An Intercomparison of Precipitable Water Vapor Measurements Obtained During the ECOWAR Field Campaign

Irene Fiorucci[a,b], Giovanni Muscari[a], Cesidio Bianchi[a], Paolo Di Girolamo[c], Francesco Esposito[c], Giuseppe Grieco[c], Donato Summa[c], Giovanni Bianchini[d], Luca Palchetti[d], Marco Cacciani[e], Tatiana Di Iorio[e], Giulia Pavese[f], Domenico Cimini[g], and Robert L. de Zafra[h]

[a] *Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*
[b] *also at Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[c] *Dipartimento di Ingegneria e Fisica dell'Ambiente, Università della Basilicata, Potenza, Italy*
[d] *Istituto di Fisica Applicata "Nello Carrara", IFAC-CNR, Sesto Fiorentino, Firenze, Italy*
[e] *Dipartimento di Fisica, Università di Roma "La Sapienza", Roma, Italy*
[f] *Istituto di Metodologie per l'Analisi Ambientale, IMAA-CNR, Tito Scalo, Potenza, Italy*
[g] *CETEMPS, Dipartimento di Fisica, Università di L'Aquila, L'Aquila, Italy*
[h] *Department of Physics and Astronomy, and Institute for Terrestrial and Planetary Atmospheres, State University of New York, Stony Brook, U.S.A.*

Abstract. In this study we present an intercomparison of measurements of very low water vapor column content obtained with a Ground-Based Millimeter-wave Spectrometer (GBMS), Vaisala RS92k radiosondes, a Raman Lidar, and an IR Fourier Transform Spectrometer**.** These sets of measurements were carried out during the primary field campaign of the ECOWAR (Earth COoling by WAter vapor Radiation) project which took place on the Western Italian Alps from 3 to 16 March, 2007.

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INTRODUCTION

Very low amounts of column water vapor are difficult to measure accurately due to the required high instrumental sensitivity to water vapor, but are especially important for climate studies. Such low precipitable water vapor (PWV) values are typical of polar regions, which are extremely vulnerable to present and projected climate changes and at the same time are the regions with the greatest potential to affect global climate.

The primary field campaign of the ECOWAR (Earth COoling by WAter vapor Radiation) project [1] provided a unique opportunity for an intercomparison of accuracy of several PWV data sets obtained by means of in situ and ground-based remote sensing concurrent measurements. The ECOWAR campaign took place at Breuil-Cervinia (45.9° N, 7.6° E, elev. 1990 m) and Plateau Rosa (also known as Testa Grigia; 45.9° N, 7.7° E, elev. 3490 m, less than 7 km apart from Breuil-Cervinia), Italy, from 3 to 16 March, 2007. It is part of an experimental program aimed at studying spectral properties of water vapor in its rotational band (17-50 μm), with particular attention to the water vapor continuum and line absorption parameters [2]. Observations of spectrally resolved radiances between 100 and 1100 cm^{-1} were realized using two Fourier Transform Spectrometers: the REFIR-PAD (Radiation Explorer in the Far InfraRed - Prototype for Applications and Development) [3] installed at Plateau Rosa and the Fourier Transform Infrared (FTIR)/ABB Bomem [4] installed only a few km away at Breuil-Cervinia. A heterodyne spectrometer (Ground-Based Millimeter-wave Spectrometer, or GBMS) provided water vapor column measurements and

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stratospheric ozone profiles from Plateau Rosa. Ancillary measurements of temperature and relative humidity were performed by the University of BASILicata Raman Lidar system (BASIL) [5] based at Breuil-Cervinia, and by Vaisala RS92k radiosondes launched from the same location.

ECOWAR PWV DATA SETS

Ground-Based Millimeter-wave Spectrometer

The Ground-Based Millimeter-wave Spectrometer (GBMS) measures rotational emission spectra of atmospheric chemical species such as O_3, N_2O, CO and HNO_3, as well as the H_2O continuum, between approximately 230 and 280 GHz. Emission lines are observed with a spectral window of 600 MHz and with a maximum resolution of 65 kHz. The inversion of the pressure-broadened spectral lines allows to retrieve vertical profiles of atmospheric chemical constituents in the altitude range 17-75 km, with a vertical resolution of 7-10 km [6].

During regular data taking the GBMS observes radiation from two different directions switched by a rotating chopper wheel at ~ 1 Hz frequency: at the zenith (reference beam, or R) and at a varying angle low (10°) above the horizon (signal beam, or S). By means of a balancing technique [6] the input power from the two beams is maintained equal and a simple balance equation allows to retrieve the atmospheric opacity in the zenith direction τ_z [7]. In the 230-280 GHz spectral region the atmospheric emission arises almost entirely from water vapor continuum in cloud-free skies, with second order contributions from molecular nitrogen and oxygen. The conversion from the atmospheric opacity τ_z to water vapor column content can hence be obtained by means of the linear relation:

$$PWV = \left[\tau_z(\lambda) - \tau_{dry}(\lambda)\right]\alpha(\lambda) \qquad (1)$$

Factors $\alpha(\lambda)$, which convert to PWV the opacity due to H_2O only, have been obtained from measurements carried out by *Zammit and Ade* (1981) [8], while $\tau_{dry}(\lambda)$ values at Plateau Rosa are obtained using the radiative transfer model discussed by *Liljegren et al.* (2005) [9].The accuracy for the resulting PWV values is estimated at 4.9%. GBMS measurements were carried out during the entire period of the ECOWAR campaign except in cases of poor weather conditions or occasional equipment malfunctioning.

RS92k sonde

During the 14-day long ECOWAR field campaign, 34 Vaisala RS92k radiosonde units were launched from Cervinia and measured vertical profiles of atmospheric temperature and water vapor. The Vaisala RS92k radiosonde is equipped with temperature, pressure and humidity sensors. Although the humidity sensor mounted on RS92 sondes is the most accurate among those installed in four types of radiosonde currently produced by Vaisala, the sensor does not have a radiation shield and it is subject to a solar radiation dry bias [10]. The magnitude of this bias and its dependence on SZA is not yet well established [11; 10; 12]. In this study data from 27 sondes were used, with only 7 sondes launched during daytime. Based on figure 10 in *Rowe et al.* (2008) [12] we deduce an 8% dry bias for the 7 daytime RS92k sondes and applied this correction to the corresponding PWV values. Following the results depicted by *Vömel et al.* (2007) [10] in their figure 9, we assign an accuracy of 5% to PWV measurements obtained using RS92 sondes.

Raman Lidar BASIL

Lidar measurements were performed by the University of BASILicata Raman Lidar system (BASIL). The major feature of BASIL is represented by its capability to perform high-resolution and accurate measurements of atmospheric temperature, both in daytime and night-time, based on the application of the rotational Raman Lidar technique in the UV [5]. Besides temperature, BASIL is capable of providing measurements of particle backscatter at 355, 532 and 1064 nm, particle extinction and depolarization at 355 and 532 nm, and water vapor mixing ratio vertical profiles both in day-time and night-time. Water vapor Lidar measurements used in this work are integrated over 10 minutes and have a vertical resolution of 150 m from the ground (~2 km altitude) to 5 km and of 300 m above 5 km altitude. The resulting PWV values have an estimated relative uncertainty of 5%.

REFIR-PAD

REFIR-PAD (Radiation Explorer in the Far InfraRed - Prototype for Applications and Development) is a Fourier transform spectroradiometer measuring the spectrum of the downward longwave radiation (DLR) emitted from the atmosphere in the wide spectral range from 100 to 1400 cm^{-1} with a maximum resolution of 0.25 cm^{-1}. During the ECOWAR campaign, REFIR-PAD was operated in the 100-1100 cm^{-1} spectral window with 0.5 cm^{-1} spectral resolution and an acquisition time of 64 s for a single scan [1]. Measurements contain the spectral signature of the pure rotational water vapor band and can be used for the characterization of the water vapor content in the atmosphere and in particular for the measurement of PWV [7]. In this work, we use REFIR-PAD spectral measurements integrated over ~5 minutes and retrieve a PWV value from each 5-minute integration. A 5% average relative uncertainty is assigned to measured PWV values.

COMPARISONS RESULTS

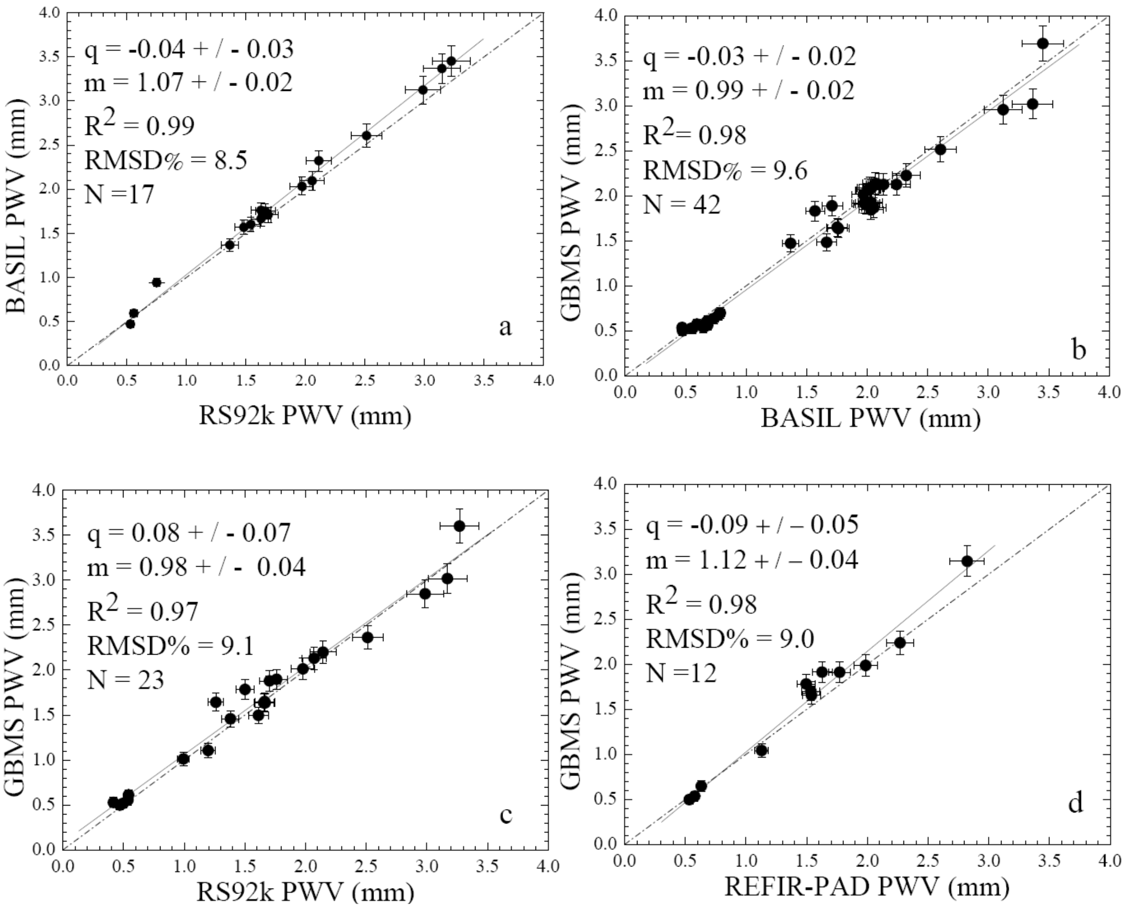

FIGURE 1. Scatter plot of BASIL versus Vaisala RS92k (panel a), GBMS versus BASIL (panel b), GBMS versus Vaisala RS92k (panel c), and GBMS versus REFIR-PAD (panel d) PWV amounts. The linear fit to the data points (y = q + mx) is represented with a solid line and the 1:1 bisector with a dashed-dotted line. The RMSD% is also reported in the legend together with the total number of correlation points N, the parameters q and m of the linear fit, and the correlation coefficient R^2.

In Figure 1 a comparison of the four correlative PWV data sets obtained during the March 2007 ECOWAR field campaign is shown. In Panel 1a, we compare values of PWV obtained from simultaneous radiosonde and Lidar measurements. Both sets of PWV values are computed integrating the water vapor content from 3.5 to 10 km altitude. Since BASIL calibration is based on RS92k humidity measurements between 2 and 3 km altitude, while all

PWV values refer to the 3.5-10 km altitude range, concurrent Lidar and sonde PWV measurements can, in practice, differ. Figure 1a shows that a good agreement between the two sets of PWV values exists, with a root mean square of the difference (RMSD%) of 8.5%. In Panel 1b, 1c, 1d we show a comparison between precipitable water vapor values estimated using the GBMS with those from the other three ECOWAR PWV data sets. BASIL PWV values compared to GBMS values (Figure 1b) are obtained integrating water vapor vertical profiles in the altitude region 3.5-10 km and using only nighttime measurements. In performing the comparison between GBMS and RS92k sonde PWV measurements (Figure 1c) radiosonde values were calculated by integrating water vapor concentrations from the pressure level of Plateau Rosa up to 10 km altitude. The corresponding GBMS PWV value is obtained from GBMS measurements carried out while radiosondes ascent from 3.5 km to 10 km altitude. REFIR-PAD PWV values used in the comparison (Figure 1d) are averages of 3 PWV retrievals obtained from 3 successive 5 minute spectral integrations carried out concurrently with a sonde's ascent from 3.5 to 10 km altitude.

GBMS PWV measurements are in good agreement with the other three data sets displaying percentage values for the root mean square of the difference between observations ranging from 9% to 9.6%. Given the considerable number of data points available for the comparison between GBMS and Lidar measurements, for this case we can provide an interpretation of slope and intercept values of the linear fit to the scatterplot which suggests very small, if any, systematic differences between the two data sets. The slope indicates a percentage systematic difference of 1% (±2%), while the intercept suggests an absolute systematic difference of 0.03 (±0.02) mm.

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