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Shorter contribution

Using cloudy AIRS fields of view in numerical weather prediction

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Introduction

The Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003; Chahine et al. 2006) was launched in 2002 on AQUA, the second of the EOS polar-orbiting satellites. The AIRS was the first of a new generation of meteorological advanced sounders able to provide hyperspectral data for operational and research use.

Initially, we briefly review the first assimilation trials to use full spatial resolution and higher spectral resolution hyperspectral radiance data, available in real time from the AIRS. The result 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 (fov) in the analysis as opposed to the use of sampled fields of view (typically one-in-eighteen) often used by numerical weather prediction (NWP) centres. Another trial showed the benefit of using hyperspectral data with expanded spectral coverage. We then describe recent experiments where radiances, derived from cloudy AIRS fovs and which represent the radiance emanating from the clear part of the cloudy fov, have been assimilated for global NWP. The beneficial impact of these data in the GDAS is recorded. The impact is an initial indication of the potential benefit of using cloudy hyperspectral radiances routinely in global NWP.

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Background

After the launch of AIRS and the subsequent six-month calibration period, the sounder was able to provide operational data. The improved spectral resolution it provided, compared to earlier passive infrared (IR) sounders, led to a significant increase in vertical resolution and accuracy in determining thermal and moisture fields, increased accuracy in the determination of the concentrations of absorbers such as ozone, and improved NWP (Chahine et al. 2006; Le Marshall et al. 2006). Here, we report the use and subsequent beneficial impact of radiances derived from cloudy AIRS fields of view on global NWP.

To gain more information from the majority of the AIRS fields of view, which are covered by cloud, radiance data from AIRS fields of view, which generally contain cloud with a single cloud-top height, have been used. The differences in cloud cover in these fields of view have enabled the estimation of radiance emanating from the cloud-free portions of these fields. Use of these radiances in these experiments has resulted in improved global forecasts in both northern and southern hemispheres and is described below.

Recent AIRS data assimilation studies

In mid-2004 the Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the northern and southern hemispheres (Le Marshall 2005a,b). This was achieved through use of an enhanced spatial and spectral AIRS observational data-set over both land and sea, 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.

Assimilation of full spatial and enhanced spectral resolution AIRS data

To examine the impact of adding full spatial and spectral resolution AIRS radiances to the operational database (without AIRS), the NCEP operational T254 64-level version of the Global Forecast System (GFS) (November 2004 version) was employed. All channels for all fields of view from the AIRS instrument on the AQUA satellite were processed into the 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 fewer.) These particular channels described most of the variance of the 2,378 AIRS channels (Susskind et al. 2003) and were used for operational NWP, to limit data communication requirements and computational expense during assimilation. The NCEP operational global analysis and prognosis system (Derber and Wu 1998; Derber et al. 2003) using the full operational database, without AIRS data, was employed as the control ('Ops'). 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 analysis methodology is described in Le Marshall et al. (2005a, b). The experiment was performed for January 2004. In a typical six-hour global assimi-

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	Multi-satellite sea-ice
SSM/I precipitation rates	SBUV/2 ozone profile and total ozone

Table 2. Conventional data used by the control forecasts.

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

lation cycle approximately 200 million AIRS radiances (i.e. 200 x 106 / 281 fields of view) were input to the analysis system, providing surface, tropospheric and stratospheric information. 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 was made of approximately 41 per cent of the data selected for possible utilisation.

A summary of the results is seen in Figs 1 and 2. Figure 1 shows the geopotential height anomaly correlations (AC) for the GFS at 500 hPa over the southern hemisphere 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 the southern hemisphere during this period. Figure 2 shows the 500 hPa AC over the northern hemisphere for January 2004. The results again show improved forecast skill. 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 five or six days normally takes several years to achieve at operational weather centres.

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

Assimilation of full and reduced spectral coverage

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 data with different channel sets.

Fig. 1 **The impact of AIRS data on GFS forecasts at 500 hPa (20°S - 80°S), 1 to 27 January 2004; the pink (blue) curve shows the anomaly correlation with (without) AIRS data.**

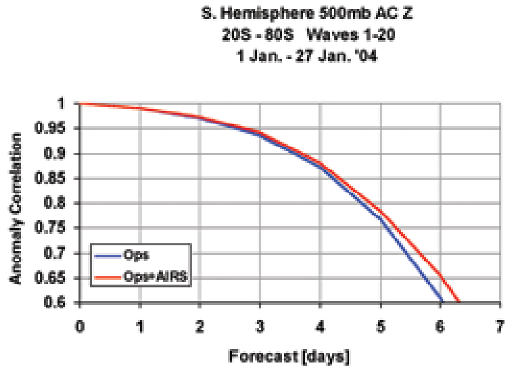


Fig. 2 **The impact of AIRS data on GFS forecasts at 500 hPa (20°N - 80°N), 1 to 27 January 2004; the pink (blue) curve shows the anomaly correlation with (without) AIRS data.**

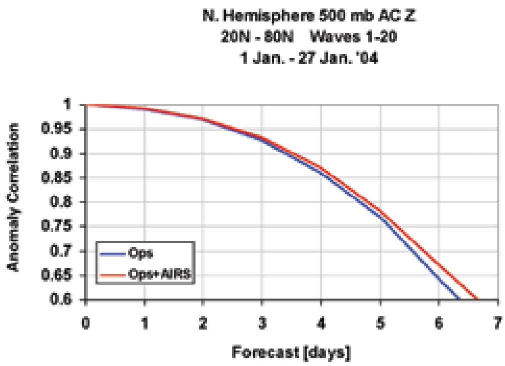
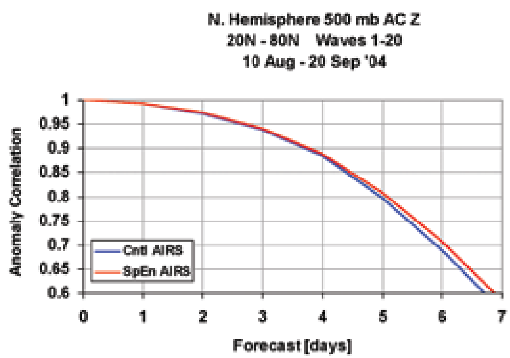


Fig. 3 **500 hPa height anomaly correlations for the GFS with thinned – one AIRS fov in 18 (Cntl AIRS) and for the GFS using all AIRS fovs (SpEn AIRS), northern hemisphere, August/September 2004**



The analyses and forecasts were undertaken for 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. The results from these experiments are seen in Fig. 4 which 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 9.3 μm, ‘airs-152ch’, ‘airs-251ch’) generally provided improved forecasts in each of the categories. The clear advantage of 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 15 January to 15 February 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 is seen in Fig. 5 where Forecast Impact evaluates which forecast (with or without AIRS) is closer to the analysis valid at the same time.

$$\text{Forecast Impact} = 100\,(Err_{AIRSDENIAL} - Err_{Ctrl})\,/Err_{Ctrl}$$

where Err_{Ctrl} is the error in the control forecast and $Err_{AIRSDENIAL}$ is the error in the AIRS denial forecast. Dividing by the error in the control forecast and multiplying by 100 normalises the results and provides a per cent improvement or degradation. A positive Forecast Impact means the forecast is better with AIRS data included. Figure 5 shows a degree of 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 281 channel set.

Fig. 4 1000 and 500 hPa height anomaly correlations for the GFS for the control, short (using 115 AIRS short-wave 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 anomaly correlation offset has been added to each channel set to allow display on a common graph.

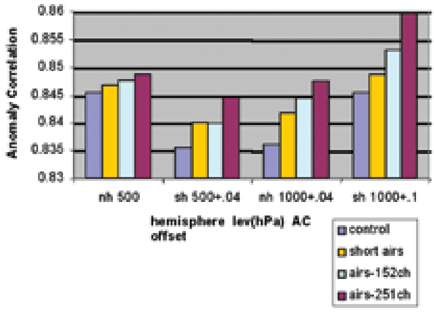
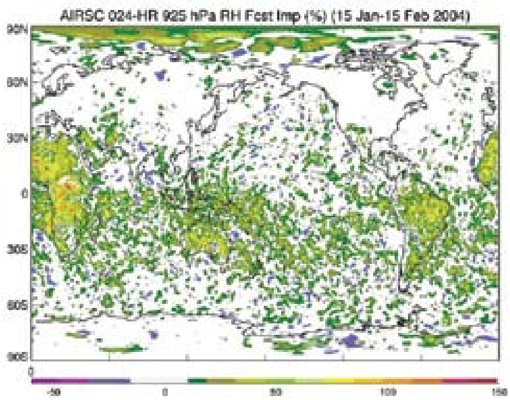


Fig. 5 Forecast Impact improvement or degradation (%) of the 24 h relative humidity forecast at 925 hPa .



Assimilating data from cloudy fields of view

Recently, attention has turned to extending the use and coverage of AIRS observations by use of cloud affected fields of view. As an initial step towards a fuller use of cloud affected radiances in NWP, fields of view with preferably single-level cloud were included in variational analyses and forecasts (Le Marshall et al. 2007). Initially, the radiances used were those where the distribution of 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 are given by

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

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 cloud amount.

A fuller description of the process is found in Susskind et al. (2003). The initial experiments used the current NCEP operational configuration – 152 AIRS channels from all 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 per cent 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 Figs 6(a) and (b) and Fig. 7, where the latter shows the impact of the data on the five-day 1000 hPa and 500 hPa forecasts. The 500 hPa results were examined employing serial correlation considerations (Seaman 1992) and the southern hemisphere results were found to be significant near the 95 per cent 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 spatial and spectral coverage than cloud-free radiances alone.

Fig. 6(a) The impact of AIRS data on GFS forecasts at 500 hPa (20°N - 80°N), 1 January to 24 February 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 affected radiances (control).

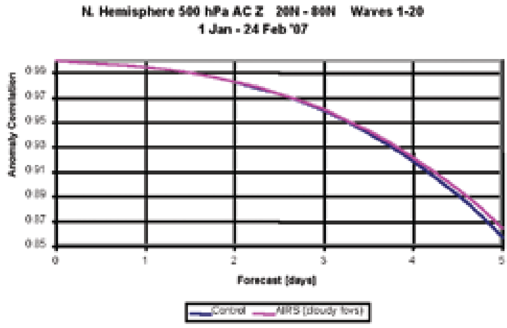
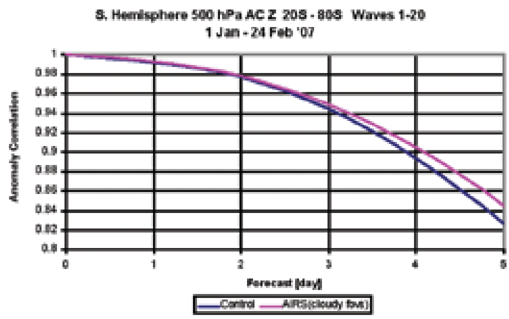


Fig. 6(b) The impact of AIRS data on GFS forecasts at 500 hPa (20°S - 80°S), 1 January to 24 February 2007; the pink curve denotes use of clear radiances from clear and cloudy AIRS fovs (see text) and the blue curve denotes use of non cloud affected radiances (control).

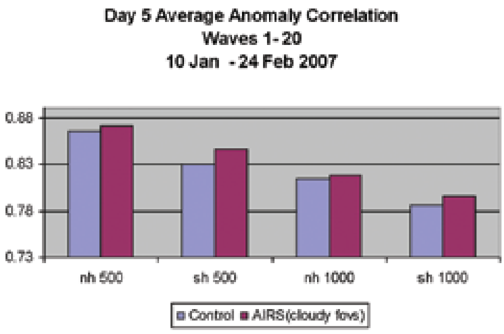


Conclusions

The introduction of AIRS hyperspectral data into environmental prognosis centres was anticipated to provide significant improvements in forecast skill. Here, we have noted results 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 is quite significant and would normally take several years to achieve at an operational weather centre. We have also noted the improvement gained from using AIRS at a spatial density greater than that initially used 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 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 has also been noted.

In a new experiment, to extend the use of AIRS radiances to cloudy fields of view, we have used radiances, preferably from fields of view with single-level cloud. We have shown 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.

Fig. 7 The impact of AIRS data on the GFS forecast at 500 and 1000 hPa at five 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 affected by clouds.



In conclusion, 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 through continued extension of the use of hyperspectral data. 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 from the Infrared Atmospheric Sounding Interferometer (IASI), and that which will become available from the Cross-track Infrared Sounder (CrIS) and geostationary instruments such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS).

Of note in this study is a first report of the forecast improvements resulting from the use of radiances in the significantly cloudy regions of the globe. The results indicate that radiances from cloudy regions of the atmosphere have the potential to provide significant information on atmospheric state in a global forecast model and their use should be further developed.

We plan to use a new BUFR format which will contain more information on the quality of the clear radiances from cloudy fields of view and to begin testing the use of raw cloudy radiances in a simple single-level cloudy inversion within the analysis (see, for example, Le Marshall et al. (1994)) as the next steps in using cloudy radiances.

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