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Some recent results of Russian measurements of surface ozone in Antarctica. A meteorological interpretation

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ABSTRACT

Surface ozone measurements were carried out at Molodezhnaya (67.40° S, 45.50° E) and Mirny (66.33° S, 93.01° E) stations in spring 1987–autumn 1988 with a Dasibi 1008-AH ozone analyzer. The data show an annual variation with a summer minimum at 15 ppbv value. The striking feature of the surface ozone record is two types of day-to-day variability. One of the types is characterized by large day-to-day variations with about 10 ppbv magnitude. The likely mechanism of such variations is the vertical transport induced by cyclonic activity. The other type occurs in synoptically quiet periods (frequent in summer) when the day-to-day ozone variations are significant but not so large. The most likely mechanism of these variations is the slope katabatic wind which transports ozone from inside the Antarctic continent. The latitudinal distribution of surface ozone for this period, measured aboard an aircraft, showed a slight increase towards Vostok (78.28° S, 106.48° E) station.

1. Introduction

The first measurements of surface ozone in Antarctica were done in the late 1950s (Wexler et al., 1960; Wisse and Meerburg, 1969). During the 1960s, there were surface ozone measurements at some Antarctic stations (Aldaz, 1965; Wisse and Meerburg, 1969; Oltmans and Komhyr, 1976; Von Kolbig and Warmbt, 1978). At present, the systematic measurements of surface ozone at Amundsen-Scott and Palmer (the Antarctic Peninsula) stations are carried out (Howard et al., 1986; Oltmans and Komhyr, 1986; Oltmans et al., 1987). The first Russian surface ozone measurements in the Antarctic were carried out in 1986 at Mirny station (Arabov et al., 1988).

One of the main features of time variability of Antarctic surface ozone is its annual variation with a winter maximum and summer minimum (Wexler et al., 1960; Aldaz, 1965; Wisse and Meerburg, 1969; Oltmans and Komhyr, 1976; Von Kolbig and Warmbt, 1978; Oltmans, 1981; Howard et al., 1986; Oltmans and Komhyr, 1986; Oltmans et al., 1987). The amplitude of an annual variation is about half of the annual-mean, which at the South Pole is slightly less than 30 ppbv and at lower latitudes is near 20 ppbv (Oltmans and Komhyr, 1976). Oltmans and Komhyr (1976) and Von Kolbig and Warmbt (1978) also noted day-to-day variations which at the South Pole are more significant in late spring and summer and at lower latitudes in spring and autumn. In the former case, these variations are thought to be connected with a summer weakening of a near-surface temperature inversions (Oltmans and Komhyr, 1976; Oltmans, 1981), while in the latter case, with a greater synoptical activity during transient seasons (Oltmans and Komhyr, 1976; Von Kolbig and Warmbt, 1978). The same authors and Oltmans (1981) noted the absence of a statistically significant average diurnal variation of surface ozone in the Antarctic. The diurnal variation was studied in more detail by Arabov et al. (1988) who found out two regimes of small period variability: one with regular daily variations and another with irregular day-to-day variations without any statistically significant diurnal variation.

Until now, insufficient attention has been paid to understanding mechanisms of time variability of surface ozone in Antarctica. The present paper deals with the results of surface ozone measurements accomplished during November 1987–April

1988 (till mid-December 1987) at Molodezhnaya (67.40° S, 45.50° E) and then at Mirny (66.33° S, 93.01° E).

2. Instrumentation and measurements

A Dasibi 1008-AH ozone analyzer was used for measurements. The instrument was calibrated using a Dasibi 1008-PC ozone generator. The precision of ozone measurements is ± 1 ppbv. The distance of the instrument intake from the snow surface was 3.5 m at Molodezhnaya and 2 m at Mirny. The site of measurements at Molodezhnaya was in the center of the station. One cannot, therefore, exclude the influence of locar air pollution on ozone content. Conditions of ozone measurements at Mirny should be considered as background. The instrument was placed upwind from the station (relative to the predominant wind directions).

3. Seasonal variation

The dashed curve in Fig. 1a shows the variations of the surface ozone 10-day mean which display a summer minimum. This agrees well with the results of other authors (see all the above-mentioned references). The maximum 10-day mean for the period of measurements at Molodezhnaya falls on the 2nd 10-days of November 1987 and equals 19 ppbv. The minimum of 13 ppbv was noted at Mirny in the 2nd 10-day period of January 1988. For the same period, the minimum daily mean of 8.5 ppbv was also observed. The maximum 10-day mean at Mirny was observed in April and equaled 23 ppbv.

A summer minimum (and winter maximum) of surface ozone content is not only characteristic for Antarctica but also for lower latitudes of the Southern Hemisphere (see, e.g., Oltmans, 1981; Logan, 1985; Galbally et al., 1986). In the Northern Hemisphere, a summer minimum was observed in some regions of Canada far away from industrial centers (Logan, 1985). To explain the annual variation of Antarctic surface ozone, Oltmans and Komhyr (1976) considered its meridional transport by synoptic scale disturbances moving from subpolar latitudes. Such mechanism is at variance with the present experimental (Fabian and Pruchnievich, 1977; Routhier et al., 1980; Marenco and Said, 1989) and model (Mahlman et al., 1980; Levy et al., 1985) results, showing decreasing ozone with increasing latitude, and needs to be modified. Particularly, the vertical transport has to be taken into account (see below and Gruzdev and Elokhov, 1992).

4. Spatial variations

On 8 February 1988, the ozone measurements were carried out aboard the IL-14 aircraft flying along the path Mirny—Vostok (78.28° S, 106.48° E, 3500 m above sea level)—Mirny. The flight was mainly in the near-surface layer at heights of 30–50 m above the Antarctic ice plateau. Ozone concentration varied in the range of 13–15 ppbv with a tendency to increase towards Vostok. Such a spatially homogeneous distribution is consistent with low temporal variability in daily surface ozone at Mirny during the period February 8–10 shown in Fig. 1a (see Section 5).

5. Day-to-day variations

A time series of daily averaged surface ozone mixing ratio at Molodezhnaya and Mirny is shown in Fig. 1a by the full curve. The vertical dashed-dotted line separates the observations at the two stations. The characteristic feature of ozone time behavior in Fig. 1a is significant day-to-day variations which are particularly large in spring and summer. The lesser day-to-day variability is noted for the period from the end of summer to the beginning of autumn (from late January to March).

Figs. 1b–d show some meteorological parameters: daily averaged surface atmospheric pressure, p, temperature, t, at the 3-km altitude at 00.00 hrs Greenwich mean time (GMT), direction, d, of surface wind at 0 GMT. Using radiosonde data at 00 GMT, the Richardson number, Ri, was calculated for the layer of the 0–1 km altitude:

$$\mathrm{Ri} = \frac{N^2}{(\Delta v/\Delta z)^2},$$

where N^2 is a squared Brunt-Väisälä frequency, $(\Delta v/\Delta z)^2$ is a squared wind shear in the layer. The

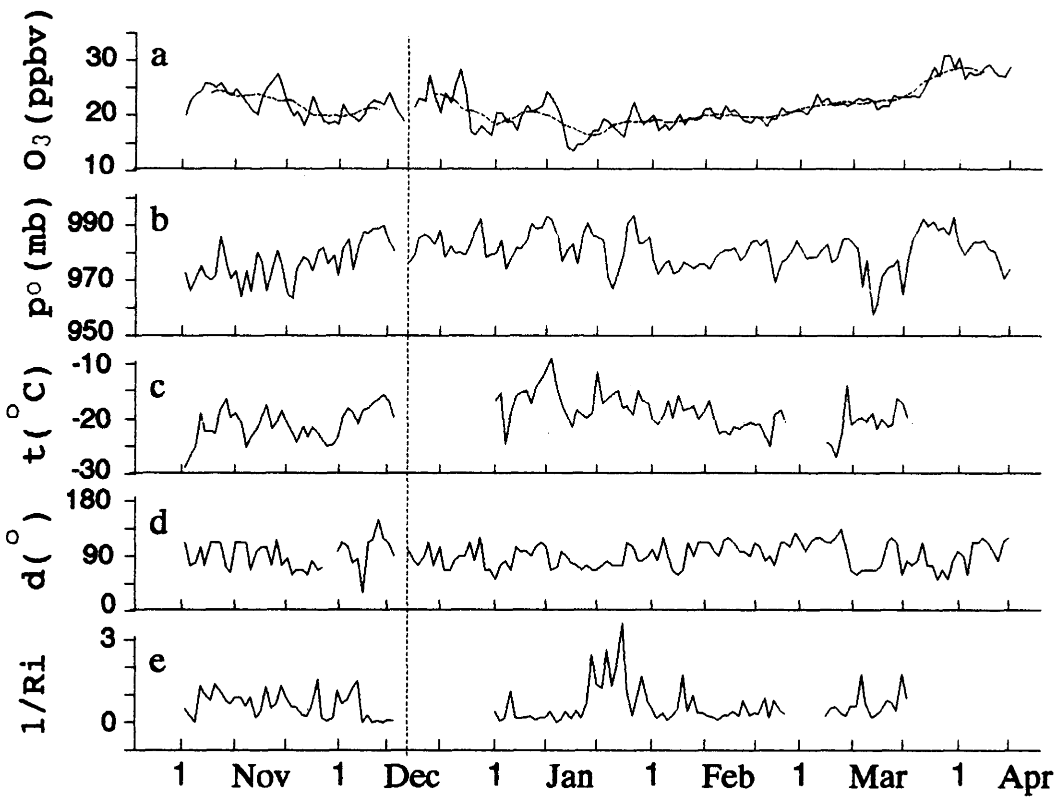

Fig. 1. (a) Daily mean (full curve) and 10-day mean (dashed curve) surface ozone mixing ratio; (b) daily mean surface atmospheric pressure; (c) temperature at 3-km altitude at 0 GMT; (d) direction of surface wind, and (e) the inverse Richardson number for the 0–1 km layer at 00 GMT. The vertical dashed-dotted line separates Molodezhnaya and Mirny data.

Richardson number can be an index of turbulent energy (Nieuwstadt and Van Dop, 1985). The inverse value, Ri^{-1}, is shown in Fig. 1e.

It follows from an analysis of Fig. 1 that the day-to-day surface ozone variations are strongly associated with meteorological processes. The greatest variations were noted for the period of developed synoptical activity in spring-summer (cf. Fig. 1a and 1b). The low day-to-day variability was observed at Mirny during the period of small variations of atmospheric pressure from February to the first 10-days of March 1988. The intensification of synoptical activity at the end of March resulted in an inrease of day-to-day ozone variations.

The relationship between ozone and meteorological parameters was investigated further. Figs. 2a, b show the correlation coefficients (CC) between surface ozone mixing ratio and temperature, surface ozone and relative humidity, and temperature and relative humidity in the troposphere from 0 to 10 km altitude for two periods of observations: from 1 November to 12 December 1987, at Molodezhnaya (Fig. 2a) and from 1 to 25 January 1988 at Mirny (Fig. 2b). A 3-day running average (inside a typical synoptical period) was made in order to remove high-frequency noise, and the linear trend was eliminated. The synoptical situations during these two periods were characterized by sequences of cyclones migrating along the sea-coast. Cyclones did not penetrate far to the center of the continent. Note that surface wind (see Fig. 1d) never had a western component. As Fig. 2 shows, there exists a high positive correlation between surface ozone and temperature of the middle troposphere above

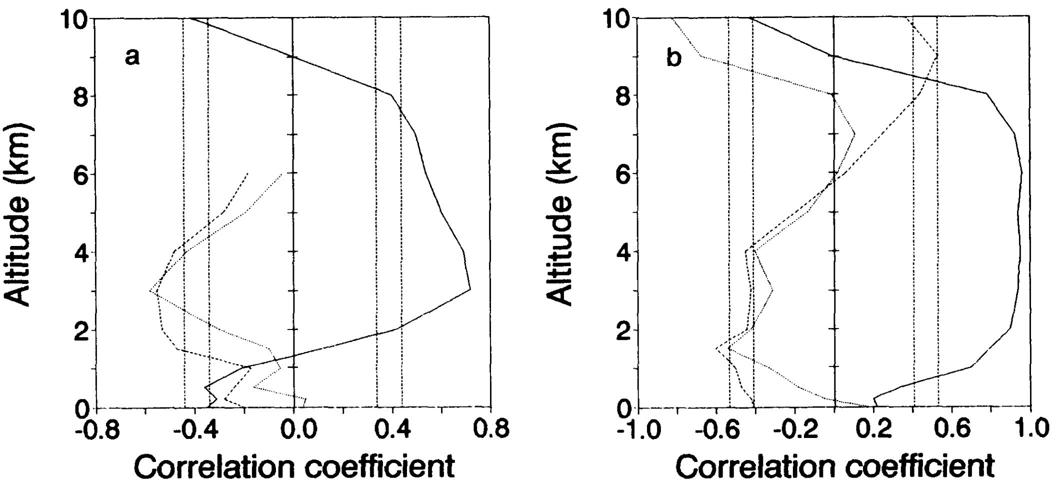

Fig. 2. The correlation coefficients between surface ozone mixing ratio and temperature (full curves), surface ozone and relative humidity (dashed curves), and temperature and relative humidity (dotted curves) as a function of altitude for two periods of measurements: (a) 1 November–12 December 1987, at Molodezhnaya, and (b) 1–25 January 1988, at Mirny. The vertical dashed-dotted lines show boundaries of 5% and 1% significance levels.

the boundary layer. The corresponding CC approaches 0.9 in summer at Mirny. The CC between surface ozone and relative humidity, as well as between temperature and relative humidity, are negative in the same layer. Inside the boundary layer, the CC are generally low and statistically insignificant. In this regard, it should be noted that temperature and humidity inside the boundary layer are influenced by underlying surfaces and local effects (see, e.g., Rusin, 1961; Schwerdtfeger, 1987), while the influence of the surface on the ozone content is small for the synoptical time-scale because of a small ozone reduction at snow and ice surfaces (Wesely et al., 1981).

In addition, surface ozone and temperature above the boundary layer correlate positively and relative humidity above the boundary layer correlates negatively with surface atmospheric pressure, although the CC values are not so large. It should be noted that in a coastal zone of the Antarctic, the relationship between pressure and other weather parameters is not always simple (Rusin, 1961; Schwerdtfeger, 1987), due to the influence of the orography of the continent.

According to Rusin (1961) and Schwerdtfeger (1987), a temperature increase, being accompanied by a decrease in relative humidity (which results in a negative temperature—relative humidity correlation), is usually connected at the coast of the Antarctic with a foehn effect of wet sea air being drawn into a slope flow down the Antarctic plateau. Analysing correlations and taking into account that the ozone mixing ratio in the Antarctic troposphere increases with increasing altitude (Aldaz, 1965; Oltmans and Komhyr, 1976; Marenco and Said, 1989; Gruzdev and Sitnov, 1992), one can suppose that during the periods of developed cyclonic activity, the important mechanism of increasing lower troposphere ozone content is ozone inflow from above as a result of descending motions in the areas of high atmospheric pressure. This hypothesis should be verified by trajectory calculations, which is not possible, however, as large-scale synoptical data are insufficiently detailed. Such calculations should also take into consideration the orography of the Antarctic continent.

From February to the 1st 10-day period of March, when pressure variations are small, there was a synoptically quiet period at Mirny. The meteorological situation in the near-surface layer was completely determined by dynamics of slope katabatic wind. Such winds are large-scale strong gravity flows of south and south-east directions, which transport any amount of air from polar to subpolar regions (Rusin, 1961; Egger, 1985; Schwerdtfeger, 1987). It follows from Fig. 1 that small ozone variations during this period can be connected with the direction of surface wind. An ozone increase is noted as a rule when the southern (slope) component of wind increases. Earlier, Arabov et al. (1988) considered a possible influence of slope (katabatic) wind on diurnal variation of surface ozone. According to the present measurements, such a relationship is noted for a greater time scale (Fig. 1). The CC between the daily averaged surface ozone content and the direction of surface wind at 00 GMT equals 0.63 for the period from 25 January to 5 March. If one excludes the 3-day period from 5 to 7 of February, when east wind prevailed (due to near cyclone), the CC value rises to 0.7. Both CC values are statistically significant at the 1% level. The hypothetical mechanism of such a relationship can be the transfer by slope wind of more ozone-abundant air, flowing in from above at the central part of the Antarctic continent, or the vertical exchange of air near the site of ozone measurements, due to enhanced turbulence in a greatly shearing slope wind zone. The latitudinal ozone gradient deduced from the spatial ozone distribution along the aircraft path (see Section 3) speaks in favour of the slope wind mechanism of ozone day-to-day variability. One could therefore expect that ozone variations would be more significant if ozone gradients were greater.

6. Diurnal variation

Fig. 3 shows three samples of ozone average diurnal variation (time is local) for three seasons: from 1 November to 14 December 1987 (spring), at Molodezhnaya; from 15 December 1987, to 29 February 1988 (summer); and from 1 March to 11 April 1988 (autumn), at Mirny. The standard deviation (due to day-to-day variability) is about 3 ppbv for all the curves. Analysing and interpreting diurnal variations one must bear in mind that the statistical significance of features of the average ozonal diurnal variations in Fig. 3 is doubtful, because diurnal variations are small

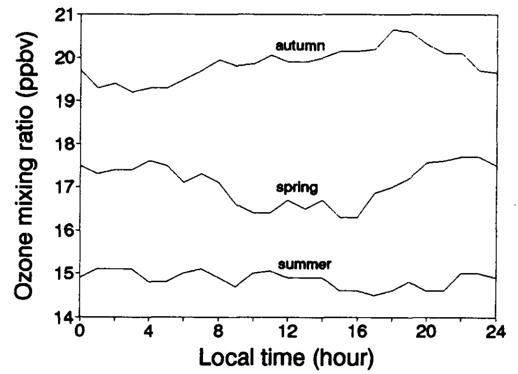

Fig. 3. Surface ozone average diurnal variations for three seasons: spring (1 November–14 December 1987) at Molodezhnaya; summer (15 December 1987–29 February 1988) at Mirny; autumn (1 March–11 April 1988) at Mirny.

compared with standard deviations. The spring average diurnal variation at Molodezhnaya is characterized by a day-time minimum and night-time maximum and is principally different from surface ozone diurnal variation typical for the Northern Hemisphere and for middle latitudes of the Southern Hemisphere (Oltmans, 1981; Kelley et al., 1984; Galbally et al., 1986), although a similar diurnal variation was observed in some regions with mountain-valley circulation (Price and Pales, 1963; Galbally et al., 1986). A similar surface ozone diurnal variation was earlier observed in Antarctica at some stations both as an average diurnal variation (Wisse and Meerburg, 1966; Oltmans and Komhyr, 1976) and as a regular diurnal variation for a short period (Arabov et al., 1988). The double amplitude of the spring curve in Fig. 3 is about 1.5 ppbv, which is essentially less than the standard deviation. The possible cause of a small day-time ozone decrease at Molodezhnaya may be local air pollution (e.g., by motor exhausts and fuel burning) resulting in ozone destruction.

There were no regular diurnal ozone variations in summer at Mirny (Fig. 3); there were only weak variations with an average magnitude of about 0.5 ppbv. This type of diurnal variation is most typical for Antarctic surface ozone (Oltmans and Komhyr, 1976; Von Kolbig and Warmbt, 1978; Oltmans, 1981; Arabov et al., 1988).

The autumn average diurnal variation at Mirny in Fig. 3 is characterized by a night-time (during the second half of night) minimum and an evening maximum. This can be a result of a higher day-time turbulent mixing which leads to a small accumulation of ozone in the surface layer. Such an assumption agrees with the March mean values of the inverse Richardson number of 3.6 and 8.1 calculated for the 0.2–0.5 km layer on the basis of radiosonde data at 00 and 12 GMT (at 5 and 17 hrs local time), respectively. The analogous Ri^{-1} values averaged for January–February are 6.1 and 5.7, respectively. They do not significantly differ from each other (cf. the summer curve in Fig. 3). For the period of measurements at Molodezhnaya, the analogous Ri^{-1} values equal 2.1 and 3.7 (corresponding to 2 and 14 hours local time), respectively. Note the particularly high Ri^{-1} value for the autumn period at Mirny.

7. Conclusion

The main results of the study are summarized below.

The annual variation of surface ozone in the coastal Antarctic has a summer minimum.

There are relatively large day-to-day variations (up to 10 ppbv value) connected with synoptical processes. A high positive correlation is found between surface ozone content and tropospheric temperature above the boundary layer.

During the synoptically quiet period (from late summer to early autumn 1988 at Mirny) the ozone time variability is not large and depends particularly on slope katabatic wind. A high positive correlation is found between surface ozone content and direction of slope wind for this period.

Diurnal variations are small and insignificant in a common statistical sense.

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