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Response of the Nevzorov hot wire probe in Arctic clouds dominated by very large droplet sizes

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Abstract

During the airborne research mission ASTAR 2004 (Arctic Study of Tropospheric Aerosols, Clouds and Radiation) performed over the island of Svalbard in the Arctic a constant-temperature hot-wire Nevzorov Probe designed for aircraft measurements, has been used onboard the aircraft POLAR 2. The Nevzorov probe measured liquid water (LWC) and total condensed water content (TWC) in supercooled liquid and partly mixed phase clouds, respectively. As for other hotwire probes the calculation of LWC and/or TWC (and thus the ice water content IWC) has to take into account the collection efficiencies of the two separate sensors for LWC and TWC which both react differently with respect to cloud phase and what is even more difficult to quantify with respect to the size of ice and liquid cloud particles. The study demonstrates that during pure liquid cloud sequences the ASTAR data set of the Nevzorov probe allowed to improve the quantification of the collection efficiency, particularly of the LWC probe part with respect to water. The improved quantification of liquid water content should lead to improved retrievals of IWC content. Simultaneous retrievals of LWC and IWC are correlated with the asymmetry factor derived from the Polar Nephelometer instrument.

1 Introduction

Condensed water content (CWC: liquid and/or ice water content) in clouds is a fundamental parameter in cloud physics research. To experimentally measure liquid water content (LWC) on research aircraft, hot-wire probes are state of the art instruments. Until today the most commonly used hot-wire devices have been the Johnson-Williams probe, the LWC-100, and the King probe (King et al., 1978). These hot-wire probes are difficult to calibrate concerning their exact collection efficiencies. This is due to uncertainties on the one hand to predict the trajectories of hydrometeors having diameters below 5–10 μm (Korolev et al., 1998), and on the other hand due to incomplete evaporation and break-up during and after impaction of hydrometeors having diameters beyond 40 μm. Another type of instrument to measure cloud liquid water content is the Particle Volume Monitor (PVM) based on the principle of light diffusion by an ensemble of droplets (Gerber, 1993). A principal problem of the PVM, as for other optical instruments, is the exact knowledge of the sample volume and an eventual drift of the baseline.

Besides these direct measurements of LWC, estimates of the total condensed water content including in particular the ice phase (IWC and/or LWC) can be derived from the integration of particle image data from Forward Scattering Spectrometer FSSP (Baumgardner, 1985), 2D-C (Knollenberg, 1981), or Cloud Particle Imager CPI (Lawson, 1998). Another method is to entirely sample the condensed water content as done with the CVI (Counterflow Virtual Impactor) sampling technique (Ogren et al., 1985), evaporating all hydrometeors in an environment of dry air to finally derive the condensed water content for example with the technique of Lyman-a hygrometry (Ström et al, 1994). An attempt to integrate the CVI technology including a hygrometer into a PMS pod has recently been developed at Droplet Measurement Technology (DMT).

Real-time information on cloud ice water content (IWC), however, stays a major challenge, particularly in mixed-phase clouds.

In 1998, Korolev et al. (1998) presented an extended characterisation of the Nevzorov instrument to overcome the lack of simultaneous and separate measurements of liquid and ice water contents. The Nevzorov probe which is a constant-temperature, hot-wire probe has been explicitly designed for rapid and simultaneous measurements of the ice and liquid water contents (phase discrimination) and thus, was extensively used on research aircraft for microphysical characterisation of mixed-phase clouds (Korolev, 2003) and in effective diameter studies (Korolev, 1999). It consists of two separate sensors for measurements of cloud liquid and total (ice plus liquid) water content, giving two linear equations for the variables LWC and IWC to be solved.

In principal, Korolev (1998) gave some insight in dry air baseline drift with airspeed, temperature, and pressure variations to explain possible offset variations for instance during vertical flight patterns. Moreover, collection efficiencies of the two separate sensors with respect to water and ice are discussed up to cloud particle (droplets, crystals) diameters of 25 μm. The probe performance is then discussed by means of measurement examples comparing the Nevzorov LWC and TWC data to the King and FSSP probe (Baumgardner, 1985) and also 2D-C probe (Knollenberg, 1981) derived data. The correlation seems to be acceptable knowing the limited performance of the FSSP in view of larger ice crystals (Gardiner and Hallet, 1985) and the underestimation of water content by the 2D-C due to the fact that below 150 μm this probe is underestimating the crystal concentration (Gayet, 1993). The quite good correlation between Nevzorov LWC and TWC sensors is lost when either ice or larger droplets are present, due to unknown and hence simplified collection efficiency assumptions for large droplets and the ice phase.

Another study (Strapp, 2003) conducted in the NASA Icing Research Tunnel (IRT) presents results on Nevzorov LWC and TWC retrievals as a function of the diameter of average volume, also denoted median volume diameter (MVD) of pure liquid droplet populations. Whereas the Nevzorov TWC sensor matches the wind tunnel LWC (within WT LWC measurement accuracy), the Nevzorov LWC sensor significantly underestimates the WT LWC, particularly for larger median volume droplet diameters. The Nevzorov probe was also studied in the NRC Altitude Icing Wind Tunnel (AIWT) to assess differences in the response of LWC and TWC sensors of the probe with respect to ice (Korolev, 2002). These tests at the NRC high-speed icing tunnel have provided verification of the TWC measurement for small frozen droplets to an accuracy of approximately 10%–20% (Korolev, 2002). Further tests have been performed after modifying the Nevzorov TWC sensor cone (Korolev, 2008). The new deep cone (60°) then is compared to the classical shallow cone (120°) concerning collection efficiencies with respect to ice particles produced in the COX Wind Tunnel facility. The ice spray in this wind tunnel is produced by shaving ice blocks. It turns out that the classical shallow cone is significantly underestimating IWC due to ice particles bouncing off the TWC cone surface back into the air stream and being swept away.

The results presented here in this study, however, are mainly dedicated to improve our knowledge of the Nevzorov probe efficiency with respect to liquid/supercooled water droplets of larger diameters.

2 Field project

The geographic anomalies (high surface albedo, low solar elevation) in Polar regions were the principal motivation to initiate the international program Arctic Study of Tropospheric Aerosols, Clouds, and Radiation (ASTAR) to experimentally investigate the direct and indirect aerosol effects in the Arctic. The ASTAR project is particularly dedicated to investigate origin, transport pathways, vertical structure, physico-chemical properties and radiatif impact of the tropospheric Arctic aerosol as well as related aerosol-cloud and cloud-radiation interactions (particularly ice phase).

Within these objectives, aircraft in situ and remote sensing measurements on the two research aircraft Polar2 and Polar4 from Alfred-Wegener Institute (AWI), Germany, were conducted from the island of Spitsbergen (Norway) to study the microphysical and optical properties of Arctic aerosol and supercooled to mixed-phase clouds.

Cloud in situ measurements were performed onboard Polar2 using a Nevzorov probe (Korolev, 1998), the Polar Nephelometer (Gayet, 1997), a Cloud Particle Imager (Lawson, 1998 and 2001), and classical FSSP and 2D-C PMS probes. In total 14 cloud flights have been performed on Polar2 during the entire ASTAR 2004 flight campaign for detailed microphysical and optical cloud in situ studies. In particular, the campaign yielded observations of iced nimbostratus, altostratus, and stratus clouds which are often found in the Arctic boundary layer. Despite just slightly negative temperatures between 0 and −20 °C encountered during Polar-2 flight missions, the ice phase (mixed phase) was observed quite frequently. Simultaneous research flights were performed on the Polar4 aircraft to characterise the aerosol particles. During the entire period, aerosol concentrations have been very low (<300 aerosol particles per cm^3). These clean conditions should have been at the origin of frequently observed particularly large supercooled cloud droplets (cf. Fig. 1), up to some hundreds of μm in diameter even in very shallow stratus type Arctic cloud layers (∼500 m between cloud base and cloud top). In addition, lowest IN concentrations (coming along with low aerosol concentrations) may slow down considerably the ice related processes including nucleation, multiplication, and precipitation. Consequently, only little precipitation was observed during ASTAR 2004. Moreover, from combined lidar and cloud in situ measurements evidence was found for the presence of the "feeder-seeder" mechanism, initiating the ice phase in low level stratocumulus cloud layers at slightly negative temperatures.

3 Instrumentation: Nevzorov probe and other cloud in situ instruments

The instrumental payload used for the cloud in situ studies on Polar-2 comprised an extensive, state-of-the art set of cloud microphysical/optical instruments including particularly: (i) a Polar Nephelometer for the measurement of the scattering phase function of ice particles, (ii) a Cloud Particle Imager (CPI) recording digitised cloud particle images at high pixel resolution (2.3 μm), and (iii) the Nevzorov probe for the measurement of the liquid and ice water content in supercooled and mixed-phase clouds. The main focus in this study will be given to the performance of the Nevzorov probe.

The two TWC and LWC sensors of the Nevzorov hot-wire probe (kept at constant temperature) are composed each of a reference and a collector/sample zone, whereby the reference zone will not undergo cloud particle impaction. Due to cloud particle impaction (and thus evaporation) the sample zone experiences heat loss, which has to be compensated, thus, making the hotwire probe a constant temperature probe. The necessary power to apply to the sensors is related to LWC and TWC, both functions of electrical powers P_{LWC} and P_{TWC}, sensor surfaces S_{LWC} and S_{TWC}, the velocity U, and the four collection efficiencies of LWC and TWC sensors with respect to water droplets and ice crystals. In addition, the known sensor resistances R_{LWC} and R_{TWC} appear in the electrical powers

$$P_{\mathrm{LWC}} = \frac{V_{\mathrm{LWC}}^2}{R_{\mathrm{LWC}}} \tag{1}$$

and

$$P_{\mathrm{TWC}} = \frac{V_{\mathrm{TWC}}^2}{R_{\mathrm{TWC}}} \tag{2}$$

supplied to the sensors via the voltages V_{LWC} and V_{TWC}. Combining P_{LWC} and P_{TWC} supplied to both sensors gives one single solution for LWC and IWC (Korolev, 1998):

$$\mathrm{LWC} = \frac{P_{\mathrm{LWC}} - \frac{P_{\mathrm{TWC}} \times \varepsilon_{\mathrm{LWC,crystals}} \times S_{\mathrm{LWC}}}{\varepsilon_{\mathrm{TWC,crystals}} \times S_{\mathrm{TWC}}}}{L_{\mathrm{Vaporization}} \times S_{\mathrm{LWC}} \times U \times \left(\varepsilon_{\mathrm{LWC,droplets}} - \frac{\varepsilon_{\mathrm{LWC,crystals}} \times \varepsilon_{\mathrm{TWC,droplets}}}{\varepsilon_{\mathrm{TWC,crystals}}}\right)}, \tag{3}$$

and

$$\mathrm{IWC} = \frac{P_{\mathrm{TWC}} - \frac{P_{\mathrm{LWC}} \times \varepsilon_{\mathrm{TWC,droplets}} \times S_{\mathrm{TWC}}}{\varepsilon_{\mathrm{LWC,droplets}} \times S_{\mathrm{LWC}}}}{\left(L_{\mathrm{fusion}} + L_{\mathrm{Vaporization}}\right) \times S_{\mathrm{TWC}} \times U \times \left(\varepsilon_{\mathrm{TWC,crystals}} - \frac{\varepsilon_{\mathrm{LWC,crystals}} \times \varepsilon_{\mathrm{TWC,droplets}}}{\varepsilon_{\mathrm{LWC,droplets}}}\right)}. \tag{4}$$

The most crucial question then is the exact knowledge of TWC and LWC sensor efficiencies, depending on particle phase (droplets, crystals) and size. Since during ASTAR 2004 we encountered pure supercooled and mixed phase conditions, but no pure ice phase clouds, we will focus the discussion of the Nevzorov probe response to flights (flight sequences) of pure liquid cloud phase in the Arctic environment. In this way we can skip two of the four efficiencies to primarily study those two efficiencies related solely to droplets: $\varepsilon_{\mathrm{LWC,\,droplets}}$ and $\varepsilon_{\mathrm{TWC,\,droplets}}$.

Thus, when ice is absent the TWC and LWC sensors individually give the liquid water content:

$$\mathrm{LWC}_{(\mathrm{LWCsensor})} = \frac{P_{\mathrm{LWC}}}{\varepsilon_{\mathrm{LWC,\,droplets}} \times L_{\mathrm{Vaporization}} \times S_{\mathrm{LWC}} \times U} \tag{5}$$

from the LWC sensor and

$$\mathrm{LWC}_{(\mathrm{TWCsensor})} = \frac{P_{\mathrm{TWC}}}{\varepsilon_{\mathrm{TWC,\,droplets}} \times L_{\mathrm{Vaporization}} \times S_{\mathrm{TWC}} \times U} \tag{6}$$

from the TWC sensor.

Both equations should give identical amounts of LWC in pure liquid cloud, where liquid water content depends on aircraft velocity U, the electrical powers P_{LWC} or P_{TWC} supplied, and the collection efficiency of LWC and TWC sensors with respect to water droplets:

$$\mathrm{LWC} = f(P_{\mathrm{LWC}}, U, \varepsilon_{\mathrm{LWC,\,droplets}}) = f(P_{\mathrm{TWC}}, U, \varepsilon_{\mathrm{TWC,\,droplets}}). \tag{7}$$

4 Description of the dataset and data processing

4.1 Cloud presence criterion

Ideally the Nevzorov probe signals should have very small to zero offsets, achievable at constant flight levels. Before entering a cloud the collector signal has to be adjusted to the reference signal to operate the sensors at zero offsets. The signal ideally returns to zero after leaving the cloud at the same level, which indicates a zero offset for the entire leg at that flight level. To avoid truncated slightly negative signals it may be even worthwhile to operate the Nevzorov probe with a very small positive offset. In addition, during the ASTAR experiment the flight pattern consisted sometimes of climbs and descents in clouds, which made it difficult to achieve the objective of zero offset. Since for the Nevzorov data it is necessary to subtract the offset in both raw signals, before calculating the condensed water contents LWC and IWC, our idea was to benefit from simultaneous measurement signals of other fast and highly sensitive cloud probes, like the Polar Nephelometer, to define precisely cloud presence (Fig. 2), such that experimentally we can calculate the offsets of Nevzorov probe raw signals for clear sky passages and interpolate the offset within cloud sequences.

4.2 Offset correction

The Nevzorov offset has to be deduced from the measured signal to get the raw cloud related signal. Figure 3 shows an example (corresponding to Nephelometer cloud detection in Fig. 2) of an unusually high offset caught during a flight. Due to the fact that the electrical power P supplied to the two sensors is proportional to the square of the corresponding voltages V, the pure cloud related signal V_{cloud} is calculated from the total raw signal V_{raw} and the offset signal V_{offset} in the following way:

$$V^2_{cloud} = \sqrt{V^2_{raw} - V^2_{offset}}. \tag{8}$$

5 Results for the Nevzorov probe response to Artic clouds

5.1 Discussion of the sensor efficiencies in liquid clouds

Strapp et al. (2003) presented a study of Nevzorov LWC and TWC sensor response with respect to large droplets (Fig. 5). The study was conducted in the NASA Glenn Icing Research Tunnel (IRT) in 1998. The Nevzorov LWC sensor with cylindrical sensor wire of 1.8 mm in diameter was found to measure solely 50% of the LWC at a median volume diameter of approximately 200 μm. The Nevzorov TWC sensor was found to agree within +/−20% of tunnel reference LWC across the entire tested range of MVD within 11–236 μm. According to Strapp (2003) the accuracy of IRT tunnel LWC is estimated to be 5% for populations of small droplets and 20% for populations of large droplets. The findings that LWC retrievals from Nevzorov TWC sensor throughout all droplet MVD are higher than IRT wind tunnel LWC measurements should indicate that the Nevzorov TWC sensor may not miss a significant amount of LWC even within droplet populations with largest MVD (~200 μm). The Nevzorov TWC sensor is therefore considered the most accurate hot-wire estimate of LWC in large droplet conditions of pure water clouds, whereas LWC sensor efficiencies remain unclear in these conditions. Thus, we will focus here primarily on the Nevzorov sensor efficiencies with respect to water, knowing that the ASTAR 2004 cloud flights sampled either supercooled or mixed phase clouds. The phase recognition of clouds was performed using the simultaneously operated Cloud Particle Imager CPI. For subsequent data analysis of pure liquid clouds or liquid cloud sequences, the Nevzorov data were analyzed when the CPI detected pure liquid phase.

Taking the above equations for LWC sensor ($LWC_{(LWCsensor)}$) and TWC sensor ($LWC_{(TWCsensor)}$) measured LWC which have to give identical results in pure water clouds we can deduce:

$$\frac{\varepsilon_{LWC,droplets}}{\varepsilon_{TWC,droplets}} = \frac{P_{LWC} \times S_{TWC}}{P_{TWC} \times S_{LWC}} = \frac{V^2_{LWC} \times R_{TWC} \times S_{TWC}}{V^2_{TWC} \times S_{LWC} \times R_{LWC}} = 1.595 \times \frac{V^2_{LWC}}{V^2_{TWC}}, \tag{9}$$

thus, taking into account known specific instrumental parameters of sensor surfaces and electrical resistances of the Nevzorov probe used during ASTAR 2004. It turns out that, plotting $1.595 \times V^2_{LWC}$ against V^2_{TWC} for all liquid cloud data does not necessarily produce a slope of 1. The TWC sensor signal V^2_{TWC} is in general dominating the LWC signal $1.595 \times V^2_{LWC}$, which means that the liquid water recovery from TWC sensor is definitely higher than the recovery from LWC sensor (Fig. 6). Merely at lower values of raw signals it nevertheless happens that the LWC signal slightly dominates the TWC sensor signal (data points above the theoretical line of equal LWC and TWC sensor efficiencies with respect to water). These data points signalize a higher efficiency for LWC sensor as compared to the TWC sensor.

For a more detailed analysis of the above results, the ratios of the two efficiencies

$\varepsilon_{\text{LWC, droplets}}$ and $\varepsilon_{\text{TWC, droplets}}$ of LWC and TWC sensors are studied as a function of the droplet diameters from droplet size distributions. Strapp et al. (2003) have chosen in their efficiency study of the Nevzorov probe the diameter of average volume MVD as a spectrum reference diameter, with

$$\text{MVD}=\sqrt[3]{\sum_i (N_i \cdot D_i^3)/N_{\text{total}}}, \tag{10}$$

which should be representative in volume for very narrow monomodal size distributions as might have been generated in the IRT wind tunnel. We propose in our study, however, to use instead the volume mean diameter VMD, with

$$\text{VMD} = \sum_i (N_i \cdot D_i^4) / \sum_i (N_i \cdot D_i^3), \tag{11}$$

since this diameter is less sensitive to vary significantly in the presence of small droplets coexisting with a larger droplet diameter mode or more generally in the case of broader size distributions. Nevertheless, it is clear that VMD will exceed MVD for whatever size distributions. The broader the size distribution the larger will be the difference between VMD and MVD. Putting together all 14 scientific research flights, Fig. 7 shows plotted ratios of the two efficiencies $\varepsilon_{\text{LWC, droplets}}$ and $\varepsilon_{\text{TWC, droplets}}$ of LWC and TWC sensors during pure liquid cloud sequences as a function of VMD. As a result we observe that for very small droplet diameters up to roughly 20–40 μm the LWC sensor seems to be more efficient than the TWC sensor, which is due to the fact that the large TWC cone represents an important obstacle for the cloud particles which begin quite early to curve around the sensor and thus don't impact as efficient as on the smaller LWC sensor obstacle. Droplet sizes beyond several tens of micrometers, however, should impact more efficiently on the TWC sensor but less efficiently on the LWC sensor with increasing droplet diameters. It is important to recall that for the two previous figures we have chosen only liquid cloud sequences automatically derived from CPI data of the entire ASTAR 2004 campaign. All data were averaged over 10 s intervals to avoid larger statistical fluctuations. The signal averaging of FSSP, CPI, 2D-C and Nevzorov data was chosen since the instruments were not mounted side by side. In addition, the evaporation of droplets on the surface of hot wire probes is not instantaneous, leading to a slightly delayed and smoothed signal as a function of droplet diameters. The 10 data averaging procedure allowed in particular a better calculation of the VMD diameter that was chosen for comparison reason with the results presented in Strapp et al. (2003), where the ratio of Nevzorov to wind tunnel LWC is plotted against MVD. The y-axis error bars reflect the standard deviation of the 10 s average calculations of the ratio of the sensor efficiencies.

To interpret the above results we recall that Korolev (1998) presented theoretical calculations of the collection efficiencies with respect to liquid droplets of (i) the cylindrical LWC sensor $\varepsilon_{\text{LWC, droplets}}$ based on Voloshchuk (1971) and (ii) of the conical TWC sensor efficiency $\varepsilon_{\text{TWC, droplets}}$ based on experimental studies (Nevzorov, 1983). These two efficiencies $\varepsilon_{\text{LWC, droplets}}$ and $\varepsilon_{\text{TWC, droplets}}$ were presented as a function of effective diameter D_{eff} limited to diameters up to 25 μm and calculated according to:

$$\varepsilon_{\text{SENSOR, droplets}} = \frac{D_{\text{eff}}^2}{D_{\text{eff}}^2 + D_0^2} \tag{12}$$

with D_0=7.5 for TWC sensor and D_0=1.7 for the LWC sensor, respectively, for an aircraft velocity in the order of 100 m/s. For droplet diameters beyond 25 μm, $\varepsilon_{\text{TWC, droplets}}$ should approach the ideal value of 1, whereas $\varepsilon_{\text{LWC, droplets}}$ may decrease to values significantly smaller than 1, at least for diameters of several hundreds of μm (Korolev, 1998). An exact behaviour of $\varepsilon_{\text{LWC, droplets}}$ curve has not been discussed yet and will be determined subsequently in this study. Not knowing the exact size distributions that led to (i) deduced MVD in the wind tunnel study of Strapp et al. (2003) and (ii) the effective diameters in the $\varepsilon_{\text{TWC, droplets}}$ efficiency calibration study of Nevzorov (1983), we make the assumption that these experimental spectra may consist of a single size mode and

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may not have presented extremely broad spectra. The assumption that

$$\frac{D_{84}}{D_{50}} = \frac{D_{50}}{D_{16}} = \sigma \leq 1.5 \quad (13)$$

(for considered lognormal distributions), then translates (within error bars calculated for σ=1.5) the effective droplet diameters from Nevzorov (1983) into MVD (Martin et al., 1994) and VMD (Hinds, 1999). Knowing the droplet size distribution, median and mean volume diameters are calculated and can be converted into each other. In addition, an extrapolation of $\varepsilon_{\mathrm{TWC,\,droplets}}$ of the conical TWC sensor to values approaching 1 for cloud droplet effective diameters far above 25 μm has been suggested by Korolev (1998). This suggestion has been supported by Strapp (2003) due to measurements in the NASA IRT wind tunnel, where the Nevzorov TWC sensor measurements are slightly, but systematically, exceeding the tunnel reference LWC measurements (as well for populations of small and as for large droplets) within the estimated accuracy of wind tunnel reference LWC measurements. Within the assumptions of the above mentioned extrapolation this allows to give an estimate of the least known efficiency $\varepsilon_{\mathrm{LWC,\,droplets}}$. The procedure is presented in Fig. 8 where the efficiency ratio from Fig. 7 has been multiplied by the extrapolated $\varepsilon_{\mathrm{TWC,\,droplets}}$ to deduce $\varepsilon_{\mathrm{LWC,\,droplets}}$. A maximum in $\varepsilon_{\mathrm{LWC,\,droplets}}$ is reached roughly around 20–30 μm, indicating that droplets smaller than 20–30 μm partly tend to curve around the LWC sensor, whereas larger ones impact with decreasing efficiencies related to a loss in droplet mass. $\varepsilon_{\mathrm{LWC,\,droplets}}$ rapidly starts to decrease (with increasing droplet size) beginning at droplet sizes beyond 30–40 μm.

This study therefore suggests for VMD diameters beyond 25 μm the following parametrization for $\varepsilon_{\mathrm{LWC,\,droplets}}$ of the Nevzorov probe:

$$\varepsilon_{\mathrm{LWC,\,droplets}}(\mathrm{VMD}) = \frac{a_0}{\left[1 + \left\{\frac{\mathrm{VMD}-a_1}{a_2}\right\}^2 * \left\{2^{\frac{1}{a_3}} - 1\right\}\right]^{a_3}} \quad (14)$$

with a_0=0.98, a_1=20, a_2=90, a_3=0.26.

5.2 Application of above calculated $\varepsilon_{\mathrm{LWC,\,droplets}}$ efficiencies to calculate IWC and LWC in observed mixed phase clouds during ASTAR 2004

For further analysis of the Nevzorov data within real mixed phase Arctic clouds sampled during ASTAR 2004, efficiencies $\varepsilon_{\mathrm{TWC,\,droplets}}$ and $\varepsilon_{\mathrm{LWC,\,droplets}}$ are applied as extrapolated and calculated above, respectively. Furthermore, the efficiency $\varepsilon_{\mathrm{LWC,\,crystals}}$ is estimated to be approximately 0.11 (Korolev, 1998), explaining a slight reaction of the LWC sensor with respect to impacting ice crystals, which then bounce off. Unfortunately, the value of 0.11 is only a rough estimate since $\varepsilon_{\mathrm{LWC,\,crystals}}$ will certainly depend on crystal size and probably shape, however, we have no other estimation than was given by the manufacturer. Finally, the efficiency $\varepsilon_{\mathrm{TWC,\,crystals}}$ is considered to equal $\varepsilon_{\mathrm{TWC,\,droplets}}$ for identical median mass aerodynamic diameters (thus, including the particle density), to take into account ice particles with estimated density of 0.9. An eventual discussion of sensor efficiency variations with ice crystal shape seems to be complicated and is beyond the scope of this study. In addition, Korolev (2008) presented evidence that ice particles may significantly bounce off from the surface of the Nevzorov TWC sensor cone (and other hot-wire sensor geometries). They demonstrated that $\varepsilon_{\mathrm{TWC,\,crystals}}$ of the commercial shallow (120°) TWC cone of the Nevzorov Probe could be up to 3 times smaller than $\varepsilon_{\mathrm{TWC,\,crystals}}$ for a modified deep cone (60°) of the same sensor. Due to the lack of ice crystal calibration standards a detailed investigation of the Nevzorov sensor efficiencies towards pure ice phase is still under discussion.

Unfortunately, during ASTAR we haven't observed pure ice cloud sequences, allowing a similar efficiency discussion for the ice phase, as presented above for the pure water phase, since the temperatures did not reach values below −25°C, such that supercooled droplets were always present in all sampled clouds. The above assumed sensor efficiencies with respect to water (high reliability) and ice (significant lack of knowledge) as a function of diameter, allow at least under the described efficiency assumptions to estimate simultaneously IWC and LWC of Arctic mixed phase clouds as described in Sect. 3.

Figure 9 presents the results of calculated IWC and LWC in terms of the fraction of ice water content IWC out of total condensed water TWC (TWC=LWC+ WC) plottet against the asymmetry parameter. The asymmetry parameter g is deduced from the scattering phase function of the Polar Nephelometer (Gayet, 1997) and gives an indication of the mean cosine of light scattered in a two-dimensional plane from cloud particles. The scattering characteristics (asymmetry factor etc.) vary with respect to cloud phase, cloud particle size, ice crystal shape, surface roughness and others. Theoretically the asymmetry factor is comprised between 0 for isotropic scattering and 1 in case that the light is not at all deviated with respect to the incident direction of light. Garrett et al. (2001) showed a quite good correlation between IWC number fraction and asymmetry parameter. Similar to Garret's results we obtain approximately 0.85 for the asymmetry factor of smallest ice mass fractions (10–20%) in mixed phase clouds and 0.74 for highest observed ice fractions (80%) during the ASTAR 2004 campaign. There is clear correlation between g and the ice fraction for all presented flights, however, the correlation coefficient is quite low due to certainly complicated relations between asymmetry factor and crystal size, shape, surface roughness, etc. The parameterised efficiencies for the two sensors, in particular $\varepsilon_{\mathrm{LWC,\,droplets}}$, seem to produce a consistent ratio between ice and total condensed water calculated from the Nevzorov probe that correlates quite well with the asymmetry factor.

6 Conclusions

Within the frame of 14 scientific cloud flights during the ASTAR 2004 measurement campaign, this study represents an extended analysis of the Nevzorov probe response in Arctic supercooled and mixed phase clouds. Knowing that the efficiencies of the LWC and TWC sensors of the Nevzorov probe have not yet been adequately characterized beyond cloud particle diameters of 25 μm, this study contributes to confine current uncertainties in Nevzorov Probe efficiencies. The efficiencies are dependent on cloud particle size and phase. In this study a reasonable response of the critical efficiency $\varepsilon_{\text{LWC, droplets}}$ (LWC sensor efficiency with respect to water) was fixed from experimental data in Arctic clouds, where large droplet sizes far beyond 25 μm have been observed quite frequently. The efficiency $\varepsilon_{\text{LWC, droplets}}$ was estimated from the calculated size-dependent ratio of $\varepsilon_{\text{LWC, droplets}}$ over $\varepsilon_{\text{TWC, droplets}}$, assuming an extrapolation for $\varepsilon_{\text{TWC, droplets}}$. The assumed extrapolation of $\varepsilon_{\text{TWC, droplets}}$ and the assessment of $\varepsilon_{\text{LWC, droplets}}$ as a function of cloud droplet diameters should lead to an improved adequacy of calculated condensed water contents (IWC, LWC). The proposed improvement in $\varepsilon_{\text{LWC, droplets}}$ is applied to calculate ice fractions sampled from the Nevzorov probe as a function of the asymmetry parameter deduced from the scattering phase function of the Polar Nephelometer.

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Table 1. Summary of cloud in situ instrumentation mounted on Polar-2 research aircraft during ASTAR 2004.

Instrument	Measurement parameter	Range
Polar Nephelometer	Scattering phase function (asymmetry parameter, extinction coefficient,...)	3–800 μm
CPI	Cloud particle microphysical and morphological properties	D>10 μm
Nevzorov	Ice and liquid water content	0.–1. g/m^3
PMS FSSP	Cloud particle size distribution	3–95 μm
PMS 2D-C	Cloud particle size distribution	25–800 μm

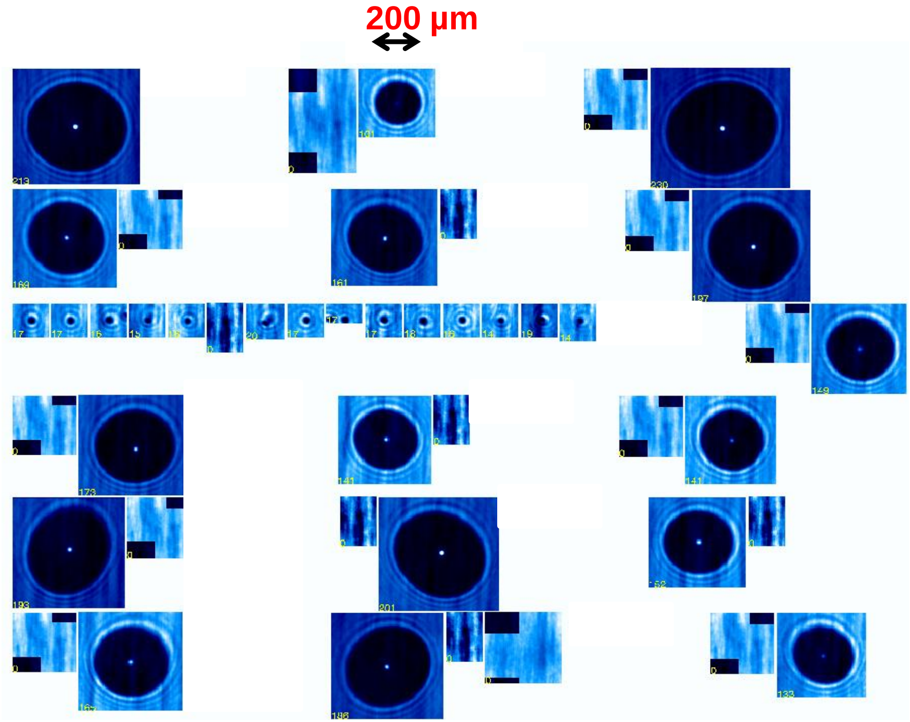

Fig. 1. Presence of giant cloud droplets (100–500 μm) in stratus type Arctic clouds during ASTAR 2004.

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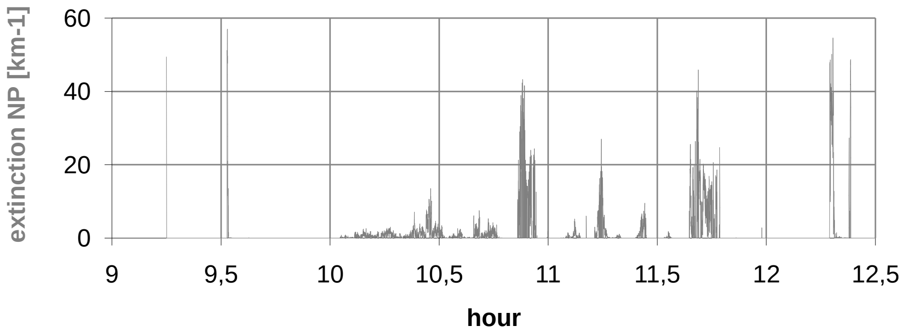

Fig. 2. Definition of cloud presence via the extinction coefficient calculated from the Polar Nephelometer (22 May 2004).

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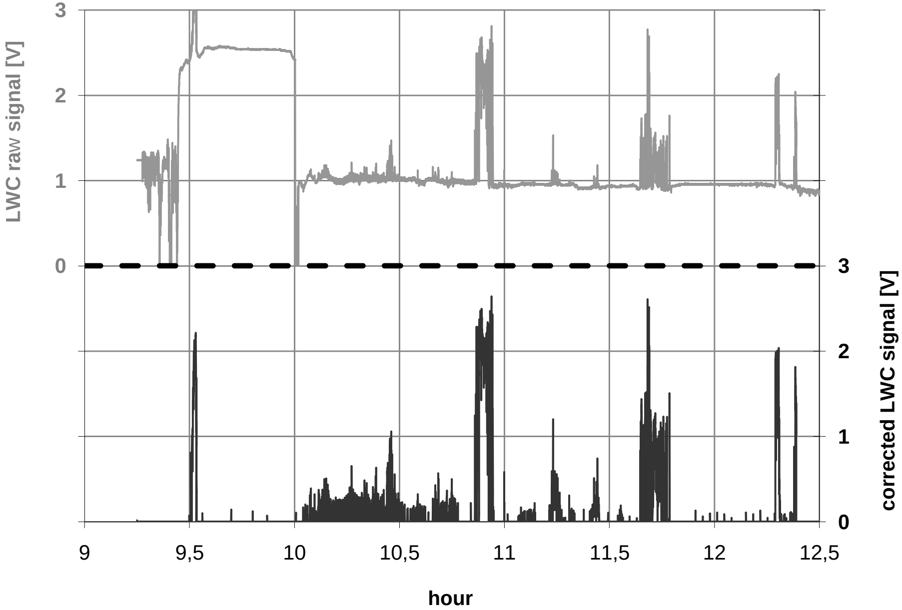

Fig. 3. Offset subtraction for a high offset example of the LWC sensor (22 May 2004).

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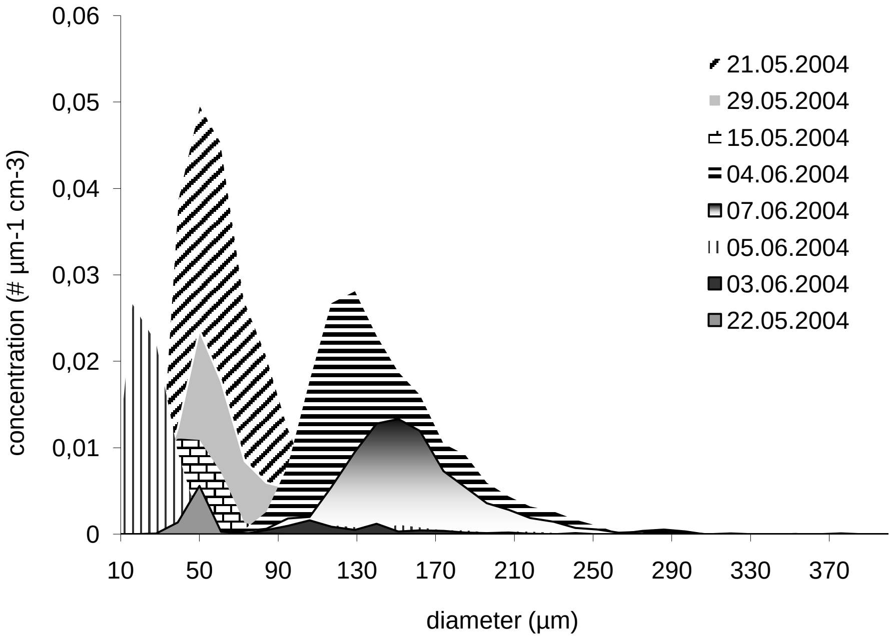

Fig. 4. Variation of droplet size spectra during ASTAR 2004.

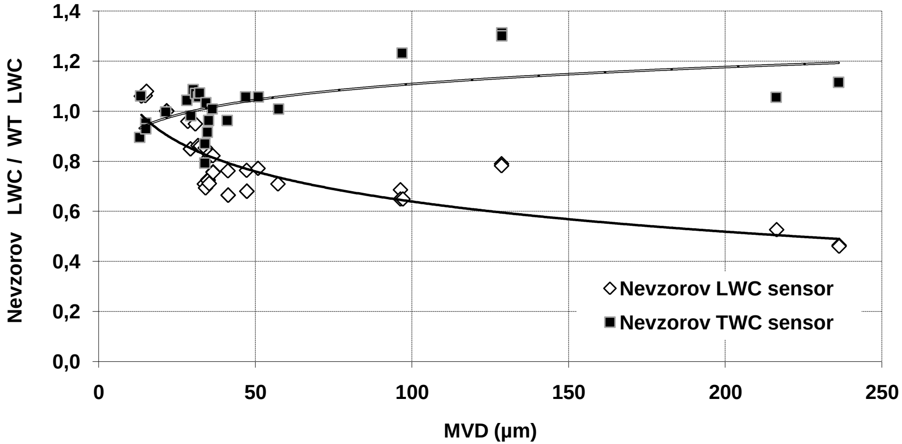

Fig. 5. Findings of Strapp et al. (2003) for the Nevzorov TWC and LWC sensor behaviour with respect to the wind tunnel reference LWC in pure liquid clouds.

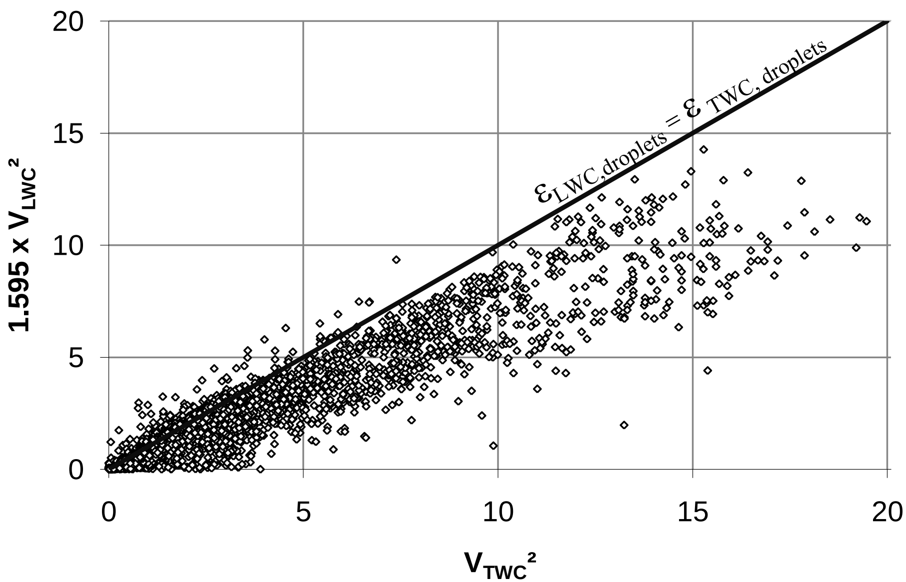

Fig. 6. "Correlation" of LWC and TWC sensor voltages in pure liquid clouds, a theoretical line of equal sensor efficiencies $\epsilon_{\mathrm{LWC,\,droplets}}=\epsilon_{\mathrm{TWC,\,droplets}}$, is added.

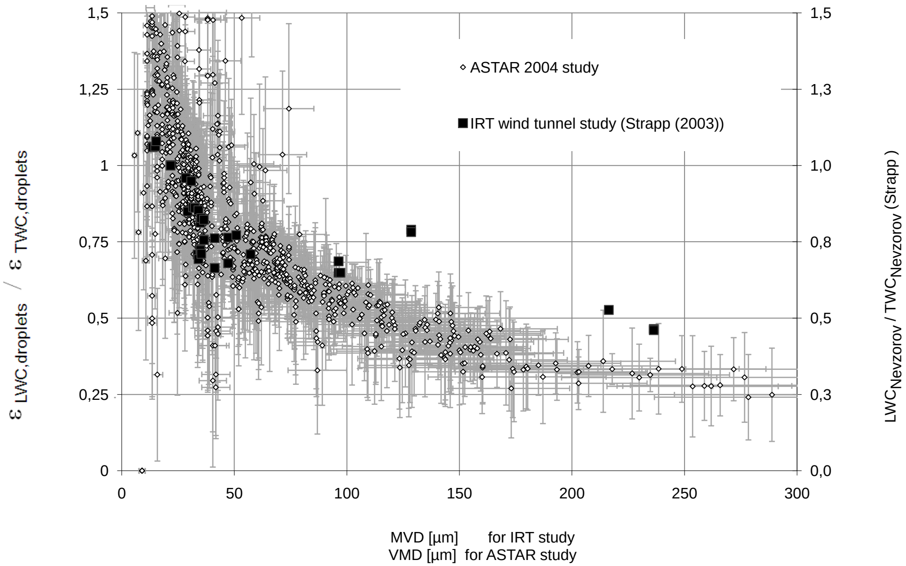

Fig. 7. Efficiency ratio of LWC to TWC Nevzorov sensors with respect to pure water droplets. In addition, ratio of Nevzorov LWC over TWC from Strapp (2003).

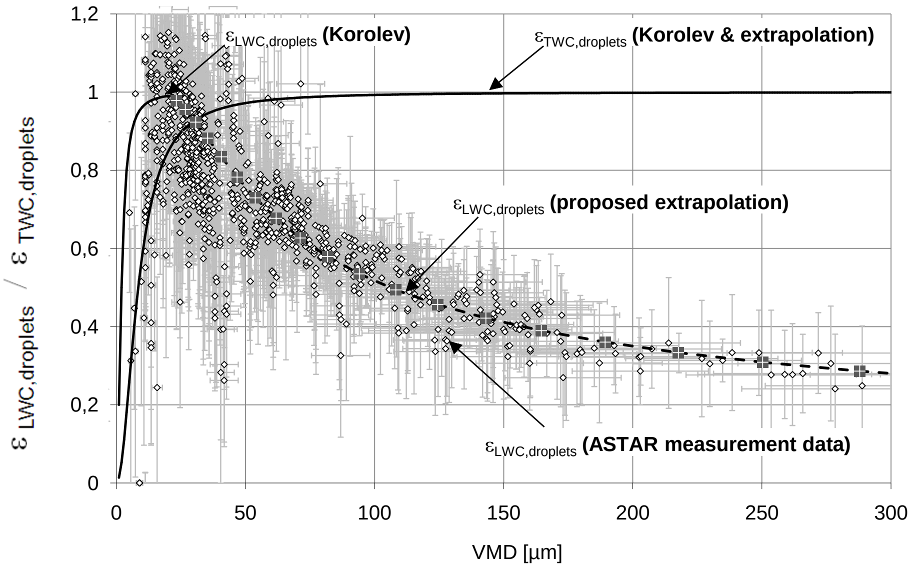

Fig. 8. Derived LWC sensor efficiency $\epsilon_{\mathrm{LWC,\,droplets}}$ assuming the TWC sensor efficiency $\epsilon_{\mathrm{TWC,\,droplets}}$ from Korolev (1998) including extrapolation of $\epsilon_{\mathrm{TWC,\,droplets}}$ for larger droplet sizes.

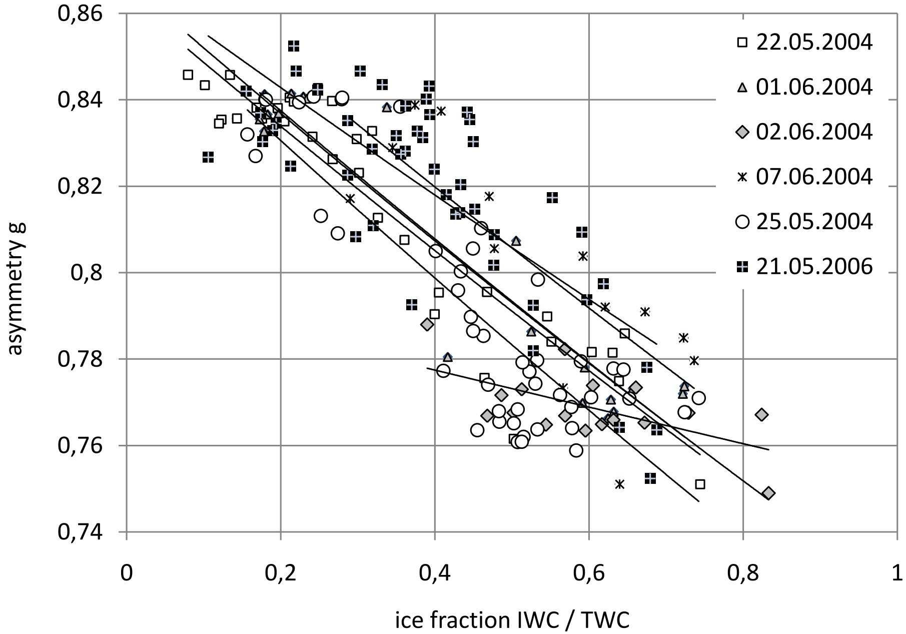

Fig. 9. Cloud ice fraction related to asymmetry parameter deduced from scattering phase functions of the Polar Nephelometer.