NOTES AND CORRESPONDENCE

A Comparison of SAGE I Data During the Stratospheric Warming of February-March, 1979**By Ronald M. Nagatani***Climate Analysis Center NOAA, Camp Springs, MD 20733 USA***M. P. McCormick and L. R. McMaster***NASA Langley Research Center Hampton, VA 23665 USA**(Manuscript received 7 November 1984, in revised form 30 January 1985)***Abstract**

The fine scale vertical structure of SAGE I ozone and aerosol data during a stratospheric warming is investigated using meteorological and SBUV ozone data. By stratifying the ozone and aerosol data for a limited time period, we are able to compare the structure of profiles under different meteorological conditions. For example, the cold air region shows more laminated structures than the other regions. In addition, vertical motions calculated at the same locations as the SAGE profiles show that they are consistent with variances found in the ozone and aerosol data.

I. Introduction

The purpose of this paper is to characterize some of the fine scale structure in profiles of ozone and aerosols during a stratospheric warming using data from the Stratospheric Aerosol and Gas Experiment (SAGE I). In order to do that, the large-scale synoptic conditions are assessed with maps produced by the U. S. National Meteorological Center (NMC). The main stratospheric products of the U. S. National Meteorological Center are globally analyzed and numerically gridded meteorological fields of heights and temperatures. These stratospheric gridded fields, at levels from 70 to 0.4 mb, have been analyzed and archived on a daily basis at NMC since September 1978. Stratospheric heights and temperatures up to 10 mb have been available since 1964. The maps have been analyzed by

an iterative correction scheme discussed by Cressman (1959) with some modifications discussed by Yanai (1964). Gelman *et al.* (1983) summarize some of the data and analysis procedures that went into the maps. They also discuss the limitations of the products. Also available as a product from NMC are hemispherically analyzed maps of ozone mixing ratios from the Nimbus 7 Solar Backscatter Ultraviolet (SBUV) instrument at the same stratospheric levels as the height and temperature data from 30 to 0.4 mb. The SBUV ozone data are also analyzed by the same scheme discussed above for the meteorological maps. These maps will be used as a guide to stratify the SAGE data.

The SAGE I program is described by McCormick *et al.* (1979) and the SBUV instrument is described by Heath *et al.* (1975). The SAGE I instrument is a four-channel photometer that measures the intensity of sunlight at sunrise and sunset events with a vertical resolution of 1 km. The stated accuracies are 5% at 25–40 km for ozone and

¹ This paper was presented at the Japan-U.S. Seminar on "Review of work related to sensing of stratospheric aerosol and gas components", Fukuoka, 12–14 June 1984.

10% for aerosols between the tropopause and 25 km and 30% at 25–35 km (Russel, 1979). SBUV senses the solar backscatter ultraviolet radiation at the nadir point, yielding more than 1000 data points over the globe each day with a vertical resolution between 5 to 8 km. Comparisons with ground truth indicate a bias of about 5% lower for SBUV below the mixing ratio peak and a 5% agreement with optical ozonesonde rockets at higher levels (Fleig *et al.*, 1982). With a clear difference in horizontal and vertical resolution for the ozone data, we see that both instruments can complement each other to enhance their capabilities. In this context, given the fine scale vertical

resolution of data from SAGE I, we will compare SAGE ozone and aerosol data together with NMC analyses of heights and temperatures and ozone analyses from the SBUV instrument on Nimbus 7.

McCormick *et al.* (1983) have looked at data from the Stratospheric Aerosol Measurement (SAM II) satellite system and found aerosol profiles with lower optical depths to lie within the lower pressure region of the polar vortex at 50 mb for a single day. Following up on their investigation, for this paper we will focus our attention on the 2 mb level near the ozone volume mixing ratio peak during a dynamically active period at this level. The

Fig. 1 2-mb temperatures (Centigrade). Letters C(cold) and W(warm) determine locations of SAGE data points plotted in Fig. 4c and 4b, respectively. a) February 27, 1979. b) February 28, 1979. c) March 1, 1979.

period investigated is during a time when a stratospheric warming was in progress in late February to early March 1979. The profiles we look at will extend to the lower stratosphere; thus we will also utilize some meteorological data at other levels.

II. Stratospheric Warming of February-March 1979

In late February 1979, by February 21, a strong warming occurred in the stratosphere between 50 to 0.4 mb culminating in a circulation reversal at 2 mb on February 27, 1979 near the polar regions. The warming is documented by Quiroz (1979). Others have investigated various phases of the winter

period that included the major warming. Wang *et al.* (1983) used SAGE I data to investigate ozone transports during the period of the warming. Nagatani and Miller (1984) used SBUV data to investigate, on a monthly basis, transports and ozone-meteorological relationships during the course of the first year of SBUV operation. We will focus our attention to the three days when the warming was already in progress from February 27 through March 1, 1979. These three days were chosen because SAGE I data were obtained at desirable latitudes and the meteorological data collected during this period were optimal also.

Figures 1a-1c show the 2 mb temperatures on February 27, 28, and March 1, 1979 while

Fig. 2. 2-mb geopotential meters. Letter L (low pressure) determines locations of SAGE data points plotted in Fig. 4d. a) February 27, 1979. b) February 28, 1979. c) March 1, 1979.

Figs. 2a-2c show the geopotential heights for the same days. On February 27, the warming had already reached its peak, with the warmest air over the Barents Sea region near the polar regions as shown in Fig. 1a. Figure 2a for the same day shows a circulation reversal near the polar regions, with the anticyclone splitting the polar vortex into two main lows and a third weaker low over the Siberian region. On the succeeding two days in Figs. 1b-1c for the temperatures and Figs. 2b-2c for the heights, the warm air weakens and recedes and the anticyclone begins to retrogress to its more normal position over the Aleutian region.

The ozone distributions at 2 mb obtained from an analysis of SBUV data for the same three days are shown in Figs. 3a-3c. We see that the warm air (Fig. 1) is accompanied by an ozone minimum over the Barents Sea region. This good negative correlation in the general patterns between temperature and ozone is expected on the basis of ozone photochemical theory in the upper stratosphere. As the warming weakens, the strength of the ozone minimum also decreases on February 28 and March 1. Note that the highest ozone amounts remain fairly static near the Kamchatka Peninsula.

Having noted how the circulation, tempera-

Fig. 3 2-mb ozone mass mixing ratios ($\mu\text{gm/gm}$). Letters H (high ozone) and L (low ozone) determine locations of SAGE data points plotted in Fig. 4a and 4b, respectively. a) February 27, 1979. b) February 28, 1979. c) March 1, 1979.

ture, and ozone behaved during the stratospheric warming, we now group the SAGE I data according to similar meteorological conditions. We first use the SBUV analyzed maps to determine the horizontal extent of highest and lowest ozone amounts and the regions affected during the three days. The location of the SAGE I profiles selected for these high and low ozone regions are represented by the

letters H and L, respectively, in Figs. 3a-3c. The profiles for the high ozone regions on these three days are then plotted in Fig. 4a. The location of the points move from day to day because of the characteristics of the satellite and we therefore do a composite of the points. As in any composite, one must be careful in interpreting any differences or similarities in the data. In the case of the

Fig. 4 Vertical profiles of ozone volume mixing ratios (ppmv) from SAGE I. Squares, triangles, and circles represent SBUV data interpolated from maps to SAGE measurement locations. a) Profiles from high SBUV ozone regions (indicated by letter H in Fig. 3). b) Profiles from warm temperature region (indicated by letter W in Fig. 1) and from low SBUV ozone region (indicated by letter L in Fig. 3). c) Profiles from low temperature region (indicated by letter C in Fig. 1). d) Profiles from low pressure region (indicated by letter L in Fig. 2).

study here, we are more interested in profiles under various conditions, so the changing conditions at a specific location is not crucial here. The squares, triangles, and circles in Figs. 4a-d represent SBUV data from analyzed maps interpolated to SAGE measurement locations. A comparison between SBUV and SAGE shows that aside from any biases between the two systems, both systems indicate similar profile shapes and changes of ozone with time.

A striking feature of the vertical profiles in Fig. 4a is the relative stability or low variability among the profiles. This should become more evident as we compare plots of other profiles under different conditions, with the level of the ozone maximum between 2 and 3 mb. Note also the sharp peak in the ozone maximum. Figure 4b shows the vertical profiles of ozone in the region of low SBUV ozone (high temperature) at 2 mb. The profiles show greater variability, especially below the ozone peak, indicating a more dynamically active region than shown in Fig. 4a for the high ozone region. A comparison between the two figures show the dramatic differences between the two regions including a lower peak between 6 and 3 mb for the low ozone (high temperature) region. The high ozone region represents a somewhat static region, where the winds are not as strong as in the other regions. The warm air or low ozone region, on the other hand, is in a highly dynamic region where the stratospheric warming is in progress and where large-scale overturning of the atmosphere is occurring. As a result, the profiles also reflect this difference. Details of the warming are found in Quiroz (1979), where he shows a circulation reversal at the mid-stratospheric level at 10 mb and he also shows time-height sections of the warming having significant amplitudes down to the lower stratospheric levels between 50 and 100 mb.

The region of low ozone amount also correspond to the region of high temperatures. We can therefore compare Fig. 4b with the next group of SAGE I profiles plotted in Fig. 4c, which correspond to the low temperature regions. The SAGE measurement locations

are represented by the letter C in Fig. 1. The vertical profiles show an interesting laminated structure, much more than the other regions, possibly being caused by advection of different layers of air into the region. Also there is no sharp distinct maximum as in the previous two figures. Note the region between 20 and 30 mb shows a secondary maximum, faintly visible on February 27 and strongly evident on February 28 and March 1. Also note that the broad upper layer shown in the February 27 and 28 profiles from 1 to 10 mb appears in the SAGE data to break up into two separate layers in the March 1 profile. We will focus our attention on this same region when we look at the aerosol plots.

A final plot of SAGE I ozone profiles, corresponding to regions in the polar vortex centered over Canada and indicated by the letter L in Fig. 2, is shown in Fig. 4d. There was a tongue of warm air coming into Canada at the time, though not as strong as the one over the Barents Sea region, associated with low ozone amounts evident in both the SBUV and SAGE data. The profiles are similar to those in Fig. 4b near the warm air region, with similar variances and structures. A slightly higher peak is evident compared to that of Fig. 4b, reflecting a situation somewhere in between that of Fig. 4a and Fig. 4b, compatible with the meteorological conditions.

Profiles of the SAGE $1\text{ }\mu\text{m}$ aerosol extinction were also plotted for the same locations as for ozone and they also show very interesting features. Figure 5a is a plot of the aerosol extinction for the high ozone region. Expected errors for February 27 are plotted as horizontal lines. While the expected errors are large at upper levels, we can still gain some insight into the differences, especially since the expected error drop off quite rapidly at the lower levels. As in the case with ozone, the variability in Fig. 5a is much less than the variability in the other plots to follow. This implies that the exchange of air with the outside is minimal throughout the column of air compared to the other regions. Figure 5b is a plot of the local vertical motions computed by the adiabatic method:

Fig. 5 Vertical profiles of $1\text{ }\mu\text{m}$ aerosol extinction from SAGE I with corresponding vertical velocities for the same points in the adjacent figure. Horizontal lines are expected errors for February 27. a-b) Same SAGE points in the high ozone region as in Fig. 4a. c-d) Same SAGE points in the low ozone (high temperature) region as in Fig. 4b. e-f) Same SAGE points in the low temperature region as in Fig. 4c.

$$w = \frac{\left(\frac{\partial T}{\partial t}\right)_n + (V_g \cdot \nabla T)_p}{\frac{p g}{R T} \left(\frac{\partial T}{\partial p}\right) - \frac{g}{c_p}}$$

where the subscript p means that the variable is evaluated at a constant pressure surface, V_g is the geostrophic wind, T is the Kelvin temperature, c_p is the specific heat

capacity at constant pressure, g is the acceleration of gravity, R is the gas constant, and $(\partial T / \partial t)_p$ is evaluated in a 48-hour period. Gridded fields of heights and temperatures are used to compute the vertical velocities and interpolated to the SAGE data points. As seen in the figure, very weak upward and downward motions are evident throughout the

column, partially accounting for the low variability.

Figure 5c shows a plot of the aerosol extinction profiles in the high temperature (low ozone) region. For February 27 and March 1, the aerosol extinction is low throughout the whole column compared to many of the other profiles. As in the case with ozone, the variability between all three profiles is largest in this dynamically active region and the vertical motions plotted in Fig. 5d confirm this activity. Compared to the plot in Fig. 5b, we see larger upward and downward motions throughout the column of air.

Finally, Fig. 5e shows the aerosol extinction profiles for the low temperature region. Note the region between 20 and 30 mb for February 28 and March 1, where a layer of air with very different properties seems to have been advected into the region as in the case with ozone. The vertical motions in Fig. 5f show weak upward and downward motions, suggesting that the layer of air mentioned previously is probably a result of horizontal advection. Papers by Danielsen and Mohnen (1977) and Evans *et al.* (1979) have found similar types of structures at lower stratospheric levels, attributed to tropopause folding events. The features seen in the SAGE data, however, are at higher levels than those investigated with ozonesondes. Evans *et al.* (1979) also suggest photochemical sinks for their "notches". However, during a stratospheric warming, the most probable explanation would be vertical or quasi-horizontal advection, especially since the vertical mesoscale features are seen in both the ozone and aerosol data.

III. Summary and conclusions

The fine vertical resolution of SAGE I provides a unique dataset capable of being used for investigating synoptic and smaller scale features consistent with meteorological data and for comparison with other ozone data such as SBUV. We have used the data here in a complementary fashion and anticipate more studies in a similar vein. With SBUV 2 having been launched in December, 1984 on NOAA-F and SAGE II having been launched

from the space shuttle also in October, 1984, the next generation of similar type instruments can also complement each other in further studies.

Summarizing some of the results of our limited study, if we focus our attention on the 2-mb level in stratifying the data for a limited time period during a stratospheric warming, we find that the cold air region shows more laminated structures than the other regions in addition to having a peak that is not well defined. The high ozone region shows a sharp peak, with the whole profile showing less variability than the other regions. Vertical motions calculated at the same locations as the SAGE profiles show that they are consistent with the variances found in the ozone and aerosol data.

Acknowledgements

This study has been supported by NASA. We wish to thank M.E. Gelman, R.S. Quiroz, and P. Wang for constructive comments on the manuscript, A.J. Miller for his helpful discussions, and D.F. Heath and A.J. Fleig for consultations on the original SBUV data.

References

- Cressman, G.W., 1959L: An Operational Objective Analysis System, *Mon. Wea. Rev.*, **87**, 367-374.
- Danielsen, E.F. and V.A. Mohnen, 1977: Project Duststorm Report: Ozone Transport, in Situ Measurements, and Meteorological Analyses of Tropopause Folding, *J. Geophys. Res.*, **82**, 5867-5877.
- Evans, W.F.J., I.A. Asbridge and C.L. Mateer, 1979: Observations of a 'Notch' in the Stratospheric Ozone Layer, *J. Geophys. Res.*, **84**, 2159-2524.
- Fleig, A.J., K.F. Klenk, P.K. Bhartia, D. Gordon and W.H. Schneider, 1982: User's Guide for the Solar Backscattered Ultraviolet (SBUV) Instrument First-Year Ozone-S Data Set, NASA Reference Publication 1095, 66 pp.
- Gelman, M.E., A.J. Miller, R.M. Nagatani and H.D. Bowman II, 1983: Mean Zonal Wind and Temperature Structure During the PMP-1 Winter Periods, *Adv Space Res.*, **2**, 159-162.
- Heath, D.F., A.J. Krueger, H.A. Roeder and B.D. Henderson, 1975: The Solar Backscatter Ultraviolet and Total Ozone Mapping Spectrometer (SBUV/TOMS) for Nimbus-G, *Opt. Eng.*, **14**, 323-331.
- McCormick, M.P., C.R. Trepte and G.S. Kent, 1983: Spatial Changes in the Stratospheric

- Aerosol Associated with the North Polar Vortex, *Geophys. Res. Letters*, **1**, 941-944.
- McCormick, M. P., T. J. Pepin, W. P. Chu, T. J. Swissler, and L. R. McMaster, 1979: Satellite Studies of the Stratospheric Aerosol, *Bull. Amer. Meteor. Soc.*, **60**, 1038-1046.
- Nagatani, R. M. and A. J. Miller, 1984: Stratospheric Ozone Changes During the First Year of SBUV Observations, *J. Geophys. Res.*, **89**, 5191-5198.
- Quiroz, R. S., 1979: Tropospheric-Stratospheric Interaction in the Major Warming Event of January-February 1979, *Geophys. Res. Letters*, **6**, 645-648.
- Russel, P. B., editor, 1979: SAGE Ground Truth Plan—Correlative Measurements for the Stratospheric Aerosol and Gas Experiment (SAGE) on the AEM-B Satellite, NASA Technical Memorandum 80076, March 1979, 157 pp.
- Wang, P., M. P. McCormick and W. P. Chu, 1983: A Study of the Planetary Wave Transport of Ozone During the Late February 1979 Stratospheric Warming Using SAGE Ozone Observation and Meteorological Information, *J. Atmos. Sci.*, **40**, 2419-2413.
- Yanai, M., 1964: An Operational Objective Analysis in the Tropics, Technical Paper No. 62, Dept. of Atmospheric Sciences, *Colorado State Univ.*, 21 pp.

1979 年 2 ～ 3 月における成層圏突然昇温期間中の SAGE I データの比較

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