SOME OPTICAL PROPERTIES OF BLOWING SNOW

By

Mary Ann Seagraves

Approved for public release; distribution unlimited.

US Army Electronics Research and Development Command
Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002

818 24 030
NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.
Windblown snow causes severe reduction in visibility and is a principal cause of obscuration in some regions of the world. Mechanisms of snow transport are presented along with particle size distributions, shape, and fall velocity. Relationships between visibility and windspeed and also between visibility and mass density in blowing snow are discussed. Variation of visible and infrared extinction coefficients with height are derived. In the near-millimeter wave region, the Rayleigh approximation is adequate for wavelengths greater than 4
20. ABSTRACT (cont)

Near-millimeter wave extinction coefficients are given as functions of visibility and visible extinction coefficients.
SUMMARY

Visibility may be severely reduced in blowing snow. It has been shown that visibility is inversely proportional to mass density at eye level and decreases with increasing windspeed.

Extinction in windblown snow is approximately independent of wavelength in the visible and infrared regions. The extinction coefficient, $\beta_{\text{vis}}$, in this wavelength region varies with height, $Z$, according to

$$\beta_{\text{vis}} = \beta_1 \left( \frac{Z}{Z_1} \right) - \frac{0.596}{u_*},$$

where $u_*$ is friction velocity and the subscripts indicate a reference height.

For near-millimeter wavelengths greater than 4 mm, the Rayleigh scattering approximation may be used to determine $\beta$. Extinction increases with increasing temperature over the range of -20°C to 0°C. The relationship between $\beta$ and visibility, $V$, for wavelength, $\lambda$, is

$$\beta = \frac{2.09}{\lambda V} \Im \left( -\frac{m^2 - 1}{m^2 + 2} \right),$$

where $m$ is the complex index of refraction for ice, $\lambda$ is in units of millimeters, and $V$ is in units of kilometers.

Note that the relationships derived in this report have not been verified by field measurements and may be subject to change should such measurements become available.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>7</td>
</tr>
<tr>
<td>MECHANISMS OF SNOW TRANSPORT</td>
<td>7</td>
</tr>
<tr>
<td>SHAPE AND FALL VELOCITY OF WINDBLOWN SNOW PARTICLES</td>
<td>10</td>
</tr>
<tr>
<td>PARTICLE SIZE DISTRIBUTIONS</td>
<td>11</td>
</tr>
<tr>
<td>VISIBILITY IN BLOWING SNOW</td>
<td>11</td>
</tr>
<tr>
<td>VISIBLE AND INFRARED EXTINCTION</td>
<td>13</td>
</tr>
<tr>
<td>NEAR-MILLIMETER WAVE EXTINCTION IN BLOWING SNOW</td>
<td>15</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>17</td>
</tr>
</tbody>
</table>
INTRODUCTION

Windblown snow is one of the principal causes of obscuration in the polar regions and can occur in many other geographical areas. When the snow on the ground is dry and composed of fine-grained, loose particles, it is easily swept into the air by gentle or moderate winds. When the wind is in the range of 4 to 6 m/s, it raises snow crystals a few feet off the ground and obscures many surface objects and features. With speeds exceeding 7 m/s, wind can carry the snow to much greater heights. These critical wind speeds are often exceeded in the polar regions where blowing snow is reported on an average of 5 to 10 percent of the observations in the winter season. At Barter Island Air Force Base, Alaska (latitude 70°N), blowing snow is reported on the average in about 25 percent of all observations in November. The snow blown along in a major blizzard in the polar regions is not necessarily confined to a very shallow surface layer but may form a cloud as deep as 300 m.

Blowing snow occurs when the wind speed and the surface roughness are sufficient to develop a shear stress great enough to break particles free from the surface. The magnitude of this critical shear stress will vary with the size of the snow grains and with the degree of intergranular bonding in the surface layer. With cold, cohesionless, fine-grained snow, windspeeds of a few meters per second may suffice to dislodge particles but not to diffuse them into the airstream by turbulent exchange. Under these circumstances the particles will roll or bounce along the surface in a thin layer, commonly no more than 10 cm thick. Not until turbulence is well developed will particles be carried up to and above eye level.

Snow particles may also be supplied directly by precipitation falling during the windstorm and would occur at much lower windspeeds than the particles lofted from the surface. In practice, it is difficult to distinguish between particles from the two sources, and in fact it may be difficult to determine whether precipitation is even occurring during the windstorm.

MECHANISMS OF SNOW TRANSPORT

Three transport mechanisms have been identified in the movement of windblown sand and snow and other fluid-borne sediments. As illustrated in figure 1, these mechanisms are:

---


1. Surface creep in which particles roll or creep along the surface and generally remain in a layer less than 1 cm thick.

2. Saltation in which particles bounce along the surface and rebound and/or eject other particles into the air when they impact. Saltation particles are primarily contained in a layer above the surface 0.1 to 1.0 m thick.

3. Turbulent diffusion in which particles are held in suspension by vertical mixing.

Figure 1. Methods of transport of windblown snow (Mellor\textsuperscript{2}).

Turbulent diffusion is the dominant mechanism for snow transport when appreciable concentrations are carried along at and above eye level. The particles carried by turbulent diffusion will be the only ones considered here since they have the major effect on visibility and the transfer of electromagnetic energy through the atmosphere. However, the saltation and surface creep particles may affect the snow background and target contrast characteristics and in that sense would affect the operation of electro-optical devices.
When stationary conditions exist in which turbulence transports upward as much snow as settles downward under the influence of gravity, Loewe found that

\[ w s = K \left( \frac{ds}{dz} \right), \]  

(1)

where

- \( w \) = fall velocity of snow particles
- \( s \) = particle concentration
- \( K \) = eddy diffusivity

When the wind profile is logarithmic, as Budd, Dingle, and Radok found to be the case in blowing snow, then the eddy viscosity, \( A \), is proportional to height, that is,

\[ A = k u_\ast (Z + Z_0), \]  

(2)

where

- \( k = 0.4 \) is von Karman's constant
- \( u_\ast \) = friction velocity (usually 0.5 to 1.0 m/s over snow)
- \( Z_0 \) = roughness length

If eddy diffusivity is equal to eddy viscosity, then (1) and (2) may be combined and integrated so that

\[ s = s_1 \left( \frac{Z}{Z_1} \right)^{w/ku_\ast}, \]  

(3)

---


where the index refers to a reference level. Equation (3) is not valid near the surface where saltation and surface creep are predominant transport methods; nor is it valid when turbulence is strong enough to carry many more particles upward than are settling downward through gravitation. It is assumed here that particles of different sizes settle at different speeds but do not interfere with each other and that equation (3) may be used to determine the variation of number density with height for particles of various sizes.

SHAPE AND FALL VELOCITY OF WINDBLOWN SNOW PARTICLES

Snow crystals blown about by strong winds are broken and abraded into roughly equidimensional grains with rounded or nearly angular corners. Particles occur in greatest numbers with effective radii in the range 10μm to 200μm, where the effective radius is 1/2√length x breadth (Mellor).

According to Budd, blowing snow particles are usually larger than those for which Stokes's law is valid for determining fall velocities but smaller than those for which a linear dependence upon size is applicable. However, in this study Stokes's law for spherical particles was used to determine \( w \):

\[
 w = - \frac{2r^2 \rho}{9n},
\]

where
\[ r = \text{particle radius} \]
\[ g = \text{gravitational acceleration} \]
\[ \rho = \text{particle density} \]
\[ n = \text{coefficient of viscosity} \]

---


\(^8\) M. Mellor, 1965, "Blowing Snow," Monograph III - A3c, US Army Cold Regions Research and Engineering Laboratory, Hanover, NH

This determination results in computed fall velocities which are usually somewhat low, perhaps as much as 10 percent. The low velocities cause larger particle number densities at higher altitudes than would otherwise occur.

**PARTICLE SIZE DISTRIBUTIONS**

Budd, Dingle, and Radok; Dyunin; and Lister measured particle size distribution of blowing snow. The size distribution given by Budd, Dingle, and Radok was used in this study since the data were taken at specific heights and published with finer resolution than the others. Figure 2 shows the size distribution that was measured at 2 m above the surface. This distribution was used as the initial size distribution. Then size distributions for various altitudes up to 200 m were determined by applying equations (3) and (4) to each size interval. Resulting mass densities for \( u^* = 1.0 \) m/s are shown in figure 3.

**VISIBILITY IN BLOWING SNOW**

Liljequist studied the relationship between visibility and mass density and found that visibility theoretically should be inversely proportional to mass density at eye level. This finding was confirmed by the measurements made by Budd, Dingle, and Radok who found that

\[
V = 0.1/\kappa, \quad (5)
\]

where

\[
V = \text{visibility (kilometers), and}
\]

\[
\kappa = \text{mass density (grams per cubic meter).}
\]

---


Figure 2. Particle size distribution of blowing snow at 2 meters above the surface (after Budd, Dingle, and Radok, 1966).

Figure 3. Variation of mass density with $\frac{Z}{Z_1}$ where $Z$ is height above the surface and $Z_1$ is the reference height, $Z_1 = 2$ meters.
Empirical relationships between visibility and windspeed were derived by Lister\(^1\) who found at Shackleton in the Antarctic that for visibility less than 1 km:

\[
\log V = 1.27825 + 0.31104U - 0.04645U^2 + 0.00117U^3 \quad \text{(summer)} \quad (6a)
\]

\[
\log V = 1.55791 + 0.08083U - 0.02585U^2 + 0.00073U^3 \quad \text{(winter)} \quad (6b)
\]

where \(U\) = windspeed (meters/second) at 10 m height and \(\log\) is to the base 10.

The Koschmieder relation

\[
\beta_{\text{vis}} = \frac{3.912}{V},
\]

where \(\beta_{\text{vis}}\) = visible extinction coefficient, may then be used to derive empirical relationships between the extinction coefficient and windspeed:

\[
\log \beta_{\text{vis}} = -0.68585 - 0.31104U + 0.04645U^2 - 0.00117U^3 \quad \text{(summer)} \quad (8a)
\]

\[
\log \beta_{\text{vis}} = -0.96551 - 0.08083U + 0.02585U^2 - 0.00073U^3 \quad \text{(winter)} \quad (8b)
\]

These relationships are for a specific location and period of time but should provide an indication of the effects of windspeed on visibility and extinction coefficient at extremely cold temperatures (winter) and somewhat warmer temperatures (summer).

VISIBLE AND INFRARED EXTINCTION

The action of the wind tends to round the windblown snow particles into more nearly spherical shapes than most snow crystals have initially. Because of this action, it is assumed here that Mie calculations for spherical particles would give valid indications of the optical properties of blowing snow. However, this assumption has not been verified with measurements.

Mie calculations confirmed that for the size distribution discussed above single scattering extinction is independent of wavelength and the geometrical optics approximation holds; that is,

\[
\beta = 2\int r^2 N(r) dr ,
\]

\(^1\)H. Lister, 1960, "Glaciology 1 Solid Precipitation and Drift Snow," T.A.E. Scientific Report No. 5, Trans-Antarctic Expedition Committee, London
where

\[ B = \text{extinction coefficient} \]

\[ N(r) = \text{particles per unit volume per unit size range} \]

\[ r = \text{particle radius} \]

The size distributions found by using equation (3) were used to calculate the variation of \( B \) with height for \( u_* = 1.0 \text{ m/s} \). These results were then used to derive an empirical relationship between \( B \) and \( Z \); thus,

\[ B = B_1 \left( \frac{Z}{Z_1} \right)^{-0.596} \]

\[ \frac{u_*}{2} \left( \frac{Z}{Z_1} \right) \]

Where \( B_1 \) is the extinction coefficient at \( Z_1 \).

The variation of \( B \) with \( u_* \) found by using equation (10) is shown in figure 4.

![Figure 4. Variation of extinction coefficient with \( \frac{Z}{Z_1} \) for various values of friction velocity \( u_* \). X's indicate computed values used in deriving the relationship \( B = B_1 \left( \frac{Z}{Z_1} \right)^{-0.596} \).](image)
Extinction measurements in falling snow have shown that extinction is not entirely wavelength independent but increases slightly with increasing wavelength. Blowing snow is expected to show a similar effect, which is probably due to increased forward scattering at shorter wavelengths.

NEAR-MILLIMETER WAVE EXTINCTION IN BLOWING SNOW

For wavelengths, $\lambda$, in the near-millimeter wave region, the Rayleigh scattering approximation may be used to compute the extinction coefficient, $\beta$, when $\lambda$ is greater than 4 mm. The resulting errors are less than 10 percent. For $\lambda < 4$ mm, the Rayleigh approximation yields extinction coefficients which are lower than those resulting from Mie calculations; and this difference is an order of magnitude for $\lambda = 0.86$ mm. The Rayleigh approximation for the extinction coefficient is given by

$$\beta = \frac{2\pi k}{\lambda \rho} \text{Im} \left( \frac{m^2 - 1}{m^2 + 2} \right),$$

(11)

where $m = n_r - in_i = \text{complex index of refraction}$ and Im indicates the imaginary part of the quantity following.

Ray\(^{12}\) discusses methods of computing the complex index of refraction for ice in the near-millimeter wave region. He found that the real part, $n_r$, is 1.78 in the near-millimeter wave region for normal atmospheric temperatures. The imaginary part varies with wavelength and temperature, increasing with either increasing temperature or wavelength. Since for ice

$n_r > > n_i$, $\text{Im} \left( \frac{-m^2 - 1}{m^2 + 2} \right)$ is approximately linearly proportional to $n_i$; then

from equation (11), $\beta$ is approximately linearly proportional to $n_i$. For example, since $n_i$ at 0°C (0.0012 at $\lambda = 1$ cm) is about five times $n_i$ at -20°C (0.00024 at $\lambda = 1$ cm), $\beta$ at 0°C is about five times that at -20°C.

The relationship between the near-millimeter wave extinction coefficient and visibility may be found by combining equations (5) and (11) to give

$$\beta = \frac{2.09}{\lambda V} \text{Im} \left( \frac{-m^2 - 1}{m^2 + 2} \right).$$

(12)

where \( \lambda \) is in units of millimeters, \( V \) is in units of kilometers, and \( \beta \) is in units of kilometers\(^{-1}\). Also, the Koschmieder relation may be used to relate \( \beta \) to the visible extinction coefficient, \( \beta_{\text{vis}} \). Thus,

\[
\beta = \frac{53.5 \, \beta_{\text{vis}}}{\lambda} \, \text{Im} \left( \frac{-m^2 - 1}{m^2 + 2} \right),
\]

(13)

where \( \lambda \) is in units of millimeters and \( \beta \) and \( \beta_{\text{vis}} \) are in units of kilometers\(^{-1}\). Equations (6) and (12) or (8) and (13) may be used to find the relationship between the extinction coefficient and the windspeed:

\[
\beta = \frac{53.5}{\lambda} \, \text{Im} \left( \frac{-m^2 - 1}{m^2 + 2} \right) 10(-0.68585 - 0.31104V + 0.04645V^2 - 0.00117V^3)
\]

(summer) (14a)

\[
\beta = \frac{53.5}{\lambda} \, \text{Im} \left( \frac{-m^2 - 1}{m^2 + 2} \right) 10(-0.96551 - 0.08083V + 0.2585V^2 - 0.00073V^3)
\]

(winter) (14b)
REFERENCES


42. Gillespie, James B., and James D. Lindberg, "A Method to Obtain Diffuse Reflectance Measurements from 1.0 and 3.0um Using a Cary 171 Spectrophotometer," ECOM-5806, November 1976.


53. Rubio, Roberto, and Mike Izquierdo, "Measurements of Net Atmospheric Irradiance in the 0.7- to 2.8-Micrometer Infrared Region," ECOM-5817, May 1977.


ELECTRO-OPTICS DISTRIBUTION LIST

Commander
US Army Aviation School
Fort Rucker, AL 36362

Commander
US Army Aviation Center
ATTN: ATZQ-D-MA (Mr. Oliver N. Heath)
Fort Rucker, AL 36362

Commander
US Army Aviation Center
ATTN: ATZQ-D-MS (Mr. Donald Wagner)
Fort Rucker, AL 36362

NASA/Marshall Space Flight Center
ATTN: ES-83 (Otha H. Vaughan, Jr.)
Huntsville, AL 35812

NASA/Marshall Space Flight Center
Atmospheric Sciences Division
ATTN: Code ES-81 (Dr. William W. Vaughan)
Huntsville, AL 35812

Nichols Research Corporation
ATTN: Dr. Lary W. Pinkley
4040 South Memorial Parkway
Huntsville, AL 35802

John M. Hobbie
C/o Kentron International
2003 Byrd Spring Road
Huntsville, AL 35802

Mr. Ray Baker
Lockheed-Missile & Space Company
4800 Bradford Blvd
Huntsville, AL 35807

Commander
US Army Missile Command
ATTN: DRSMI-OG (Mr. Donald R. Peterson)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-OGA (Dr. Bruce W. Fowler)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-REL (Dr. George Emmons)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-REO (Huey F. Anderson)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-REO (Mr. Maxwell W. Harper)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-REO (Mr. Gene Widenhofer)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-RHC (Dr. Julius Q. Lilly)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
Redstone Scientific Information Center
ATTN: DRSMI-RPRD (Documents Section)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-RRA (Dr. Oskar Essenwanger)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-RRO (Mr. Charles Christensen)
Redstone Arsenal, AL 35809

Commander
US Army Missile Command
ATTN: DRSMI-RRO (Dr. George A. Tanton)
Redstone Arsenal, AL 35809
Director
US Army Night Vision & Electro-Optics Laboratory
ATTN: DELNV-VI (Mr. Thomas W. Cassidy)
Fort Belvoir, VA 22060

Director
US Army Night Vision & Electro-Optics Laboratory
ATTN: DELNV-VI (Mr. Richard J. Bergemann)
Fort Belvoir, VA 22060

Commander
US Army Training & Doctrine Command
ATTN: ATCD-AN
Fort Monroe, VA 23651

Commander
US Army Training & Doctrine Command
ATTN: ATCD-AN-M
Fort Monroe, VA 23651

Commander
US Army Training & Doctrine Command
ATTN: ATCD-F-A (Mr. Chris O'Connor, Jr.)
Fort Monroe, VA 23651

Commander
US Army Training & Doctrine Command
ATTN: ATCD-1E-R (Mr. David M. Ingram)
Fort Monroe, VA 23651

Commander
US Army Training & Doctrine Command
ATTN: ATCD-M-I/ATCD-M-A
Fort Monroe, VA 23651

Commander
US Army Training & Doctrine Command
ATTN: ATxDC-TA (Dr. Marvin P. Pastel)
Fort Monroe, VA 23651

Department of the Air Force
OL-I, AWS
Fort Monroe, VA 23651

Department of the Air Force
HQS 5 Weather Wing (MAC)
ATTN: 5 WW/DN
Langley Air Force Base, VA 23655

Commander
US Army INSCOM/Quest Research Corporation
ATTN: Mr. Donald Wilmot
6845 Elm Street, Suite 407
McLean, VA 22101

General Research Corporation
ATTN: Dr. Ralph Zirkind
7655 Old Springhouse Road
McLean, VA 22102

Science Applications, Inc.
8400 Westpark Drive
ATTN: Dr. John E. Cockayne
McLean, VA 22102

US Army Nuclear & Chemical Agency
ATTN: MONA-WE (Dr. John A. Berberet)
7500 Backllick Road, Bldg 2073
Springfield, VA 22150

Director
US Army Signals Warfare Laboratory
ATTN: DELSW-EA (Mr. Douglas Harkleroad)
Vint Hill Farms Station
Warrenton, VA 22186

Director
US Army Signals Warfare Laboratory
ATTN: DELSW-OS (Dr. Royal H. Burkhardt)
Vint Hill Farms Station
Warrenton, VA 22186

Commander
US Army Cold Regions Test Center
ATTN: STECR-TD (Mr. Jerold Barger)
APO Seattle, WA 98733

HQDA (SAUS-OR/Hunter M. Woodall, Jr./Dr. Herbert K. Fallin)
Rm 2E 614, Pentagon
Washington, DC 20301

COL Elbert W. Friday, Jr.
OUSDRE
Rm 3D 129, Pentagon
Washington, DC 20301