THE EFFECT OF SPATIAL AVERAGING ON THE RELATIVE HUMIDITY AND PHASE COMPOSITION OF CLOUDS

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1. Introduction

Relative humidity in clouds plays a crucial role in precipitation formation, phase transformation and life cycle of clouds. The in-cloud water vapor pressure is commonly assumed to be saturated with respect to liquid water in liquid clouds, and saturated with respect to ice in ice clouds. The humidity in mixed phase clouds has been debated in the cloud community for years. The water vapor pressure (E_w) in mixed phase clouds is generally approximated as a weighted average of the respective saturation values over liquid water (E_{ws}) and ice (E_{is})

$$E_w = fE_{ws} + (1-f)E_{is} \quad (1)$$

where f is the weighting factor ($0 \le f \le 1$). The value of f in mesoscale and global circulation models (GCM) is usually specified as a function of temperature (e.g. Fowler et al. 1996; Jakob 2002) or cloud liquid (LWC) and ice (IWC) water content (e.g. Lord et al. 1984; Wood and Field 2000, Fu and Hollars 2004). In some numerical schemes (Rostyan et al. 2000; Tremblay and Glazer 2000) the water vapor in mixed clouds assumed to be saturated with respect to liquid water, i.e. f=1.

In-situ measurements showed that the proportion between liquid and ice in mixed phase clouds is a function of temperature (Korolev et al. 2003). Besides temperature, the partitioning between ice and liquid is expected to depend on the spatial averaging scale. When the averaging scale is large enough, locally mixed phase clouds become alternated with single phase ice clouds, where relative humidity is *a priori* different from that in mixed phase clouds. Therefore, the relative humidity in clouds is anticipated to depend on the averaging scale as well. The existing humidity parameterizations do not include dependence on the averaging scale. A proper description of the relative humidity in mixed phase clouds plays an important role for accurate simulations within GCMs.

A new parameterization of the relative humidity in mixed phase clouds is discussed here. The new parameterization is based on consideration of the spatial fractions of liquid ice and mixed phase clouds. It is shown that the average relative humidity in mixed phase clouds should be weighted by the spatial fraction of ice clouds rather than by the mass fraction of ice which is frequently used in GCMs.

2. Prerequisite

There are two extreme situations which may occur in mixed phase clouds: (1) liquid droplets and ice particles are uniformly mixed and (2) liquid droplets and ice particles are separated in space and they form single-phase “ice” and “liquid” clusters. In the framework of this study the first category will be recognized as “genuinely” mixed clouds. The second category, where genuinely mixed phase and liquid clouds are mixed with ice clouds, will be referred to as “conditionally” mixed. A cartoon of a conditionally mixed phase cloud is shown in Fig.1.

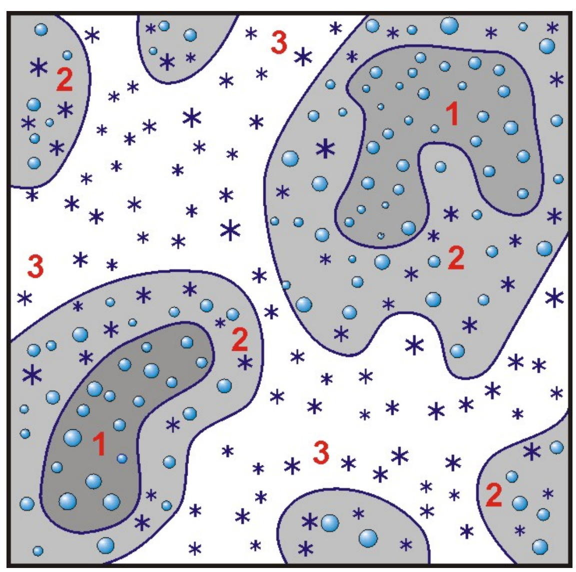

Figure 1. Conceptual diagram of conditionally mixed phase cloud. Numbers indicate genuinely mixed phase (1), liquid (2) and ice (3) clouds regions.

In a general case for the ensemble of ice, liquid and mixed phase clouds, the average humidity can be calculated as an average weighted by cloud volume fractions

$$\overline{E} = \upsilon_w \overline{E}_w + \upsilon_m \overline{E}_m + \upsilon_i \overline{E}_i \quad (2)$$

Here $\overline{E}_w$, $\overline{E}_i$, $\overline{E}_m$ are average humidity in single phase liquid and ice, and genuinely mixed phase clouds, respectively; υ_w, υ_i, υ_m are volume fractions ($\upsilon_* = V_* / \Delta V$) of liquid, ice, liquid and mixed phase clouds, respectively; V_* is the volume of cloud regions (ice, liquid or mixed phase) sampled in a cloud with volume ΔV. The cloud volume fractions are normalized so, that $\upsilon_w+\upsilon_i+\upsilon_m=1$. It can be shown (Russ and Dehoff 2000) that for random samples $\lim_{\Delta L \to \infty} L_* / \Delta L = V_* / \Delta V$, where L_* is the length of cloud regions (ice, liquid or mixed phase) sampled along the cloud with the total length ΔL. Since in-situ techniques do not allow measurements of V_*, the ratio $L_* / \Delta L$ is used for estimation of υ. Therefore, Eq.2 can be rewritten as

$$\overline{E} = \lambda_w \overline{E}_w + \lambda_m \overline{E}_m + \lambda_i \overline{E}_i \quad (3)$$

Here λ_w, λ_i, λ_m are spatial fractions ($\lambda_* = L_* / \Delta L$) of liquid, ice, and genuinely mixed phase clouds, respectively, and $\lambda_w+\lambda_i+\lambda_m=1$.

As was found from a theoretical analysis (Korolev and Mazin 2003) and in-situ observations (Korolev and Isaac 2006) the vapor pressure in liquid and genuinely mixed clouds is close to saturation with respect to water, i.e. $\overline{E}_w = E_{ws}$ and $\overline{E}_m = E_{ws}$. Substituting $\overline{E}_w$, $\overline{E}_w$ in Eq.3, and taking into account that $\lambda_w+\lambda_m=1-\lambda_i$ yields

$$\overline{E} = (1-\lambda_i) E_{ws} + \lambda_i \overline{E}_i \quad (4)$$

Eq.4 can be rewritten in terms of relative humidity with respect to water as

$$\overline{RH}_w = (1-\lambda_i) 100 + \lambda_i \overline{RH}_{wi} \quad (5)$$

where $\overline{RH}_{wi}$ is the average relative humidity with respect to water in ice clouds.

Korolev and Isaac (2006) found that in ice cloud, the vapor pressure does not necessarily equal to saturation over ice, but it varies between saturation over water and that over ice, and in many cases it can be undersaturated with respect to ice. Based on the results obtained in Korolev and Isaac (2006) $\overline{RH}_{wi}$ at temperatures $-45<T<0$C can be parameterized as

$$\overline{RH}_{wi} = a_3 T^3 + a_2 T^2 + a_1 T + a_0 \quad (6)$$

Here $a_3 = 7.529*10^{-5}$; $a_2=1.408*10^{-2}$; $a_1=0.8897$; $a_0=99$; T is in degrees Celsius, and $\overline{RH}_{wi}$ is in %. Figure 2 shows measured and parameterized relative humidity in ice clouds. Eqs. 5 and 6 yield the parameterization of the average relative humidity in conditionally mixed phase clouds.

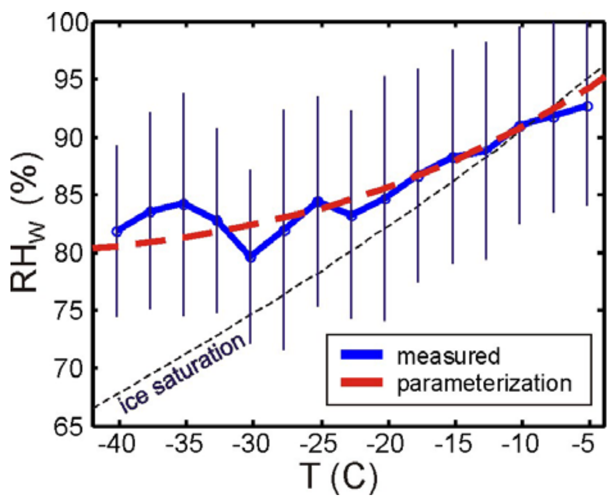

Figure 2. Average relative humidity with respect to water in ice clouds versus temperature. The red dashed line indicates the parameterization of Eq.6. Vertical lines indicate the standard deviation of the measurements. The data adapted from Korolev and Isaac (2006).

In the following sections we compare the humidity parameterization described by Eqs. 5 and 6 with that obtained from in-situ measurements in mixed phase clouds at different spatial scales.

3. Instrumentation and data set

The measurements of humidity in clouds with different phase composition were conducted using the National Research Council (NRC) Convair-580. A detailed description of the instrumentation, accuracy issues and data processing is provided in Korolev and Isaac (2006). Below we briefly describe the probes used in this study for measurements of humidity and characterization of cloud microphysics.

The air temperature was measured by the Rosemount total-air temperature probe (model 102DJ1CG). The water vapor concentration was measured by a Licor HO_2 analyzer (model LI-6262, LI-COR Inc.). The liquid water content (LWC), the ice water content (IWC) and the ice water fraction (μ=IWC/(LWC+IWC)) were deduced from the measurements of the Nevzorov probe (Korolev et al. 1998). Concentration and sizes of cloud droplets were measured by two PMS (Particle Measuring Systems) FSSP-100s (Forward Scattering Spectrometer Probe) (Knollenberg, 1981), operated in the size ranges 3 - 47 μm and 5 - 95 μm. Large cloud particles were measured by 2D-imaging optical array probes (OAP): PMS OAP-2DC (25 - 800 μm); a PMS OAP-2DP (200 - 6400 μm) (Knollenberg, 1981) and the SPEC Inc. High Volume Spectrometer Precipitation Spectrometer (HVPS) (200μm-4cm) (Lawson et al. 1998). All three instruments provided shadow binary images and concentrations of hydrometeors within their respective size ranges. The Rosemount Icing Detector (RICE) was used for identifying the presence of liquid phase in clouds with LWC>0.01g/m^3 (Cober et al. 2001; Mazin et al. 2001).

The Licor probe was calibrated every flight in liquid clouds such that the dew point deduced from its measurements was forced to be equal to the air temperature. The accuracy of the RH measurements utilizing this technique was estimated as 1% (Korolev and Isaac 2006). The Nevzorov IWC measurements were affected by bouncing of ice particles from the TWC sensor cone, which resulted in the underestimating of IWC. The IWC measurements were corrected for the ice bouncing following Korolev et al. (2008).

Because of the residual effect of ice on the Nevzorov LWC sensor, ice particles may mask the presence of a small amount of liquid water in mixed clouds. In order to reduce ambiguity in identifying low LWC in mixed clouds, the RICE probe was used as a detector of clouds with LWC>0.01g/m^3. Based on this, liquid and mixed clouds were defined from the Nevzorov and RICE measurement using the following conditions: if the ice water fraction μ<0.1, then the cloud was considered liquid; if 0.9≥ μ ≥0.1 and then the cloud was considered as mixed phase. Clouds with the concentration of ice particles N_{ice}>10m^{-3} and LWC<0.01g/m^3 were determined as ice clouds.

The data were collected during three field campaigns: FIRE.ACE in April 1998 over Canadian North and Arctic Ocean, and the Alliance Icing Research Study projects (phases 1.5 and 2) over Southern Ontario and Quebec during two winter seasons 2002/03 and 2003/04 (Isaac et al. 2001 and 2005). The bulk of the data was sampled in stratiform clouds (*St, Sc, Ns, As, Ac, Ci*), associated with frontal systems. The measurements were averaged over 1-second time intervals, which correspond to the spatial resolution of approximately 100m at the Convair-580 airspeed. The total number of flights included in the analysis is 36, with the total in-cloud portion analyzed here being approximately 22,840 km. The temperature was limited to the range -5^{o}C to -45^{o}C. The altitude of measurements ranged from 0 to 7 km.

4. Results

The data analysis of the relative humidity started from segregating cloud and cloud free regions. All cloud free measurements were excluded from the analysis. Then the clouds were sorted by temperature in three sub-ranges -35<T<-20^{o}C, -20<T<-10^{o}C and -10<T<-5^{o}C. After that the newly formed cloud regions were arranged in a sequence one after another in each temperature sub-range. The relative humidity, IWC, and LWC were calculated as a moving average with spatial windows 1km, 5km, 10km, 20km and 50km.

Figure 3 shows $\overline{RH}_w$ versus spatial ice cloud fraction λ_i in conditionally mixed phase clouds. The computation was done for different averaging scales in three temperature intervals. The two dashed lines indicate the theoretical values for $\overline{RH}_w$ calculated from Eqs.5 and 6 for minimum and maximum temperatures corresponding to each of the diagrams. As seen from Fig.3 the relative humidity $\overline{RH}_w$ decreases with an increase in the spatial ice fraction. The slopes of the $\overline{RH}_w$ curves are in

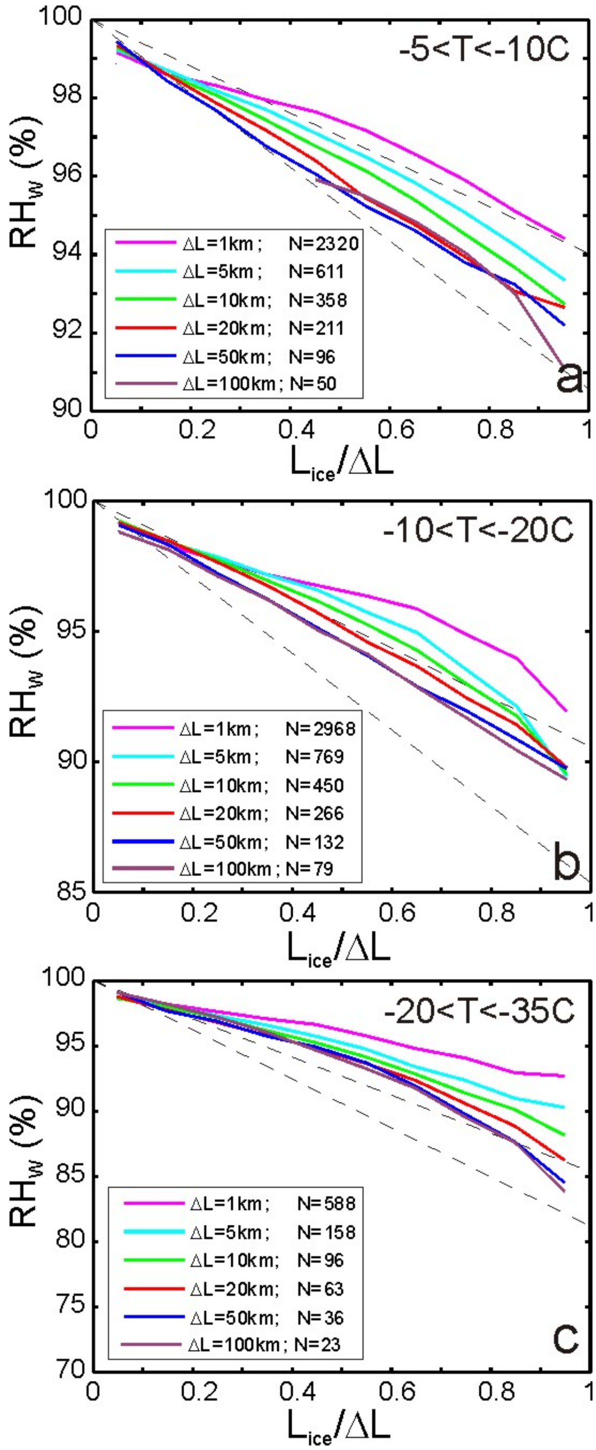

Figure 3. Relative humidity in conditionally mixed phase clouds versus ice cloud spatial fraction ($\lambda_i = L_i / \Delta L$). Dashed lines indicate the parameterization of RH_w based on Eqs. 5 and 6 for minimum and maximum temperatures corresponding to each diagram.

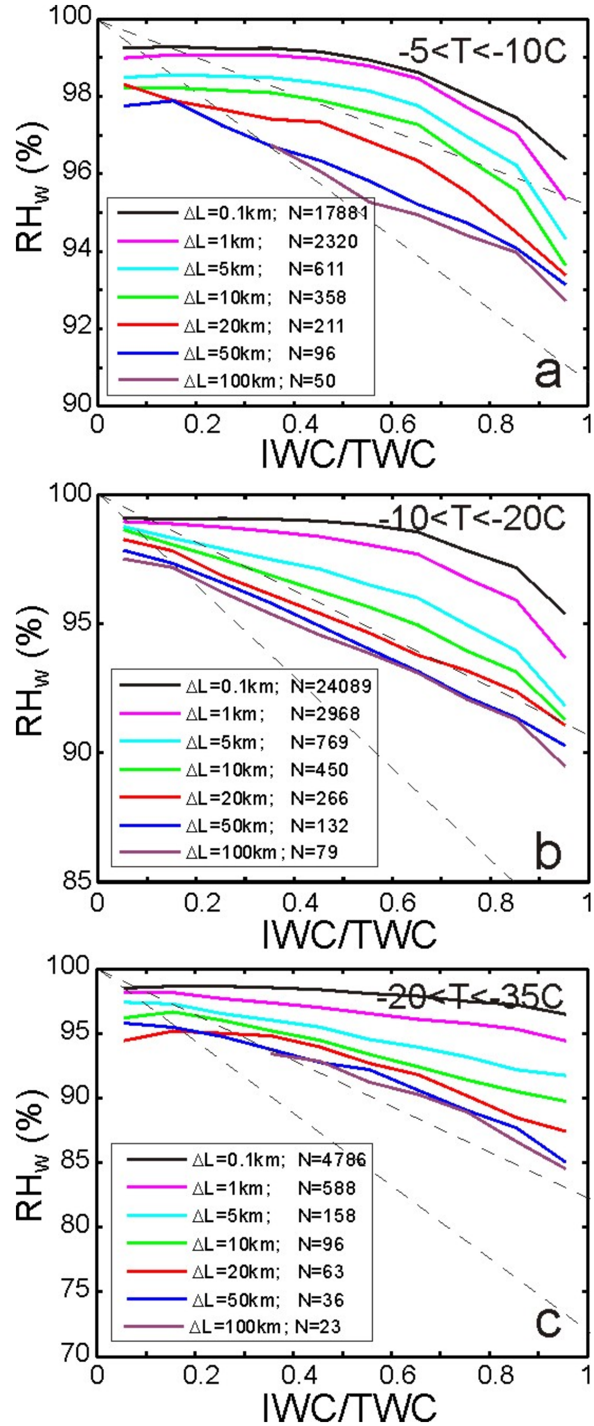

Figure 4. Relative humidity in mixed phase clouds versus ice mass fraction ($\mu_i = IWC / TWC$). Dashed lines indicate the parameterization of RH_w based on Eq. 7 for minimum and maximum temperatures corresponding to each diagram.

general agreement with that predicted by Eqs.5 and 6 (dashed lines). Fig.3 also indicates that the average relative humidity decreases when the spatial averaging increases from 1 to 20 km. However, for ΔL=50 and 100km the $\overline{RH}_w$ curves are grouped close to each other. Such behavior suggests that at the spatial scale 1 to 20km the humidity is higher in the vicinity of liquid and mixed phase clouds. Such an increase of the humidity may occur due to the horizontal transport of water vapor. At a spatial scale ΔL>50km the clouds becomes more homogenized and an increase in averaging scale does not result in changes in $\overline{RH}_w$.

Figure 4 shows $\overline{RH}_w$ versus mass ice water fraction μ_i in mixed phase clouds in three temperature intervals and different averaging scales. Two dashed lines indicate theoretical values for $\overline{RH}_w$ calculated for minimum and maximum temperatures corresponding to each of the diagrams from equation

$$RH_w = (1-\mu_i)100 + \mu_i RH_{wsi} \qquad (7)$$

Here $RH_{wsi} = 100 E_{is}/E_{ws}$ is the relative humidity over water at saturation over ice, $\mu_i = IWC/TWC$ ice mass fraction, *TWC*=*IWC*+*LWC* is the total water content.

The general behavior of the mass weighted $\overline{RH}_w$ is generally the same as that for the spatial weighted $\overline{RH}_w$. However, simple visual comparison of Figs 3 and 4 indicate that the mass weighted $\overline{RH}_w$ have less slope and deviate more from the theoretical values than spatial weighted $\overline{RH}_w$.

In sake of better interpretation of Figs 3 and 4 it should be noted that the value of the spatial ice fraction λ_i gives an unambiguous answer whether the cloud is genuinely (λ_i=0) or conditionally (0<λ_i<1) mixed. However, the ice mass fraction μ_i does not allow any conclusions about type of mixed phase clouds. Preliminary results based on the analysis of the spatial inhomogeneity of mixed phase regions enable conclusion that most data points shown in Fig.4 for ΔL>5km are related to conditionally mixed phase clouds.

5. Conclusion

In the frame of this study we found that parameterization of the humidity weighted by spatial ice fraction agrees better with the results of in-situ measurements than humidity parameterization weighted by ice mass fraction

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