The Assimilation of Satellite Observations for the U.S. Navy's Operational Forecast Models

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Naval Research Laboratory

•*Monterey – Marine Meteorology Division*
- Research and development of global, mesoscale and shipboard atmospheric analysis and prediction systems
- Coupled atmosphere-ocean modeling
- Development of forecaster aids and automated weather interpretation system

•*Washington, D.C. – Remote Sensing Division*
- Design and build satellites (Windsat, POAM)
- GPS and ozone assimilation

•*Stennis Space Center, MS – Ocean Division*
- Ocean data assimilation and modeling

Customers

•*Fleet Numerical Meteorology and Oceanography Command (FNMOC)*
- produces and distributes products from numerical prediction models of the ocean and atmosphere
- ocean modeling

•*Other Customers*
- Navy and Marine Corps, Air Force and other DoD activities
- Civilian - US Coast Guard search and rescue planners

•*Objective*
- Provide the best global and/or regional analysis at any time,
  - from upper levels (for ballistic missile support),
  - to lower levels for EM/EO support, visibility, winds for flight operations, etc.
  - Analysis variables are temperature, humidity and winds
- Provide the best initial conditions for the NWP model forecasts

NRL/FNMOC Forecast Suite

•*NOGAPS - Navy Operational Global Atmospheric Prediction System*
- Spectral T239, L30
- NAVDAS – NRL Atmospheric Variational Atmospheric Variational Analysis System (3DVAR) operational October 1, 2003

•*COAMPS™ - Coupled Ocean/ Atmosphere Mesoscale Prediction System*
- Nonhydrostatic; globally relocatable, nested grids; explicit prediction of moisture variables
- NAVDAS will replace soon the multivariate optimum interpolation (MVOI) system

COAMPS™ is a trademark of the Naval Research Laboratory, Monterey, CA.

NAVDAS Features

(1) $\mathbf{z} = \left[\mathbf{H}\mathbf{P}_b\mathbf{H}^T + \mathbf{R}\right]^{-1}\left[\mathbf{y} - H(\mathbf{x}_b)\right]$ Solver

(2) $\mathbf{x}_a - \mathbf{x}_b = \mathbf{P}_b\mathbf{H}^T\,\mathbf{z}$ Post-multipler

- $\mathbf{y}$ - observation vector
- $\mathbf{x}_b$ - the background vector
- H - forward or observation operator
- $\mathbf{P}_b$ – background error covariance
- $\mathbf{x}_a$ – analysis vector
- R – observation error covariance
- $\mathbf{H}$ – observation operator linearized about the background

•*Formulates the solution in observation space (not model space)*
- Applicable to any model or grid projection (global or mesoscale)
- Computes the solution much faster for data-sparse areas/ dense grids
- Runs on mainframes or workstations (uses MPI and standard Fortran)
- Cost is proportional to the number of observations assimilated

•*Provides flexibility in specifying background errors*
- Eigenvector decomposition is used in the vertical
- This provides an enormous computational advantage (factor of 25) for the assimilation of profile observations (i.e. radiosondes, radiances).
- Equally importantly, it permits a non-separable formulation of the background error correlation.
  - Shorter horizontal correlations for temperatures and shorter vertical correlations for winds than for geopotentials.
  - The horizontal correlation length can vary vertically (increasing in the stratosphere) and modally (increasing for deep modes).
  - Tropical vertical correlation lengths can be different (shorter) than in high latitudes.
  - Divergent and rotational winds can have different structures.
- Adapts easily to flow-dependent background errors
  - A straightforward transformation to isentropic coordinates (based on the background state estimate) can be easily incorporated. The background error correlations then become sensitive to frontal structures, static stability, marine boundary layers, the tropopause and the jet streams.

•*Supports nested grids*
- Analyzes all simultaneously
- Assures complete coupling between all of the nests

•*Direct assimilation of radiances, SSM/I TPW and wind speeds; nonlinear for wind speed*

•*NAVDAS adjoint*
- Useful diagnostic tool that provides sensitivity of forecast aspect (e.g., error) to the observations.

•*Lays the foundation for cycling representer algorithm*

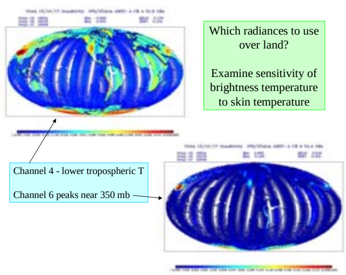
•*Designed by Roger Daley with Edward Barker, Keith Sashegyi, Patricia Pauley, James Goerss, Nancy Baker, Tom Rosmond, Tim Hogan, Bill Campbell, Clay Blankenship, Liang Xu, Randal Pauley, Peter Steinle, Tom Lougheed*

•*Sponsors: NRL, ONR, SPAWAR*

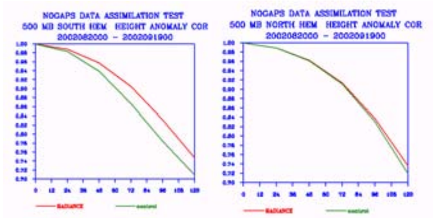
AMSU-A Radiance Assimilation for NOGAPS and COAMPS

• **Approach:** Assimilate radiances directly using NAVDAS
- Use channels 4-11; screen land/ice/snow observations depending upon whether channels "sees" the surface
- Every 4th observation; additional thinning to remove overlapping passes/satellites; final spacing ~ 150 km
- QC removes sporadic bad data, and radiances affected by cloud liquid water, precipitation, surface ice or land
- Bias corrections are an essential component, modified Harris and Kelly approach

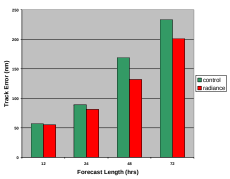
• **Results**
- Modifications to bias correction method led to excellent improvements in forecast skill and quality of the assimilated radiances
- Radiances strengthen circulation in SH; better fit with radiosondes and other observations; improved tropical cyclone track predictions



NAVDAS/NOGAPS Forecast Impact
AMSU-A Radiances vs. NESDIS Retrieval Assimilation
500 mb Height Anomaly Correlation



Tropical Cyclone Track Improvement
(May 1, 2002 to June 15, 2002)



	Tau 12	Tau 24	Tau 48	Tau 72
Western N. Pacific	13	13	10	7
Eastern N. Pacific	11	9	6	5
S. Hemisphere	16	14	11	8
Total	40	36	27	20

Number of Cases

Bias Correction Method

•Most weather centers predict (and correct) bias statistically via multiple linear regression, using either actual satellite radiances or NWP model variables as predictors.

• *Any* approach runs the risk of either throwing out signal with bias, or not throwing out enough bias, although careful choice of time scales can mitigate this risk.

• NRL is investigating hybrid approaches, which use both satellite radiances and NWP model variables as bias predictors.

• Three bias correction schemes are compared offline, using two weeks of data to construct regression coefficients, which are then applied to the next two weeks of data.

•Harris and Kelly (HK) method
- Latitude band regression (18 separate zonal regressions)
- Model predictors (tropospheric and stratospheric thicknesses, TPW, and SST)

•NRL test method (based on suggestions by J. Derber)
- Global regression
- Model predictors (latitude-modulated tropospheric and stratospheric thicknesses, TPW, SST, and cloud liquid water)

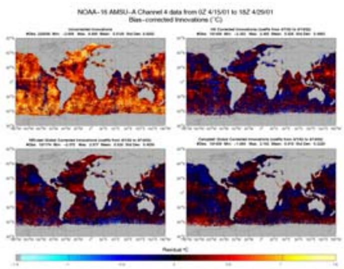
•Campbell global and latitude band hybrids
- Global or latitude band regressions
- All NRL test predictors, plus radiances from all AMSU-A channels *except* the channel being evaluated

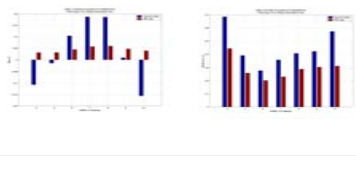
•Channel 4 (52.8 GHz) has some sensitivity to moisture, so cloud liquid water as predictor in the NRL test method helps it to have a lower RMS error than the HK method.

•The Campbell hybrid methods have the lowest RMS in all channels (except for the global hybrid method in Channel 10).

•Note that both latitude band methods, but in particular the Harris and Kelly method, show a discontinuity in the bias correction along latitude band boundaries (every 10 degrees). This may cause their performance in an assimilation run to suffer, despite lower RMS error in offline tests.

• In preliminary testing, the NRL test method significantly improved both NOGAPS forecast skill, quality of radiances, and stability of bias corrections over time.





AMSU-B Radiance Assimilation for NOGAPS and COAMPS

• *Motivation*

–NOGAPS and COAMPS use few observations of mid- to upper-tropospheric humidity

–Assimilate water vapor profiles from AMSU-B microwave observations

• *Approach*

–Observations from from the AMSU-B microwave radiometer on the NOAA-16 polar orbiter.

–150 GHz and 183.31±1, 3, and 7 GHz channels

–Thinned to every fourth point of every fourth scan (May 2002 runs) or one ob per 2°x2° degree box spacing in tropics (equivalent higher latitudes) for August 2002 runs.

–Land, coast, and sea ice are screened out, as are points with high scattering index (Greenwald and Christopher, 2002).

– Algorithm is a physical optimal estimation inversion of the observed brightness temperatures (based on Blankenship et al. (2000))

–Equivalent to a one-dimensional variational assimilation (1DVAR) of radiances at each observation point.

–NOGAPS background (6-hour forecast) humidity profile

–Temperature profile, sea surface temperature, and surface wind speed from the NOGAPS forecast (held constant)

–Clouds are turned off in this version of the retrieval

–No bias correction (known upper tropospheric moist bias in NOGAPS makes traditional bias correction techniques problematic)

–Retrievals which failed to converge (usually due to heavy cloud or precipitation in the scene), or which failed gross temperature departure checks were also rejected.

– NAVDAS assimilates the 1DVAR profiles of pseudo relative humidity

–1DVAR used due to limitations with present NAVDAS configuration

–Approximately 45,000 retrievals (5000 for August runs) from the NOAA-16 AMSU-B per 6-hour update cycle are assimilated.

• *Results*

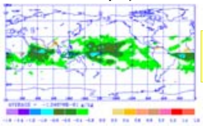
– Corrects NOGAPS tendency to be too moist above 500 mb

– Enhances humidity gradients in the Intertropical Convergence Zone and South Pacific Convergence Zone

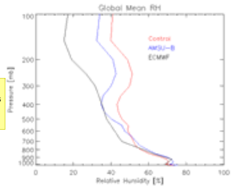
– There is also an enhanced humidity gradient at 20° W off the western African coast. The stronger gradient there is consistent with the model's wind field, which indicates that the air mass origin is continental north of 10° N but maritime south of that.

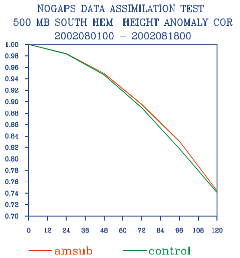
–These enhanced gradients are largely maintained out to 4 days

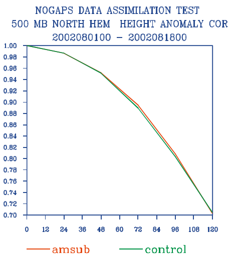
1DVAR AMSU-B minus Control
NOGAPS/NAVDAS Assimilation Tests
400 hPa q; May 2002



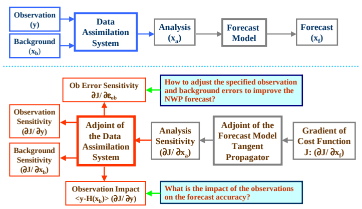
Conclusion: 1DVAR retrieval assimilation dries out NOGAPS in the mid to upper troposphere







NAVDAS Adjoint System



Data Assimilation Adjoint Theory

•Begin with the linear analysis equation

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}_b),$$

where

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$$

•The sensitivities of the analysis to the observations and background are

$$\frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} = \mathbf{K}^T,$$

$$\frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_b} = (\mathbf{I} - \mathbf{K}\mathbf{H})^T.$$

•Using the chain rule, the sensitivities of the forecast aspect *J* to the observations and background are

$$\frac{\partial J}{\partial \mathbf{y}} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} \frac{\partial J}{\partial \mathbf{x}_a} = \mathbf{K}^T \frac{\partial J}{\partial \mathbf{x}_a},$$

$$\frac{\partial J}{\partial \mathbf{x}_b} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{x}_b} \frac{\partial J}{\partial \mathbf{x}_a} = (I - \mathbf{H}^T\mathbf{K}^T)\frac{\partial J}{\partial \mathbf{x}_a},$$

Baker and Daley (2000)
Doerenbecher and Bergot (2001)

Observation Sensitivity Applications

•Diagnostic (observation taken and forecast error known)

– Impact of observations on forecast error

– Tuning of error variances and other parameters

• Targeting (observation and forecast error not known)

–Test the impact of hypothetical observations

–Potential benefit of satellite data prior to launch

–Alternative networks of satellite and in-situ observations

•NRL Core Systems – NAVDAS[1] and NOGAPS[2]

•NRL Predictability Research Group

1. Daley and Barker (2000a,b) 2. Hogan and Rosmond (1991); Rosmond (1997)

Observation Impact on NOGAPS Forecast Error

$$\delta e_{24}^{30} = \left\langle (y - Hx_b), \frac{\partial J_{24}}{\partial y} + \frac{\partial J_{30}}{\partial y} \right\rangle$$

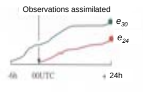
δe_{24}^{30} = adjoint estimate of difference between the 30h and 24h forecast error in global model (scalar)

y = observation vector (~ 250,000 obs)

$\mathbf{X}_b$= background (6h) forecast

•We want an estimate of the impact of the observations on the NOGAPS forecast error in *observation space*

Choice of Cost Function



•Observations are assimilated at 00UTC, creating initial conditions for a new trajectory, which has forecast error *e24*.

• The old trajectory starts from 18UTC (-6h), and has forecast error *e30* . It also provides the background for the analysis at 00UTC.

• Both forecasts verify at time +24h.

•The difference between the errors *e24 – e30* is due solely to assimilation of observations.

•Nonlinear forecast error is given by $\Delta e_{24}^{30} = e_{24} - e_{30}$, where $e_f = \langle (\mathbf{x}_f - \mathbf{x}_t), C(\mathbf{x}_f - \mathbf{x}_t) \rangle$ and **C** is the total (dry) energy-weighted error norm.

•Quadratic measure forecast error (J kg^{-1}) that combines temperature, wind and pressure from ~ 150 hPa to the surface

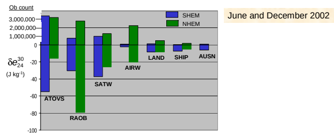
•NOGAPS at T79L30 resolution; verifying analyses produced by NAVDAS

• The impact function δe_{24}^{30} gives an estimate of the contribution of each observation assimilated by NAVDAS in the global domain to a reduction or increase in e_{24}-e_{30}.

• For complete derivation, see Langland and Baker (2003)

•Fourrié *et al.* (2002) and Doerenbecher and Bergot (2001) use similar cost functions

Global Observation Impact (by hemisphere)

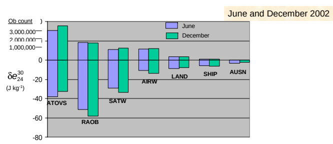


•Observation impact (δe_{24}^{30} J kg^{-1}) for Southern and Northern Hemispheres, partitioned by instrument type

•Includes all observations assimilated in NAVDAS at 00UTC.

•ATOVS-temperature retrievals, RAOB-rawinsondes, SATW-cloud and feature-track winds, AIRW-commercial aircraft observations, LAND-land surface observations, SHIP-ship surface observations, AUSN-synthetic sea-level pressure data (Southern Hemisphere only).

Global Observation Impact (by season)



• Global observation impact (δe_{24}^{30} J kg^{-1}) for June and December 2002

•Includes all observations assimilated in NAVDAS at 00UTC.

Acknowledgements

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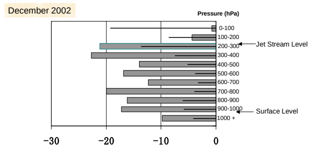
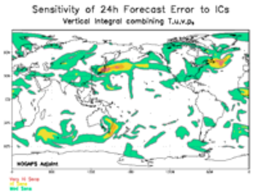
Global Observation Impact (by vertical level)



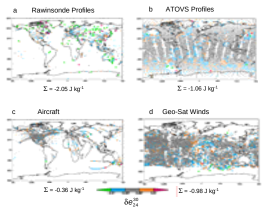
• Global observation impact (δe_{24}^{30} , J kg^{-1}) partitioned by pressure level for December 2002.

•Black solid line within gray bar is proportional to number of observations in each pressure layer

Sensitivity to Initial Conditions
December 10, 2002



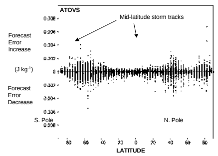
Global Observation Impact (J Kg-1)
00 UTC 10 December 2002



•Green: large reduction in 24h global forecast error. Red: large increase

•Blue: moderate reduction Orange: moderate increase Grey: small reduction or increase

Global Observation Impact for ATOVS



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