5.1 THE USE OF GLOBAL AIRS HYPERSPECTRAL OBSERVATIONS IN NUMERICAL WEATHER PREDICTION

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1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) was the first of the hyperspectral sounders able to provide real time data for operational and research meteorology. Over subsequent years new generation advanced sounders will become part of an upgrade to the Global Observing System. These instruments include the US Cross-track Infrared Sounder (CrIS) and the European Infrared Atmospheric Sounding Interferometer (IASI). Demonstration of the benefits of hyperspectral data on Numerical Weather Prediction (NWP) remains a high priority. Observing System Experiments (OSEs) designed to examine effective methods to use hyperspectral radiances in NWP are summarized here.

First we discuss the range of satellite data being used in the operational NCEP global forecast system. Then experiments showing the benefit of using hyperspectral radiance data, available in real-time from the AIRS instrument, in systems already using the full operational data base, are reviewed. Effective methods of data thinning and noise reduction are noted. The importance of using the full spatial resolution of the data used is documented. The importance of channel selection for NWP is shown. We also note the current use of variable hyperspectral emissivity over the entire globe and related studies. We also note a number of methods being used to detect cloud in hyperspectral fields of view. Finally, note is made of the benefits to be gained by the enhanced use of hyperspectral data in NWP and some discussion is provided on desirable characteristics for infrared sounders related to their efficient application to NWP

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2. DATA ASSIMILATION TRIALS

The Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the Northern and Southern Hemispheres (Le Marshall et al., 2005a and b) in mid 2004. This was achieved through use of an enhanced spatial and spectral AIRS observational data set in combination with an analysis methodology that paid additional attention to the possible presence of clouds. Experiments demonstrating the benefits of AIRS data assimilation and the contribution of enhanced spatial and spectral resolution data are presented below.

3. ASSIMILATION OF FULL SPATIAL RESOLUTION AIRS DATA

The impact of adding full spatial resolution (all footprints) AIRS radiance observations to the US National Centers for Environmental Prediction (NCEP) operational data base (without AIRS) was examined using the NCEP operational T254 64 level version of the Global Forecast System (GFS) (November, 2004 version). All channels for all fields of view (*fov*s) from the AIRS instrument on the AQUA satellite were processed into the current operational BUFR format. This provided 281 channels of AIRS data at each footprint of which 251 were suitable for assimilation. The NCEP operational GFS (Derber and Wu, 1998, Derber et al, 2003) using the full operational data base, available within real-time cut-off constraints and without AIRS data, was employed as the *control* ("Ops"). The data base included all available conventional data and the satellite data listed in Table1.

The radiances from the AQUA AMSU-A instrument were not included in the control or experimental data base. Radiative transfer calculations were performed using the JCSDA Community Radiative Transfer Model (CRTM), (Kleespies et al., 2004). The *experimental* system also employed the GFS with the full operational database (i.e. the control data base) plus full spatial resolution AIRS radiance data ("Ops + AIRS"), available within operational time constraints. The global analysis was modified to include the use of these AIRS data and the experimental system designed to determine the impact on real time operations of the hyperspectral AIRS radiance data.

Table1: The satellite data base used by the *control* forecasts

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

The analysis approach is described in Le Marshall et al.(2005a and b). The AIRS data were passed through the analysis screening procedure and the warmest (clearest) data were chosen for each analysis sub-grid, on the basis of the brightness temperature of the window channel information and their proximity to the center of each of the analysis sub-grids, which were a little larger than one degree squares. Another option which has been developed in the thinning process is the ability to average the stratospheric AIRS channels. This noise reducing approach has resulted in far better fitting to the upper level radiances in the six hour forecast analysis first guess. After the initial selection process, the data were subject to a stringent SST based cloud test. The model SST was compared to the SST estimated from AIRS window channel radiances using a multi-channel algorithm and the data were flagged as cloudy or clear. *At night*, the AIRS data were *initially* deemed to be clear if the AIRS determined SST was greater than the model SST minus 0.8 degrees. The data that passed this initial clear test then had to pass low-cloud/cirrus checks which involved examining the difference between the 3.4 micron and 11 micron channels. Data passing all checks were assumed to be clear of cloud. *During the day* the clear check was an AIRS based SST check. Once this enhanced dataset was prepared for the analysis and it had been determined which of the fields of view (*fov*s) were clear, the balance of the data set was further examined in relation to the forecast radiances to determine which of the individual channel radiances were cloud free. The radiances which were deemed clear by the SST and cloud checks (ie those from clear *fov*s), and those determined to be clear by the forecast check were then employed in the 3D VAR analysis down to the surface in its multivariate determination of atmospheric state. In a typical six hour global assimilation cycle approximately 200 million AIRS radiances were input to the analysis system. From these data about 2,100,000 radiances (281 radiances (channels) in approximately 7450 analysis boxes) were selected for possible use, and result in about 850,000 radiances free of cloud effects being used in the analysis process. That is effective use is made of approximately 41% of the data selected for possible use. The data volumes are summarized in Table 2.

Table 2: AIRS Data Usage per Analysis Cycle

Total Data Input to Analysis $\sim 200 \times 10^6$ radiances
Data Selected for Possible Use $\sim 2.1 \times 10^6$ radiances
Data Used in 3D VAR Analysis (Clear Radiances) $\sim 0.85 \times 10^6$ radiances

4. FULL AND REDUCED SPATIAL RESOLUTION AIRS DATA IN DATA ASSIMILATION

To examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view often used for NWP, results from a data assimilation experiment for August/September 2004 have been recorded. In this study, forecasts which used radiances from the currently available thin (one in eighteen fovs) real time AIRS data set in addition to the full operational data base ("Cntl AIRS"), have been compared to results from the use of a full spatial resolution (Spatially Enhanced, all footprints-"SpEn AIRS") AIRS data set in addition to the operational data base. In these cases the operational data base *included AQUA AMSU-A* . The trial again used the NCEP operational T254, 64 level GFS (November, 2004 version).

5. FULL AND REDUCED SPECTRAL COVERAGE AIRS DATA IN DATA ASSIMILATION

The full NCEP operational data base *including AQUA AMSU-A*, for the period 2 January – 15 February, 2004, has been used to provide a series of control analyses and forecasts from the operational NCEP operational T254 64 level GFS (June, 2005 version). The analyses and forecasts have been repeated using the full operational data base plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3µm ("short AIRS"). In a third series of analyses and forecasts, the full operational database has been used with 152 channels of AIRS data i.e., full spatial resolution, including 152 of the 281 channels currently available for real time NWP covering the full spectral range, 3.7-15.4 µm ("airs – 152ch"). In a fourth series of analyses and forecasts, the full operational database has been used with all (251 channels) of AIRS data ("airs – 251ch") i.e., using full spatial resolution, including 251 of the current 281 channels available in BUFR format for real time NWP, covering the full spectral range, 3.7-15.4 µm.

6. DATA ASSIMILATION RESULTS

7. FULL SPATIAL RESOLUTION AND SPECTRAL COVERAGE AIRS DATA

In the impact studies using full spatial resolution AIRS data with the NCEP GFS, cloud free AIRS radiance data were identified and used, via the methods described previously. The verification statistics were derived using the NCEP operational verification scheme.

A summary of the results is seen in Figures 1. It shows the geopotential height Anomaly Correlations (AC) for the GFS at 500hPa over the Northern Hemisphere for January 2004 at one to five days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast skill over the Northern Hemisphere during this period. The results for the 500hPa AC over the Southern Hemisphere for January 2004, also show improved forecast skill.

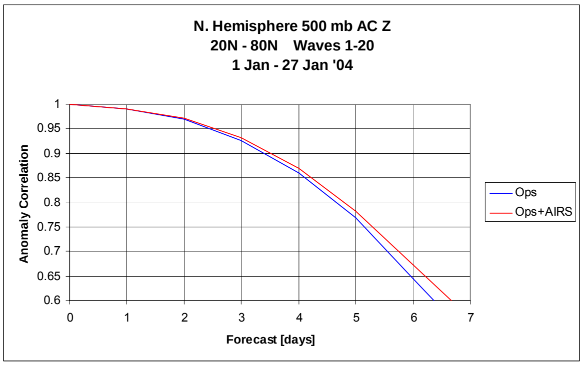

Figure 1 500hPa Z Anomaly Correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, Northern hemisphere, January 2004

During a similar series of impact studies using full spatial resolution AIRS data, an examination was undertaken of the moisture field in the lower troposphere. An example of the Forecast Impact is seen in Figure 2 where *Forecast Impact* evaluates which forecast (with or without AIRS) is closer to the analysis valid at the same time.

Forecast Impact = 100* [Err(Cntl) – Err(AIRS)] / Err(Cntl)

where the first term on the right is the error in the Control forecast. The second term is the error in the AIRS forecast. Dividing by the error in the control forecast and multiplying by 100 normalizes the results and provides a percent improvement or degradation. A positive Forecast Impact means the forecast is better with AIRS data included. Fig.2 shows a degree of improvement over a significant area in the 925hPa relative humidity in the 12 hour forecast with AIRS. Significant areas of improvement were also seen in the 850 hPa relative humidity and the Total Precipitable Water at 12 hours.

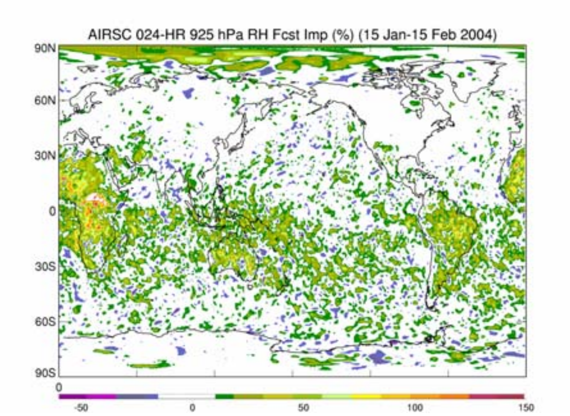

Fig 2. Forecast Impact improvement or degradation (%) of the 12 hr Relative Humidity forecast at 925 hPa .

8. IMPACT OF FULL AND REDUCED SPATIAL RESOLUTION AIRS DATA

In an experiment to examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view often used in NWP, results for an assimilation experiment in August/September 2004 are provided. In this study, forecasts which used radiances from the currently available thinned (one in eighteen fovs) real time AIRS dataset in addition to the operational data base, were compared to results from the use of a full spatial resolution (thick) data set in addition to the operational data base (see Fig. 3). In these cases the operational data base *included AQUA AMSU-A* . It is clear, the increased information related to atmospheric temperature and moisture, contained in the (thick) full spatial density data set, has resulted in improved analyses and forecasts.

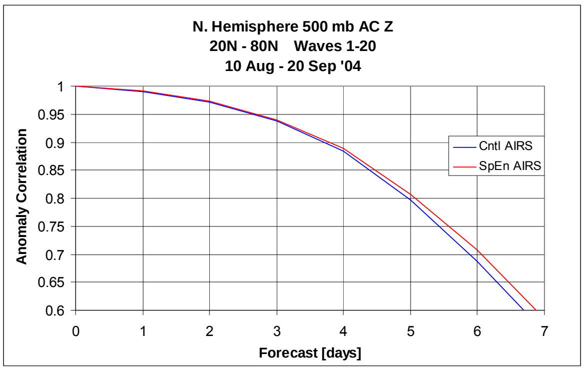

Figure 3. The 500hPa Z Anomaly Correlations for the GFS with current thinned – one AIRS fov in 18 (Cntl AIRS) and for the GFS using all AIRS fovs (SpEn AIRS), Northern Hemisphere, August/September, 2004

9. IMPACT OF FULL AND REDUCED SPECTRAL COVERAGE

Results from a comparison of forecasts from i) the control (full operational database, including AQUA/ AMSU-A), ii) using the full operational data base plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3µm (“short AIRS”), iii) a third series of analyses, where the full operational database has been used with 152 AIRS channels (central wavelengths 3.7 to 15.4 µm) of AIRS data, “AIRS-152ch”, and iv) a series of analyses and forecasts, where the full operational database has been used with all (251 channels, central wavelengths 3.7 to 15.4 µm) AIRS data, “AIRS-251ch” are displayed in Figure 5.

A Bar graph shows the 1000hPa and 500 hPa geopotential height (Z) five day forecast Anomaly Correlations for the Northern and Southern Hemispheres. It was apparent in this trial that addition of the shortwave channels (“short AIRS”) to the operational observation database generally provided a positive increment at five days with a larger improvement being seen in the Southern Hemisphere 1000hPa fields. It was also clear for this period, that *addition* of longwave channels (channels whose central wavelength is greater than 9.3µm, “airs-152ch”, “airs-251ch”) generally provided improved forecasts in each of the categories. The clear advantage from using the full spectral range with 251 channels of AIRS data was also apparent in these experiments for this period.

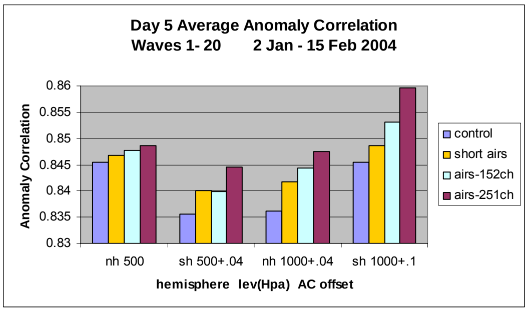

Figure 4. 1000 and 500hPa Z Anomaly Correlations for the GFS for the Control, Short (using 115 AIRS shortwave channels), airs-152ch using 152 out of the 281 channels available for real time NWP and airs-251ch using 251 out of the 281 channels available for real time NWP, Northern and Southern Hemisphere, 2 January to 15 February, 2004. An Anomaly Correlation offset has been added to each Channel set to allow display on a common graph.

In addition to use of improved spectral coverage in the radiance data base, the spectral resolution of the surface emissivity fields is now being improved in the move from the current NCEP operational SSI analysis to the next generation GSI analysis system. The new IR hyperspectral emissivity model is part of the JCSDA's Community Radiative Transfer Scheme (V1.0) , V0 is currently used in Operations. The quality of the hyperspectral emissivity fields are still being improved through use of additional data bases and also through physical modelling and estimation of emissivity using cloud free AIRS observations.

10. CONCLUSIONS

The introduction of AIRS hyperspectral data into environmental prognosis centers was anticipated to provide improvements in forecast skill. Here we have noted results where AIRS hyperspectral data, used within stringent operational constraints, have shown significant positive impact in forecast skill over both the Northern and Southern Hemisphere for January 2004. The magnitude of the improvement is quite significant and would normally take several years to achieve at an operational weather center. We have also noted the improvement gained from using AIRS at a spatial density greater than that used generally for operational NWP. In addition we have completed some studies to look at the impact of spectral coverage and found for the period studied, use of a fuller AIRS spectral coverage (251 channels) and the full AIRS spectral range, namely 3.7 to 15.4 µm, provided superior forecasts.

In conclusion, given the opportunities for future enhancement of the assimilation system and the resolution of the hyperspectral data base, 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 use of higher spectral and spatial resolution data. Further improvements may also be anticipated through use of cloudy data and the use of complementary data such as Moderate Resolution Imaging Spectroradiometer (MODIS) radiances for determining cloud characteristics. Improvements are also expected from the effective exploitation of the new hyperspectral data which will become available from the IASI, CrIS and geostationary instruments such as the Geostationary Imaging Fourier Transform Spectrometer (GIFTS).

It is also clear that in the design of future instruments, spectral and spatial resolution need be consistent with the NWP system resolution, for instance instrument spatial resolution should (if practicable/possible) result in clear data with a density optimal for the numerical analysis. In addition vertical resolution, cloud detection and surface temperature and emissivity estimation for example, should be taken into account when selecting fields for distribution to NWP Centers.

11. REFERENCES

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