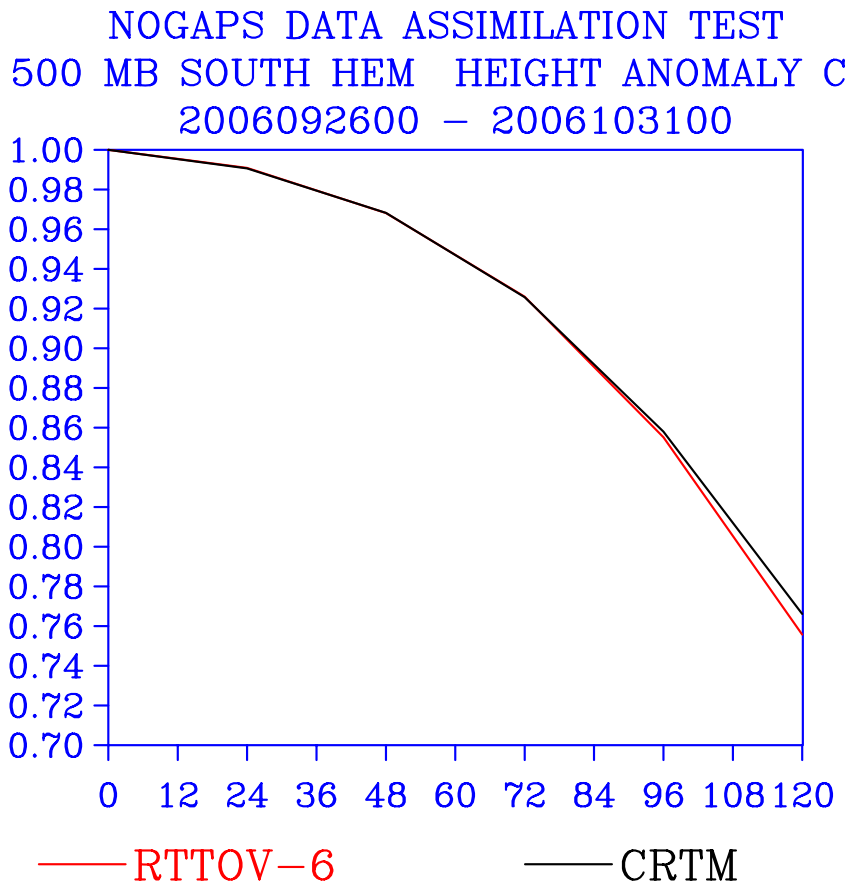




"CRTM" Impact
500 mb Height Anomaly Correlation



Northern Hemisphere

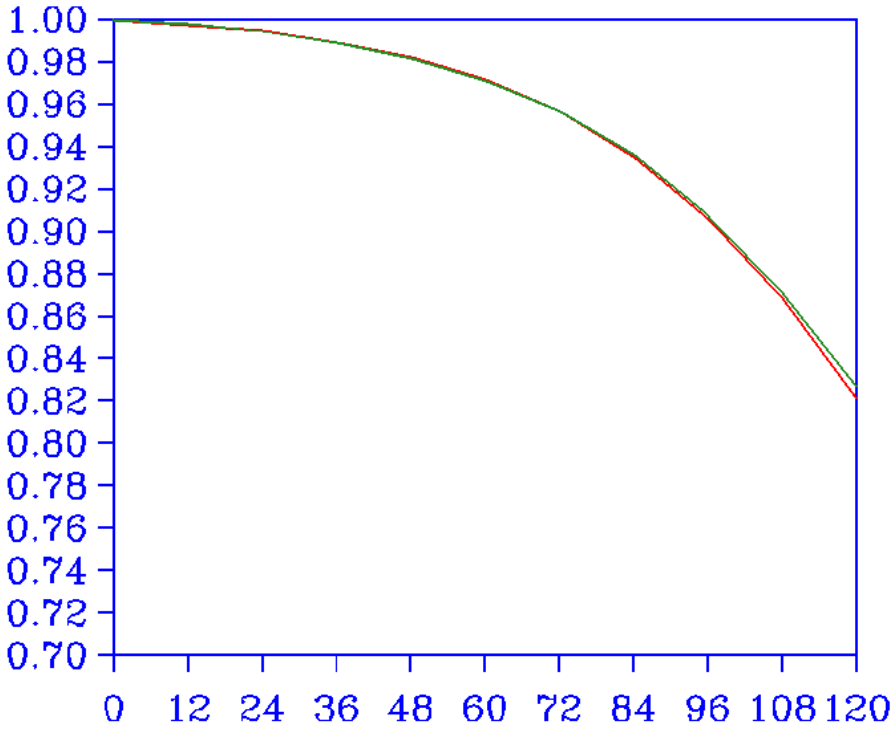


Southern Hemisphere

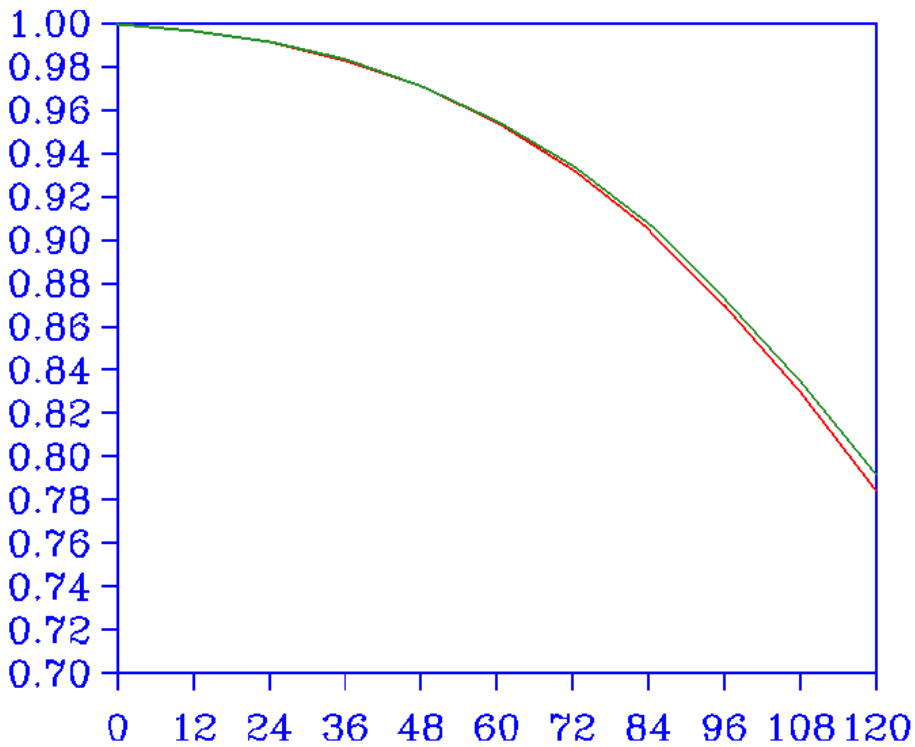
September 26 - October 19, 2006

WindSat Impact
500 mb Height Anomaly Correlation

Northern Hemisphere



Southern Hemisphere



WindSat

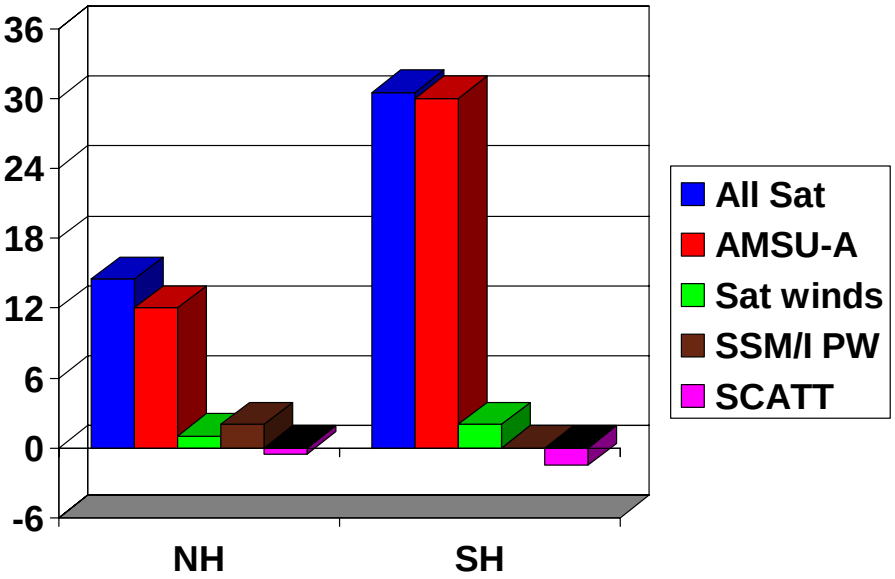
No WindSat

November 8 - 24, 2006

Model versus Initial Condition

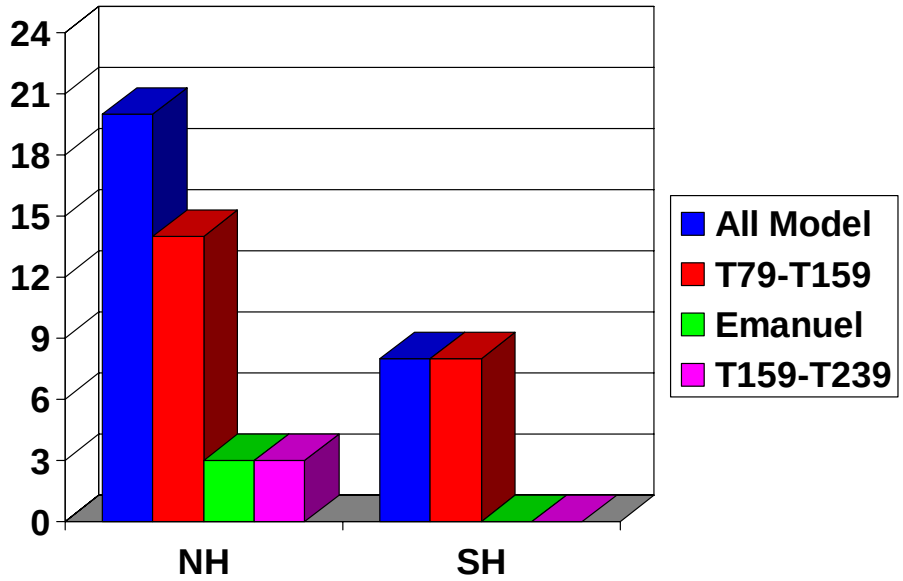
- Observing System Experiments
- Current operational NOGAPS/NAVDAS data assimilation system
  - Different combinations of observational data
  - Different configurations of the NOGAPS global spectral model
- August 14-September 30, 2004
- Active period with 12 hurricanes, 5 typhoons, and 7 tropical storms
- Evaluated tropical cyclone forecast track error and extra tropical forecast skill

Extra-tropical 120-h Forecast Improvement (Hours)

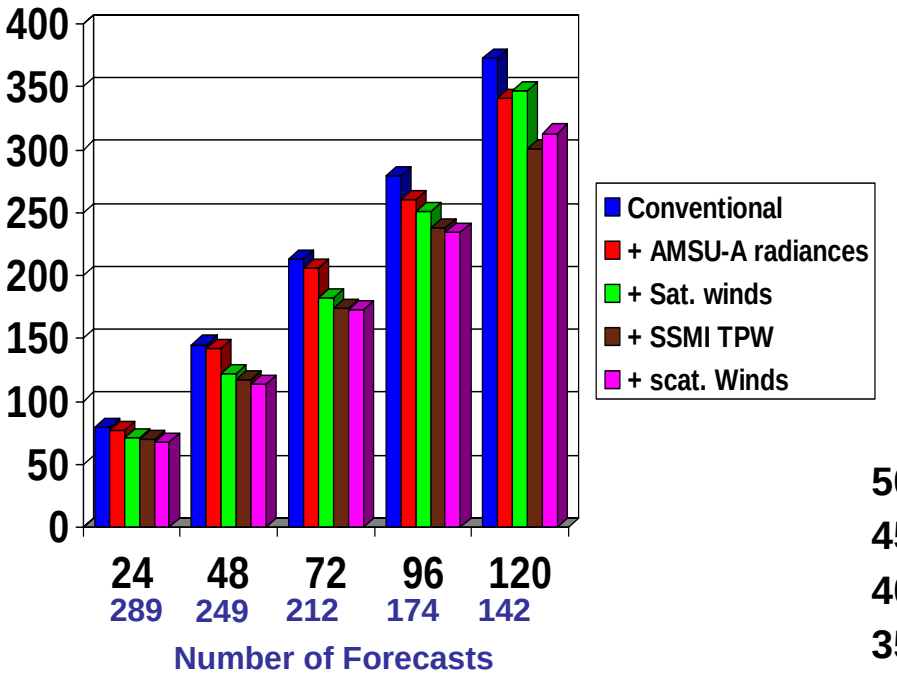


- AMSU-A radiance assimilation accounts for most of the improvements due to satellite assimilation (12 h for NH; 30 h for SH)
- Increased model resolution dominates the forecast improvements due to model changes (17 h in NH, 8 h in SH)

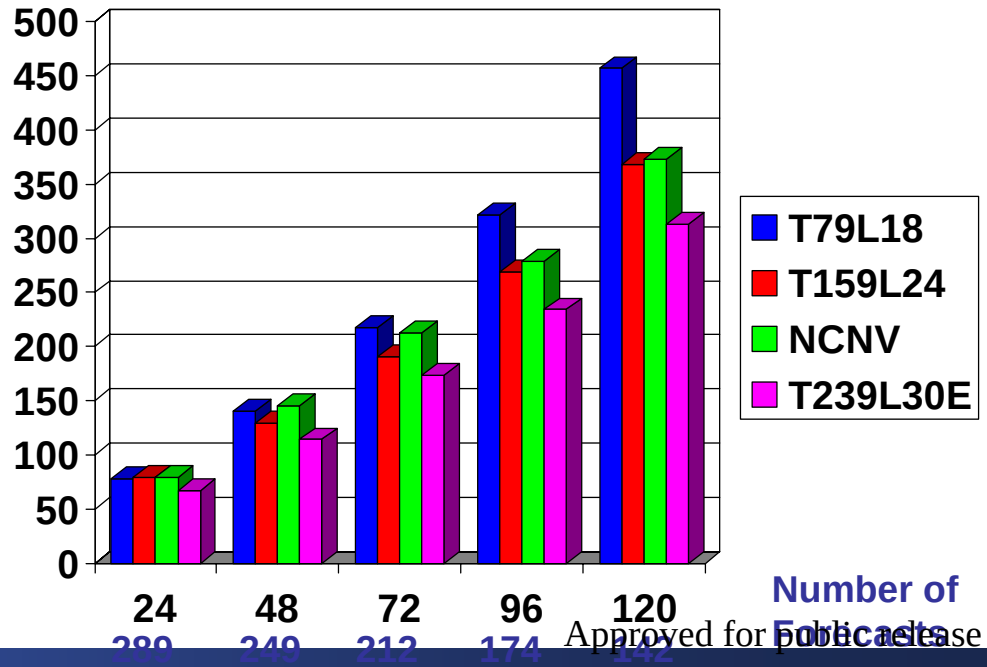
- Northern Hemisphere (NH): improvements in forecast skill are roughly comparable for model enhancements (20 h) and satellite assimilation (12 h)
- Southern Hemisphere (SH): improvements in forecast skill are much greater for satellite assimilation (30 h) than for model improvements (8 h)



Forecast and Observation System Experiments
TC Forecast Error (nm)



- For 1 to 3 day forecast range:
  - –Forecast improvements due to satellite assimilation[1] and forecast model improvements[2] are comparable
- For 4-5 day range:
  - –Forecast improvements due to all model changes are 2-3 times greater than impact of assimilation of all satellite observations



[1]All satellite observations

[2]Emanuel replacing Arakawa-Schubert; T79L18 to T239L30

From Jim Goerss and Tim Hogan

Approved for public release

NAVDAS Aerosol Assimilation

Goal of program: Develop world's first operational aerosol optical depth (AOD) data assimilation system to aid in the forecast of air quality and visibility.

Benefit for JCSDA partners: Error characteristics and QC techniques for aerosols, demonstration that model quality and observation quality are adequate for operational assimilation of aerosols. Observation operators for AOD.

Input: Terra and Aqua MODIS level 2 AOD after screening and empirical corrections.

Status: Development of an over ocean level 3 DA quality satellite dataset has been completed, and aerosol optical depth has been added to NAVDAS. 6 month test run show significant improvements in aerosol model forecasts

To be completed in FY07: Begin quasi-operational runs at NRL. Complete assessment of MODIS data collect 5 over land product.

Future sensors: NPP/NPOESS, AVHRR, METOP, MSG, AATSR, GOES-R

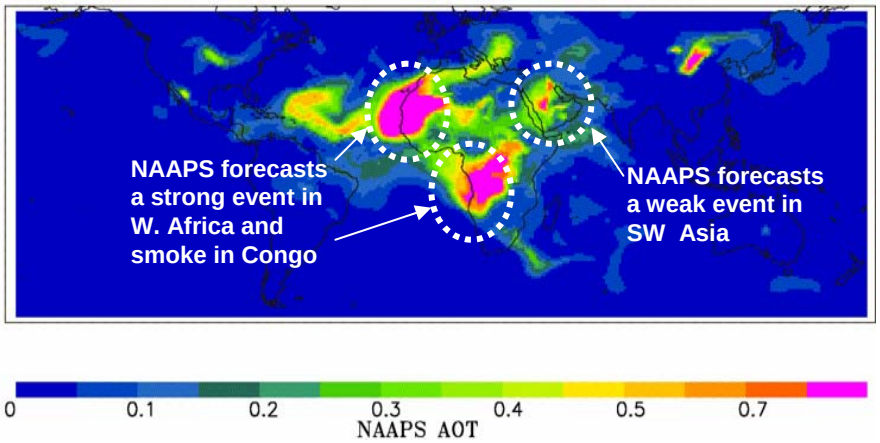
Output:

Aerosol analysis:	3-d distribution of four species
Horizontal resolution:	1x1° (soon to be 0.5x0.5°)
Temporal resolution:	6 hourly, forecasts to 144 hours
Distribution:	Internal, plots on web

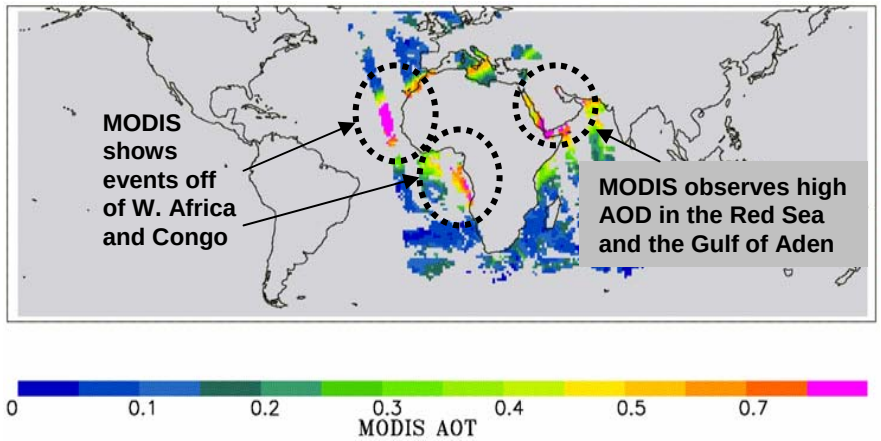
NAVDAS: Results for 12Z 19 July, 2005

Assimilation of MODIS optical depth

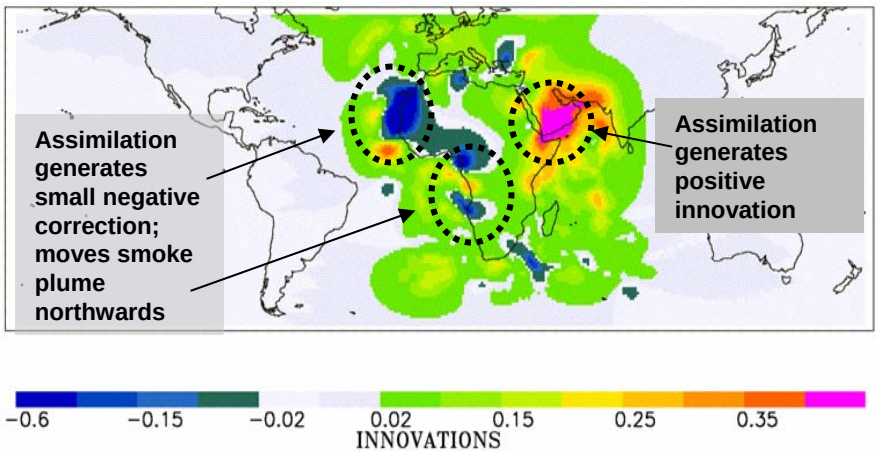
NAAPS first guess of AOD (12-h forecast) for 12Z, July 19, 2005



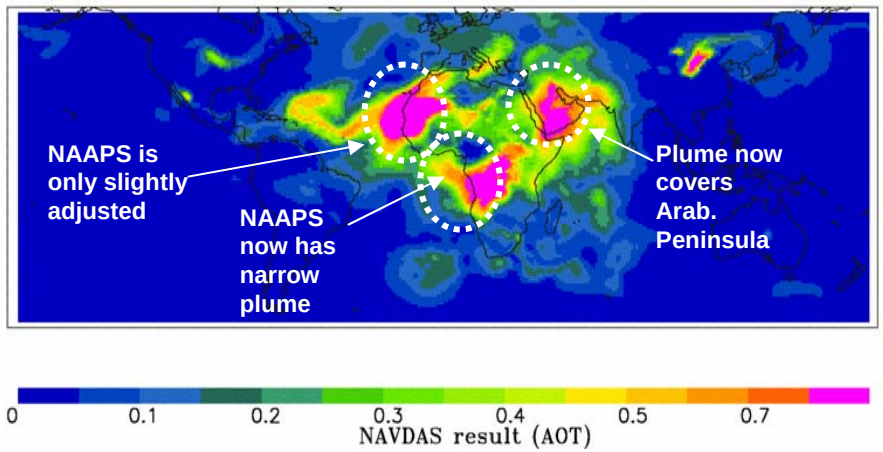
MODIS retrieved AOD for 09-15Z, July 19, 2005



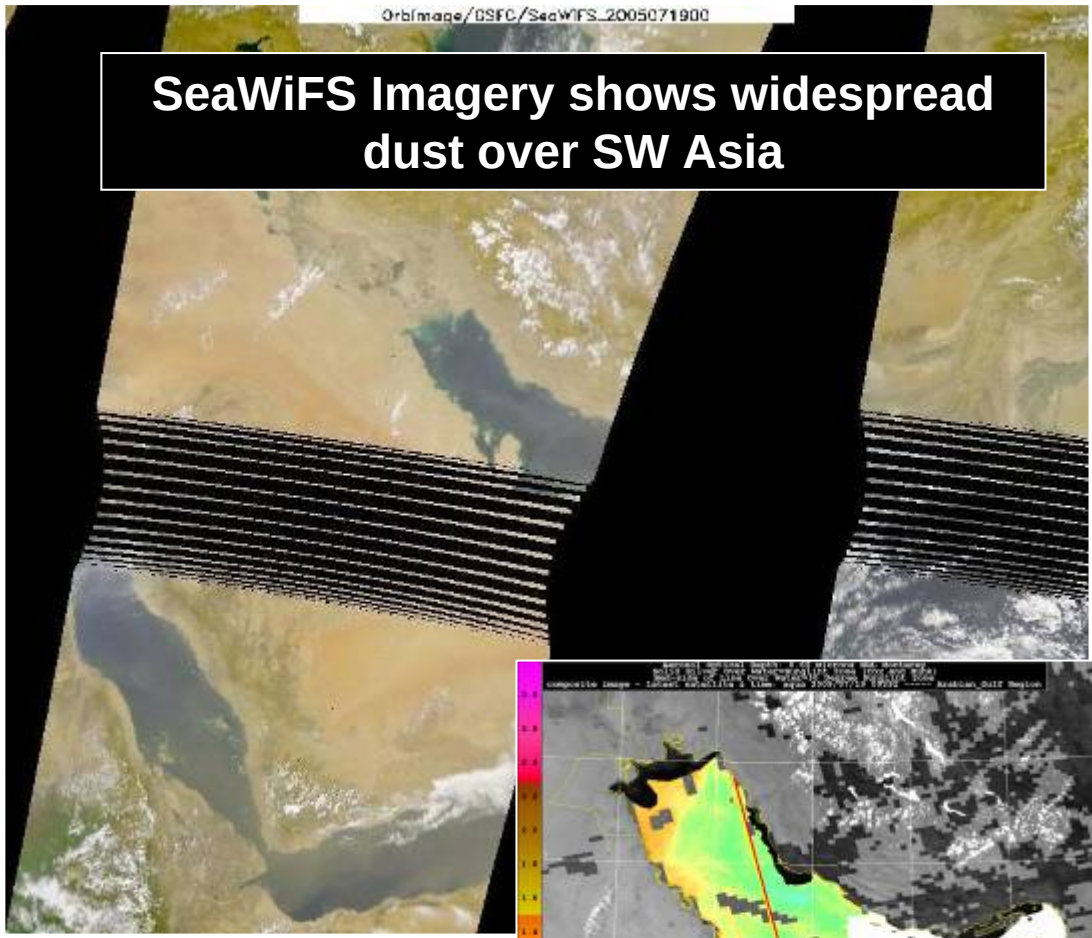
NAVDAS innovation (NAAPS first guess + MODIS assimilation)



NAAPS updated AOD analysis (NAVDAS innovation + first guess)

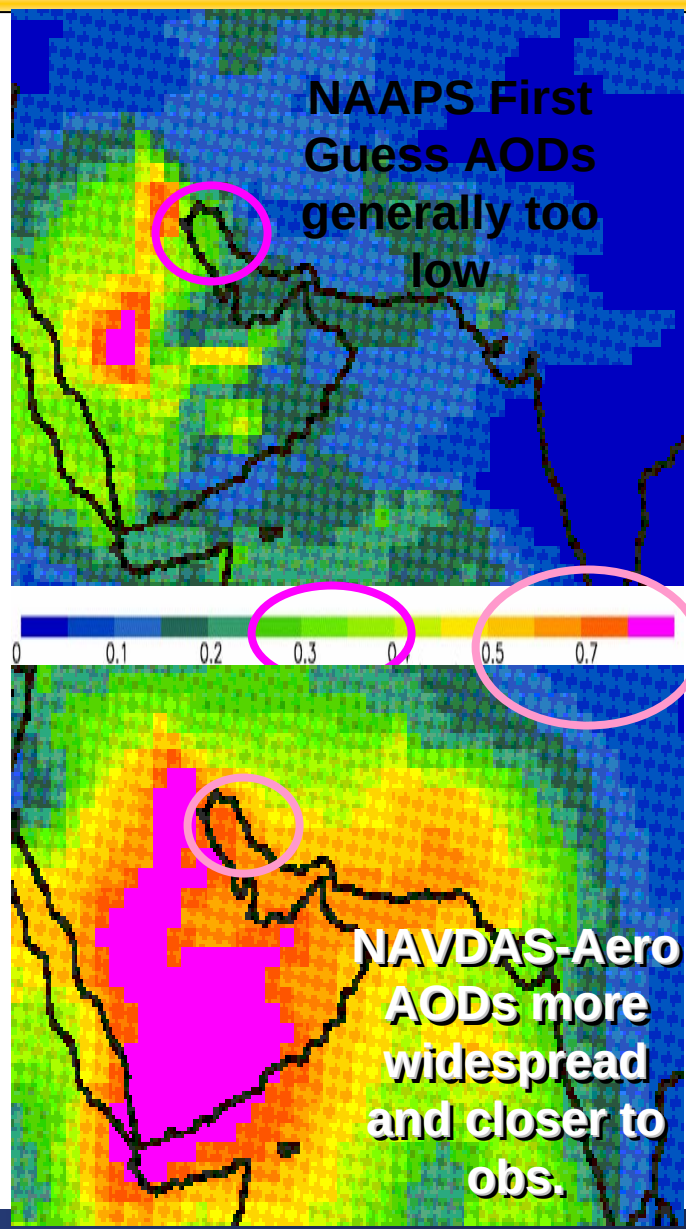


NAVDAS: Details for 12Z 19 July, 2005



SeaWiFS Imagery shows widespread dust over SW Asia

NRL's NOAA AOD retrievals are 0.6 – 1.0 over N. Arabian Gulf



Operational Multivariate Ocean Data Assimilation

James A. Cummings
Naval Research Laboratory, Monterey, CA

Fourth WMO International Symposium
Assimilation of Observations in Meteorology and Oceanography

Prague, Czech Republic April 18-22, 2005

Multivariate Ocean Data Assimilation

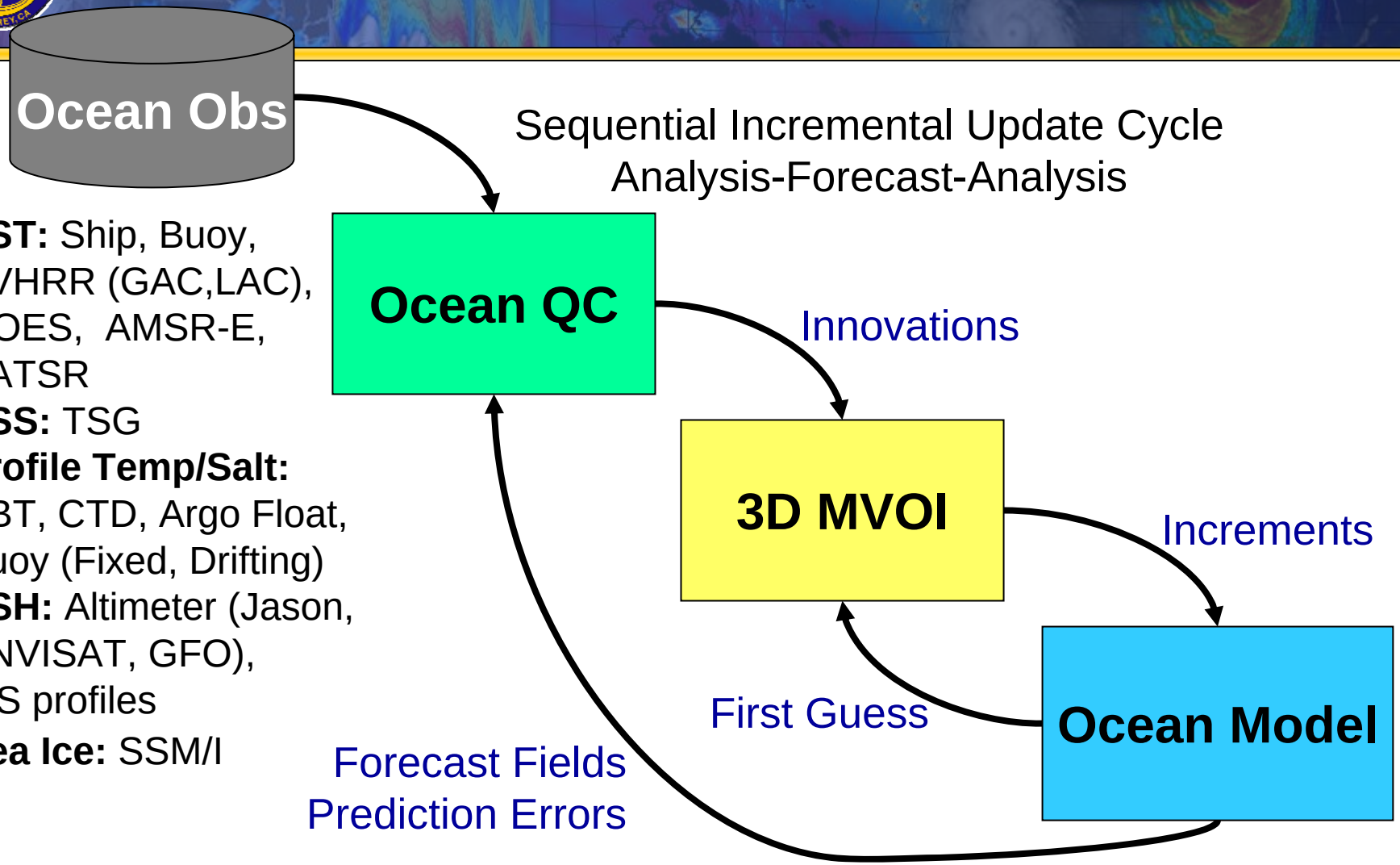
Flexible System

- global or regional applications
- re-locatable, multi-scale analyses on nested, successively higher resolution grids (3:1 nest ratios)
- update ocean forecast model or run stand-alone
  - 2D analyses of sea ice and SST (NWP boundary conditions)
  - 3D temperature and salinity analysis (geostrophic currents)
  - 3D MVOI sequential incremental update cycle

Designed as Complete End-to-End Analysis System

- data quality control
- analysis
- performance diagnostics

Multivariate Ocean Data Assimilation



Model forecast fields and prediction errors are used in the QC of newly received ocean observations

Multivariate Ocean Data Assimilation

Operational at U.S. Navy Production Centers

- Naval Oceanographic Office (NAVOCEANO)
- Fleet Numerical Meteorology and Oceanography Center (FNMOC)

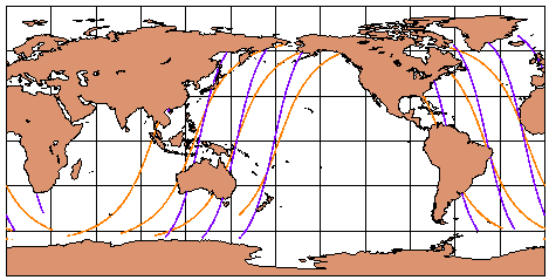
Assimilation Component in Several Ocean Forecast Modeling Systems

- Hybrid Coordinate Ocean Model (HYCOM)
  - NOPP/GODAE project - U.S. contribution to GODAE
- Navy Coastal Ocean Model (NCOM)
  - coupled ocean atmosphere model project (COAMPS)
- Parallel Ocean Program (POP)
  - ONR global coupled model project
- Shallow Water Analysis Forecast System (SWAFS)
  - operational ocean forecast system at NAVOCEANO

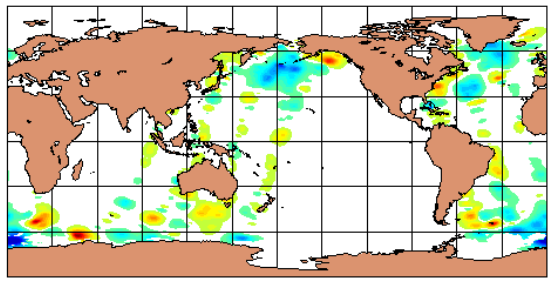
Ocean Wave Assimilation

- Significant wave height assimilation NCODA v2.1
- QC of altimeter SWH data and free run of WW3 model as control
- Verification includes independent buoys and yet-to-be-assimilated altimeter data – SWH, mean wave period, and buoy spectra vs. model spectra

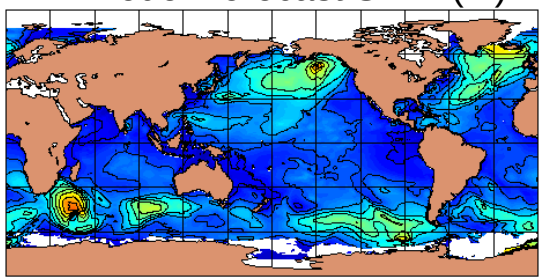
Altimeter SWH Observations



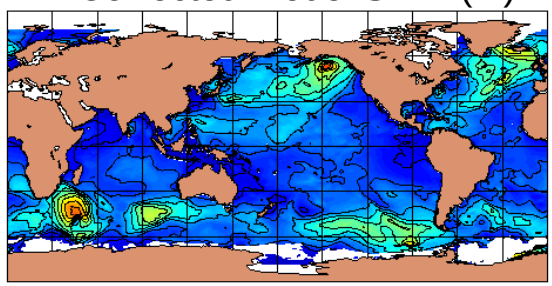
Analyzed Increment SWH (m)



Model Forecast SWH (m)

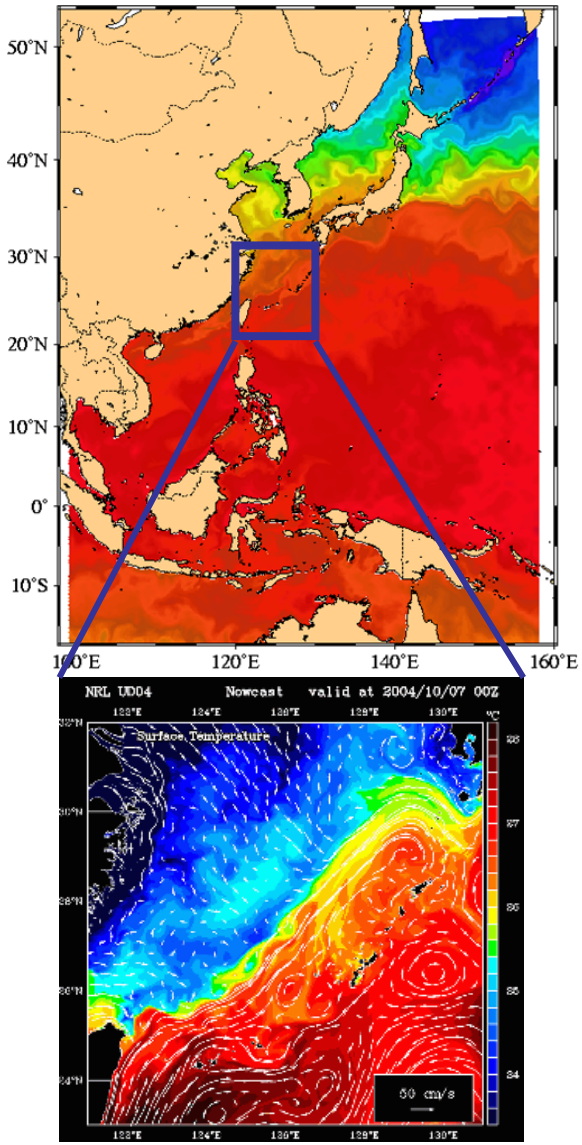


Corrected Model SWH (m)



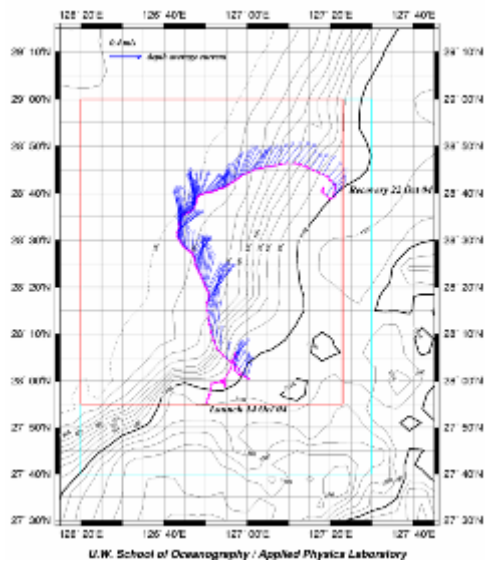
Assimilation via 6-Hour Sequential Incremental Update Cycle

Future Plans for Ocean DA



- Conversion MVOI to 3DVar solver based on NAVDAS
- Ensemble forecasts for limited area nested models
- Transform ensemble of forecast perturbations into ensemble of analysis perturbations using ETKF
- Use ETKF derived flow dependent error covariances in the assimilation
- Ensemble system will be used with gliders in adaptive sampling program to reduce forecast error

Seaglider track in West Pac
163 profiles in 8 days



Current And Future Research Efforts

- Upper atmosphere assimilation and modeling (NRL-DC)
  - To 120 km and above
  - Ozone chemistry (NOGAPS and GFS)
  - Higher-peaking SSMIS channels – CRTM with Zeeman
  - Microwave limb sounder for temperature, humidity and ozone
- IASI – need beta CRTM
- Comparison of adjoint impact results with GMAO and EC
- SSMIS Unified radiance pre-processor
- Cloudy radiance assimilation
- Land surface assimilation
- NAVDAS-AR
- Ensembles
- Exploiting NAVDAS for mesoscale data assimilation (e.g., data assimilation, isentropic coordinates)

Advanced Data Assimilation

How Do We Turn Disparate Information into a Coherent Picture?

Minimize a generalized cost function

$$J = J^r + J_0^b + J^q$$

$$J^r = \frac{1}{2}\left[y - \mathcal{H}(x)\right]^T R^{-1}\left[y - \mathcal{H}(x)\right]$$

$$J_0^b = \frac{1}{2}\left[x_0^b - x_0\right]^T \left[P_0^b\right]^{-1}\left[x_0^b - x_0\right]$$

$$J^q = \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N}\left[x_n - \mathcal{M}\left(x_{n-1}\right)\right]^T Q_{nn'}^{-1}\left[x_{n'} - \mathcal{M}\left(x_{n'-1}\right)\right]$$

Estimation of a 4-dimensional state, the analysis x^a

Scientific Issue: ***How to specify the error covariances?***
Computational Issue: ***How to accurately and efficiently minimize the cost function?***
Challenge: ***Observations y might be 10^8 degrees of freedom; 4-d state vector x might be 10^9***

3DVAR (e.g., NRL's NAVDAS):

- Most data not assimilated at actual observation time.
- Prediction model not used for time evolution in analysis window.
- Influence of obs distributed through specified error covariance.

$$2J_{min} = \left[x_0^b - x_0^a\right]^T \left[P_0^b\right]^{-1}\left[x_0^b - x_0^a\right] + \left[y - \mathcal{H}(x_0^a)\right]^T R^{-1}\left[y - \mathcal{H}(x_0^a)\right]$$

Strong Constraint 4DVAR (e.g., ECMWF):

- Observations are assimilated at times of observations.
- Prediction model is used to constrain the analysis.
- Perfect model assumption has to be made, such that Q=0.

$$x_n^a = \mathcal{M}\left(x_{n-1}^a\right)$$

$$2J_{min} = \left[x_0^b - x_0^a\right]^T \left[P_0^b\right]^{-1}\left[x_0^b - x_0^a\right] + \left[y - \mathcal{H}(x^a)\right]^T R^{-1}\left[y - \mathcal{H}(x^a)\right]$$

Weak Constraint 4DVAR (e.g., NAVDAS-AR):

- Observations are assimilated at times of observations.
- Prediction model is used to constrain the analysis.
- Perfect model assumption is not necessary.

$$J = J_0^b + J^q + J^r$$

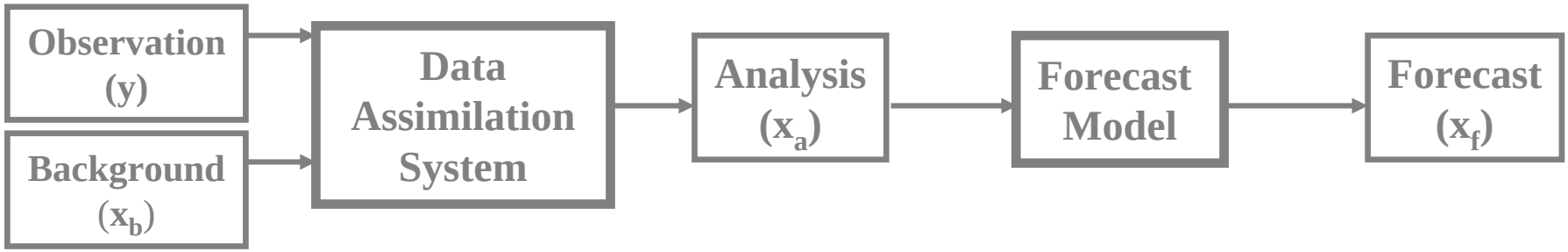
SCIENTIFIC ACHIEVEMENTS: ***Published 17 JA, 5 NRL Reports, 16 PP, 1 PhD dissertation.***

Liang Xu and Roger Daley (*Awarded prestigious AMS Charney medal*) formulated a unique cycling accelerated representer algorithm as the backbone of the 4DVAR.

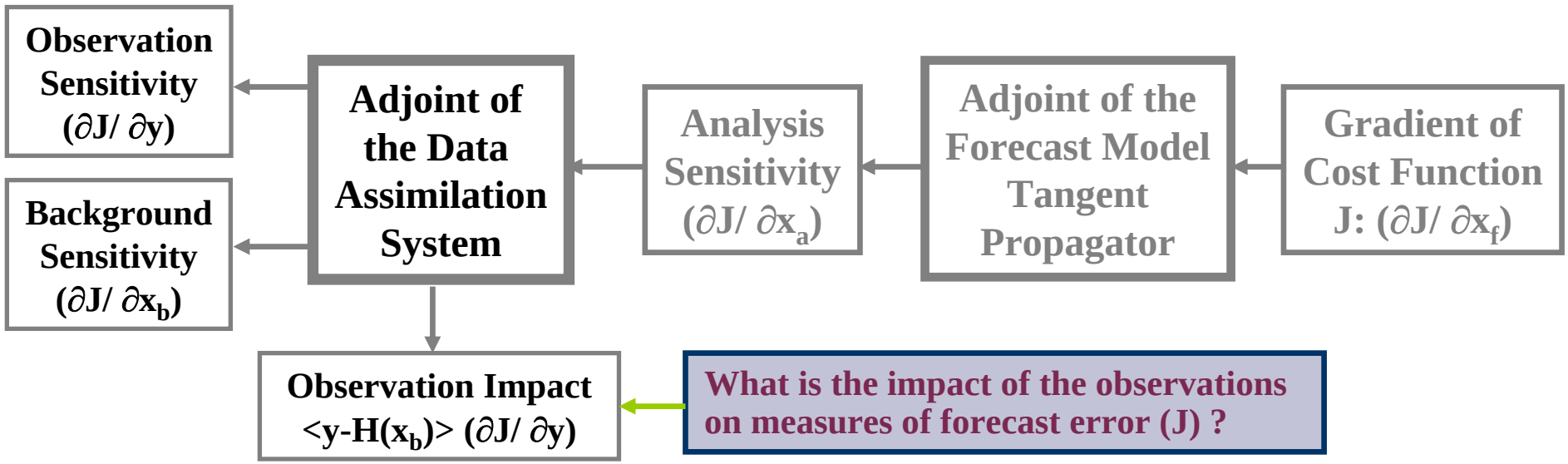
Provided internally consistent background error covariances using a reduced rank eigenvector representation.

Solved the generalized inverse problem efficiently using preconditioned Conjugate Gradient solvers.

NAVDAS Analysis – NOGAPS Forecast System



NAVDAS – NOGAPS Adjoint System

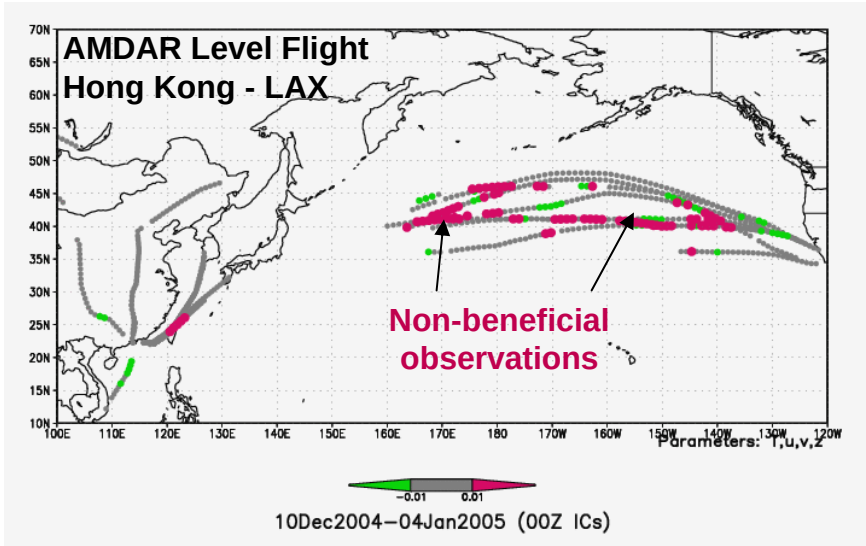


Isolated aircraft tracks

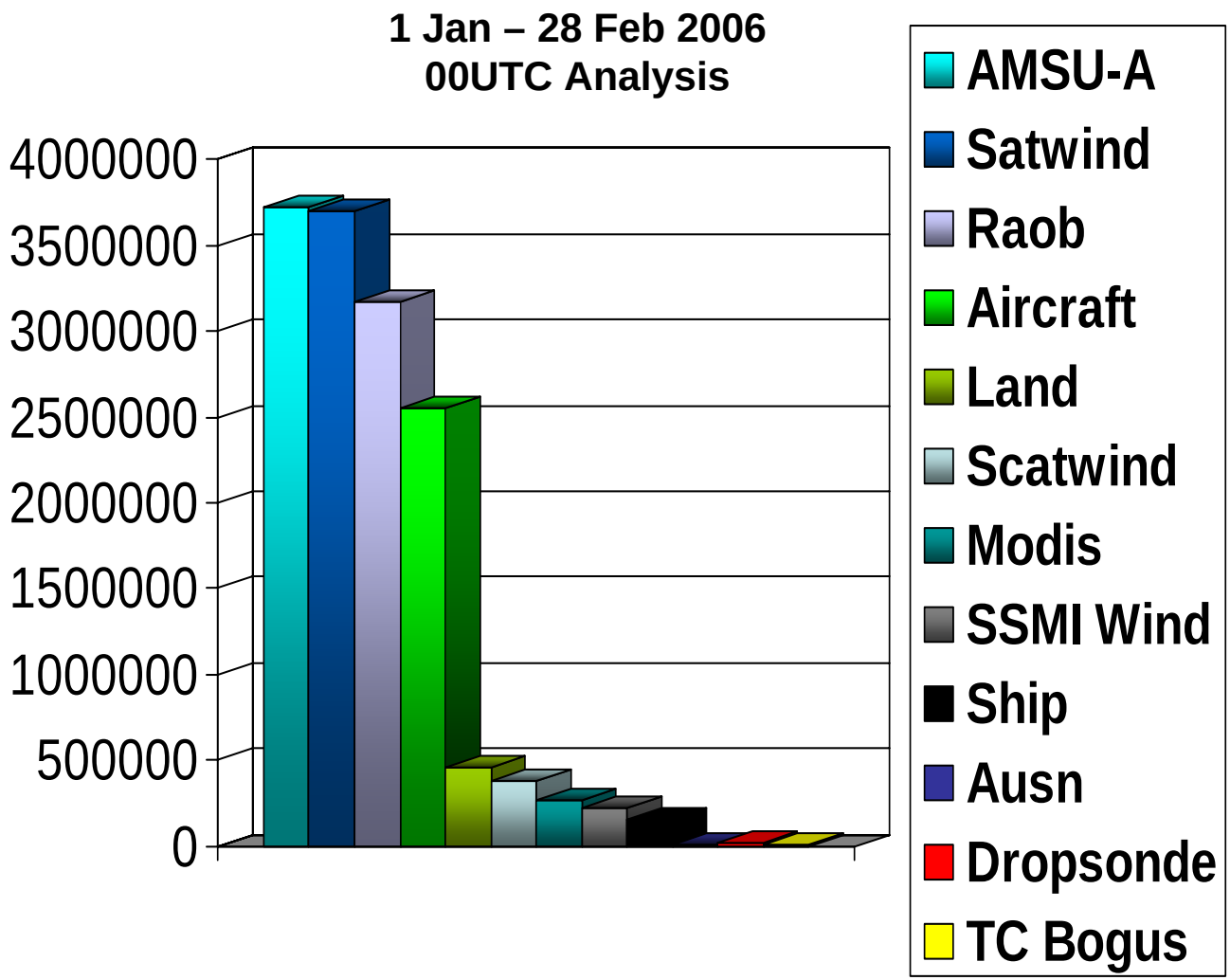
Date: First noticed Jan 05, ongoing in several regions

Issue: aircraft flies in jet max eastbound, outside of jet max westbound: observation error representativeness problem ?

Action Taken: HK0001 blacklisted by FNMOC (for a while)



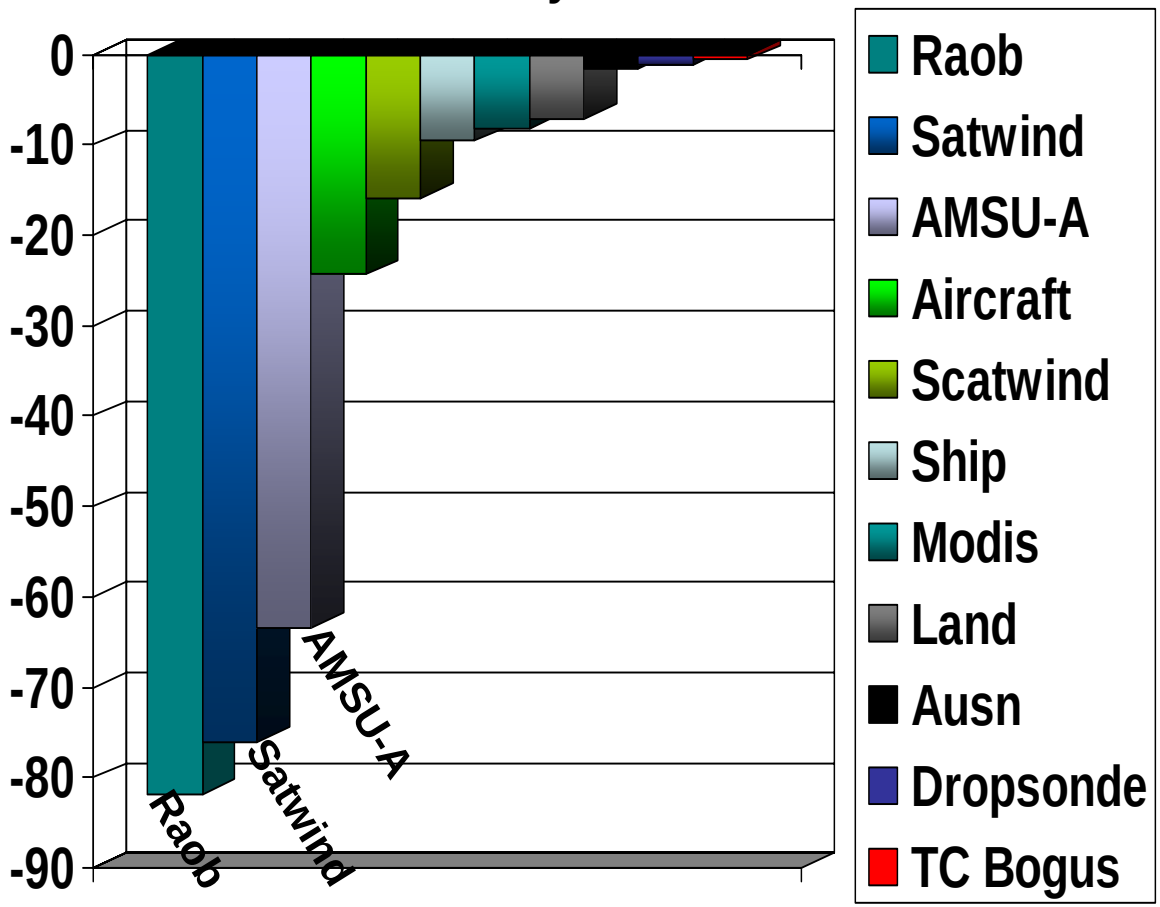
Instrument type data count



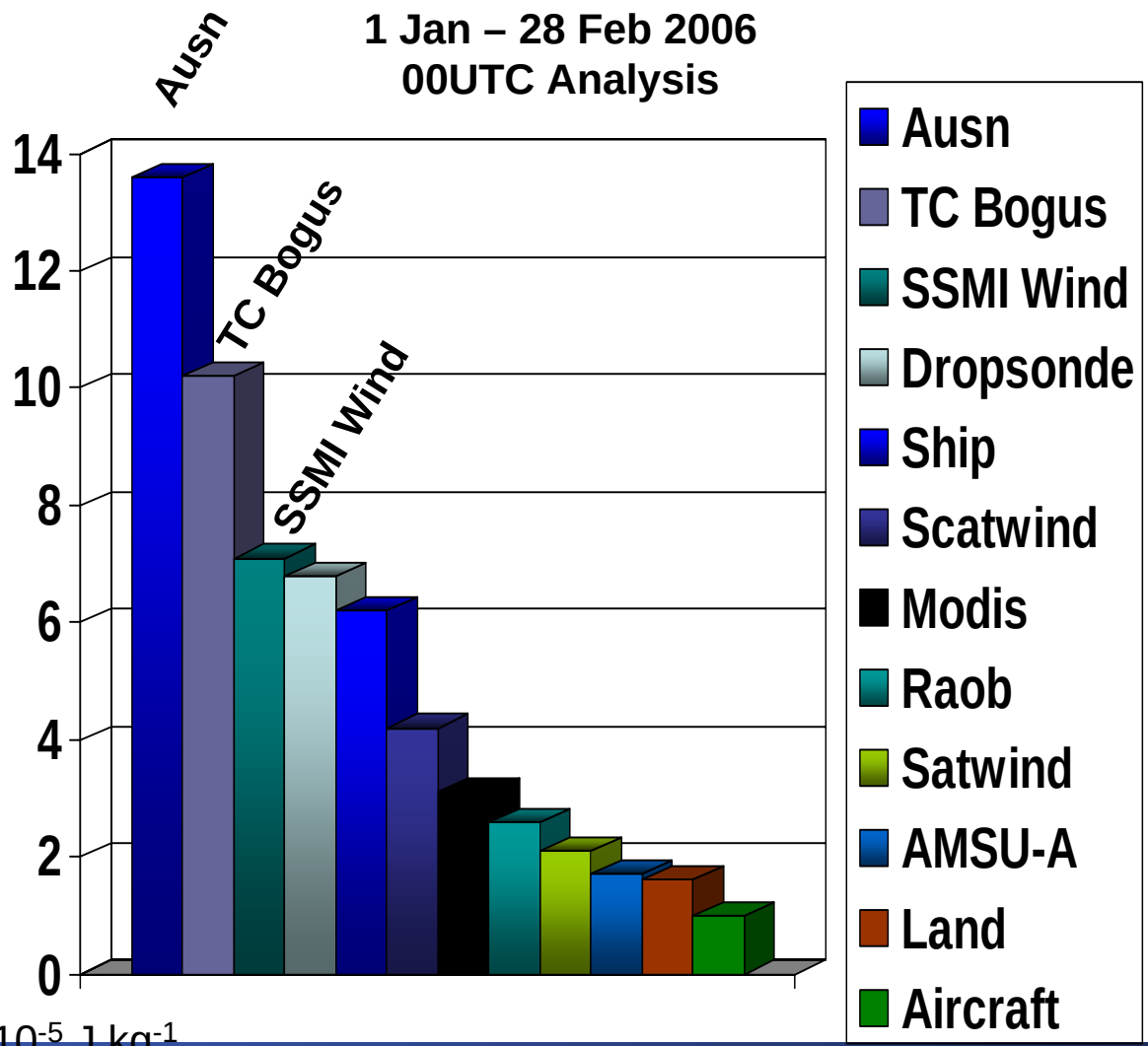
Total impact by observation type

Units of impact = J kg^{-1}

1 Jan – 28 Feb 2006
00UTC Analysis



Impact magnitude **per observation** by instrument type

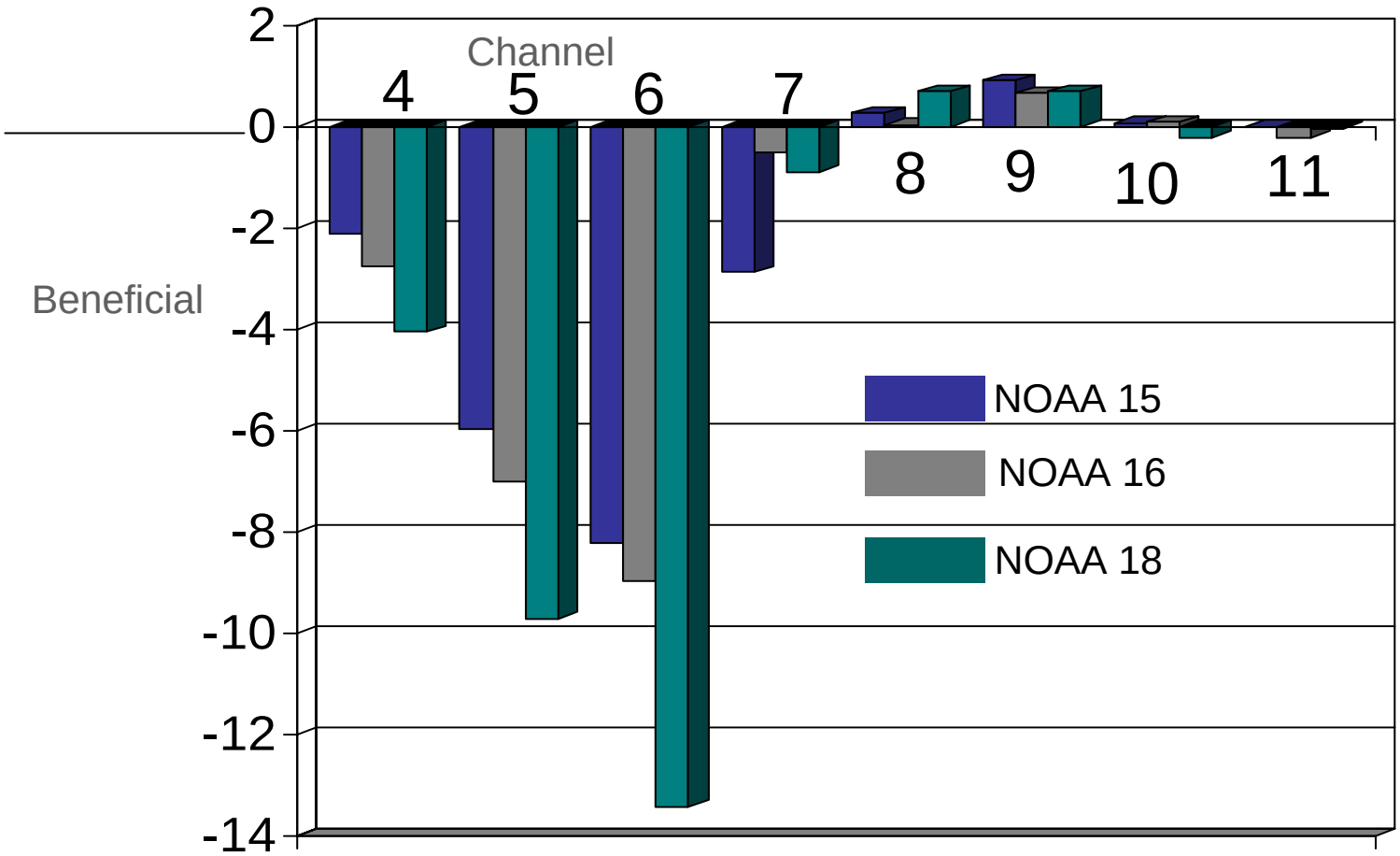


Units of impact = 10^{-5} J kg^{-1}

Impact for AMSU-A channels

Units of impact = J kg^{-1}

1 Jan – 28 Feb 2006
00UTC Analysis



Ch. peak near

11: 20mb

10: 50mb

9: 90mb

8: 150mb

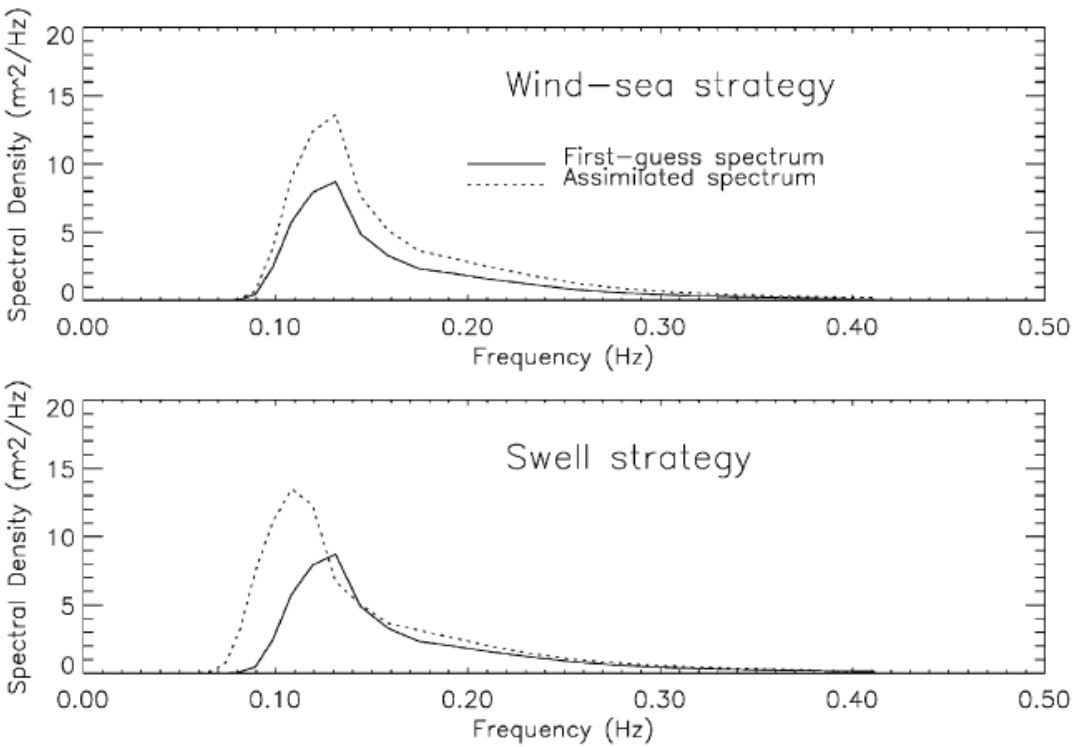
7: 250mb

6: 350mb

5: 600mb

4: surface

Wave Spectra Adjustment



SWH is proportional to the integral of the wave spectral energy across all frequencies and directions.

No unique method of adjusting the wave spectrum to obtain the analyzed SWH.

Two alternative correction strategies will be tested.

1. **Wind-Sea Strategy**: simple uniform scaling of amplitude of model spectrum - alters the slope of the spectrum and can cause a rapid dissipation of the assimilated information.

2. **Swell Strategy**: constrains the spectral slope to remain constant by shifting energy to different frequencies as the total energy is adjusted - shift is to lower frequencies if model under estimates SWH (see above), or higher frequencies if model over predicts SWH.