Visual Range in Ice Fog

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ABSTRACT

This article presents the results of an experimental investigation into the relationship between visual range and the size distribution of ice fog particles at Fairbanks, Alaska. An empirical function is developed for the constant appearing in the Trabert formula. Use of this function gives visual ranges that agree with measured values for size distributions of different width.

1. Introduction

In arctic and subarctic climates, cities are frequently covered with dense ice fog during winter. The ice fog appears at temperatures \( \leq -30^\circ C \) in the lowest layer of atmosphere with a thickness ranging from 50–100 m. The ice fog causes many traffic and health problems to inhabitants, as well as hampering airport activities because of poor visibility. Water vapor and pollutants from combustion processes which are injected into this low temperature mass of stagnant air provide the raw material for the development of microscopic ice particles—ice fog. Because of the large concentration of these ice fog particles, a severe restriction in visibility frequently results.

For water fogs and clouds, a relationship between the meteorological visual range and the liquid water content, originally developed empirically by Trabert (1901), has the form

\[
V_m = 1.36 (d/w),
\]

where \( V_m \) is the visual range (meters), \( d \) the mean diameter of the droplets (microns), and \( w \) is the liquid water content (gm m\(^{-3}\)). The constant \( \theta \) is determined by the width of the size (diameter) distribution of droplets and can be computed for spherical droplets by using the scattering coefficients computed from Mie (1908) theory, provided the size distribution is known (from Kampe and Weickmann, 1952). This computation is subjected to possible error due to uncertainty in the correct criterion to be used for defining visibility (Neiburger, 1953). As the distribution becomes narrow, the theoretical value for \( \theta \) approaches unity. However, for droplets several microns in diameter, half of the scattered intensity (that portion scattered by diffraction) lies in a very small solid angle about the forward direction so that an appreciable amount of scattered light enters any actual detector (Johnson, 1954). Thus, the apparent visual range is nearly twice the theoretical value. This effect may be taken into consideration by assigning \( \theta \), in the Trabert formula, a lower bound of 2 instead of 1. Since any real distribution has a finite width, we can expect the empirical value of \( \theta \) to be somewhat greater than 2, the exact value depending on the droplet size distribution. Richardson (1919) has determined it as 2.2 and Köhler (1927) arrived at a value of 2.3.

The present investigation was undertaken to determine if the Trabert formula is also valid for ice fog particles, which are irregular in shape rather than exactly spherical; and if so, what value for \( \theta \) should be used. During several periods of ice fog, the particles were sampled to determine the size distribution, the visual range being measured by a transmissometer or estimated visually. There is known to be a large variability in the width of ice fog particle-size distributions (Huffman, 1968), and for this reason it has been found during the course of the investigation that no constant factor \( \theta \) can, in general, be determined. However, an empirical function relating \( \theta \) to the distribution width has been determined and gives good agreement with the measured visual range when used in Eq. (1).

2. Experiment

Size distributions were obtained from ice fog particles collected during the winter of 1966–67 at Fairbanks,
Table 1. Characteristics of particular observations in Fairbanks area (winter, 1967).

<table>
<thead>
<tr>
<th>Observation</th>
<th>Date</th>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>27 January 1967</td>
<td>2100</td>
<td>-32</td>
<td>Fairbanks downtown</td>
</tr>
<tr>
<td>b</td>
<td>27 January 1967</td>
<td>2330</td>
<td>-34</td>
<td>Fairbanks downtown</td>
</tr>
<tr>
<td>c</td>
<td>28 January 1967</td>
<td>1230</td>
<td>-34</td>
<td>Fairbanks downtown</td>
</tr>
<tr>
<td>d</td>
<td>28 January 1967</td>
<td>1330</td>
<td>-33</td>
<td>Fairbanks downtown</td>
</tr>
<tr>
<td>e</td>
<td>28 January 1967</td>
<td>1545</td>
<td>-34</td>
<td>Fairbanks downtown</td>
</tr>
<tr>
<td>f</td>
<td>14 February 1967</td>
<td>0030</td>
<td>-40</td>
<td>Eielson AFB</td>
</tr>
<tr>
<td>g</td>
<td>14 February 1967</td>
<td>2230</td>
<td>-38</td>
<td>Fairbanks Airport</td>
</tr>
<tr>
<td>h</td>
<td>14 February 1967</td>
<td>2400</td>
<td>-39</td>
<td>Fairbanks Airport</td>
</tr>
</tbody>
</table>

Alaska, and at the nearby locations of Fairbanks International Airport and Eielson Air Force Base. Eight sets of observations were made, some details of which are given in Table 1. The samples were obtained by the method of impaction onto microscope slides coated with a silicone oil film and photographed under a microscope (Kozima et al., 1953). The size distributions were later determined from enlargements of the original photomicrographs using the Carl Zeiss particle-size-analyzer model TGZ-3. These distributions are presented in Table 2. Other investigations have determined ice fog particles to be somewhat larger in size. Thuman and Robinson (1954) measured a mean diameter of about 13μ and Kumai (1964) reported that ice fog crystals are ~7μ in diameter. These investigators collected samples by gravitational precipitation, taking into account the effect of size on precipitation rate. However, the presence of air turbulence (Ohtake, 1964) or updrafts (Benson, 1965) near the surface may have caused them to miss many of the smaller particles.

Concurrently with the collection of each ice fog sample at Fairbanks International Airport and Eielson Air Force Base, the transmissivity was measured over a 500-ft base line. The transmissometers used were filtered to simulate the response of the human eye.

The attenuation of a plane light wave in traversing a distance x is given by the Bouguer-Lambert law in the form

\[ I = I_0 e^{-kx}, \]

where I is the intensity at x, I_0 the initial intensity, and k the extinction coefficient; the ratio I/I_0 is called the transmissivity. With the aid of an expression for the visual range \( V_m \) in terms of the extinction coefficient k (Koschmieder, 1924), i.e.,

\[ V_m = 3.912/k, \]

and (2), the measured transmissivity was converted to visual range. At downtown Fairbanks, a transmissometer was not available and visual range was estimated by counting utility poles along the highway.

Referring to Table 3, \( N, \omega, \bar{d} \) and \( d_a \) were determined from the measured size distributions. The diameters used for calculating \( \bar{d} \) and \( d_a \) are those for spheres having the same magnitude of geometric cross sections as the ice fog particles. Column seven of Table 3 gives the measured visual range while column eight gives the visual range calculated from (1) with \( \theta = 2 \). Except for distributions a and e, these calculated values are in poor agreement with the measured values for the visual range. Since the value of \( \theta \) depends on the width of the

Table 3. Observed ice fog particle characteristics and comparisons of measured and calculated visual range during the ice fog conditions of Table 1.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>N (cm⁻³)</th>
<th>ω (gm m⁻³)</th>
<th>( \bar{d} ) (μ)</th>
<th>( d_a ) (μ)</th>
<th>( \theta )</th>
<th>Measured</th>
<th>( V_m ) (meters) Calculated*</th>
<th>Calculated**</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>104</td>
<td>0.0700</td>
<td>8.1</td>
<td>11.3</td>
<td>2.1</td>
<td>260</td>
<td>276 (+6)</td>
<td>290 (+12)</td>
</tr>
<tr>
<td>b</td>
<td>131</td>
<td>0.0916</td>
<td>7.2</td>
<td>11.4</td>
<td>2.6</td>
<td>240</td>
<td>188 (-22)</td>
<td>245 (+3)</td>
</tr>
<tr>
<td>c</td>
<td>167</td>
<td>0.0367</td>
<td>7.5</td>
<td>9.3</td>
<td>1.5</td>
<td>220</td>
<td>278 (+26)</td>
<td>209 (-5)</td>
</tr>
<tr>
<td>d</td>
<td>203</td>
<td>0.1110</td>
<td>8.1</td>
<td>10.3</td>
<td>1.8</td>
<td>140</td>
<td>174 (+24)</td>
<td>157 (+12)</td>
</tr>
<tr>
<td>e</td>
<td>668</td>
<td>0.0090</td>
<td>4.8</td>
<td>6.6</td>
<td>2.1</td>
<td>120</td>
<td>124 (+3)</td>
<td>130 (+8)</td>
</tr>
<tr>
<td>f</td>
<td>85</td>
<td>0.0068</td>
<td>4.5</td>
<td>5.5</td>
<td>1.5</td>
<td>1280</td>
<td>1586 (+24)</td>
<td>1190 (-7)</td>
</tr>
<tr>
<td>g</td>
<td>30</td>
<td>0.0127</td>
<td>5.5</td>
<td>9.9</td>
<td>3.1</td>
<td>1660</td>
<td>1026 (-40)</td>
<td>1590 (-4)</td>
</tr>
<tr>
<td>h</td>
<td>94</td>
<td>0.0035</td>
<td>3.5</td>
<td>4.3</td>
<td>1.3</td>
<td>1660</td>
<td>2640 (+59)</td>
<td>1720 (+4)</td>
</tr>
</tbody>
</table>

† Calculated from Eq. (4).
* Using \( \theta = 2 \) from Eq. (1).** Using \( \theta \) as determined from Eq. (4).

Note: The number in parenthesis after each value of the calculated visual range is the per cent deviation from the measured value.
size distribution (at least for spherical water droplets), it may be possible to express \( \theta \) as an empirical function of some parameter that is characteristic of the distribution width. A desirable parameter may be the ratio of the mean volumetric diameter to the mean linear diameter, \( d_v/d \), since the mean volumetric diameter is related to the water content by the particle concentration; in such a case the Trabert formula could then be used to provide a relationship between the visual range, water content, linear size and concentration of ice fog particles.

Trial functions for \( \theta \) were constructed in an attempt to force agreement between the visual ranges computed from (1) and the measured values. It was found that good agreement is obtained when \( \theta \) is given the empirical form

\[
\theta = \frac{1}{5} \left[ 5 \left( \frac{d_v}{d} \right) - 3 \right].
\]  

(4)

Column six of Table 3 gives the values for \( \theta \) calculated from Eq. (4), while column nine gives the visual range computed from (1) using this value for \( \theta \). Eq. (1), with the variable for \( \theta \), is seen to give good agreement with the measured visual range for all eight distributions.

We see from Table 3 that \( \theta \) can assume values considerably less than the lower bound of 2 which was discussed previously. In fact, (4) predicts the theoretical limit of unity. This result is most likely due to the small size of ice fog particles and the large optical base lines (100 m) used. The lower bound of 2 is arrived at by assuming all diffused light reaches the detector, an assumption which is strictly valid only for large scattering diameters and a small base line. However, small particles result in larger angular scattering by diffraction; thus, for a large baseline, appreciable intensity reaches the detector only from the small percentage of scattering particles near the detector.

3. Conclusion

As future development of arctic and subarctic regions progresses, the effects of ice fog will become of increasing concern to human activities. This paper presents information concerning one such effect—that of visibility. The results presented here are preliminary and further investigations are necessary to bear out the validity of (4).

By combining (1) and (4), the visual range can be expressed as

\[
V_m = \frac{1.3}{2w} \left( 5d_v - 3d \right),
\]

(5)

which is a modification of the form originally developed by Trabert (1901). Furthermore, \( w \) and \( d \) are related by

\[
w = \frac{\pi \rho N}{6} d^3,
\]

(6)

where, in this case, \( \rho \) is the density of ice. Thus, (5) and (6) can be combined to give

\[
V_m = 1.3 \left[ \frac{3.2 \left( \frac{w}{N} \right) ^{\frac{4}{3}}}{5d_v - 3d} \right] ^{\frac{1}{2}}.
\]

(7)

It is of interest to know how the size of ice fog particles is related to temperature and other environmental factors and to trace their development and growth through an ice fog event. During ice fog conditions, \( V_m \) and \( w \) are easily measured. It should also be possible to determine \( N \) directly with a suitable particle counter. By monitoring \( V_m, w \) and \( N, d \) could be traced in time by use of (7). Such a method would eliminate the tedious and time consuming task of sizing individual particles.

Of more general interest, (7) may well be valid for cirrus clouds having ice crystals of much larger size, although this remains to be demonstrated. For this purpose, (7) could be used to determine \( V_m \) from the measured size distribution.

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REFERENCES


