Statistical Evaluation of Water Vapour Radiometric Profiling

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ABSTRACT

A dataset gathered over 369 days in various mid-latitude sites with a multi-frequency microwave radiometer profiler is used to perform a statistical comparison between radiometer retrieved water vapour profiles and those provided by an operational radiosonde sounding dataset.

The microwave profiler is automated, providing atmospheric sounding up to 10 km height. It observes brightness temperature at twelve frequencies. Atmospheric profiles are retrieved using a neural network based on historical local radio soundings. Results show a good agreement for the mean water vapour content profiles. The water vapour content distribution for radiometric and radio sounding data are weibull distributed with two parameters scale and shape. The scale parameters in the two cases are very similar. The shape parameter from radio sounding is, as the radiometric one, almost constant and close to the radiometric values for T < -5℃. For T > -5℃ it is l ower than the radiometric values.

Another evaluation is performed by comparing integrated water vapour distribution retrieved from the microwave radiometric profiler and the one calculated from the European reanalysis meteorological database ERA 15. Results show a good agreement.

1. INTRODUCTION

Water vapour is a fundamental driver of weather and climate. Most of the water vapour data used in global weather forecasting is measured by radiosondes launched twice-daily. However, these soundings are insufficient for capturing the spatial and temporal variations such as those related to the diurnal cycle. Consequently, the use of newly developed instruments, able to provide water vapour data with a high temporal frequency, should be evaluated to determine if they provide more information. One such instrument is the Radiometrics corporation TP/WVP-3000, a multi-channel ground based microwave radiometer [1]. This remote sensing instrument provides real time vertical profiles of temperature, water vapour and cloud liquid water in nearly all weather conditions. it measures radiometric brightness temperatures through a sequential scan of 12 frequencies inside the microwave spectrum, 5 in the K band, on the flank of the 22 GHz water vapour absorption line, and 7 in the V band, on the flank of the 60 GHz molecular oxygen complex. The radiometer also includes some in situ sensors for the ground level measurement of temperature, pressure, and humidity, as well as a zenith looking infrared thermometer and a liquid water (precipitation) detector.

By inversion of the radiances measured at the different channels through a neural network application, based on historical local radio soundings, the radiometer retrieves the vertical profiles of temperature (T) and water vapour (WVC), cloud base temperature, vertically integrated water vapour (IWV) and liquid water (ILW).

Because of one of the most basic properties of an environmental variable is its Statistical distribution, in this paper we seek to access the accuracy of statistical water vapour modelling. This is done through a comparison between statistical parameterization of water vapour from radiometric retrievals, sounding data and European reanalysis meteorological database ERA15.

2. RADIOMETRIC DATA

The data were collected at three different sites located in the South-West of France (Toulouse, Lannemezan and Aire-sur-l'Adour) during a period distributed over the four seasons. This dataset is considered to be representative of coastal oceanic mid-latitude climate [2]. During the data acquisition at the various sites, it rained for 7.5% of the time, clouds were present 72% of the time and clear sky 28% of the time.

Profile retrievals are obtained at 250 m intervals from the surface to 10 km, the training of the neural network was performed with 10 years of radio sounding data from Bordeaux-Mérignac, a meteorological station located on the Atlantic Coast assumed to be representative of the atmosphere over the coastal, oceanic, midlatitude Western Europe.

One profile, corresponding to one 23 s measurement cycle, was retained each 92 s, to reduce statistical redundancy, which gives 309927 profiles for the whole 369 days of the observing period. One profile includes in fact the two 41 level basic profiles of temperature and WVC, the two integrated values IWV and ILW, and the surface parameters. Profiles associated with the presence of rain as detected by the rain detector of the radiometer were removed, as well as the profiles associated with an ILW higher than 2 mm. ILW > 2 mm is due to the presence of precipitation aloft that can bias the retrievals [3].

To assess how the results presented in the present paper are biased by the retrieval uncertainty, we use the RMS error vector affecting the retrieved profiles. To compute the RMS error on the retrievals, we have added to each retrieved profile a Gaussian noise with zero mean and a standard deviation equal to the RMS error for each layer.

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3. WATER VAPOUR CONTENT DISTRIBUTION

To analyze the WVC distribution, Probability density functions (pdf) were calculated by temperature class of width ΔT = 10℃, WVC bin of 0.2 g m^{-3}, between 20 and -45℃, as was the fitting for two analytical forms: lognormal and Weibull. These forms were selected among others from empirical tests and from physical and bibliographical considerations. They are frequently used for atmospheric and cloud characteristic representation because they are related to physical processes relevant for atmospheric phenomena. The lognormal distribution is associated with the statistical process of proportionate effects. The lognormal form is found to be convenient for many cloud characteristics such as rain cell size distributions, rain rate distributions, precipitable water, and relative humidity. The Weibull form is found convenient for variables whose distribution is limited by extreme values, for example life variables or wind when the velocity is limited by turbulence. For the WVC distribution the upper limit is the vapour density at saturation in the presence of condensation (cloudy sky). In clear air there is no upper limit.

The lognormal probability density function (pdf) is written:

$$f(x;\mu_y,\sigma_y)=\frac{1}{\sqrt{2\pi}\ x\ \sigma_y}\exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right] \tag{1}$$

where $y=\ell n\ x$. The two parameters of the distribution are the mean μ_y and variance σ_y^2 of y, defined as:

$$\mu_y = \ell n\left\{\mu_x\left[1+\left(\frac{\sigma_x}{\mu_x}\right)^2\right]^{1/2}\right\} \tag{2}$$

$$\sigma_y^2 = \ell n\left[1+\left(\frac{\sigma_x}{\mu_x}\right)^2\right]. \tag{3}$$

The Weibull pdf is:

$$f(x;k,\lambda)=\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}\exp\left[-\left(\frac{x}{\lambda}\right)^k\right]. \tag{4}$$

The two parameters of the distribution are the scale λ and the shape k. The mean μ_x and variance σ_x^2 are defined as:

$$\mu_x = \lambda\ \Gamma\left(1+1/k\right), \tag{5}$$

$$\sigma_x^2 = \lambda^2\ \Gamma\left(1+2/k\right)-\mu^2. \tag{6}$$

Γ is the gamma function.

3.1 Water vapour distribution from radiometric data

The numeric values of the fitting parameters and correlation coefficients for radiometric data are given in Table 1. Weibull distribution is found better than lognormal at temperatures between –20 and 10℃ and the two distributions are almost equivalent at T < -20℃ and >10℃. The Weibull fitting gives better results because the WVC fluctuations have limits related with the condensation process when the WVC reaches saturation. Consequently our data sample which is cloudy at 72% permits the occurrence of Saturation with a big percentage.

Table1. *Fitting parameters and correlation coefficients for pdfs' radiometric data*

Temperature class (℃)	Radiometric data					
	Lognormal			Weibull		
	μ_y	σ_y	r	λ	k	r
[-45; -35]	-2.42	0.55	1.00	0.12	2.08	1.00
[-40; -30]	-1.91	0.51	0.87	0.19	2.17	0.93
[-35; -25]	-1.43	0.50	0.99	0.30	2.20	0.99
[-30; -20]	-0.98	0.51	0.99	0.48	2.20	0.98
[-25; -15]	-0.55	0.52	0.97	0.74	2.21	0.98
[-20; -10]	-0.12	0.53	0.96	1.14	2.25	0.98
[-15; -5]	0.34	0.52	0.94	1.79	2.35	0.99
[-10; 0]	0.81	0.50	0.85	2.80	2.68	0.98
[-5; 5]	1.19	0.42	0.85	3.93	3.34	0.99
[0; 10]	1.49	0.35	0.94	5.19	3.61	0.99
[5; 15]	1.73	0.32	0.98	6.58	3.51	0.97
[10; 20]	1.93	0.32	0.98	7.98	3.59	0.98

3.2 Water vapour distribution from soundings

To perform a comparison between the radiometer retrieved WVC pdfs and those provided by a radiosonde dataset, we have used the two daily RS gathered at Bordeaux during the period when the radiometer was active.

Table 2 gives the coefficients of the WVC pdfs calculated from the RS data and fitted with lognormal and Weibull functions. The Weibull fitting is clearly very good and better than the lognormal one.

Table2. *Fitting parameters and correlation coefficients for pdfs' sounding data*

Temperature class (℃)	Sounding data					
	Lognormal			Weibull		
	μ_y	σ_y	r	λ	k	r
[-45; -35]	-2.43	0.52	1.00	0.11	2.33	1.00
[-40; -30]	-2.10	0.61	1.00	0.16	2.91	1.00
[-35; -25]	-1.59	0.61	0.90	0.27	2.96	0.98
[-30; -20]	-1.13	0.63	0.94	0.43	2.93	0.99
[-25; -15]	-0.67	0.62	0.91	0.68	2.01	0.98
[-20; -10]	-0.25	0.62	0.91	1.03	2.00	0.97
[-15; -5]	0.17	0.63	0.89	1.60	1.98	0.95
[-10; 0]	0.60	0.63	0.80	2.45	2.06	0.91
[-5; 5]	1.01	0.60	0.66	3.60	2.30	0.88
[0; 10]	1.38	0.56	0.66	5.08	2.52	0.91
[5; 15]	1.60	0.50	0.68	6.66	2.83	0.94
[10; 20]	1.90	0.44	0.77	8.13	3.24	0.97

3.3 Weibull parameters as temperature functions

Curves with error bars in figure 1 shows the best fitting of the variation as a function of the temperature of Weibull parameters, shape k and scale λ, and of the skewness and kurtosis for the pdf of WVC calculated from the radiometer retrievals for 24 classes of temperature of width ΔT = 10℃ between -45 and 20℃.

For $\gamma_1 > 0$, skewness is on the left side (the mode is lower than the average) and there is a tail on the right side. For $\gamma_1 < 0$, it is the reverse, that is to say skewness is on the right and tail on the left. γ_1 and k convey partly the same kind of information. For $k < 2.6$, the Weibull pdfs are positively skewed (with a right side tail). For $2.6 < k < 3.6$, skewness coefficient approaches zero (no tail), that is to say pdf is quasi normal. For $k > 3.6$, Weibull pdfs are negatively skewed, and the tail is on the left. It is what Fig. 1 shows. At cold temperature, WVC pdfs are positively skewed. While temperature increases, skewness diminishes and WVC pdf evolves toward a normal shape. For temperature between about -2℃ and 12℃, k pdfs is higher than 3.6, that is to say slightly negatively skewed.

This evolution of the WVC Weibull pdf parameters with temperature can be explained, at least in part, by considering the WVC limit of saturation. In the absence of limit, WVC is lognormally distributed as most of dynamically controlled atmospheric parameters. Limits linked to saturation create a truncation on the right side of the pdfs and thus induces a reverse skewness. The bump observed on the radiometric k curve, for -10℃ < T < 15℃, corresponds tightly to the average liquid cloud water vertical distribution associated with mid latitude cumulus clouds [4]. In the upper panel, horizontal lines at k = 2.6 and 3.6 show the domain where pdfs are quasi normal.

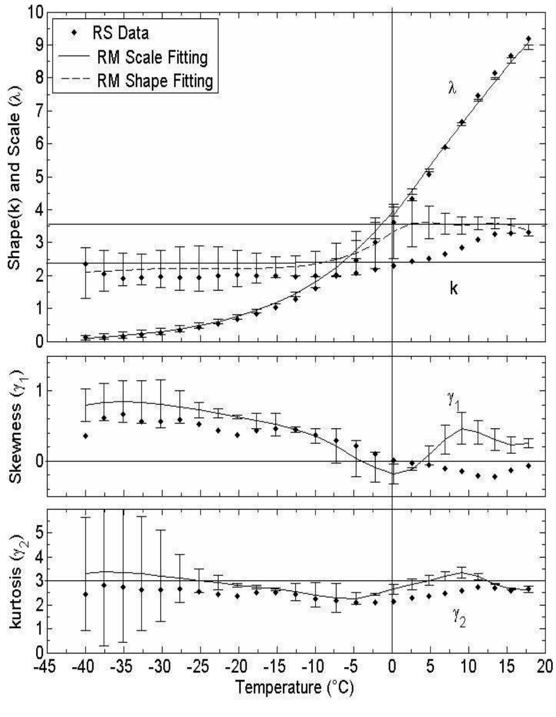

Figure 1. Variation as a function of the temperature of Weibull parameters, skewness and kurtosis for the pdf of RS and radiometric (RM) WVC.

The dots in fig. 1 show the variation as a function of the temperature of the mean WVC calculated from the RS dataset. Scale λ from RS is very close to the radiometer retrieval one. RS Shape k is, as the radiometric one, almost constant and close to the radiometric values for T < -5℃. For T > -5℃ it is lower than the radiometric values but enclosed between 2.6 and 3.6, that is quasi normal. There is no bump on the RS k curve, because of the coarse sampling frequency which does not permit access to some important aspect of the WVC distribution related with short life cycle phenomena like mid-latitude cumulus clouds. Skewness and kurtosis are rather similar for RS and radiometer. Curves k(T) of Fig. 1 can be fitted with a general model of Gauss2 form, namely:

$$k(T) = a_1 \exp\left[-\left(\frac{T-b_1}{c_1}\right)^2\right] + a_2 \exp\left[-\left(\frac{T-b_2}{c_2}\right)^2\right] \qquad (7)$$

with coefficients given in Table 3.

Table 3. *Fitting and correlation coefficients for the shape parameter (radiometric data)*

	a_1	b_1	c_1	a_2	b_2	c_2	r
T≤ 0℃	1.59	279	9.6	2.23	256	100	0.99
T > 0℃	1.91	273	7.58	3.51	288	15.1	0.97

Curves λ(T) of Fig. 1 can be fitted very well with a function of the same form as the Clausius-Clapeyron equation that is:

$$\lambda(T) = \frac{a_3}{T} \exp\left[\frac{b_3\,(T - 273.15)}{T - c_3}\right] \qquad (8)$$

with coefficients given in Table 4 and T in K.

Table 4. *Fitting and correlation coefficients for the scale parameter (radiometric data)*

	A	B	C	r
T ≤ 0℃	1079	17.2	51.9	0.99
T > 0℃	1039	2.43	245	0.99

4. MEAN WATER VAPOUR CONTENT PROFILES

Because it is more representative physically, the WVC mean, μ_{WVC}, for sounding data has also been plotted. μ_{WVC} for radiometric data has been fitted and the curve fitting shown in Fig. 2. The best fitting is achieved by a function of the same form as the Clausius-Clapeyron equation namely:

$$\mu_{WVC}(T) = \frac{A}{T} \exp\left(\frac{B\,(T - 273.15)}{T - C}\right), \qquad (9)$$

whose parameters are given in Table 5.

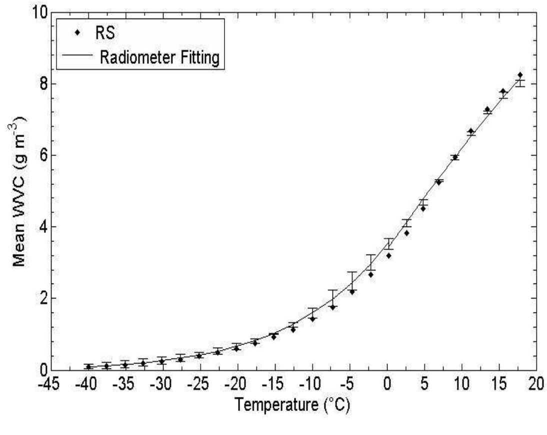

Figure 2. *Variation as a function of the temperature of the mean WVC for RS radiometric*

The mean of WVC then depends only on the temperature. The mean RS WVC variation with temperature is very similar to radiometric one.

Table 5. *Fitting parameters and correlation coefficients for the mean WVC (radiometric data)*

	A	B	C	r
T ≤ 0℃	968	19.6	26.3	0.99
T > 0℃	933	2.35	246	0.99

5. DISTRIBUTION OF IWV

As for WVC, pdf of IWV was calculated and fitted with lognormal and Weibull distributions. the Weibull distribution is the best.

5.1 Comparison with ERA15

Using 15 years of European Centre for Medium-range Weather Forecast reanalysis meteorological database ERA 15, the Weibull parameters k and λ for the IWV distribution were calculated. Isolines of k and λ over the western European area, where the radiometric data were collected, are presented in Fig. 3.

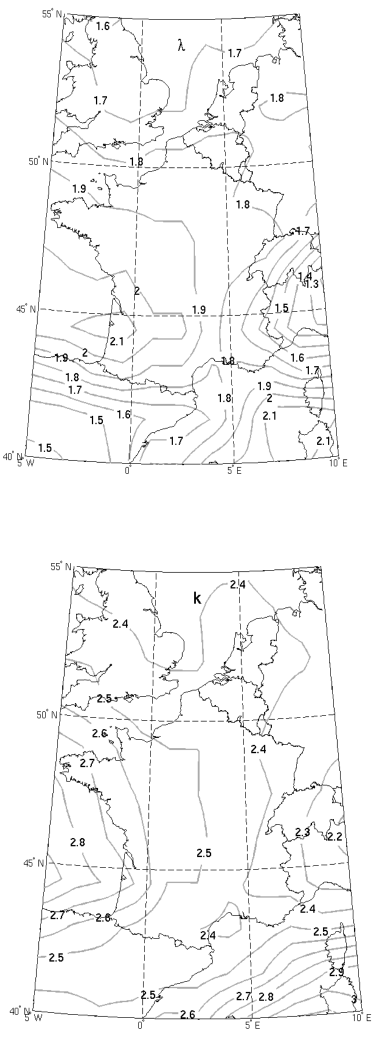

Figure 3. *Isolines of the Weibull distribution parameters for the fitting pdf of IWV calculated from ERA 15.*

The fields of k and λ values are rather homogeneous showing the validity of our assumption that this area can be considered as a single climatological entity for WVC distribution. Averaged values over the area represented in Fig. 3 are k = 2.5 and λ = 1.9 which compare very well with the radiometric ones those are k = 2.8 and λ = 1.9. This agreement can be seen as supporting the validity of the rariometric IWV.

6. SUMMARY AND CONCLUSIONS

The distribution of the vapour phase of tropospheric water was studied from radiometric, sounding and ERA15 data of various sites situated in Western Europe. Several forms of distribution were considered to fit the pdf of the atmospheric water vapour profiles observed with the profiler or provided by an operational radiosonde sounding dataset. For the sake of clarity, only lognormal and Weibull distributions were discussed in the present paper because they proved to be the most efficient for the pdf fitting. The lognormal function is associated with the statistical process of proportionate effect, frequently identified in the atmosphere. The Weilbull function is convenient for random variables whose distributions are limited by extreme values such as water vapour when condensation occurs.

The WVC pdf inside 10℃ temperature classes between 20 and -45℃ are found to be accurately fitte d by Weibull distributions for radiometric and sounding data. The two parameters of the Weibull distribution, the shape k and scale λ, are shown to be well described by analytical functions of temperature T. The mean WVC vertical profile and the scale parameters in the two cases are very similar. The shape parameter from radio sounding is, as the radiometric one, almost constant and close to the radiometric values for T < -5℃. For T > -5℃ it is lower than the radiometric values. This is due to the coarse sampling frequency of sounding which does not permit capturing of the variations of WVC related to short cycle phenomena.

The pdf of the vertically integrated WVC, or precipitable water, is found to be Weibull distributed rather than lognormal. The values retrieved from the microwave radiometric profiler compare very well with the ones calculated from the ERA 15 reanalysis meteorological database.

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