Testing Mixed-Phase Cloud Water Vapor Parameterizations with SHEBA/FIRE–ACE Observations

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ABSTRACT

The parameterization of in-cloud water vapor pressure below 0°C is examined using in situ aircraft observations from Canadian National Research Council (NRC) Convair-580 flights during the Surface Heat Budget of the Arctic Ocean (SHEBA)/First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment–Arctic Cloud Experiment (FIRE–ACE) campaign. The accuracy of in-cloud water vapor measurements is evaluated against the saturated water vapor pressure in liquid water clouds as derived from measured temperatures, which have a mean bias of about −1%. This study reveals that the parameterization used in the ECMWF cloud scheme, which employs a temperature-weighted average of the values with respect to ice and liquid water underestimates the saturated water vapor by ∼9% when applied to all in-cloud data from the campaign. It is found that a parameterization that relates the weighting to the cloud liquid and ice water contents agrees well with the observations. This study also reveals that it is incorrect to assume that water vapor is in equilibrium with liquid water in mixed-phase clouds.

1. Introduction

Cloud schemes in numerical models require specification of saturated water vapor pressure. The in-cloud water vapor is often assumed to be saturated with respect to liquid water and ice, respectively, for pure water and ice clouds. There is an ambiguity, however, in defining the water vapor pressure for mixed-phase clouds. Figure 1 shows the saturated water vapor pressure with respect to liquid water and ice (Fig. 1a; e.g., Rogers and Yau 1989), and their relative differences (Fig. 1b), for temperatures from −40° to 0°C. In this temperature range, mixed-phase clouds may exist. From Fig. 1b, the relative difference increases as the temperature decreases. At a temperature of −20°C, the relative difference is about 22%.

Various parameterizations have been used in numerical models to specify the in-cloud water vapor pressure at temperatures below 0°C. In this study, in situ aircraft observations from the Surface Heat Budget of the Arctic Ocean (SHEBA)/First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment–Arctic Cloud Experiment (FIRE–ACE) campaign are used to examine these parameterizations.

Section 2 describes the in-cloud water vapor parameterizations that are widely used in numerical models. Section 3 presents the field campaign, instrumentation, and analysis method associated with this study. The accuracy of in-cloud water vapor measurements is discussed in section 4. In section 5, the parameterization of saturated water vapor is examined using the in situ aircraft observations. The implications of the results revealed in this study in climate simulations and data assimilation are discussed in section 6. The summary and conclusions are given in section 7.

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2. Parameterization of in-cloud water vapor pressure

The in-cloud water vapor pressure E_s is generally approximated in numerical models in the form

$$E_s = RE_{sl} + (1 - R)E_{si}, \tag{1}$$

where E_{sl} and E_{si} are the saturated water vapor pressure with respect to liquid water and ice, respectively; R is a weighting factor, such that $R = 1$ for liquid water clouds and $R = 0$ for ice clouds, and $0 < R < 1$ for mixed-phase clouds. The value of R in numerical models is often specified as a function of either temperature or cloud liquid and ice water contents.

In the European Centre for Medium-Range Weather Forecasts (ECMWF) cloud scheme (Jakob 2002), R depends only on temperature. Pure ice clouds exist for temperatures lower than −23°C, mixed-phase clouds occur between −23° and 0°C, and pure liquid water clouds are formed at temperatures above 0°C. The value of R for mixed-phase clouds is estimated as

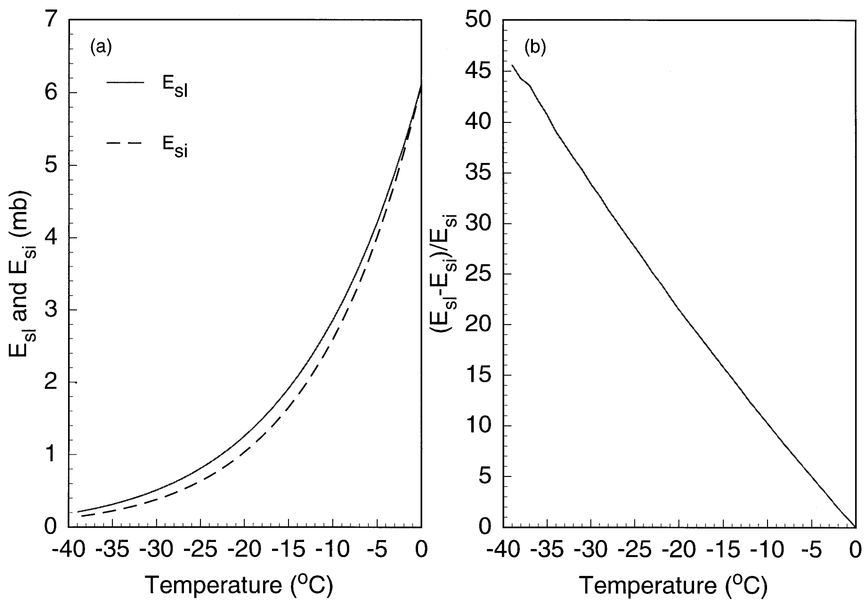

FIG. 1. (a) Saturated water vapor pressures with respect to liquid water (E_{sl}) and ice (E_{si}), and (b) their relative differences, as functions of temperature.

$$R = [(T + 23)/23]^2, \quad (2)$$

where $-23° < T < 0°C$.

In the cloud microphysics scheme developed by Fowler et al. (1996) for general circulation model (GCM) applications, water and ice clouds are formed at temperatures above 0° and lower than −20°C, respectively. Supercooled cloud water and cloud ice are allowed to coexist in the temperature range $-20° < T < 0°C$, and the weighting R is specified as a linear function of temperature in the form

$$R = (T + 20)/20. \quad (3)$$

This specification of saturated water vapor pressure is used in many GCMs.

For convenience, in this study, relative humidity (RH) is defined with respect to ice. Using Eq. (1), RH in clouds with temperatures below 0°C can be written in the form

$$\mathrm{RH} = RE_{sl}/E_{si} + 1 - R. \quad (4)$$

Hereafter, RH using $R = 0$ and 1, and R from Eqs. (2) and (3), are referred to as RH_{ice} (=1), RH_{liquid}, RH_{ECMWF}, and RH_{linear}, respectively. Figure 2 shows RH_{ice}, RH_{liquid}, RH_{ECMWF}, and RH_{linear} as functions of temperature. The RH_{ECMWF} and RH_{linear} reach maximum values of 103.4% and 105.1% at temperatures of −8° and −10°C, respectively. The differences between RH_{ECMWF} and RH_{linear} for a given temperature are less than 2.2%.

Another widely used scheme is to relate R to the cloud water contents (e.g., Lord et al. 1984; Wood and Field 2000) so that

$$R = \mathrm{LWC}/(\mathrm{LWC} + \mathrm{IWC}), \quad (5)$$

where LWC and IWC are the liquid and ice water contents, respectively, and LWC + IWC is the total water content (TWC). In this study, the RH using the cloud-water-weighted R in Eq. (5) is noted as $\mathrm{RH}_{cw\text{-}weighted}$.

In some recent cloud schemes used in mesoscale models (e.g., Trembly and Glazer 2000) and GCMs (Rotstayn et al. 2000), the water vapor in mixed-phase clouds is assumed to be saturated with respect to liquid water,

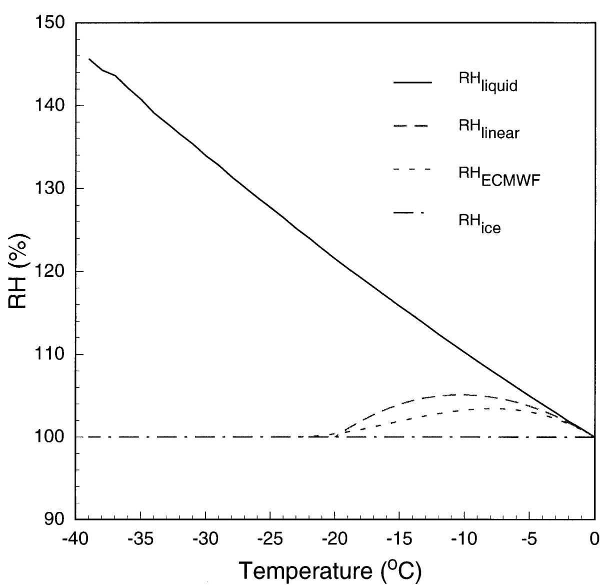

FIG. 2. In-cloud RH with respect to ice as a function of temperature for water vapor pressures that are saturated with respect to liquid water (RH_{liquid}) and ice (RH_{ice}), and that based on ECMWF (RH_{ECMWF}) and linear (RH_{linear}) parameterizations.

that is, RH_{liquid}. This assumption will also be tested with observational data.

The $RH_{measured}$ in this study is the RH derived from in-cloud water vapor measurements, which is obtained from $E_{sl}(T_d)/E_{si}(T)$, where T_d and T are the measured dewpoint and temperature in clouds, respectively. To test different parameterizations for R, RH as derived from Eq. (4) will be compared with $RH_{measured}$, which requires in situ aircraft observations of in-cloud temperature, dewpoint, and cloud liquid and total water contents.

3. Observations and data analysis

The observational data are taken from the SHEBA/FIRE–ACE field campaign, which began in April 1998 and ended in July 1998 (Curry et al. 2000). In situ aircraft observations were made in April by the Cloud Physics Research Division of the Meteorological Service of Canada (MSC) from the Canadian National Research Council (NRC) Convair-580. The data are available from the National Aeronautics and Space Administration (NASA) Langley Atmospheric Sciences Data Center (ASDC). The Canadian dataset is unique for this study because both LWC and TWC were directly measured. The data from all 18 individual flights from 8 to 29 April 1998 are analyzed.

The instruments used in this investigation include those measuring temperature (Rosemount reverse-flow temperature sensors), water vapor (LiCor hygrometer), and cloud liquid and total water content (Nevzorov probe). Based on the Canadian Convair-580 data report (Cloud Physics Research Division of MSC 1999), the temperature measurements were accurate within about 1°C. The accuracy of the LiCor hygrometer was not reported. In this study the accuracy of in-cloud water vapor measurements will be examined in section 4. The accuracy of the Nevzorov probes has been discussed in details in Korolev et al. (1998). Below, a brief discussion on the instruments and related data analysis are given first.

Korolev et al. (1998) describe the Nevzorov TWC/LWC probe. It has two separate hot-wire sensors: one for TWC and another for LWC measurements. Comparisons with icing cylinders and King probe measurements in high-speed wind-tunnel experiments showed that the instruments were capable of measuring both LWC and TWC to within 15% with a sensitivity of 0.003–0.005 g m^{-3}. Owing to the response of the hot-wire LWC probes to ice crystals, a small portion of ice water content is reflected as a false LWC on the Nevzorov probe (Cober et al. 2001; Korolev et al. 2003). In this study, an average value of 11% as estimated by Korolev et al. (2003) is used to eliminate the residual effect of ice particles. Following Korolev et al. (1998) and Korolev et al. (2003), the corrected LWC and IWC are derived from

$$\text{TWC}^* = \text{LWC} + 1.12\,\text{IWC},$$
$$\text{LWC}^* = \text{LWC} + 0.11\,\text{IWC}, \qquad (6)$$

where TWC* and LWC* are apparent total water and liquid water contents from Nevzorov probes, respectively. The coefficient of 1.12 in Eq. (6) takes into account the effect of difference in latent heat between ice sublimation and liquid water evaporation.

For the Nevzorov probe data submitted to the NASA Langley ASDC (Cloud Physics Research Division of MSC 1999), artificial baseline biases of TWC and LWC resulting from changes in aircraft speed and altitude (Korolev et al. 1998) were removed during the data processing (G. A. Isaac 2003, personal communication). Such drifts from zero were also independently adjusted by A. V. Korolev (2003, personal communication) with the help of special software using complementary information from other cloud probes (Korolev et al. 2003). Our sensitivity study shows that the use of the Nevzorov data analyzed by Korolev as compared to those from the NASA Langley ASDC has little impact on this study. But since the offsets were more carefully removed by Korolev, his Nevzorov probe data will be used here.

In this study, the aircraft observations were considered to be within clouds when the TWC from the Nevzorov probe was larger than 0.01 g m^{-3} following Korolev et al. (2003). Instead of using 30-s-averaged data as in Boudala et al. (2002a,b), 1-s measurements are used, to avoid possible clear-sky regions. Since in-cloud water vapor pressure should be between E_{si} and E_{sl}, only those measurements that satisfy $0.9RH_{ice} < RH_{measured} < 1.1\,RH_{liquid}$, where RH_{ice} and RH_{liquid} are derived from the reverse-flow temperature measurements, and $RH_{measured}$ is derived from LiCor hygrometer dew points and reverse-flow temperatures, are considered. The excluded data are related to the anomalous behavior of water vapor and temperature probes, or to TWC measurements that show TWC > 0.01 g m^{-3} for clear-sky regions. Only about 10% of the data were excluded. Also flight 6 and half of flight 18, when the LiCor hygrometer was not working, were not considered in this study.

Following Boudala et al. (2002a) and Korolev et al. (2003), cloud phases were determined using the following criteria: for ice clouds, LWC/TWC < 0.1; for liquid clouds, LWC/TWC > 0.9; and for mixed-phase clouds, $0.1 \leq$ LWC/TWC ≤ 0.9. Of the $\sim$11 500 in-cloud measurements analyzed in this study, about 51% are within liquid water clouds, 23% within mixed-phase clouds, and 26% within ice clouds.

4. Accuracy of in-cloud water vapor measurements

Under equilibrium conditions, water vapor is saturated with respect to liquid water and ice, within pure liquid and ice clouds, respectively. Therefore, the accuracy of in-cloud water vapor measurements can be

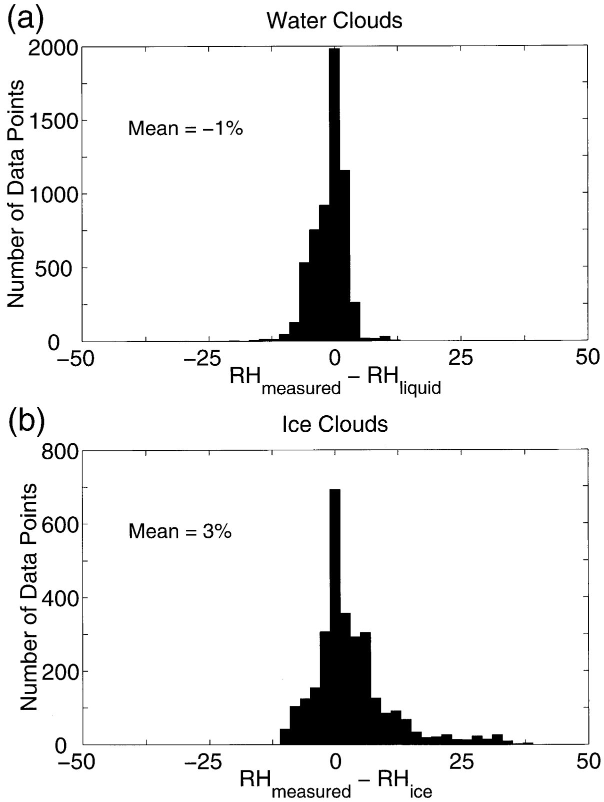

FIG. 3. Histogram distributions of differences between (a) $RH_{measured}$ and RH_{liquid} (%) in liquid water clouds, and (b) $RH_{measured}$ and RH_{ice} in ice clouds; $RH_{measured}$ is the observed relative humidity.

evaluated using the saturated water vapor within pure liquid and ice clouds, which can be derived from measured temperatures following the Clausius–Clapeyron equation (e.g., Rogers and Yau 1989). Four static outside air temperature measurements from the Convair-580 aircraft are available for use. Although the accuracy of all temperature measurements is suggested to be ~1°C, the mean bias, as well as random errors, for the reverse-flow temperature is expected to be much smaller. This temperature is most recommended for use by the data report.

Figure 3 shows histogram distributions of differences in RH between in-cloud water vapor measurements and saturated water vapor with respect to liquid water and ice within water and ice clouds, respectively. The mean differences are −1% for liquid water clouds, and 3% for ice clouds. Since the condensation/evaporation processes are fast in liquid water clouds with a typical characteristic time of a few seconds, the supersaturation there is usually less than 0.01%–0.1% (Squires 1952; Warner 1968; Paluch and Knight 1984; Politovich and Cooper 1988; Khvorostyanov and Sassen 2002), although some estimates of water supersaturations, by comparing cloud droplet number concentrations with cloud condensation nucleus activation spectra measured in cloud inflow, suggest that supersaturations in certain cloud regions can be sometimes as large as 1% (Hegg et al. 1995, 1996). Thus, the RH in liquid water clouds should be RH_{liquid}. Therefore, the apparent subsaturation suggested by the measurements in liquid water clouds must be an observational error. Thus, the mean bias of in-cloud water vapor measurements is estimated to be close to about −1%.

For ice clouds where characteristic times can vary from 0.5 to 5 h depending on the nucleation mechanism, the depositional process is much slower (Khvorostyanov and Sassen 2002). Therefore, even after a few hours of cloud development, there are typically vapor supersaturations with respect to ice on the order of about 5%–10% (Khvorostyanov and Sassen 2002). By subtracting a mean bias of −1% in water vapor measurements from the mean difference of 3% between the measurements and saturated water vapor with respect to ice, a mean vapor supersaturation of 4% is obtained in observed ice clouds, which is consistent with Khvorostyanov and Sassen (2002). These results confirm the need for introducing a characteristic deposition time in cloud schemes to convert supersaturated vapor to ice water content. By relaxing the residual supersaturation to zero at each model time step, the simulated IWC may be overestimated (Khvorostyanov and Sassen 2002).

The consistencies between saturated water vapor and in-cloud water vapor measurements further justify the criteria used in section 3 to identify cloud regions and phases. Note that a mean bias of about −1% for in-cloud water vapor measurements is also obtained with a much more conservative method to identify regions of liquid water clouds, which uses measurements from not only the Nevzorov LWC and TWC probes but also the forward scattering spectrometer probe (FSSP), King LWC, and the Rosemount icing detector (Cober et al. 2001).

The standard deviation of differences between $RH_{measured}$ and RH_{liquid} in liquid water clouds (see upper panel of Fig. 3) is estimated to be ~3.5%. This deviation can be attributed to the random errors of both LiCore hygrometer and temperature measurements.

For the differences between $RH_{measured}$ and RH_{ice} within ice clouds (see lower panel of Fig. 3), there is appreciable frequency of occurrence at values greater than ~25%. Ice supersaturations of 20%–30% have also been observed in cirrus clouds from FIRE-II (Heymsfield and Miloshevich 1995) and at the Atmospheric Radiation Measurements (ARM) Southern Great Plains (SGP) site (T. Ackerman 2003, personal communication). The clouds with such supersaturation may represent the early developing stage of these clouds. Koop et al. (2000) suggest that the liquid water saturation line and the homogeneous ice nucleation line represent upper limits for the relative humidities that can be sustained in the atmosphere at temperatures above and below −39°C, respectively. In situ measurements of upper-tropospheric relative humidity during recent field campaigns have revealed that ice supersaturation is very common and

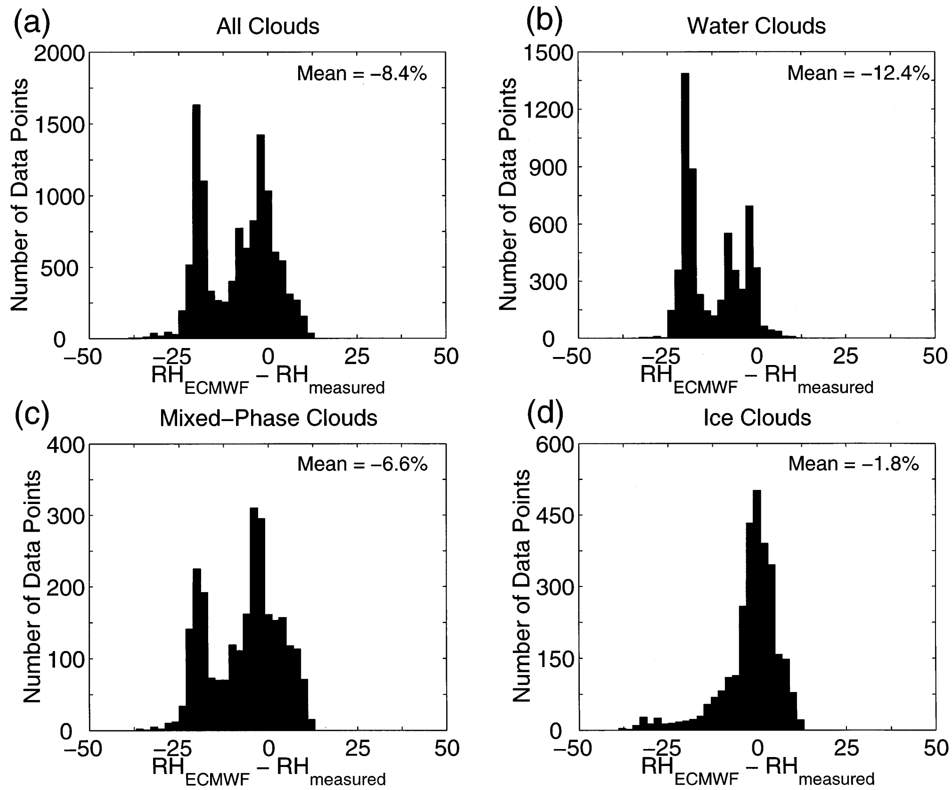

FIG. 4. Histogram distributions of differences between RH_{ECMWF} and $RH_{measured}$ (%) for (a) all clouds, (b) liquid water clouds, (c) mixed-phase clouds, and (d) ice clouds.

that very large relative humidities with respect to ice of up to 160% are frequently observed (e.g., Gierens et al. 1999; Ovarlez et al. 2002; Strom et al. 2003). Note that heterogeneous ice nuclei might induce ice formation at lower saturation ratios at all temperatures.

5. Test of in-cloud water vapor parameterizations

Figure 4 shows the comparison of in-cloud water vapor RH between the ECMWF parameterization [Eq. (2)] and observations for all clouds, liquid water clouds, mixed-phase clouds, and ice clouds. The ECMWF parameterization works reasonably well for ice clouds. This is because the mean temperature of observed ice clouds is ∼−20°C at which the ECMWF parameterization is close to ice saturation (Fig. 2). However, the ECMWF parameterization has large negative differences of −12.4% and −6.6% when applied to liquid water and mixed-phase clouds, respectively. During the SHEBA/FIRE–ACE field campaign in April, the temperatures in all observed liquid water clouds were below 0°C, which are all treated by the ECMWF parameterization with $R < 1$. By applying the ECMWF parameterization to all in-cloud data from the campaign, the mean difference is −8.4%. The bimodal distribution shown in Fig. 4 for all clouds is caused by different cloud phases, mainly liquid water clouds versus ice clouds. The multimodal distribution in Fig. 4 for liquid water clouds is because the observed cloud layers are located at different heights with different temperature modes. By removing the −1% mean bias in water vapor measurements, mean biases of the ECMWF parameterization become −9.4%, −13.4%, −7.6%, and −2.8%, for all clouds, liquid water clouds, mixed-phase clouds, and ice clouds, respectively.

The parameterization that specifies the weighting as a linear function of temperature between 0° and −20°C [Eq. (3)] was also examined using the in situ aircraft observations, as shown in Fig. 5. The mean differences between RH_{linear} and those from observations are −7.4%, −11.4%, −5.7%, and −0.9% for all clouds, liquid water clouds, mixed-phase clouds, and ice clouds, respectively, which become −8.4%, −12.4%, −6.7%, and −1.9% after removing the observational bias. These results are similar to those from the ECMWF parameterization.

Figure 6 shows the comparison of in-cloud water vapor RH between the cloud-water-weighted parameterization [Eq. (5)] and observations (the data with LWC/TWC < 1.15 are considered to exclude the outliers of LWC/TWC). The distributions become single modal regardless of cloud types and sampling levels. This indicates that the correct physics is considered in this parameterization. For liquid water clouds, mixed-phase

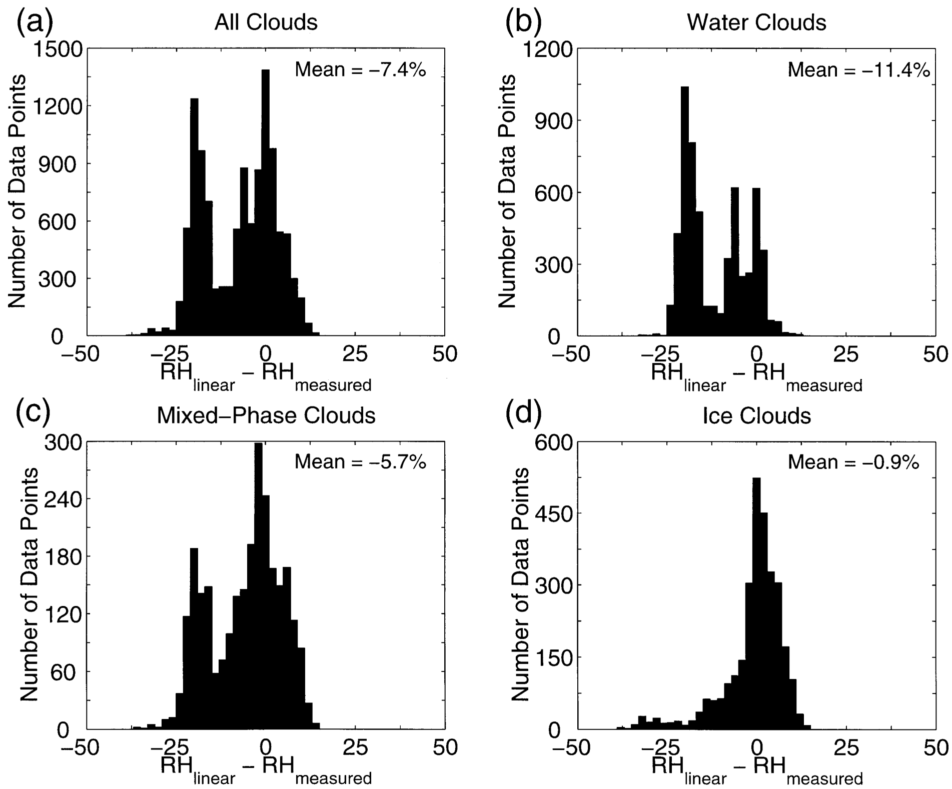

FIG. 5. Same as Fig. 4, but between RH_{linear} and $RH_{measured}$ (%).

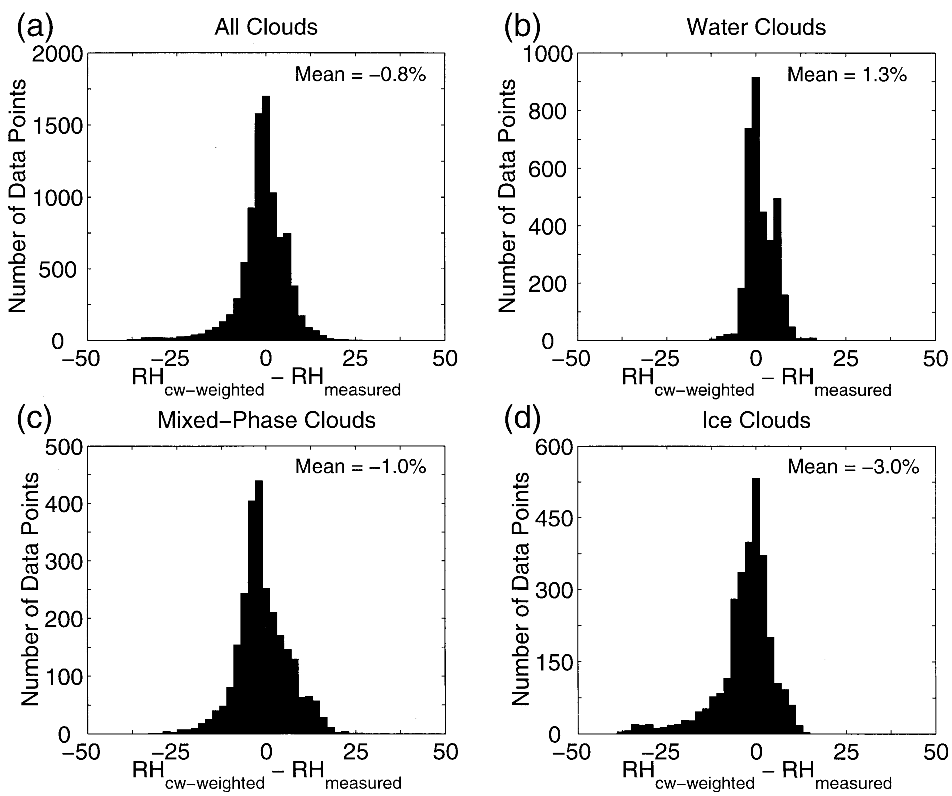

FIG. 6. Same as Fig. 4, but between $RH_{cw\text{-}weighted}$ and $RH_{measured}$ (%).

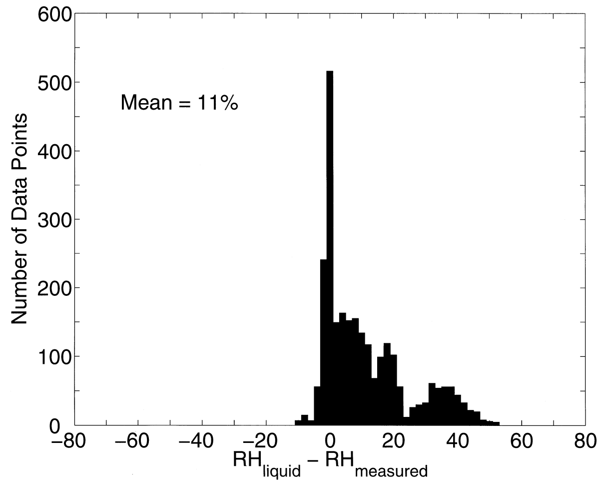

FIG. 7. Histogram distributions of differences between RH_{liquid} and $RH_{measured}$ (%) for mixed-phase clouds.

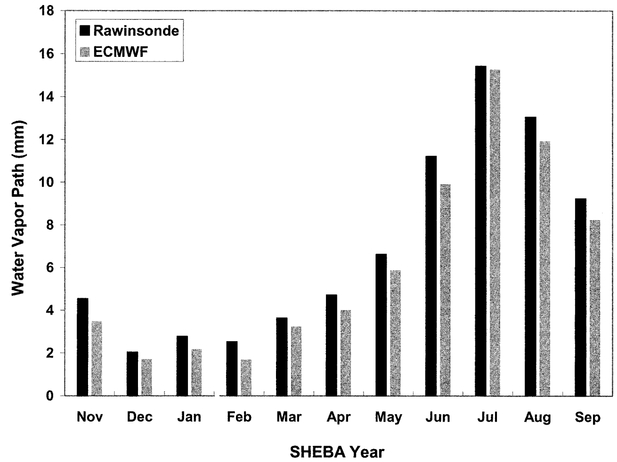

FIG. 8. Comparison of monthly mean integrated water vapor path between the ECMWF and radiosonde data at the SHEBA site.

clouds, and ice clouds, the mean differences are 1.3%, −1.0%, and −3%, respectively. By applying the cloud-water-weighted parameterization to all in-cloud data, the mean difference is −0.8%. After removing a mean bias of −1% from $RH_{measured}$, the mean biases of the cloud-water-weighted parameterization for all clouds, liquid water clouds, mixed-phase clouds, and ice clouds are −1.8%, 0.3%, −2%, and −4%, respectively. The −2% bias for mixed-phase clouds may be attributed to errors in the liquid water and total water content measurements, while the −4% bias for ice clouds is owing to the supersaturation in observed ice clouds. Hence, the cloud-water-weighted parameterization agrees with in situ aircraft observations within the measurement errors for both water and mixed-phase clouds.

For mixed-phase clouds, both liquid and ice microphysical processes are operating. In some cloud schemes (e.g., Trembly and Glazer 2000; Rotstayn et al. 2000), it is assumed that the mixed-phase clouds are saturated with respect to liquid water. Figure 7 shows the histogram distribution of differences in RH between saturated water vapor with respect to liquid water and those from measurements within mixed-phase clouds. The mean difference is as large as 11%. Note that the mixed-phase clouds observed during the SHEBA/FIRE–ACE campaign have a mean cloud temperature of about −18°C and a mean LWC/TWC of ~0.45. Therefore, the assumption of saturated water vapor within mixed-phase clouds used in Trembly and Glazer (2000) and Rotstayn et al. (2000) is not justified by the observations. The use of this assumption in numerical models would significantly reduce the lifetime of mixed-phase clouds.

Numerical studies (e.g., Juisto 1971; Korolev and Mazin 2003; Korolev and Isaac 2003) suggest that the RH in mixed-phase clouds should be close to the saturation with respect to liquid water. This result is true under the assumption that liquid droplets and ice crystals are well mixed and uniformly distributed in space, and is due to the fact that droplet evaporation is a much faster process than ice deposition for typical cloud particle concentrations and sizes. Figure 7, however, seems to suggest that even in the observational scale of ~100 m, the water droplets and ice crystals are not well mixed but may occur in patches. Further observational and theoretical studies are needed to understand the discrepancy between the model and observations.

6. Discussion

This study shows that in the Arctic the specification of saturated water vapor pressure used in the ECMWF cloud scheme was lower by about 9% as compared with in situ aircraft observations. This is caused by the underestimation of the saturated water vapor in supercooled liquid water clouds and mixed-phase clouds, which are common in the Arctic. M. D. Shupe et al. (2002, personal communication) found that during the SHEBA year (Uttal et al. 2002), the annual cloud occurrence was 74% and a pure liquid water layer was present somewhere in the atmospheric column 55% of the year. It was also found that mixed-phase clouds were present somewhere in the atmospheric column 41% of the time.

The underestimation of saturated water vapor in numerical weather prediction models might lead to a drier model atmosphere by converting more water vapor into cloud liquid/ice water content and precipitation. Figure 8 shows the comparison of monthly mean integrated water vapor path at the SHEBA site between the ECMWF reanalysis data (C. Bretherton et al. 2002, personal communication) and radiosonde observations. The underestimation of saturated water vapor as revealed in this study might partly explain why the ECMWF water vapor path is systematically smaller than the observations.

To test and improve GCM cloud and radiation parameterizations in the Arctic region, a single-column model (SCM) annual cycle simulation was carried out using ECMWF forcing with a nudging technique (J. Yuan et al. 2002, personal communication). The SCM simulation was found to be very sensitive to the water vapor profile used in the nudging. As a result, the simulated surface precipitation was too small as compared to the SHEBA surface observations due to using a drier ECMWF water vapor profile.

Referencing cloud initiation to a lower saturation water vapor in climate models would make a qualitative difference in the model's energy budget and circulation. Because lower saturation is easier to achieve, clouds are more frequent and more cloud water is formed. This has a direct impact on the global radiative energy budget. The implication of uncertainty in saturated water vapor at temperatures between the homogeneous nucleation point and freezing on GCM was discussed by Del Genio (2002).

The present study examines in-cloud water vapor parameterizations with in situ aircraft observations. The temperature-weighted parameterizations [Eqs. (2) and (3)] significantly underestimate the in-cloud water vapor pressure mainly because the liquid water clouds below 0°C are not properly considered. This result holds regardless of the scales to which the Eqs. (2) and (3) are applied. The assumption that water vapor in mixed-phase clouds is close to saturation over liquid water is also examined, which significantly overestimates the mixed-phase cloud water vapor, even in the spatial resolution of the measurements. This assumption could become even worse when applied to the GCM grid scales (~100 km) since it is valid only if the cloud droplets and ice crystals are well mixed. The cloud-water-weighted parameterization [Eq. (5)] that is often used in cloud-resolving models (e.g., Tao et al. 1989, 2003; Krueger et al. 1995; Fu et al. 1995) is validated with in situ observations. Further study is needed to investigate the scale dependence of this parameterization for the GCM applications.

7. Conclusions

In this study, the parameterization of saturated water vapor in clouds when temperatures are below 0°C has been examined. In situ observations of Canadian NRC Convair-580 flights during the SHEBA/FIRE-ACE campaign were used. The error of in-cloud water vapor measurements was evaluated using the saturated water vapor in liquid water clouds, which has a mean bias of about −1%. This study reveals that the two schemes that use a weighted average of the values with respect to ice and liquid water with the weightings specified as functions of temperature underestimate the saturated water vapor by ~9% when applied to all in-cloud data from the campaign. A scheme that relates the weightings to the cloud liquid and ice water contents, however, is shown to agree well with the observations. It is also shown that the use of saturation with respect to liquid water is incorrect for describing the water vapor in mixed-phase clouds. It is argued that the use of lower saturated water vapor in climate models would lead to a drier model atmosphere, more frequent cloud occurrence, and more cloud water, which might have a direct impact on the global radiative energy budget and general circulation.

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