

# Using Clear and Cloudy AIRS Data in Numerical Weather Prediction

*J. Le Marshall<sup>(1,2)</sup>, J. Jung<sup>(1,3)</sup>, M. Goldberg<sup>(4)</sup>, L-P Riishojgaard, C. Barnett<sup>(4)</sup>,  
W. Wolf<sup>(4)</sup>, J. Derber<sup>(5,1)</sup>, R. Treadon<sup>(5,1)</sup> and S. Lord<sup>(5,1)</sup>*

<sup>1</sup>*Centre for Australian Weather and Climate Research (CAWCR), Docklands, Victoria, Australia*

<sup>2</sup>*NASA, NOAA and DoD Joint Center for Satellite Data Assimilation (JCSDA), USA*

<sup>3</sup>*Cooperative Institute for Meteorological Satellite Studies CIMSS), - University of Wisconsin, Madison, Wisconsin, USA*

<sup>4</sup>*National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite Data and Information Service (NESDIS), Center for Satellite Applications and Research (STAR), Camp Springs, Maryland, USA*

<sup>5</sup>*National Oceanic and Atmospheric Administration, National Weather Service (NWS), National Centers Environmental Prediction (NCEP), Camp Springs, Maryland, USA*

## Abstract

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. Experiments which have shown the benefit of improved spatial coverage, spectral coverage and the use of moisture channel data, have been briefly summarised in this paper. In addition, an experiment which has recorded the benefit of using hyperspectral radiance data from fields of view containing clouds is also described. Again it is demonstrated that a more complete use of the information content in the observations available from hyperspectral sounders has resulted in improved benefits to numerical weather prediction. This conclusion is also supported by early experiments reported using IASI data.

## 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. After the launch of the AIRS and the subsequent six-month calibration period, the AIRS 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 numerical weather prediction (NWP), (Chahine et al. 2006, Le Marshall et al. 2006). Here, the use and beneficial impact of radiances free from cloud effects, on global NWP is reviewed. The use and subsequent beneficial impact of radiances derived from cloudy AIRS fields of view (fovs) on global NWP is also described.

The first radiance assimilation trial to use full spatial resolution and higher spectral resolution hyperspectral data, available in real time from the AIRS instrument is briefly reviewed here. The

result from this assimilation trial 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, which was an experiment which showed the advantage of using all AIRS fields of view (fovs) in analysis as opposed to the use of sampled fields of view (typically one-in-eighteen) commonly used at the time of the experiment, by NWP Centers, is also reviewed. Another trial which showed the benefit of using hyperspectral data with expanded spectral coverage is also described.

To gain more information from the majority of the AIRS fields of view, which are covered to some extent 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. Recent experiments are then described, 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 both the Northern and Southern Hemispheres on the GDAS is recorded. This may be the first example of the beneficial impact of using cloudy hyperspectral radiances in global NWP. A final experiment is also described which shows the beneficial impact of using Infrared Atmospheric Sounding Interferometer (IASI) hyperspectral data in global NWP.

## **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 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., 2006b) 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 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, 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.

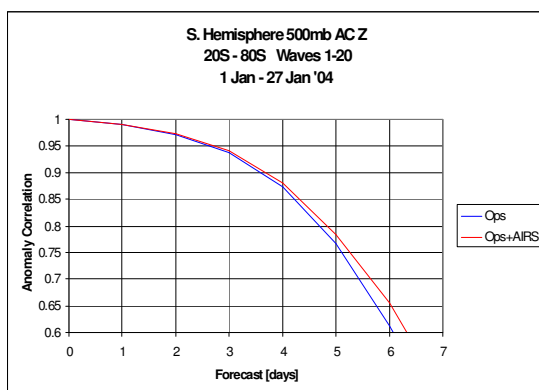
**Table 1: The satellite data used by the control forecasts**

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

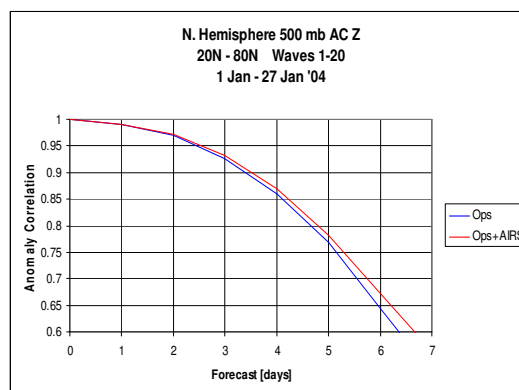
**Table 2. Conventional data used by the control forecasts**

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 & 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

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 assimilation cycle approximately 200 million AIRS radiances (i.e. 200x106 / 281 fields of view), 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 resulted in about 850,000 radiances free of cloud effects being



**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.**



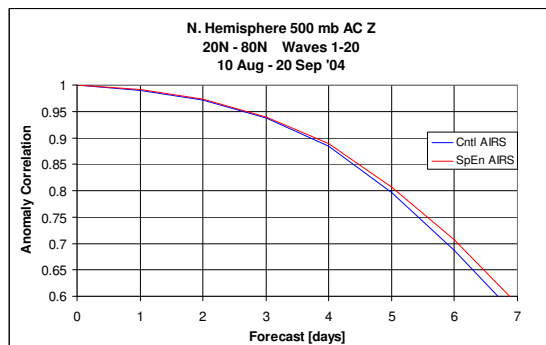
**Figure 2 : The impact of AIRS data on GFS forecasts at 500hPa (20°N - 80°N), 1 – 27 January 2004; the pink (blue) curve shows the AC with (without) AIRS data.**

used in the analysis process. That is effective use was made of approximately 41 per cent of the data selected for possible utilization.

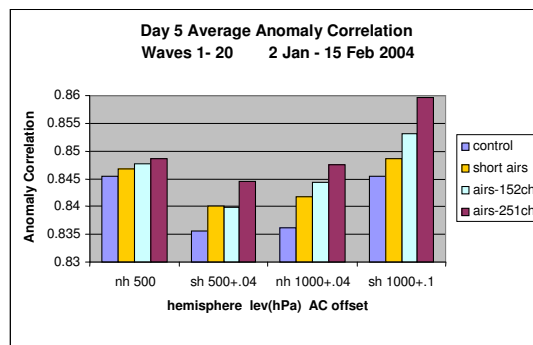
A summary of the results is seen in Figures 1 and 2. Figure 1 shows the geopotential height anomaly correlations (AC) for the GFS at 500 hPa over the southern hemisphere for January 2004 at one to seven days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast 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 5 or 6 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 Figure 3. It is clear, that the increased information related to atmospheric temperature and moisture contained in the (spatially enhanced - SpEn) full spatial



**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**



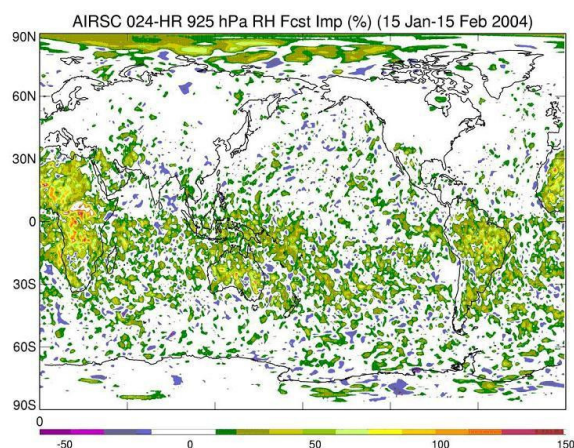
**Figure 4 : 1000 and 500hPa height ACs for the GFS for the Control, Short ( using 115 AIRS shortwave channels), aires-152ch using 152 out of the 281 channels available for real time NWP and aires-251ch using 251 out of the 281 channels available for real time NWP. An AC offset has been added to each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

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.

## 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 data with different channel sets.

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  $\mu\text{m}$  ('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  $\mu\text{m}$  ('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  $\mu\text{m}$ . 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 9.3 $\mu\text{m}$ , '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.



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

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.

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

where  $Err_{\text{Ctrl}}$  is the error in the Control forecast.  $Err_{\text{AIRSDENIAL}}$  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 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.

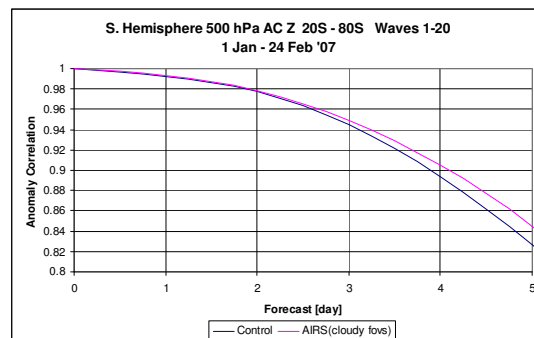
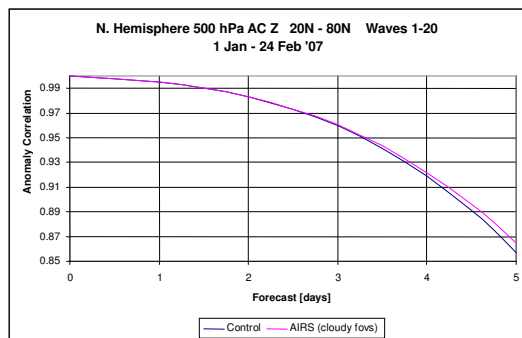
## Assimilating data from cloudy fields of view

Recently, attention has turned to extending the use and coverage of AIRS observations by use of cloud effected fields of view. As an initial step towards a fuller 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). 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,  $R_j$  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  $\alpha_j$  is effective cloud cover. The nine fofs on each AQUA AMSU-A footprint were used to estimate  $R_{Clr}$  with the assumption that the only variability in the AIRS fofs was the cloud amount.

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

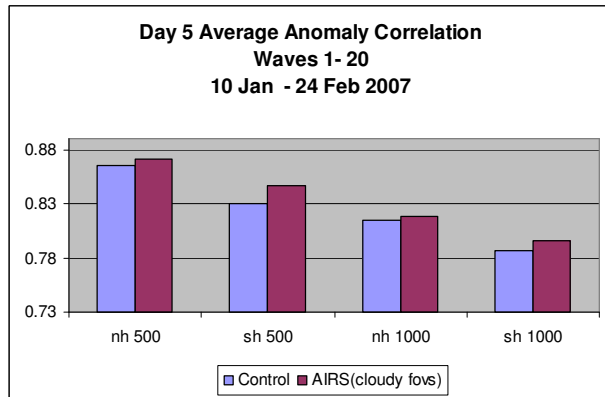


**Figure 6 (a): The impact of AIRS data on GFS forecasts at 500hPa (20°N - 80°N), 1 Jan. – 24 Feb. 2007; The pink curve denotes use of clear radiances from clear and cloudy AIRS fofs (see text) and the blue curve denotes use of non cloud effected radiances (Control).**

**Figure 6 (b): 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 fofs (see text) and the blue curve denotes use of non cloud effected radiances (Control).**

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

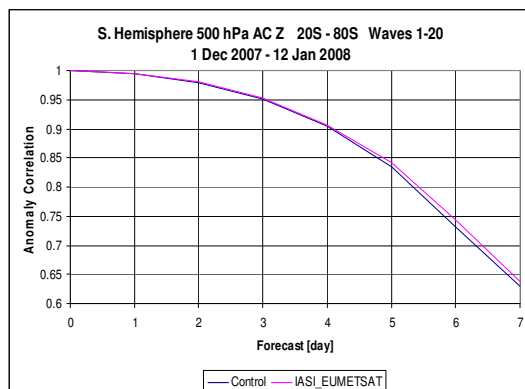


**Figure 7: The impact of AIRS data on the GFS forecast at 500 and 1000hPa at 5 days. The red columns denote use of clear radiances from clear and cloudy fields of view and the blue columns denote use of AIRS radiance observations not affected by clouds.**

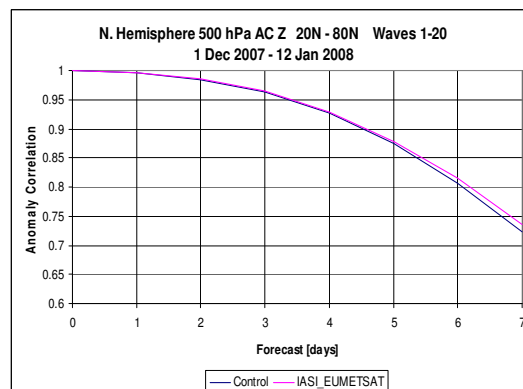
from the clear parts of cloudy fields of view resulted in a 10% increase in this experiment in the number of channels used in the analysis from each radiance profile. Forecast verifications from northern and southern hemisphere forecasts are seen in Figure 6 (a) and (b) and Figure 7, where the latter shows the impact of the data on the 5-day 1000 hPa and 500 hPa forecasts. The 500hPa results were examined employing serial correlation considerations (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 spatial and spectral coverage than cloud free radiances alone.

## The future

Recently, NWP experiments have been undertaken to examine the impact of additional hyperspectral radiance observations on the current NCEP GDAS. The additional hyperspectral data was from the Infrared Atmospheric Sounding Interferometer (IASI) on METOP2. The control and experimental runs used the December 2007 operational configuration of the GDAS. The Control experiment used the full operational database including AQUA AIRS data for the period 1 December 2007 to 12



**Figure 8 : 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 9 : 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.**



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 8 and 9 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.

## Conclusions

The introduction of AIRS hyperspectral data into environmental prognosis centres was anticipated to provide significant improvements in forecast skill. Here, results are noted 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 noted was the improvement gained from using AIRS at a spatial density greater than that initially used for operational NWP. In addition some studies have been completed to look at 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  $\mu\text{m}$ , 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, 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 from the Infrared Atmospheric Sounding Interferometer (IASI), and those 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 manuscript 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.

In terms of the future it is also intended 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 to test 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.



## References

- Aumann, H.H., Chahine, M.T., Gautier, C., Goldberg, M., Kalnay, E., McMillin, L., Revercomb, H., Rosenkranz, P.W., Smith, W.L., Staelin, D., Strow, L. and Susskind, J. 2003. AIRS/AMSU/HSB on the AQUA mission: Design, science objectives data products and processing systems. *IEEE Trans. Geosci. Remote Sens.*, **41**, 410-17.
- Chahine, M.T., Pagano, T.S., Aumann, H.H., Atlas, R., Barnet, C., Blaisdell, J., Chen, L., Divakarla, M., Fetzer, E., Goldberg, M., Gautier, C., Granger, S., Hannon, S., Irion, F., Kakar, R., Kalnay, E., Lambrigtsen, B., Lee, S-Y., Le Marshall, J., McMillan, W., McMillin, L., Olsen, E., Revercomb, H., Rosenkranz, P., Smith, W., Staelin, D., Strow, L., Susskind, J., Tobin, D., Wolf, W. and Zhou, L. 2006. AIRS Improving Weather Forecasting and Providing New Data on Greenhouse Gases. *Bull. Amer. Meteor. Soc.* **87**, 911 – 926.
- Derber, J.C. and Wu, W.S. 1998. The use of TOVS cloud cleared radiances in the NCEP SSI Analysis system. *Mon. Weath. Rev.*, **126**, 2287-99.
- Derber, J.C., Van Delst, P., Su, X.J., Li, X., Okamoto, K. and Treadon, R. 2003. Enhanced use of radiance data in the NCEP data assimilation system. *Proceedings of the 13th International TOVS Study Conference. Ste. Adele, 20 October–4 November, Canada.*
- Le Marshall, J.F., Riley, P.A., Rouse, B.J., Mills, G.A., Wu, Z.-J., Stewart, P.K. and Smith, W.L. 1994. Real-time assimilation and synoptic application of local TOVS raw radiance observations. *Aust. Meteor. Mag.*, **43(3)**, 153 – 166.
- Le Marshall, J., Jung, J., Derber, J., Treadon, R., Lord, S., Goldberg, M., Wolf, W., Liu, H.C., Joiner, J., Woollen, J. and Todling, R. 2005a. AIRS hyperspectral data improves southern hemisphere forecasts. *Aust. Meteor. Mag.*, **54**, 57 - 60.
- Le Marshall, J., Jung, J., Derber, J., Treadon, R., Lord, S., Goldberg, M., Wolf, W., Liu, H.C., Joiner, J., Woollen, J. and Todling, R. 2005b. Impact of Atmospheric Infrared Sounder Observations on Weather Forecasts. *EOS*, **86, 109**, 115, 116.
- Le Marshall, J., Jung, J., Zapotocny, T., Derber, J., Treadon, R., Lord, S., Goldberg, M. and Wolf, W. 2006. The application of AIRS radiances in numerical weather prediction. *Aust. Meteor. Mag.*, **55**, 213 - 217.
- Le Marshall, J., Jung, J., Lord, J., Derber, J., Goldberg, M., Wolf, W., Weng, F., Riishojgaard, L-P. and Yoe, J. 2007. Recent advances in satellite data assimilation. *Proceedings of the Joint 2007 EUMETSAT Meteorological Satellite Conference and the 15<sup>th</sup> AMS Satellite Meteorology And Oceanography Conference, Amsterdam, The Netherlands, 24-28 September, 2007.*
- Seaman, R. S. 1992. Serial correlation considerations when assessing differences in prediction skill. *Aust. Meteor. Mag.*, **40**, 227 - 237.
- Susskind, J., Barnet, C. and Blaisdell, J. 2003. Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB under cloudy conditions. *IEEE Trans. Geosci. Remote Sens.*, **41**, 390 - 409.