Ground-Based FSSP and PVM Measurements of Liquid Water Content

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ABSTRACT

Recently published ground-based measurements of liquid water content (LWC) measured in fogs by two microphysical instruments, the FSSP-100 and PVM-100, are evaluated. These publications had suggested that the PVM-100 underestimated LWC significantly in comparison to the FSSP-100 when the fog droplets were large. The present evaluation suggests just the opposite: The FSSP-100 overestimates LWC for large droplets because these droplets are unable to follow the curved streamlines of the flow generated by drawing air into the FSSP-100's sensitive volume at 25 m s^{-1}. This inertial effect causes droplets to accumulate near the active volume of the instrument's laser beam and to produce large and spurious droplet concentration and LWC values for the largest droplets. Model calculations estimate the magnitude of this error for the FSSP-100.

1. Introduction

In a recent *Journal of Atmospheric and Oceanic Technology* paper Wendisch (1998) describes intercomparisons of liquid water content (LWC) measurements made in fog during ground-based measurements in 1994 on the Brocken mountain (Germany) and in the Po Valley (Italy) in 1994 with IfT (Institut fuer Troposphaeren Forschung) and other FSSP-100 and PVM-100 instruments. While the Brocken measurements showed very good agreement between the LWC measurements under conditions where droplet sizes were relatively small, the Po Valley LWC measurements showed large differences on occasions when the average droplet size was unusually large. Wendisch (1998) and Wendisch et al. (1998) describe these differences in detail and conclude that their cause may be the underestimate of LWC by the Particle Volume Monitor (PVM) because it did not respond sufficiently to the LWC contribution from larger fog droplets.

The present paper looks at this conclusion in the light of a similar comparison between forward-scattering spectrometer probe (FSSP) and PVM instruments made in the Energieondrzoek Centrum Nederland, Petten, the Netherlands, cloud chamber (Arends et al. 1992; Gerber et al. 1994), where similar experimental results were found, but a different conclusion was reached. In those measurements the FSSP again measured more LWC than the PVM when droplets were large; however, the FSSP also measured a similar excess of LWC in comparison to the Petten reference method that consists of measuring LWC by weighing droplets collected in a filter. These results led to the conclusion that the FSSP was overestimating LWC when large droplets were present for a reason that was not apparent (Gerber et al. 1994).

Differences of up to 650% in LWC measured by the FSSP and PVM (Wendisch 1998), and up to 200% (Gerber et al. 1994), are much larger than the expected accuracies given for both instruments. Baumgardner (1996) gives the accuracy of FSSP LWC measurements as 30%–50%, and Gerber et al. (1994) gives the accuracy of PVM LWC measurements as 5%–10%. Both instruments are designed to respond to droplets over about the same droplet size range of 3- to 50-μm diameter.

This paper also takes a brief look at the performance of the ground-based FSSP under conditions of low wind speed. Droplet trajectories into the FSSP's sampling tube are calculated with a simple model, and droplet

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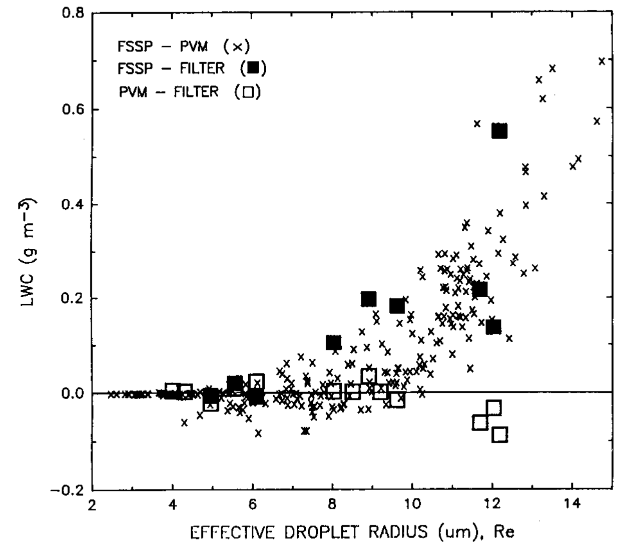

FIG. 1. Measurements of LWC differences measured by pairs of probes as a function of the Re of fog droplets. The (×) data are for measurements in Po Valley fogs (Wendisch 1998; Wendisch et al. 1998), and the (□) and (■) data are for measurements of fog generated in the Petten cloud chamber (Gerber et al. 1994).

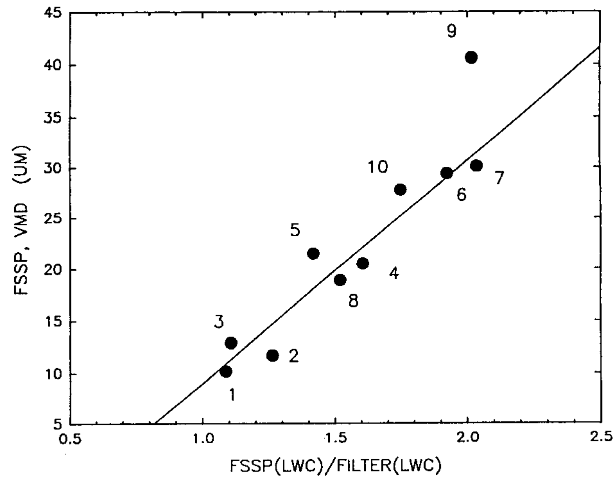

FIG. 2. The ratio of FSSP LWC to reference-filter LWC as a function of VMD of fog droplets generated in the Petten cloud chamber. The numbers identify individual tests represented by the data points; from Gerber et al. (1994).

concentrations are estimated at the central axis of this tube where the FSSP laser beam interacts with the droplets. The curved surfaces of the accelerator insert used with the FSSP during its ground-based operation suggested to us that deviations of the droplets from the streamlines of the air flow generated by suction into the tube to the usual and nominal 25 m s^{-1} might cause unexpected behavior. This suspicion was supported by a calculation of the stopping distance l_i (Fuchs 1964) for droplets with a radius of 25 μm. The value of l_i = 20 cm for such droplets, given a characteristic initial velocity of 25 m s^{-1}. This distance is of the same order of magnitude as the dimensions of the insert, suggesting that droplets of that size may not closely follow curved streamlines and thus could possibly affect the droplet concentration in the tube.

Given the previous experimental results and the present analysis we attempt to answer the question: Is the PVM underestimating LWC when droplets are large, as suggested by Wendisch (1998) and Wendisch et al. (1998), or is the FSSP overestimating LWC when droplets are large, as suggested by Gerber et al. (1994)?

2. Previous results

LWC intercomparison measurements made in Petten (Gerber et al. 1994) and in the Po Valley (Wendisch 1998; Wendisch et al. 1998) are illustrated in Fig. 1, where the measured LWCs are given versus the effective radius, Re, of the droplet spectra (Re is the third moment of the spectrum divided by the second moment of the spectrum). The Po Valley measurements of the difference of LWC (FSSP − PVM data in Fig. 1) measured by the collocated FSSP and PVM were made during an intercomparison period on 13 and 14 November 1994 when larger droplets were sometimes present in the fog. A tendency for the FSSP to measure larger LWC when Re of the droplets increases is seen in the data. This difference suggested to Wendisch (1998) that the PVM was underestimating LWC because of his careful calibration and error correction of the IfT FSSP (Wendisch et al. 1996; Wendisch 1998) and because FSSP and PVM LWC measurements agreed closely when droplets were small on the average.

A similar tendency for the FSSP to measure larger LWC as Re increases is seen in the difference between LWC (FSSP − filter data in Fig. 1) measured by the FSSP by the reference filter method in the Petten cloud chamber (Mallant 1988; Arends et al. 1992; Gerber et al. 1994). This result, in slightly different form, was already described earlier [see Fig. 2 reproduced from Gerber et al. (1994)].

On the other hand, the difference in the LWC (PVM − filter data in Fig. 1) measured (Gerber et al. 1994) with the PVM and Petten filter is minimal, except for a small deviation for the largest values of Re.

Other comparisons of ground-based LWC measurements were made with the FSSP and PVM in an earlier Po Valley fog experiment (Arends et al. 1992) and in cloud over Cheeka Peak (Kowalski et al. 1997). In the former work, the FSSP measured larger LWC when the droplet volume median diameter (VMD) was in excess of 20 μm, and in the latter work the agreement was generally good given that the droplets were usually small. In the rare cases in which droplet VMD exceeded 20 μm, Kowalski et al. (1997) found that two collocated PVMs that gave precise agreement for small droplets now showed an LWC difference of 9%.

Comparing the results produced by FSSP−PVM

TABLE 1. Operation conditions of the FSSP instruments used in the Po Valley and Petten LWC measurements.

	Po Valley FSSP-100	Petten FSSP-100
Flow accelerator	Yes	Yes
Cone	No	No
Glass bead calibration	Yes	Yes
Wind speed	<2 m s^{-1}	2.15 m s^{-1}

measurements decribed in all these experiments requires a knowledge of the ambient wind speed, instrument orientation with respect to the wind direction, and instrumentation configuration because these can effect the measured value of LWC. Wind speed leads to a "wind-ramming" effect that enhances the value of LWC in the FSSP (Fairall 1984; Choularton et al. 1986; Vong and Kowalski 1995), and the orientation of the FSSP should be parallel to the wind direction to prevent inertial droplet losses (Norment 1987). The best position of optical axis of the PVM is perpendicular to the wind direction to prevent some droplet losses due to shadowing of the axis by the arms of the instrument (Kowalski et al. 1997). The FSSP manufacturer provides a flow accelerator for insertion in the sampling tube and a conical extension for attachment to the tube; both are recommended for ground-based use of the instrument. The use of these accessories must be specified since they affect the FSSP measurements.

We find that it is not possible to compare properly the results of all the preceding experiments because the operating conditions for the FSSP and PVM either differ or are unknown. The wind velocity and orientation with respect to the FSSP and the configuration of the FSSP used in the early Po Valley experiment (Arends et al. 1992) are unknown. Kowalski et al. (1997) used a custom-designed cylindrical inlet with their FSSP and oriented the FSSP into the wind. The Petten (Gerber et al. 1994) and the Po Valley (Wendisch 1998) experiments can, however, be compared with some confidence because of the similarity of the operating conditions for the FSSP and PVM. Table 1 summarizes these conditions for the FSSP. The measurements made at Petten and the Po Valley with different PVM instruments can also be compared with some confidence because the PVM instruments are calibrated with a light-diffusing disk that has a predetermined and reproducible response. Some of the remaining uncertainty in the PVM measurements, as well as in the FSSP measurements, is the unknown orientation of both instruments to the wind direction. However, given the minimal wind speed in these two experiments, the orientation and wind-ramming effects should be minimal.

The Petten and Po Valley LWC comparisons also depend on the size distribution of the droplets that were present in both locations. The distributions are listed in Gerber (1993) and plotted in Gerber et al. (1994) for the Petten measurements, and some distributions are

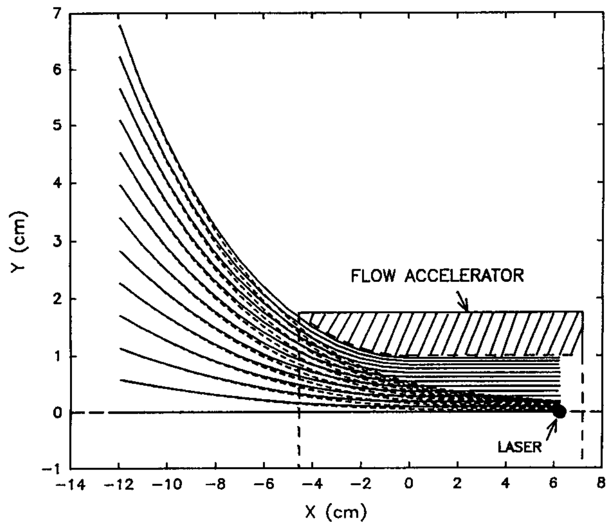

FIG. 3. Model streamlines (solid lines) and droplet trajectories (dashed lines) associated with the flow accelerator used in the inlet tube of the FSSP. Ambient flow velocity is zero, the droplet size is 15-μm radius, and suction into the accelerator produces a velocity of 25 m s^{-1} near the position of the laser.

plotted by Wendisch (1998) and Wendisch et al. (1998) for the Po Valley experiment. The distributions given for both locations are reasonably similar, with comparable total droplet concentrations and with substantial numbers of larger droplets present occasionally. These larger droplets extend in size to the approximate 50-μm-diameter upper size limit of the FSSP and PVM, and thus make it possible to draw some conclusions here on the response of each instrument to the largest droplets that it is supposed to measure. The Po Valley fog of 14 November had a greater concentration of large droplets in comparison to the other Petten and Po Valley fogs.

The earlier results, as illustrated in Figs. 1 and 2, suggest that the FSSP was measuring too much LWC in the Petten and Po Valley ground-based measurements when droplet sizes were large; however, these results give no indication why this appears to be the case.

3. Droplet trajectories in FSSP-100

We use a simple droplet trajectory model to learn if suction used to draw droplets into the sampling tube of the FSSP can cause changes in the droplet concentration at the point in the tube where the laser beam interacts with the droplets. Figure 3 shows, drawn to scale, the cross section of one-half of the flow accelerator insert that is placed in the sampling tube of the FSSP for ground-based use. The overall shape of the insert is that of a circular cylinder (width 3.8 cm, length 11.75 cm) with a cavity of circular cross section that converges from a radius R = 1.7 cm at X = −4.56 cm to R = 1.0 cm at X = 0.0 cm. This decreasing value of R

accelerates the flow from a nominal 8.6 m s^{-1} at the entrance of the cavity to 25 m s^{-1} in the uniform tube section that includes the location of the sensitive laser volume. The converging part of the cross section for -4.56 cm $< X <$ 0.0 cm has a circular shape with a radius of 14.78 cm.

The solid lines in Fig. 3 are streamlines that are prescribed in the following manner. The curvature of the streamline in contact with the inside wall of the converging part of the insert has a radius equivalent to that of the insert wall (14.78 cm), and the radii of the other streamlines are chosen so that their convergence rate is constant for increasing X. The velocities specified for these streamlines, under the assumption that the ambient air velocity is zero, are inversely proportional to the area decribed by a circle with a radius given by the value of Y for the streamline closest to the insert's inner wall. At $X = -12$ cm the velocities are 50 cm s^{-1}, and the velocity is a constant 25 m s^{-1} for $X > 0.0$ cm. This simple arrangement of streamlines and velocities is unlikely to be the same as predicted by an exact Navier–Stokes solution for this geometry; however, the main features are likely similar in that the flow converges and accelerates into the insert. A pattern with similar features is shown by flow into a funnel (Walton 1954; Fuchs 1964) and is shown by our potential-flow solution (not shown) of the Navier–Stokes equation for an infinite slit with suction. Our simplified arrangement of streamlines and velocities has the advantage of providing an analytical expression that is practical for use with the calculation of the droplet trajectories. This arrangement also produces streamlines near the centerline of the insert that resemble closely the slit-solution streamlines in the vicinity of the slit center. Our streamlines near the insert wall show significant deviation from those of the slit; however, they do not contribute significantly to the concentration enhancement in the insert, as calculated in the following. The streamlines below the centerline of the insert are not shown in Fig. 3 because they are a mirror image of those above the line.

Given the prescribed flow field as shown in Fig. 3, it is possible to calculate the trajectory of droplets injected into the flow by solving the following equations of motion of the droplets for the x and y coordinates:

$$\frac{dV_x}{dt} = \frac{1}{\tau}(U_x - V_x) \qquad (1)$$

and

$$\frac{dV_y}{dt} = \frac{1}{\tau}(U_y - V_y), \qquad (2)$$

where V is the velocity of droplet, U is the velocity of air, $\tau = (2r^2\rho/9\eta)$ = droplet relaxation time, r is the radius of droplet, ρ is the droplet density, and η is the air viscosity.

Equations (1) and (2) are solved by numerical integration using the method described in Fuchs (1964). The dashed lines in Fig. 3 show calculated droplet trajectories under the conditions where the droplets have r = 15 μm, and where the droplets are introduced into the left end of the streamlines at the same velocity of 50 cm s^{-1} found at $X = -12$ cm. Figure 3 shows that these 15-μm-radius droplets are unable to follow the curved streamlines leading into the insert and, due to the droplets' inertia, accumulate near the centerline of the insert where the laser-sensitive volume is located.

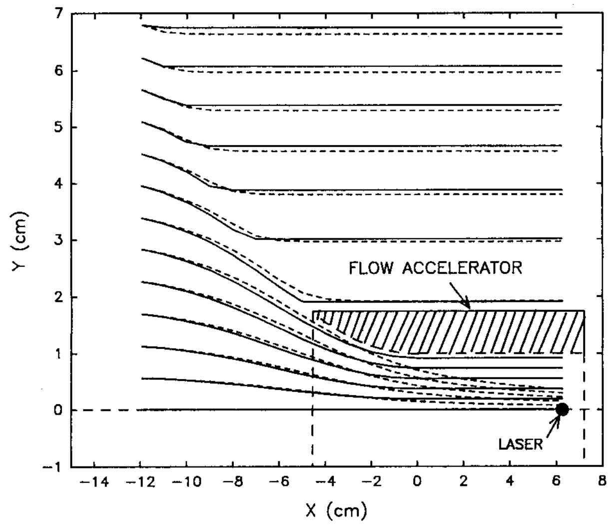

FIG. 4. Same as Fig. 3, except that an ambient horizontal flow from left to right of 2 m s^{-1} has been added.

Results of a second set of calculations also using droplets with r = 15 μm are shown in Fig. 4 where an ambient air speed of 2 m s^{-1} toward the flow accelerator is added to the prescribed flow used in Fig. 3. The deviation of the droplets from the streamlines is not as much as the preceding case; however, the tendency of the droplets to accumulate near the laser volume still exists.

4. Concentration enhancement in FSSP-100

Under the assumption that the deviation of the droplets from the initial streamlines has circular symmetry, the ratio of the increase of the droplet concentration near the centerline of the insert near the laser beam due to the droplet inertial effects is given by

$$F = \frac{Y_{s+1}^2 - Y_s^2}{Y_{r+1}^2 - Y_r^2}, \qquad (3)$$

where the locations of adjacent streamlines near the laser are given by Y_s and Y_{s+1}, and where Y_r and Y_{r+1} are the new locations near the laser of droplets of radius r, following their deviation from those adjacent streamlines. Calculated values of F at the centerline of the insert are affected primarily by streamlines and droplets originating at a distance above the center line equivalent to not more than about one-half the width of the insert opening.

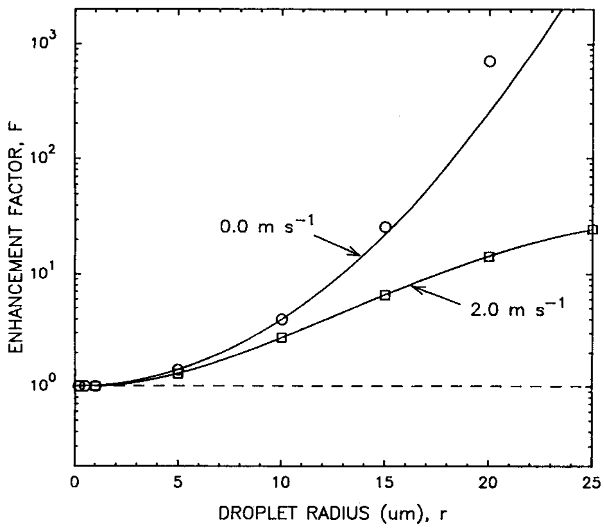

FIG. 5. The modeled enhancement factor F of droplet concentration along the centerline of the accelerator near the laser as a function of droplet size and ambient air speed.

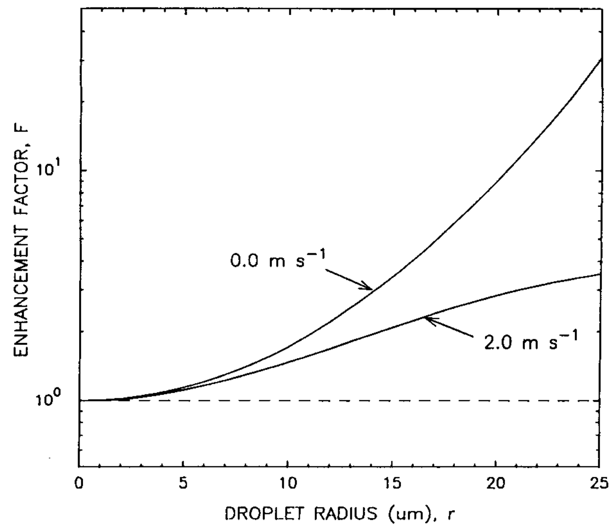

FIG. 6. Same as Fig. 5, except that the modeled F has been scaled so that the Petten FSSP and reference-filter LWC measurements coincide.

Values of F were calculated for several values of droplet radii that span the usual droplet-size sensitivity range of the FSSP and are shown in Fig. 5 for the ambient air speed of 0.0 and 2.0 m s^{-1}. Both datasets show sharp increases of F with increasing droplet size; and the increase of F for the 0.0 m s^{-1} data is the larger. Curves were fit to the data points in Fig. 5. For the zero air speed data the solid line is given by a parabolic fit where $\log F = f(0.0)$ and $f(0.0) = 0.0060r^2$, and for the 2 m s^{-1} data the line is given by a fourth-order polynomial fit where $\log F = f(2.0)$ and $f(2.0) = -0.002\,299\,8 - 0.004\,166\,3r + 0.006\,970\,2r^2 - 0.000\,237\,7r^3 + 0.000\,002\,2r^4$.

These functional forms of F can be tested by applying the factor $1/F$ to the FSSP size distribution data from the Petten measurements and then comparing LWC calculated from these "corrected" FSSP distributions to the reference LWC measurements made by the Petten filter measurements. When this procedure is followed, the corrected FSSP LWC gives LWC values that are too small in comparison to the filter LWC values. This infers that our simple model for calculating droplet trajectories produces values of F in Fig. 5 that are too large. Possible reasons for this disagreement include 1) the representation of the streamlines in our model is inaccurate, 2) the sedimentation velocity due to gravity of the droplets is not included in the model, 3) the flow in the flow-accelerator insert is turbulent as predicted by the Reynold's number of the flow and causes turbulent diffusion of the droplets, and 4) the concentration enhancement is calculated at the centerline of the insert rather than over the several millimeters perpendicular to this line over which the sensitive volume of the laser beam extends.

If the assumption is made that the shapes of the curves for F in Fig. 5 do not change, then a correction factor C can be derived for these curves by inverting the following integral,

$$\text{LWC(Petten Filter)} = \frac{4}{3}\pi \int_r 10^{-Cf(2.0)} r^3 n(r)\, dr, \quad (4)$$

which is written for the case where ambient velocity is 2.0 m s^{-1}, and $n(r)$ is the size distribution of the droplets measured by the Petten FSSP. When Eq. (4) is applied to all the data points in Fig. 5, an average value of $C = 0.3925$ is found for the 2.0 m s^{-1} case, and $C = 0.002\,38$ for the 0.0 m s^{-1} case. The functional forms of F drawn in Fig. 6 are then $\log F = 0.3925f(2.0)$ and $\log F = 0.002\,38f(0.0)$, which show that at a droplet radius of 25 μm the concentration enhancement can vary between a factor of 3.5 and 30, depending on the ambient air velocity, and that for droplets smaller than about 5-μm radius the enhancement is less than 10%.

It is unlikely that these new functional forms of F accurately represent the dependence of the FSSP correction on droplet size because these new forms are only constrained by the requirement to give a value of $F \approx 1$ at $r = 0$ μm and by the calculated mean value of C that scales the average FSSP LWC to the Petten filter LWC. The Petten filter is used as a reference, given that its LWC measurements are based on flow and mass measurements traceable to other measurement standards (Mallant 1988) and that its LWC measurements compare within 5% to another LWC measurement method that is directly dependent on the Mie theory prediction that 11-μm infrared transmittance through a cloud is directly related to LWC (Chýlek 1978; Gerber 1998.) The principal difficulty in developing a more accurate form of $1/F$ for Eq. (4) is the uncertainty caused by the predicted turbulent diffusion of the droplets in the FSSP insert. The unknown strength and distribution of the turbulence, and the approximate inverse relationship of the amount of droplet diffusion and τ, will cause the dependence of the FSSP correction on droplet radius to be more complex than given in Eq. (4).

The results shown in Fig. 6 compare reasonably well with those described by Wendisch (1998), who found the Po Valley FSSP measuring larger values of LWC than the PVM in fogs with mean droplet sizes exceeding about 4.5-μm radius, with LWC larger by a factor of as much as 6.5 for the 14 November fog where droplets reached a maximum volume mean radius between 15- and 20-μm radius. However, given the uncertainties in the development of the FSSP correction factor of $1/F$ as decribed, this reasonable comparison may be fortuitous.

5. Conclusions and recommendations

We conclude that the large observed differences in ground-based LWC measurements made with the FSSP and the PVM (Wendisch 1998; Gerber et al. 1994) may be a result of the FSSP behaving as an inertial droplet concentrator that generates spurious droplet concentration values much larger than ambient values. This source of FSSP error, apparently overlooked until now, is predicted to be small for droplet sizes less than about 5-μm radius, but thereafter increases rapidly with increasing droplet size and has the largest value for ambient wind speeds approaching zero. Thus the suggestion by Wendisch (1998) that the PVM underestimates LWC when droplets are large may be invalid because another possible reason for the difference is the overestimate of LWC by the FSSP due to this inertial effect. This conclusion is supported by the consistency of the FSSP and PVM comparisons made in the Petten cloud chamber and in the Po Valley fog, and by the present modeling effort that shows that the ground-based use of the FSSP, where a flow-accelerator insert is used, is vulnerable to droplet inertial effects.

Values of LWC up to 1.3 g m^{-3} measured by the FSSP in the 14 November 1994 Po Valley fog (Wendisch et al. 1998; Wendisch 1998) were greater by a factor of 6.5 than the LWC measured at the same location with the PVM. The PVM values are likely more accurate because the FSSP LWC values are unrealistically high, given that these measurements were made not far from the surface, that this fog behaved like a stratocumulus cloud with vertical motion (Wendisch et al. 1998), and that this LWC is much greater than the estimated adiabatic LWC value. These excessive FSSP LWC values are likely symptomatic of this inertial error source for the FSSP, given the unusually large droplets in this fog and the low ambient wind speed.

The following recommendations are made.

1) The simple approach used in this paper to model droplet trajectories in the FSSP sampling tube is inadequate to establish accurately the magnitude of this inertial enhancement effect. It may be useful to apply the sophisticated software available in the computational fluid dynamics field, from which numerical solutions of the Navier–Stokes equation can likely be applied to the present problem. However, the unknown nature of the turbulent flow in the insert may cause modeling complexities that prevent improved model predictions.
2) It appears that experimental work in the laboratory or cloud chamber is a better way to quantify the predicted behavior of the FSSP as an inertial concentrator. Experiments with suction of aerosol particles into dummy flow accelerator are suggested.
3) Conditional sampling and comparisons should be conducted as a function of air speed and LWC values of the available FSSP–PVM databases of ground-based measurements to derive the magnitude of the FSSP inertial concentration error as a function of ambient conditions.
4) The conical attachment should be utilized when making ambient measurements with the FSSP. This should reduce the presence of curved streamlines generated by suction into the flow accelerator of the FSSP inlet tube and thus reduce the inertial concentration effect.
5) The flow accelerator should be redesigned to eliminate the curved surfaces in the direction of the flow—surfaces that now appear to be the main cause of the inertial error.

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