Issues in the assimilation of cloud and precipitation affected radiances and prospects for future instruments

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ABSTRACT

The assimilation of radiances affected by cloud and precipitation remains an important area of research and development in remote sensing for weather and climate. For many years efforts have focused primarily on the identification and avoidance of cloud and precipitation when assimilating satellite data. Increasingly more sophisticated data assimilation and radiative transfer is allowing new opportunities for using cloudy radiances, especially those only weakly sensitive to cloud or only sensitive to one aspect of the cloud (e.g. its liquid water content). In this paper three techniques are compared which adopt different approaches to solving the problem. Two involve analysing cloud in order to try and extract as much temperature and humidity information as possible from instruments whose primary purpose is atmospheric sounding. The third approach presented also uses data from a sounding instrument but the focus is extracting information on cloud liquid water. The potential for future missions is discussed, focusing on proposals for a sub-mm mission for ice cloud and polarimetric radiometry for near surface ocean wind vectors.

1. Introduction

A conventional view of satellite remote sensing is that clouds are opaque in the infrared region of the spectrum and transparent in the microwave. Neither statement is true and but both hint at the problem which must be solved in using different spectral bands. The absorption and scattering of light by hydrometeors depends primarily on their size and dielectric properties. Although the dielectric properties of pure water change rapidly with frequency in the microwave region, the main parameter influencing the changing scattering and absorption is simply the wavelength of observation with respect to hydrometeor size. This is especially true for ice hydrometeors. As the wavelength of observation is increased the radiation reaching a satellite sensor originates deeper in the cloud. For the infrared sometimes it is a good approximation to consider the cloud to be opaque and therefore radiating as a black body corresponding to a cloud top temperature. In the far infrared through to the sub-mm part of the spectrum, the radiating depths are still primarily in the top region of clouds which are usually composed of ice hydrometeors. It should be noted that the ice hydrometeors absorb weakly so the source term for sub-mm remote sensing of ice cloud is primarily scattered light. In the microwave the thermal radiation can originate from the liquid phase of the cloud or even from below the cloud. Therefore the longwave part of the microwave region (< 15 GHz) is the only direct spaceborne passive remote sensing of precipitation. Between 15 and 40 GHz microwave radiometers provide the only passive spaceborne information on cloud liquid water (other than visible observations by day). The sub-mm and far infrared could potentially provide the only passive spaceborne measurements of cloud ice water and microphysical parameters. The hydrometeor size to which the observations are most sensitive changes through the sub-mm region. In the infrared the highest sensitivity is to small particles (~10 μm). In the sub-mm the highest sensitivity is to large particles (~100-1000 μm). In terms of the bulk physical cloud properties, microwave to sub-mm wavelengths give unique information on many aspects of a precipitating cloud. However the long wavelengths make remote sensing of clouds at these wavelengths very expensive. The achievable field of view size is limited by diffraction and at 10 GHz is of order 40 km from a 800 km polar orbit even with a large and expensive antenna (antenna size for the Advanced Scanning Microwave Radiometer

(AMSR) was 2 m; AMSR-E antenna size was 1.6 m but the Aqua satellite orbits at 700 km). A 40 km field of view is too large for convective scale precipitation processes. At 89 GHz a field of view size of 5 km has been achieved by AMSR but the 89 GHz channel has a particularly non-linear sensitivity to cloud parameters, and it is sensitive to many aspects of the cloud. In the sub-mm convective scale fields of view are achievable from a low earth polar orbiting satellite, of order a kilometer, but the sensitivity is to ice cloud only not directly from precipitation. From geostationary orbit antenna sizes are prohibitively expensive to achieve a useful field of view size below 100 GHz. Only in the sub-mm (and shorter wavelengths) are field of view sizes of order tens of kilometers realistic from geostationary orbit and this is too large for convective scale processes. For this reason infrared observations of cloud, though only providing information about the environment at or near the cloud top, remain very important. Only these observations are sensitive to clouds on the spatial and temporal scale of the convective cloud processes. Many attempts have been made to combine microwave and infrared measurements as they are providing very different information about clouds. However in this instance the information is so different it has proven difficult to do this effectively. The intermediate sub-mm frequencies have never been used on a cloud remote sensing mission but provide unique and potentially very valuable information with a useful horizontal scale. The potential of the sub-mm for cloud remote sensing is discussed in more detail in section 4.

Whilst from the perspective of achieving a complete description of cloud processes passive microwave measurements have inadequate spatial and temporal resolution, data assimilation for numerical weather prediction has different requirements. The models only resolve large scale cloud processes, a scale of tens of kilometers. This is consistent with the spatial scales of the microwave observations in low earth orbit or sub-mm observations from geostationary orbit. Section 3 examines an attempt to assimilate radiances affected by cloud liquid water from the Advanced Microwave Sounding Unit (AMSU).

In the next section two different approaches for cloud screening data are discussed.

2. Cloud screening of data

In data assimilation systems a balance is sought between the complexity of the observation operator and the data screening prior to assimilation. For example if no attempt is made to model cloud effects on a radiance measurement the data screening must ensure no cloud-affected radiances are assimilated. The vast majority of satellite data is pre-screened for cloud and precipitation affects. Exceptions include C-band scatterometer and GPS radio occultation. These observations sense the spectrum at wavelengths over 5cm and both scattering and absorption by cloud and rain are negligible. Figure 1 illustrates the effect of cloud and rain screening on Ku-band scatterometer, microwave temperature sounding observations, microwave humidity sounding observations and infrared temperature sounding observations.

In Figure 1 it can be seen that, as expected, the largest loss of data due to cloud and rain screening is for the infrared data, with the microwave humidity sounder losing a significant but lower amount of data, the microwave temperature sounder less still (but still with significant gaps). The QuikScat usually has good coverage, as it operates without difficulty in the presence of cloud, but there are gaps due to heavy precipitation. There are no gaps in the ERS-2 scatterometer coverage, though this is only available in selected regions.

For microwave observations the cloud screening is complex as the cloud effects are changing rapidly with wavelength due both to size parameter changes (ratio of hydrometeor size to wavelength of observation) and dielectric changes and the respective importance of scattering and absorption is also changing. Add to that the variation in the water vapour continuum, which is strong above 50 GHz and the variability of the surface emissivity and it readily becomes apparent that microwave cloud screening needs a range of window channels to infer correctly the impact of cloud and rain on the main sounding bands at 50 GHz (temperature) and 183 GHz (water vapour).

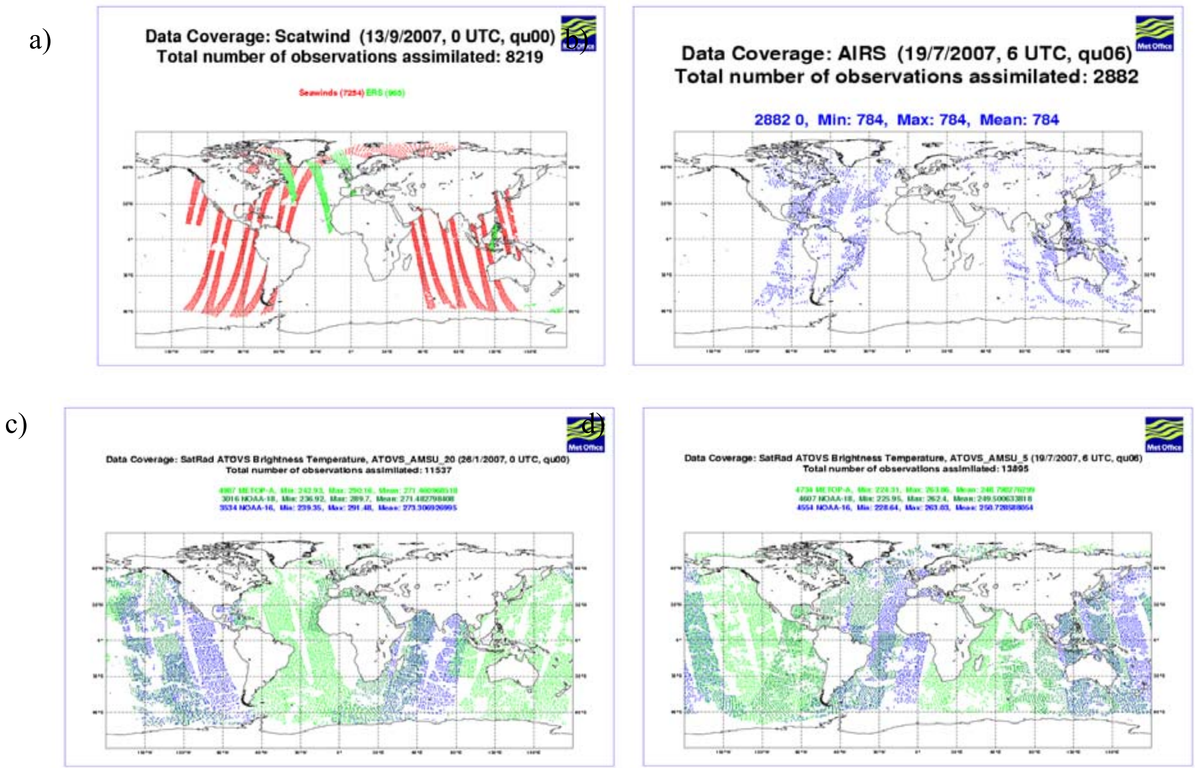

Figure 1: Data coverage for (a) QuikScat and ERS-2 scatterometer (b) AIRS, (c) MHS, (d) AMSU-A illustrating loss of data due to rain and cloud screening.

3. 1D-var analysis of cloud

3.1. AIRS cloud analysis

It has already been demonstrated that AIRS provides information of unprecedented quality. McNally et al. (2006) showed that when data from one satellite instrument is assimilated at a time AIRS data provides the largest single impact. It has also been shown that less conservative use of AIRS (more channels, higher spatial resolution when data first presented to the data assimilation, lower assumed observation errors, more use of AIRS above cloud top) can increase the impact of AIRS. Pavelin *et al.* (2007/8) proposed that if cloud could be analysed in 1D-var using a simple cloud model and radiative transfer model then channels with Jacobians primarily sensitive to the atmosphere above the cloud top could be assimilated. They performed a study using simulated data which proved the concept and subsequently ran assimilation experiments which have demonstrated useful positive impact from the additional AIRS data above cloud. They compared their method to the approach used at ECMWF (McNally and Watts 2003) and the performance is similar. However the Pavelin *et al.* scheme could be extended to allow for increasingly complex cloud radiative transfer and microphysical modelling, allowing the possibility of a less strict screening of cloudy radiances in future.

3.2. EOF analysis of cloud and rain affected AMSU and MHS radiances

Boukabarra *et al.* (2007) proposed that cloud and precipitation profiles could be represented in eigenvector space and the leading eigenvectors used as control variables in a 1D-var using AMSU and MHS data in cloudy regions. The eigenvector analysis reduces the state space allowing convergence to be achieved, even in very difficult situations such as hurricanes. Full details are given in Boukabarra *et al.* but the paper demonstrates the eigenvector representation of the profile within 1D-var works well in cloud-free conditions and for microwave observations of cloud and rain profiles. Boukabarra *et al.* also showed that the method could be extended to analysing surface emissivity, though this was not working well for all surfaces.

4. Direct assimilation of cloud affected AMSU radiances

O'Keeffe *et al.* (2006) attempted to assimilate AMSU radiances directly in 4D-var even in the presence of liquid water using a cloud incrementing operator. The method uses a single total water moisture control variable in 4D-var and an incrementing operator which relates increments in total water to increments in specific humidity, temperature and liquid water which are model variables in a perturbation forecast model (which evolves increments in time). It was assumed that the cloud radiative transfer modelling was very good. There is evidence supporting this from aircraft experiments described in English (1995) and in Figure 2 it is shown that the modelling of the cloudy radiances by RTTOV-8 from a six hour forecast produces a realistic guess. Bias corrections from cloud-free conditions were applied to all data and observation errors were set at 4 K, the same values used in cloud-free conditions.

Surprisingly significant positive impact was found on mass fields from assimilating the liquid water information and the first guess fit to the AMSU data most sensitive to liquid water was also significantly improved.

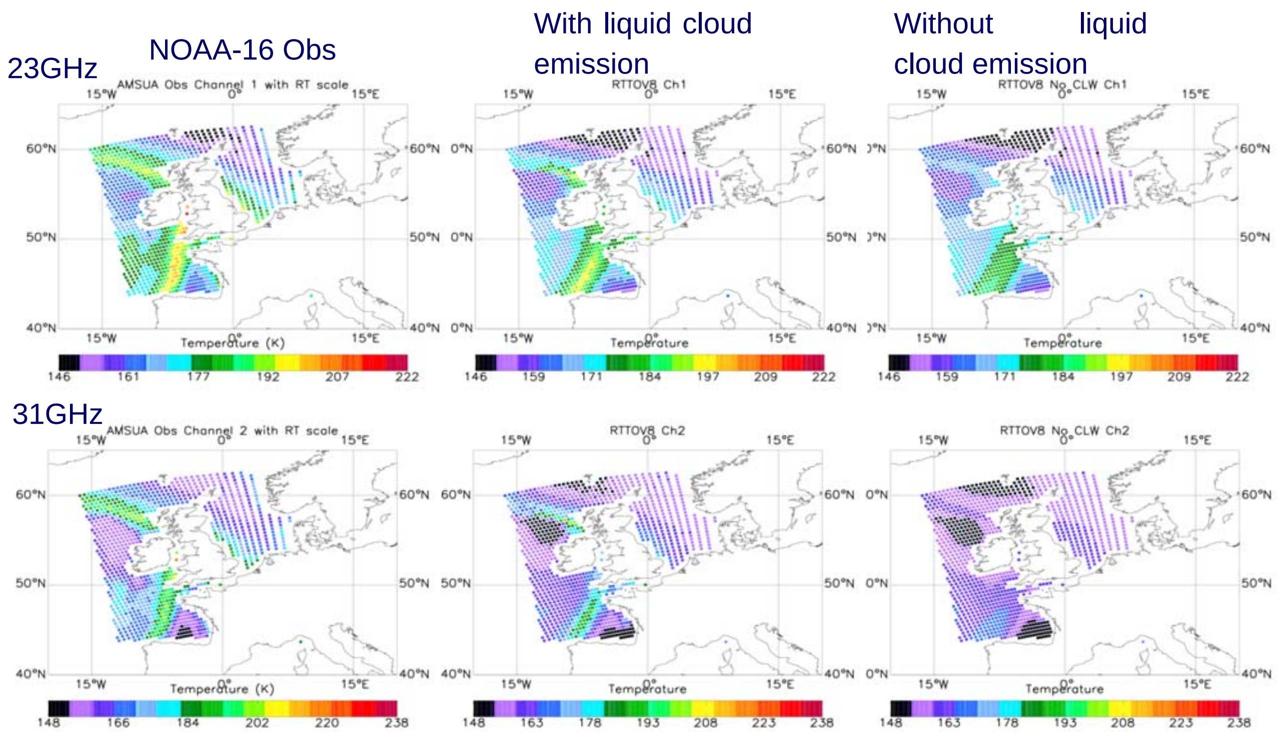

Figure 2: Short range (six hour) Met Office mesoscale model forecast fit to AMSU-A window channel radiances with and without use of model cloud liquid water simulated using RTTOV-8.

5. Potential of future instruments

5.1. Sub-mm missions for ice remote sensing

In section 1 the variation of scattering by hydrometeors with wavelength was noted to vary rapidly through the sub-mm spectral range. At 100 GHz only ice hydrometeors in excess of 0.2 mm give rise to significant scattering. As these particles are rather rare they do not contribute significantly to the total scattering coefficient at much shorter wavelengths. It has been proposed (Kunzi *et al*., 2001, Evans *et al.* 2005, Buehler *et al.* 2007) to build a radiometer with many channels in the sub-mm region. with these channels selected carefully to avoid trace gas spectral features and to have comparable water vapour absorption strength. The water vapour would effectively mask emission from low altitudes so such a sensor would be an all-terrain, all-weather ice water content monitoring mission, providing information on ice water path, ice particle size and, if dual polarised, some information on ice particle habit. Some proposals also have sounding channels at a range of wavelengths through the sub-mm which would enable very coarse changes in the vertical structure of the ice cloud to be detected.

Climate models vary by an order of magnitude in their climatology of ice water path (John and Soden 2006). Doherty *et al.* (2007) and Deblonde *et al.* (2007) have shown the inconsistency in ice analysis from NWP models and the difficulty this poses in modelling satellite radiances. A mission to measure the sub-mm for ice cloud monitoring for the first time is therefore a credible proposal which deserves serious consideration.

5.2. Polarimetric radiometry

It has been shown how important a high quality microwave imager is for cloud and precipitation monitoring. One possible spin-off from such a mission is wind vector products, if the mission provides measurements of the full polarisation state. This potential was recognised by Wentz (1992), and Gaiser and Ruf (2006) describe the WindSat mission, which has provided the first fully polarimetric passive microwave measurements in space. English *et al.* (2006) discuss the application in full but in essence it relies on the fact that anisotropic emission leads to signals in the 3rd and 4th elements of the Stokes vector. These anisotropic effects arise primarily from different paths encountered in surface reflection and therefore, to a reasonable approximation, all signal in the 3rd and 4th elements arises from the anisotropy of the surface, with the signal attenuated but not added to by the atmosphere. Over the ocean the anisotropy arises from waves, which at shorter scales align with the instantaneous wind vector. Therefore the wind direction can be obtained. Windspeed can be obtained from dual polarised microwave measurements as it has a large impact on surface reflectance. Despite being scientifically new, WindSat used tested technology to measure the full Stokes vector. The wind vector retrievals have been developed rapidly and the quality now matches QuikSCAT at high windspeed. The signal is too weak at windspeeds less than 5ms^{-1} to provide useful information. English *et al.* (2006) showed that QuikSCAT data above 5ms^{-1} are responsible for most of the extra-tropical impact for medium range forecasts but that the lower windspeeds are important at shorter range (particularly the one day forecast) and in the tropics. This result was then confirmed by English *et al.* (2007) with real WindSat wind vectors once the WindSat wind vector product was considered mature enough to justify longer assimilation trials. The fit of various sources of near surface wind vector information was compared with background by comparing the zonal wind from a six hour forecast with the observed zonal wind. Fig. shows that the root mean square fit to background for WindSat, QuikSCAT and the ERS scatterometer are comparable, whereas ASCAT is slightly better. In situ measurements generally fit the model less well than satellite estimates.

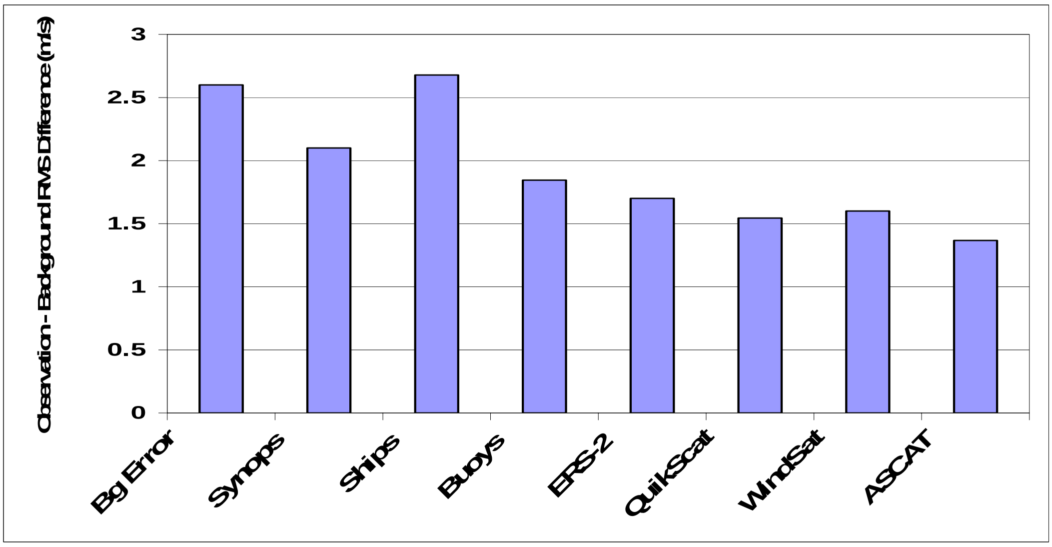

Figure 3: Fit of short range (six hour) forecast zonal wind to various wind observations. The background error (bg error) assumed in the data assimilation is also plotted.

6. Conclusions

This short report has shown that the state of the art in processing of cloud and precipitation affected radiances is advancing on two fronts. Firstly increasingly sophisticated techniques are being used to isolate the radiances unaffected by cloud (e.g. because they peak above cloud) or by modelling small residual effects of cloud on radiances, especially at microwave frequencies. However little progress has been achieved assimilating information below cloud using partly cloudy infrared observations. The second front is showing success in assimilating the cloud and rain information both in the form of radiances (as described herein) and as retrieved geophysical quantities (Deblonde *et al.* 2007). It has been argued that sub-mm frequencies would meet a requirement for ice water observations which is not currently met by the global observing system and which is important, especially for climate models. Finally it was shown that polarimetric radiometry can provide much of the impact of scatterometer, but with notable exceptions in the tropics and at short range owing to the lack of sensitivity to wind direction for windspeeds below 5ms^{-1}.

References

Buehler, S. A., C. Jimenez, K. F. Evans, P. Eriksson, B. Rydberg, A. J. Heymsfield, C. Stubenrauch, U. Lohmann, C. Emde, V. O. John, T.R. Sreerekha and C.P. Davis, 2007. A concept for a satellite mission to measure cloud ice water path and ice particle size, *Q. J. R. Meteorol. Soc*., in press.

Boukabara S-A, F. Weng, R. Ferraro , L. Zhao , Q. Liu , B. Yan, A. Li, W. Chen, N. Sun, H. Meng, T. Kleespies, C. Kongoli, Y. Han, P. Van Delst, J. Zhao and C. Dean., 2006: Introducing NOAA's Microwave Integrated Retrieval System (MIRS). In *Proceedings of ITSC*-15, Maratea, Italy. Ed. R. Saunders and T. Achtor. Available from http://cimss.ssec.wisc.edu/itwg/.

Doherty, A.M., T.R. Sreerekha, U.M. O'Keeffe and S.J. English, 2007: Ice hydrometeor microphysical assumptions in radiative transfer models at AMSU-B frequencies. *Q. J. Royal Meteorol. Soc*. **133** 1305-1212.

Deblonde G., Mahfouf J. F., Bilodeau B., 2007: One-dimensional variational data assimilation of SSM/I observations in rainy atmospheres at MSC. *Mon. Wea. Rev.,* **135**, 152-172.

English, S. J. 1995: Airborne radiometric observations of cloud liquid water emission at 89 and 157 GHz: Application to retrieval of liquid water path. *Q. J. Royal Meteorol. Soc*. **121**, 1501-1524.

English, S.J. , B. Candy, A. Jupp, D. Bebbington, S. Smith and A. Holt, 2006: An evlaution of the potential of polarimetric radiometry for numerical weather prediction using QuikSCAT. *IEEE Trans. Geosci. Remote Sensing*, **44**, 668-675.

English, S.J., B. Candy, D.Bebbington, 2007. Final report on potential of polarimetric radiometry for numerical weather prediction, *ESA Contract Report* CAO/CB/02.1025.

Evans, K. F., J. R. Wang, P. E. Racette, G. Heymsfield, L. Li, 2005: Ice cloud retrievals and analysis with data from the Compact Scanning Submillimeter Imaging Radiometer and the Cloud Radar System during CRYSTAL-FACE. *J. Appl. Meteor*., **44**, 839–859.

Gaiser P.W and C. Ruf, 2006: Foreward to the special issue on the WindSat spaceborne radiometer – calibration/validation and wind vector retrievals. *IEEE Trans. Geosci. Remote Sensing*, **44**, 467-468.

John, V. O. and B. J. Soden 2006. Does convectively-detrained cloud ice enhance water vapor feedback?, *Geophys. Res. Lett*., **33**, L20701.

Kunzi, K., 2001: Cloud Ice Water Sub-millimetre Imaging Radiometer (CIWSIR). Submitted in Response to the Second Call for Proposals for Earth Explorer Opportunity Missions. Available from http://www.sat.ltu.se/projects/ciwsir/

McNally AP, Watts PD, 2003: A cloud detection algorithm for high-spectral-resolution infrared sounders . *Q.J.R.Meteorol Soc*. **129**, 3411-3423.

McNally AP, Watts PD, Smith JA, Engelen R, Kelly GA, Thepaut JN, Matricardi M, 2006: The assimilation of AIRS radiance data at ECMWF. *Q.J.R. Meteorol Soc*., **132**, 935-957.

O'Keeffe, U., M. Sharpe and S.J.English, 2006. Assimilation of cloudy AMSU-A microwave radiances in 4D-Var. *Proceedings of the 3rd IPWG Workshop*, Melbourne, 23-27 October 2006. Eds: B. Ebert, J. Turk and A. Hollis. Available from http://www.isac.cnr.it/~ipwg/.

Pavelin, E., English S.J. and Eyre J.R., 2007/8: The assimilation of cloud-affected infrared satellite radiances for numerical weather prediction. Submitted to *Q. J. Royal Meteorol. Soc.* 2007. Expected to appear in 2008.

Wentz, F.J., 1992: Measurement of oceanic wind vector using satellite microwave radiometers. *IEEE Geosci. Remote Sensing*. 30, 960-972.