1. Introduction

Fog forms over various time and space scales under a variety of meteorological conditions. There have been many studies related to fog forecasting (Smirnova et al., 2000), remote sensing (Gultepe et al., 2007), and observations (Jacobs et al., 2007). Unfortunately, because of the difficulty in measuring fog microphysical parameters e.g., droplet number concentration \(N_d\), liquid water content \(LWC\), and effective radius \(R_{ef}\), the results from previous studies need to be reevaluated. These studies were related to mostly marine fog, radiation fog, and frontal fog conditions. Unfortunately, cold fog conditions (temperature \(Tc\)) have also not been studied in detail as much as warm fog conditions (Gultepe et al. 2007; Gultepe et al., 2008; Bott et al., 1990).

The Fog Remote Sensing and Modeling (FRAM) project was designed to focus on 1) development of microphysical parameterizations for numerical model applications, 2) development of remote sensing methods for fog detection, 3) understanding instrument capabilities and limitations for observations of fog and related parameters, and 4) integration of model and observation data for developing nowcasting applications. The main objective of this paper is to describe a research project on warm and cold fog conditions and visibility forecasting, and to summarize the results that have been obtained to date.

2. Observations

Surface observations during the FRAM field project were collected 1) at the Center for Atmospheric Research Experiment (CARE) site near Toronto, Ontario during the winter of 2005-2006 (Gultepe et al., 2008), 2) in Lunenburg, Nova Scotia during the summers of 2006 and 2007 (Gultepe et al., 2008) and 3) at the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program at the North Slope Alaska (NSA) site, Barrow, Alaska during April of 2008 for the Indirect and Semi-Direct Aerosol Campaign (ISDAC) field program (called ISDAC-FRAM-B) (Gultepe et al., 2008). The main observations used in the analysis are fog droplet spectra from a fog measuring device (FMD; DMT Inc.), visibility (Vis) and precipitation rate (PR) from the VAISALA FD12P all-weather sensor and the OTT laser based optical disdrometer called ParSiVel (Particle Size and Velocity), and relative humidity with respect to water \((RH_w)\) together with temperature \((T)\) from the Campbell Scientific HMP45 sensor. Table 1 summarizes the Environment Canada (EC) instruments available during the ISDAC-FRAM-B project that took place near Barrow, Alaska. Liquid water path \((LWP)\) and liquid water content \((LWC)\) were obtained from a microwave radiometer (MWR; Radiometric Inc.). Fog coverage and some microphysical parameters such as droplet size, phase, and LWP were also obtained from satellites e.g., such as GOES, NOAA, and Terra and Aqua MODIS products (Minnis et al., 2005). Note that not all instruments were available for each phase of the FRAM projects. Details on some of the instruments shown in Fig. 1 used for data collection during the ISDAC-FRAM-B can be found in Gultepe et al. (2007) and are discussed here briefly.

The FD12P Weather Sensor is a multi-variable sensor for automatic weather stations and airport weather observing systems (VAISALA Inc.). The sensor combines the functions of a forward scatter Vis meter and a present weather sensor. Figure 2 shows an example of FD12P measurements for the June 18 2006 case. This sensor also measures the accumulated amount and instantaneous PR for both liquid and solid precipitation, and provides the Vis and precipitation type related weather codes given in the World Meteorological Organization (WMO)
standard SYNOP and METAR messages. The FD12P detects precipitation droplets from rapid changes in the scatter signal. Based on the manufacturer’s specifications, the accuracy of the FD12P measurements for Vis and PR are approximately 10% and 0.05 mm h⁻¹ respectively. The fog-related microphysics parameters e.g. LWC, size, and droplet number concentration (N_d) were calculated from the FMD spectra for both liquid and ice clouds. Although an ice particle counter was available, its measurement size range is likely beyond the upper limit of the typical fog particle size, e.g., 50 μm. For subsaturated conditions, the Climatronics Aerosol Profiling (CAP) probe was used for measuring aerosol size and spectra between 0.3 and 10 μm. In saturated conditions, CAP measures the nucleated particles’ characteristics.

The NOAA AVHRR (and/or GOES) observations were also available during FRAM projects, and some retrieval methods were used to detect fog conditions and its microphysics.

The analyses are divided into four subsections and given below.

a. Warm fog microphysics
Warm fog conditions were observed very often during FRAM-L projects (~35% of time). In many cases, Vis dropped down to less than 100 m (Fig. 2). Here, a case study using observations from both ground-based instruments and satellites is summarized and a parameterization is developed.

The analyses are divided into four subsections and given below.

Table 1: Summarizes instruments available from the Environment Canada during ISDAC-FRAM-B.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Characteristics</th>
<th>FRAM-B/FRAM-L</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) FMD fog monitor</td>
<td>Droplet/ice spectra</td>
<td>&lt;50 μm</td>
<td>√/√</td>
</tr>
<tr>
<td>(2) CIP probe</td>
<td>Droplet/ice spectra</td>
<td>15-860 μm</td>
<td>NA</td>
</tr>
<tr>
<td>(3) CAP aerosol</td>
<td>Droplet/aerosol spectra</td>
<td>0.3-10 μm; 8 channels</td>
<td>√/√</td>
</tr>
<tr>
<td>(4) OTT Distrometer</td>
<td>Droplet/ice particle spectra</td>
<td>400-25000 μm</td>
<td>√/Na</td>
</tr>
<tr>
<td>(5) YU IPC</td>
<td>Particle spectra</td>
<td>30-500 μm</td>
<td>√/Na</td>
</tr>
<tr>
<td>(6) FD12P vis</td>
<td>Vis/precip amount</td>
<td>0.1 mm/h</td>
<td>√/√</td>
</tr>
<tr>
<td>(7) Sentry Vis</td>
<td>Vis</td>
<td>&gt;10 m</td>
<td>√/√</td>
</tr>
<tr>
<td>(8) DMIST Vis</td>
<td>Vis, images, and extinction</td>
<td></td>
<td>√/√</td>
</tr>
<tr>
<td>(9) YES TPS</td>
<td>Precip amount</td>
<td>0.25 mm/h</td>
<td>√/√</td>
</tr>
<tr>
<td>(10) VRG101</td>
<td>Precip amount</td>
<td>0.5 mm/h</td>
<td>√/√</td>
</tr>
<tr>
<td>(11) DSCT11</td>
<td>Precip amount/friction</td>
<td>-</td>
<td>√/√</td>
</tr>
<tr>
<td>(12) DSTT11</td>
<td>Surface temperature</td>
<td>-</td>
<td>√/√</td>
</tr>
<tr>
<td>(13) SR50AT</td>
<td>Snow depth</td>
<td>-45 to 50°C</td>
<td>√/Na</td>
</tr>
<tr>
<td>(14) Eppley IR/SW</td>
<td>Broadband radiative fluxes</td>
<td>10%</td>
<td>√/√</td>
</tr>
<tr>
<td>(15) Campbell RH/T</td>
<td>RH and T</td>
<td>5% and 1°C uncertainty</td>
<td>√/√</td>
</tr>
<tr>
<td>(16) Young Ultra wind</td>
<td>3D wind and turbulence</td>
<td>4-32 Hz sampling rate</td>
<td>√/√</td>
</tr>
<tr>
<td>(17) SPN-1</td>
<td>Radiative flux, cloud cover</td>
<td>0.4-2.7 μm</td>
<td>√/Na</td>
</tr>
<tr>
<td>MWR TP3000</td>
<td>LWC, T, LWP, RH</td>
<td>-</td>
<td>√/√</td>
</tr>
<tr>
<td>Ceilometer</td>
<td>Backscatter, cloud base</td>
<td>-</td>
<td>√/√</td>
</tr>
<tr>
<td>ARM Lidar</td>
<td>Backscatter and Dep. ratio</td>
<td>-</td>
<td>√/Na</td>
</tr>
</tbody>
</table>

Fig. 1: Shows the instrument platform of the DOE ARM NSA site during ISDAC project.

3. Analysis and Results

b. Warm fog microphysics
Warm fog conditions were observed very often during FRAM-L projects (~35% of time). In

Fig. 2: A marine fog event occurred over Lunenburg, NS, Canada on June 18 2006 during the FRAM-L field project.
is based on liquid water content (LWC) and droplet number concentration (Nd). The US current Rapid Update Cycle (RUC) model uses a Vis-LWC relationship for fog visibility (Smirnova et al. 2000; Stoelinga and Warner, 1999). Using information that Vis decreases with increasing Nd and LWC, a relationship between Vis_{obs} and (LWC.Nd)^{-1} called the “fog index” is determined as

$$\text{Vis}_{obs} = \frac{1.002}{(\text{LWC} \cdot \text{Nd})^{0.6473}}. \quad (1)$$

This fit suggests that Vis is inversely related to both LWC and Nd. The maximum limiting LWC and Nd values used in the derivation of (1) are about 400 cm^{-3} and 0.5 g m^{-3}, respectively. The minimum limiting Nd and LWC values are 1 cm^{-3} and 0.005 g m^{-3}, respectively. In (1), Nd can be fixed as 100 cm^{-3} for marine environments and 200 cm^{-3} for continental fog conditions. These values of Nd, which were traditionally used in modeling applications, cannot be valid for all environmental conditions (Gultepe and Isaac, 2004). Examples of the fog microphysical characteristics for June 27, 2008 are shown in Fig. 3. Figures 3a, 3b, and 3c show Vis versus LWC, Nd, and f(LWC;Nd), respectively. Figure 3d shows the fog settling rate versus f(LWC, Nd) that can be used for model verification. Figure 3c suggests that Vis should be a function of both LWC and Nd, not only LWC as in forecasting models (Gultepe and Milbrandt, 2007).

![Figure 3](image)

**Fig. 3**: Visibility function of LWC (a), Nd (b), and f(LWC;Nd) (c), and settling rate versus f(LWC, Nd) (d) on June 27 2006 for a warm fog event case.

b) Cold fog microphysics
The ice fog case during ISDAC-FRAM-B lasted 4 days from April 9 to April 12 2008 (Fig. 4). During this fog event, Vis decreased down to about 100 m and project flights were cancelled. Ice fog forecasting is usually not performed with forecasting models because ice water content (IWC) and ice crystal number concentration (Ni) are not accurately obtained from existing microphysics algorithms. If both parameters were available from a high-resolution fog/cloud model, they could be used for delineating ice fog regions and forecasting Vis. Ice fog occurs commonly in northern latitudes when T is below -15°C. The formation of ice fog usually develops when the RH becomes saturated with respect to ice (RH_i) without precipitation. Ice fog develops because of a deposition nucleation process that depends on nuclei size and concentration, and temperature.
suggested that frost formation on the IPC counter (Table 1) was likely due to condensation of vapor and small ice particles at ice saturation conditions e.g., RH=100%. During this event, several instruments were unable to collect accurate measurements.

Using aircraft observations collected during the First International Regional Experiment-Arctic Cloud Experiment (FIRE-ACE; Gultepe et al. 2008; 2003) found out that the frost point temperature (T\textsubscript{f}) can be related to dew point temperature (T\textsubscript{d}) as:

\[ T_{f} = T_{d} + \Delta f, \]

where T\textsubscript{d} [°C] and T\textsubscript{f} [°C] were obtained using LiCOR instrument humidity measurements (Gultepe et al., 2003) and their difference is parameterized as:

\[ \Delta f = p_{1}T_{d}^{2} + p_{2}T_{d} + p_{3} + p_{4}, \]

where \( p_{1} = 0.000006; \) \( p_{2} = -0.0003; \) \( p_{3} = 0.1122; \) and \( p_{4} = 0.1802. \) If T\textsubscript{d} is known, then T\textsubscript{f} [°C] is calculated using, (2) and (3). The following equation is given for saturated vapor pressure by Murray (1967) as

\[ e_{s} = 6.1078 \exp \left[ \frac{a(T - 273.16)}{(T - b)} \right], \]

where T [K], e [mb], \( a = 21.8745584 \) (17.2693882); \( b = 7.66 \) (35.86) over the ice (water) surface. Then, using T\textsubscript{f} and T\textsubscript{d}, relative humidity with respect to ice (RH\textsubscript{i}) is obtained from the following equation

\[ RH_{i} = \frac{e_{i}(T_{d} + \Delta f)}{e_{s}(T_{f})}. \]

If RH\textsubscript{w} and T are known, then T\textsubscript{d} is calculated using an equation similar to (5) but for water. Using (2)-(5), RH\textsubscript{i} is then calculated. If RH\textsubscript{i} is greater than approximately 95%, T<-10°C, and no precipitation occurs, then ice fog regions can be obtained from a forecasting model. If Ice Water Content (IWC) is prognostically obtained, then Vis for ice fog, assuming that Ni and mean equivalent mass diameter (d) are known, can be calculated as (Ohtake and Huffman, 1969):

\[ Vis = \frac{1}{3} \left[ \frac{3.2 IWC}{N_{i}} \right]^{1/3} - 1.5d. \]

Equation 6 shows how Vis changes with IWC, Ni, and d. In this work, it is suggested that Ni and d can be taken as 200 cm\textsuperscript{-3} and 7.2 μm (for high IWC e.g.>0.1 g m\textsuperscript{-3}), and as 80 cm\textsuperscript{-3} and 4.5 μm (for low IWC, e.g.,>0.01 g m\textsuperscript{-3}). If ice crystals form due to deposition of vapor directly onto ice nuclei at cold T, Ni can be parameterized as a
function of $RH_i$. A relationship between $N_i$ and $RH_i$ for ice fog has not been demonstrated. Note that (6) needs to be verified using measurements from the ISDAC-FRAM-B project. Preliminary results using FRAM-B observations as shown in Fig. 7 suggest the following relationship:

$$Vis = 0.242(N_i IWC)^{-0.52}$$  \hspace{1cm} (7)

In this equation, $Vis$ is indirectly correlated with the product of $IWC$ and $N_i$ that cannot be obtained from the 2DC optical probe measurements when ice crystal sizes $<$ 50 µm (Gultepe et al., 2001). This relationship needs to be further verified with additional observations.

During the ice fog event (April 9-12), NOAA AVHRR images clearly indicated the region of ice fog coverage. The fog did not originate in the same manner as a warm fog because it occurred at $T$ $<$ -20°C and $RH_w$ $\sim$ 80% during which glazed ice was not observed over the instrument surfaces. On April 10 2008, the ARM MPL observations (Flynn et al., 2007) were available and used to confirm the ice fog occurrence. Figures 8a and 8b show the time-height cross section of uncalibrated attenuated aerosol backscatter ratio ($\beta$) and linear depolarization ratio ($\delta$) measured by the ARM polarized MPL on April 10 2008, respectively. Figure 8a shows a very shallow fog layer below about 100 meters. This fog layer shows a high depolarization ratio in Fig. 8b as expected from ice fog. This is consistent with low $RH_e$ values measured by chilled mirror hygrometers mounted at the four different levels along a meteorological tower (not shown) showing negligible LWC during the fog event.

![Vis vs. 1/(IWC*Ni) (delta=1sec), 10-Apr-2008](image-url)

Fig. 7: Vis versus fog index (y-axis) based on observations collected during the April 10 2008 ice fog event from the ISDAC-FRAM-B project.

c) Numerical fog forecasting

Visibility can be estimated by using parameters produced from detailed cloud schemes such as those available in the GEM model. Applying observation-based parameterizations (e.g., Eq. 1) as an alternative to those based on specific hydrometeor size distribution functions can be used to compute extinction coefficients directly. Researchers in Environment Canada are currently working on the implementation of a more detailed two-moment version of the cloud microphysics scheme (Milbrandt and Yau, 2005a; 2005b) to treat grid-scale clouds in the high-resolution version (2.5-km grid-spacing) of the GEM model. In this scheme, both $LWC$ and $N_d$ are independent prognostic variables. This will allow a more flexible application of the visibility parameterization of (1), without the restriction of prescribing a value of $N_d$. A simulation done using the GEM model to obtain $Vis$ based on (1) is shown in Fig. 9. It suggests that improvements in the computed $Vis$ estimates can be improved by 50% (Gultepe et al., 2007).
Fig. 9: Simulated warm fog event using (1) and a double moment microphysical scheme on June 27 2006. It was obtained using a GEM simulation based on a 14 hr forecast valid at 0600 UTC.

d) Satellite retrievals

The remote sensing study of the June 27 warm fog case is performed using 1) Terra MODIS satellite retrievals and 2) GOES and GEM model output work (Gultepe et al., 2007). The retrieval results suggest that integration of satellite observations with model output improved fog forecasting. The $R_{ef}$ obtained from the MODIS observations of ~7 µm over the project site (not shown) were found to be comparable with the FMD measurements (Fig. 10) where median value of $R_{ef}$ is estimated to be 6-8 µm. Figure 11 shows the warm fog area as detected using the integration of GOES observations and GEM model output. In this image, the model-based surface temperature and screen level RH were used in the integration of satellite observations. Gultepe et al. (2007) showed that inclusion of model output in the fog analysis together with satellite observations improved fog detection up to 30% of time.

During the April 10 2008 ice fog case, the NOAA AVHRR RGB image (Fig. 12) showed that ice fog covered a large area over the northern Alaska and Canada. It is optically thin as evident from the visibility of surface features underneath it. The ice fog conditions at the NSA site were characterized using surface observations. In this case, IWC reached to 0.2 g m$^{-3}$ and $Vis$ was less than about 100 m. Further analysis of this case using the retrieval techniques will help us to better detect the ice fog conditions in the northern latitudes.

5. Discussion

To accurately forecast/nowcast fog $Vis$, accurate model output parameters are required, e.g., $LWC$,
If model output values for rain, snow, RH, and LWC are not accurate to better than 20-30%, the uncertainty in Vis can be more than 50% (Gultepe et al., 2006). If fog LWC and \( N_d \) or \( N_i \) are not accurately known from a model at the levels closest to the surface, then Vis based on other parameters e.g., such as PR or RH, or both, cannot be used to obtain accurate Vis values. Fog LWC (or IWC) and \( N_d \) (or \( N_i \)) are the major factors required for accurate Vis calculations and they should be obtained to an accuracy of about 10-20%. Figure 13 shows the measured Vis values from the FD12P and Sentry Vis sensors collected during an ice fog event over the ISDAC-FRAM-B project site. The Vis from the FD12P is comparable to the Sentry Vis sensor especially when Vis is less than 5 km. This suggests that for ice fog conditions both instruments can be used for Vis measurements when Vis is less than 5 km. For the higher Vis conditions, Sentry Vis values are found to be about 30% less than FD12P Vis values but opposite was true when light snow conditions existed during ISDAC project (not shown).

![Fig. 13: Sentry Vis versus FD12P Vis values from an ice fog event over 4 days during ISDAC-FRAM-B field project.](image)

Marine fog nowcasting/forecasting needs detailed surface fog measurements, high-resolution forecasting model outputs, and satellite observations. Integration of the data from various platforms can be used to obtain accurate fog Vis. As shown, satellite retrieved parameters integrated with model output can be very useful for improving fog forecasting skills. Over the Arctic regions, both satellite retrievals and microphysical parameterizations used in numerical models should be tested over various environmental conditions, e.g., over ice surface versus polynyas. To validate ice fog forecasting skills, lidar measurements can be useful for applications because they provide both \( \delta \) and \( \beta \), and the vertical extent of fog conditions.

### 6. Conclusions

The results from the GEM simulations suggest that the microphysics parameterization presented for warm fog, which includes \( N_d \), can improve Vis values obtained from forecasting models. A new microphysical scheme to be used in the GEM limited area model (LAM) (Milbrandt and Yau, 2005a; 2005b) will provide both \( N_d \) and LWC values in a prognostic way that should lead to more accurate calculations of Vis values. The same analogy can also be applied for ice fog conditions.

For ice fog conditions, ice particle shape and size affect Vis as much as number concentration. Particle cross-sectional area (used in the calculation of extinction) of an ice crystal is related to particle habit, which affects Vis significantly. The combination of IWC and ice particle size (or \( N_i \)) can be used for Vis calculations if a particle shape is known accurately.

An ice fog visibility parameterization is suggested for model simulations of Vis at cold temperatures and an ice fog area coverage detection based on a new parameterization of RH, to be used with numerical simulations is also proposed. These can be used in nowcasting/forecasting applications. A new equation is given for the frost point \( T \) calculation that can be used in RH calculation over a model grid area. The ice fog Vis parameterization (Ohtake and Huffman, 1967) needs to be verified and this will be done using the observations obtained during ISDAC-FRAM-B field project.

Remote sensing observations, including those from satellites and lidars data, can be effectively used for model validations and their integration together with surface observations will certainly increase the level of probability of accurate fog detection (Gultepe et al., 2007). Unfortunately, there are not enough statistics to develop detailed ice microphysical parameterizations to be used in
forecasting applications but a future ice fog project in Arctic will be performed to improve the data quality in ice fog conditions.

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