2.5 PARAMETERIZATION OF LIQUID FRACTION IN TERMS OF TEMPERATURE AND CLOUD WATER CONTENT IN STRATIFORM MIXED PHASE CLOUDS

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1. INTRODUCTION

The radiative properties of clouds can be altered in the presence of ice crystals (*Foot*, 1988, *Sun and Shine* 1994). *When* supercooled cloud droplets and ice crystals coexist in a given cloud, the ice crystals can grow rapidly to initiate precipitation. Supercooled drops may coexist with ice crystals in clouds at temperatures as low as –40 °C (*Sassen* 1992). A modeling study by *Sun and Shine* (1994) show that the radiative properties of clouds are very sensitive to how the clouds are assumed to be mixed. Generally, a definition of 'mixed phase cloud' is taken to be a cloud with liquid and ice co-existing. However, ice crystals may be embedded in super-cooled liquid layers (*Heymsfield et al.* 1990) or a supercooled liquid layer may be topped by a glaciated layer (*Rauber and Tokay* 1991). Such distributions of liquid and identification of cloud mixing can be important for parameterization of cloud phase in small-scale models. For the scale of general circulation models, however, ensembles of clouds may exist in a mixture of phases, thus such distinctions of cloud phase may not be that important. Usually, liquid fraction (f_L) is defined as

$$f_L = \frac{LWC}{IWC + LWC}, \tag{1}$$

where LWC is the liquid water content and IWC is the ice water content. There have been some studies of LWC and IWC from in-situ aircraft measurements (*Cober et al*. 2001; *Boudala et al.* 2002; *Korolev et al.* 2002). However, there have been few studies of their ratios in mixed phase clouds (e.g. *Smith* 1990; *Sun* 1995; *Bower et al*. 1996; *Moss and Johnson* 1994, *Korolev et al.* 2002; *Cober et al*. 2001). *Smith* (1990) developed a parameterization of liquid fraction as a function of temperature based on in-situ aircraft measurements for application in the UK

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Meteorological Office Atmospheric General Circulation Model (UKMO AGCM). In this scheme, it is assumed that all clouds are liquid at temperatures greater than 0 and all ice at temperatures lower than -15°C. *Bower et al.* (1996) have parameterized liquid fraction as a function of temperature for convective and frontal clouds separately based on limited in-situ aircraft measurements. However, the parameterization of liquid fraction has been very difficult mainly because of large uncertainties in the determination of cloud water contents and the separation of cloud water phases. Derivation of IWC in mixed phase clouds, based on ice particle spectra measured using two dimensional optical array probes such as the PMS 2D-C and 2D-P, is particularly problematic. This is partly because the circular images of cloud particles can be either water droplets or ice crystals, and small ice particles (D<100um) may not be reliably measured. Another difficulty is related to how to determine the ice particle mass from its 2D image. *Tremblay et al. (1996)* parameterized liquid fraction in terms of temperature, total water content (TWC), and vertical velocity. Their work suggests that a parameterization of liquid fraction as a function of temperature alone may be questionable. It is worth noting, in their scheme all clouds are assumed to be glaciated for temperatures less than –20°C and all liquid for temperatures greater than 0 °C which may not always be true.

The aim of this work is to develop an accurate parameterization of liquid fraction in terms of temperature and cloud water content measured in stratiform clouds containing an ensemble of phases.

2. MEASUREMENTS

The data were collected during five projects which are described below. The National Research Council (NRC) Convair-580 aircraft was used in all five projects. The Beaufort and Arctic Storms Experiment (BASE) field project was conducted in October 1994 over the Canadian Western Arctic (*Gultepe et al*. 2000). The FIRE Arctic Cloud Experiment (FIRE.ACE) project began in April 1998 and ended in July 1998, with the Convair-580 measurements being made in April (*Curry et al*. 2000). The First Canadian Freezing Drizzle Experiment (CFDE I) project was conducted in March 1995 over Newfoundland and the Atlantic Ocean. The Third Canadian Freezing Drizzle (CFDE III) started in December 1997 and ended in February 1998. During CFDE III, the aircraft flew over Southern Ontario and Quebec, Lake Ontario and Lake Erie (*Isaac et al*.

2001a; Cober et al. 2001). The Alliance Icing Research Study (AIRS) was conducted between 29 November 1999 and 19 February 2000 (*Isaac et al*. 2001b).

The types of instrumentation used in these projects are described in *Isaac et al*. (2001a, 2001b). The instruments used for this work are the Nevzorov liquid water content (LWC) and total water content (TWC), and the PMS 2D-C and 2D-P probes, which measure size, shape and concentration of hydrometers. The temperature has been measured with a Rosemount temperature probe.

The 2D-C images were processed following a *center in* scheme. This scheme includes all partly imaged particles that have their centers within the sampling area. Their sizes are determined by reconstruction of their shapes assuming circular geometry (*Cober et al. 2001*). The 2D-P images are processed following an *entire-in* scheme *(Knollenberg 1970).* This method is based on ignoring any particle that occludes either end of the photodiode array.

Korolev et al. (1998) describe the Nevzorov TWC/LWC probe. The probe has two separate sensors (hot wires), one for total water content (TWC) and the other for liquid water content (LWC) measurements. Comparison measurements made with Nevzorov and similar types of probes in high speed wind tunnel experiments suggests that the probe can measure LWC and TWC within an accuracy of 15% and the sensitivity of the instrument is estimated to be in the range of 0.003 to 0.005 $g\,m^{-3}$. The Nevzorov LWC responds to ice crystals in glaciated or mixed phase clouds and this response is estimated to be about 15% of the IWC measurements (*Cober et al.* 2001). For the mixed phase cloud case, the Nevzorov LWC may be corrected for this error by solving two simultaneous equations following Cober et al. (2001) as

$$\begin{aligned} LWC &= TWC_{Nev} - IWC \\ LWC &= LWC_{Nev} - 0.15 IWC, \end{aligned} \qquad (2)$$

where LWC_{Nev} and TWC_{Nev} are the LWC and TWC measured with Nevzorov probe respectively. To the first order, all clouds are assumed to be mixed if the calculated liquid fractions from the Nevzorov TWC/LWC probe measurements are between 0.15 and 0.85. The Rosemount icing detector and 2D images are used to further identify the phase of clouds as liquid, mixed or glaciated. The threshold value for the Nevzorov TWC measurements is assumed to be 0.01 $g\,m^{-3}$.

3. LIQUID FRACTION

Fig. 1 Shows liquid fraction averaged for every $2\,^{o}C$ temperature interval of 30s averaged data plotted against temperature. The data shown in the figure includes all the data CFDE I, CFDE III, FIRE.ACE, and AIRS and the mean standard deviation (MSD) of the calculated liquid fraction was 0.35. The standard deviation for individual points can be smaller or larger than the MSD, in any case, the calculated MSD is quite large because of a considerable scatter in f_L based on 30s average data. This indicates the significant variability observed in the degree of glaciation in a given cloud and temperature. No apparent relationship between f_L and temperature can be found based on 30s averaged data, but for the temperature averaged data, f_L generally increases with increasing temperature. It is worth noting the small minimum in liquid fraction between temperatures about –2.5 °C and – 8°C. This area is normally associated with secondary ice multiplication due to ice splintering during riming of large particle such as graupel (Hallett and Mossop 1974) or chattering of symmetrically freezing of large droplets (*Mossop and Wishart* 1978; *Griggs and Choularton* 1983).

In the presence of supercooled drops in a cloud, the ice crystals can grow at the expense of the drops due to the flux of water onto the ice surface. This is because the vapor pressure over the liquid surface is higher than that over an ice surface. The maximum ice crystal growth rate occurs near –14 °C (*Pruppecher and Klett,* 1997) which may partly explain the significant minimum in liquid fraction near –15 °C. These processes are believe to be more active in stratiform clouds than in convective clouds (*Bower et al. 1996*). Another microphysical process that may be operating in this temperature region is secondary ice multiplication due to water droplets shattering during freezing or fragmentation of dendritic crystals (*Vardiman* 1978) as suggested by *Bower et al.* (1996).

Ice particle concentrations measured with PMS 2D probes during the four projects (CFDE I, CFDE III, FIRE.ACE, and BASE) are shown in Fig. 2. Generally, there is no strong evidence suggesting a dependence of ice concentration on temperature and this is consistent with the previous observation of *Gultepe et al.* (2001) using the same data.

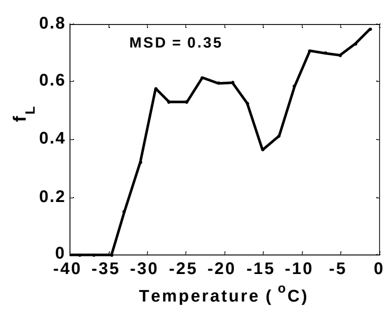

Fig. 1. The 30s averaged liquid fraction was averaged for every 2 °C temperature interval and plotted against temperature.

As shown in Fig. 2, although there are some indications of high ice crystal concentrations during some measurement periods, the mean ice crystal concentrations are not significantly higher than in temperature regions where ice multiplication might occur. *Cober et al.* (2001) have shown similar trends based on ice crystal concentrations (D>100µm) measured during CFDE I and CFDE III projects. It should be noted that the data shown in Fig. 2 include all clouds and some of the clouds at the same temperature may not be favorable for ice multiplication process. It is also worth noting the fact that small particles were not included in the analysis which may contribute significantly to the measured ice crystal concentrations. Therefore, further investigation is required to understand the microphysics responsible for some the changes in liquid fraction shown in Fig. 1.

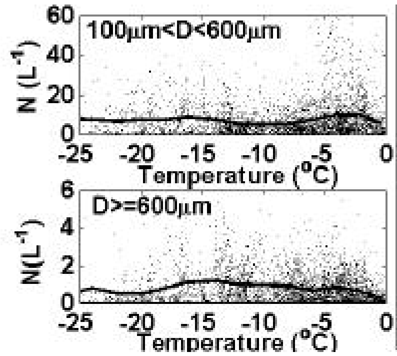

Fig. 2. Ice crystal concentration plotted with temperature. See also *Gultepe et al*. (2001).

As indicated in Fig. 3, f_L increases with both increasing super cooled LWC and TWC. Therefore, a parameterization of f_L as a function of both temperature and TWC or LWC seems to be more reasonable as suggested by *Tremblay et al*. (1996). Note that Tremblay et al. have included vertical velocity in their parameterization. In this work, however, this parameter is not included in the parameterization because of the absence of accurate measurements of that quantity. However, a parameterization given in the form

$$f_{LP} = k_1 TWC^{k_2} \exp(k_3 T) \begin{bmatrix} k_1 = 1.00 \\ k_2 = 0.107 \\ k_3 = 0.035 \end{bmatrix} \qquad (3)$$

captures the variability of the mean f_L with correlation coefficients (r^2) of 0.7. The constants k_1, k_2 and k_3 are determined from data fitting, T is the temperature in °C (see Fig. 4). As indicated in Fig. 4, the parameterization, overestimates (underestimates) at the lower(higher) measured liquid fraction. Fig. 5 shows f_L plotted against the TWC for various temperature intervals. For a given TWC, the proportion of super cooled liquid water decreases with decreasing temperature and this is consistent with the *Tremblay et al*. (1996) parameterization. However, the ice fraction ($1 - f_{LP}$) decreases with increasing TWC and this is contrary to finding of *Tremblay et al*. (1996). In principle, however, the TWC in glaciated cloud does not go to zero. Therefore, when liquid fraction goes to zero, TWC should approach the IWC, thus this effect will be considered in the next stage of this research. The maximum 30s averaged liquid fraction and TWC measured at given temperature is shown by an arrow. This line provides a possible limit for applicability of the parameterization in large scale models. It should also be mentioned that there are few measurements made near -40^o C, so the relationship should be used cautiously near that temperature. No liquid water was observed at temperatures near -40^o C.

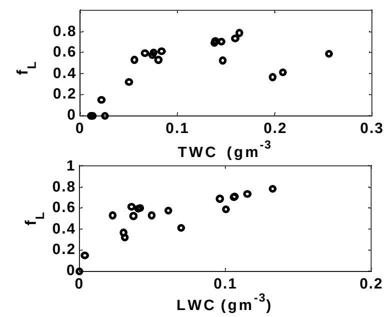

Fig. 3. The liquid fraction is plotted against the measured LWC and TWC with Nevzorov TWC/LWC probes. This data was corrected using Eq. 2.

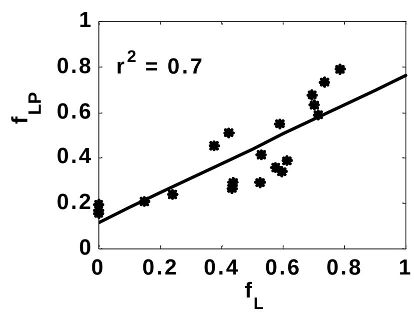

Fig. 4. The parameterized liquid fraction plotted against the measured liquid fraction.

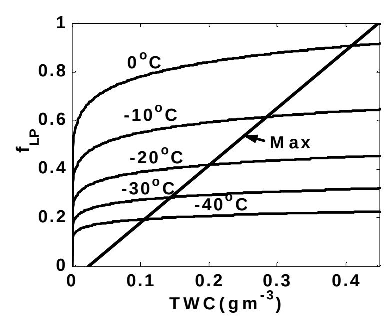

Fig. 5. The parameterized liquid fraction plotted against arbitrary TWC for 10 °C temperature interval, maximum measured values at given temperature interval are indicated by an arrow.

4. SUMMARY AND CONCLUSION

A parameterization of liquid fraction as a function of temperature and TWC has been developed, using more than 10,790 30s averaged data points covering about 32,370 km in cloud aircraft measurements made in the geographical region extending north of latitude 45°N. The parameterization correlates well with the calculated liquid fraction from the observed data (see Eq. 3). Generally this work indicates that f_L increases with, increasing TWC, LWC, and temperature. Particularly, the parameterization of f_L shows a strong relationship with temperature at high TWC or LWC, but at low TWC or LWC, f_L is mostly determined by TWC or LWC.

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