Observations of boreal forest fire smoke in the stratosphere by POAM III, SAGE II, and lidar in 1998

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Abstract. A substantial increase in stratospheric aerosol was recorded between May and October 1998 between 55° and 70°N. This phenomenon was recorded in the absence of reported volcanic eruptions with stratospheric impact potential. The POAM III and SAGE II instruments made numerous measurements of layers of enhanced aerosol extinction substantially higher than typical values 3 to 5 km above the tropopause. A comparison of these observations with lidar profiles, TOMS aerosol index data, and forest fire statistics reveals a strong link between stratospheric aerosol and forest fire smoke. Our analysis strongly suggests that smoke from boreal forest fires was lofted across the tropopause in substantial amounts in several episodes occurring in Canada and eastern Russia. Observations reveal a broad zonal increase in stratospheric aerosol that persisted for at least three months.

Introduction

The important role of aerosols in the Earth's radiation budget, cloud microphysical processes, and catalytic chemical reactions leading to ozone destruction is widely recognized. Other than polar stratospheric clouds the only currently recognized source of enhanced stratospheric aerosols is injection by volcanic eruption. In this paper we report observations of substantially enhanced stratospheric aerosol at high northern latitudes, between May and October of 1998, by the Polar Ozone and Aerosol Measurement (POAM) III instrument, corroborated by measurements from ground-based lidar and the Stratospheric Aerosol and Gas Experiment (SAGE) II instrument. These observations occurred in the absence of any significant report of volcanic activity. We postulate that the observed stratospheric aerosol increase is linked to episodic injections of smoke from boreal forest fires across the tropopause by intense convection.

Boreal forest fires are a natural and dominant disturbance factor in high northern latitudes. Typically 30,000-40,000 wildfires fires burn in Alaska, Canada, Scandinavia, and Russia annually; in peak years as many as 12 million hectares are burned [*Stocks et al.*, 2000]. Some of these fires produce large amounts of smoke with considerable horizontal and vertical transport [*Westphal and Toon*,1991; *Chung*, 1986; and *Stocks and Flannigan*, 1987]. The 1998 boreal fire season (defined as May–October) was notably active. Forest fire activity was simultaneously high in both Russia and Canada compared with recent years [*Kasishcke et al.*, 1999]. *Hsu et al.* [1999] performed a case study using Total Ozone Mapping Spectrometer (TOMS) aerosol index (AI) data [*Hsu et al.*, 1996], to track tropospheric smoke from wildfires in northwestern Canada on August 3, 1998 that spread east of the Greenwich meridian by August 8. We will show, using an ensemble of multi-platform aerosol measurements, that the 1998 fire season was also noteworthy for the occurrence of repeated and extensive vertical as well as long lived horizontal transport of aerosols. Using auxiliary data and isentropic trajectories, we also identify a mechanism and conditions for troposphere-to-stratosphere exchange of non-volcanic material.

Most of the aerosol measurements used in this study are from the POAM III [*Lucke et al.*, 1999] and SAGE II [*Mauldin et al.*, 1985] satellite experiments. Both instruments are uv/visible photometers operating in the solar occultation mode, with a vertical resolution of 1-2 km and a horizontal resolution of about 250 km. POAM III is in a polar orbit, sampling the high latitude northern hemisphere on a nearly continuous basis. SAGE II is in a 57° inclination orbit, sampling the high latitude northern hemisphere for roughly 10-day periods at about 6-week intervals.

Stratospheric Aerosol Increase in 1998: May-October

Figure 1 shows the temporal/longitudinal pattern of stratospheric aerosol optical depth during the 1998 fire season. The data are from POAM III's 1 μm aerosol extinction channel; the optical depth is a 5-km thick column of integrated aerosol extinction. The lower and upper bound of the column is defined relative to the tropopause; the bottom is the height of the tropopause plus 2 km, to segregate the column from tropospheric influence. The tropopause definition is based on potential vorticity (PV); we use the altitude at which PV=3×10^{-6} K kg^{-1} m^2 s^{-1}. This is typically well within 0.1 km of the WMO tropopause definition. (Except for SAGE tropopause data, all the meteorological data in this study are from United Kingdom Meteorological Office (UKMO) gridded analyses [*Swinbank and O'Neill*, 1994] and from the Atmospheric Environment Service of Environment Canada (AESEC)). During the 1998 fire season the median height of the tropopause at the POAM III measurement latitude is 9.6 km.

Figure 1 reveals that lower stratospheric aerosol optical depth is low and nearly uniform from May through July. Isolated, brief enhancements are seen in early and mid May. June values are consistently low. Around July 9 an episodic enhancement starts at about 270°E and translates east across the Greenwich meridian some days later. On about August 5 the aerosol optical depth increases substantially from the background near 320°E. This enhancement grows in intensity and translates east, to about 90°E by August 11. A separate area of greatly enhanced aerosol is seen to appear at 100°E on about August 14, spreading east in time, remaining intact and seeming to merge with a rather thick nucleus of high aerosol centered at about 300°E on August 25. Just prior to August 25 yet another nucleus of high aerosol appears at roughly 310°E and translates across the Greenwich meridian. The aerosol optical depth after the middle of August is substantially higher, first in longitudinal swaths, and later in a more completely zonal spread, than in the May-July period. The aerosol pattern does not return to May-June values until very late October.

We investigated the possibility that one or more volcanic eruptions were responsible for the stratospheric aerosol

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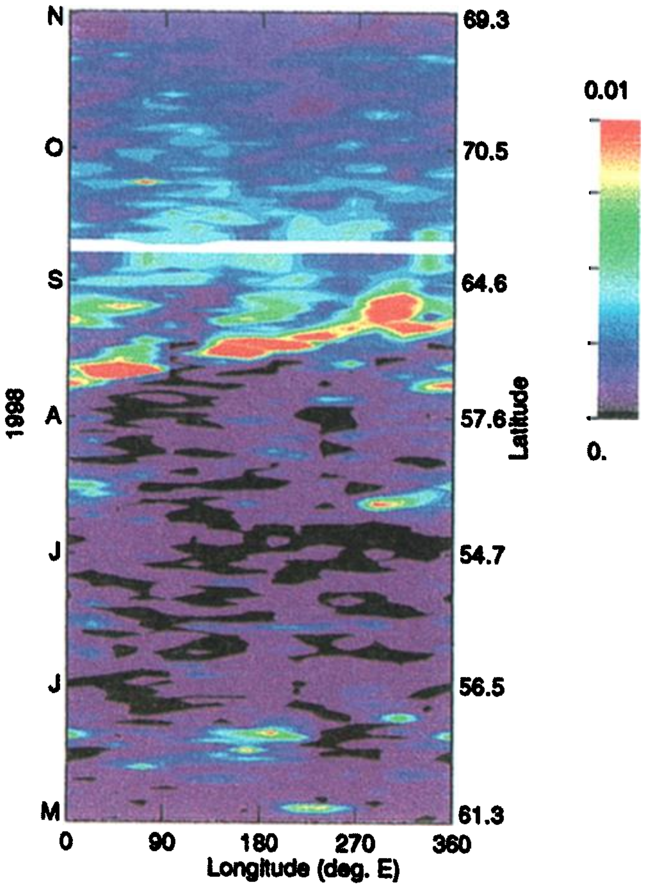

Figure 1. Longitude/time series analysis of POAM III 1 μm aerosol optical depth in a 5-km thick column relative to and starting 2 km above the tropopause. See text for details of the optical depth calculation. The period is May through October 1998. POAM measurement latitude, which changes gradually, is annotated along the right side. The white bar is a 5-day data gap.

enhancements in Figure 1. Only one northern hemispheric eruption of any consequence was reported; Korovin volcano (52° N, 186° E) in the Aleutian chain erupted on June 30 [*Smithsonian*, 1998]. An account of this eruption and other 1998 volcanic activity [D. Schneider, personal communication, 1999] suggests that neither the Korovin plume nor any other volcanic cloud reached stratospheric altitudes.

Case Study: July 4-18, 1998

Between July 9 and 18, 1998, POAM, SAGE, and ground-based Rayleigh lidar operated by the University of Bonn at Kiruna, Sweden (67.9°N, 21.1°E) made measurements of significant aerosol enhancements in the lower stratosphere, as high as 14 km. Figure 2 shows the aerosol extinction ratio, defined as the total extinction (aerosol + molecular) divided by the molecular extinction. The lidar backscatter (measured at 532 nm) ratio is analogously defined. POAM's peak extinction ratios, between 20 and 40, far exceed levels in the immediately preceding period; between June 15 and July 11 the maximum extinction ratio at 14 km was 4.9. *Siebert et al.*, [2000] reported that the derived lidar depolarization factor at the altitude of the backscatter enhancement was 4% and concluded that the particles were solid. POAM observed aerosol layers beginning on July 12 over eastern Canada. On each day thereafter through July 16, POAM made one or more layer observations at successively more eastward longitudes. The POAM layer observation on July 16 (at 20:04 UTC) at 14 km and the lidar observation are closely matched. An isentropic trajectory at the level of the aerosol layer links the POAM and lidar observations within 16 km and 2 hours. SAGE's observation on July 9 at 67°N, 260°E was the earliest of this ensemble. In each one of these profiles the center of the aerosol layer was 2 to 5 km above the tropopause. Moreover, the aerosol layers were 1-3 km higher than the temperature inversion altitude, the upper extent of the tropopause region.

We computed isentropic back trajectories to determine common characteristics of the parcel histories and to assess the possibility that these aerosol layers were caused by the eruption of Korovin volcano. Each trajectory (Figure 3) was run back to June 27, before the eruption date. None make a satisfactory match in both time and space. Considering this result and the fact that stratospheric aerosol enhancement commenced only after July 9 even though POAM and SAGE were measuring in the latitude "neighborhood" of Korovin and other Aleutian and Kamchatkan volcanoes, we conclude that these aerosol enhancements were not caused by a reported volcanic eruption.

A portion of each trajectory is highlighted (the gray shaded portion) in Figure 3. Each highlighted segment is for an identical time period: July 4-7, 12 UTC. This view reveals that all of the aerosol parcel histories share a common narrow path through northwestern Canada, between the Alaskan border and Great Bear Lake in Northwest Territories (NWT). In this region a particularly intense combination of forest fire activity and atmospheric instability occurred between July 4 and 7. The smoke/fire detection algorithm of *Li et al.* [2000], applied to NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery, revealed multiple, extensive fire hot spots and smoke clouds (not shown). Plume-dominated fires (i.e. fires with associated high smoke/convection plumes) were observed on July 4 [Beaver, personal communication, 1999] in the vicinity of Whitehorse, Yukon (61.3°N, 225°E). TOMS AI began increasing from null values starting on July 4 at 65°N near the Alaska/Yukon border. Between July 4 and 7 significant AI enhancements were located (not shown) in the vicinity of the highlighted trajectory segments. Tropospheric weather conditions favored the development of widespread deep convection throughout this region and period; several severe weather thunderstorm watches and warnings were issued [AESEC, personal communication, 1999]. We visually evaluated

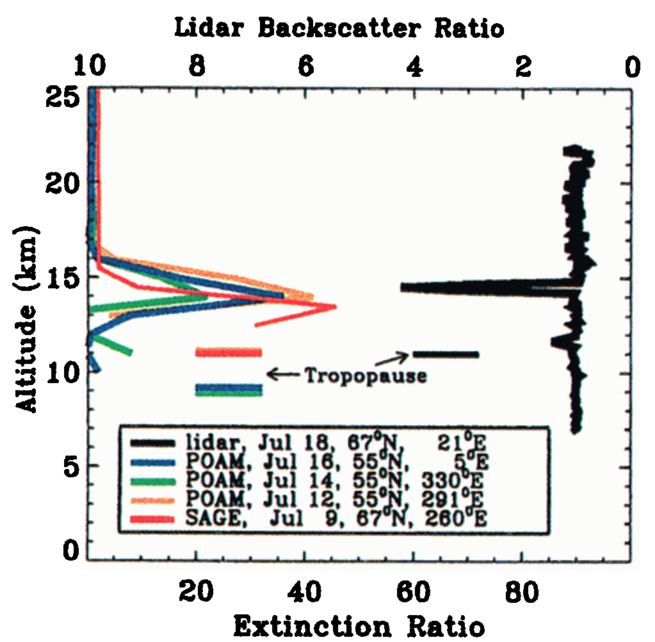

Figure 2. Selected aerosol extinction and backscatter ratio profiles showing stratospheric enhancements between July 9 and 18, 1998. Tropopause height collocated with each profile is shown by a matching color-coded horizontal bar.

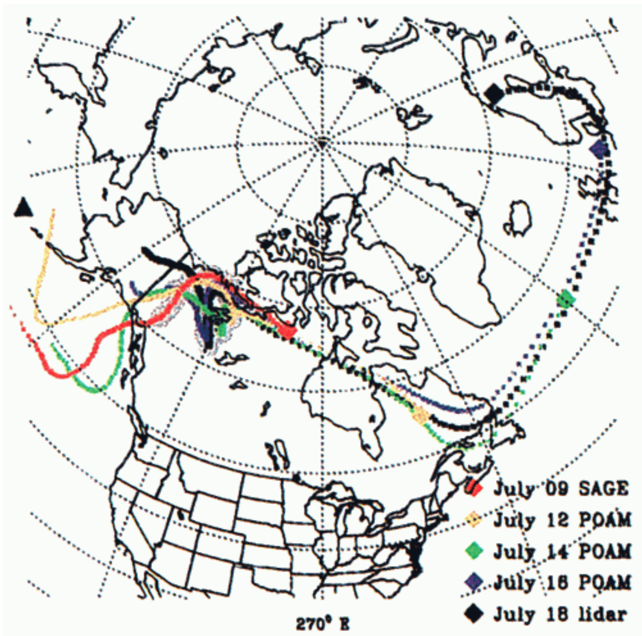

Figure 3. Orthographic projection with isentropic back trajectories from the aerosol layers, as color coded in Figure 2. Each trajectory ends on June 27, 1998. Filled diamonds mark observation points. The trajectories were run on the potential temperature surface of the peak backscatter or extinction ratio. The gray shaded portion of each trajectory shows is parcel location between 12 UTC July 4 and 7. The filled triangle marks Korovin volcano.

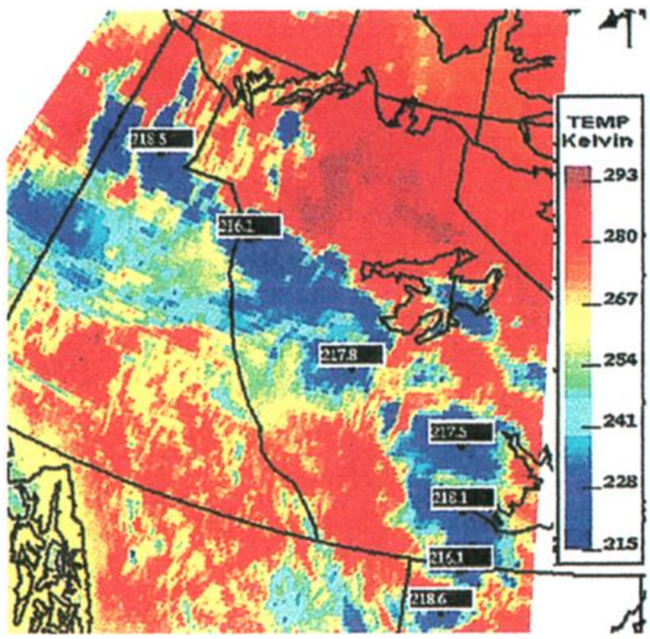

Figure 4. Brightness temperature (K) derived from GOES-9 10.7 µm radiance on July 7, 1998, 00 UTC. Area shown centers on the Yukon/Northwest Territories boundary, roughly 65°N, 228°E. Selected extrema are annotated.

visible AVHRR imagery and detected several vigorous thunderstorm complexes in this region between July 4 and 7. Thus it is evident that in this particular region, over which all of the aerosol layer trajectories passed, there is an abundance of forest fire smoke and vigorous vertical transport.

We estimated the vertical extent of the upward motion in these thunderstorms by analyzing NOAA's Geostationary Operational Environmental Satellite (GOES-9) 10.7 µm channel brightness temperatures between 00 UTC July 4 and 7, in relation to tropopause temperature. The brightness temperature is a reliable proxy for cloud-top altitude when the emitting surface is optically thick. At 62°N, 240°E, the horizontal resolution of GOES-9 is approximately 12 km [Ellrod, personal communication, 1999]. Thus, resultant brightness temperatures will be a conservative estimate (i.e., biased low) of cloud top height, since certainly some of the clouds in the GOES image will be somewhat translucent and there will be scales of motion in thunderstorms smaller than the 12-km resolution. Figure 4 shows the brightness temperatures on 00 UTC July 7 between the Yukon and Great Bear Lake, NWT, where an extensive arc of thunderstorms was occurring. In several locations, cloud-top temperatures were below 220 K; the lowest was 216K. The tropopause temperature reported by radiosonde at Norman Wells, NWT (65.3°N, 233.2°E) at 00 UTC July 7, was 217 K; tropopause height was approximately 11.6 km. Considering the multiple observations of enhanced aerosol by POAM, SAGE, and lidar that trace precisely to this common place and time, we consider it plausible that the widespread severe convection occurring in concert with a very active wildfire regime transported smoke to the lower stratosphere.

Smoke and Stratospheric Aerosol Link: May-October

Figure 5a is a time series during the 1998 fire season of daily average (which is roughly equivalent to a zonal average) POAM III optical depth (computed as in Figure 1). Also shown is the optical depth in the 5-km column fixed between 16 and 20 km. Here we also introduce SAGE II optical depth, computed in an analogous manner. (Note: SAGE data are provided with a collocated tropopause height, which is determined by the standard WMO tropopause definition [*Nagurny*, 1998]). Because of SAGE's relatively rapid change in measurement latitude, it

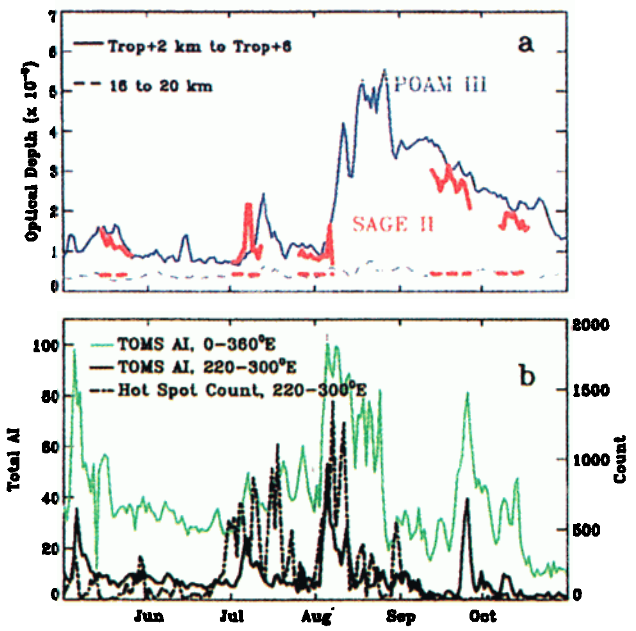

Figure 5. Time series, May through October 1998. Panel (a) shows daily average aerosol optical depth, computed as in Figure 1 (solid line) and in the fixed altitude range of 16-20 km (dashed line). POAM III data are blue; SAGE, red. Only SAGE data north of 55°N are plotted. Panel (b) shows daily Canadian forest fire hot spot count (dot dash line) and TOMS aerosol index (see text for details of calculation) over Canada (black solid line) and over all longitudes (green).

samples north of 55°N in several brief intervals during the 1998 fire season. Figure 5a shows that the vertical extent of the aerosol enhancements seen in Figure 1 is effectively capped at 15 km; both SAGE and POAM optical depths above 15 km are similarly featureless throughout. However, in the column relative to the tropopause both instruments recorded significant variability--the early, small increases in May, the early-to-mid-July enhancement, and the dramatic growth of the aerosol burden after early August. Between June and the peak enhancement period in the second half of August, POAM daily average aerosol optical depth increases five fold. In mid-October, the aerosol burden measured by POAM and SAGE is still roughly twice the pre-August values.

A useful measure of the amount of forest fire activity is hot spot count, which is a daily aggregate over a region (Canada in this case) of individual loci of active fires, based on the fire/smoke detection algorithm of *Li et al.* [2000] applied to AVHRR imagery. We compare daily hot spot count with TOMS AI in Figure 5b. The AI is taken from a global gridded data set. We compute a daily value by averaging in latitude, between 45.5°-79.5°N (the approximate meridional extent of the boreal forests), then summing in longitude. To permit a comparison with the hot spot data, we plot AI for Canadian longitudes (220° to 300°E), the black solid line in Figure 5b. The hot spot data show that Canadian forest fire activity had brief, small increases in May, then more substantial episodic development in July and then again in August, followed by quiescence after September 1. There is a strong qualitative similarity in the pattern of hot spots and Canadian TOMS AI. (Our examination of AI maps revealed that the spike in late September is due to smoke that originated in eastern Russia a few days earlier.) This agreement permits us to conclude that the full zonal pattern of AI in Figure 5b (the green solid line) characterizes the season-long pattern of smoke generated by boreal forest fires in both Canada and Russia. The full zonal TOMS AI shows that particularly large increases in aerosol occurred in the first half of May, nearly the entire month of August, and in late September. Comparing Figure 5a and b, it is evident that the stratospheric aerosol increases are linked with some of the TOMS AI perturbations, indicating that a subset of the boreal fire events were accompanied by extreme vertical transport.

Conclusion

The TOMS, POAM, and SAGE information taken together show several significant episodes of tropospheric and stratospheric aerosol increase in the 1998 fire season. Perhaps the most notable feature of Figure 5 is the gradual decrease in lower stratospheric optical depth observed between late August and October. During this interval TOMS AI decreases suddenly (late August) and remains relatively low, except for a perturbation late in September. POAM profiles (not shown) reveal that on August 21 an aerosol cloud was detected at 16 km, the highest altitude of the fire season. As the season progresses through September and October, the altitude of the peak extinction decreases gradually along with the optical depth. These data strongly suggest that substantial, repeated intrusions of aerosols from forest fire smoke occurred in 1998; in a subset of these events the aerosols were lofted to lower stratospheric altitudes, especially during August, and were followed by a two-month period of gradual decay.

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