3.2 COMPARISON OF AMSR-E RETRIEVALS OF TOTAL WATER VAPOR OVER THE OCEAN WITH SHIP BASED MEASUREMENTS

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1. INTRODUCTION

Atmospheric water vapor is an important part of the Earth's hydrological cycle and plays a crucial role in many aspects of the climate system. The main source of the atmospheric moisture is the ocean surface. Until recently the information we had about the distribution of atmospheric water vapor over the oceans was based on a relatively sparse distribution of radiosonde stations. In order to cover the global distribution of water vapor in the atmosphere measurements from spaceborne instruments are necessary.

Such measurements are becoming available from the new fleet of satellites launched in recent years but need to be validated by comparison with already established techniques. In this paper we compare measurements over the ocean of the total precipitable water vapor (PWV) from the space-based Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) with measurements from ship based remote sensing instruments and radiosondes, and with the PWV from the ECMWF (European Centre for Medium-Range Weather Forecasts) 40-year re-analysis dataset (ERA-40). The shipboard remote sensing instruments include a microwave radiometer (MWR), and the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI). The instruments and measurements are described in section 2. The measurements of PWV by various instruments are compared in section 3. The summary of the results and discussion follow in section 4.

2. Instruments and Data

2.1 Advanced Microwave Scanning Radiometer (AMSR-E)

The Advanced Microwave Scanning Radiometer (AMSR-E) was launched on May 4, 2002, aboard NASA's *Aqua* spacecraft. AMSR-E provides measurements of the PWV over the oceans and other geophysical variables including sea surface temperature (SST), wind speed, cloud liquid water, and rain rate.

2.2 Microwave Radiometer

The microwave radiometer used in this study is the Radiometrics Corporation WVR-1100. It operated continuously throughout the cruises measuring atmospheric emission at 23.8 and 31.4 GHz. The PWV is retrieved using coefficients that were derived by a bilinear regression between the atmospheric brightness temperature at the two frequencies and the PWV obtained from radiosonde soundings.

2.3 Marine-Atmospheric Emitted Radiance Interferometer

The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) is a Fourier transform infrared interferometric spectroradiometer that measures spectra spanning the ~3 to ~18μm wavelength interval with a resolution of ~0.5 cm^{-1}. It uses two infrared detectors cooled to ~78 K by a Stirling cycle mechanical cooler to reduce the noise equivalent temperature difference to levels well below 0.1K. The radiometric calibration of the M-AERI is done using two internal blackbody cavities which are sampled before and after taking each set of oceanic and atmospheric spectra. The control computer integrates the interferometric measurements over a pre-selected time interval, usually a few tens of seconds, to obtain a satisfactory signal to noise ratio. A typical cycle of measurements including two up-looking views of the atmosphere at different zenith angles, one down-looking view of the ocean, and blackbody calibration measurements, takes about ten minutes. The instrument is described more fully by Minnett et al. (2001).

An example of the atmospheric emission spectrum measured by the M-AERI on 9 August 2002 on the *Explorer of the Seas* is shown in Figure 1. Such atmospheric emission spectra contain information about the vertical distribution of the temperature and the water vapor in the lower troposphere.

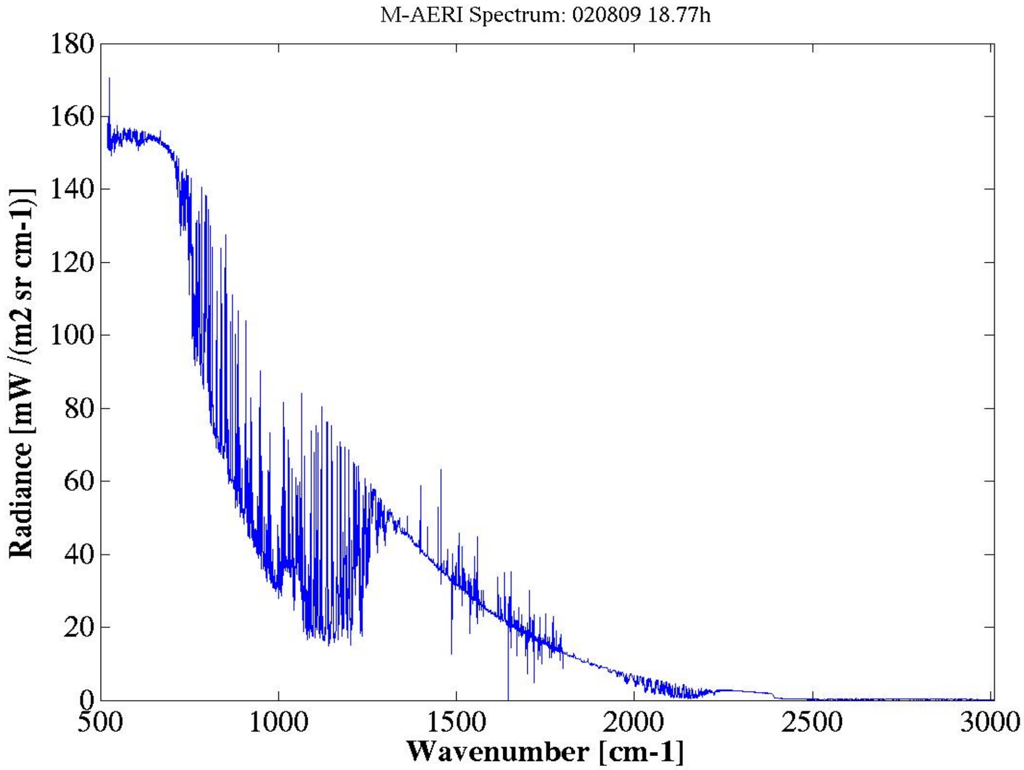

Figure 1. An example of the spectrum of atmospheric emission measured by the M-AERI.

The method of inverting M-AERI spectra to retrieve the profiles of temperature and water vapor in the lowest 3 km of the atmosphere is described in Smith et al. (1999) and is routinely used with the land-based AERI at a number of the ARM (Atmospheric Radiation Measurement program; Stokes and Schwartz, 1994) observing sites (Feltz et al., 2003). The retrieval process is an iterative technique that requires an initial guess of the temperature and moisture profiles. A first guess profile can be a radiosonde measurement or a model profile from the ECMWF re-analysis and both approaches are used in the current analysis. The retrieved lower troposphere profiles are extended above the 3 km level by blending the retrieval with the first guess profile.

2.4 Vaisala RS80/90 Radiosondes

In situ measurements of temperature and water vapor profiles were obtained throughout the cruises using commercial Vaisala RS80-H and RS90 balloon-borne radiosondes. The moisture profiles were integrated over the height to yield the PWV. The radiosonde measurements were also used as the first guess for in the M-AERI profile retrieval.

Typical accuracies of the radiosonde measurements are ± 0.5 K for temperature, ± 1 hPa for pressure, and about ± 5% for relative humidity (Elliott and Gaffen, 1991). The humidity measurement by Vaisala radiosondes is also a subject to a measurement bias, for which several sources have been identified (Miloshevich et al., 2004). Since new (past June 2000) RS80-H and RS90 radiosondes were used in this study, the measurements used here should be practically free of such errors, which are more noticeable at low temperatures and pressures.

2.5 ECMWF ERA-40 dataset

The ECMWF ERA-40 re-analysis project provides global fields of atmospheric variables that were obtained by operational analysis and comprise data assimilation suite combining observations, previous forecasts, and model assumptions about the evolution of the meteorological variables. The ERA-40 dataset available from the ECMWF website covers the period from September 1957 to August 2002 and provides fields of meteorological variables every 6 hours with a horizontal grid-spacing of about 2.5^{o} and 23 vertical levels from 100 to 0.1 hPa.

The ERA-40 profiles of atmospheric temperature and moisture were used to compute PWV for comparisons with AMSR-E retrievals and ship based measurements, and as the first guess to initialize the M-AERI profile retrieval. The ERA-40 data were interpolated in time and space to the time and position of the ship-based measurement.

3. Results

Figure 2 shows profiles of the atmospheric temperature and the dew point temperature measured on 9 August 2002 by instruments on the *Explorer of the Seas* and the corresponding profiles from the ECMWF ERA-40 dataset. The continuous lines represent the radiosonde profiles (blue and red for the air temperature and the dew point temperature respectively), the broken lines (green and black) represent ECMWF profiles of temperature and dew point temperature, and the dotted lines represent M-AERI retrieved profiles. The blue and red dotted lines correspond to the profiles retrieved with the radiosonde profile as the first guess and the green and black dotted lines correspond to profiles retrieved with the ECMWF ERA-40 data used as the first guess. The feasibility of using radiosonde data and model or global analysis data to initialize M-AERI retrievals is discuss elsewhere (see Szczodrak et al., 2006).

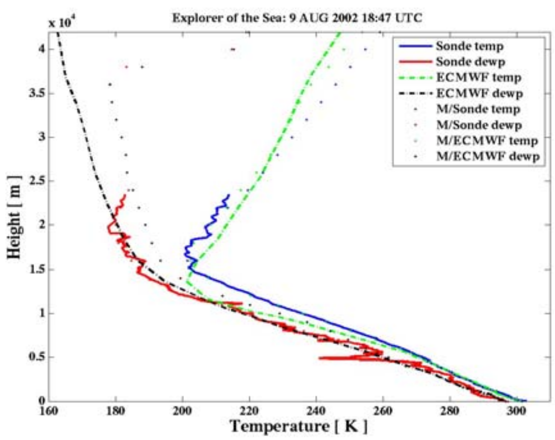

Figure 2. Profiles of air temperature and dew-point temperature derived from several sources on 9 August 2002 .M/Sonde and M/ECMWF indicate M-AERI retrievals initialized with radiosonde and ECMWF data.

The atmospheric moisture profiles like those shown in Figure 2 obtained from radiosonde measurements, M-AERI retrievals and ECMWF dataset are integrated over height to yield the PWV. The PWV thus obtained from the *Explorer of the Seas* measurements on 9 August 2002 are shown in Figure 3 together with the PWV from the AMSR-E and the PWV measured continuously by the ship-based microwave radiometer. The values of PWV obtained with each of the presented

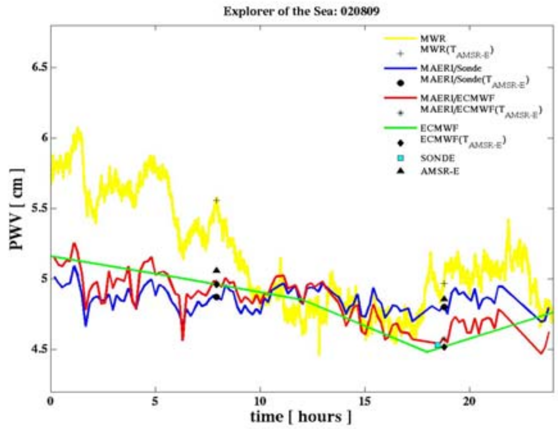

Figure 3 Time series of PWV measured on the *Explorer of the Seas on* 9 August 2002*.* Symbols labeled (T_{AMSR-E}) denote measurements taken at the times of the overpass of *Aqua*.

approaches are compared in Figures 4 to 6 for the *Explorer of the Seas* measurements in the Caribbean, in Figures 7 to 8 for the *Healy* transit around North America, and in Figures 9 to 10 for the Urania cruise in the Mediterranean.

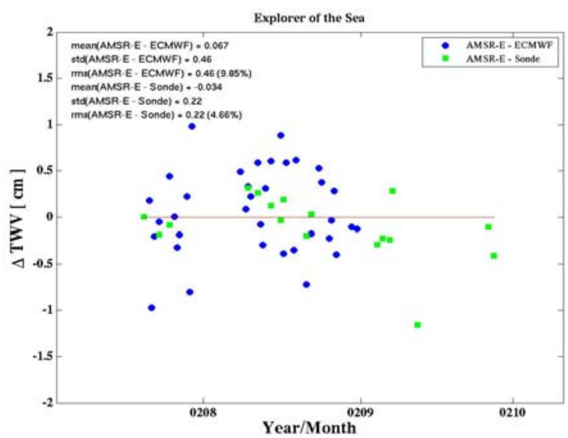

Figure 4. Differences in PWV measured by AMSR-E and ECMWF ERA-40 dataset (blue), and AMSR-E and radiosonde measurement (green) for the positions of the *Explorer of the Seas*.

These figures show the difference between coincident PWV measurements (ΔPWV) obtained with two different methods. The mean value, standard deviation (std) and the root mean square (rms) are given in each figure.

For the *Explorer of the Seas*, Figure 4 shows the ΔPWV for AMSR-E and ECMWF ERA-40 dataset (blue), and AMSR-E and radiosonde measurement (green). Figure 5 shows the ΔPWV for AMSR-E and M-AERI retrievals with ECMWF ERA-40 first guess (blue), and) radiosonde profile first guess (green). In Figure 6 the ΔPWV for

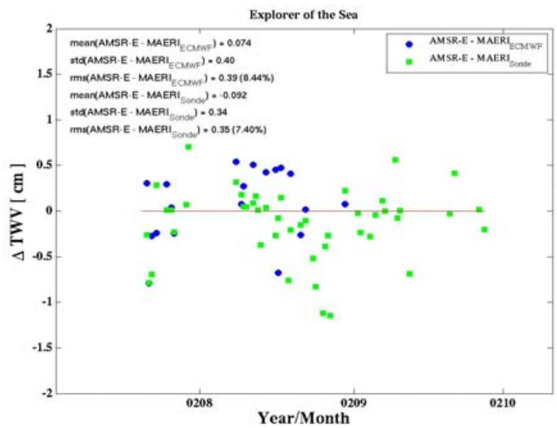

Figure 5. As Figure 4, but for AMSR-E and M-AERI retrievals with ECMWF ERA-40 first guess (blue), and) radiosonde profile first guess (green).

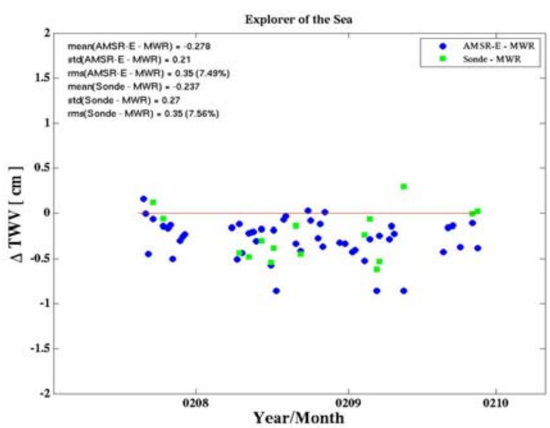

Figure 6. As Figure 4, but for MWR and AMSR-E (blue), and radiosondes (green).

AMSR-E and MWR (blue) and radiosonde and MWR (green) measurements are shown.

For the Healy cruise, the ΔPWV between the AMSR-E retrievals and the radiosonde measurements is shown in Figure 7. Figure 8 shows the ΔPWV for the AMSR-E retrievals and MWR measurements (blue) and the radiosonde measurements and MWR (green).

The ΔPWVs for the *Urania* cruise are presented in Figure 9 where ΔPWV between the AMSR-E and radiosondes is shown, and Figure 10 which shows the ΔPWV between AMSR-E and MWR (blue) and radiosonde and MWR (green).

No ECMWF ERA-40 data are available for this study for the periods of the *Healy* and *Urania* cruises therefore no ECMWF PWV values nor ECMWF based M-AERI are shown in Figures 7 to 10.

The mean value, standard deviation (std) and the root mean square for each ΔPWV are summarized in Table 1, which also lists the mean PWV for each cruise. Inspection of ΔPWV values presented in Figures 4 to10 and Table 1 reveals that in terms of rms, AMSR-E retrievals agreed with radiosonde measurements to better than 6% of the average PWV for all three cruises and does not show any obvious biases. In Figure 7

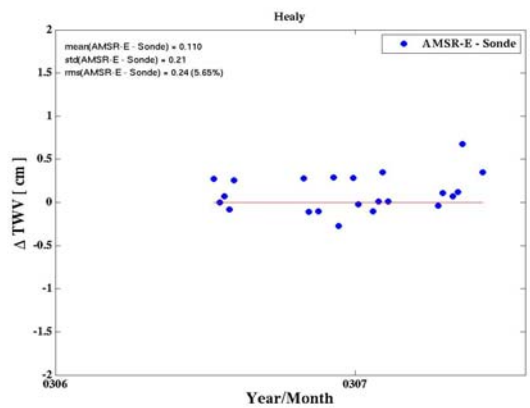

Figure 7. As Figure 4, but for the *Healy* cruise

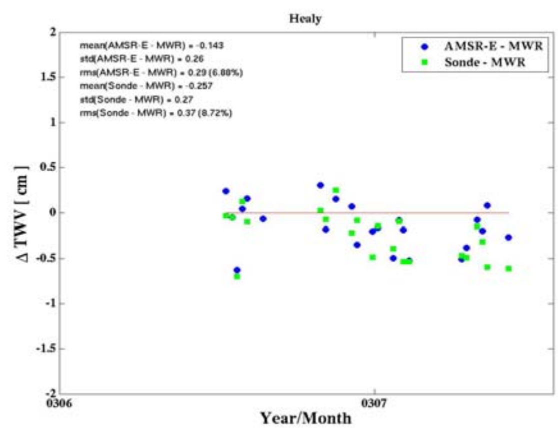

Figure 8. As Figure 6, but for the *Healy* cruise

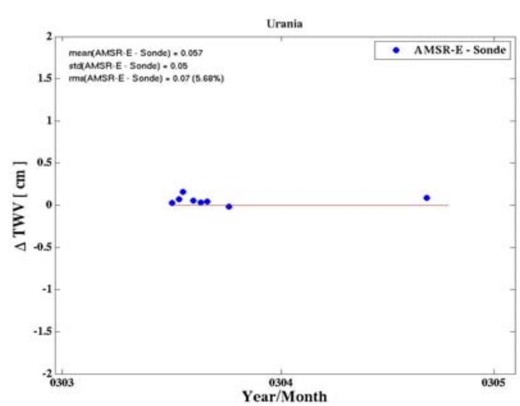

Figure 9. As Figure 7, but for the *Urania* cruise

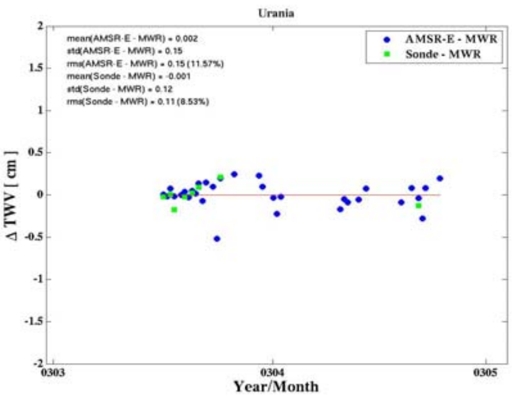

Figure 10. As Figure 8, but for the *Urania* cruise

however, a clear bias is visible between AMSR-E and MWR measured PWV. There also appears to be a negative bias between AMSR-E and MWR measurements throughout the second half of the *Healy* cruise. That time corresponds to the Healy sailing through the tropical and sub-tropical waters of the Gulf of Mexico and the Caribbean before turning North towards Nova Scotia at the end of the cruise. No bias between AMSR-E and MWR was observed in the Mediterranean during the *Urania* cruise.

4. Summary and Discussion

Several methods of obtaining PWV over the ocean were investigated and compared. The measurements from three sea deployments were analyzed in the Caribbean, Mediterranean, and around North America. Most measurement types yield PWV values within 10% of the mean without obvious biases. The exception is the MWR measurements in tropical and subtropical conditions that show a clear negative bias with respect to other methods (see Table 1). In the Mediterranean the absolute differences in PWV between different approaches are similar to or lower then corresponding ΔPWVs observed for the Caribbean and North American cruises. However the mean PWV measured in the Mediterranean during the *Urania* cruise is almost four times lower then the typical PWV encountered during the *Explorer of the Seas* and *Healy* deployments. This results in certain cases in larger values of the relative errors for the *Urania* measurements.

The occurrence of the bias between the MWR and other measurements in the Caribbean and its absence in the Mediterranean data seem to suggest the coefficients used in the processing if the MWR data work well for atmospheres with low PWV but might not be optimized for atmospheres with high PWV loadings. An extension of this work will aim to derive MWR retrieval coefficients for the Caribbean area and test their validity over other regions of the world ocean where conditions of high PWV prevail.

This study highlights the difficulty in obtaining accurate and credible measurements of atmospheric water vapor over the oceans in a routine fashion. Radiosondes have long been used as the main source of such measurements, but comparative studies have indicated significant biases (Miloshevich et al., 2001). Satellite microwave radiometry provides a mechanism for taking globally consistent measurements, but such retrievals require validation over the open ocean away from the contamination from land emission that enters the satellite measurements through the antenna side-lobes. This can be best achieved with ship-based instruments. The study presented here ought to be repeated on a larger scale to establish the error characteristics of the different measurement schemes in a wider range of atmospheric conditions.

5. Acknowledgments

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Table 1. Statistics of the differences in the measurements of precipitable water vapor. Each cell contains the mean, standard deviation and root mean square values.

	Explorer of the Seas	*Healy*	*Urania*
Mean PWV [cm]	4.67	4.19	1.31
AMSR-E – ECMWF	0.067 0.46 0.46 (9.85%)	N/A	N/A
AMSR-E – SONDE	-0.034 0.22 0.22 (4.66%)	0.110 0.21 0.24 (5.65%)	0.057 0.05 0.07 (5.68%)
AMSR-E - $\text{M-AERI}_{\text{ECMWF}}$	0.074 0.40 0.39 (8.44%)	N/A	N/A
AMSR-E - $\text{M-AERI}_{\text{SONDE}}$	-0.092 0.34 0.35 (7.40%)	0.012 0.36 0.35 (8.28%)	0.114 0.20 0.22 (16.96%)
AMSR-E - MWR	-0.278 0.21 0.35 (7.49%)	-0.143 0.26 0.29 (6.88%)	0.002 0.15 0.15 (11.57%)
ECMWF - MWR	-0.205 0.43 0.47 (10.06%)	N/A	N/A
$\text{M-AERI}_{\text{ECMWF}}$ - Sonde	-0.041 0.40 0.38 (8.13%)	N/A	N/A
$\text{M-AERI}_{\text{SONDE}}$ - Sonde	-0.031 0.26 0.25 (5.38%)	0.171 0.33 0.36 (8.67%)	0.033 0.05 0.05 (4.17%)
$\text{M-AERI}_{\text{ECMWF}}$ - MWR	-0.220 0.42 0.46 (9.86%)	N/A	N/A
$\text{M-AERI}_{\text{SONDE}}$ - MWR	-0.145 0.42 0.44 (9.49%)	-0.028 0.50 0.49 (11.59%)	-0.091 0.25 0.26 (19.90%)
$\text{M-AERI}_{\text{ECMWF}}$ - $\text{M-AERI}_{\text{SONDE}}$	-0.150 0.36 0.38 (8.10%)	N/A	N/A
SONDE – MWR	-0.237 0.27 0.35 (7.56%)	-0.257 0.27 0.37 (8.72%)	-0.001 0.12 0.11 (8.53%)