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ATMOSPHERIC INFRARED SOUNDER ASSIMILATION EXPERIMENTS USING NCEP's GFS

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1. INTRODUCTION

In May 2002, the Atmospheric Infrared Sounder (AIRS) along with the Advanced Microwave Sounding Unit (AMSU) and the Humidity Sounder for Brazil (HSB) were launched on the Aqua satellite of the Earth Observing System (EOS). AIRS is the first infrared spectrometer/radiometer to provide routine operational data in the 3.7 to 15.4 µm spectral range with hyperspectral resolution.

The quality of global analyses and forecasts are heavily dependent on satellite observations. This strong dependence has been documented in a series of studies where satellite data have been withheld in data assimilation experiments (Zapotocny et al. 2005a and b, Lord et al. 2004). The introduction of the AIRS hyperspectral observations from the Aqua satellite into environmental analysis and forecast centers, with current modeling, data assimilation, and computing capacity, was anticipated to provide improvements in forecast skill.

In collaboration with the National Aeronautical and Space Administration (NASA), the National Oceanic and Atmospheric Administration's branches of National Environmental Satellite, Data, and Information Service (NOAA/NESDIS), and National Weather Service/National Center for Environmental Prediction (NOAA/NWS/NCEP), the Joint Center for Satellite Data Assimilation (JCSDA) has been conducting radiance assimilation experiments with AIRS using NCEP's Global Forecast System (GFS).

2. AIRS BACKGROUND

AIRS, AMSU and HSB were successful launched on May 4, 2002 on the EOS Aqua spacecraft into a 705 km high circular sun-synchronous 1:30 P.M. orbit. First-light data from AIRS were received on June 13, 2002. The calibration phase for AIRS was completed after 90 days in orbit.

AIRS and AMSU form an integrated cross-track-scanning temperature and humidity sounding system on the EOS Aqua spacecraft. In addition to supporting NASA's interest in process study and climate research, AIRS is the first hyperspectral IR radiometer designed to support NOAA/NCEP's operational requirements for numerical weather forecasting during its expected seven year lifetime.

AIRS, together with the AMSU microwave radiometer, will achieve global retrieval accuracy better than 1^{o}K/km in the lower troposphere under clear and partly cloudy conditions (Aumann et al. 2003). Based on the excellent radiometric and spectral performance demonstrated by AIRS during the on-orbit testing, Aumann et al. (2003) expect the assimilation of AIRS data into the numerical weather prediction (NWP) forecast models to result in significant forecast improvements.

The alignment and synchronization of the AQUA instrument suite are essential to the ability to achieve the required 1^{o}K/km retrieval accuracy in the presence of clouds. AMSU-A is comprised of two separate sensor units, AMSU-A1 and AMSU-A2, with co-aligned, synchronized, and equal sized field of views (FOV). The AMSU-A footprint is three times wider than the AIRS and HSB footprint and covers a cluster of nine AIRS footprints.

The AIRS instrument provides spectral coverage in the 3.74-4.61 µm, 6.20-8.22 µm, and 8.8-15.4 µm infrared wavebands at a nominal spectral resolution of $\lambda/\Delta\lambda$ = 1200. The AIRS instrument also includes four visible/near-IR channels between 0.40 and 0.94 µm with a 2.3 km FOV (Aumann et al. 2003). Details of the AIRS radiometric, spectral and spatial calibration are discussed by Pagano et al. 2003, Strow et al. 2003, Gaiser et al. 2003, and Hagan and Minnett 2003.

Passes of the Earth Observing System (EOS) Aqua over a ground receiving station occur for every orbit (about every 100 minutes). Data from a ground station overpass are received within 22 min at the Earth Data Operating System (EDOS) and are sent to the NOAA/NESDIS server and the Goddard Space Flight Center / Distributed Active Archive Center (GSFC/DAAC) as high-rate buffered data (or Level 0). At NOAA/NESDIS, the Level 0 data are converted to Level 1b and are quality-controlled using software supplied by the Jet Propulsion Laboratory (JPL) Team Leader Science Computing Facility (TLSCF). The data

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are then thinned from 2378 channels to 281 key sounding channels at the center of every AMSU-A footprint. These data are then distributed to NWP centers using the Binary Uniform Format Representation (BUFR). Data distribution is explained in greater detail by Goldberg et al. (2003).

3. GFS BACKGROUND

The analysis scheme is a three-dimensional variational (3DVAR) scheme cast in spectral space and is referred to as the Spectral Statistical Interpolation (SSI) alogorithm (Derber et al. 1991: Parrish and Derber 1992). With this type of analysis system, the incorporation of the radiances directly in an analysis and assimilation system has become practical. The analysis becomes a 3D retrieval of mass, momentum and moisture fields derived from all available data including the radiances. In October 1995 the direct use of clear and cloud-cleared satellite radiances in the construction of mass, momentum and moisture fields was first introduced (Caplan et al. 1997). The methodology for using the radiance data (including the bias correction, ozone analysis, skin temperature, and quality control) are described in Derber and Wu (1998) with the latest upgrades described in Derber et al. (2003). The JCSDA Community Radiative Transfer Model (CRTM) explained by Kleespies et al. 2004 has been incorporated into the SSI to improve radiance assimilation.

The full operational database was used including the real-time data cut-off constraints. The database includes all available conventional data and the satellite data listed in Table 1.

HIRS sounder radiances	TRMM precipitation rates
AMSU-A sounder radiances	ERS-2 ocean surface wind vectors
AMSU-B sounder radiances	Quickscat ocean surface wind vectors
GOES sounder radiances	AVHRR SST
GOES, GMS, Meteosat wind vectors	AVHRR vegetation fraction
GOES precipitation rate	AVHRR surface type
SSM/I ocean surface wind speed	Multi-satellite sea ice
SSM/I precipitation rate	SBUV/2 ozone profile and total ozone

Table 1. Satellite data used within the NCEP Global Forecast System

The SSI uses a thinning routine which identifies the optimal radiance profile for each satellite sensor type (AIRS, AMSU, HIRS, MSU, etc.) in a pre-designated grid box. The optimal radiance profile is determined by its departure from the model background temperature, distance from the center of the grid box, temporal departure from the assimilation time, and surface features (ocean, land, ice).

For this experiment, the AIRS data are thinned according to the aforementioned criteria with two more tests added. The first is a much more sensitive to cloud contamination SST check. This test uses a multiple window channel algorithm developed by Goldberg et al. 2003 with the AIRS radiances. The second test is a low-cloud/cirrus check which involves looking at the brightness temperature difference between the 3.9 µm and 11.0 µm channels and is only used at night. If the brightness temperature difference is less than 1.5K, and the SST check is within 0.8K of the model SST, the radiance profile is determined to be clear. During the day, the SST check must be within 0.2K to be considered clear.

All of the satellite sensor types are used at their full vertical resolution except AIRS. The AIRS data are thinned spectrally from 2378 to 281 channels due to data volume.

Comprehensive documentation of the global forecast model was completed by the National Meteorological Center (NMC) (now NCEP) Development Division (1988) and can be found at http://wwt.emc.ncep.noaa.gov/gmb/wd23ja/doc/web2/tocold1.html. Subsequent model developments have been summarized by Kanamitsu (1989), Kalnay (1990), and Kanamitsu et al. (1991). Updates to the radiation, surface layer, vertical diffusion, gravity wave drag, convective precipitation, shallow convection and non-convective precipitation can be found at http://sgi62.wwb.noaa.gov:8080/research/SONGYU/doc/physmrf1.html. The most recent information about the GFS atmospheric model (2003) is in NCEP Office Note #442 or http://emc.ncep.noaa.gov/officenotes/newernotes/OF442.pdf. A summary of GFS changes and references are at http://www.emc.ncep.noaa.gov/gmb/moorthi/gam.html and at http://www.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html.

For these AIRS radiance assimilation experiments, the 11/20/2003 operational version and resolution of the GFS was used. A horizontal resolution of 254 spectral triangular waves (T254) was used with a Gaussian grid of 768 X 384 or approximately equal to 0.5 X 0.5 degrees latitude and longitude. The vertical domain ranges from the surface to approximately 0.27 hPa. and is divided into 64 unequally spaced sigma layers with enhanced resolution near the bottom and top. There are 15 layers below 800 hPa and 24 layers above 100 hPa.

4. RESULTS

For this study, AIRS data were assimilated by NCEP's operational analysis at the operational resolution (T254L64). The AIRS data were spectrally reduced to 281 channels but retained their full horizontal resolution. The cloud-free AIRS radiance data were identified and used, employing the methods described earlier. NCEP's operational verification schemes were also used.

Figures 1A and B show anomaly correlation (AC) scores for the GFS over the southern hemisphere for Jan/Feb 2004 at one to seven days, with and without AIRS data for 1000 hPa and 500 hPa, respectively. Figure 1C shows the daily variations of anomaly correlation for the 5-day forecast at 1000 hPa. It is clear the AIRS data have a consistent and beneficial effect on the forecast skill over the southern hemisphere during this period. The anomaly correlations over the northern hemisphere also show improved forecast skill, but of a smaller magnitude. This was expected as the northern hemisphere has greater data coverage. Also, the AIRS data have only been used to a limited extent in the lower troposphere over land.

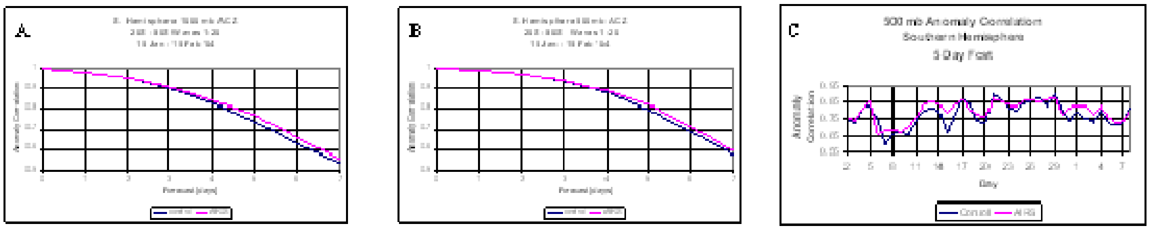

Figure 1. Anomaly correlation scores in the Southern Hemisphere for (A) 1000 hPa and (B) 500 hPa. (C) is the daily variation in 5 –day anomaly correlations.

In addition to the anomaly correlations, the geographical fore impacts were also evaluated using:

$$FI = 100 \times \left\{ \left(\sqrt{\frac{\sum_{i=1}^{N}(D_i - A_i)^2}{N}} - \sqrt{\frac{\sum_{i=1}^{N}(C_i - A_i)^2}{N}} \right) \Big/ \sqrt{\frac{\sum_{i=1}^{N}(C_i - A_i)^2}{N}} \right\} . \quad (1)$$

In (1) the first term on the right is the error in the experiment forecast. The second term is the error in the control forecast. Dividing by the error in the control and multiplying by 100 normalizes the results and provides a percent improvement with respect to the RMS error of the control forecast. A positive forecast impact means the forecast compares more favorably to the corresponding analysis. In (1) N is the total number of grid points in the diagnostic evaluation, the variables C and D are the 24 hr control and experiment forecasts respectively, and A is the 00-hr control analysis.

Figure 2 represents the 24 hr 925 and 850 hPa relative humidity geographical distribution of forecast impact for the assimilation of AIRS radiances. The largest impacts are realized over Africa and South America. Figure 3 represents the geographical distribution of forecast impact for total column precipitable water at 12 and 24 hours.

5. SUMMARY

The introduction of AIRS hyperspectral data into NCEP's GFS was anticipated to provide improvements in forecast skill. Here we have demonstrated AIRS hyperspectral data, used within stringent constraints of the operational NCEP system, have shown significant positive impact in forecast skill over the southern hemisphere for Jan/Feb 2004. Given the opportunities for future enhancement of the assimilation system, the results indicate a considerable opportunity to improve current analysis and forecast systems through the application of hyperspectral data. It is anticipated current results will be further enhanced through improved physical modeling, a less constrained operational environment allowing use of higher spectral and spatial resolution and cloudy data. The use of complementary data such as MODIS radiances and the effective exploitation of the new hyperspectral data which will become available from the Infrared Atmospheric Sounding Interferometer (IASI), the Cross-track Infrared Sounder (CrIS), the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), and GOES-R instruments also stand to enhance NWP.

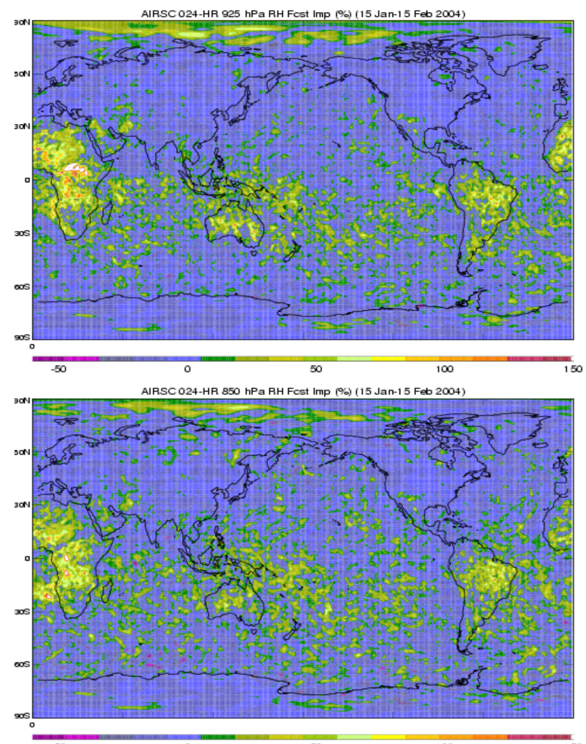

Figure 2. Geographical distribution for 925 and 850 hPa of 12 hr relative humidity forecast impact (%).

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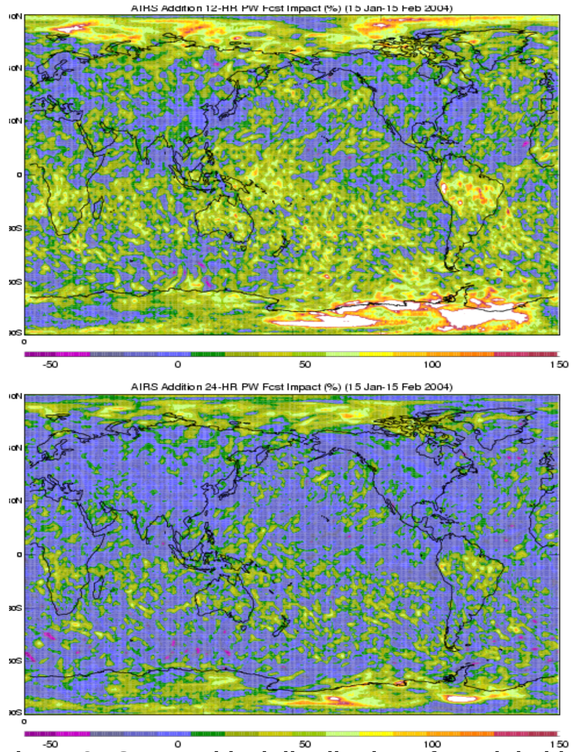

Figure 3. Geographical distribution of precipitable water of 12 and 24-hr forecast impact (%).

7. REFERENCES

Aumann, H. H., M. T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L. M. McMillin, H. Revercomb, P. W. Rosenkranz, W. L. Smith, D. H. Staelin, L. L. Strow, and J. Suskind, 2003: AIRS/AMSU/HSB on the Aqua Mission: Design, Science Objectives, Data Products, and Processing System. *IEEE Trans. Geosci. Remote Sensing*, **41**, 253-264.

Caplan, P., J. C. Derber, W. Gemmill, S. Hong, H. Pan, and D. F. Parrish, 1997: Changes to the 1995 NCEP Operational Medium-Range Forecast Model Analysis-Forecast System. *Wea. Forecasting*, **12**, 581-594.

Derber, J. C., D. F. Parrish, and S. J. Lord, 1991: The New Global Operational Analysis System at the National Meteorological Center. *Wea. Forecasting*, **6**, 538-547.

Derber, J. C. and W.-S. Wu, 1998: The use of TOVS Cloud-Cleared Radiances in the NCEP SSI Analysis System. *Mon. Wea. Rev*., **126**, 2287-2299.

Derber, J. C., P. Van Delst, X. Su, X. Li, K. Okamoto, and R. Treadon, 2003: Enhanced use of radiance data in the NCEP data assimilation system. Proceedings of the 13th International TOVS Conference. St. Adele, Canada., 20 Oct – 4 Nov.

Gaiser, S. L., H. H. Aumann, L. L. Strow, S. E. Hannon, and M. Weiler, 2003: In-Flight Spectral Calibration of the Atmospheric Infrared Sounder. *IEEE Trans. Geosci. Remote Sensing*, **41**, 287-297.

Goldberg, M. D., Y. Qu, L. M. McMillin, W. Wolf, L. Zhou, and M. Divakarla, 2003: AIRS Near-Real-Time Products and Algorithms in Support of Numerical Weather Prediction. *IEEE Trans. Geosci. Remote Sensing*, **41**, 379-389.

Hagan, D. E., and P. J. Minnett, 2003: AIRS Radiance Validation Over Ocean from Sea Surface Temperature Measurements. *IEEE Trans. Geosci. Remote Sensing*, **41**, 432-441.

Kalnay, E., M. Kanamitsu, and W.E. Baker, 1990: Global Numerical Weather Prediction at the National Meteorological Center. *Bull. Amer. Meteor. Soc*., **71**, 1410-1428.

Kanamitsu, M., 1989: Description of the NMC Global Data Assimilation and Forecast System. *Wea. Forecasting*, **4**, 335-342.

Kanamitsu, M., J.C. Alpert, K.A. Campana, P.M. Caplan, D.G. Deaven, M. Iredell, B. Katz, H.-L. Pan, J. Sela, and G.H. White, 1991: Recent Changes Implemented into the Global Forecast System at NMC. *Wea. Forecasting*, **6**, 425-435.

Kleespies, T. J., P. Van Delst, L. M. McMillin, and J. C. Derber, 2004: Atmospheric Transmittance of an Absorbing Gas. OPTRAN Status Report and Introduction to the NESDIS/NCEP Community Radiative Transfer Model. *Applied Optics*, **43**, 3103-3109.

Le Marshall, J., J. Jung, J. Derber, R. Treadon, S. Lord, M. Goldberg, W. Wolf, H.C. Liu, J. Joiner, J. Wollen, R. Todling, P. van Delst and Y. Tahara, 2005: AIRS Hyperspectral Data Improves Southern Hemisphere Forecasts. Aust. Met. Mag. 54, 57-60.

Lord, S., T. Zapotocny, and J. Jung, 2004: Observing System Experiments with NCEP's Global Forecast System. Third WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, World Meteorological Organization., Alpbach, Austria.

Pagano, T. S., H. H. Aumann, D. E. Hagan, and K. Overoye, 2003: Prelaunch and In-Flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS). *IEEE Trans. Geosci. Remote Sensing*, **41**, 265-273.

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's Spectral Statistical Interpolation Analysis System. *Mon. Wea. Rev*., **120**, 1747-1763.

Strow, L. L.,S. E. Hannon, M. Weiler, K. Overoye, S. L. Gaiser, and H. H. Aumann, 2003: Prelaunch Spectral Calibration of the Atmospheric Infrared Sounder (AIRS). *IEEE Trans. Geosci. Remote Sensing*, **41**, 274-286.

Zapotocny. T. H., W. Paul Menzel, J. A. Jung, and J. P. Nelson III, 2005a: A four season impact study of rawinsonde, GOES and POES data in the Eta data assimilation system. Part I: Total contribution. *Wea. Forecasting,* **20**, 161-177.

Zapotocny. T. H., W. Paul Menzel, J. A. Jung, and J. P. Nelson III, 2005b: A four season impact study of rawinsonde, GOES and POES data in the Eta data assimilation system. Part II: Contribution of the components. *Wea. Forecasting,* **20**, 178-198.