THE BENEFITS OF INCREASED USE OF THE INFORMATION CONTENT OF HYPERSPECTRAL

J14.4 **OBSERVATIONS IN NUMERICAL WEATHER PREDICTION**

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1. INTRODUCTION

Expanded use of the information content of infrared hyperspectral radiance data has resulted in an improvement in the beneficial impact of these data on numerical weather prediction. The first of the new generation of meteorological advanced sounders, The Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003, Chahine et al., 2006) was launched in 2002. AIRS was able to provide hyperspectral data for operational and research use. The improved spectral resolution it provided compared to earlier passive infrared sounders, led to a significant increase in vertical resolution and accuracy in determining thermal and moisture fields and improved numerical weather prediction (NWP), (Chahine et al. 2006, Le Marshall et al. 2006). The first assimilation trials to use full spatial resolution and higher spectral resolution hyperspectral radiance data, available in real time from the AIRS are reviewed here. The results from these assimilation trials was significant improvement in forecast skill in the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS), compared to the global system without AIRS data over both the northern and southern hemispheres. A second trial was an experiment which showed the advantage of using all AIRS fields of view (fovs) in the analysis as opposed to the use of sampled fields of view (typically one-in-eighteen) often used by NWP Centers. Another trial showed the benefit of using hyperspectral data with expanded spectral coverage. Beneficial impact has also been seen in recent experiments where radiances, derived from cloudy AIRS fovs and which represent the radiance emanating from the clear part of the cloudy fovs, have been assimilated for global NWP. This impact is an indication of the potential benefit of using cloudy hyperspectral data routinely in global NWP. Generally it has been demonstrated that a more complete use of the information content in the data available from hyperspectral sounders has resulted in improved benefits to NWP. This conclusion is also supported by early experiments reporting the benefits from using IASI data. Overall, the results indicate the significant benefits to be derived from hyperspectral data assimilation and importantly the benefits yet to be gained from an enhanced use of the information content contained in hyperspectral radiance observations.

2. RECENT SELECTED AIRS DATA ASSIMILATION STUDIES

The Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the northern and southern hemispheres in mid-2004 (Le Marshall 2005a, b). This was completed using an enhanced spatial and spectral AIRS observational dataset in conjunction 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 (Le Marshall et al., 2006) are summarised below.

2.1 Assimilation of enhanced spatial and spectral resolution AIRS data

The impact of adding full spatial and enhanced spectral resolution AIRS radiances to the

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NCEP operational database (without AIRS) was examined, using the NCEP operational T254 64-level Global Forecast System (GFS), (November 2004 version). All channels for all fields of view from the AIRS instrument on the AQUA satellite were processed into the then current BUFR format. This provided 281 channels of AIRS data at each footprint, or field of view, of which 251 were found suitable for assimilation. (Note: Current operational systems usually assimilate 152 channels or less). These particular channels described most of the variance of the 2,378 AIRS channels (Susskind et al. 2003). The NCEP operational global analysis and prognosis system (Derber and Wu 1998; Derber et al. 2003) using the full operational database, without AIRS data (Zapotocny et al., 2008), was employed as the control ('Ops')

Table 1: The satellite data used by the control forecasts

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

Table 2. Conventional data used by the control forecasts

Rawinsonde temperature humidity, u and v	Surface land synoptic and Metar temperature, humidity, u and v, station pressure
AIREP and PIREP aircraft temperatures, u and v	Ship temperature, humidity and station pressure
Flight-level reconnaissance and dropsonde temperature, humidity, u and v and station pressure	Surface marine ship, buoy and c-man temperature, humidity, u, v and station pressure
ASDAR aircraft temperatures, u and v	Pibal u and v Wind Profiler u and v
MDCARS aircraft temperatures, u and v	NEXRAD Vertical Azimuth Display u and v

The database included all available conventional data and the satellite data listed in Tables 1 and 2. The radiances from the AQUA Advanced Microwave Sounding Unit-A (AMSU-A) instrument were not included in the control or experimental database. The experimental system also employed the GFS with the full operational database (i.e. the control database) plus full spatial resolution AIRS radiance data ('Ops +AIRS'), available within operational time constraints.

The experiment was performed for January 2004. The analysis methodology is described in Le Marshall et al. (2005a, b). 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 were selected for possible use, and resulted in about 850,000 radiances free of cloud effects being used in the analysis process. That is effective use was made of approximately 41 per cent of the data selected for possible utilization.

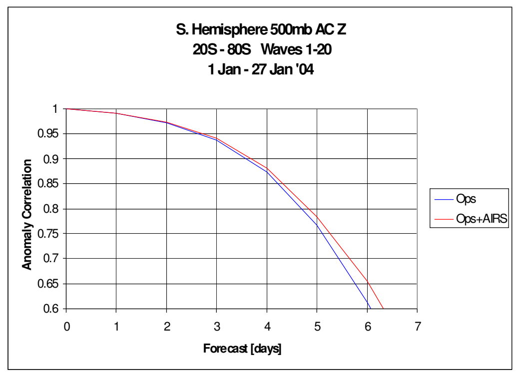

Figure 1 : The impact of AIRS data on GFS forecasts at 500hPa (20°S - 80°S),1 – 27 January 2004; the pink (blue) curve shows the AC with (without) AIRS data.

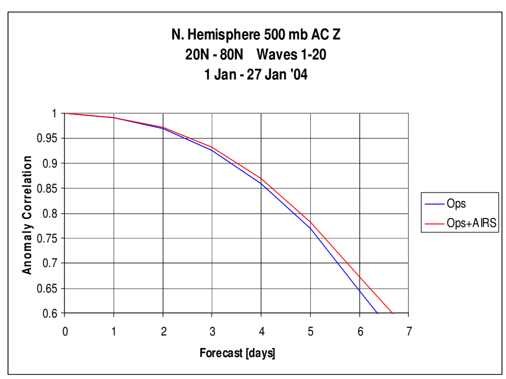

Figure 2 : The impact of AIRS data on GFS forecasts at 500hPa (20°N - 80°N), 1 – 27 January 2004; the pink (blue) curve shows the AC with (without) AIRS data.

A summary of the results is seen in Figures 1 and 2 which show the geopotential height anomaly correlations (AC) for the GFS at 500 hPa over the southern and northern hemispheres for January 2004 at one to seven days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast skill over both hemispheres during this period. This improvement is quite significant when compared to the rate of general forecast improvement over the last decade. A several hour increase in forecast range at 5 or 6 days normally takes several years to achieve at operational weather centres.

2.2 Assimilation of full and reduced spatial resolution AIRS data

To examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view used, earlier, for operational NWP, further experiments were run. In these cases, the operational control (CNTL) database was as before with the addition of AQUA AMSU-A and one in eighteen AIRS fovs. The experimental runs (SpEn AIRS) used full spatial resolution AIRS data . The trial again used the NCEP operational T254, 64 level GFS (November 2004 version). The experiments were performed during August – September 2004. Identical versions of the GFS were used in both cases

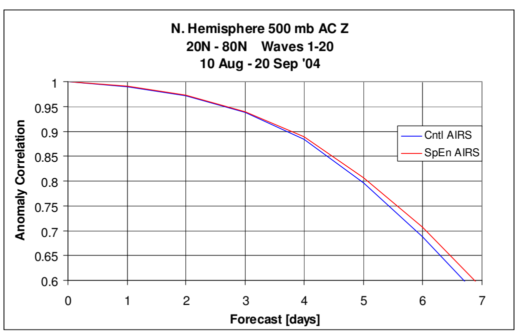

Figure 3: 500 hPa height Anomaly Correlations for the GFS with thinned – one AIRS fov in 18 (Cntl AIRS) and for the GFS using all AIRS fovs (SpEn AIRS), Northern Hemisphere, August/September, 2004

Results may be seen in Figure 3. It is clear, that the increased information related to atmospheric temperature and moisture contained in the (spatially enhanced - SpEn) full spatial density dataset and the thinning of the data set paying attention to cloud distribution, has resulted in improved analyses and forecasts. The improvement in forecast skill at 6 days is equivalent to gaining an extension of forecast capability of several hours.

2.3 Assimilation of full and reduced spectral coverage AIRS data

The Control experiment used the full NCEP operational database including AQUA AMSU-A for the period 2 January to 15 February 2004 to provide a series of control analyses and forecasts from the NCEP operational T254 64 level GFS (June 2005 version). The forecasts were then repeated using AIRS BUFR data with different channel sets, including the full set of available channels.

The analyses and forecasts were undertaken using the full operational database plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 µm (‘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. full spatial resolution, including 251 of the current 281 channels available for real-time NWP covering the full spectral range 3.7 - 15.4 µm.

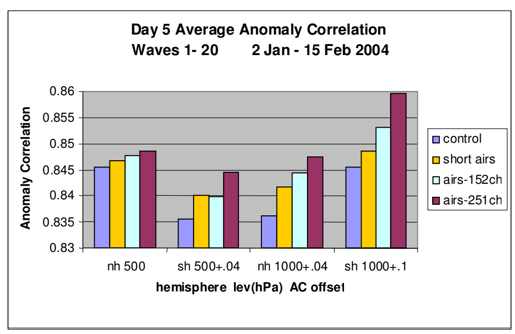

Figure 4 : 1000 and 500hPa height ACs for the GFS for the Control, Short (using 115 AIRS shortwave channels), airs-152ch using 152 out of the 281 channels available for real time NWP and airs-251ch using 251 out of the 281 channels available for real time NWP. An AC offset has been added to each Channel set to allow display on a common graph.

The results from these experiments are seen in Figure 4. This figure shows the 1000 hPa 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 short wave channels (‘short AIRS’) to the operational observation database generally provided a positive forecast skill increment at five days with a larger improvement being seen in the southern hemisphere 1000 hPa fields. It was

also clear for this period that addition of long wave 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 the experiments for this period.

During a similar series of impact studies from January 15 to February 15, 2004, using 251 AIRS channels and full spatial resolution AIRS data, an examination was undertaken of the forecast moisture field in the lower troposphere. An example of the Forecast Impact is seen in Figure 5 where *Forecast Impact* evaluates which forecast (with or without AIRS) is closer to the analysis valid at the same time.

Forecast Impact

$$=100\ (Err_{AIRSDENIAL} - Err_{Ctrl})\ /Err_{Ctrl}$$

where Err_{Ctrl} is the error in the Control forecast. $Err_{AIRSDENIAL}$ is the error in the AIRS denial 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. Figure 5 shows a degree of

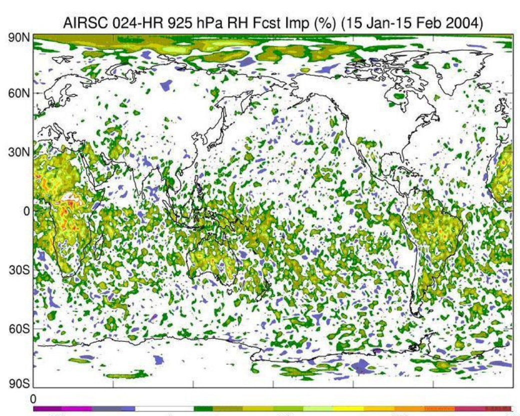

Figure 5: Forecast Impact improvement or degradation (%) of the 24 hr Relative Humidity forecast at 925 hPa .

improvement over a significant area in the 925 hPa relative humidity in the 24 hour forecast with AIRS. Significant areas of improvement were also seen in the 850 hPa relative humidity and the Total Precipitable Water at 12 and 24 hours. This result is not unexpected, given the large number of channels sensing water vapour in the full 281 channel set.

3. ASSIMILATING RADIANCES FROM CLOUDY FIELDS OF VIEW

To extend the coverage of AIRS observations employed in NWP, use has recently been made of cloud effected fields of view. As a step towards a more complete use of cloud effected radiances in NWP, fields of view with preferably single level cloud were included in variational analyses and forecasts (Le Marshall et al. 2007). The radiances used were those where the cloud coverage has allowed accurate estimation of radiances from the clear parts of the fields of view. In these initial experiments, between 1 January 2007 and 24 February 2007, the observed channel radiances in each fov, R_j is given by

$$R_j = (1-\alpha_j)R_{Clr} + \alpha_j R_{Cld}$$

where R_{Clr} is the radiance from a clear field of view, R_{Cld} is the radiance if the fov was totally covered with single level cloud and α_j is effective cloud cover. The nine fovs on each AQUA AMSU-A footprint were used to estimate R_{Clr} with the assumption that the only variability in the AIRS fovs was the cloud amount.

A fuller description of the method is found in Susskind et al., 2003. The initial experiments used the current NCEP operational configuration of 152 AIRS channels from all

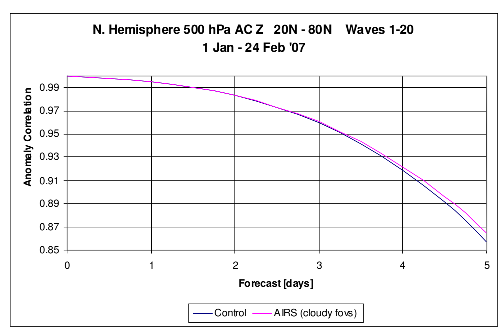

Figure 6 : The impact of AIRS data on GFS forecasts at 500hPa (20°N - 80°N), 1 Jan. – 24 Feb. 2007; The pink curve denotes use of clear radiances from clear and cloudy AIRS fovs (see text) and the blue curve denotes use of non cloud effected radiances (Control).

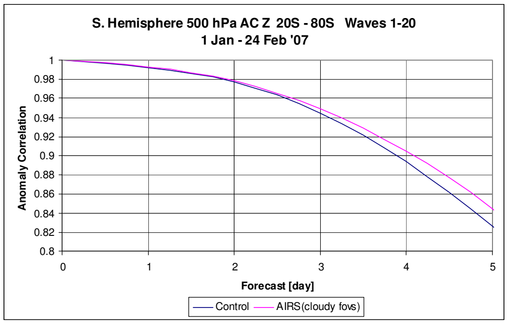

Figure 7): The impact of AIRS data on GFS forecasts at 500hPa (20°S - 80°S), 1 Jan. – 24 Feb. 2007; The pink curve denotes use of clear radiances from clear and cloudy AIRS fovs (see text) and the blue curve denotes use of non cloud effected radiances (Control).

AIRS footprints with operational thinning. The experimental runs used the operational configuration minus the operational AIRS data, and added AIRS cloud free radiances and radiances from the clear air part of selected cloudy fovs (with operational thinning).

The radiances were processed as potentially cloud-affected. Use of the data representing radiances from the clear parts of cloudy fields of view resulted in a 10% increase in this experiment in the number of channels used in the analysis from each radiance profile. Forecast verifications from northern and southern hemisphere forecasts are seen in Figures 6, 7 and 8, where the latter shows the impact of the data on the 5-day 1000 hPa and 500 hPa forecasts.

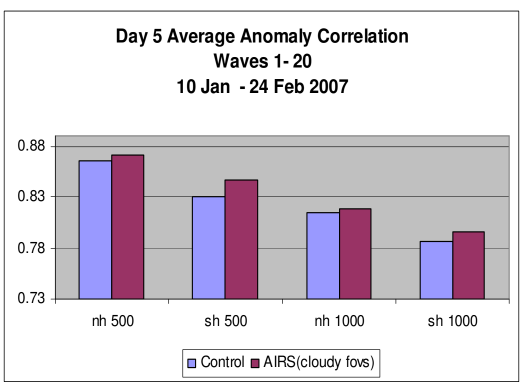

Figure 8: The impact of AIRS data on the GFS forecast at 500 and 1000hPa at 5 days. The red columns denote use of clear radiances from clear and cloudy fields of view and the blue columns denote use of AIRS radiance observations not effected by clouds.

The 500hPa results were examined taking into account serial correlation (Seaman, 1992) and the southern hemisphere results were found to be significant near the 95% level while those for the northern hemisphere were found to be significant at a much reduced level. These figures provide an indication of potential gains which may be had by the use of cloudy radiances, which provide far greater coverage than cloud free radiances alone.

4. THE OUTLOOK

Recently, NWP experiments with the current NCEP GDAS have been undertaken to examine the impact of additional hyperspectral radiance observations, from the Infrared Atmospheric Sounding Interferometer (IASI) on METOP2. The control and experimental runs used the December 2007 operational configuration of the GDAS.

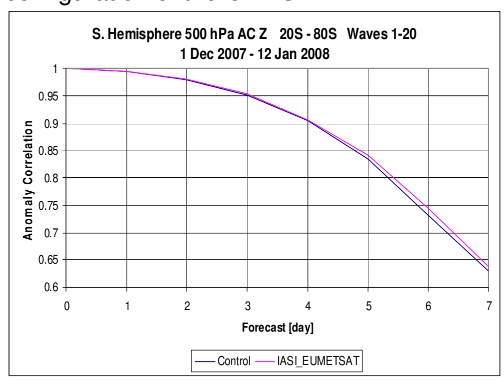

Figure 9 : The impact of IASI data on GFS forecasts at 500hPa (20°S - 80°S),1 December 2007 – 12 January 2008; the pink (blue) curve shows the AC with (without) IASI data.

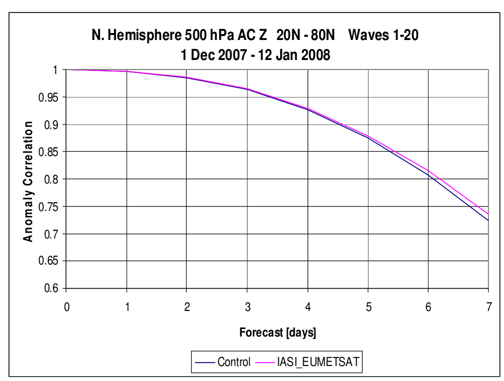

Figure 10 : The impact of IASI data on GFS forecasts at 500hPa (20°N - 80°N), 1 December 2007 – 12 January 2008; the pink (blue) curve shows the AC with (without) IASI data.

The Control experiment used the full operational database including AQUA AIRS data for the period 1 December 2007 to 12 January 2008, to provide a series of control analyses and forecasts. The experimental analyses and forecasts were then produced for the same period using IASI data plus the full operational database. In these experiments 165 IASI longwave channels were employed to improve the accuracy of the analysis. The results of this experiment can be seen in Figures 9 and 10 where it is apparent the addition of the IASI hyperspectral observations has added to the accuracy of the ensuing forecasts both in the northern and southern hemispheres.

5. CONCLUSIONS

The introduction of AIRS hyperspectral data into environmental prognosis centres was anticipated to provide significant improvements in forecast skill. In this document, results are reviewed where AIRS hyperspectral data at higher spectral and spatial resolution than usual have shown significant positive impact in forecast skill over both the northern and southern hemisphere for January 2004. The magnitude of the improvement was quite significant and would normally take several years to achieve at an operational weather centre. Also reviewed was the improvement gained from using AIRS at a spatial density greater than that initially used for operational NWP. In addition some studies have reviewed the impact of spectral coverage and they found for the period studied, use of a fuller AIRS spectral coverage and the full AIRS spectral range, namely 3.7 to 15.4 µm, provided superior forecasts. The efficacy of using higher spatial and spectral resolution data for depicting the moisture field was also recorded.

In a new experiment, to extend the use of AIRS radiances to cloudy fields of view, radiances, preferably from fields of view with single level cloud, were used. The potential for gaining improved coverage in channels sensing the lower part of the troposphere and also the potential gains in forecast skill that may be obtained by the use of radiances generated from the clear parts of cloudy fields of view were shown. Finally, results have been reported for an experiment where data from the Infrared Atmospheric Sounding Interferometer, IASI on METOP2 have been assimilated into the current NCEP GDAS and have provided positive forecast impact. This again shows an improvement in forecast capacity, with use of increased information from hyperspectral instruments.

In conclusion, the results demonstrate the significant benefits to be derived from hyperspectral data assimilation and *importantly the benefits yet to be gained from an enhanced use of the information content contained in hyperspectral radiance observations*. Given the opportunities for future enhancement of assimilation systems and for improved use of the hyperspectral database, the results indicate a considerable opportunity to improve current operational analysis and forecast systems. It is anticipated that future gains will be made through use of higher spectral and spatial resolution data and from use of cloudy data. The gains may be further increased through 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 Cross-track Infrared Sounder (CrIS) and geostationary instruments such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS).

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