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Spectrally resolved observations of atmospheric emitted radiance in the H_2O rotation band

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[1] This paper presents the project Earth Cooling by Water Vapor Radiation, an observational programme, which aims at developing a database of spectrally resolved far infrared observations, in atmospheric dry conditions, in order to validate radiative transfer models and test the quality of water vapor continuum and line parameters. The project provides the very first set of far-infrared spectral downwelling radiance measurements, in dry atmospheric conditions, which are complemented with Raman Lidar-derived temperature and water vapor profiles. **Citation:** Bhawar, R., et al. (2008), Spectrally resolved observations of atmospheric emitted radiance in the H_2O rotation band, *Geophys. Res. Lett.*, *35*, L04812, doi:10.1029/2007GL032207.

1. Introduction

[2] The relevance to Earth's energy budget of the spectral region 17 to 50 μm has been put forward by many authors [see, e.g., *Clough et al.*, 1992; *Sinha and Harries*, 1997; *Stamnes et al.*, 1999; *Mertens et al.*, 1999]. Nevertheless, the far-infrared portion of the atmospheric emission spectrum is not yet sufficiently explored and very few measurements have been made in the past [*Tobin et al.*, 1999]. Furthermore, despite the many efforts into the spectroscopy of water vapor [see, e.g., *Gordon et al.*, 2007], it is largely recognized that continuum and line parameters in the far infrared (especially below $\approx$400 cm^{-1}) deserve more validation under atmospheric conditions.

[3] ECOWAR (Earth COoling by WAter vapor Radiation) is an experimental project which aims at developing a suitable database of spectrally resolved radiances, which can contribute to bridge the knowledge gap on optical properties of water vapor in the far infrared. This work presents the status of ECOWAR and illustrates the spectral database at the end of the March 2007 Alps field campaign. ECOWAR exploits observations from Fourier Transform Spectrometers (FTS), which are able to sense the downwelling atmospheric emitted radiance in the spectral range from 100 to 1100 cm^{-1} with a spectral resolution of about 0.5 cm^{-1}. In addition to these spectrally resolved radiance observations in the infrared, ancillary information on the thermodynamic state of the atmosphere is obtained by using a conventional radiosonde system (VAISALA system, sonde type RS92k), a Raman Lidar system that provides simultaneous profiles of temperature and water vapor and a Ground-Based Millimeter-wave Spectrometer for observations of precipitable water. ECOWAR has established a collaboration with the ENVISAT MIPAS science team to consolidate the database with water vapor and temperature fields derived from the satellite MIPAS (Michelson Interferometer for Passive Atmospheric Sounding [*Fischer et al.*, 2007]) measurements. ECOWAR observations parallel and complement the series of spectral observations performed at US Dept. of Energy ARM (Atmospheric Radiation and Measurement) sites [see, e.g., *Ackerman and Stokes*, 2003]. In particular, ARM observations have led to a series of revisions to the CKD water vapor continuum model developed by *Clough et al.* [1989]. Among many others, we acknowledge the contribution to such a topic by *Strow et al.* [1998], *Mlawer et al.* [1999], and *Tobin et al.* [1999].

2. Experimental Methods and the Measuring Site

[4] The ECOWAR instrumental set includes the REFIR-PAD (Radiation Explorer in the Far InfraRed - Prototype for Applications and Development [*Palchetti et al.*, 2006]) instrument. This is an FTS with an uncooled DLATGS (deuterated L-alanine-doped triglycene sulfate) pyroelectric detector, which measures the spectrum of the atmospheric emitted radiance over the spectral range 100 to 1100 cm^{-1} with a spectral resolution of 0.5 cm^{-1}. REFIR-PAD was developed as a feasibility demonstrator of an uncooled FTS in the Radiation Explorer in the Far InfraRed (REFIR) project (see e.g. http://www.adgb.df.unibo.it/projects/refir-bb/). REFIR-PAD, together with TAFTS (Tropospheric Airborne Fourier Transform Spectrometer information is available at the url site, http://www.sp.ph.ic.ac.uk/tafts/) and FIRST (The Far-Infrared Spectroscopy of the Troposphere) [*Mlynczak et al.*, 2006] has contributed to new instrument developments to measure the far infrared spectrum from aircraft and balloons,

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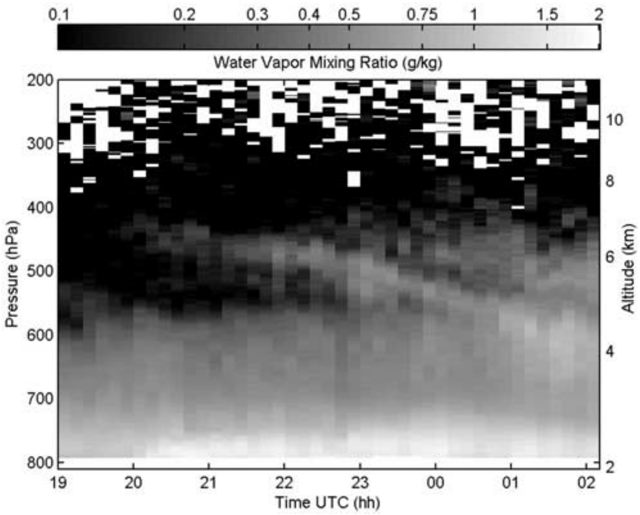

Figure 1. Example of water vapor mixing ratio time series from Lidar measurements during the night of March 10–11, 2007, at Cervinia station (2000 m).

in perspective of a future far-infrared spectrometer satellite mission. Also available to ECOWAR is the FTIR/ABB *instrument* extended in the far-infrared. This is an AERI-type FTS fabricated by ABB Bomem Inc. of Quebec, Canada. AERI stands for Atmospheric Emitted Radiance Interferometer and this acronym designates the type of FTS which is operational in many ARM sites. The new configuration, extended in the far infrared, has been obtained by replacing the usual Zn/Se beamsplitter by a Silicon window and installing a new detector which is the standard DLATGS offered in ABB's standard FTLA104 series spectrometers (ABB Assembly Number IOH1048). The instrument has the capability to be used either with the DLATGS (un-cooled) or the Mercurium-Cadmium-Telluride (MCT) detector (cooled with liquid Nitrogen), which gives flexibility to the spectrometer. Because of the new laser-metrology, the spectral resolution has improved to the value of 0.3931 cm^{-1} against the old 0.4822 cm^{-1}. Combining the free spectral range of both detectors, the new configuration results in a spectral coverage from 5 to 100 μm. *Lidar measurements* were performed by the University of BASILicata Raman Lidar system (BASIL). The system was substantially upgraded prior to the measurement campaign with the implementation of an additional receiver dedicated to the detection of low level echoes. The major feature of BASIL is represented by its capability to perform high-resolution and accurate measurements of atmospheric temperature based on the application of the rotational Raman Lidar technique in the UV [*Di Girolamo et al.*, 2004]. Besides temperature, BASIL provides measurements of particle backscatter at 355, 532 and 1064 nm, particle extinction and depolarization at 355 and 532 nm, and water vapor mixing ratio both in day-time and night-time. For a time resolution of 5 min and a vertical resolution of 150 m, day-time measurement uncertainty at 2 km altitude is typically 5% for the particle backscattering coefficient (at all wavelengths), 20% for the particle extinction coefficient, 10% for water vapor mixing ratio and 2 K for temperature. The night-time measurement uncertainty at 2 km is typically 2% for the particle backscattering coefficient, 10% for particle extinction coefficient, 5% for water vapor mixing ratio and 1 K for temperature. Finally, the Ground-Based Millimeter-wave Spectrometer (GBMS) measures rotational emission spectra of atmospheric chemical species between approximately 230 and 280 GHz (or 7.7 and 9.3 cm^{-1}). It was designed and built at the Physics and Astronomy Department of the State University of New York at Stony Brook. GBMS measurements are averaged over time intervals of 15 min, although the maximum time resolution is $\approx$10 s. GBMS is particularly suited for low values of water vapor content. The conversion of the micro-wave radiances to water vapor columnar content (or precipitable water vapor, PWV) is described by *de Zafra et al.* [1983].

[5] The ECOWAR most intense measurement campaign took place in March 2007 in the Alps. The reason to move to a mountain site is due to the need of performing infrared observations with a relatively low water vapor load. The various FTS instruments are deployed at the ground and the water vapor rotational band is normally opaque because of the strong absorption. However, in the case of suitable dry conditions, the emission spectrum shows narrow spectral intervals (micro-windows) where the atmosphere becomes transparent. These conditions are normally achieved at high latitudes or at mountain sites. Two sites were used during the campaign. A base camp was located close to the city of Cervinia (45°56′N, 7°38′E) at an altitude of about 2000 m. In this base camp the Lidar system and the mobile van with the VAISALA sounding unit and the FTIR/ABB were deployed side-by-side to ensure space co-location between Lidar and FTS. A second camp was located at the higher Testa Grigia station (45°56′N, 7°42′E, altitude of about 3500 m). At this site the REFIR-PAD and the GBMS radiometer were deployed. The two sites are only 5 km apart. Moreover, the possibility of observing the down welling radiance from two different altitudes gains flexibility to the project. In addition, differentiation of the spectral radiance allows us to insulate the emission of the atmospheric layer between the two sites. Observations were performed from March 4 to 16, 2007. A detailed calendar of the measurements, overpasses of the various satellites and pictures of two test sites along with the dislocation of the instruments, is available at the ECOWAR web site https://www.difa.unibas.it/jFM/dlf/Progetti/cobra/index.htm.

3. Alps Campaign and Conclusions

[6] During the Alps campaign, the precipitable water (at the base camp) ranged from less than 1.5 mm to some 5–6 mm, whereas at Testa Grigia station, values as low as 0.5 mm were observed. An example of water vapor time evolution at Cervinia station is given in Figure 1, which shows Raman Lidar observations (integration time of 10 min) recorded for the night of 10–11 March, 2007. During this night we observed the driest conditions with PWV less than 1.5 mm at Cervinia station and less than 0.5 mm at Testa Grigia. From March 4 to 11, 2007 the FTIR/ABB was equipped with the DLATGS pyroelectric detector. Based on the preliminary analysis of the observations, it was verified that the system was able to sense down to $\approx$350 cm^{-1} before the atmosphere became completely opaque. From the morning of March 11, 2007 until the end of

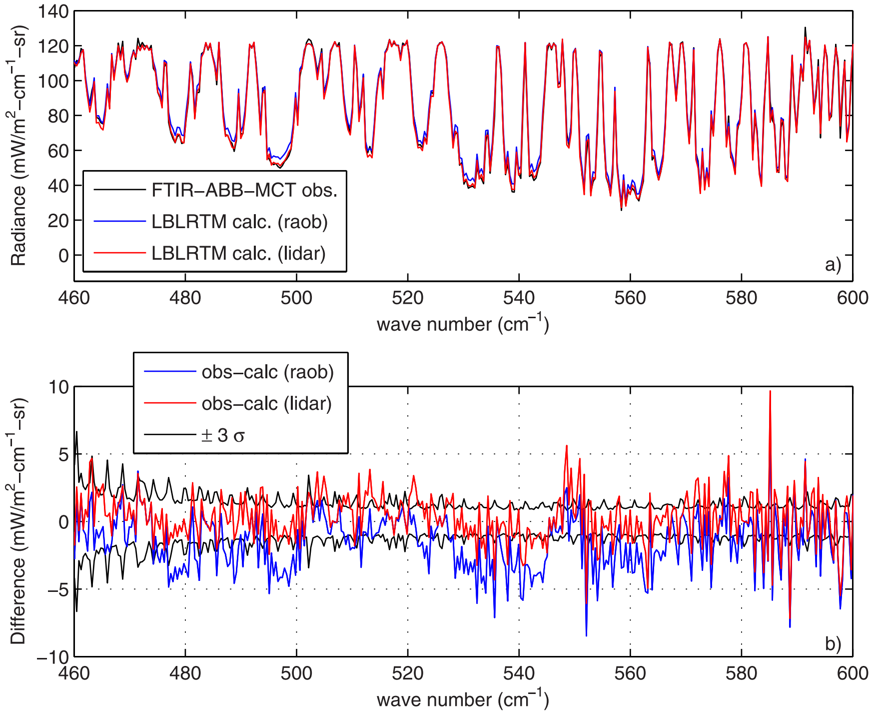

Figure 2. Illustrative comparison of FTIR/ABB-MCT observations with calculations performed with Lidar and radiosonde derived inputs.

the campaign, the FTIR/ABB was equipped with the MCT detector. Although this choice limited the spectral range to about 450 cm^{-1}, from the side of the longwave region, it improved the signal-to-noise ratio and considerably extended the spectral range from the side of the shortwave region. For illustrative purposes, Figure 2 compares the FTIR/ABB-MCT spectral observation recorded during the night of March 14, 2007 to calculations performed with the version 11.1 of LBLRTM [*Clough et al.*, 1992], using the high-resolution transmission molecular absorption (HITRAN) 2004 database [*Rothman et al.*, 2005], with water vapor parameters updated according to *Gordon et al.* [2007], and with all the updates for other molecules available at the date of January 2007. The calculations have been performed using as input: the time co-located water vapor and temperature Lidar products, and the radiosonde observations. The spectral observation was recorded between 19:06:36 and 19:08:53 UTC (2 min and 18 s, integration time), while the radiosonde products were

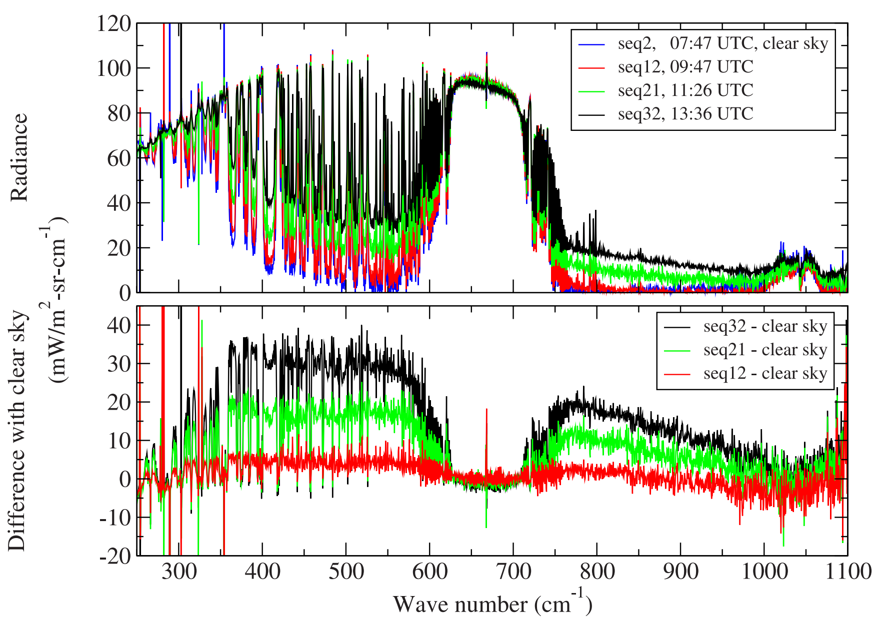

Figure 3. (top) Example of REFIR-PAD spectra (Testa Grigia Station, 3500 m). (bottom) The differences between cloudy and clear sky spectra.

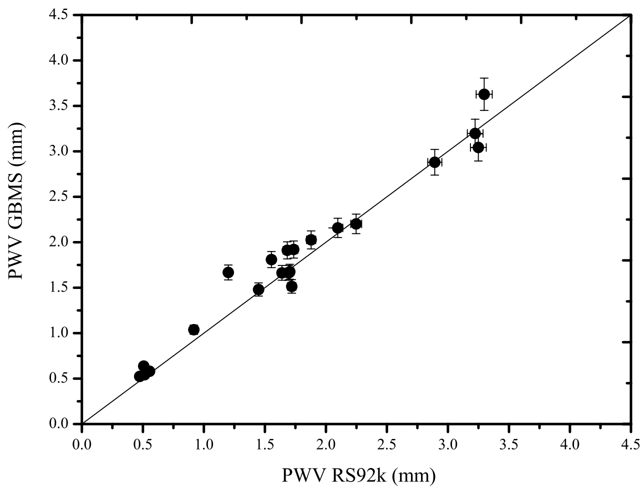

Figure 4. Scatter plot of precipitable water estimated by GBMS and computed on the basis of the radiosonde observations.

time interpolated from the two consecutive launches at 18:56 UTC and 21:14 UTC. Although illustrative, Figure 2 allows one to identify issues that will be addressed in the forthcoming analysis of the data. First, it can be seen that the water vapor rotational band is well resolved in its more transparent regions generating narrow *micro-windows*, which in Figure 2 appear as spectral regions with a relatively low value of radiance. These micro-windows make the present observations highly effective for the analysis of both forward radiative transfer and derivation of water vapor continuum absorption coefficients. Second, the analysis of the spectral residual shown in Figure 2 (bottom) demonstrates that the Lidar input, once compared to the radiosonde input, improves the quality of the difference between observations and calculations, which is likely the result of a better time-space co-location of the Lidar. Third, by comparing the spectral residual to the $\pm 3\sigma$ interval (Figure 2, bottom), it is seen that there are inconsistencies between observations and calculations. Spectral line parameters and the state of the continuum model accounts for much of the discrepancy [see, e.g., *Esposito et al.*, 2007; *Gordon et al.*, 2007], although, to a less extent, instrument uncertainties as well as atmospheric-state input can contribute. Finally, it is noteworthy that the radiometric noise ($\pm 1\sigma$) is better that 0.5 mW/m^2 cm^{-1} in the region of interest. The FTIR/ABB-DTGS is characterized by a similar level of noise for the same spectral range (and even better in the far infrared).

[7] Observations from Testa Grigia station were simultaneously performed with those at the Cervinia station. An example of spectral radiance measured by REFIR-PAD (total integration time of $\approx$5 min) in dry and cloudy conditions is shown in Figure 3. This figure again allows us to exemplify important issues that will be addressed in forthcoming studies. First, it is possible to see that the transparency of the micro-windows appears further enhanced. Second, micro-windows open in between 250 to 350 cm^{-1}, which makes the clear-sky REFIR-PAD data particularly attractive to explore line and continuum parameters in a spectral regions where upper tropospheric cooling takes place. Third, the arrival of clouds in the instrument field of view is also visible in the figure: it is evident that the differential radiance from clear sky conditions is larger in the rotational band than in the atmospheric window, which stresses the importance of far infrared observations for cloud characterization. It is also worth mentioning that the signal-to-noise ratio in most parts of the rotation band is close to 100 with an integration time of 1 min. Finally, the GBMS spectrometer was mostly intended to provide ancillary information about humidity fields and to check for the water vapor variability between the two stations. Figure 4 shows a comparison between the precipitable water as computed by the radiosonde observations and that estimated by the GBMS. From the comparison it is possible to see that a good agreement exists, which evidences the good quality of the newest RS92k humidity sonde.

[8] In conclusion, ECOWAR is unique in terms of passive and active systems capability. The related measurements provide a database of spectrally resolved infrared radiance in conditions of clear-sky and dry conditions and in the presence of light cirrus clouds and altostratus to address outstanding problems such as (1) validation of models of atmospheric radiative transfer in cloudy and clear skies; (2) evaluation of the modeling capability in clear and cloudy conditions and reconstruction of the radiative diabatic effects. ECOWAR welcomes collaborations as well as sharing of the data.

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References

Ackerman, T. P., and G. M. Stokes (2003), The atmospheric radiation measurement program, *Phys. Today*, *56*, 38–44.
Clough, S. A., F. X. Kneizys, and R. W. Davies (1989), Line shape and the water vapour continuum, *Atmos. Res.*, *23*, 229–241.
Clough, S. A., M. J. Iacono, and J.-L. Moncet (1992), Line-by-line calculations of atmospheric fluxes and cooling rates: Application to water vapor, *J. Geophys. Res.*, *97*, 15,761–15,785.
de Zafra, R. L., A. Parrish, P. M. Solomon, and J. W. Barrett (1983), A quasi continuous record of atmospheric opacity at λ = 1.1 mm over 34 days at Mauna Kea observatory, *Int. J. Infrared Millimeter Waves*, *4*, 757–765.
Di Girolamo, P., R. Marchese, D. N. Whiteman, and B. B. Demoz (2004), Rotational Raman Lidar measurements of atmospheric temperature in the UV, *Geophys. Res. Lett.*, *31*, L01106, doi:10.1029/2003GL018342.
Esposito, F., G. Grieco, G. Masiello, G. Pavese, R. Restieri, C. Serio, and V. Cuomo (2007), Intercomparison among line-parameters spectroscopic databases using downwelling spectral radiance, *Q. J. R. Meteorol. Soc.*, *133*(S3), 191–202, doi:10.1002/qj.131.
Fischer, H., et al. (2007), MIPAS: An instrument for atmopsheric and climate research, *Atmos. Chem. Phys. Discuss.*, *7*, 8795–8893.
Gordon, I. E., L. S. Rothman, R. R. Gamache, D. Jacquemart, C. Boone, P. F. Bernath, M. W. Shephard, J. S. Delamere, and S. A. Clough (2007), Current updates of the water-vapor line list in HITRAN: A new "diet" for air-broadened half-widths, *J. Quant. Spectrosc. Radiat. Transfer*, *108*, 389–402, doi:10.1016/j.jqsrt.2007.06.009.
Mertens, C. J., M. G. Mlynczak, R. R. Garcia, and R. W. Portmann (1999), A detailed evaluation of the stratospheric heat budget: 1. Radiation transfer, *J. Geophys. Res.*, *104*, 6021–6038.
Mlawer, E. J., S. A. Clough, P. D. Brown, and D. C. Tobin (1999), Recent developments in the water vapor continuum, paper presented at the Ninth Atmospheric Radiation Measurement Science Team Meeting, ARM, San Antonio, Tex., 22–26 Mar.
Mlynczak, M. G., et al. (2006), First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument, *Geophys. Res. Lett.*, *33*, L07704, doi:10.1029/2005GL025114.
Palchetti, L., C. Belotti, G. Bianchini, F. Castagnoli, B. Carli, U. Cortesi, M. Pellegrini, C. Camy-Peyret, P. Jeseck, and Y. Te (2006), First spectral measurement of the Earth's upwelling emission using an uncooled wide-band Fourier transform spectrometer, *Atmos. Chem. Phys.*, *6*, 5025–5030.

Rothman, L. S., et al. (2005), The HITRAN 2004 molecular spectroscopic database, *J. Quant. Spectrosc. Radiat. Transfer*, *96*, 139–204.

Sinha, A., and J. E. Harries (1997), The Earth's clear-sky radiation budget and water vapor absorption in the far infrared, *J. Clim.*, *10*(7), 1601–1614.

Stamnes, K., R. G. Ellingson, J. A. Curry, J. E. Walsh, and B. D. Zak (1999), Review of science issues, development strategy and status for the ARM North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO), *J. Clim.*, *12*(1), 46–63.

Strow, L. L., D. C. Tobin, W. W. McMillan, S. E. Hannon, W. L. Smith, H. E. Revercombe, and R. O. Knuteson (1998), Impact of a new water vapor continuum and line shape model on observed high resolution infrared radiances, *J. Quant. Spectrosc. Radiat. Transfer*, *59*, 303–317.

Tobin, D. C., et al. (1999), Downwelling spectral radiance observations at the SHEBA ice station: Water vapour continuum measurements from 17 to 26 μm, *J. Geophys. Res.*, *104*, 2081–2092.

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