Improving tropospheric and stratospheric moisture analysis with hyperspectral infrared radiances

John Le Marshall[1], James A. Jung[2], Jin Lee[1], Chris Barnet[3] and Eric S. Maddy[4]
[1]Bureau of Meteorology
[2]Cooperative Institute for Meteorological Satellite Studies
[3]NOAA/NESDIS/SMCD,
[4]Science and Technology Corporation

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The accurate analysis of humidity fields on a global scale is essential in numerical weather prediction to forecast extreme weather and for monitoring and predicting climate. Tropospheric humidity is not well observed by the conventional observing system where radiosonde and aircraft based observations still leave large volumes unobserved, particularly over the southern oceans and in the tropics. As a result, use of satellite remote sensing is essential to produce accurate humidity fields. Through use of hyperspectral infrared radiances and a nine month Observing System Experiment (OSE) from 1 March to 30 November 2010, we show results demonstrating considerably improved analysis and short-term forecast humidity fields when verified against radiosonde data. This improvement of analysed moisture fields is potentially an important precursor to improved modeling of moisture fields and, as a result, improved prediction of severe weather, rainfall and cloud cover in a number of circumstances.

Background

Water in all its phases is not well observed by conventional observing systems, particularly in the tropics and southern hemisphere. Consequently, the generation of accurate and timely moisture fields requires effective use of earth observations from space. The use of the water vapour radiances from the High Resolution Infrared Radiation Sounder (HIRS) (Smith et al., 1979), the Microwave Humidity Sensor (MHS) (NOAA, 2007) and the Geostationary Operational Environmental Satellite (GOES) Sounder have improved the humidity fields in numerical weather prediction (NWP) analyses and forecasts. Recently, the use of the hyperspectral infrared sounders such as the Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003, Chahine et al., 2006) and the Infrared Atmospheric Sounding Interferometer (IASI) (Chalon et al., 2001, Blumstein et al., 2007) has demonstrated the potential to considerably improve tropospheric humidity fields as a consequence of their improved spectral resolution in the water vapour absorbing region and, to an extent, their improved spatial resolution (e.g. Le Marshall et al., 2006).

Historically, moisture products and, in particular, infrared water vapour radiances have been difficult to assimilate into NWP models. The reasons for the water vapour radiance observations being difficult to assimilate include; the non-linearity of their Jacobians, their multi-variate nature (the radiances measure both temperature and moisture) and the non-gaussian nature of some moisture variable's error distribution. The overall result can be a large increase in the penalty function associated with the variational analysis, poor convergence, and super-saturation in the moisture field during minimisation. One problem that has been observed in some cases in the first few hours of a forecast is excessive amounts of precipitation in regions where various precipitable water products were assimilated.

A number of methods have been tried to resolve some of these issues, including improving quality control, increasing the number of iterations used by the assimilation system, increasing the error associated with these radiances and, in some cases, just not using particular satellite channels.

Corresponding author address: John Le Marshall, email: j.lemarshall@bom.gov.au.

The water vapour channels from IASI and AIRS have also presented these challenges in terms of assimilation. The innovations (corrections to the first guess) calculated for the temperature channels are typically near zero after the first outer loop of the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System/Global Forecast System (GDAS/GFS) analysis. The innovations for the water vapour channels can continue to fluctuate throughout the assimilation cycle.

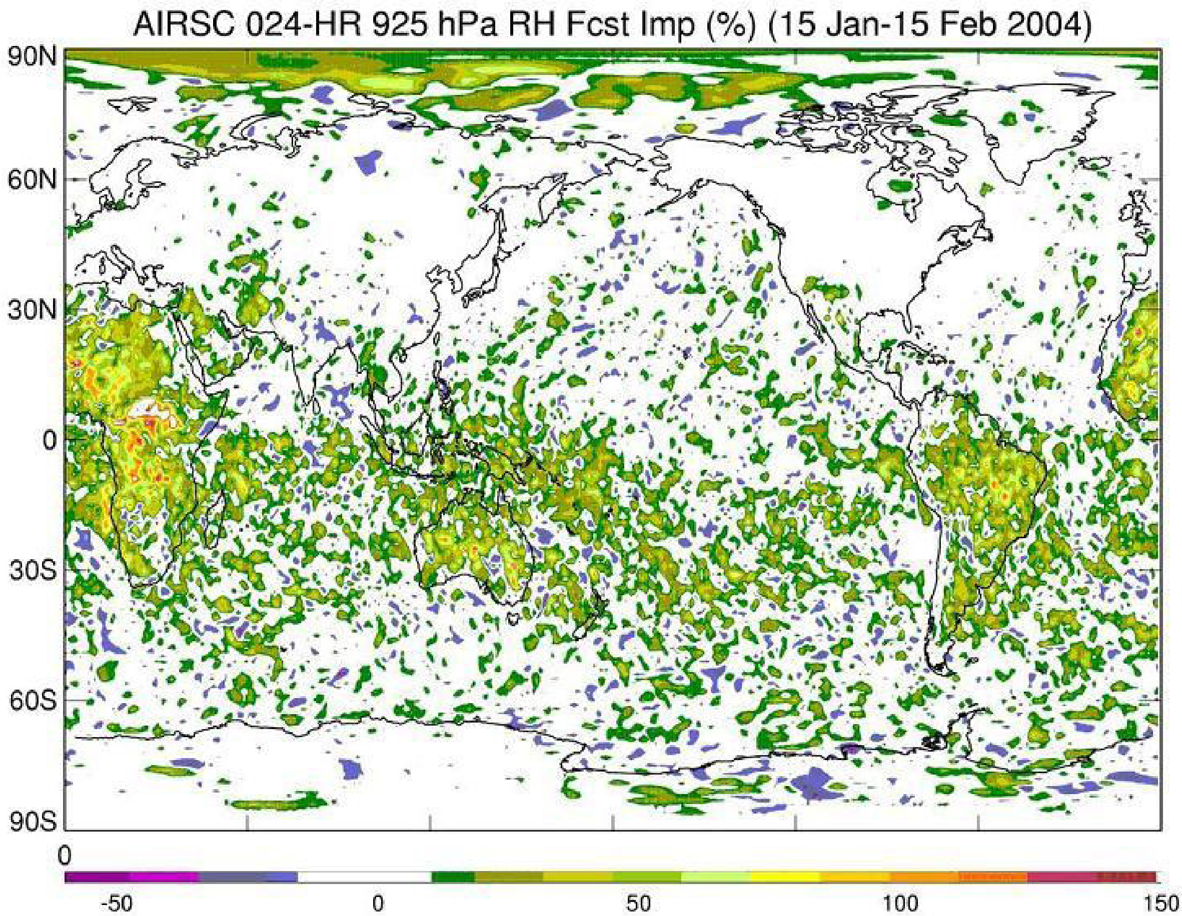
An earlier study

In an earlier study, a method for assimilating hyperspectral water vapour radiances was successfully tested. It involved perturbing the first guess moisture fields using small moisture related innovations. In the study using observations from AIRS, Le Marshall et al. (2006) examined the period from 15 January to 15 February 2004. They used the 2004 version of the operational NCEP GDAS/GFS using 251 of the available 281 AIRS channels available in binary universal form for the representation of meteorological data (BUFR) format at full spatial resolution. This included a number of tropospheric moisture channels. An examination was undertaken of the forecast moisture field in the lower troposphere produced with and without AIRS data. The forecast impact from this experiment is seen in Fig. 1 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 normalises the results and provides a percent improvement or degradation. A positive forecast impact means the forecast is better with AIRS data included. Figure 1 shows a degree of improvement over a significant area in the 925 hPa relative humidity field in the 24 hour forecast with AIRS data. 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 was not unexpected, given the large number of channels sensing water vapour in the 281 channel set used. This early experiment showed the potential benefit from using hyperspectral water vapour channels to delineate the tropospheric moisture field. As noted, it also tested a methodology for successfully assimilating water vapour radiances by continuously perturbing the first guess moisture fields using small moisture related innovations. This work is extended here to include additional tropospheric

Fig. 1. Forecast Impact improvement or degradation (%) of the 24 hr relative humidity forecast at 925 hPa.



AIRS moisture channels, stratospheric AIRS channels and tropospheric and stratospheric IASI channels.

Assimilating further channels

Recently, further studies have been conducted to more effectively exploit the information contained in the tropospheric and stratospheric moisture channels of the Advanced Sounders AIRS and IASI. In these studies, the 2010 operational version of the NCEP GDAS/GFS was used in an OSE between 1 March and 30 November 2010. The system used the 281 channel AIRS and 616 channel IASI BUFR data sets available at NCEP.

The method

As in earlier studies, an initial thresholding (guess error/difference check) of the moisture channel data being assimilated was used. Typically in the analysis, a radiance gross error/difference check has been used to catch outliers that may have passed the quality control procedures. The standard deviation is calculated by deriving a distribution of the difference between the observed radiance and the radiance calculated from the model background. The gross error check within the NCEP GDAS/GFS was typically set to about three times the standard deviation. For the infrared water vapour channels this is around 4.5 K. In an attempt to minimise the inherent problems associated with the non-linearity of the moisture related Jacobians and the multivariate nature of the channels (temperature and moisture dependence), we used the gross error/difference check as a threshold, rather than a check for outliers. By reducing the gross error/difference check, in our case to around 0.9 K, most of the problems associated with assimilating the water vapour channels were significantly reduced. The stability of the bias also improved and was similar to the temperature channels. A related method was used when assimilating AIRS data in the NCEP Spectral Statistical Interpolation (SSI) analysis in Le Marshall et al. (2006) with, as it transpires, similar beneficial results. It should also be noted similar experiments to this are also being conducted with the operational Australian Community Climate and Earth System Simulator (ACCESS) NWP system at the Bureau of Meteorology in Melbourne.

Table 1. (a) The satellite data used by the control forecasts.

HIRS radiances	TRMM precipitation rates
AIRS radiances	ERS-2 ocean surface winds
IASI radiances (temperature only)	WindSAT ocean surface winds
AMSU-A radiances	MODIS polar atmospheric motion vectors
MHS radiances	GOES atmospheric motion vectors
GOES Sounder radiances	Meteosat atmospheric motion vectors
GPS-RO	MTSAT atmospheric motion vectors
AVHRR SST , surface type, and vegetation fraction	SBUV ozone profiles and total ozone
Multi-satellite snow cover and sea ice	

The experiment

A global OSE was undertaken between 1 March and 30 November 2010 using the operational NCEP GDAS/GFS of 2010. All of the observations used at NCEP in their operational data base for the GDAS/GFS operational forecast model were used in the control runs. The operational data base is shown in Table 1 (a) and (b).

The data base includes selected moisture observations from the GOES IR Sounder, HIRS, MHS, the 281 channel subset of AIRS and the 616 subset of IASI.

For the experimental runs, the observations were the full operational data base used in the control plus 122 AIRS and IASI water vapour channels. Also, the gross error checks for MHS, HIRS, and the GOES Sounder were reduced to 2.0 K. The gross error checks for AIRS and IASI water vapour channels were set to 0.9 K.

For moisture sounding of the stratosphere, mid-wave (water vapour) channels, with a narrow spectral response close to a water vapour absorption line were used. They provided additional vertical information compared to channels with a broader spectral response function. Both AIRS and IASI have these types of channels. IASI mid-wave channels have an even narrower spectral response than AIRS and hence have a greater sensitivity to water vapour in the stratosphere. These IASI channels provide

Table 1. (b) Conventional data used by the control forecasts.

Rawinsonde temperature and humidity	Rawinsonde and PIBAL *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*
NEXRAD vertical azimuth display *u* and *v*	Wind profiler *u* and *v*

additional information to the assimilation that can benefit both stratospheric and tropospheric moisture radiance assimilation. Figure 2 is an example of Jacobians for IASI with a narrow spectral response. For comparison, the Cross-track Infrared Sounder (CrIS) at half and full spectral resolution and HIRS mid-wave channel 12 has been included. These Jacobians were generated using *k* Compressed Radiative Transfer Algorithm (kCARTA) and using the United States standard atmosphere (Anderson et al. 1986) as the input profiles. They indicate the rate of change in channel brightness temperature with change in atmospheric moisture.

In this study, the water vapour experimental runs set the gross error/difference checks on MHS, the water vapour channels of HIRS and the GOES Sounder to 2.0 K, the 29 water vapour channels on AIRS to 0.9 K and added 53 IASI channels (also at 0.9 K) mainly sensitive to moisture in the troposphere only. An additional 31 IASI and 9 AIRS water vapour channels which are sensitive to moisture in the troposphere and stratosphere were also added in addition to the 122 channels mentioned before. These channels are listed in Table 2.

The results

The results of the nine month (1 March to 30 November 2010) OSE have been analysed with particular emphasis on verification against radiosonde observations. The impact on the analysed and forecast moisture fields which arise from exploiting the extra sensitivity of the narrower spectral response of the hyperspectral instruments, improvements to radiative transfer modeling and the new data assimilation method were determined.

The improvements in the water vapour analysis and short term forecasts from these experiments are shown below. In relation to the troposphere, Fig. 3 shows the RMS difference (RMSD) time series of specific humidity at 500 hPa in the GDAS/GFS compared to rawinsondes at analysis time and for 6, 12, 24, 36 and 48-hour forecasts during March, April and May 2010 (June to November show similar results). Both the analysis and six hour forecast specific humidity statistics were significantly improved when assimilating the water vapour channels in this experiment. In this study, there was little impact on the 12 to 48 hour forecasts as a result of error growth in the moisture field related to the modelling of the hydrological cycle.

This trend of improvement in specific humidity in the analysis and six hour forecast was consistent throughout the troposphere for the experiment for the full nine month period. All model levels in the troposphere up to about 300 hPa showed similar improvements as can be seen in Fig. 4.

Overall, it would appear that additional hyperspectral moisture channels have improved the moisture analysis and short term moisture forecasts in the troposphere. This should facilitate and improve modeling of moisture in the troposphere with potential attendant benefits in areas such as severe weather prediction, rainfall prediction and cloud cover prediction.

In relation to the stratosphere, both tropospheric and stratospheric moisture channels were assimilated. The stratospheric Jacobians associated with these channels indicate less sensitivity to atmospheric moisture than is generally seen in the troposphere. After assimilation of these channels the zonal profile of the GFS stratospheric

Fig. 2. Water vapour Jacobians for IASI channel 3168 (black), which is sensitive to moisture in the stratosphere, similar CrIS channels half (red) and full (dark blue) spectral resolution and the HIRS channel 12 (light blue).

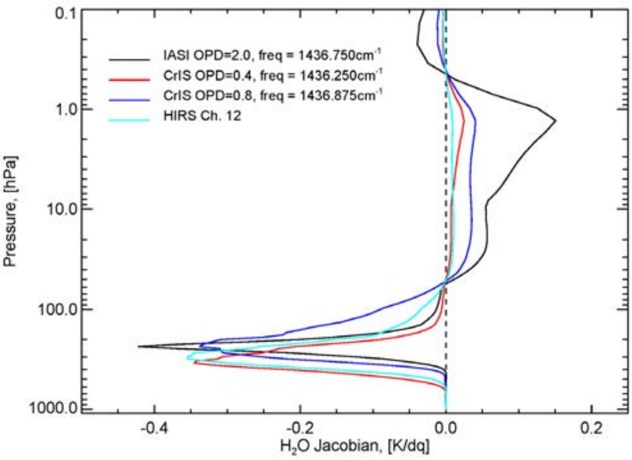


Table 2. A list of the AIRS and IASI water vapour channels added to the operational data base for the water vapour experimental runs.

Tropospheric channels	*AIRS tropospheric channels* (2378 channel set): 1301, 1304, 1449, 1455, 1477, 1500, 1519, 1545, 1565, 1583,1593, 1627, 1636, 1652, 1669, 1694, 1708, 1723, 1740, 1748, 1771, 1777, 1783, 1794, 1800, 1806, 1826, 1843, 1852
	IASI tropospheric channels (8461 channel set): 2701, 2741, 2819, 2889, 2907, 2910, 2939, 2944, 2951, 2958,2977, 2985, 3002, 3069, 3087, 3107, 3110, 3127, 3136, 3151, 3160, 3165, 3207, 3228, 3252, 3256, 3312, 3440, 3499, 3504,3509, 3527, 3586, 3599, 5368, 5371, 5379, 5381, 5383, 5397,5399, 5401, 5403, 5405, 5455, 5480, 5483, 5492, 5502, 5507,5509, 5517, 5558
Stratospheric channels	*AIRS channels:* AIRS stratospheric channels (2378 channel set): 1466, 1614, 1644, 1681, 1717, 1751, 1763, 1803, 1812
	IASI channels: IASI stratospheric channels (8461 channel set): 3168, 3248, 3281, 3309, 3378, 3416, 3442, 3444, 3446, 3448, 3450, 3452, 3454, 3491, 3506, 3555, 3575, 3577, 3580, 3582, 3589, 3638, 3653, 3658, 3661, 3700, 3726, 3888, 4032, 4095, 4160

Fig. 3. Time series of specific humidity RMS difference (RMSD) statistics with respect to rawinsonde data during March, April and and May 2010 for the (a) water vapour experiment and (b) control. The various colors are for the analysis, 6 (Ges), 12, 24, 36 and 48-hour forecasts. Note the considerable specific humidity RMSD improvement to the analysis and six-hour forecasts for the water vapour experiment (a).

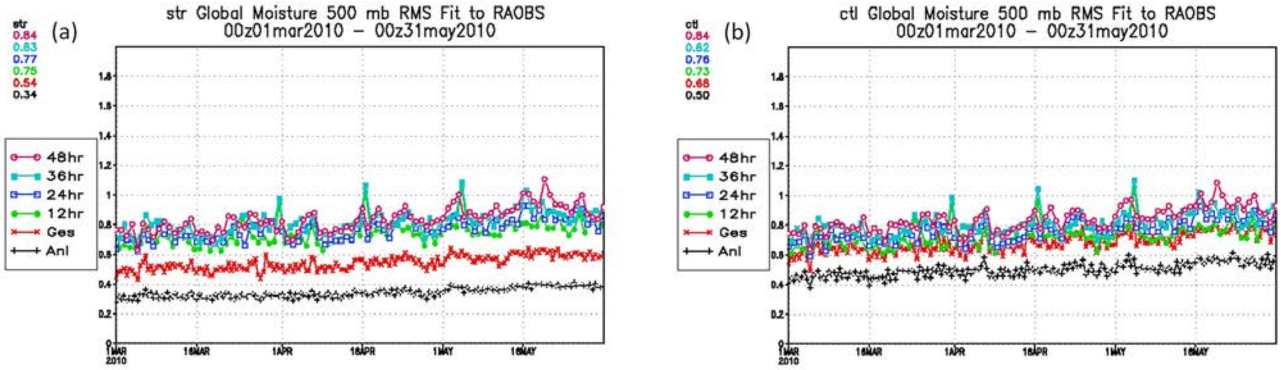
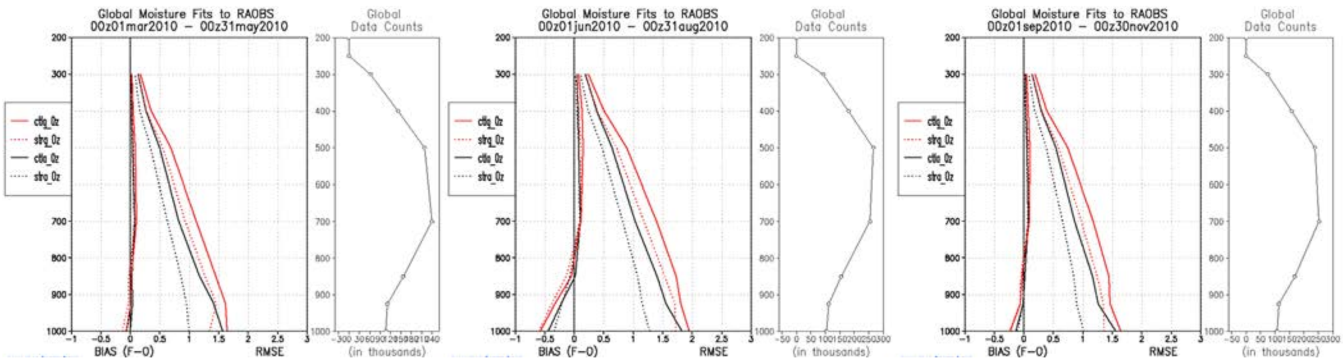


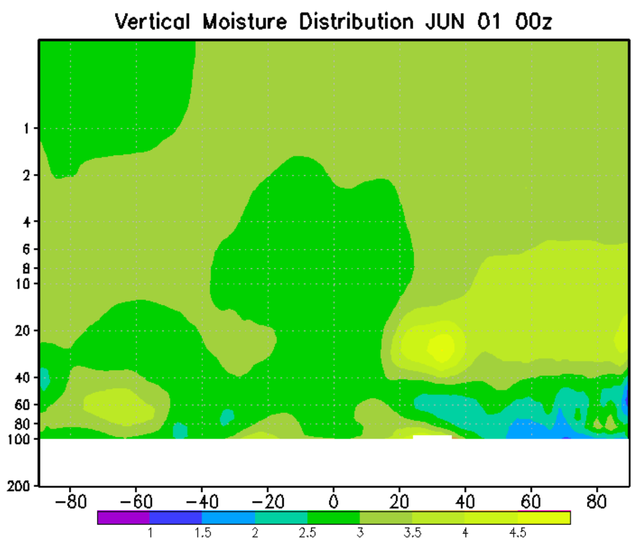
Fig. 4. Specific humidity vertical profile of bias (left) and RMSE (right) with respect to rawinsonde data during the time period of Mar–May (left), Jun–Aug (centre) and Sept–Nov 2010 (right). The solid lines are the control and the dotted lines are the water vapour experiment. Red are the first guess, black are the analysis. There are RMS improvements in specific humidity for all levels.



moisture (specific humidity) field at 0000 UTC on 1 April 2010 is shown in Fig. 5. The latter gives an indication of the vertical structure of the stratospheric moisture field. In terms of verification, the fit of the stratospheric and tropospheric moisture channels to the first guess field was improved in the experimental run, however direct verification of the accuracy of the stratospheric moisture fields is difficult as, for instance, radiosonde moisture data is not suitable for this task. Verification of these stratospheric assimilation experiments is now being pursued through use of space based data such as observations from the Microwave Limb Sounder (MLS) on the National Aeronautics and Space Administration's Earth Observing System AQUA satellite. At present, however, having additional water vapour (and temperature) data in the troposphere and stratosphere reduces assimilation errors for these channels and other observations during the assimilation process, indicating that the data may be beneficial to the analysis. These results are similar to preliminary results being found with the ACCESS model.

Water vapour also affects the heating rates throughout the atmosphere. Assimilating water vapour information in the

Fig. 5. A cross section of zonally averaged GFS stratospheric moisture field at 0000 UTC on 1 June 2010. Latitude is along the x-axis and pressure along the y-axis. Color bar units are in 10^{-6} [Kg/Kg]. Values greater than 5×10^{-6} are removed for contrast.



stratosphere also has the potential to improve the model's radiation budget thus improving longer term temperature forecasts, for example by removing temperature drift. The stratospheric temperature in the NCEP GDAS/GFS showed less drift and was more stable with time when the narrow spectral response water vapour channels (both tropospheric and stratospheric) from AIRS and IASI were assimilated. This is not however, a direct measure of the accuracy/utility of the moisture field and this remains an area for future investigation.

The future

Future improvements to the analysis of moisture fields appear to be possible from the current and future hyperspectral observing systems. Similar sensitivity to stratospheric water vapour of AIRS may be possible from CrIS if the mid-wave band water vapour channel observations are transmitted to the ground at full spectral resolution (transmission in this mode is technically possible.) In this mode, CrIS will have spectral resolutions comparable to AIRS, a factor of two improvement over the current CrIS instrument configuration. CrIS also has lower noise and greater spectral coverage than AIRS. The lower noise of CrIS will improve the sensitivity to stratospheric water vapour. The fact that CrIS has broader spectral coverage will allow selecting more stratospheric channels, and allow further reduction of noise by signal averaging. The next generation IASI is planned to have an even narrower spectral resolution (0.25 cm^{-1}) than the current IASI. This should also improve NWP water vapour analyses. It is important to note similar improvements in the assimilation of other trace gases are also possible with the narrower spectral responses of these hyperspectral radiances.

Summary and conclusions

The narrow spectral response of AIRS and IASI in the mid-wave region allows data assimilation systems to exploit more water vapour information than from normal broad band sensors.

In the experiments reported here, it has been shown that the use of these tropospheric and stratospheric moisture channels has considerably improved the accuracy of tropospheric moisture fields in NCEP global model analyses and forecasts. The humidity field has been improved on a global scale which is potentially of benefit for operational NWP in predicting extreme weather, climate monitoring and forecasting. It is also interesting to note recent advances in radiative transfer/data assimilation have also been obtained with the advent of these hyperspectral sensors (eg. Strow et al., loc. cit.).

In summary, a number of current operational NWP models are yet to exploit the full water vapour information content of current observed hyperspectral radiances. We have shown the potential advantage of assimilating additional moisture channels into an operational NWP system. The results indicate a considerable improvement in tropospheric moisture fields. The IR hyperspectral sounders have constrained both the tropospheric and stratospheric water vapour. These constraints have had a positive impact on the resultant horizontal and vertical moisture distribution. In this study, the improved moisture distribution has also led to reduced temperature drift in stratospheric temperature forecasts in the NCEP model.

In conclusion, it appears that the global NWP moisture analysis can be improved by the inclusion of selected additional hyperspectral moisture channels. In the future it could be expected even further use of hyperspectral moisture channels (eg. with CrIS and the next generation IASI) would again provide further improved global moisture analyses.

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