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Clear-sky far-infrared measurements observed with TAFTS during the EAQUATE campaign, September 2004†

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ABSTRACT: Observed clear-sky far-infrared (FIR) radiances measured by the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS) are presented. These measurements were taken when flying on board the Facility for Atmospheric Airborne Measurements British Aerospace 146 aircraft over the UK on 18 September 2004 in the upper troposphere between 8.3 and 9.2 km altitude, during the European AQUA Thermodynamic Experiment (EAQUATE). Upwelling clear-sky measurements from the TAFTS short-wave channel (330 to 500 cm^{-1}) are shown and these measured radiances are compared to model radiances where various dropsonde data are incorporated. The variations in the water vapour profiles below the aircraft are explored in terms of the FIR spectra. The downwelling measurements from TAFTS long-wave channel (90 to 230 cm^{-1}) are also compared to model spectra, produced in this case from the UK Met Office (UKMO) mesoscale model. The variation in the UKMO mesoscale modelled downwelling radiance over the flight leg is seen to have a standard deviation of 0.5 to 2 mW $(m^2\ sr\ cm^{-1})^{-1}$, that is of the order of TAFTS detection limit in this particular campaign. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Observed clear-sky far-infrared (FIR) radiances measured by the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS) *in situ* in the troposphere during the European AQUA Thermodynamic Experiment (EAQUATE) campaign are presented. The EAQUATE campaign comprised a series of flights by the UK Facility for Atmospheric Airborne Measurements (FAAM) British Aerospace (BAe) 146 aircraft. On 18 September 2004, FAAM flew in clear skies over the Southwest Approaches of the UK at a maximum altitude of 9.2 km. TAFTS (Canas *et al.*, 1997), on board FAAM, measured upwelling and downwelling radiances in the FIR. Instrumentation also included Airborne Vertical Atmospheric Profiling System (AVAPS) dropsondes, temperature sensors and hygrometers. As the primary aim of EAQUATE was the validation of the Atmospheric InfraRed Sounder (AIRS) on board the Aqua satellite, excellent sampling of the atmosphere has allowed confident modelling of spectra for comparison with the FIR radiances observed by TAFTS.

The motivation for this TAFTS-based study is primarily that the influence of atmospheric humidity on the Earth's climate system represents a significant uncertainty in our present understanding of how the climate system works (Houghton *et al.*, 2001). To improve this situation, and increase the accuracy of the parametrization with which humidity–radiation processes are described in general circulation models, accurate observations of how water vapour interacts with the radiation field are required. A number of difficult problems remain for the clear-sky case. For example, the spectroscopy of water vapour is not yet fully determined and a number of revisions have been made to the strength of the water vapour continuum in recent years (Clough *et al.*, 2005). Also, the distribution of humidity in the troposphere and the consequences for the global greenhouse effect, surprisingly, remain very uncertain, particularly in the mid and upper levels (Slingo and Webb, 1997). Discussions include whether the atmosphere dries in certain areas as a result of global warming (so producing negative feedback), or whether globally a positive feedback exists (increasing temperature, humidity, and therefore greenhouse trapping) (Lindzen, 1990). Observations *in situ* will allow assessment and improvement of current modelling of water vapour concentrations and its spectroscopy.

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In particular, in the FIR, water vapour has been shown to have a dominant effect on the radiative cooling of the planet to space (King, 1993; Sinha and Harries, 1995). It is known that emission in the FIR, from the pure rotation band of water vapour, is very important; a significant fraction of the atmosphere's cooling to space takes place via the water vapour pure rotation band (100–500 cm^{-1}) from the mid and upper troposphere (Rodgers and Walshaw, 1966; Clough *et al.*, 1992; Slingo and Webb, 1997; Brindley and Harries, 1998). Indeed, radiative transfer modelling suggests that between 20% and 50% of this cooling takes place in the FIR. It is therefore of particular importance that FIR *in situ* observations of the radiation field are undertaken.

TAFTS is a FIR spectro-radiometer designed to operate in the 80–600 cm^{-1} (17 to 125 μm) spectral region at an apodized spectral resolution of 0.12 cm^{-1}, observing both upwelling and downwelling radiation. With TAFTS, spectrally resolved measurements of the atmospheric radiative balance in the FIR from an airborne platform are now possible. These radiative measurements will lead to an improved understanding of the role of water vapour in regulating the planet's energy loss to space, and the validation of the water vapour spectroscopy data used in current radiative transfer models. Presently, there are no high-resolution space-based instruments observing in the FIR, but progress is being made to cover this spectral region. Although TAFTS is the only FIR high-resolution radiometer installed on an aircraft, there are two other observational FIR interferometers operating. The Far InfraRed Spectroscopy of the Troposphere (FIRST) instrument (Mlynczak *et al.*, 2006) and the Radiation Explorer in the Far InfraRed (REFIR; Palchetti *et al.*, 2006) are both balloon-based instruments that have flown in recent years, designed as test-beds for future satellite instruments.

The first published upwelling and downwelling radiance measurements in the FIR from TAFTS are presented here. The measurements of upwelling radiation in the 330–500 cm^{-1} region are compared with modelled spectra produced using measurements of humidity and temperature from both dropsondes and aircraft instrumentation. Measurements of downwelling radiation in the 80–230 cm^{-1} region are compared with modelled spectra produced from the Met Office (UKMO) mesoscale model fields of temperature and humidity, along with aircraft measurements.

2. The TAFTS instrument

TAFTS (Canas *et al.*, 1997) is a Fourier transform spectrometer of a polarizing Martin–Puplett type (Martin and Puplett, 1969) that measures the difference between two inputs, combined, by transmission and reflectance respectively, on an input polarizer. The unapodized spectral resolution is 0.10 cm^{-1} and the instrument field of view is ±0.81°. The detectors and associated optics are housed in a liquid helium-cooled cryostat. There are two spectral channels: the long-wave (90–300 cm^{-1}) and the short-wave (330–600 cm^{-1}), utilizing GeGa and SiSb photo-conductor detectors respectively. The detectors are situated at each of the complementary outputs of the interferometer. When operating aboard an aircraft, TAFTS runs scan sequences that include sky views (nadir and zenith) and internal black-body views for calibration purposes. TAFTS had previously been installed, during other observation campaigns, on the UKMO C130 (Green, 2003) and the Airborne Research Australia (ARA) Egrett aircraft (Straine, 2006). The EAQUATE campaign was the first flight of TAFTS aboard FAAM. Below, details of the acquired datasets and TAFTS' performance are given.

3. TAFTS observations and analyses

The 18 September 2004 EAQUATE flight was a clear-skies study over the Southwest Approaches of the UK. Figure 1 shows the FAAM flight track. A number of straight and level reciprocal runs were performed along a 146 km northwest–southeast track with the underlying atmospheric column sampled by 13 dropsondes over the course of 90 minutes. During this period, FAAM flew from an altitude of 8.3 km to a maximum of 9.2 km.

This section gives details, initially of the modelling method used, TAFTS datasets and then details of both upwelling and then downwelling radiation measurements of TAFTS.

3.1. Details of method of spectral radiance modelling

The radiative transfer model used throughout this work is LBLRTM_v9.4 which uses the mt_ckd_1.2 water vapour continuum (Clough *et al.*, 2005) and HIgh-resolution TRANsmission molecular absorption database (HITRAN; Rothman *et al.*, 2005). For this study, the atmosphere is defined in terms of water vapour concentration and temperature which are taken from dropsonde and aircraft measurements below, or the UKMO mesoscale model above, the aircraft. The concentrations of other atmospheric constituent gases (CO_2, O_3, N_2O, CO and CH_4) are taken from the US 1976 standard atmosphere (NOAA *et al*, 1976), which is adequate for this study. Profile data of water vapour contentration and temperature are provided approximately every 10 hPa in the radiative transfer model. The model is run at a high resolution of 0.0603 cm^{-1}, and then the resolution is reduced to match the apodized resolution of TAFTS (0.12 cm^{-1}) for direct comparisons with the measured TAFTS spectra in its long-wave channel, or further reduced to 0.5 cm^{-1} to compare with TAFTS at a reduced resolution in the TAFTS short-wave channel. The results of this modelling are given in subsections 3.2.2 and 3.2.3.

3.2. Details of TAFTS spectral datasets

The TAFTS spectral radiance measurements are presented as long-wave (90–230 cm^{-1}) downwelling and short-wave (330–500 cm^{-1}) upwelling sections. The

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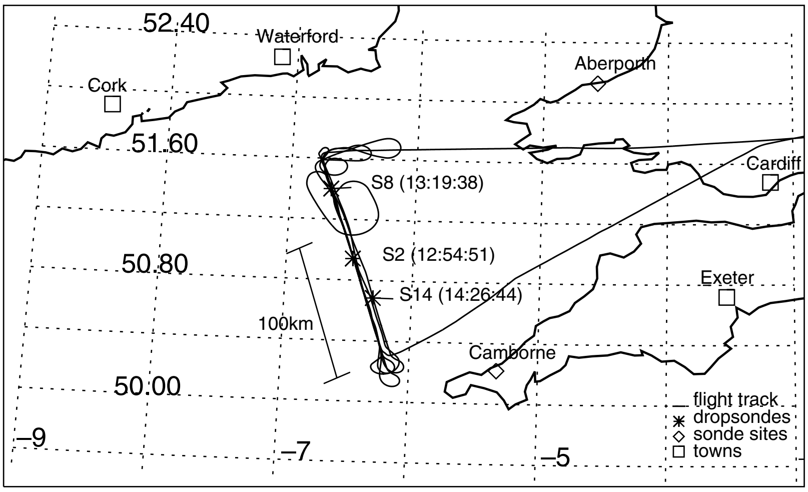

Figure 1. The flight path of the FAAM BAe 146 on 18 September 2004. The aircraft took off from Cranfield (UK) and made a sortie to the Southwest Approaches, where straight and level runs were performed through clear skies. The three dropsondes were released at 12 : 54 : 51 UTC (sonde 2), 13 : 19 : 38 UTC (sonde 8) and 14 : 26 : 44 UTC (sonde 14), at the positions shown.

spectral opacity of the atmosphere varies significantly across the spectral range of the TAFTS detector channels (The band optical depth decreases by around 3 orders of magnitude between 100 and 550 cm^{-1}). The strong water vapour rotational lines lie within the spectral range of TAFTS long-wave channel and these cause the atmosphere below the aircraft to become rapidly opaque. The long-wave channel is however very sensitive to the very low concentrations of water vapour above the aircraft. The short-wave channel covers a relatively transparent spectral region between the water vapour rotational lines and the very strong CO_2 band centred at 667 cm^{-1}. The short-wave channel is particularly sensitive to the variable water vapour column below the aircraft in the mid-troposphere. The two spectral regions are therefore discussed separately.

3.2.1. Radiance calibration of the measured TAFTS spectra

The spectral radiance calibration data used in the calibration of the TAFTS instrument is measured as it is in flight, to take account of the change in instrument response with time. The spectral response function of the instrument is calculated from a combination of hot and ambient temperature black-body views. The views repeatedly alternate between upwelling and downwelling scene views and black-body calibration targets. The instrument spectral response can thus be tracked as a function of time and altitude. Applying the instrument response to the scene view data yields calibrated upwelling and downwelling radiances. The calibration accuracy is limited by knowledge of the black-body temperature to within approximately 1 K (JE Murray 2007, personal communication). The level of precision of the measured radiances for TAFTS is limited, in the case of the EAQUATE flight, by the excessive noise levels (a factor of 3 above that observed on other aircraft on which TAFTS has flown) seen for these flights on our detectors, particularly the long-wave detectors. This noise, not seen on previous campaigns, was attributed to grounding issues in TAFTS electronics and aircraft cabling that could not be rectified at the time of the campaign. Despite this, coaddition of scans has allowed the calibration of a sufficient number of observations for comparison with modelled radiation fields and allows accuracy of 0.5–5 $mW(m^2\ sr\ cm^{-1})^{-1}$ across the spectral range.

To achieve a reasonable signal-to-noise ratio, the short-wave spectra that are reported in this paper consist of up to five coadded spectra (total of 10 seconds acquisition time), while the long-wave spectra required considerably more coadded spectra – up to 74 (148 seconds acquisition time). The scans used in the coadded spectra are not consecutive due to intermittent calibration scans and rejection of poor-quality data interspersed with better quality data. Therefore, the actual time period over which the average spectra are acquired may be considerably longer than the acquisition time for each total coadded spectrum. This total integration time varies between 8 and 140 seconds for the short-wave, and between 11 and 23 minutes for the long-wave spectra. The radiance uncertainties are due to both systematic and random errors. In addition to the 1 K black-body temperature uncertainty, there are also errors present contributing to the overall radiance uncertainty. In particular, random errors due to instrument noise, calculated from the scan-to-scan standard deviation of the raw spectra used in the coaddition of the final calibrated spectra. There are also enhanced noise levels (of around a factor of 2) due to absorption features in the TAFTS window and beamsplitter substrates, polypropylene and mylar respectively. These can be noted at 380 cm^{-1} and 440 cm^{-1} where mylar has strong absorption features, and at 460 cm^{-1} where polypropylene has strong absorption features.

3.2.2. Upwelling radiance measurements

Upwelling short-wave TAFTS spectra were compared with modelled radiances using profiles of humidity and

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temperature from three selected dropsondes. Two dropsondes, representing the driest (sonde 8 released at 9.22 km) and most moist (sonde 14 released at 8.64 km) atmospheres, and the third (sonde 2 released at 8.95 km) which had a water vapour profile between these two, are shown in Figure 2. The modelled upwelling spectra were compared to TAFTS upwelling spectra. These comparisons are shown in Figures 3 to 5, plotted as brightness temperature (BT). The TAFTS spectra are concurrent with the release of the respective dropsondes to within 91, 100 and 70 seconds for sondes 2, 8 and 14 respectively. The spectral resolution has been degraded to 0.5 cm^{-1}. This reduces the very fine detail observable in the spectra, but is advantageous as the signal-to-noise ratio is improved. In Figures 3 to 5, the differences between the model and the observations are given below each spectrum, as well as the BT uncertainties in the TAFTS spectrum. The number of scans used for each spectra concurrent with sonde 2, sonde 8 and sonde 14 are 3, 5 and 4 respectively. The comparison of the measured TAFTS and modelled spectra are now discussed, together with the sources of uncertainty.

The upwelling radiance as seen at the flight level is modelled using the dropsonde profiles. The dropsondes take about 100 hPa to acclimatize, so profile data

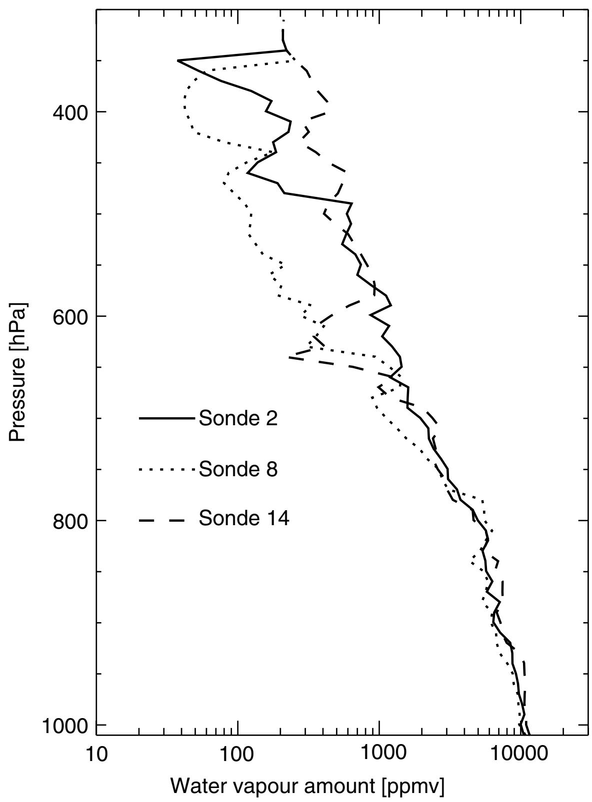

Figure 2. The water vapour profile for the three chosen sondes (2, 8 and 14). The measurements of water vapour amount are derived from the RH and temperature taken directly from the sondes below pressure levels of 340, 350 and 400 hPa for sondes 2, 8 and 14 respectively. Above these levels, the *in situ* aircraft measurements of water vapour concentration and temperature are used. The uncertainties in the water vapour concentration (ppmv) measurements are 5%.

from aircraft measurements of water vapour and temperature are incorporated into the modelled atmosphere lying immediately below the aircraft down to where the dropsonde profiles are used. Although maximum errors of 5% are assigned to the water vapour profile measured by the dropsonde based upon the accuracy of its humidity measurements, producing a maximum BT error of 0.5 K, it is important to note that the profile used in the model may not be the most representative one for the atmosphere when the spectra are taken. This is because the dropsondes take measurements over a time period of 10–15 minutes, while TAFTS measurements are integrated over a period of one minute, containing up to 10 seconds of scan time. Therefore variations in the water vapour profile may occur over the time-scale of sonde measurements, or the sonde could be advected by prevailing winds to sample the atmosphere in a different location. Another source of uncertainty is associated with the FAAM measurements of water vapour concentration and temperature that are included in the modelled atmosphere lying immediately below the aircraft. The ascent of the aircraft can occur over large distances and will not therefore, be sampling the body of air directly below the aircraft when TAFTS is viewing upwelling radiance.

The model, however, shows broad agreement within uncertainties with the measured upwelling spectra. The differences between model and observations in the peaks of the water vapour absorption lines do not lie within the TAFTS uncertainty level. This may be due to uncertainties in the water vapour profile used to model the spectra, or the spectroscopy of the water vapour, particularly the strength of the continuum, could be in error. It is not possible to use these TAFTS data to provide validation of the spectroscopy of water vapour due to the significant noise seen in the TAFTS spectra during EAQUATE.

An investigation was undertaken into the variation of the radiance in the modelled spectra using the three different water vapour profiles from the dropsondes. The *in situ* temperatures of the atmosphere at release of sondes 8, 2 and 14 are 231.7, 233.6 and 233.5 K $\pm$0.2 K respectively. Differences in the strong water lines between the three spectra would be expected due to these ambient temperature differences at each viewing altitude. However, it is the differences in BT visible in the microwindow regions that are related to the variability of water vapour in the atmosphere. This is because the transparency of the atmosphere in these microwindow regions is sensitive to the column concentration of water vapour in the atmosphere below the aircraft. These microwindow regions in TAFTS spectra are investigated to ascertain whether variations in concentrations of water vapour in the atmosphere could indeed be detected.

The BT differences in the microwindows for the modelled and measured upwelling spectra are shown in Figure 6. In Figure 6(a), the difference in BT for TAFTS spectra concident with sonde 14 and sonde 2 are shown, and the difference in BT for modelled spectra using profiles of temperature and water vapour concentration from sondes 14 and 2. Figure 6(b) shows corresponding

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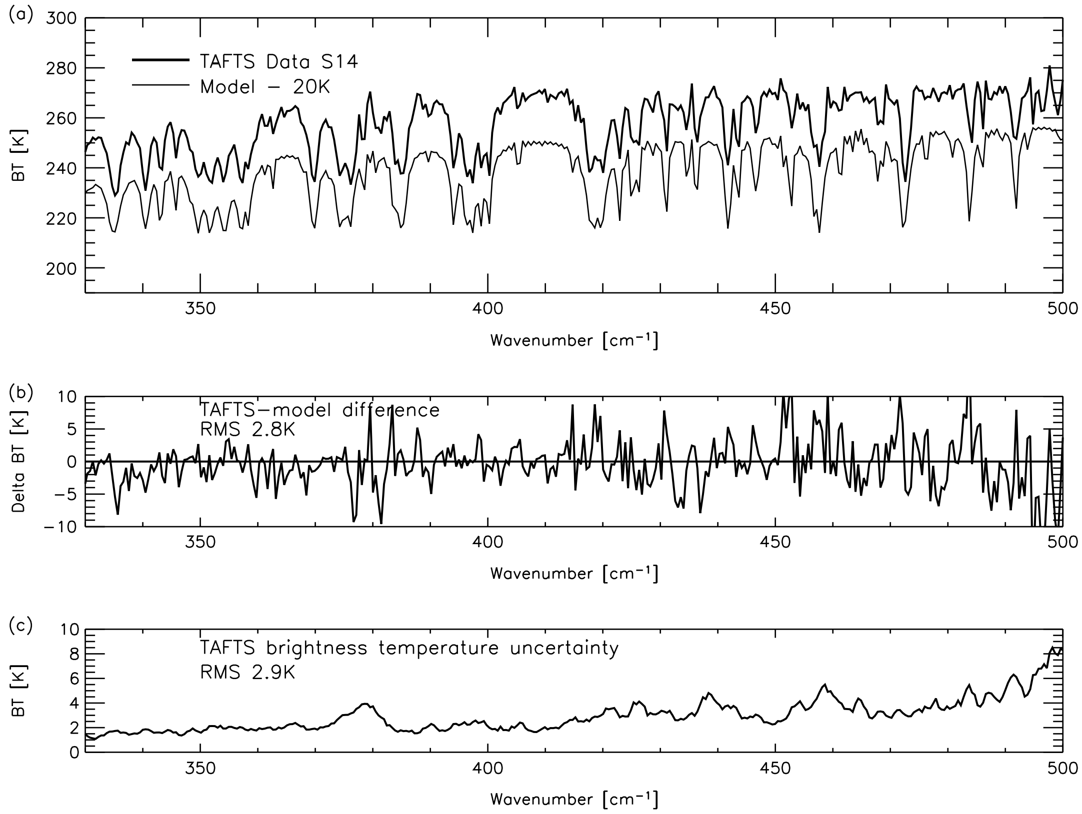

Figure 3. (a) shows the measured TAFTS spectrum compared to the modelled spectrum (using LBLRTM and mt_ckd_1.2 water vapour continuum) offset by 20 K. The TAFTS spectral measurements coincide with dropsonde 14 released at 8.64 km. The model is run using the sonde 14 measured profile. (b) gives the differences between the measured and modelled spectra (RMS difference 2.8 K over the plotted wavenumber region) and (c) the TAFTS uncertainty in brightness temperature (RMS 2.9 K).

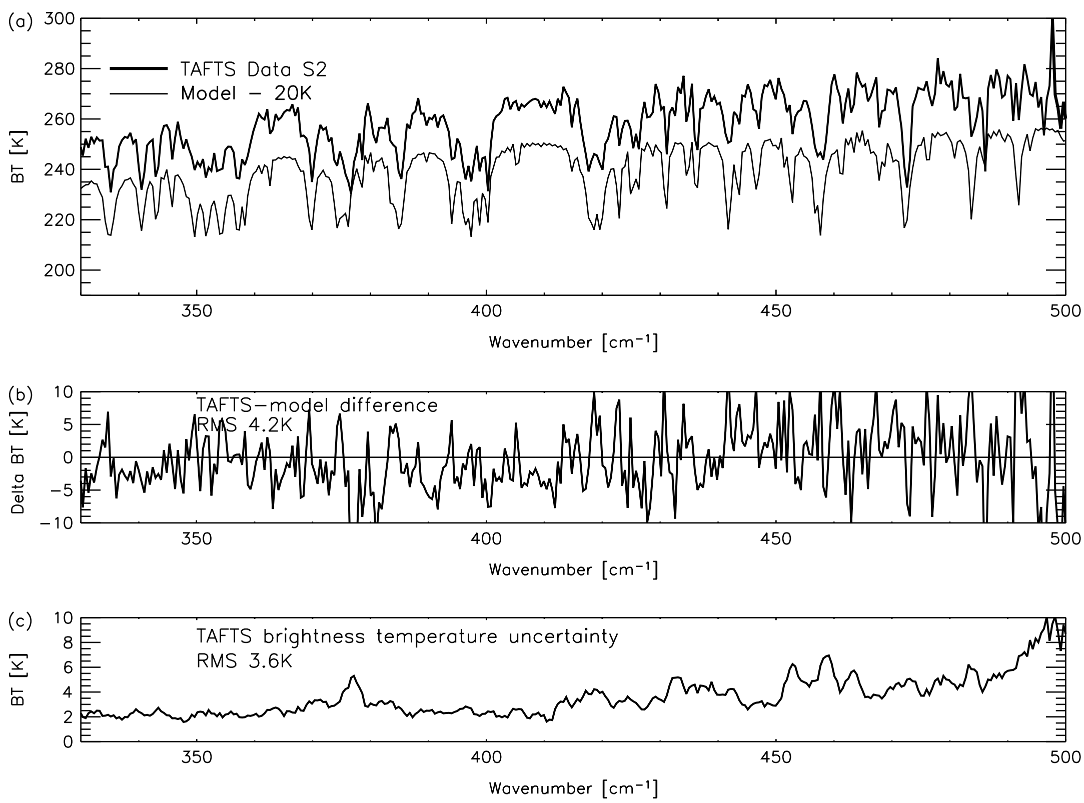

Figure 4. As Figure 3, but using TAFTS spectral measurements coinciding with dropsonde 2 released at 8.95 km. The model is run using the sonde 2 measured profile. In the coadded spectrum, three scans are used (6 seconds acquisition time) in a time period of 86 seconds.

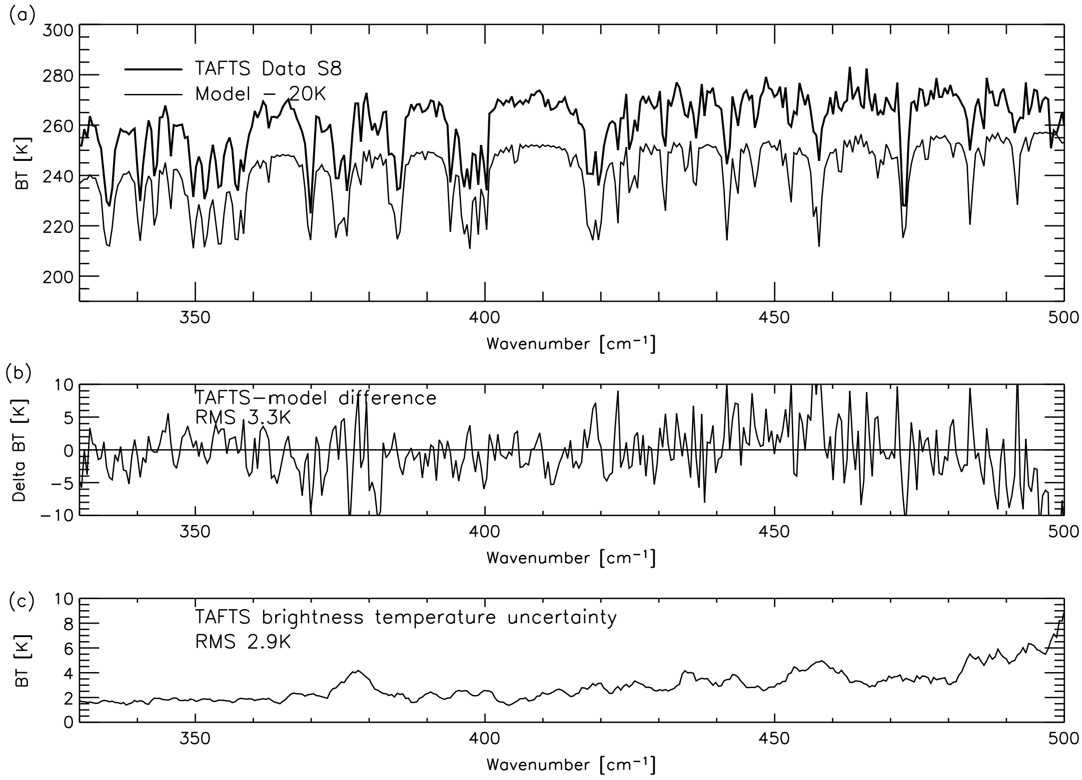

Figure 5. As Figure 3, but using the TAFTS spectral measurements coinciding with dropsonde 8 released at 9.22 km. The model is run using the sonde 8 measured profile. In the coadded spectrum, 5 scans are used (10 seconds acquisition time) in a time period of 140 seconds.

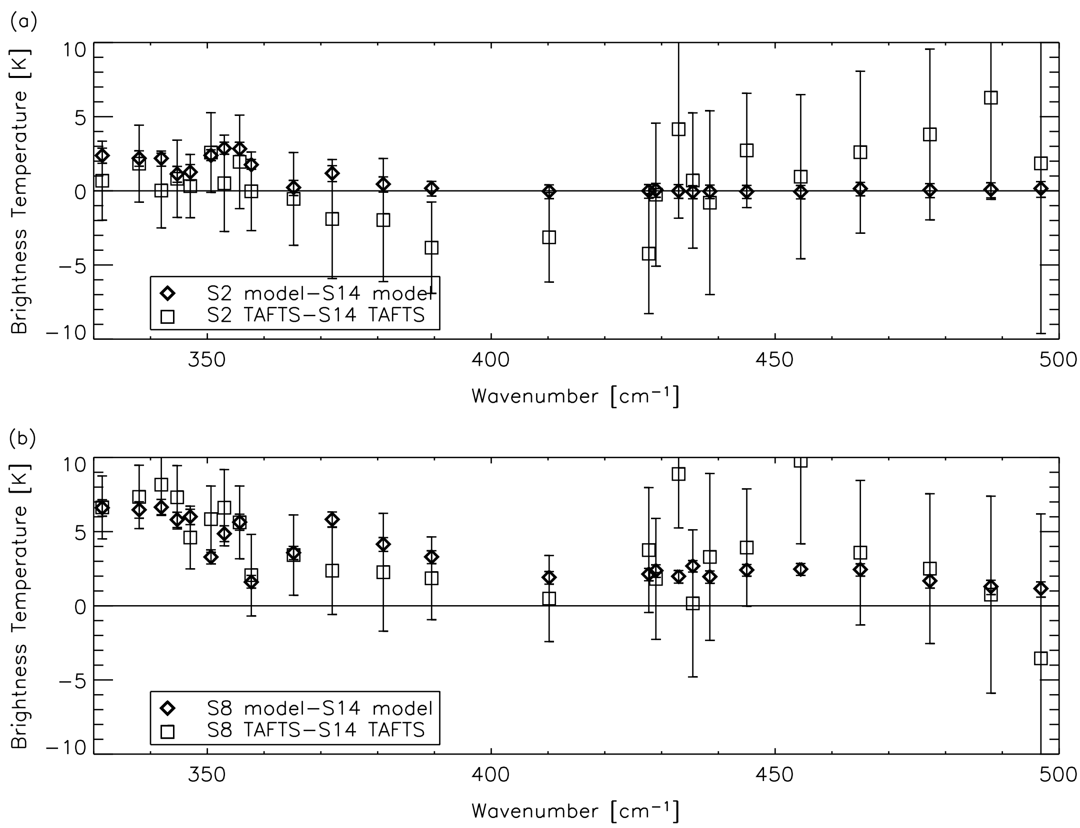

Figure 6. (a) shows the differences in brightness temperature in the microwindow regions between the spectrum TAFTS recorded at the release of sonde 2 and the spectrum at the release of sonde 14. Also plotted are the equivalent differences in the modelled spectra for profiles from sondes 2 and 14. The error bars indicate BT uncertainties from TAFTS measured spectra (long bars), and the modelled spectra (short bars), originating from the humidity measurement accuracy. (b) is as (a), but for sondes 8 and 14.

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results for sondes 14 and 8. The error bars on both plots indicate BT uncertainties from TAFTS measured spectra, and the modelled spectra, originating from the humidity measurement accuracy. It can be seen in Figure 6(a) that there is less than 1 K difference between sonde 2 and 14 at wavenumbers above 360 cm^{-1}; below 360 cm^{-1} there are differences of up to 3 K in BT. This 3 K difference indicates that the spectrum is sensitive to differences in the water vapour concentration profiles over some range of the atmospheric column. The water vapour profiles for these sondes (Figure 2) show a drier atmosphere for spectra measured at the time of sonde 2 than that for spectra relating to sonde 14 above 500 hPa, indicating that the upwelling radiances are sensitive to these changes in the atmosphere above this level. The comparison for sondes 8 and 14 in Figure 6(b) shows larger BT differences across all wavenumbers, implying differences in the water vapour column over a greater range of atmosphere. A comparison of the measured water profiles for sondes 8 and 14 in Figure 2 reveals the significant dryness of sonde 8 from 650 hPa up to 350 hPa, where the sonde measurements start, in agreement with the spectral observations.

Despite the higher than typical noise level seen in these TAFTS spectra, it was still possible to detect variations in outgoing radiance likely to be due to the water vapour concentration variations occurring in the atmosphere.

3.2.3. *Downwelling radiance measurements*

The TAFTS long-wave downwelling spectra were acquired during level runs at three altitudes: 8.30, 8.95 and 9.22 km. Each coadded spectrum contains 40 (80 seconds acquisition time), 40 and 74 (148 seconds acquisition time) individual scans respectively. In order to produce modelled downwelling spectra to compare with TAFTS observed spectra, the atmospheric column water vapour concentration and temperature profile above FAAM are required. A radiosonde launch at Camborne at 1200 UTC gives upper-tropospheric measurements that could be used. However, the release of the sonde was up to 2.5 hours prior to the measurement of the TAFTS spectra, and approximatley 100–150 km from the location of the spectral measurement. Also available is the UKMO mesoscale model that is also run for 1200 UTC. This time preceeds the TAFTS measurements, which were recorded between 1250 UTC and 1402 UTC. In order to achieve near-contemporaneous TAFTS measurements and UKMO model profiles, the UKMO model coordinates have been moved to account for advection. Wind velocities from the UKMO model were used to find the displacement of the air mass at the time of the TAFTS measurements, and therefore to move the coordinates by the corresponding amount. The UKMO mesoscale model values of humidity and temperature have been moved by advection, using the wind fields from the model, to ensure the TAFTS measurements and UKMO model are contemporaneous. The UKMO mesoscale model has poor vertical resolution, but has grid points geographically closer to the area under study than the radiosonde location. Therefore the UKMO mesoscale model is used in preference to the Camborne radiosonde measurements when modelling the downwelling spectra.

A modelled spectrum has been produced for downwelling observations at 9.22 km using the mesoscale model data, for comparison with the measured TAFTS spectrum. The aircraft profile measurements of water vapour and temperature are then used to model TAFTS spectra at 8.95 km and 8.30 km, using the UKMO model profile above 9.22 km. Several mesoscale model grid points around the area enclosing the flight path were chosen from which to take the water vapour and temperature profile. The modelled spectrum that has given the best fit to the TAFTS spectrum is shown in Figure 7. The spectrum produced by the mesoscale model profile provides a good fit that lies within TAFTS spectral errors, apart from at higher wavenumbers (around 220 cm^{-1}), where the BT uncertainty increases.

The TAFTS spectra recorded at 8.95 and 8.30 km altitude are now modelled using the profile from the mesoscale model above 300 hPa, and the *in situ* measurements of water vapour concentration and temperature taken on the aircraft by the auxiliary instrumentation between 329 and 300 hPa. Since the modelled spectrum is in agreement with the TAFTS spectrum measured at 9.22 km, it is expected that the profile above 9.22 km used in the modelling of the TAFTS spectra at 8.95 and 8.30 km is the most representative. Any discrepancies between the modelled and measured TAFTS spectra at the lower two altitudes are then likely to be due to the atmospheric profile used between 8.30 and 9.22 km. At 8.95 km (Figure 8(a)), TAFTS indicated a drier atmosphere than the model above the aircraft, apparent in the low BT in the microwindows of the TAFTS spectra, which may point to an overestimate of water vapour concentration in the model layer between 8.95 and 9.22 km. At 8.30 km (Figure 8(b)), the agreement is again converging between TAFTS measurements and model in some microwindows, however with a slightly wetter atmosphere indicated by TAFTS. The differences observed by TAFTS in the 8.95 and 9.22 km layer could be due to the aircraft water vapour measurements not being co-located in time and space with the TAFTS observations, and may suggest that the layer around 300 hPa is quite variable in terms of water vapour concentration, as discussed next.

The mesoscale model shows some interesting variations in the water vapour concentration over the region in which the aircraft flew. The water vapour field is very variable at the 300 hPa pressure level, as shown in Figure 9. The atmosphere shows an increased amount of water vapour to the northwest, and if FAAM were flying across the observed contour lines, TAFTS would expect to see some significant changes in the long-wave spectra during a level run. The downwelling spectra have been modelled for 9.22 km altitude at four points in the

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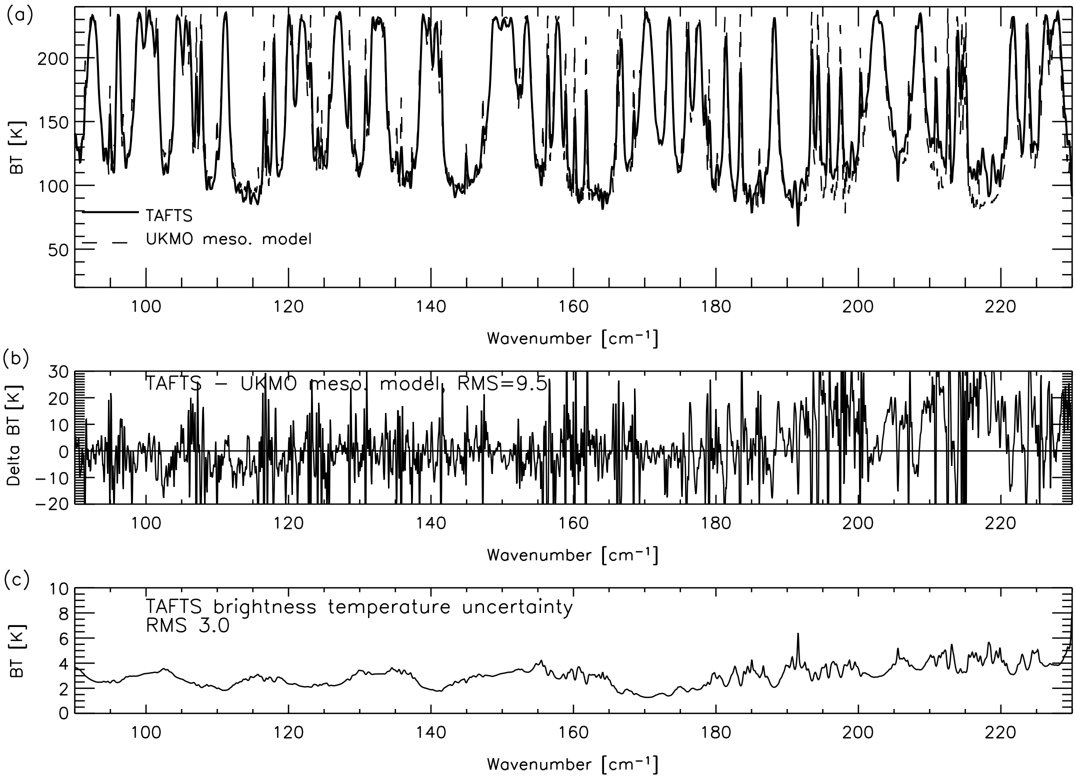

Figure 7. (a) The measured downwelling TAFTS spectrum, compared to a modelled spectrum at an altitude of 9.22 km. The number of individual spectra used in the coadded TAFTS spectrum is 74 (148 seconds acquisition time), taken over a time period of 23 minutes. The modelled spectrum is produced by using a profile of water vapour concentration and temperature from the UKMO mesoscale model. (b) gives the differences between the measured spectrum and modelled spectrum, and (c) shows the TAFTS brightness temperature uncertainty.

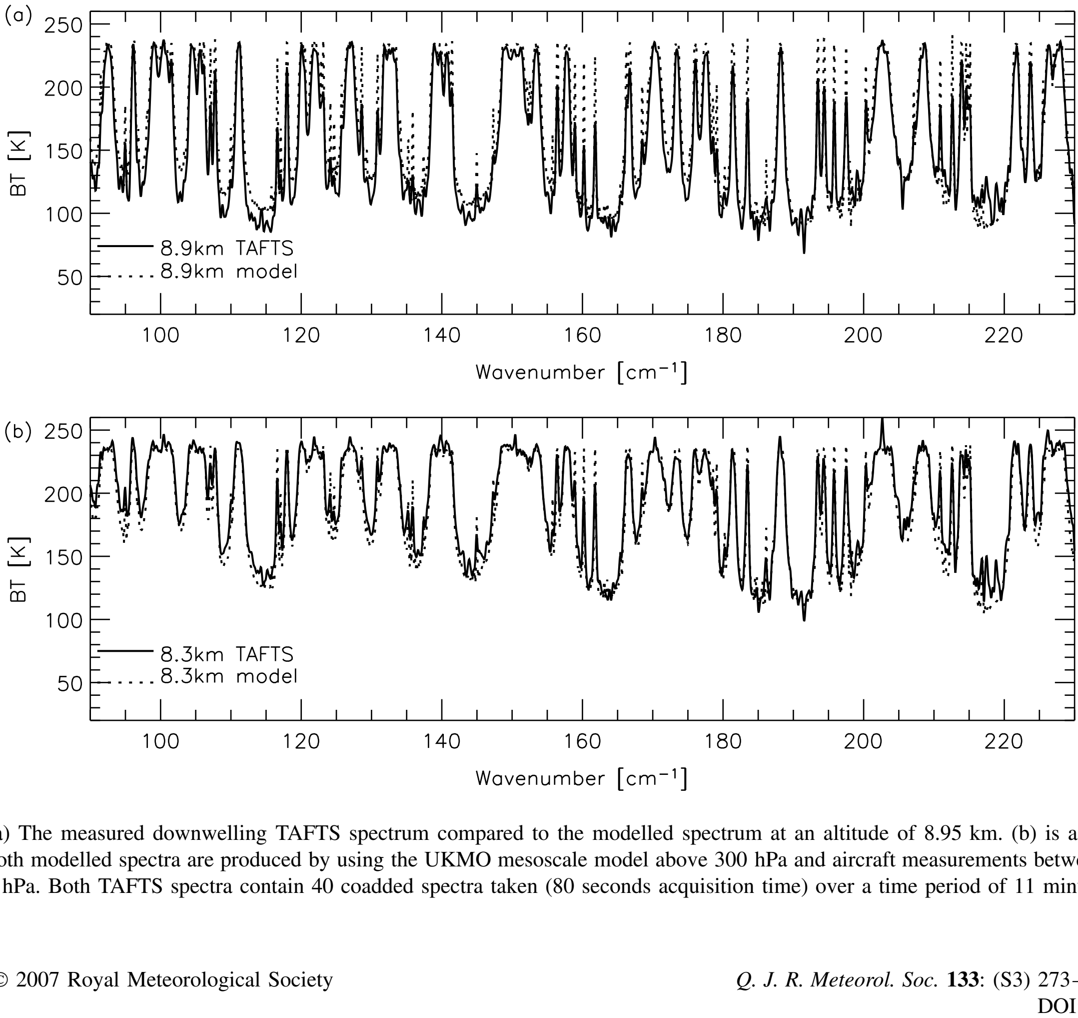

Figure 8. (a) The measured downwelling TAFTS spectrum compared to the modelled spectrum at an altitude of 8.95 km. (b) is as (a), but at 8.30 km. Both modelled spectra are produced by using the UKMO mesoscale model above 300 hPa and aircraft measurements between 329 and 300 hPa. Both TAFTS spectra contain 40 coadded spectra taken (80 seconds acquisition time) over a time period of 11 minutes.

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mesoscale model as indicated in Figure 9. The variability of TAFTS spectra along the flight run at 9.22 km is shown in Figure 10(a). The spectra were subdivided into four time segments, each containing one minute of coadded data taken over a 3-minute period. The temporal separation between segments is 1 minute and the spectra

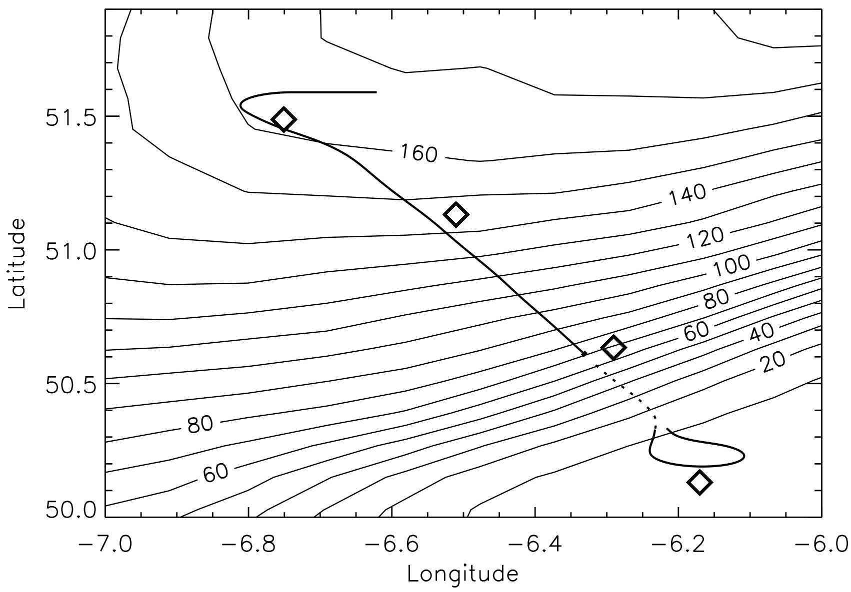

Figure 9. The path taken by FAAM when flying at an altitude of 9.22 km, indicating the integration of TAFTS downwelling measurements by the solid black line. The dotted line shows when the aircraft flies back along the same path. Overplotted are contour lines showing the water vapour amount (ppmv) at a pressure of 300 hPa, from the UKMO mesoscale model at 1334 UTC, the mid time between the beginning and end of TAFTS downwelling measurements. The diamonds indicate the grid positions at which profiles of water vapour concentration and temperature are taken from the UKMO mesoscale model.

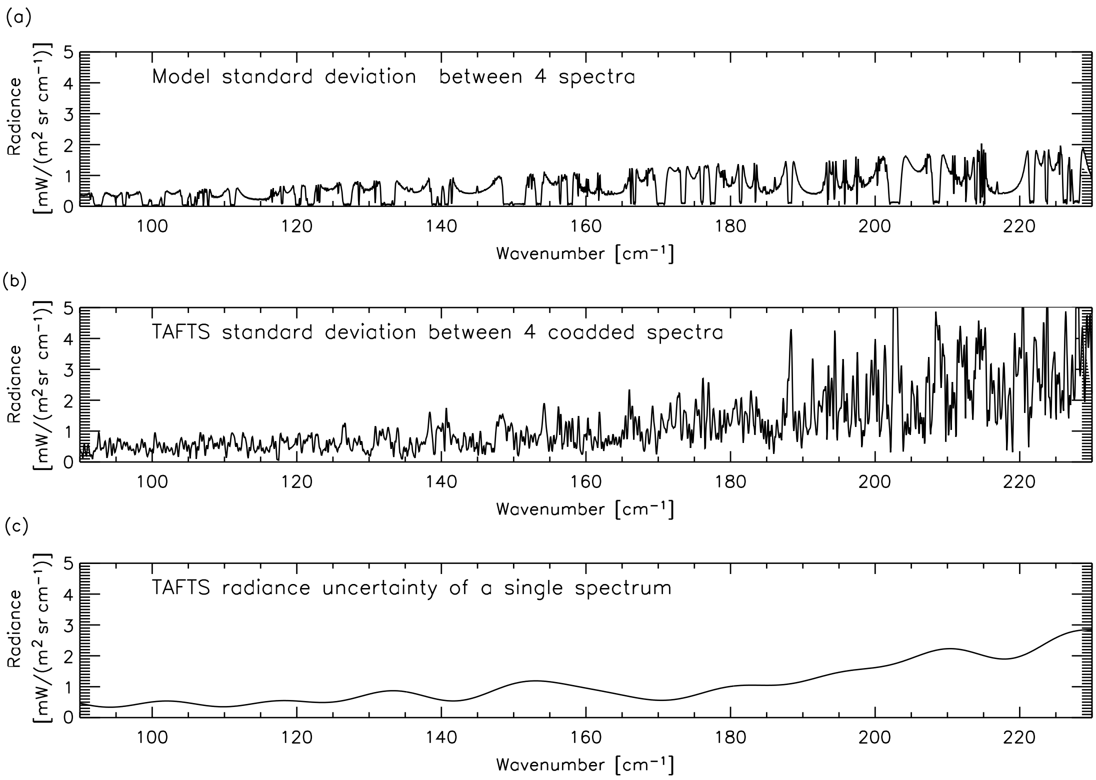

Figure 10. (a) shows the standard deviation between individual measured TAFTS spectra taken at 9.2 km; the number of individual spectra used in the coadded TAFTS spectrum is 40, taken over a time period of 11 minutes. (b) shows the TAFTS smoothed radiance uncertainty, and (c) shows the standard deviation between modelled spectra, using the variation in water vapour concentration present in the UKMO mesoscale model at 1200 UTC.

extend over a single reciprocal run. Figure 10(b) shows TAFTS radiance uncertainty for a single spectrum, and Figure 10(c) shows the variability between the four modelled spectra along the flight path. This comparison can be used to give confidence in the modelled radiances and indicates that the observed horizontal variations of the water vapour profile are reproduced by the model. However, the standard deviation seen in the modelled spectra is of the order of TAFTS enhanced noise levels and so no quantitative analysis of the profile can be made in this case. TAFTS noise will be much reduced in future campaigns and should allow for a similar, but quantitative analysis.

4. Conclusions

Until recently, the radiatively important FIR had been a poorly observed spectral region of the Earth's atmosphere. With the development of the TAFTS instrument it has been possible, for the first time, to make *in situ* high-resolution measurements of the radiative properties of the atmosphere in the upper troposphere from an aircraft. The EAQUATE campaign has offered a unique opportunity for comparison of TAFTS radiative measurements against an atmosphere that has been simultaneously monitored by many other instruments and well characterized by multiple dropsondes over a very short time period. Presented in this paper is a first comparison of TAFTS radiances against equivalent model simulations which have utilized the detailed ancillary atmospheric sampling.

The modelled upwelling spectra, produced using dropsonde and aircraft profile measurements of water vapour concentration and temperature, are in agreement with the TAFTS spectra within instrument BT uncertainties. The dropsondes show a variability in the water vapour profile that is reflected in coincident TAFTS spectra. The significant variability of atmospheric water vapour concentration over the spatial and temporal scales in which the spectra were measured suggests that, even on these short scales, co-location must be carefully considered in comparisons. Ideally TAFTS can be used to obtain high temporal soundings of the atmosphere, however more work is required on improving the signal-to-noise ratio of the TAFTS dataset and improved water vapour spectroscopy.

The modelling of the downwelling radiances, using the UKMO mesoscale model and aircraft measurements of water vapour and temperature, implied some variation in the detail of the water vapour profile between 8.95 and 9.22 km, demonstrated in differences between TAFTS observed and model radiances. This reiterates the need for careful consideration of co-location of profiles and spectral measurements.

Continuing work will study the detail of the upper-tropospheric water vapour profile and link the measurements of the two channels together by looking at the transmission of the atmosphere between the altitude levels at which the aircraft flew: 8.30–8.95 km and 8.95–9.22 km. There is also potential to compare retrievals of tropospheric humidity and temperature, performed by other instruments which took part in the campaign (NAST-I; Cousins and Smith, 1997), with TAFTS spectra.

TAFTS continues to fly on the FAAM BAe 146 and is taking part in the Cirrus and Anvils: European Satellite and Airborne Radiation measurements (CAESAR) campaign where the focus is on the radiative properties of cirrus clouds.

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References

Brindley HE, Harries JE. 1998. The impact of far IR absorption on clear sky greenhouse forcing: Sensitivity studies at high spectral resolution. *J. Quant. Spectrosc. Radiat. Transfer* **60**: 151–180.

Canas AA, Murray JE, Harries JE. 1997. The Tropospheric Airborne Fourier Transform Spectrometer. *Proc. SPIE* **3220**: 91–102.

Clough SA, Iacono MJ, Moncet JL. 1992. Line-by-line calculations of atmospheric fluxes and cooling rates – Application to water vapor. *J. Geophys. Res.* **97**: 15 761–15 785.

Clough SA, Shephard MW, Mlawer E, Delamere JS, Iacono M, Cady-Pereira K, Boukabara S, Brown PD. 2005. Atmospheric radiative transfer modeling: A summary of the AER codes. *J. Quant. Spectrosc. Radiat. Transfer* **91**: 233–244.

Cousins D, Smith WL. 1997. National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed-Interferometer (NAST-I). *Proc. SPIE,* **3127**: 323–331.

Green PD. 2003. 'The development of a Fourier Transform Spectrometer to measure far-infrared fluxes in the upper troposphere'. PhD thesis, University of London.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA. (eds). 2001. *Climate Change 2001: The scientific basis.* Contribution of the Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York, USA.

King MD. 1993. Radiative properties of clouds. Chapter 5 in *Aerosol-cloud-climate interactions.* Hobbs PV. (ed.) Academic Press.

Lindzen RS. 1990. Some coolness concerning global warming. *Bull. Am. Meteorol. Soc.* **71**: 288–299.

Martin DH, Puplett E. 1969. Polarisation interferometric spectrometer for millimeter and submillimeter spectroscopy. *Infrared Phys.* **10**: 105–109.

Mlynczak MG, Johnson DG, Latvakoski H, Jucks K, Watson M, Kratz DP, Bingham G, Traub WA, Wellard SJ, Hyde CR, Xu L. 2006. First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument. *Geophys. Res. Lett.* **33**: L07704, DOI: 10.1029/2005GL025114.

NOAA, NASA and USAF. 1976. *US Standard Atmosphere 1976.* US Government Printing Office: Washington DC.

Palchetti L, Belotti C, Bianchini G, Castagnoli F, Carli B, Cortesi U, Pellegrini M, Camy-Peyret C, Jeseck P, Te Y. 2006. Technical note: First spectral measurement of the Earth's upwelling emission using an uncooled wideband Fourier transform spectrometer. *Atmos. Chem. Phys.* **6**: 5025–5030.

Rodgers CD, Walshaw CD. 1966. The computation of infrared cooling rate in planetary atmospheres. *Q. J. R. Meteorol. Soc.* **92**: 67–92.

Rothman LS, Jacquemart D, Barbe A, Benner DC, Birk M, Brown LR, Carleer MR, Chackerian C, Coudert LH, Dana V, Devi VM, Flaud JM, Gamache RR, Goldman A, Hartmann JM, Jucks KW, Maki AG, Mandin JY, Massie ST, Orphal J, Perrin A, Rinsland CP, Smith MAH, Tennyson J, Tolchenov RN, Toth RA, Vander Auwera J, Varanasi P, Wagner G. 2005. The HITRAN 2004 molecular spectroscopic database. *J. Quant. Spectrosc. Radiat. Transfer* **96**: 139–204.

Sinha A, Harries JA. 1995. Water vapour and greenhouse trapping: the role of far IR absorption. *Geophys. Res. Lett.* **22**: 2147–2150.

Slingo A, Webb MJ. 1997. The spectral signature of global warming. *Q. J. R. Meteorol. Soc.* **123**: 293–307.

Straine GK. 2006. 'Far-infrared cooling rates in the upper troposphere: Reconciling models and observations'. PhD thesis, University of London.