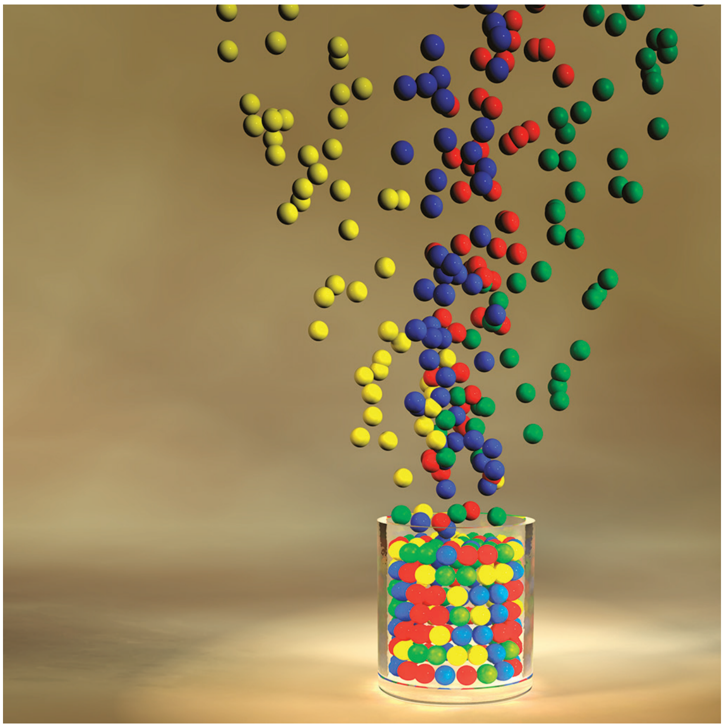
ECMWF Feature article

from Newsletter Number 116 – Summer 2008

METEOROLOGY

Improving the radiative transfer modelling for the assimilation of radiances from SSU and AMSU-A stratospheric channels



www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/e7hab85vrt

This article appeared in the Meteorology section of ECMWF Newsletter No. 116 – Summer 2008, pp. 43-47.

Improving the radiative transfer modelling for the assimilation of radiances from SSU and AMSU-A stratospheric channels

Shinya Kobayashi, Marco Matricardi, Dick Dee, Sakari Uppala

Stratospheric analyses using satellite observations have been available for almost three decades. They provide important information about the dynamical behaviour of the upper atmosphere. There has been a growing concern about the changing amounts of trace constituents in the upper atmosphere, where they protect life from solar ultraviolet radiation. The abundance of trace constituents is controlled by their transport as well as the chemical processes. Thus high quality stratospheric analyses are required for the accurate analysis and prediction of trace constituents. Another role of stratospheric analyses is to provide numerical weather prediction (NWP) systems with "boundary conditions". The radiances observed by the tropospheric channels are partly sensitive to the temperature structure in the stratosphere, because their weighting functions extend to the stratosphere. Thus accurate stratospheric analyses are important to produce good quality initial conditions for NWP.

Stratospheric temperature analyses, dominated by satellite data, are strongly affected by the possible biases in stratospheric channels. Changing bias characteristics are often reflected in stratospheric temperature analyses as jumps that correspond to satellite transitions or drifts due to slower changes in biases. These artificial features can mask the true climate signals and make it difficult to estimate reliable long-term temperature trends. Thus biases in observations have to be accounted for to produce a consistent atmospheric dataset that is appropriate for climate research.

Satellites make indirect observations of physical properties of the earth system. Use of satellite data in an assimilation system requires a fast radiative transfer model (RTM) to simulate radiances using model fields. Several different RTMs are in use at NWP centres, e.g. the radiative transfer model for TOVS (RTTOV) (*Saunders et al.,* 1999) and the Community Radiative Transfer Model (CRTM) (*Kleespies et al.,* 2004). Especially for early satellite instruments, biases can be generated by improper characterization of the spectral response functions or by changes in the concentration of radiatively active constituents that are unaccounted for in the RTMs. Those biases in the RTMs have to be addressed when using satellite observations for atmospheric reanalysis.

Inter-satellite biases

Stratospheric temperatures have been retrieved from radiance observations made by the NOAA polar orbiting satellites since 1978. Data from infrared channels of the Stratospheric Sounding Unit (SSU) on the TIROS-N to NOAA-14 satellites has been used to retrieve stratospheric temperature information. From NOAA-15 onward the SSU was replaced by a higher vertical resolution microwave instrument, the Advanced Microwave Sounding Unit (AMSU-A). Raw SSU radiances were first assimilated in a reanalysis carried out at ECMWF (ERA-40) and more recently in the Japanese 25-year Reanalysis (JRA-25). Both reanalyses encountered difficulties in fully utilising the SSU radiance data due to large biases in the background temperatures combined with inadequate data coverage for much of the period. Particularly problematic periods are the early 1980s, when SSUs had large inter-satellite biases, and the late 1990s, when AMSU-A data first became available.

Figure 1 shows time series of inter-satellite biases between NOAA-6 and NOAA-7 for SSU channel 3 over the Antarctic, estimated using the Simultaneous Nadir Overpass (SNO) technique (*Cao et al.,* 2005). This technique compares observations made by different satellites at the same time and location. Since both instruments sense the same atmospheric profiles, this comparison produces reliable estimates of the inter-satellite biases that are entirely attributable to differences in the radiometric and spectroscopic performance of the instruments. The seasonal dependence of the relative biases evident in Figure 1 can be correlated with the lapse rate in the upper stratosphere, indicating that the weighting functions are not identical.

The inter-satellite radiance differences between SSU and AMSU-A were also estimated with the SNO technique – see Figure 2. The discrepancy between the measured radiance differences and the differences simulated using RTTOV is especially significant in spring and winter. This is not easily explained by instrument errors alone, which suggests that the RTTOV radiance simulations themselves might be inaccurate.

doi:10.21957/e7hab85vrt

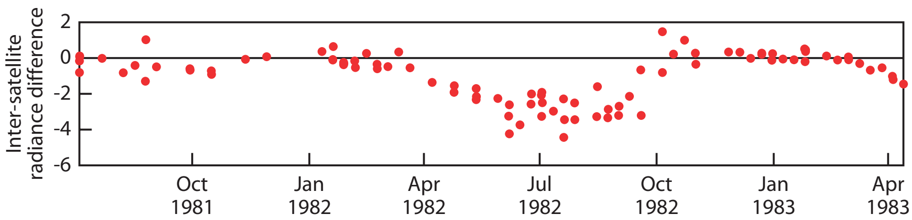


Figure 1 Inter-satellite differences between radiance measurements from SSU channel 3 on NOAA-6 and NOAA-7 over the Antarctic, obtained with the SNO technique.

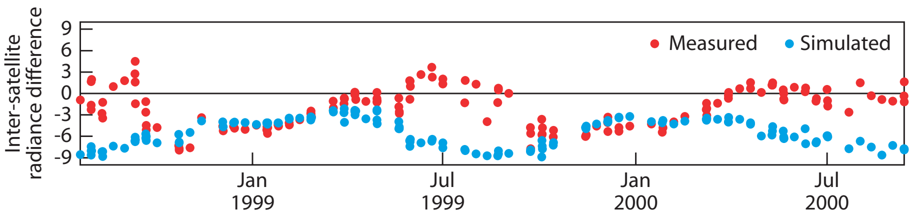


Figure 2 Inter-satellite differences between radiance measurements from SSU channel 3 on NOAA-11 and AMSU-A channel 14 on NOAA-15 over the Antarctic, obtained with the SNO technique (red) and the corresponding simulated differences using RTTOV (blue).

Radiative transfer modelling – SSU

SSU is a three-channel infrared radiometer designed to measure radiances in the 15 µm carbon dioxide absorption band. The SSU uses a pressure modulation technique where the pressure in a cell of carbon dioxide gas in the instrument's optical path is varied in a cyclic manner. The spectral performance of the instrument depends on the mean cell pressure whose long-term stability is crucial for time-consistent observations. As it turned out, a sealing problem caused cell pressures to increase during storage on the ground and then to decrease after launch. The Met Office, which produced the instrument, has routinely monitored and recorded the mean cell pressure at six-month intervals subsequent to the launch of each spacecraft. Figure 3 shows daily values of the mean cell pressures estimated from these records. The gradual reduction of cell pressure affects the level of peak energy for the SSU channels. Figure 4 shows typical changes to the weighting functions. The channels most affected are channels 2 and 3, which both peak in the upper stratosphere.

We studied the impact of the recorded SSU cell pressure changes by accurately modelling their effect on the radiances using the LBLRTM line-by-line model (*Clough et al.,* 2004). Figure 5 shows time series of the line-by-line simulated inter-satellite biases for the same pair of satellites shown in Figure 1, together with the actual biases obtained with the SNO technique. Although discrepancies between the observed and simulated inter-satellite biases still exist (possibly due to uncertainties in the band-pass filter and the calibration algorithm), the seasonal cycle is much better captured in the line-by-line calculations. On this basis, new RTTOV coefficients for the SSU have been generated that properly take into account the variation of the mean pressure in the carbon dioxide cell.

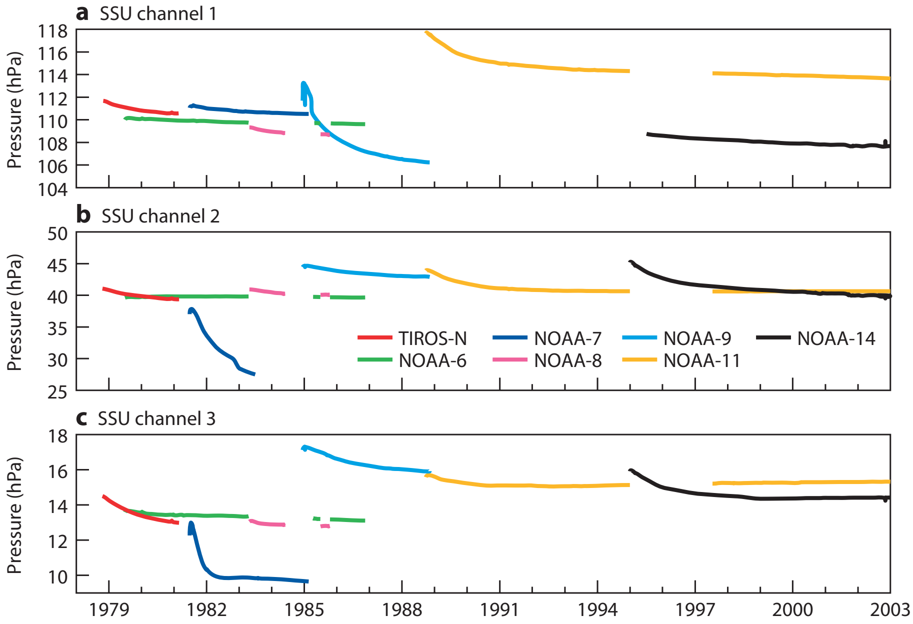


Figure 3 Daily values of the mean cell pressures for channels 1, 2 and 3 of all the SSU instruments are shown as time series. The values have been interpolated from the Met Office's six-monthly estimates using a linear relationship between the mean cell pressure and the modulation frequency.

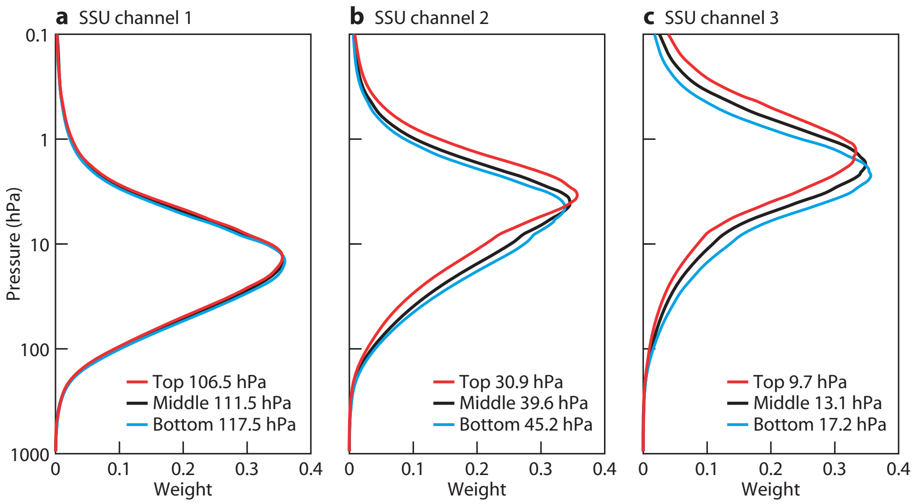


Figure 4 Impact of the changes in mean cell pressure on the weighting functions for (a) channel 1, (b) channel 2 and (c) channel 3 of the SSU for the US Standard Atmosphere 1976 with carbon dioxide at 330 ppmv (parts per million by volume).

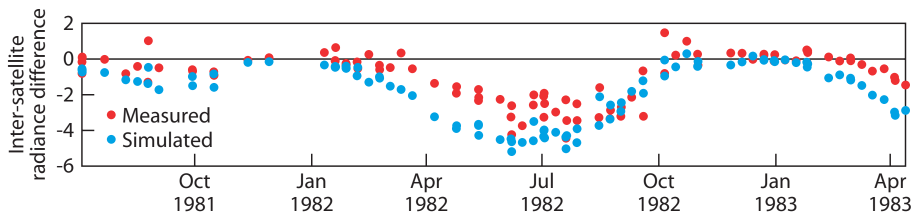


Figure 5 Inter-satellite differences between the radiance measurements from SSU channel 3 on NOAA-11 and AMSU-A channel 14 on NOAA-15 over the Antarctic, obtained with the SNO technique (as shown in Figure 1) and the corresponding simulated differences using the LBLRTM model to account for the pressure loss in the carbon dioxide cell.

doi:10.21957/e7hab85vrt

Radiative transfer modelling – AMSU-A

AMSU-A is a multi-channel microwave radiometer designed to retrieve vertical profiles of temperature from about 3 hPa (45 km) to the surface. The AMSU-A stratospheric channels measure the radiance originating from the 60-Ghz oxygen absorption lines. These magnetic-dipole absorption lines are split by the terrestrial magnetic field. This splitting is due to the Zeeman effect which is particularly important at low pressures when the magnitude of the line splitting is comparable to or smaller than the line width and can thus affect the high-peaking stratospheric channels of AMSU-A.

RTTOV represents the Zeeman effect by a scalar approximation described in *Liebe et al.* (1993), which models the effect simply by increasing the line-broadening parameter for the oxygen absorption lines. We compared attenuation rates at frequencies that include the pass bands of AMSU-A channel 14, using three alternative representations of the Zeeman effect: the RTTOV scalar approximation; explicit simulation using a line-by-line model; and omission of the Zeeman effect. Figure 6 shows that the scalar approximation is accurate at the frequencies near the centre of the oxygen absorption line, but overestimates the attenuation rates within the pass bands of AMSU-A channel 14. As shown in Figure 7, this results in an anomalous upward shift of its weighting function.

Figure 7 also shows that for AMSU-A channel 14 the RTTOV weighting function computed without the Zeeman effect is much closer to that obtained by explicit simulation. Therefore the scalar approximation of the Zeeman effect results in radiance simulations that are less accurate than would be obtained by omitting it completely. Although the optimal solution would be to include an explicit model for Zeeman splitting in RTTOV, this would require a long-term effort. As a practical short-term solution to improve the RTTOV simulation of AMSU-A radiance data, we have trained RTTOV by performing new line-by-line computations which include cell pressure variations but exclude Zeeman splitting.

Figure 8 shows the time series of the inter-satellite radiance differences calculated with the revised radiative transfer model for the same pair of satellites shown in Figure 2, together with the actual inter-satellite radiance differences obtained with the SNO technique. The remarkable agreement between the measured and the computed radiance differences indicates a significant improvement of the accuracy of the revised RTTOV radiative transfer simulations.

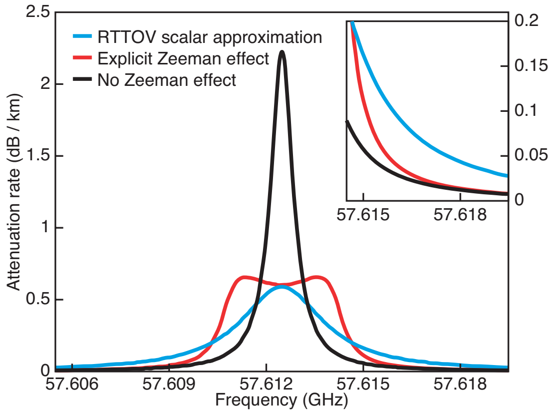


Figure 6 Simulation of attenuation rates at the frequencies around the pass bands of AMSU-A channel 14 at 0.29 hPa using the RTTOV scalar approximation, an explicit representation of the Zeeman effect, and no Zeeman effect.

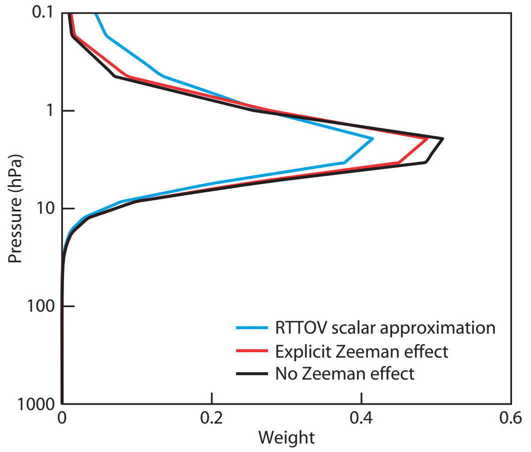


Figure 7 Weighting functions for AMSU-A channel 14 based on the US Standard Atmosphere 1976, using the RTTOV scalar approximation, an explicit representation of the Zeeman effect, and no Zeeman effect.

doi:10.21957/e7hab85vrt

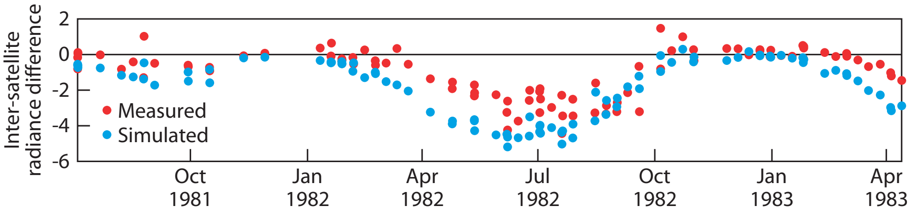


Figure 8 Inter-satellite differences between radiance measurements from SSU channel 3 on NOAA-11 and AMSU-A channel 14 on NOAA-15 over the Antarctic, obtained with the SNO technique (red, as shown in Figure 2) and the corresponding simulated differences using the revised version of RTTOV (blue).

Impact on the stratospheric temperature analysis

Assimilation experiments for testing the new AMSU-A coefficients have been performed. The period of the experiments is one year starting August 1998, which is when AMSU-A data first became available. The experiments utilised the ERA-Interim configuration (T255L60 with the top level at 0.1 hPa; for details see *ECMWF Newsletter No. 110*), using the current AMSU-A coefficients for the control assimilation and the revised AMSU-A coefficients for the new radiative transfer experiment. All satellite radiance data were subject to variational bias correction (VarBC; see *ECMWF Newsletter No. 107*).In order to constrain the upper-stratospheric temperature analysis in the presence of a large, warm, forecast model bias, radiances from AMSU-A channel 14 were corrected for scan biases only.

Figure 9 shows the evolution of the vertical temperature structures in polar regions. The control assimilation tends to create spurious peaks around model levels 6 and 10 (2 and 5 hPa respectively) when the strong polar vortex develops in winter. This is because the weighting function for AMSU-A channel 14 in the operational RTTOV is located too high, which results in too warm radiance simulations when the mesosphere is warmer than the stratosphere. Such a situation occurs in the polar regions in winter. In the experiment performed with the revised RTTOV model, these spurious peaks have been reduced and the vertical temperature structure varies more smoothly with the seasons.

Assimilation experiments for testing the new SSU coefficients are currently underway. Preliminary results show a significant reduction in the standard deviations of first-guess departures (observations minus their modelled equivalents) for SSU data. This suggests an improvement of the accuracy of the RTTOV radiative transfer simulations. The impact on the long-term temperature trends of the stratospheric temperature analysis is now being investigated.

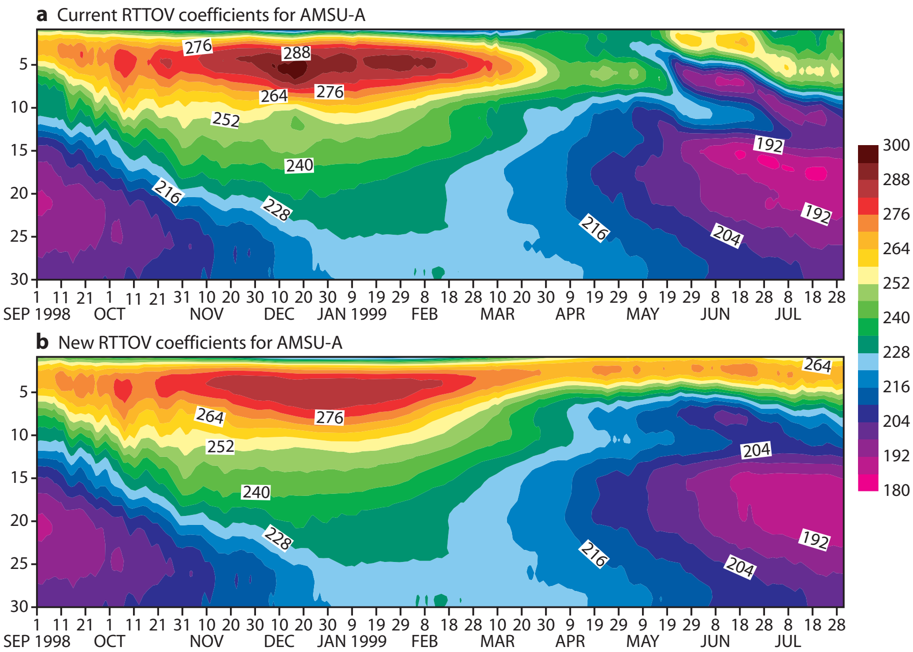


Figure 9 Evolution of the vertical temperature structures over the Antarctic (60° to 90°S) from September 1998 to July 1999 for assimilations using (a) the current RTTOV coefficients for AMSU-A and (b) the new RTTOV coefficients for AMSU-A. The vertical axes represent model levels.

doi:10.21957/e7hab85vrt

Current and future improvements

For a better use of the SSU and AMSU-A observations in reanalyses, the radiative transfer modelling for these instruments has been re-examined. This has led to a revision of the RTTOV coefficients based on more accurate radiative transfer computations. Forward calculations using the revised coefficients have proved to be more accurate than those using the operational RTTOV coefficients. While the new SSU coefficients are still being tested in assimilation experiments, the new AMSU-A coefficients are soon to be released with the RTTOV-9 package. We expect that the revised RTTOV modelling for SSU and AMSU-A will significantly improve the time consistency of upper-stratospheric temperature analyses.

Looking ahead, a proper representation of the Zeeman splitting effect in fast radiative transfer models was studied by *Han et al.* (2007) with the aim of improving the accuracy of the SSMI/S upper atmosphere channel simulations. This scheme has already been implemented in the CRTM fast model and has been selected for implementation in RTTOV-10 for SSMI/S (Special Sensor Microwave Imager/Sounder) and possibly AMSU-A channels. This development is expected to further improve our understanding of the dynamical behaviour of the upper atmosphere.

Further reading

Cao, C., H. Xu, J. Sullivan, L. McMillin, P. Ciren & **Y.T. Hou,** 2005: Intersatellite Radiance Biases for the High-Resolution Infrared Radiation Sounders (HIRS) on board NOAA-15, -16, and -17 from simultaneous nadir observations. *J. Atmos. Oceanic Technol.,* **22,** 381–395.

Clough, S.A., M.W. Shephard, E.J. Mlawer, J.S. Delamere, M.J. Iacono, K. Cady-Pereira, S. Boukabara & **P.D. Brown,** 2004: Atmospheric radiative transfer modeling: a summary of the AER codes. *J. Quant. Spectrosc. and Radiat. Transfer,* **91,** 233–244.

Han, Y., F. Weng, Q. Liu & **P. van Delst,** 2007: A fast radiative transfer model for SSMIS upper atmosphere sounding channels. *J. Geophys. Res.,* **112,** D11121, doi:10.1029/2006JD008208.

Kleespies, T.J., P. van Delst, L.M. McMillin & **J. Derber,** 2004: Atmospheric Transmittance of an Absorbing Gas. 6. OPTRAN Status Report and Introduction to the NESDIS/NCEP Community Radiative Transfer Model. *Appl. Optics,* **43,** 3103–3109.

Liebe, H.J., G. A. Hufford & **M.G. Cotton,** 1993: Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000 GHz. In *Proc. NATO/AGARD Wave Propagation Panel, 52nd Meeting, Paper No. 3/1–10,* Mallorca, Spain, May 1993.

McNally, A.P., T. Auligné, D. Dee & **G. Kelly,** 2006: A variational approach to satellite bias correction. *ECMWF Newsletter No.107,* 18–23.

Saunders, R., M. Matricardi & **P. Brunel,** 1999: An improved fast radiative transfer model for assimilation of satellite radiance observations. *Q. J. R. Meteorol. Soc.,* **125,** 1407–1425.

Simmons, A., S. Uppala, D. Dee & **S. Kobayashi,** 2006: ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter No. 110,* 25–35.