Technical Report Series on the Boreal Ecosystem-Atmosphere Study (BOREAS)

Forrest G. Hall and Jaime Nickeson, Editors

Volume 58

BOREAS RSS-11 Ground Network of Sunphotometer Measurements

B.L. Markham and J. Schafer

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

August 2000
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BOREAS RSS-11 Ground Network of Sunphotometer Measurements

Brian L. Markham, Goddard Space Flight Center, Greenbelt, Maryland
Joel Schafer, Raytheon ITSS

National Aeronautics and Space Administration
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Greenbelt, Maryland 20771

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BOREAS RSS-11 Ground Network of Sunphotometer Measurements

Brian L. Markham, Joel Schafer

Summary

The BOREAS RSS-11 team operated a network of five automated (Cimel) and two hand-held (Miami) solar radiometers from 1994 to 1996 during the BOREAS field campaigns. The data provide aerosol optical depth measurements, size distribution, phase function, and column water vapor amounts over points in northern Saskatchewan and Manitoba, Canada. The data are useful for the correction of remotely sensed aircraft and satellite images. The data are provided in tabular ASCII files.

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1. Data Set Overview

1.1 Data Set Identification

BOREAS RSS-11 Ground Network of Sunphotometer Measurements

1.2 Data Set Introduction

A ground-based sunphotometer network was installed within the BORereal Ecosystem-Atmosphere Study (BOREAL) study areas to characterize the size and distribution of atmospheric aerosols and column water vapor amount and to aid in the correction of aircraft and satellite imagery. Automated sunphotometer data are available fairly continuously from early 1994 through 1996 for two sites in the Northern Study Area (NSA) and two in the Southern Study Area (SSA). Data were collected from a fifth automated instrument located at the Flin Flon airport at the Manitoba/Saskatchewan border; this instrument was moved in 1996 to Paddockwood, SK, in the SSA. Measurements made by two additional hand-held instruments, operated during the 1994-96 time period at each of the study areas, are also a part of this data set. A local observer made the hand-held measurements near noon when the Sun was not obscured by any clouds.
1.3 Objective/Purpose

The purpose was to establish a data set of aerosol, water vapor, and ozone atmospheric properties in the BOREAS region for a 3-year period for use by BOREAS in atmospheric correction of remotely sensed data. Another goal was to establish an aerosol climatology of the region by specifying, for example, the annual cycle of aerosol loading across the region.

1.4 Summary of Parameters

Parameters:
- Direct solar irradiance (340, 380, 440, 500, 670, 870, 1020 nm)
- Sky radiance (440, 670, 870, 1020 nm)
- Aerosol optical thickness
- Column water vapor amount

1.5 Discussion

A network of five automated (Cimel) and two hand-held (Miami) solar radiometers were operated during the 1994-96 time period for BOREAS to provide aerosol optical depth measurements, size distribution, phase function, and column water vapor amounts. The purpose was to establish a data set of aerosol, water vapor, and ozone atmospheric properties in the BOREAS region for a 3-year period for use by BOREAS in atmospheric correction of remotely sensed data.

1.6 Related Data Sets

BOREAS RSS-03 Reflectance Measured from a Helicopter-Mounted Barnes MMR
BOREAS RSS-12 Airborne Tracking Sunphotometer Measurements
BOREAS RSS-12 Automated Ground Sun Photometer Measurements in the SSA
BOREAS RSS-18 Ground Sunphotometer Measurements in the SSA

An additional data set collected and used in comparison was sunphotometer measurements made by Norman O'Neill (RSS-19) at the Canada Centre for Remote Sensing (CCRS). These data were not submitted to the BOREAS Information System (BORIS).

2. Investigator(s)

2.1 Investigator(s) Name and Title

Brian L. Markham
Physical Scientist

2.2 Title of Investigation

Characterization of Atmospheric Optical Properties for BOREAS

2.3 Contact Information

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(301) 286-0239 (fax)
Jaime.Nickeson@gsfc.nasa.gov

3. Theory of Measurements

Sunphotometers measure direct surface irradiance. Because direct solar irradiance depends on the atmospheric transmission, the components affecting this transmission such as aerosol optical thickness (AOT), water vapor column abundance, ozone absorption, and molecular scattering can either be estimated or measured.

Optical thickness is calculated from spectral extinction of direct beam radiation at each wavelength based on Beer's Law:

\[ V_\lambda = V_o \cdot R^2 \cdot e^{- (m \cdot \tau)} \]

where:
\( V_\lambda \) = digital voltage measured at wavelength \( \lambda \)
\( V_o \) = extraterrestrial voltage
\( m \) = optical airmass
\( \tau \) = total optical thickness
\( R \) = relative Earth-Sun distance

Attenuation due to Rayleigh scatter, and absorption by ozone and gaseous pollutants is estimated and removed to isolate the AOT (\( \tau \)).

The dependence of transmission, \( T_w \), on water column abundance can be written as the following [Halthore et al., 1992, Bruegge et al., 1992]:

\[ T_w = e^{-a \cdot m \cdot b \cdot W^b} \]

where:
\( W \) = vertical column abundance (cm)
\( a, b \) = constants that depend on the wavelength position, width and shape of the filter function, and atmospheric conditions.

Sky radiance measurements are inverted with radiative transfer equations [Nakajima et al., 1983] to provide aerosol properties of size distribution and phase function over the particle size range of 0.1 to 5 \( \mu m \).
4. Equipment

4.1 Sensor/Instrument Description

4.1.1 Collection Environment
The automated sunphotometers operated during nonwinter months according to their diurnal schedule (Section 4.1) when there was no precipitation and the atmosphere is clear enough to allow the instrument to focus on the Sun with a four-quadrant detector (AOT roughly <6.0). Precipitation activates an externally mounted wet sensor that causes the instrument to remain in the parked (nadir) position.

4.1.2 Source/Platform
All instruments were mounted on the roof of a building or hut, with a clear view of the sky above 5 degrees elevation angle. The hand-held instruments were held by the human observer.

4.1.3 Source/Platform Mission Objectives
The building roof provided a convenient place to mount the sunphotometers. The objective of the human observer during the measurement times was to obtain good measurements.

4.1.4 Key Variables
Direct solar irradiance  Sky radiance

4.1.5 Principles of Operation
Eight interference filters are located in a filter wheel that is rotated by a direct drive stepping motor. A thermistor measures the temperature of the detector, allowing compensation for any temperature dependence in the silicon detector.

The sensor head is pointed by stepping azimuth and zenith motors with a precision of 0.05 degrees. A microprocessor computes the position of the Sun based on time, latitude, and longitude and directs the sensor head to within approximately 1 degree of the Sun. Then, a four-quadrant detector tracks the Sun precisely prior to a programmed measurement sequence.

4.1.6 Sensor/Instrument Measurement Geometry
The Cimel automatic sunphotometers take direct solar irradiance and sky radiance measurements with a 1.2-degree Field of View (FOV).

4.1.7 Manufacturer of Sensor/Instrument
The automatic sunphotometers were made by:
Cimel Electronique
5 Cite de Phalsbourg
75011 Paris, France

The hand-held sunphotometers were made by:
University of Miami
Dept. of Meteorology
Coral Gables, FL 33124

4.2 Calibration
A number of automatic sunphotometers from the Goddard Space Flight Center (GSFC) were regularly taken to the Mauna Loa Observatory in Hawaii, where the Langley method of calibration [Shaw, 1983] was used for absolute calibration. Instruments used for BOREAS were calibrated by intercomparison with reference instruments using measurements conducted on the top of a building at GSFC on clear days with low aerosol loading. On occasion, in-field Langley calibrations were performed.
For the 940-nm channel that includes water absorption, calibration was performed using the following procedure.

At 940 nm, the measured digital voltage is:

\[ V = V_0 \cdot R^2 \cdot e^{-(m \cdot \tau)} \cdot T_w \]

where \( \tau \) is the extinction due to Rayleigh and aerosol scatter and water vapor absorption, and \( T_w \), again, is water vapor transmission.

Combining this relation with that of Section 3 describing

\[ T_w = e^{-(a \cdot m^b \cdot W^b)} \]

yields:

\[ \ln V + m \cdot \tau = \ln(V_0) - a \cdot m^b \cdot W^b \]

Plotting the left-hand side of the above equation against \( m^b \) gives a straight line with the desired y-intercept \( \ln(V_0) \) and slope \( W^b \) [Halthore et al 1997]. This modified Langley method was used only for calibrating the water vapor band.

Hand-held instruments are intercalibrated at the beginning and end of the season with collocated automatic instruments on clear days of low aerosol.

4.2.1 Specifications

The automatic instruments used were Cimel CE-318s, which, during 1994, had 10-nm bandpass filters in the visible and near-infrared with center wavelengths at 340, 380, 440, 670, 870, 940, and 1020 nm, with an additional 50-nm bandpass filter centered at 940 nm. The two 940-nm channels were to be used for column water vapor abundance determination. The wider bandpass filter proved unnecessary for determining water vapor column abundance, so it was replaced with a 10-nm bandpass filter centered at 500 nm in spring of 1995. In addition to measuring solar irradiance with an FOV of 1.2 degrees, these instruments measure the sky radiance in four spectral bands (440, 670, 870, and 1020 nm) along the solar principal plane (i.e., at constant azimuth angle, with varied solar zenith angles) up to nine times a day and along the solar almucantar (i.e., at constant solar zenith angle, with varied azimuth angles) up to six times a day.

The two hand-held sunphotometers have four channels (500, 670, 870, and 940 nm). They are capable of only the direct solar measurements and require manual data entry. They have a peak hold feature that allows them to record the highest voltage response when pointed in the general direction of the Sun.

4.2.1.1 Tolerance

If the aerosol conditions were considered to be constant during the Langley procedures at Mauna Loa, then deviation of measurements from the linear regression line gives an indication of the sunphotometer precision. Triplet variability from three reference instruments deployed at Mauna Loa was calculated based on 168, 264, and 288 observations, respectively. For all wavelengths, the variability of a triplet was always less than 1%, and generally about 0.3%, suggesting that uncertainty due to instrument precision is minimal [Holben et al., 1996].

Page 5
4.2.2 Frequency of Calibration

The instruments were intercompared at GSFC on clear days with reference Cimels calibrated by Langley or modified Langley techniques at Mauna Loa. This process was done before and after each field campaign, and the reference instrument (#13) was taken to Mauna Loa every 6 months. Occasionally, filter changes during deployment or short-term contamination by spider webs in the collimator warranted the use of in-field Langley calibrations.

4.2.3 Other Calibration Information

The instrument referred to below as #13 is the reference instrument used for BOREAS.

### 1994 Cimel Sun Photometer Data Calibration

The ratios of the post season to preseason calibrations follow for each instrument in the order. The bracketed numbers are for instrument #31 and #32.

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<th>Wavelength</th>
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<th>Preseason</th>
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<td>1.00224738</td>
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<td>#12 Flin Flon</td>
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<td>#31 SSA-YJP</td>
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<td>#32 Waskesiu</td>
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### 1995 Cimel Sun Photometer Data Calibration

The time and date are given for each zero airmass voltage ($V_0$) and for each wavelength and the seasonal change in filter response is given as well.

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### 1996 Cimel Sun Photometer Data Calibration

The time and date are given for each zero airmass voltage ($V_0$) and for each wavelength, and the seasonal change in filter response is given as well, where appropriate.

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<td>DATE: 29-Dec-95</td>
<td>15980.247</td>
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<td>28336.05</td>
<td>22616.378</td>
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#### #35 NSA-YJP

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<td>18035.776</td>
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<td>DATE: 07-Jun-95</td>
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<td>Post/preseason</td>
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#### #10 Paddockwood

<table>
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<tbody>
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<td>13491.316</td>
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<tr>
<td>DATE: 04-Nov-96</td>
<td>13557.683</td>
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<table>
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<tbody>
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<tr>
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Page 8
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<tr>
<th>#10 Paddockwood</th>
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<tr>
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<td>Wavelength</td>
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<tr>
<td>DATE: 29-Dec-95</td>
<td>15980.247</td>
<td>18374.366</td>
<td>28336.050</td>
<td>22616.378</td>
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<td>9523.237</td>
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<td>Post/preseason</td>
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<table>
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<td>670</td>
<td>500</td>
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<td>13602.240</td>
<td>9565.654</td>
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<td>Post/preseason</td>
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<td>0.991</td>
<td>0.999</td>
<td>1.001</td>
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<td>Wavelength</td>
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<td>380</td>
<td>340</td>
<td>940</td>
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<tr>
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</table>
5. Data Acquisition Methods

A preprogrammed sequence of measurements is taken by these instruments starting at an airmass of 7 in the morning and ending at an airmass of 7 in the evening. During the large airmass periods, direct Sun measurements are made at 0.25 airmass intervals; at smaller airmasses, the interval between measurements is typically 15 minutes. The almucantar measurements are taken at 0.5-degree intervals near the Sun (within 6 degrees) and increase from 2 to 10 degree intervals away from the solar position. The data are collected and transmitted via the Geostationary Operational Environmental Satellite (GOES) at 1-hour intervals to a computer at Wallops Island Flight Facility [Holben et al., 1996].

The hourly transmitted radiometer data stream includes date, time, temperature, battery voltage, wet sensor status, and time of transmission as well as several levels of identification numbers. The Vitel transmitter adds a time stamp at the time of transmission, as does the Wallops receiving station. The transmitter also checks for parity errors and signal strength of the transmission. After data are downloaded from the central receiving station, a status report and a troubleshooting report are automatically generated and e-mailed to appropriate system and instrument managers. The status report provides a comprehensive assessment of the operation of the radiometer and the Vitel transmitter for the data transmitted with the current download. Network managers then have sufficient information to assess the operation of individual stations.

Within Demontrat, a package of user-friendly UNIX software, the raw data (voltages) are converted to AOT or precipitable water using the relevant instrument-specific calibration coefficients.

6. Observations

6.1 Data Notes

The data sets are generally complete from May to October or September with some exceptions noted below.

1994
#11 NSA-YJP 26-Jun - 04-Jul collimator obstruction
#32 Waskesiu, SK 21-Jul - 25-Jul collimator obstruction

1995
#11 Waskesiu, SK 01-Aug - 22-Aug collimator obstruction
#31 SSA-YJP 04-Sep - 07 Sep
12-Sep - 22-Sep
01-Jun - 01-Jul removed because of local forest fire

1996
#10 Paddockwood 18-Apr - 27-Apr * Installed in February *
02-Sep - 14-Sep
#11 Waskesiu, SK 01-May - 12-May
04-Sep - 30-Sep
#31 SSA-YJP 23-Sep - 02-Oct
15-May - 29-May
04-Sep - 08-Sep (440-nm unusable)
12-Sep - 23-Sep (440-nm unusable)
#35 NSA-YJP 24-Sep - 03-Oct

The hand-held records are generally complete for the whole year depending on availability of the observer.
6.2 Field Notes
None given.

7. Data Description

7.1 Spatial Characteristics

7.1.1 Spatial Coverage
The North American Datum of 1983 (NAD83) coordinates of the sites are:

<table>
<thead>
<tr>
<th>Deployment Sites</th>
<th>Latitude</th>
<th>Longitude</th>
<th>UTM Easting</th>
<th>UTM Northing</th>
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<tbody>
<tr>
<td><strong>1994:</strong></td>
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<td></td>
</tr>
<tr>
<td>Flin Flon, MB</td>
<td>54.67777N</td>
<td>101.67843W</td>
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<td>6062229</td>
</tr>
<tr>
<td>NSA-YJP</td>
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<td>98.28706W</td>
<td>544583.9</td>
<td>6194706.9</td>
</tr>
<tr>
<td>NSA-Thompson Airport</td>
<td>55.78344N</td>
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<tr>
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<td>53.87581N</td>
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<tr>
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<td>NSA-YJP</td>
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<td>SSA-Lake Waskesiu</td>
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<td>106.06717W</td>
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<td>5974783.3</td>
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<td>101.67843W</td>
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<td>6062229</td>
</tr>
<tr>
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<td>55.75N</td>
<td>97.8867W</td>
<td>571137</td>
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<tr>
<td><strong>1996:</strong></td>
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<td></td>
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<tr>
<td>SSA-YJP</td>
<td>53.87581N</td>
<td>104.64529W</td>
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<td>5969762.5</td>
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<td>NSA-YJP</td>
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<td>SSA-Lake Waskesiu</td>
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<td>106.06717W</td>
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<td>55.75N</td>
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<td>571137</td>
<td>6178837</td>
</tr>
</tbody>
</table>

In addition, a hand-held sunphotometer was operated at Lake Waskesiu and Thompson during each year.

7.1.2 Spatial Coverage Map
Not available.

7.1.3 Spatial Resolution
Each sunphotometer takes measurements that are generally representative of the local area under quiescent conditions. During forest fire episodes, however, the spatial resolution depends on the nature of smoke dispersion.

7.1.4 Projection
Not applicable.

7.1.5 Grid Description
Not applicable.
7.2 Temporal Characteristics

7.2.1 Temporal Coverage
Automatic sunphotometer data are acquired at 0.25 or 0.5 airmass intervals from an airmass of 7 up to 2. Air mass is approximately equal to 1/cos(zenith angle). Then, measurements are made every 15 minutes until an afternoon airmass of 2, where time intervals are again dictated by airmass fractions.

7.2.2 Temporal Coverage Map
The following are the operation periods for the Cimel automatic sunphotometers during the 1994, 1995, and 1996 BOREAS campaigns:

<table>
<thead>
<tr>
<th>1994 OPERATION PERIODS</th>
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</thead>
<tbody>
<tr>
<td>Flin Flon, MB</td>
</tr>
<tr>
<td>18-May - 07-Sep</td>
</tr>
<tr>
<td>NSA-YJP</td>
</tr>
<tr>
<td>18-May - 26-Jun, 01-Jul - 01-Nov</td>
</tr>
<tr>
<td>SSA-YJP</td>
</tr>
<tr>
<td>23-May - 13-Oct</td>
</tr>
<tr>
<td>Waskesiu, SK</td>
</tr>
<tr>
<td>25-May - 01-Jun, 01-Jul - 12-Sep, 22-Sep - 21-Nov</td>
</tr>
<tr>
<td>Thompson, MB</td>
</tr>
<tr>
<td>08-Jun - 13-Jun, 27-Jul - 10-Sep</td>
</tr>
<tr>
<td>Prince Albert, SK</td>
</tr>
<tr>
<td>17-May - 06-Jun, 20-Jul - 26-Jul, 12-Sep - 18-Sep</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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</thead>
<tbody>
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<tr>
<td>18-May - 07-Sep</td>
</tr>
<tr>
<td>NSA-YJP</td>
</tr>
<tr>
<td>16-May - 03-Nov</td>
</tr>
<tr>
<td>SSA-YJP</td>
</tr>
<tr>
<td>25-May - 01-Jun, 01-Jul - 12-Sep, 22-Sep - 21-Nov</td>
</tr>
<tr>
<td>Waskesiu, SK</td>
</tr>
<tr>
<td>24-May - 01-Aug, 22-Aug - 04-Nov</td>
</tr>
<tr>
<td>Thompson, MB</td>
</tr>
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<td>15-May - 29-Oct</td>
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</table>

<table>
<thead>
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<th>1996 OPERATION PERIODS</th>
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<tbody>
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<td>27-Feb - 07-Nov</td>
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<tr>
<td>NSA-YJP</td>
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<tr>
<td>14-May - 24-Sep, 30-Sep - 09-Oct</td>
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<td>SSA-YJP</td>
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<td>20-May - 14-May, 28-May - 20-Sep, 01-Oct - 23-Oct</td>
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<td>Waskesiu, SK</td>
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<td>08-May - 14-May, 23-May - 04-Sep, 29-Sep - 27-Oct</td>
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<tr>
<td>Thompson, MB</td>
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<td>14-May - 09-Sep</td>
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</table>

The following are the operation periods for the hand-held sunphotometers during 1994, 1995, and 1996 BOREAS campaigns. Gaps may indicate extended cloudy conditions, instrument problems, or operator unavailability.

<table>
<thead>
<tr>
<th>1994 OPERATION PERIODS</th>
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<tr>
<td>04-Jan - 03-Mar, 22-Mar - 26-Sep, 10-Oct - 22-Dec</td>
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<td>Thompson, MB</td>
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<td>01-Jan - 29-Jun, 01-Aug - 21-Oct</td>
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</table>

<table>
<thead>
<tr>
<th>1995 OPERATION PERIODS</th>
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</thead>
<tbody>
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<tr>
<td>01-Jan - 11-Apr, 04-May - 02-Sep, 21-Sep - 08-Oct</td>
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<td>04-Feb - 20-Dec</td>
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<td>03-Jan - 31-Dec</td>
</tr>
</tbody>
</table>

7.2.3 Temporal Resolution
Cimels operated approximately every 15 minutes from morning to evening. Hand-held sunphotometers were operated near noon only.
7.3 Data Characteristics

7.3.1 Parameter/Variable

The parameters contained in the data files on the CD-ROM are:

<table>
<thead>
<tr>
<th>Column Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE_NAME</td>
</tr>
<tr>
<td>SUB_SITE</td>
</tr>
<tr>
<td>DATE_OBS</td>
</tr>
<tr>
<td>TIME_OBS</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_340</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_380</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_440</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_500</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_670</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_870</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_1020</td>
</tr>
<tr>
<td>COLUMN_WATER_VAPOR</td>
</tr>
<tr>
<td>AIR_TEMP</td>
</tr>
<tr>
<td>AIRMASS</td>
</tr>
<tr>
<td>CRFTCN_CODE</td>
</tr>
<tr>
<td>REVISION_DATE</td>
</tr>
</tbody>
</table>

7.3.2 Variable Description/Definition

The descriptions of the parameters contained in the data files on the CD-ROM are:

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE_NAME</td>
<td>The identifier assigned to the site by BOREAS, in the format SSS-TTT-CCCCC, where SSS identifies the portion of the study area: NSA, SSA, REG, TRN, and TTT identifies the cover type for the site, 999 if unknown, and CCCCC is the identifier for site, exactly what it means will vary with site type.</td>
</tr>
<tr>
<td>SUB_SITE</td>
<td>The identifier assigned to the sub-site by BOREAS, in the format GGGGG-IIIII, where GGGGG is the group associated with the sub-site instrument, e.g. HYD06 or STAFF, and IIIII is the identifier for sub-site, often this will refer to an instrument.</td>
</tr>
<tr>
<td>DATE_OBS</td>
<td>The date on which the data were collected.</td>
</tr>
<tr>
<td>TIME_OBS</td>
<td>The Greenwich Mean Time (GMT) when the data were collected.</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_340</td>
<td>The aerosol optical thickness measured between 0.339 and 0.341 micrometers.</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_380</td>
<td>The aerosol optical thickness measured at 0.380 micrometers.</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_440</td>
<td>The aerosol optical thickness measured between 0.438 and 0.441 micrometers.</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_500</td>
<td>The aerosol optical thickness measured at 0.499 or 0.500 micrometers.</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_670</td>
<td>The aerosol optical thickness measured between 0.666 and 0.670 micrometers.</td>
</tr>
</tbody>
</table>
### 7.3.3 Unit of Measurement

The measurement units for the parameters contained in the data files on the CD-ROM are:

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE_NAME</td>
<td>[none]</td>
</tr>
<tr>
<td>SUB_SITE</td>
<td>[none]</td>
</tr>
<tr>
<td>DATE_OBS</td>
<td>[DD-MON-YY]</td>
</tr>
<tr>
<td>TIME_OBS</td>
<td>[HHMM GMT]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 340</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 380</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 440</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 500</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 670</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 870</td>
<td>[unitless]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 1020</td>
<td>[unitless]</td>
</tr>
<tr>
<td>COLUMN WATER VAPOR</td>
<td>[grams][millimeter^-2]</td>
</tr>
<tr>
<td>AIR_TEMP</td>
<td>[degrees Celsius]</td>
</tr>
<tr>
<td>AIRMASS</td>
<td>[unitless]</td>
</tr>
<tr>
<td>CRTFCN_CODE</td>
<td>[none]</td>
</tr>
<tr>
<td>REVISION_DATE</td>
<td>[DD-MON-YY]</td>
</tr>
</tbody>
</table>

### 7.3.4 Data Source

The sources of the parameter values contained in the data files on the CD-ROM are:

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE_NAME</td>
<td>[Assigned by BORIS Staff]</td>
</tr>
<tr>
<td>SUB_SITE</td>
<td>[Assigned by BORIS Staff]</td>
</tr>
<tr>
<td>DATE_OBS</td>
<td>[Cimel sunphotometers, Miami hand-held sunphotometers]</td>
</tr>
<tr>
<td>TIME_OBS</td>
<td>[Cimel sunphotometers, Miami hand-held sunphotometers]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 340</td>
<td>[Cimel sunphotometers, Miami hand-held sunphotometers]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 380</td>
<td>[Cimel sunphotometers, Miami hand-held sunphotometers]</td>
</tr>
<tr>
<td>AEROSOL OPT THICK 440</td>
<td>[Cimel sunphotometers, Miami hand-held sunphotometers]</td>
</tr>
</tbody>
</table>
### 7.3.5 Data Range

The following table gives information about the parameter values found in the data files on the CD-ROM.

<table>
<thead>
<tr>
<th>Column Name</th>
<th>Minimum Data Value</th>
<th>Maximum Data Value</th>
<th>Missng Data Value</th>
<th>Unrel Data Value</th>
<th>Below Detect Limit</th>
<th>Data Limit</th>
<th>Collectd</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE_NAME</td>
<td>NSA-999-WTH01</td>
<td>TRN-999-FFN02</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>SUB_SITE</td>
<td>RSS11-SPH01</td>
<td>RSS11-SPH01</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>DATE_OBS</td>
<td>01-JAN-94</td>
<td>30-DEC-96</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>TIME_OBS</td>
<td>0</td>
<td>2359</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_340</td>
<td>0.015899</td>
<td>6.079923</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_380</td>
<td>0.017223</td>
<td>6.168681</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_440</td>
<td>0.008924</td>
<td>5.590672</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_500</td>
<td>0.000247</td>
<td>5.315648</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_670</td>
<td>0.000386</td>
<td>3.080577</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_870</td>
<td>0.000049</td>
<td>3.084524</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>AEROSOL_OPT_THICK_1020</td>
<td>0.000005</td>
<td>3.109977</td>
<td>-999</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>COLUMN_WATER_VAPOR</td>
<td>0.61</td>
<td>53.06</td>
<td>-999</td>
<td>-888</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>AIR_TEMP</td>
<td>-34.8</td>
<td>41.3</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>AIRMASS</td>
<td>1.16</td>
<td>7.08</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Blank</td>
<td>None</td>
</tr>
<tr>
<td>CRTFCN_CODE</td>
<td>CPI</td>
<td>CPI</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>REVISION_DATE</td>
<td>30-DEC-96</td>
<td>17-JUN-97</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Minimum Data Value -- The minimum value found in the column.

Maximum Data Value -- The maximum value found in the column.

Missng Data Value -- The value that indicates missing data. This is used to indicate that an attempt was made to determine the parameter value, but the attempt was unsuccessful.

Unrel Data Value -- The value that indicates unreliable data. This is used to indicate an attempt was made to determine the parameter value, but the value was deemed to be unreliable by the analysis personnel.

Below Detect Limit -- The value that indicates parameter values below the instruments detection limits. This is used to indicate that an attempt was made to determine the parameter value, but the analysis personnel determined...
that the parameter value was below the detection limit of the instrumentation.

Data Not Collected -- This value indicates that no attempt was made to determine the parameter value. This usually indicates that BORIS combined several similar but not identical data sets into the same data base table but this particular science team did not measure that parameter.

Blank -- Indicates that blank spaces are used to denote that type of value.

N/A -- Indicates that the value is not applicable to the respective column.

None -- Indicates that no values of that sort were found in the column.

7.4 Sample Data Record
The following is a sample of the first few records from a sample data table on the CD-ROM:

**Automatic Sunphotometer Data**
SITE_NAME, SUB_SITE, DATE_OBS, TIME_OBS, AEROSOL_OPT_THICK_340, AEROSOL_OPT_THICK_380, AEROSOL_OPT_THICK_440, AEROSOL_OPT_THICK_500, AEROSOL_OPT_THICK_670, AEROSOL_OPT_THICK_870, AEROSOL_OPT_THICK_1020, COLUMN_WATER_VAPOR, AIR TEMP, AIRM ASS, CRTFCN_CODE, REVISION DATE

**Handheld Sunphotometer Data**
SITE_NAME, SUB_SITE, DATE_OBS, TIME_OBS, AEROSOL_OPT_THICK_340, AEROSOL_OPT_THICK_380, AEROSOL_OPT_THICK_440, AEROSOL_OPT_THICK_500, AEROSOL_OPT_THICK_670, AEROSOL_OPT_THICK_870, AEROSOL_OPT_THICK_1020, COLUMN_WATER_VAPOR, AIR TEMP, AIRM ASS, CRTFCN_CODE, REVISION DATE
'SSA-999-WSK01', 'RSSII-SPH01', 04-MAY-94, 1712, .., .08099, .071275, .033016, .386, 1.66, 'CPI', 17-JUN-97
'SSA-999-WSK01', 'RSSII-SPH01', 04-MAY-94, 1714, .., .081449, .070921, .032415, .391, 1.65, 'CPI', 17-JUN-97

8. Data Organization

8.1 Data Granularity
The smallest unit of data that is tracked by BORIS is all of the data for a given day at a given site.

8.2 Data Format(s)
The Compact Disk-Read-Only Memory (CD-ROM) files contain American Standard Code for Information Interchange (ASCII) numerical and character fields of varying length separated by commas. The character fields are enclosed with single apostrophe marks. There are no spaces between the fields.

Each data file on the CD-ROM has four header lines of Hyper-Text Markup Language (HTML) code at the top. When viewed with a Web browser, this code displays header information (data set title, location, date, acknowledgments, etc.) and a series of HTML links to associated data files and related data sets. Line 5 of each data file is a list of the column names, and line 6 and following lines contain the actual data.
9. Data Manipulations

9.1 Formulae

<table>
<thead>
<tr>
<th>Equation</th>
<th>Used For:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_\lambda = V_o \cdot R^2 \cdot e^{-(m \cdot \tau)}$</td>
<td>Calculation of optical depth</td>
</tr>
<tr>
<td>$T_w = e^{-a \cdot m^b \cdot W^b}$</td>
<td>Calculation of precipitable water</td>
</tr>
<tr>
<td>$\ln V + m \cdot \tau = \ln(V_o) - a \cdot m^b \cdot W^b$</td>
<td>Calibration of water vapor channel</td>
</tr>
<tr>
<td>$\alpha = -\left(\frac{\Delta \ln \tau}{\Delta \ln \lambda}\right)$</td>
<td>Cloud-screening procedure</td>
</tr>
</tbody>
</table>

9.1.1 Derivation Techniques and Algorithms

Optical thickness is calculated from spectral extinction of direct beam radiation at each wavelength based on Beer's Law:

$$V_\lambda = R^2 \cdot e^{-(m \cdot \tau)}$$

where: $V_\lambda =$ digital voltage measured at wavelength $\lambda$  
$m =$ optical airmass  
$\tau =$ total optical thickness  
$R =$ relative Earth-Sun distance

Attenuation due to Rayleigh scatter and absorption by ozone and gaseous pollutants is estimated and removed to isolate the AOT ($\tau$).

The dependence of transmission, $T_w$, on water column abundance can be written as the following [Halthore et al., 1992, Bruegge et al., 1992]:

$$T_w = e^{-a \cdot m^b \cdot W^b}$$

where: $W =$ vertical column abundance (cm)  
a, b = constants that depend on the wavelength position, width and shape of the filter function, and atmospheric conditions.

Sky radiance measurements are inverted with radiative transfer equations [Nakajima et al., 1983] to provide aerosol properties of size distribution and phase function over the particle size range of 0.1 to 5 $\mu$m.
9.2 Data Processing Sequence

9.2.1 Processing Steps

The automatic radiometers acquire data regardless of sky conditions, except for rain, and thus require cloud-screening procedures. Three quality control schemes are considered to reject data obtained under marginal conditions. The Cimels perform three scan sequences spaced 30 seconds apart, and thus acquire three AOT measurements at each wavelength. If any of these triplets exhibit a coefficient of variation of more than 12%, the data derived from all channels are rejected. Secondly, data exhibiting an increasing or nearly flat AOT with wavelength between 440 nm and 870 nm are considered cloud-contaminated. Therefore, data with an Angstrom coefficient, a, of less than or equal to zero are removed. The Angstrom coefficient is calculated by:

\[ \alpha = -\left( \frac{\Delta \ln \tau}{\Delta \ln \lambda} \right) \]

for \( \tau \) at 440 nm and 870 nm, where \( \lambda \) is wavelength.

Finally, the remaining data are plotted along with the direct Sun observations acquired during almucantar measurements exhibiting high azimuthal symmetry about the solar plane, which are expected to represent cloudless conditions. A regression line through these almucantar observations is plotted as well. The abscissa shows the AOT at 440 nm, while the ordinate depicts the ratio of this AOT to the Angstrom coefficient described above. The core of the remaining data set is found to follow the trend of the almucantar regression, and outliers are removed by subjectively drawn polygons.

Data from the hand-held sunphotometers are cloud-screened in a similar, but less rigorous, manner because the manual instruments do not take triplet measurements. The same plotting technique is used with axes of \( x: \) [500-nm AOT] and \( y: \) [500-nm / \( a \) (500/870)], although no almucantar measurements are available to plot simultaneously.

9.2.2 Processing Changes

None.

9.3 Calculations

None.

9.3.1 Special Corrections/Adjustments

None.

9.3.2 Calculated Variables

Water vapor, AOT.

9.4 Graphs and Plots

None.
10. Errors

10.1 Sources of Error

<table>
<thead>
<tr>
<th>Error</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking misalignment</td>
<td>Overestimation of AOT and/or reduced reproducibility</td>
</tr>
<tr>
<td>Filter degradation</td>
<td>Generally underestimation of AOT</td>
</tr>
<tr>
<td>Detector response</td>
<td>Over- or underestimation of AOT</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>Over- or underestimation of AOT at 1020 nm</td>
</tr>
<tr>
<td>Collimator obstruction</td>
<td>Overestimation of AOT</td>
</tr>
<tr>
<td>Failure to find peak response</td>
<td>Overestimation of AOT</td>
</tr>
</tbody>
</table>

10.2 Quality Assessment

All data have been cloud-screened and checked for almucantar symmetry.

10.2.1 Data Validation by Source

Pre/postdeployment intercomparison was made with reference instruments, pre/postdeployment filter calculations were made, and agreement of proximal instruments was verified.

10.2.2 Confidence Level/Accuracy Judgment

Data are generally good, with an absolute AOT accuracy of typically ±0.02 for the automatic sunphotometers and ±0.04 for the hand-held sunphotometers. Precipitable water measurements have agreed within 10% of radiosonde measurements [Halthore et al., 1997].

10.2.3 Measurement Error for Parameters and Variables

The Cimels make three direct Sun measurements at each wavelength in a 30-second scan sequence. This group of three measurements is referred to as a triplet. The coefficient of variability of the triplets for three reference instruments deployed at Mauna Loa was calculated based on 168, 264, and 288 observations, respectively. For all wavelengths, the variability of a triplet was always less than 1%, and generally about 0.3%, giving an estimate of the instrument’s reproducibility [Holben et al., 1996]. The calibration coefficients, Vo, are usually determined by averaging the y-intercepts from three to seven Langley plots at Mauna Loa Observatory. The averaged Vo values from all calibration sessions at Mauna Loa have a coefficient of variability of -0.25% to 0.5% for the visible and near-infrared wavelengths, -0.5% to 2% for the ultraviolet, and -1.0% to 3.0% for the water vapor channel [Holben et al., 1996]. The overall accuracy of AOT measurements is expected to be in the range of ±0.02 at an airmass of 1.0. The hand-held sunphotometers were calibrated by intercomparison with colocated Cimels. The estimated level of uncertainty for these instruments is greater (0.04) because of less frequent recalibration. For the sky radiance measurements, calibration was performed at the NASA GSFC Calibration Facility using a calibrated integrating sphere to an accuracy of ±/- 5%. For the 940-nm channel that includes water absorption, calibration was performed using a variant of the modified Langley method as described in Halthore et al. [1997]. The method used is similar to that described elsewhere; for instance, Bruegge et al., 1992b, and Halthore et al., 1992b. Column amounts of precipitable water derived from sunphotometer measurements at BOREAS have compared favorably with radiosonde observations [Halthore et al., 1997] to within ±/- 10%.

10.2.4 Additional Quality Assessments

None given.

10.2.5 Data Verification by Data Center

BORIS personnel have reviewed portions of the actual parameter values and generated plots for use in visually spotting any anomalous values.

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11. Notes

11.1 Limitations of the Data
None given.

11.2 Known Problems with the Data
Most data are good, though occasionally the AOT at 1020 nm will exceed that at 870 nm, or the AOT at 500 nm will exceed that at 440 nm for very low aerosol conditions (AOT 500 < 0.04), when sensitivity to aerosol is minimal and calibration errors are greatly accentuated. Most of the apparent errors are on the order of 0.01 in AOT, so it is typically a minor concern. On most instruments, the 340- and 380-nm channels are less reliable than the longer wavelengths, likely because of the nature of the filter design, and at times, they yield AOT values that are lower for 340 nm than 380 nm.

Triplet variation is larger for instrument #31, which is currently suspected to result from a 4-quadrant detector that is misaligned or otherwise functioning inadequately. Similar problems in other instruments at GSFC not involved with BOREAS are being investigated.

11.3 Usage Guidance
None given.

11.4 Other Relevant Information
None given.

12. Application of the Data Set
The AOT data can be used as input for standard radiative transfer programs such as LOW-resolution Radiative Transfer Code (LOWTRAN-7), MODerate Resolution Radiative Transfer Code (MODTRAN), or the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) to perform atmospheric correction of remotely sensed data.

13. Future Modifications and Plans
Possible fully objective cloud-screening routine.

14. Software

14.1 Software Description
"Demonstrat" is a package of user-friendly UNIX software developed at GSFC used for data analysis and can be found at spamer.gsfc.nasa.gov.

Within Demonstrat, the raw data (voltages) are converted to AOT or precipitable water using the relevant instrument-specific calibration coefficients.

14.2 Software Access
Guest accounts are available and accessible via X-term window. Contact persons: Brent Holben (Brent.N.Holben.l@gsfc.nasa.gov) or Ilya Slutsker (Ilya.Slutsker.l@gsfc.nasa.gov).
15. Data Access

The RSS-11 sunphotometer data are available from the Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

15.1 Contact Information
For BOREAS data and documentation please contact:

ORNL DAAC User Services
Oak Ridge National Laboratory
P.O. Box 2008 MS-6407
Oak Ridge, TN 37831-6407
Phone: (423) 241-3952
Fax: (423) 574-4665
E-mail: ornldaac@ornl.gov or ornl@eos.nasa.gov

15.2 Data Center Identification
Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics

15.3 Procedures for Obtaining Data
Users may obtain data directly through the ORNL DAAC online search and order system [http://www-eosdis.ornl.gov/] and the anonymous FTP site [ftp://www-eosdis.ornl.gov/data/] or by contacting User Services by electronic mail, telephone, fax, letter, or personal visit using the contact information in Section 15.1.

15.4 Data Center Status/Plans
The ORNL DAAC is the primary source for BOREAS field measurement, image, GIS, and hardcopy data products. The BOREAS CD-ROM and data referenced or listed in inventories on the CD-ROM are available from the ORNL DAAC.

16. Output Products and Availability

16.1 Tape Products
None.

16.2 Film Products
None.

16.3 Other Products
These data are available on the BOREAS CD-ROM series.
17. References

17.1 Platform/Sensor/Instrument/Data Processing Documentation
None.

17.2 Journal Articles and Study Reports


17.3 Archive/DBMS Usage Documentation

None.
18. Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol optical depth</td>
<td>A dimensionless measure of the extinction of the direct solar beam due to scattering and absorption by atmospheric particulates.</td>
</tr>
<tr>
<td>Air mass</td>
<td>Approximately equal to 1/cos(solar zenith angle)</td>
</tr>
<tr>
<td>Almucantar</td>
<td>Sun photometer procedure that measures the sky radiance in four spectral bands (440, 670, 870, and 1020 nm) at constant solar zenith angle, with varied azimuth angles ranging from 0.25-degree intervals near the solar azimuth position to 10-degree intervals far from the solar azimuth position.</td>
</tr>
<tr>
<td>Asymmetry parameter</td>
<td>Average cosine of the scattering angle weighted by the phase function.</td>
</tr>
<tr>
<td>Phase function</td>
<td>A dimensionless measure of the relative scattering intensity of a particle as a function of angle relative to the original propagation direction.</td>
</tr>
<tr>
<td>Rayleigh scatter</td>
<td>Scatter of solar energy by gaseous molecules that is highly predictable for a given atmospheric pressure.</td>
</tr>
</tbody>
</table>

19. List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>6S</td>
<td>Second Simulation of the Satellite Signal in the Solar Spectrum</td>
</tr>
<tr>
<td>AOT</td>
<td>Aerosol Optical Thickness</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>BOREAS</td>
<td>BOREal Ecosystem-Atmosphere Study</td>
</tr>
<tr>
<td>BORIS</td>
<td>BOREAS Information System</td>
</tr>
<tr>
<td>CCRS</td>
<td>Canada Centre for Remote Sensing</td>
</tr>
<tr>
<td>CD-ROM</td>
<td>Compact Disk-Read-Only Memory</td>
</tr>
<tr>
<td>DAAC</td>
<td>Distributed Active Archive Center</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observing Satellite</td>
</tr>
<tr>
<td>EOSDIS</td>
<td>EOS Data and Information System</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GMT</td>
<td>Greenwich Mean Time</td>
</tr>
<tr>
<td>GOES</td>
<td>Geostationary Operational Environmental Satellite</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>HTML</td>
<td>HyperText Markup Language</td>
</tr>
<tr>
<td>LOWTRAN</td>
<td>LOW resolution radiative TRANSfer code</td>
</tr>
<tr>
<td>MODTRAN</td>
<td>MODerate resolution radiative TRANSfer code</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NSA</td>
<td>Northern Study Area</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>PANP</td>
<td>Prince Albert National Park</td>
</tr>
<tr>
<td>RSS</td>
<td>Remote Sensing Science</td>
</tr>
<tr>
<td>SSA</td>
<td>Southern Study Area</td>
</tr>
<tr>
<td>URL</td>
<td>Uniform Resource Locator</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>YJP</td>
<td>Young Jack Pine</td>
</tr>
</tbody>
</table>
20. Document Information

20.1 Document Revision Date
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When using these data, please include the following acknowledgment as well as citations of relevant papers in Section 17.2:

If using data from the BOREAS CD-ROM series, also reference the data as:

Also, cite the BOREAS CD-ROM set as:

20.5 Document Curator

20.6 Document URL
The BOREAS RSS-11 team operated a network of five automated (Cimel) and two hand-held (Miami) solar radiometers from 1994 to 1996 during the BOREAS field campaigns. The data provide aerosol optical depth measurements, size distribution, phase function, and column water vapor amounts over points in northern Saskatchewan and Manitoba, Canada. The data are useful for the correction of remotely sensed aircraft and satellite images. The data are provided in tabular ASCII files.