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Visibility Parameterization For Forecasting Model Applications

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Abstract
In this study, the visibility (Vis) parameterizations developed during Fog Remote sensing And Modelling (FRAM) projects, conducted in central and eastern Canada, and Barrow, Alaska, US will be summarized and their use for forecasting/nowcasting applications will be discussed. Parameterizations developed for reductions in visibility due to 1) fog, 2) rain, 3) snow, and 4) relative humidity (RH) during FRAM will be given and uncertainties in the parameterizations will be discussed. Observations used in this study were obtained using a fog measuring device (FMD) for fog parameterization and a Vaisala all-weather precipitation instrument called FD12P for rain and snow visibility parameterizations.

1. Introduction
Because fog can form over time and space scales of minutes and meters, high-resolution models have been developed to better nowcast fog [1]. Unfortunately, high-resolution models are not always available; therefore, visibility parameterizations have been used in forecasting models. Gultepe et al [2] performed three field projects to study warm fog conditions and developed microphysical parameterizations suitable for application to fog and precipitation measurements. Presently, visibility parameterizations related to the precipitation type in forecast models are not adequate because they represent mid-latitude cloud systems [3]. Some previous work concerning snow visibility (Vis) has shown that particle phase is an important factor in the visibility calculation but usually it is ignored [4]. The objective of this work is to summarize the relationships of Vis versus RH with respect to water (RH_w), fog liquid water content (LWC) or ice water content (IWC), and precipitation rate (for rain; PR_R or snow; PR_S); these parameters were obtained using surface observations. Also, Vis versus both droplet (ice) number concentration ($N_d(N_i)$) and LWC (IWC) were derived for non-precipitating boundary layer conditions.

2. Observations
Surface observations during the FRAM field project were collected 1) at the Center for Atmospheric Research Experiments (CARE) site near Toronto, Ontario and Pearson Airport in Toronto, Ontario during the winter of 2005-2006 (FRAM-C), 2) in Lunenburg, Nova Scotia during the summers of 2006 and 2007 (FRAM-L), 3) at the DOE ARM NSA site, Barrow, Alaska in the April of 2008 during the Indirect and Semi-Direct Aerosol Campaign (ISDAC) field program (called ISDAC-FRAM-B), and 4) at the Mirabel Airport from 3 November 2003 to 12 February 2004 during the Alliance Icing Research Study (AIRS 2; [5]). The main observations used in the analysis were fog droplet spectra from a FMD (DMT Inc.), Vis and PR from the VAISALA FD12P all-weather precipitation instrument, and RH_w together with temperature (T) from the Campbell Scientific HMP45 sensor. Figures 1 and 2 show ice fog and time series of the FD12P measurements [6].

3. Analysis and Results
In this work, the Vis (from FD12P) values were compared to RH_w, and PR for snow and rain (from FD12P). The FMD-based Vis was compared to fog LWC and N_d (also for IWC and N_i).

The extinction parameters (β_{ext}), using Koschmieder's Law and assuming a brightness contrast threshold (ε) of 0.05, is converted to Vis as follows:

$$Vis = -\ln(0.05)\beta_{ext}^{-1} . \qquad (1)$$

The FD12P measurements are then used to obtain 1-min averaged values of Vis. In this work, the simulations from the Canadian GEM and US Rapid Upper Cycle (RUC) models are used for Vis comparisons. The RUC uses the parameterizations [7] given for snow, rain and fog visibility calculations. The Canadian Global Multiscale (GEM) Numerical Weather Prediction (NWP) model uses the results from the current work.

3.1 Visibility versus RH_w
The relationship between Vis and RH_w determined from a few field campaigns are shown in Fig. 3 and Table 1 where RH_w is between 30 and 100%. In general, the Vis obtained from the RUC model near RH_w=100% is about 2 times smaller than the Vis values obtained from the other data sets. Note that the total Vis in a numerical model is obtained using both Vis-RH_w and the Vis-PR relationships.

3.2 Visibility parameterization for fog
Visibility versus particle number concentration for a fog type has always been ignored in forecast models [2;6;8]. Using state of the art observations of N_d and N_i from new optical probes, such as DMT FMD, Vis versus N_d, and Vis

versus N_i as well as the best fits are shown in Figs. 4a and 4b, respectively. These relationships are obtained as

$$vis_{Nd} = 238 N_d^{-1.31} \quad (2)$$

and

$$vis_{Ni} = 18 N_i^{-0.56}, \quad (3)$$

where Vis is in [km], N_d and N_i are in [cm^{-3}]. These equations are given here to emphasize the importance of the number concentration for Vis calculations.

The aircraft in-situ observations are used to develop a parameterization for fog Vis [2] that is based on both LWC and N_d. Figure 4c shows Vis versus f(LWC;N_d). Using information that Vis decreases with increasing N_d and LWC, an empirical relationship between Vis_{obs} and $(LWC.N_d)^{-1}$ (Fig. 4c) called the "fog index" using FRAM-L observations collected at the surface is determined as

$$Vis_{obs} = \frac{0.8771}{(LWC \cdot N_d)^{0.49034}}. \quad (4)$$

This empirical fit suggests that Vis is inversely related to both LWC and N_d.

The Vis parameterization for ice fog conditions can be challenging because of unknown ice crystal number concentrations and its shape when ice crystal sizes are smaller than 100 micron. The FMD measurements from the 3 day ice fog event (April 9-11 2008) occurred during ISDAC in Barrow, Alaska are used for Vis [km] versus N_i [cm^{-3}] relationship; then Vis versus ice fog index is obtained as

$$Vis_{obs} = \frac{0.242}{(IWC \cdot N_i)^{0.5147}} \quad (5)$$

where IWC has unit of [$g\ m^{-3}$]. Note that these equations are obtained using FMD measurements at T~-18°C and RH_i>100%. The uncertainty in N_i and IWC can be very large.

3.3 Vis versus PR for rain

The Vis-PR_R observations from FRAM-L are shown in Figure 5 and the corresponding percentile fits to this data are given in Table 2. These equations given in Table 2 as a function of PR_R can be used in model simulations, depending on the rain type as follows: Using the rain rate classification (heavy rain fall: PR_R >7.6 mm h^{-1}, moderate rain fall: 2.6 mm h^{-1}<PR_R<7.5 mm h^{-1}, and light rain fall: PR_R<2.6 mm h^{-1}; [9]), the 5% fit equation curve may be used to estimate Vis when heavy rain precipitation occurs and the 95% curve can be used for Vis calculations under the light precipitation conditions.

3.4 Vis versus PR for snow

The results from the FRAM projects are presented in Figure 6 with T<-1°C, representing snow conditions. Overall, a trend for snow conditions exists with decreasing Vis for higher precipitation rates but the variability is large. Some of the data points (red dots) just above the snow condition points (black dots) are for wet snow conditions and this needs to be further researched. It should also be stated that PR_S less than 0.1 mm h^{-1} are not reliable due to sampling issues.

Using the FD12P measurements without considering specific particle density and type, Vis-PR_S relationships depending on snow type (heavy snow fall: PR > 2.5 mm h^{-1}, moderate snow fall: 1 mm h^{-1} < PR < 2.5 mm h^{-1}, and light snow fall: PR < 1 mm h^{-1}; [10]) are given in Table 3. For example, when heavy snow precipitation occurs, the 5% fit equation (Table 3) can be used to estimate Vis. It can be seen that 50% of the observed points are found above or below the 50% fit.

3.5 Integrated Vis

Next, equations given for Vis-PR_R in Table 2 combined with Vis-RH_w parameterizations given in Table 1 can be used to obtain integrated Vis values. In the case of both fog and precipitation occurring together: first, the calculated Vis values (with respect to RH_w, fog LWC, and PR_R) are converted to extinction coefficients using Eq. (1) and, then, an integrated extinction coefficient is obtained [4] as

$$\beta_{int} = \beta_{RHw} + \beta_{LWC} + \beta_R. \quad (6)$$

The final value of Vis is then calculated using (1) which utilizes β_{int} from (6). Note that the conditions set for the probability curves need to be tested for various geographical regions because of varying characteristics of CCN related to their composition and hygroscopicity.

3.6 Application

For a fog event that occurred on 11 Feb 2009 (Figs. 7a and 7b), the derived equations are applied to model runs. Figure 7c shows Vis obtained from the probabilistic parameterizations (e.g. 5%, 50%, and 95% curves), a RUC model forecast run, and an integrated fog parameterization. The results compare well with observed FD12P Vis. Integrated Vis values (black circles filled with yellow color) are found comparable to the observed Vis (green line) between 1400 UTC and 1830 UTC, and to RUC Vis (blue line with triangles) after 1500 UTC. In this plot, the GEM model, using the time dependent RH_w, PR_R, and LWC values, is used to predict Vis [11]. In the GEM simulations, LWC within the lowest model layer (<50 m) is assumed to be same as the total water content at warm temperatures.

4. Summary and Conclusions

In the present work, surface observations from the various instruments, measuring N_d, N_i, PR (for rain and snow), Vis, RH_w, and T, were used in the analysis and parameterizations are suggested. Based on the results, the following conclusions can be drawn:

- The relationships previously used in forecast models, especially for RH_w, should not be utilized because of an underestimation of Vis at values close to saturation (Fig. 3). Eq. 4 should replace the previous relationship used in the forecasting models.
- Overall, a large variability in the Vis-PR relationships suggests that these relationships need to be improved, especially for snow.
- The relationships between Vis versus N_d and N_i clearly indicate that number concentration of the particles needs to be considered for parameterizations..
- Applying observation-based parameterizations (e.g. Eq. 4) as an alternative to those based on specific hydrometeor size distribution functions can be used to compute extinction coefficients directly.

These conclusions suggest that the new visibility parameterizations can significantly improve visibility estimates but additional tests utilizing the forecasting models are needed. An ice fog project planned for 2010-2011 winter will further help to develop the new parameterizations based on measurements of a GCIP instrument.

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Fig. 1: An ice fog event occurred over Barrow, Alaska on April 10 2008 during the ISDAC-FRAM-B project.

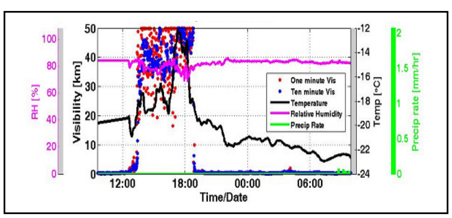

Fig. 2: A time series of RH_w, *Vis*, temperature (*T*), and precipitation rate (*PR*) on April 10 2008 for an ice fog event that occurred during ISDAC.

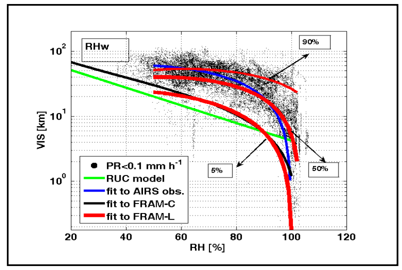

Fig. 3: Summary of FRAM observations for Vis versus RH_w. The black solid line is from the Pearson Airport site during FRAM-C. The green line represents the RUC model parameterization (Smirnova et al., 2000).

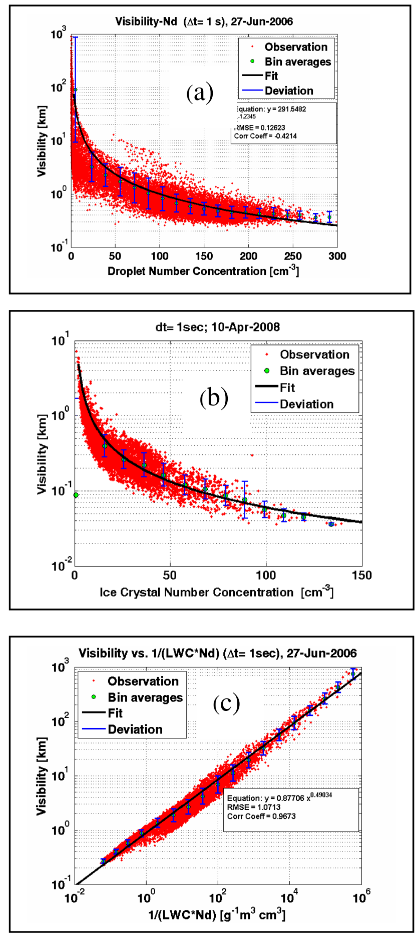

Fig.4: Visibility function of N_d (a) and f(LWC,N_d) (b) for droplets, and Vis- f(*IWC, N_i*) (c) for ice crystals on June 27 2006 and April 10 2008, respectively.

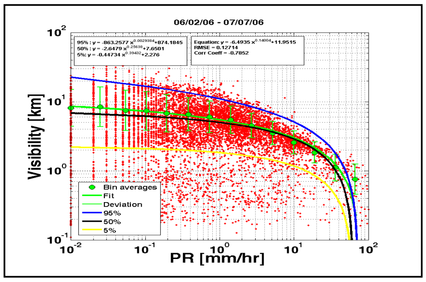

Fig. 5: The Vis versus PR for rain_R from all observations (red dots) obtained during FRAM-L.

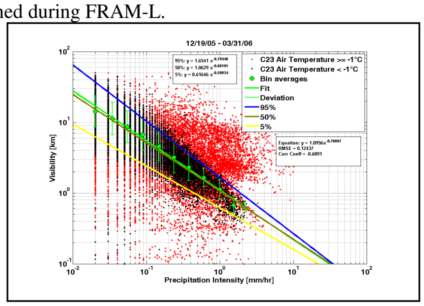

Fig. 6: The *Vis* versus *PR* for snow (black dots) from observations obtained during FRAM (November 2005-April 2006). The red dots are for *T*>-1°C.

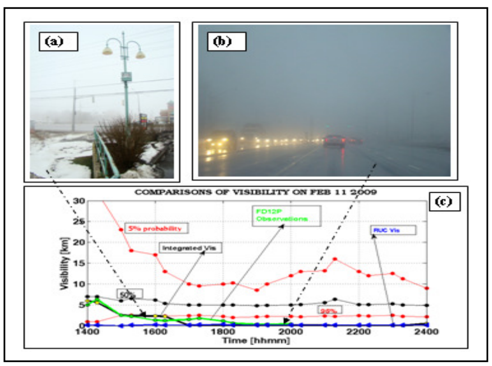

Fig. 7: A heavy fog event at 9:57 AM LST (a) and at 4:48 PM LST (b) on Feb 11 2009 after a heavy rain occurrence (*T*=9°C). Vis versus time is shown in (c).

Table 1: Visibility (*Vis* [km]) versus relative humidity (RH_w).

Percentile %	Vis-RH_w relationships
Mean	$Vis_{FRAM-C} = -41.5\ln(RH_w) + 192.30$
95%	$Vis_{FRAM-L(95\%)} = -0.000114 RH_w^{2.70} + 27.45$
50%	$Vis_{FRAM-L(50\%)} = -5.19*10^{-10} RH_w^{5.44} + 40.10$
5%	$Vis_{FRAM-L(5\%)} = -9.68*10^{-14} RH_w^{7.19} + 52.20$

Table 2: Visibility (*Vis* [mm h^{-1}]) versus *PR* [mm h^{-1}] for rain.

Percentile %	Vis-PR_R relationships
Mean	$Vis_R = -4.12 PR_R^{0.176} + 9.01$
50%	$Vis_R = -2.65 PR_R^{0.256} + 7.65$
95%	$Vis_R = -0.45 PR_R^{0.394} + 2.28$
5%	$Vis_R = -863.26 PR_R^{0.003} + 874.19$
Mean(drz)	$Vis_D = -2.66 PR_R^{-0526} + 6.54$

Table 3: Visibility (*Vis* [mm h^{-1}]) versus *PR* [mm h^{-1}] for snow.

Percentile	Vis-*PRs* relationships
Mean	$Vis_S = 1.10 PR^{-0.701}$
50%	$Vis_S = 1.06 PR^{-0.682}$
95%	$Vis_S = 0.62 PR^{-0.590}$
5%	$Vis_S = 1.65 PR^{-0.795}$

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