Aerosol Optical Depth for Atmospheric Correction of AVHRR Composite Data

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RÉSUMÉ

Le système de géocodage et de composition (GeoComp-n) du Centre canadien de télédétection (CCT) sert à traiter les données de la série des satellites porteurs de radiomètres perfectionnés à très haut pouvoir de résolution (AVHRR) de la National Oceanic and Atmospheric Administration (NOAA) des États-Unis. Le système GeoComp-n produit des cartes composées monodates ou multidates de la réflectance de la surface de la masse continentale canadienne dans les bandes spectrales du visible et du proche infrarouge à une résolution spatiale de 1 km. Les données doivent d'abord être traitées en unités géophysiques exactes pour permettre l'utilisation de ces cartes et des produits dérivés dans le cadre de diverses études du changement climatique planétaire et de la couverture terrestre. Dans le cas des données de satellites, cela exige non seulement un étalonnage radiométrique exact, mais également l'application aux données d'images de la correction appropriée des effets atmosphériques. L'épaisseur optique des aérosols est l'un des paramètres clés nécessaires pour la correction effets atmosphériques. Le Réseau de photomètres solaires canadien (AEROCAN) fournit une couverture éparse, mais en temps quasi-réel (saisonnière), de l'épaisseur optique des aérosols sur l'ensemble du Canada. L'un des objectifs du projet AEROCAN est l'établissement d'une climatologie des aérosols utilisable pour la correction opérationnelle des effets atmosphériques dans les données des satellites.

Dans ces notes de recherche on examine les archives actuellement détenues dans la base de données après dénubélisation sur les aérosols de l'AEROCAN. Les tables de données et les profils saisonniers présentés appuient la conclusion voulant que, pour le moment, l'utilisation d'une unique épaisseur optique invariable en fonction du temps pour l'ensemble du Canada est très acceptable pour la correction opérationnelle de premier ordre des effets atmosphériques dans les données d'images composites de l'AVHRR. La meilleure estimation de cette épaisseur optique des aérosols à une longueur d'onde de 500 nm (AOD500) est de 0,07 avec une incertitude de +0,07 à –0,035. Cette épaisseur optique des aérosols à une longueur d'onde de 550 nm (AOD550) est de 0,062 avec une incertitude de +0,062 à –0,031.

SUMMARY

The Canada Centre for Remote Sensing (CCRS) Geocoding and Compositing system (GeoComp-n) processes the Advanced Very High Resolution Radiometer (AVHRR) data from the United States National Oceanic and Atmospheric Administration (NOAA) series of satellites. The GeoComp-n system produces single- or multi-date composite maps of surface reflectance of the Canada landmass in the AVHRR visible and near-infrared spectral bands at a spatial resolution of 1 km. The data must first be processed into accurate geophysical units in order to utilize these maps and their derived products for various global climate and land cover change studies. In the case of satellite data, this not only implies the accurate radiometric calibration but also the proper atmospheric correction of image data. One of the key parameters required for atmospheric correction is the aerosol optical depth. The Canadian sunphotometer network, AEROCAN, provides spatially sparse but near real-time (seasonal) aerosol optical depth coverage across Canada. One of the goals of AEROCAN is to develop an aerosol climatology that can be used for operational atmospheric correction of satellite data.

This research note reviews the current holdings in the AEROCAN aerosol database after cloud screening. The data tables and seasonal profiles presented support the conclusion at this time that a single, Canada-

wide, time-invariant optical depth is acceptable for the first order operational atmospheric correction of AVHRR composite image data. The best estimate of this aerosol optical depth at a wavelength of 500 nm (AOD500) is 0.07, with an uncertainty of +0.070/-0.035, as generated from the AEROCAN database. This corresponds to an aerosol optical depth at a wavelength of 550 nm (AOD550) of 0.062, with an uncertainty of +0.062/-0.031, for purposes of the atmospheric correction code in GeoComp-n. A sensitivity study demonstrates that this uncertainty in AOD500 produces an absolute error in surface reflectance of ±1% for the worst case of a black spruce forest, which is acceptable for GeoComp-n with an accuracy requirement of ±5%.

INTRODUCTION

The CCRS GeoComp-n system (Adair *et al.*, 2000) has processed NOAA 14 AVHRR data from 1993 to 1999 into 10-day composite maps of surface reflectance and temperature across the Canada landmass. Cihlar *et al.* (1998) assessed the impact of atmospheric correction on inter-annual global change studies. Atmospheric correction is required to generate surface reflectance data in the visible and near-infrared bands from the top-of-atmosphere radiance data. The Simplified Method for the Atmospheric Correction (SMAC) radiative transfer code (Rahman and Dedieu, 1994) corrects the calibrated radiance data for atmospheric effects in a coarse average fashion by applying nominal values of atmospheric parameters. A number of such atmospheric parameters must be defined. Of these the aerosol optical depth and water vapour content are the most variable in space and time. While the AEROCAN network can provide information on both of these atmospheric constituents, this research note is dedicated to the estimation of aerosol optical depth for operational correction of AVHRR composite data.

In this research note, we review the current state of knowledge on aerosol measurements. We then look at the AEROCAN network as the prime source of aerosol optical properties for Canada. This leads to a discussion on the generation of an aerosol database with cloud screening. We then present monthly modal statistics to estimate the AOD500 under clear sky conditions. This follows with a sensitivity study to assess the absolute errors in surface reflectance for typical ground targets when specifying different AOD500 values for atmospheric correction. This research note concludes by recommending an AOD500 for operational correction of AVHRR composite data across the Canada landmass.

BACKGROUND ON AEROSOLS

Aerosols modify the satellite signal in two opposite ways: (i) they increase the signal, by adding a term called the atmospheric reflectance that represents the amount of light backscattered towards the satellite sensor by the intervening aerosols and molecular gases; and (ii) they attenuate the signal and disperse the amount of light that reaches the ground and eventually returns to the satellite. Atmospheric radiative transfer codes such as SMAC use the aerosol optical depth to compute the two components. An over-estimation of the aerosol optical depth will result in possible negative surface reflectances for dark targets such as clear lakes. An under-estimation of the aerosol optical depth will result in surface reflectances that are nominally brighter than the actual reflectances, again, for dark targets such as boreal forests.

The origins of aerosols are both natural (sea salt, soil dust particles, biogenic gas oxidation products, volcanic) and anthropogenic (sulphur oxides, black carbon, organic gas oxidation products). The knowledge of the spatial and temporal extent of aerosol concentration is very limited and uncertain (Houghton *et al.*, 1995). Moreover, since the beginning of the industrial era, the emission rate of anthropogenic aerosols such as sulphate (Benkovitz *et al*., 1996) has increased constantly as has aerosol loading generated by land surface modification such as soil erosion or biomass burning (Tegen *et al.,* 1996). In recent times, remote sensing has been used to map aerosols in the troposphere (King *et al.,* 1999).

In certain cases the aerosols display peak concentrations during the summer (Markham *et al*., 1997). The variability of aerosols is augmented by the introduction of smoke from forest and grass fires. Between the increase in natural fires as a possible result of global warming and the increase in anthropogenic fires required to clear additional land for growing crops and grazing animals, global aerosol concentrations may be on the rise. Numerous authors have studied the impact of biomass burning on aerosols. Ferrare *et al.* (1990) have investigated the use of satellite remote sensing. Holben *et al.* (1996) have applied sunphotometry to monitor biomass burning.

In terms of global warming, the Arctic has always been looked to for first signs of weather/climate change. With respect to aerosol studies in the Canadian Arctic, sunphotometer measurements have been made consistently throughout the year by several investigators (Shaw, 1982; Freund, 1983; Robinson, 1962). Shaw and Khalil (1989) reviewed the Arctic aerosol data in their publication on Arctic haze. A typical effect of global pollution is the pollution-derived climate in the Arctic. The compounds of the northern polar atmosphere undergo a strong and repeatable annual variation, with a maximum mass loading between February and April (Smirnov *et al.*, 1996; Barrie, 1986). It is well know that the jet stream can carry air pollution from mid-latitude Eurasia into the Alaskan Arctic. Some studies in Alaska have revealed that aerosol particles responsible for such air pollution have their origin outside of Alaska (Tyson, 1990; Stonehouse, 1986). The seasonal variation in aerosol optical depth at Resolute in the Canadian Arctic as reported by McGuffie *et al*. (1985) is similar to what Shaw and Khalil reported for Alaska. A mean AOD500 of 0.1 was observed from March to May decreasing to less than 0.02 in summer. The low aerosol optical depth in summer contributes to clear sky conditions that closely approximate a Rayleigh atmosphere with minimal tropospheric aerosols.

AEROCAN SUNPHOTOMETER NETWORK

The Canadian sunphotometer network, AEROCAN (World Wide Web home page at http://callisto.si.usherb.ca/~abokoye/aerocan_index.html), is a source of aerosol optical depth data. The AEROCAN network consists of eight autonomous CIMEL™ CE-318 sky/sun-scanning radiometers (Bokoye *et al.*, 2000). The AEROCAN sunphotometer sites are strategically located. These sites with their start-up year listed in brackets are as follows: Waskesiu, Saskatchewan (1994); Thompson, Manitoba (1994); Sherbrooke, Québec (1995); Egbert, near Toronto, Ontario (1996); Bratt's Lake, Saskatchewan (1996); Saturna Island, British Columbia (1997); Kejimkujik National Park, Nova Scotia (1998); and Churchill, Manitoba (1999).

The Canada Centre for Remote Sensing (CCRS) at Natural Resources Canada initiated AEROCAN in 1995. The remote sensing group (CARTEL) at the Université de Sherbrooke manages the network. CCRS, the Meteorological Service of Canada (MSC) at Environment Canada, the Natural Sciences and Engineering Research Council (NSERC), and the Université de Sherbrooke provide funding for the Canadian network. The National Aeronautics and Space Administration’s Goddard Space Flight Center (NASA/GSFC) provide in-kind support. NASA/GSFC (Holben *et al.*, 1998) process and archive the data from this network as part of the global AERONET (AErosol RObotic NETwork) (World Wide Web home page at http://aeronet.gsfc.nasa.gov:8080/). NASA/GSFC jointly manage the Waskesiu and Thompson stations as part of AERONET. A ninth CIMEL sunphotometer serves as a swap-out instrument when periodic calibrations are performed on AEROCAN network instruments at NASA/GSFC.

AEROCAN's mission is to acquire sufficient spatial and temporal data to develop and validate a Canadian climatology for aerosol optical properties and derived particle size parameters. This climatology is targeted towards atmospheric correction applications in remote sensing and towards the development of a validated Northern Aerosol Regional Climate Model (NARCM) (Spacek *et al*., 2000).

AEROSOL DATABASE GENERATION

AERONET is an optical ground-based network for aerosol monitoring supported by NASA's Earth Observing System and expanded into a global federation with the participation of many non-NASA institutions. The network hardware consists of identical automatic sun-sky scanning spectral radiometers owned by national agencies and universities. AEROCAN is an affiliate of this global network, and as such operates under similar measurement protocols (Holben *et al.*, 1998).

The CIMEL instruments collect sun and sky radiance data at predetermined times across eight spectral bands (with wavelength centres at 340, 380, 440, 500, 670, 870, 940 and 1020 nm). The NASA/GSFC AERONET facility processes and archives these data according to a standardized procedure for the retrieval of aerosol properties. These aerosol properties include aerosol spectral optical depths, single scattering albedo, refractive index (real and imaginary part) at 440, 670, 870 and 1020 nm, aerosol size distributions, and precipitable water vapour in diverse aerosol regimes. The method used to generate the total spectral optical depth is based on measuring the spectral extinction of the direct beam radiation according to the Beer-Lambert-Bouguer law as described by Holben *et al.* (1998). The total spectral optical depth is the sum of the Rayleigh and aerosol optical depth after correction for the transmission of absorbing gases.

Bruegge *et al.* (1992), Thome *et al.* (1992), Markham *et al.* (1997), and Halthore *et al*. (1997) have investigated the recovery of precipitable water vapour content from sunphotometer data. Like aerosol optical depth, the precipitable water vapour content is highly variable in space and time. It is typically a second order input to the atmospheric correction of satellite data in the visible and near-infrared bands, since remote sensing bands are typically chosen to avoid spectral regions characterized by significant water vapour absorption (the AVHRR near-infrared band being a notable exception). While water vapour data are available from the AEROCAN network, the validation of these data remains to be done.

Automatic, globally distributed networks for monitoring aerosol optical depth provide measurements of natural and anthropogenic aerosol loading important in many local and regional studies as well as global change research investigations. The strength of such networks relies on imposing a standardization of measurement and data processing that allows for multi-year and large-scale comparisons. The development of AERONET for systematic ground-based sunphotometer measurements of aerosol optical depth is an essential and evolving step in this process. The growing database requires the development of a consistent, reproducible and system-wide cloud screening procedure. For manual sunphotometer instruments, it is in principle very easy to deal with the presence of clouds. Human observers can detect clouds based on subtle textural and spatial patterns and therefore they normally do not make observations under those conditions (Kaufman and Fraser, 1983). Deployment of automatic instruments poses the problem of defining an effective cloud screening procedure. Smirnov *et al.* (1999) developed and validated a cloud-screening algorithm, largely based on the filtering of temporal excursions in aerosol optical depth, for the Level I data in the AERONET database as acquired from the network. This intensive cloud screening filters the data to provide a high quality (Level II) dataset. The procedure has been comprehensively tested on experimental data obtained in different geographical regions and under diverse atmospheric conditions. These conditions include biomass burning events in Brazil and Zambia, hazy summer conditions in the Washington DC area, clean air advected from the Canadian Arctic, and variable cloudy conditions.

The cloud screening criteria implemented at NASA/GSFC were modified in this study to retain only very low frequency diurnal variations in aerosol optical depth. Between 30% to 50% of the measurements affected by sub-visible cirrus and thin clouds are removed by applying the three-sigma threshold that is part of the multi-step cloud-screening algorithm. A greater level of low frequency filtering can be accomplished by decreasing the three-sigma threshold. This would increase the probability of retaining only the clearest stable days while potentially removing haze- or smoke-affected measurements that might be useful to aerosol researchers. Rejections of the latter type were concluded to represent low probability events in composite images. Thus, any AOD500 data point that differed from the daily mean AOD500 by more than one sigma was removed for the purpose of this study. Also, any AOD500 data point characterized by an Angstrom coefficient less than or equal to zero was rejected because such values are most likely associated with thin cloud events and/or instrumentally induced spectral artefacts. Finally, any AOD500 data points that were identified visually to be abnormally high (>1.0) though stable were rejected. The filtered AOD500 data set of individual observations was then averaged to yield monthly statistics.

The monthly modal AOD500 data with a bin size of 0.01 rather than the monthly mean AOD500 data were used in this study. The AOD500 for typical clear sky conditions is better represented by the monthly modal value; while the monthly mean value may be biased by a few large AOD500 values. The monthly modal data were visually screened for abnormally high values (>0.20) that might be contaminated by smoke, haze and sub-visible cirrus or caused by instrument problems. These data were removed from the final analysis. The assumption underlying the visual screening is that only pixels from clear days would be used in 10-day composite maps based on the criterion of selecting pixels with maximum NDVI as computed from AVHRR visible band (channel 1) and near-infrared band (channel 2) (Holben, 1986; Cihlar and Huang, 1994). There is the danger that this assumption could be defeated by a long-lived forest fire or hazy air mass.

Possible reasons for the anomalous behaviour of the rejected monthly modal AOD500 data are given here. High monthly modal values for Thompson and Waskesiu in June and July of 1994 and 1995 are attributed to forest fires (Li *et al.*, 1997) in the vicinity. High monthly modal values for Egbert in February and November 1998 are probably due to instrument fogging/frosting or local haze/fog contamination. The high monthly modal values observed for Kejimikujik in March, May (<10 observations) and September of 1999 are probably due to fog/haze or instrument misalignment. High monthly modal values for CARTEL in April 1995 and 1996 may be due to fog/haze and in December 1998 may be due to instrument frosting (<10 observations) or instrument misalignment.

AEROCAN AOD500 RESULTS

The refined monthly modal AOD500 data were analyzed for spatial and temporal trends. While AOD500 data for individual stations for certain months are missing (because no data were collected, the AOD500 data were rejected during the automated cloud screening, or the monthly modal statistics were rejected by visual screening), it was still hoped that seasonal trends could be derived from multi-year analysis.

The monthly modal AOD500 values that were derived from the filtered AEROCAN database and averaged for all the Canadian sites are displayed by month for the period of 1994 to 1999 in Table 1a. Annual averages and multi-year averages by month were computed from the monthly averages and used to generate a grand average for the complete data set. All averages from the monthly modal AOD500 data presented in this study are based on the geometric mean, weighted by the number of monthly values (not shown). In addition, averages for the months of April to October (GeoComp-n operational period) were computed. The sample sizes (number of days and observations) for each value in Table 1a are reported in Table 1b. It is important to note that the monthly statistics were computed directly from all the observations rather than from the daily averages. No significant trends can be observed in the seasonal monthly modal AOD500 data that are displayed for all years in Figure 1.

Averages of monthly modal AOD500 values over the GeoComp-n operational period (April 1 to October 30) are presented by year in Table 2a for each site and for all of Canada. The annual averages by site were used to generate multi-year site averages and a grand average for Canada over all years. Again, the sample sizes (number of days and observations) for each value in Table 2a are reported in Table 2b. The annual and seven-month (GeoComp-n period) monthly modal AOD500 averages are plotted against year in Figure 2. No significant inter-annual changes are observed.

The cumulative histogram distribution of monthly modal AOD500 values is shown in Figure 3. The 151 points are reasonably well distributed with 50% occurring below an AOD500 of 0.065. The steep slope of the curve at AOD500 of 0.05 and 0.065 indicate a clustering of points around these values. This curve might suggest that the final average of the monthly modal data should be based on the median or modal value rather than the geometric mean.

Table 1a.
AOD500 monthly modal statistics averaged for all CIMEL sites in the AEROCAN network

Month	1994	1995	1996	1997	1998	1999	Average
Jan	0.087	0.044	0.099		0.096	0.053	0.072
Feb	0.060	0.036	0.063		0.043	0.052	0.067
Mar	0.057		0.091		0.068	0.057	0.070
Apr	0.064						0.067
May	0.055	0.047	0.159	0.076	0.037	0.097	0.081
Jun	0.085	0.097	0.117	0.055	0.087	0.114	0.091
Jul	0.073	0.089	0.075	0.065	0.066	0.083	0.074
Aug	0.057	0.049	0.048	0.063	0.087	0.083	0.068
Sep	0.058	0.033	0.088	0.058	0.090	0.077	0.067
Oct	0.046	0.038	0.039	0.063	0.067	0.069	0.058
Nov	0.045	0.049		0.042	0.085		0.069
Dec				0.061	0.126		0.106
Annual Average	0.062	0.057	0.084	0.065	0.082	0.076	0.073
Ave. for months 4 to 10	0.061	0.058	0.084	0.062	0.076	0.080	0.072

Table 1b.
Sample size for AOD500 monthly statistics for all CIMEL sites
in the AEROCAN network given in number of days and observations (in brackets)

Month	1994	1995	1996	1997	1998	1999	Total
Jan	3(12)	4(30)	2(26)	0	4(20)	20(185)	33(273)
Feb	6(46)	19(168)	11(119)	0	12(85)	24(319)	72(737)
Mar	6(29)	5(82)	4(74)	0	14(165)	27(631)	56(981)
Apr	16(127)	7(103)	0	0	0	66(1340)	89(1570)
May	12(68)	22(340)	22(540)	1(5)	26(798)	65(1424)	148(3175)
Jun	9(54)	19(560)	51(1021)	51(679)	43(719)	107(2035)	280(5068)
Jul	12(75)	47(892)	59(1324)	102(2000)	88(1852)	157(2773)	465(8916)
Aug	35(630)	57(891)	60(1594)	110(1988)	120(2526)	141(2155)	523(9784)
Sep	24(660)	48(991)	25(385)	96(1909)	87(1472)	51(847)	331(6264)
Oct	2(7)	29(413)	32(436)	69(1163)	49(631)	73(1422)	254(4072)
Nov	2(6)	8(157)	0	20(191)	19(140)	0	49(494)
Dec	0	0	0	25(155)	21(209)	0	46(364)
Annual Total	127(1714)	265(4627)	266(5519)	474(8090)	483(8617)	731(13131)	2346(41698)
Total for months 4 to 10	110(1621)	229(4190)	249(5300)	429(7744)	413(7998)	660(11996)	2090(38849)

Table 2a.
AOD500 monthly modal statistics averaged for April to October (GeoComp composite season)
for each CIMEL site in the AEROCAN network

Year	BRATT'S L.	CARTEL	EGBERT	KEJIMKUJIK	SATURNA IS.	THOMPSON	WASKESIU	Average
1994						0.056	0.063	0.061
1995		0.075				0.056	0.042	0.058
1996		0.045				0.079	0.095	0.084
1997	0.047	0.052	0.080			0.068	0.067	0.062
1998		0.090	0.087	0.072		0.080	0.059	0.076
1999	0.049	0.070	0.088	0.134	0.074	0.075	0.088	0.080
Average	0.048	0.069	0.086	0.103	0.074	0.071	0.069	0.072

Table 2b.
Sample size for AOD500 monthly statistics for April to October (GeoComp composite season)
for each CIMEL site in the AEROCAN network given in number of days and observations (in brackets)

Year	BRATT'S L.	CARTEL	EGBERT	KEJIMKUJIK	SATURNA IS.	THOMPSON	WASKESIU	Total
1994						34(1163)	76(458)	110(1621)
1995		109(2506)				96(1595)	24(89)	229(4190)
1996		13(142)				116(2554)	120(2604)	249(5300)
1997	107(2313)	88(1715)	48(562)			83(932)	94(2222)	420(7744)
1998		47(838)	89(2257)	41(494)		84(960)	141(3449)	402(7998)
1999	120(1934)	125(2650)	180(3516)	44(371)	116(2487)	41(612)	34(426)	660(11996)
Total	227(4247)	382(7851)	317(6335)	85(865)	116(2487)	454(7816)	489(9248)	2070(38849)

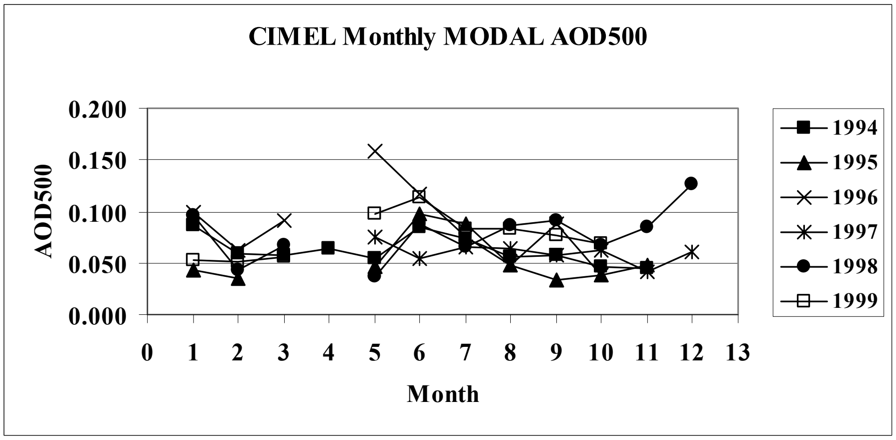

Figure 1. Seasonal trend in monthly modal AOD500 in the various years averaged for all CIMEL sites in the AEROCAN network.

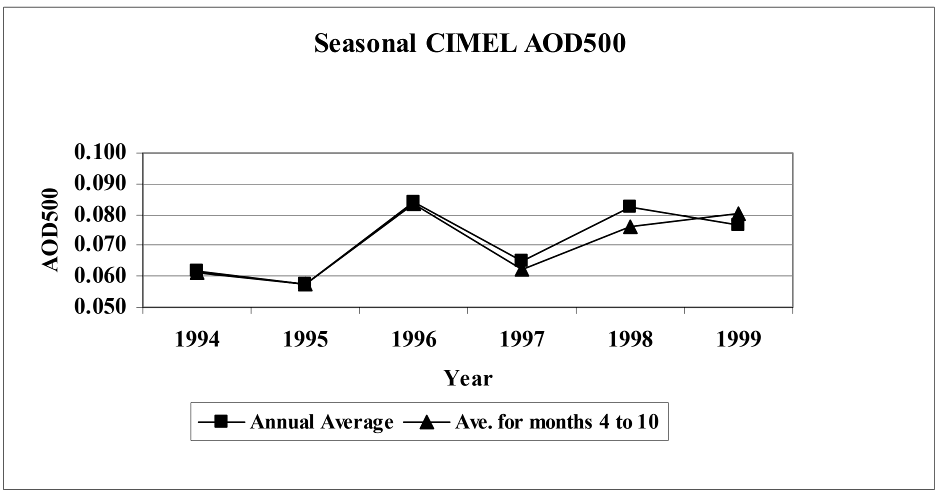

Figure 2. Multi-year trend in monthly modal AOD500 for all CIMEL sites in the AEROCAN network averaged over the year and for the GeoComp operational period.

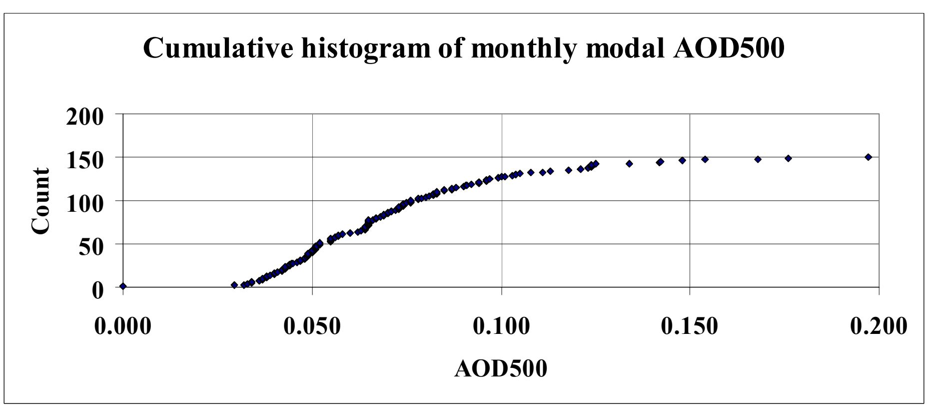

Figure 3. Cumulative histogram of monthly modal AOD500 for all CIMEL sites in the AEROCAN network from all years.

IMPLEMENTATION OF AOD500 RESULTS

Aerosol optical properties can be derived from aerosol transport and chemical models of various degrees of sophistication; but initial conditions of the aerosols must still be defined. Studies have indicated for example that a very simple but useful approach is to relate aerosol optical depth variation to the synoptic air mass (Smirnov *et al*., 1996, Smirnov *et al.*, 1994). For each air mass type, seasonal estimates of the AOD500 can be derived from the network data. If a real-time air mass map could be obtained electronically, then the appropriate AOD500 value could be applied in the operational atmospheric correction of the AVHRR composite data in GeoComp-n. As digital synoptic air mass maps are not operationally available, digital techniques of this nature will be addressed in a future version of the GeoComp-n processing software.

The use of in-situ AOD500 data co-incident with satellite data acquisition or within-scene AOD500 estimation using a multi-altitude approach (Zagolski *et al.*, 1999) would be preferred as a source of AOD500 data. However, adequate spatial coverage for coincident AOD500 data collection is not provided by AEROCAN and further investigation of within-scene AOD500 retrieval methods is required before being deemed operational. In the absence of scene-specific AOD500 data, the possibility of using AOD500 data derived from the AEROCAN network as seasonally varying or a fixed value has been investigated. Based on the existing AEROCAN data set, an average AOD500 of 0.07 was computed from the mean of all the monthly modal values. This AOD500 is deemed representative for most of continental Canada for the GeoComp-n operational period from April 1 to October 31.

As can be observed in Table 1a and Figures 1 and 2, the temporal and spatial distribution of the cloud-screened AOD500 data from all the Canadian sites in the AEROCAN database are insufficient to develop a statistically meaningful aerosol climatology in space or time. There is a lack of spatial coverage by the AEROCAN network in the Canadian Arctic (north of 60 degrees latitude) that represents a large part of the Canada landmass. Uncertainty in the AOD500 for the Arctic can result in surface reflectance retrieval errors. While the snow/ice albedo in the Arctic is important for radiation budget modelling, the Arctic is not critical to vegetation productivity and land cover change studies.

Uncertainties in AOD500 from AERONET of ±0.02 for the Level I aerosol database and ±0.01 for the Level II aerosol database are quoted by Smirnov *et al.* (1999). Based on an average monthly modal value of AOD500 of 0.07, the uncertainty is roughly estimated to be $0.07 \times 2^{\pm 1}$ or +10**(log10(0.07) + log10(2))/-10**(log10(0.07) - log10(2)) which reduces to +0.070/-0.035 (Bokoye *et al.*, 2000). This uncertainty is attributed more to the natural variability of the aerosols rather than the mostly instrumental uncertainty reported by Smirnov.

SENSITIVITY ANALYSIS

The Canadian Advanced Modified 5S (CAM5S) atmospheric radiative transfer code (O'Neill *et al.,* 1996) was used in a sensitivity analysis of the impact of aerosol correction on surface reflectance retrieval for three typical vegetated targets (O'Neill *et al.,* 1997; Zagolski *et al*., 1999). Surface reflectance retrievals were made for atmospheric conditions with no aerosol and with typical values of aerosol optical depth. These values include the recommended aerosol optical depth based on the average monthly modal value for all years and all sites, and the lower and upper bounds for the aerosol optical depth based on the estimated uncertainty. In addition, two terrain elevations (0.0 km and 0.5 km above sea level) and two sun angles (45 degrees and 70 degrees solar zenith angle) were evaluated to represent possible conditions within GeoComp-n composite images. Nadir viewing was assumed (a geometrical condition chosen to mimic typical composite pixel conditions). No attempt was made to represent the extreme or true average conditions to be expected in GeoComp-n composite images. The results of the CAM5S runs for uniform surface targets of lush meadow, native rangeland and black spruce forest are shown in Tables 3, 4 and 5, respectively. The surface reflectance for lush meadow and native rangeland is near the critical reflectance such that atmospheric scattering and absorption results in a surface reflectance similar to the top-of-atmosphere reflectance. NDVI was computed from the difference over the sum of surface reflectances in AVHRR channels 2 and 1, respectively. CAM5S and SMAC require the aerosol optical depth to be specified at 550 nm (AOD550) instead of at 500 nm (AOD500) as retrieved from the AEROCAN network. Transformations between aerosol optical depth at wavelengths of 500 nm and 550 nm were performed assuming a standard power law relationship (using the Angstrom coefficient) for optical depth spectra. For this study, the AOD500 values of 0.035, 0.070 and 0.140 were entered in CAM5S as AOD550 values of 0.031, 0.062 and 0.124, respectively. For the purpose of the discussion on the CAM5S sensitivity analysis, the AOD500 values will be used.

Absolute errors in surface reflectance retrieval in the absence of atmospheric correction were computed for cases where the actual AOD500 was 0.0, 0.035, 0.070 and 0.140. For the lush meadow case, absolute errors of up to +0.3%, -13.0% and –0.108 are observed in the top half of Table 3 for NOAA 14 AVHRR channels 1, 2, and NDVI, respectively, at high solar zenith angles when no atmospheric correction was made (where the actual AOD500 is 0.070). Similarly, for the native rangeland case, absolute errors of up to -0.1%, -5.2% and –0.139 are observed in the top half of Table 4 for NOAA 14 AVHRR channels 1, 2, and NDVI, respectively. As well, for the black spruce forest case, absolute errors of up to +2.8%, -2.3% and –0.371 are observed in the top half of Table 5 for NOAA 14 AVHRR channels 1, 2, and NDVI, respectively. The greater part of the magnitude of the observed errors in channel 2 reflectance and in NDVI are attributed to water vapour effects. The absolute error in channel 1 is largely due to Rayleigh scattering in the absence of aerosols. These results demonstrate the importance of performing atmospheric correction even when aerosol optical depths are low. While accurate specification of AOD500 will improve the surface reflectance in AVHRR channel 1, the uncertainty in estimating the water vapour for atmospheric correction of AVHRR channel 2 still remains.

The retrieval of accurate surface reflectance is determined in part by the estimation of atmospheric parameters such as aerosol optical depth used in the atmospheric correction. Aerosol optical depth is typically variable in space and time. If we limit ourselves to a single fixed value, it is important that this value be judiciously chosen to ensure the retrieval of accurate surface reflectance. The computations in the top half of Tables 3, 4 and 5 are repeated in the bottom half except that an atmospheric correction using the nominal value of AOD500 of 0.070 has been applied. For nadir pixels near sea level, the greatest errors are observed at high solar zenith angles in the case of the atmospherically corrected tabulations.

For lush meadow (Table 3), the uncertainty in AOD500 results in absolute errors in surface reflectance retrieval in the AVHRR channel 1 of +0.1% and –0.2% when the simulated atmosphere was characterized by an AOD500 of 0.035 and 0.140 (uncertainty limits), respectively. Similarly, absolute errors in surface reflectance retrieval for the AVHRR channel 2 are –0.6% and +1.1% for AOD500 of 0.035 and 0.140, respectively. Absolute errors in the Normalized Difference Vegetation Index (NDVI) are –0.008 and +0.018 for an AOD500 of 0.035 and 0.140, respectively.

For dry native rangeland (Table 4), the uncertainty in AOD500 results in absolute errors in surface reflectance retrieval in the AVHRR channel 1 of +0.1% and –0.2% when the simulated atmosphere was characterized by an AOD500 of 0.035 and 0.140 (uncertainty limits), respectively. Similarly, absolute errors in surface reflectance retrieval for the AVHRR channel 2 are -0.1% and +0.2% for AOD500 of 0.035 and 0.140, respectively. Absolute errors in the Normalized Difference Vegetation Index (NDVI) are –0.007 and +0.014 for an AOD500 of 0.035 and 0.140, respectively.

For black spruce forest (Table 5), the uncertainty in AOD500 results in absolute errors in surface reflectance retrieval in the AVHRR channel 1 of +0.3% and –0.6% when the simulated atmosphere was characterized by an AOD500 of 0.035 and 0.140 (uncertainty limits), respectively. Similarly, absolute errors in surface reflectance retrieval for the AVHRR channel 2 are +0.1% and –0.1% for AOD500 of 0.035 and 0.140, respectively. Absolute errors in the Normalized Difference Vegetation Index (NDVI) are –0.025 and +0.050 for an AOD500 of 0.035 and 0.140, respectively.

The sign of the absolute errors would be reversed if the satellite data were corrected with AOD500 of 0.070 while the actual AOD500 was either 0.035 or 0.140. Thus, for cases where the composite data are strongly affected by smoke or haze, the NDVI would be under-estimated by applying an AOD500 of 0.070 in the atmospheric correction in GeoComp-n. Retrieving accurate NDVI is important because the NDVI seasonal curve is used in many land cover and climate change studies, and is often used to estimate annual crop yields.

The uncertainty in AOD500 thus results in an absolute error of no more than ±1% in the surface reflectance. This is acceptable in an operational satellite data correction system that promises an absolute uncertainty of no better than ±5% in surface reflectance, where the major error contribution in the atmospheric correction is expected to be from the estimate of AOD500.

If we accept an absolute error of ±1% in the surface reflectance retrieval due to uncertainties in aerosol optical depth, then the observed distribution of AOD500 values in Table 2 for the various sites in 1999 being within the estimated AOD500 uncertainty does not justify modelling of a spatially dependent aerosol optical depth. Likewise, the seasonal variation over the years remaining within the estimated AOD500 uncertainty does not justify modelling of a time-dependent aerosol optical depth. In the end, given the constraints of a production system as complex as GeoComp-n, one can conclude that a single, Canada-wide aerosol optical depth of 0.07 at 500 nm, although primitive in nature, is appropriate for the atmospheric correction of AVHRR composite data during the growing season.

Table 3. CAM5S sensitivity study on AOD500 correction of NOAA 14 AVHRR data for lush meadow

CAM5S nominal input parameters:
Mid-latitude summer atmosphere model (water vapour = 2.93 gm/cm^2, ozone = 0.319 cm-atm)
Continental aerosol model
Lush meadow as uniform surface target
Channel 1 surface reflectance = 0.1198
Channel 2 surface reflectance = 0.5086
Surface NDVI = 0.6187
Nadir viewing (GeoComp composite pixel selection favours nadir pixels)

Terrain Elevation = 0.0 km ASL						
Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.001	-0.098	-0.072	0.001	-0.119	-0.093
0.035	0.001	-0.100	-0.075	0.002	-0.125	-0.100
0.070	0.001	-0.103	-0.078	0.003	-0.130	-0.108
0.140	0.002	-0.109	-0.085	0.005	-0.141	-0.126

Terrain Elevation = 0.5 km ASL						
Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.001	-0.089	-0.066	0.002	-0.109	-0.085
0.035	0.001	-0.091	-0.069	0.002	-0.115	-0.092
0.070	0.002	-0.094	-0.072	0.003	-0.121	-0.100
0.140	0.002	-0.100	-0.078	0.005	-0.131	-0.117

Terrain Elevation = 0.0 km ASL						
AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.001	-0.005	-0.006	0.001	-0.012	-0.015
0.035	0.000	-0.003	-0.003	0.001	-0.006	-0.008
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	-0.001	0.006	0.007	-0.002	0.011	0.018

Terrain Elevation = 0.5 km ASL						
AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.001	-0.005	-0.006	0.001	-0.012	-0.015
0.035	0.000	-0.003	-0.003	0.001	-0.006	-0.008
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	-0.001	0.006	0.007	-0.002	0.011	0.018

Table 4. CAM5S sensitivity study on AOD500 correction of NOAA 14 AVHRR data for native rangeland

CAM5S nominal input parameters:
Mid-latitude summer atmosphere model (water vapour = 2.93 gm/cm^2, ozone = 0.319 cm-atm)
Continental aerosol model
Native rangeland as uniform surface target
Channel 1 surface reflectance = 0.1271
Channel 2 surface reflectance = 0.2140
Surface NDVI = 0.2548
Nadir viewing (GeoComp composite pixel selection favours nadir pixels)

Terrain Elevation = 0.0 km ASL

Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.000	-0.041	-0.104	0.000	-0.049	-0.127
0.035	0.001	-0.042	-0.107	0.001	-0.051	-0.133
0.070	0.001	-0.043	-0.110	0.001	-0.052	-0.139
0.140	0.001	-0.045	-0.116	0.003	-0.054	-0.154

Terrain Elevation = 0.5 km ASL

Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.000	-0.037	-0.092	0.000	-0.045	-0.114
0.035	0.001	-0.038	-0.095	0.001	-0.046	-0.119
0.070	0.001	-0.039	-0.098	0.001	-0.048	-0.126
0.140	0.001	-0.041	-0.105	0.003	-0.050	-0.140

Terrain Elevation = 0.0 km ASL

AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.000	-0.002	-0.006	0.001	-0.003	-0.013
0.035	0.000	-0.001	-0.003	0.001	-0.001	-0.007
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	0.000	0.002	0.006	-0.002	0.002	0.014

Terrain Elevation = 0.5 km ASL

AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.000	-0.002	-0.006	0.001	-0.003	-0.012
0.035	0.000	-0.001	-0.003	0.001	-0.001	-0.006
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	0.000	0.002	0.006	-0.002	0.002	0.014

Table 5. CAM5S sensitivity study on AOD500 correction of NOAA 14 AVHRR data for black spruce

CAM5S nominal input parameters:
Mid-latitude summer atmosphere model (water vapour = 2.93 gm/cm^2, ozone = 0.319 cm-atm)
Continental aerosol model
Black spruce forest as uniform surface target
Channel 1 surface reflectance = 0.0232
Channel 2 surface reflectance = 0.1186
Surface NDVI = 0.6728
Nadir viewing (GeoComp composite pixel selection favours nadir pixels)

Terrain Elevation = 0.0 km ASL						
Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.015	-0.020	-0.234	0.023	-0.023	-0.322
0.035	0.017	-0.020	-0.247	0.026	-0.023	-0.347
0.070	0.018	-0.020	-0.260	0.028	-0.023	-0.371
0.140	0.021	-0.020	-0.288	0.034	-0.022	-0.420

Terrain Elevation = 0.5 km ASL						
Actual AOD500	Absolute Error in surface reflectance without atmospheric correction					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.015	-0.018	-0.218	0.022	-0.020	-0.302
0.035	0.016	-0.018	-0.231	0.025	-0.020	-0.326
0.070	0.017	-0.018	-0.245	0.027	-0.020	-0.351
0.140	0.020	-0.018	-0.272	0.033	-0.020	-0.401

Terrain Elevation = 0.0 km ASL						
AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.003	0.000	-0.026	0.005	0.000	-0.049
0.035	0.001	0.000	-0.014	0.003	0.000	-0.025
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	-0.003	0.000	0.028	-0.006	-0.001	0.048

Terrain Elevation = 0.5 km ASL						
AOD500	Absolute Error in surface reflectance wrt AOD500 = 0.07					
	Solar Zenith = 45 degrees			Solar Zenith = 70 degrees		
	ch1	ch2	NDVI	ch1	ch2	NDVI
none	0.003	0.000	-0.026	0.005	0.000	-0.049
0.035	0.001	0.000	-0.014	0.003	0.000	-0.025
0.070	0.000	0.000	0.000	0.000	0.000	0.000
0.140	-0.003	0.000	0.028	-0.006	-0.001	0.050

RECOMMENDATIONS

One can conclude that an AOD500 of 0.070 derived for purely Canadian (AEROCAN) sunphotometer sites is a reasonable estimate of a single, Canada-wide, time-invariant aerosol optical depth for operational atmospheric correction. This is similar to the AOD550 value of 0.05 reported by Ahern *et al.* (1991) based on a full season of sunphotometer data for rural continental Canada. This value is also consistent with the modal value of AOD500 of 0.08 $\pm$0.02 derived for Arctic air masses at urban, rural and Maritime stations in Canada as well as Arctic and polar air masses at the rural continental station of Wynyard Saskatchewan (Smirnov *et al.,* 1996). The AOD500 data from AERONET sites outside of Canada (not presented here) with a similar cloud screening applied produced average monthly modal values of AOD500 between 0.06 and 0.08.

Thus, an AOD500 of 0.070 with an uncertainty of +0.070/-0.035 (or AOD550 of 0.062 with an uncertainty of +0.062/-0.031) is recommended as the best estimate of a single, Canada-wide, time invariant optical depth for operational atmospheric correction of AVHRR composite image data in production systems such as GeoComp-n until a detailed aerosol climatology can be built. The sensitivity analysis demonstrates that this uncertainty produces absolute errors in surface reflectance for typical land cover types of less than $\pm$1%, well within the $\pm$5% accuracy requirement for GeoComp-n products.

In future, the cloud-screened AOD500 data will be statistically averaged into 10-day bins corresponding to the GeoComp-n composite periods (April 1 to 10, 11 to 20 and 21 to 30, etc.). With additional years of data and network sites, temporal and spatial trends in AOD500 may become evident and appropriate seasonal values of aerosol optical depth may be recommended for atmospheric correction of GeoComp-n 10-day composite data in the future.

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