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Comparison of techniques for measurements of fog liquid water content

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ABSTRACT

During the Po Valley Fog Experiment 1989, four different methods for the measurement of the liquid water content in fog have been operated side by side. In order to check the performance of the PVM-100 (Particulate Volume Monitor) under field conditions, the data were compared to the results of the measurements with two FSSP-100 (Forward Scattering Spectrometer Probes), a Johnson Williams heated wire probe, and a Lyman-α instrument. Accuracy, limitations, and calibrations of these instruments are discussed. Results of fog chamber calibrations of a PVM-100 are shown. The PVM-100 was concluded to be the best instrument under laboratory and field conditions.

1. Introduction

The liquid water content (LWC) of fogs and clouds can be measured by optical, thermal, or sampling measurements. Most methods are less reliable resulting in errors of 50% or more. For a calculation of the mass balance of the compounds between gas and water phase, an accurate LWC measurement is necessary. In order to gain more information on the quality of LWC instruments a lot of experimental and theoretical investigations were performed.

Valente et al. (1989) compared a Forward Scattering Spectrometer Probe (FSSP-100), a prototype Particulate Volume Monitor (PVM-100), a TVA Valente filter, and other instruments in ground-based clouds at Whitetop Mountain, VA. The conclusion of this study was that the TVA-Valente filter was one of the best instruments in fog unless there were periods of intermittent clouds.

Baumgardner (1983) compared different instruments for aircraft measurements of the LWC. These were the FSSP, the axially scattering spectrometer probe, the cloud gun droplet impactor, the Johnson Williams probe, and a CSIRO probe. He came to the conclusion that both the Johnson Williams probe as well as the FSSP can have large errors. Another intercomparison of different LWC measuring devices in an aircraft has been done by Personne et al. (1982). They compared a FSSP, a Johnson Williams probe, and a Lyman-α photometer combined with a dewpoint measurement. In the comparison, both the FSSP and the Johnson Williams heated wire had large deviations from the Lyman-α instrument, which was concluded to be the best instrument.

The aim of this study is to gain more information on the performance of the new developed PVM-100. For this reason the PVM-100 was compared to other LWC-instruments under

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ground-based cloud and laboratory conditions. In the field study (Po Valley Fog Experiment 1989) next to the PVM-100 two FSSP-100, a Johnson Williams heated wire probe, and a Lyman-α hygrometer measuring humidity after evaporation of the droplets were used.

In the laboratory study, which took place in the wind tunnel CHIEF at ECN (Netherlands Energy Research Foundation), the PVM-100 was compared to the FSSP-100 and a filter technique.

The PVM-100 is a new instrument whose field performance was not yet known. Although it was known from the above mentioned investigations (Valente et al., 1989; Baumgardner, 1983; Personne et al., 1982) that the results of the other LWC instruments can have large errors, these techniques are used to evaluate accuracy, reliability, reproducibility, and handling of the PVM-100.

2. Description of the methods

2.1. *PVM-100*

The PVM-100 instrument is a forward scattering laser spectrometer for particulate volume measurements (Gerber, 1984, 1991). In this instrument a laser beam crosses the air over a length of 42 cm with an optical probing volume of 3 cm^3, and light scattered forward in a small angle (0.32–3.58°) is registered. The measuring principle takes advantage of the linear relationship between LWC and scattered light flux. Therefore, a special receiver optics (Gerber, 1991) is used which guarantees, according to the manufacturer, linearity between scattering intensity and LWC for droplet diameters from 3–45 μm.

The PVM-100 was calibrated in the CALSPAN chamber (Buffalo) using extinction measurements. The instrument was calibrated additionally in the wind tunnel at ECN by comparison with filter measurements (see Section 4). During the field experiment the calibration was checked daily by the light diffusing disk supplied with the instrument.

2.2. *FSSP-100*

The Forward Scattering Spectrometer Probe (FSSP) is a single particle counting laser instrument (Knollenberg, 1981). The optical sensing volume is small (0.08 mm^3).

The FSSP measures the droplet number in 60 channels with different size bins. From this droplet distribution, the total volume of liquid water can be calculated. The instrument is calibrated with monodisperse glass beads of different diameters.

In the field, two FSSPs were used, one sizing particles between 1 and 95 μm diameter and the other between 0.5 and 47 μm. The first FSSP was operated 1.5 m above the ground, the second instrument was mounted on an elevator and measured at different heights. The FSSPs were equipped with a blower which effects a wind speed of 26 m s^{-1} in the instrument. The instruments were sampling with a standard horn provided by PMS (Particle Measuring Systems, Inc.) in order to sample close to isokinetic conditions under low atmospheric wind speeds. The device was oriented into the wind by hand. The instruments were calibrated in the laboratory according to the instructions of the manufacturer and the calibration was checked twice a week.

2.3. *Johnson Williams sensor*

The Johnson Williams heated wire (JW) measures the resistance of a wire on which droplets are impacted and compares this to the resistance of a reference wire (Neel, 1973). As the instrument was originally designed for aircraft use, it was combined with an air pump and an inlet to reduce losses from anisokinetic sampling. The instrument was calibrated electronically with a "dummy head" supplied by the manufacturer. This calibration head replaces the sensor head and can simulate two different LWCs.

2.4. *Lyman-α*

The Lyman-α hygrometer was used in combination with a counterflow virtual impactor (CVI) described by Noone et al. (1988). The CVI only collects droplets above a given diameter, which are evaporated thereafter. The Lyman-α (Zuber and Witt, 1987) measures UV absorption by water vapor at a wavelength of 121.6 nm and compares it to a reference chamber with dry air. As the relation between water vapor concentration and absorption is well known, this method can be regarded as an absolute technique. The measuring error of the Lyman-α is within 3% of the amount of water

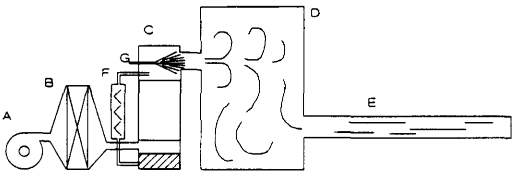

Fig. 1. Fog chamber CHIEF: A = blower, B = aerosol filter, C = humidifier, D = equilibration vessel, E = wind tunnel, 5 m long, F = water pump, G = nebulizer.

vapor in the system. A complete description of the methods and the setup of the Po Valley Fog Experiment 1989 is given in Fuzzi et al. (1992).

2.5. CHIEF

Some LWC comparisons were done in the windtunnel called CHIEF (Chamber for Investigation with Equilibrated Fog), which was described in detail by Mallant (1988), see Fig. 1. Fog is created behind the humidifier by an ultrasonic generator (Heyer 77) or by a pneumatic nebulizer (Lee Instac, TCDA6201150H). The droplet spectra of the two nebulizers measured at the end of the windtunnel are shown in Fig. 2. After the fog generation, a large equilibration vessel provides an optimal mixing of the air. Then, the air enters a tunnel of 5 m length with a diameter of 50 cm. Wind speeds in the tunnel were varied between 1 and 5 m s^{-1} during the tests.

The LWC was determined by hydrophobic filters (Pall) which were operated isokinetically. The filters were equilibrated for at least two hours with air of 100% humidity. During sampling, air flow through the filter was registered by a calibrated gas meter. In order to control whether the filter was not obstructed by water or salt, the pressure drop over the filter should not exceed 120 Pa. Always two filter measurements were done at the same time. The standard deviation of repeated filter measurements performed in a constant fog was 5%.

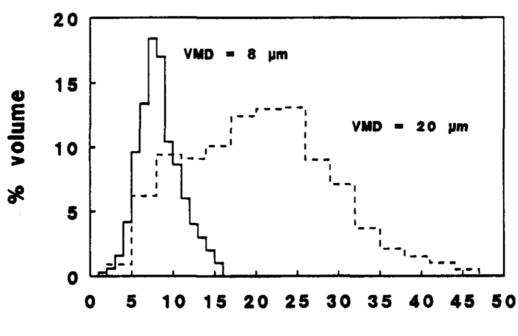

Fig. 2. Volume distribution of the Heyer nebulizer (VMD = 8 μm) and the Lee nebulizer (VMD = 20 μm).

3. Comparison of the results of the field campaign

During the Po Valley Fog Experiment in fall 1989 the instruments were operated side by side for more than 90 hours in dense fog. Starting from 11 November, a well mixed high reaching fog persisted for 63 hours. Fig. 3 illustrates the observed LWC on 12 November of the two FSSP-100, the PVM-100 and the Johnson Williams probe.

For the FSSP on the elevator (which was called FSSPt) only the measurements for heights < 10 m were taken. The general course of LWC was the same for all instruments, although the values differ up to a factor of 2.5. The lowest LWC over the entire period was detected by the PVM-100, whereas the Johnson Williams device showed the highest results.

A more detailed comparison between PVM and FSSP data can be gained considering the volume median diameter (VMD) of the droplet size distributions which were calculated from the FSSP measurements. In most cases (85% of the com-

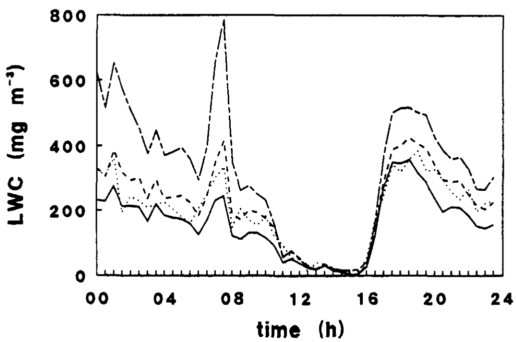

Fig. 3. Comparison of half-hourly average LWC of PVM, two FSSPs and the Johnson Williams on 12 November 1989. Full line (PVM), dashed line (FSSP ground), dotted line (FSSP tower), dashed dotted line (JW).

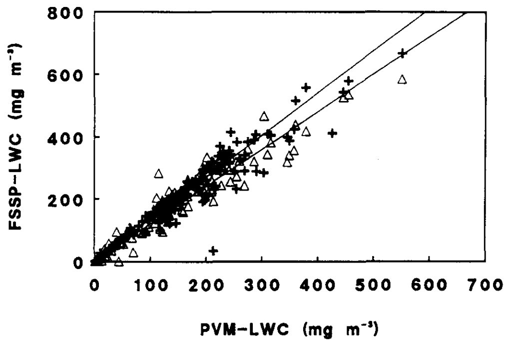

Fig. 4. Correlation between PVM and FSSP LWC for the two FSSP probes. Crosses (FSSP ground), triangles (FSSP tower). The FSSPs give higher values by a factor of 1.35 for the ground and 1.2 for the tower.

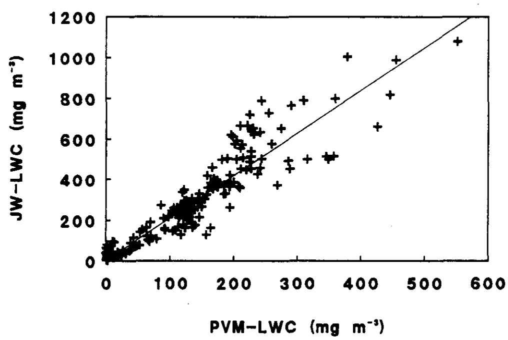

Fig. 6. Correlation between PVM and Johnson Williams LWC. The correlation factor for the JW is 2.

plete dataset) the VMD was larger than 20 μm, and the differences of measured LWC between FSSPs and PVM were significant. The correlation between PVM-100 and the two FSSP probes for this group of data (VMD > 20 μm) is shown in Fig. 4. The ratio of FSSPt to PVM is found to be 1.2, the ratio of FSSPg (ground) to PVM 1.35. The appropriate correlation coefficients are 0.95 and 0.96.

For the observations with VMDs between 10 and 20 μm the LWC ratios FSSP/PVM are close to unity. The correlation coefficient for this case is 0.98 for the FSSPg. In Fig. 5 the + symbols display the LWC ratio for the FSSPg versus PVM as a function of VMD for all observations of the field experiment. The strong scatter up to a VMD of 10 μm was probably caused by errors in measurements because the LWC in these cases were relatively low with values of 25 to 50 mg m^{-3}. Therefore, we refrained from including these data in the discussion. The remaining observations indicate a weak increase of the LWC ratio with increasing VMD.

The Johnson Williams device always gives higher results than the other methods. Especially at low LWC (< 25 mg m^{-3} measured by PVM-100) the Johnson Williams gives too high results with an offset of up to 60 mg m^{-3}. For a correlation between the PVM and the Johnson Williams sensor, LWCs < 25 mg m^{-3} are omitted. In Fig. 6 the LWC data of JW and PVM are compared. The LWC ratio JW/PVM results in a factor of 2 with a

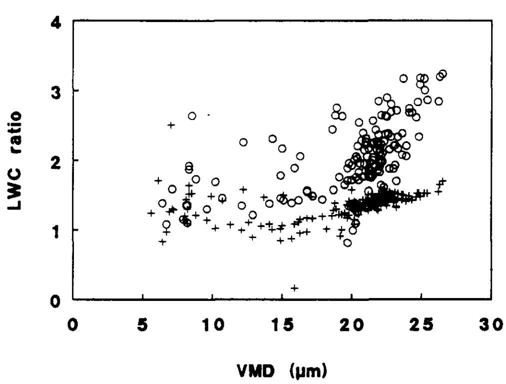

Fig. 5. LWC ratios correlated to the volume median diameter (VMD). Crosses (FSSPg/PVM), circles (JW/PVM). The ratio of FSSP/PVM-LWC is relatively constant, while the ratio JW/PVM-LWC is increasing for higher VMDs. At low VMD, the LWC is often low which causes higher errors.

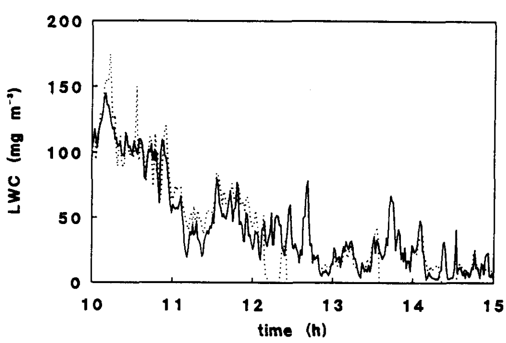

Fig. 7. Comparison of the PVM and the Lyman-α minute averages of LWC. Full line (PVM), dotted line (Lyman-α). At 12:15, the Lyman-α is checked with zero air. Only periods are taken where the minimum droplet diameter of the CVI inlet is lower than 6 μm.

correlation coefficient of 0.93. Fig. 5 (dots), however, displays that this LWC ratio increases strongly for droplet spectra with VMD > 20 μm. The Johnson Williams sensor shows large variations at lower VMD, which can be explained by a zero-point offset and possible errors in measurement at low LWCs.

The data of the Lyman-α hygrometer were only used for a comparison in shorter periods when the lower cut-size of the CVI was kept at 5 or 6 μm. In Fig. 7, 1-min average LWC data of the PVM-100 and the Lyman-α hygrometer, measured during daytime of 12 November, are shown. This period can be characterized by low wind speeds and the presence of small droplets (average VMD = 14 μm). Under these conditions only minor inlet losses of the CVI could be expected. The observed good agreement between these two instruments is remarkable, since a calibration is very difficult to maintain for these low LWCs detected in this period. In most other periods during the field campaign the Lyman-α LWC observations were slightly lower than the observations performed by the PVM-100, with a ratio (Lyman-α/PVM) of 0.96 and a correlation coefficient of 0.92.

To determine the reproducibility of the PVM, three PVM-100 instruments were compared to each other at another field campaign in 1990 on the Kleiner Feldberg in FRG. The instruments were placed side-by-side with a distance of less than 10 m. The agreement between these instruments was within 10% for LWC values higher than 50 mg m^{-3} and usually better. Deviations occurred most often at low LWC, after a lapse or an inaccurate adjustment of the zero value during field measurements. This shows that it is important to check the zero-point frequently.

4. Comparison of FSSP, PVM-100 and filter measurements in a wind tunnel

Before and after the field campaign, the PVM-100 and the two FSSPs were calibrated by comparison to filter measurements in the wind tunnel CHIEF. Fig. 8 shows the results of this investigation. These tests were performed with two different droplet spectra (Fig. 2) and at a wind speed of 2.2 m s^{-1}. The amount of liquid water in the wind tunnel was varied for both types of

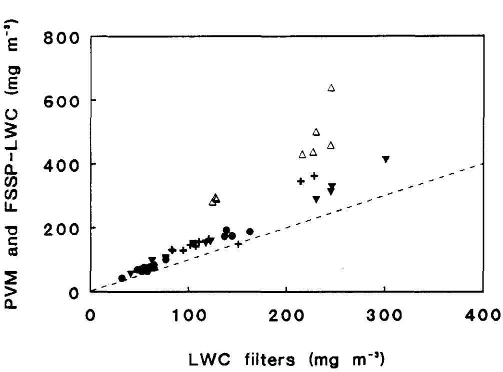

Fig. 8. Comparison of PVM- and FSSP-LWC with filter samples taken in CHIEF. Crosses (FSSP with 9 μm droplets), open triangles (FSSP with 20 μm droplets), solid circles (PVM with 9 μm droplets), solid triangles (PVM with 20 μm droplets). The droplet spectra of the tests are shown in Fig. 2.

droplet size distributions in a range from 30 to 300 mg m^{-3}. The results show that the PVM-100 provides LWC values which are 20% higher than the results of the filter technique. Furthermore, the PVM results achieve a fairly linear relationship to the filter LWC for both droplet spectra. The FSSPs show linearity for fogs with small droplet spectra, but significantly stronger deviations for the larger spectra with a VMD of 20 μm.

The PVM results of this investigation are based on the calibration factor of the manufacturer (Gerber, 1991). Hereby, the PVM-100 was calibrated by an IR transmissiometer at a wavelength of 10.6 μm. There should be a linear relationship between the LWC and the extinction coefficient e up to droplet diameters of 28 μm:

$$\mathrm{LWC} \times k = e.$$

The constant k has been calculated by Chylek (1978) from Mie theory to be 0.128 m^2 g^{-1} for a wavelength of 11 μm. Nolan and Jennings (1987) calculated the constant k for a wavelength of 10.59 μm, and here k was 0.147 m^2 g^{-1}. The manufacturer used the constant from Chylek for his calibration of the PVM-100.

Our windtunnel investigations (Fig. 8) have shown that the PVM-LWC was 20% higher than the results of the filter technique by using this factor. This results in a correction factor of 0.8 for the PVM which was used for the field observations discussed in Section 3. If, however, the manufacturer would use the Nolan factor, which in fact is the correct factor for the wavelength of 10.6 μm, the calibration by the extinction method and in CHIEF would agree within 10%.

5. Discussion

The gravimetric filter sampling method can be regarded as an absolute measuring technique, which provides under laboratory conditions (see Chapter 4) a reliable value for the LWC with an error below 10 mg m^{-3}. From these experiments it can be seen that the PVM-100 is an instrument for the determination of the LWC with high reproducibility and high linearity. The laboratory experiments confirm this linearity up to a LWC of 300 mg m^{-3}. Obviously, also different droplet size distributions do not effect the linearity up to VMD of 20 μm at least.

Another validation of the performance of the PVM-100 can be obtained by a comparison with other instruments.

The field observations with the FSSPs gave in general LWCs which exceeded the PVM results by 20–30%. But the deviation of the field observations from the results of the PVM/FSSP comparison in CHIEF (Fig. 8) is relatively small at least for droplet spectra with small VMDs. However, we want to point out here that a quantitative comparison between the results gained in the field and in the laboratory is not reasonable. The operation of the FSSP has shown that a small shifting of the calibration can result by the rougher handling in the field site. Furthermore, inlet errors can be larger in the field because of varying wind directions. The only qualitative statement that can be emphasized from the intercomparison is the fact that in both cases overestimations of the FSSP-LWC are observed for droplet spectra with large VMDs.

Deviations of the FSSP can be explained by errors such as coincidence and dead time losses (Baumgardner et al., 1985), a broadening of the peak caused by coincidence (Cooper, 1988), variability in the beam fraction between total and accepted particles (Baumgardner, 1983), fluctuations in the Mie scattering curve (Pinnick et al., 1981), and inlet losses. A correction for the activity and the beam fraction variability could reduce the possible error in LWC from up to 105% down to 34% according to Baumgardner (1983). As coincidence can be neglected at the low number densities in the laboratory, a variability of the beam fraction for larger droplets or calibration errors are the most probable reason for the overestimation of the LWC for larger droplets. Mie calculations for the FSSP and PVM showed that the large amounts of light absorbing substances in the polluted Po Valley did not influence the response of the instruments.

The comparison of the PVM with the Lyman-α is useful, as this is an absolute method to check the calibration of the PVM-100. For a good comparison inlet losses have to be reduced as much as possible. The comparison (Fig. 7) shows that the PVM-100 calibration is good for low LWC values. Nothing can be said about situations of higher LWC, as the inlet losses of the Lyman-α were significant in these periods.

The Johnson Williams heated wire is the only non optical instrument in this comparison. It shows the largest deviations from the PVM LWC with a factor of 2. Unfortunately, the JW instrument used during the field campaign was not calibrated in a wind tunnel. Baumgardner (1983) estimated the error of the JW larger than 20% if it had not been calibrated in a wind tunnel. Strapp and Schemenauer (1982) showed in a laboratory comparison that some JW sensor heads were good while others had large errors. Gayet (1986) found in measurements done in a wind tunnel that an air speed of 51 m s^{-1} or lower at the wire led to overestimations of the LWC. Major problems with this instrument were caused by pollution of the sensing wire due to the high soot concentrations in the ambient air. This significantly effected the sensitivity and the zero offset of the JW probe. Furthermore, large droplets which were formed at the inlet walls during operation, could have become detached and possibly hit the sensing wire. JW instruments are known to measure droplets up to at least 32 μm (Baumgardner, 1983), while larger droplets might be removed from the wire before evaporating, which would lead to lower results. Thus, there is no reason why droplets in the diameter size range between 20 and 30 μm should give too high results (see Fig. 5). This might indicate that the PVM gives too low LWCs at VMDs larger than 20 μm. Fig. 5 also maintains this finding from the FSSP/PVM comparison.

The PVM-100 should have a linear ratio of scattering efficiency factor to droplet diameter up to 30 μm droplets, according to diffraction theory (Gerber, 1984). Gerber tries to increase the linearity up to droplet diameters of 45 μm, by introducing weighing factors for different scattering angles. The results from the laboratory tests show that this succeeded at least up to VMDs of 20 μm. Larger droplets could not be generated in a stable way in the fog chamber. But the field experiments indicate that there seems to be a deviation of the PVM-100 for VMDs larger than 20 μm.

The main advantage of the PVM-100 is, that this device measures LWC in situ without using a sampling inlet. A prerequisite for a correct operation of the other instruments used in this investigation is the performance of isokinetic sampling. Otherwise, inlet losses or overestimations can lead to large errors. Furthermore, the PVM-100 shows a very good reproducibility, an easy handling in calibration and regular operation.

The results show that some instruments give deviating results caused by an erroneous calibration.

A purely experimental method like the gravimetric filter sampling method should be regarded as absolute, as long as the fog is constant during the measurements and the method is performed as described aloft. This limits the use of filter measurements in the field as there are inhomogenities of LWC, wind speed and direction.

Instruments in which the calibration can be checked by a simple method, like the optical filter for the PVM-100 or the electrical method for the Johnson Williams instrument, should be calibrated at least once in a cloud chamber by comparison with a gravimetric or extinction method. Once the calibration factor is known, a field calibration with the reference method should be sufficient.

6. Conclusions

For field observations of fog or ground-based cloud LWC measurements, the PVM-100 is the best choice at the moment. The instrument has no problem with inlet losses, and the calibration can easily be performed in the field. But it should be kept in mind that the maximum droplet diameter which is reliably seen is probably less than 30 μm. Even with this limitation, the error of the PVM measurement is smaller than the possible errors of the other instruments. For field experiments, the combination of a PVM-100 and a FSSP seems the optimal configuration. The PVM should be used for LWC measurements and the FSSP for measurements of droplet size distributions.

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