On relation between the surface ozone concentration and the mixing layer height

V.I. Demin, M.I. Beloglazov, and N.F. Elansky

Polar Geophysical Institute, Kola Scientific Center of the Russian Academy of Sciences, Apatity, Murmansk Region

Received April 26, 2004

The variability of the surface ozone concentration (SOC) depending on some dynamic processes in the Arctic atmosphere is analyzed. The SOC measurements and aerologic sensing on Kola Peninsula, as well as INTERNET meteorological data are used. Regression dependence of maximal hourly average SOC on maximal mixing layer height (MLH) is found; the correlation coefficient is equal to 0.7. Based on the fact that MLH is different in different air masses, the features of the surface ozone dynamics due to alternation of synoptic processes are explained.

According to generally accepted ideas, main sources of ozone in the surface layer are its transfer from the stratosphere and upper layers of the troposphere, where it is in abundance, as well as its photochemical generation in the surface layer. However, the peculiarities of the mechanism of such transfer are poorly studied, especially in the high-latitude zone. The purpose of this paper is to analyze the variability of the surface ozone concentration (SOC) depending on some dynamical processes in the Arctic atmosphere. Measurements of SOC at the observatory Lovozero and at the Apatity atmospheric field site of the Polar Geophysical Institute situated in the center of Kola Peninsula were used for the analysis. The measurements were carried out by means of the UV ozonometers "DASIBI" 1008AH (designed in USA) and "Monitor Labs" ML9810B (UK). The internet-assessable data of the Berlin Meteorological Institute and the German Meteorological Service, as well as the results of aerological sensing in Kandalaksha situated approximately 60 km to the south-west of Apatity were used for analysis of synoptic situations.

It is well known from the data of vertical sensing (see, for example, Refs. 1 and 2 or http://www.fmi.fi/research_atmosphere/atmosphere_4.html), that in summer the ozone mixture ratio always increases (often by several times) from the ground level to the boundary layer top (1…2 km) up to 40–45 ppb. Hence it follows that the vertical air exchange between the surface layer and the free troposphere must be accompanied by increase of the surface ozone concentration up to the levels characteristic of the atmospheric boundary layer (ABL) top. Since there exists a close correlation between the height of the mixing layer H_{ml} and the height of the boundary layer H_{bl} (correlation coefficient is about 0.95), then, using the relationship[3]

$$H_{ml} = 0.74k_1 / f$$

(here k_1 is the turbulence coefficient at the height of 1 m, f is the Coriolis parameter) we can estimate H_{bl} based on the climatic data on the turbulent exchange coefficient.[3] In summer it varies, in average, from 300–400 to 1300–1500 m. If to assume that the vertical profile of ozone above the Sodankyulya observatory represents the characteristic regional profile, the intense turbulent mixing can cause the increase of the surface ozone concentration, in average, up to 45 ppb. As observations show, in more than 98% of events the SOC value on Kola Peninsula in summer, including the polar day period, does not exceed 40–45 ppb (Table).

Table. Repetition of daily SOC values in summer (June–July) above Lovozero (1999–2003)

Gradation of SOC, ppb	Repetition, %
0…5	0
5…10	0.24
10…15	4.2
15…20	18.2
20…25	30.5
25…30	20.5
30…35	14.0
35…40	9.0
40…45	2.1
45…50	1.4
50…55	0.07
> 55	0

The value of H_{ml} is determined experimentally by means of the aerological diagram using the radiosensing and meteorological data on maximal air temperatures. The daily maximal H_{ml} is determined on the aerological diagram as the intersection point of the temperature vertical distribution curve with the dry adiabatic line passing through the point of the maximal near-ground temperature.[3–6] In cases when indifferent stratification is observed in the aerological diagram or the state curve lies no more than 1°C to the left of the stratification curve, the mixing layer top is at the height where these conditions break.[7]

The height of the mixing layer for July and August 2003 was calculated from the aerological sensing data obtained in Kandalaksha at 4 p.m. (Moscow time). We took into account that the air temperature maximum in this period is observed near 3 p.m.,[8] therefore the

0235-6880/04/08 595-04 $02.00

determined H_{ml} approximately corresponded to its maximum or correlated with it.

Correlation between maximal hourly averaged SOC in Apatity and maximal H_{ml} above Kandalaksha is shown in Fig. 1.

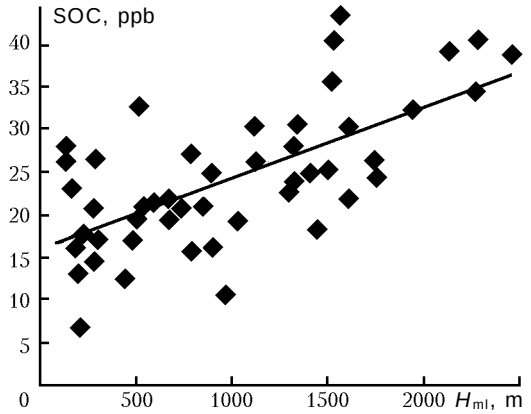

Fig. 1. Correlation between maximal daily ozone concentrations in Apatity and maximal mixing layer height.

The regression equation for the distribution in Fig. 1 is

$$[O_3]_{max} = (0.0082 \pm 0.0015)\, H_{ml} + (15.7 \pm 1.8).$$

The scatter of points around the straight line is, obviously, caused by different vertical profiles of ozone corresponding to different days at the same height of the mixing layer. Most likely, correlation between H_{ml} and SOC is greater at time intervals of a few days when advection processes can be neglected and the vertical profile is insignificantly transformed.

According to the synoptic analysis, there was a stationary Arctic air mass over Kola Peninsula from 5 to 9 of July 2003. The correlation between daily SOC and respective H_{ml} maxima in this period is shown in Fig. 2. This example shows that the correlation becomes significantly higher, if the ozone vertical profile obtained immediately above the observation site is used as the second predictor.

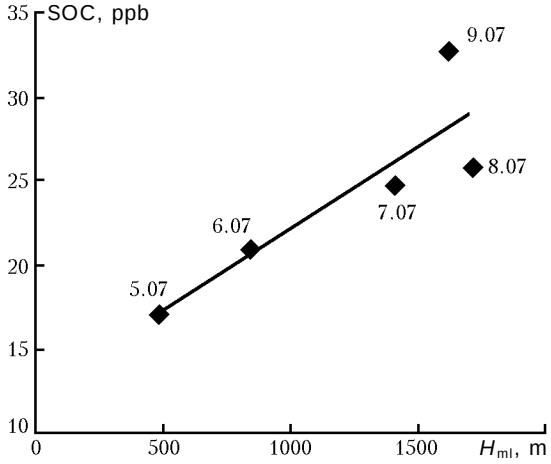

Fig. 2. Correlation between maximal daily ozone concentrations in Apatity and the maximal mixing layer height on July 5–9, 2003.

One more reason of the scatter is that the above method neglects the dynamic turbulence caused by the vertical wind shift. The latter leads to the fact that the method becomes practically inapplicable in the periods of the atmospheric front passages.

Nevertheless, the correlation coefficient between maximal heights of the mixing layer and maximal SOC values is high and equal to 0.70, that is demonstrated by similarity of their diurnal variations (Fig. 3).

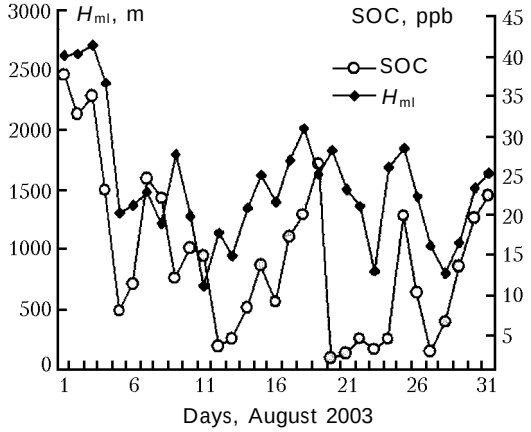

Fig. 3. Variations of the maximal mixing layer height and maximal daily ozone concentration in Apatity in August 2003.

We should note that the positive correlation between the selected parameters, in our opinion, points to mainly dynamic origin of the surface ozone field in the atmosphere of high-latitudes. If it were not and the photochemical ozone generation processes prevailed in the surface layer (as is often observed in low- and mid-latitudinal industrially developed regions), a negative correlation should be expected, because in that case less concentrations would correspond to a greater height of the mixing layer.

The dynamics of the atmospheric boundary layer has the same peculiarities as air temperature oscillations in the surface layer, because the both processes are determined by variations of the radiation budget of the underlying surface. Thus the high correlation between the diurnal behavior of SOC and air temperature in summer becomes clear.[9] The correlation between SOC and H_{ml} makes it possible to explain the observed correlation between the diurnal behavior of the air temperature and surface ozone concentration, because a change of the air temperature by even a few degrees can essentially affect the height of the mixing layer. For example, the increase of the surface temperature by "only" 5°C (from 25 to 30°C) for the temperature profile of July 26, 2003 has led to increase of the mixing layer top from 1.9 to 3.5 km and, hence, to significant increase of SOC.

Based on the found correlation between H_{ml} and maximal daily SOC, it is possible to explain some peculiarities of the surface ozone dynamics caused by changes of synoptic processes, because the types of stratification in lower atmospheric layers and, hence, H_{ml} are different in different air masses and synoptic

objects.[10–12] Let us show this by the example of SOC variations during passages of cold fronts (CF) over Kola Peninsula.

The surface water temperature of the Barents Sea in summer (June–August) is 4–8°C, which is lower than the temperature of the above air. Therefore, air masses of continental or Atlantic origin cool down here and acquire a stable stratification. The mechanism of cooling is quite effective: according to Ref. 13, the loss of energy by the atmospheric lower layer for heating and evaporation of the upper water layer at a surface temperature of 4–8°C is 150–250 W / m^2, while radiative income of heat is even less, approximately 100–130 W / m^2. When the air mass, formed above the sea, comes to the cyclone's rear, it is stable in the beginning of its way and becomes instable only while moving to the land.

In the initial period of the marine Arctic air staying over land in the rear of CF, its instability is limited by the lowest atmospheric layers and increases with the air heating. In this case, at the moment of CF passing the SOC magnitude sharply increases due to the convergence of airflows and intensive dynamic turbulence, but then decreases in a few hours after CF passing. Then, as the incoming air heats up, the instability and the height of the mixing layer increase, hence, the SOC also increases. Besides, the "standard" diurnal behavior is re-established. For example, before CF, on July 3, 2003 the height of the mixing layer exceeded 1500 m, and then on July 4 it became less than 800 m. Evidently, this affected the maximum ozone concentration in the surface layer, which was 44 and 16 ppb, respectively. The temperature of the incoming air mass was quite low, and the difference between maximal temperatures on July 3 and 4 exceeded 10°C. Transformation of the incoming air mass under conditions of continuous cloudiness lasted a few days. As it was heated from below, the power of the mixing layer and simultaneously the surface ozone concentration increased (Fig. 4). However, the situation can be different at another relations between mixing layer heights.

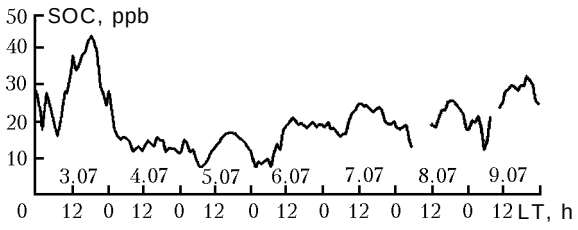

Fig. 4. Variations of the surface ozone concentration in Apatity on July 3–10, 2003.

In the warm sector of the cyclone on July 24, 2003 (Fig. 5) under conditions that the isothermy was observed in the 240–370 m layer and the inversion – in the 580–850 m layer, the height of the mixing layer did not exceed 200 m and SOC in the daytime decreased to 10 ppb, because the elevated inversion "blocked" the way to upper tropospheric layers. Passing of CF resulted in destruction of the "locking" layers, intensification of the turbulent exchange, and increase of the ozone concentration in the evening of the same day up to 33 ppb.

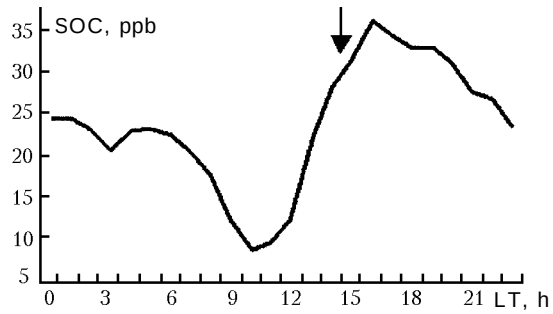

Fig. 5. Variations of the surface ozone concentration in Apatity at CF passing on July 24, 2003 (the moment of the passage is marked by arrow).

In winter, when the atmospheric stratification is stable, the above procedure for determination of the mixing layer height becomes inapplicable. However, it is possible to estimate the mixing layer height based on the fact that there is a close correlation between the heights of the mixing and boundary layers.[3]

According to the climatic data,[3] the mean turbulence coefficient in Apatity in November–December is 0.04 m^2/s. It corresponds to the mean value of a mixing layer of about 250 m. Based on the mean ozone profiles above the Sodankyulya observatory, we obtain mean maximal ozone concentrations in the surface layer of about 25–30 ppb. Mean maximal values above Lovozero are usually 28 ppb in December, 26 in January, and 28 in February.

Under invariable synoptic conditions in winter there are no diurnal variations of the turbulence coefficient[3] and the height of the mixing layer, therefore the constancy of turbulent fluxes causes approximate constancy of the SOC level, that corresponds to the really observed situation.

Thus, the presented examples demonstrate a very important role of the thermodynamic state of the low troposphere in formation of the surface ozone concentration in the atmosphere of high-latitudes. This allows us to explain the variations of SOC, observed in experimental quasi-background measurements on Kola Peninsula, in terms of the atmospheric dynamics.

Acknowledgments

Authors thank specialists of the Lovozero observatory, the Apatity field site, and the "Arctic Atmosphere" laboratory for technical provision of long-term measurements on Kola Peninsula.

The work was supported in part by the Russian Foundation for Basic Research (grant No. 02–05–64114 and 02–05–79148), INTAS (grant No. 01–0016), INCO-COPERNICUS (grant No. ICA2–CT–2000-10038), as well as the Program of Basic Research of Department of Physical Sciences RAS "Atmospheric

Physics: Electric Processes, Radiophysical Methods of Investigations" (State Contract No. 10002–251 / DPS–12 / 059–063 / 060603–547).

References

1. *Ozone Data for the World.* Canad. Environ. Service (WMO, Downsview–Ontario, 1974–2001.)
2. M.A. Zvyagintsev and I.N. Kuznetsova, Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **38**, No. 4, 486–495 (2002).
3. *Climatic Conditions of Propagation of Admixtures in the Atmosphere.* Handbook (Gidrometeoizdat, Leningrad, 1983), 328 pp.
4. E.Yu. Bezuglaya, *Monitoring of the State of Atmospheric Pollution in Cities* (Gidrometeoizdat, Leningrad, 1984), 200 pp.
5. E.Yu. Bezuglaya, *Meteorological Potential and Climatic Peculiarities of Urban Air Pollution* (Gidrometeoizdat, Leningrad, 1980), 184 pp.
6. M.E. Berlyand, *Modern Problems of Atmospheric Diffusion and Atmospheric Pollution* (Gidrometeoizdat, Leningrad, 1975), 448 pp.
7. *Guidance for Short-Term Weather Forecasts* (Gidrometeoizdat, Leningrad, 1986), Part 1, 703 pp.
8. *Handbook on Climate of USSR* (Gidrometeoizdat, Leningrad, 1965), Issue 2, Part 1, 144 pp.
9. O.A. Tarasova and A.Yu. Karpetchko, Atmos. Chem. Phys. **3**, No. 6, 941–949 (2003).
10. S.P. Khromov, *Principles of Synoptic Meteorology* (Gidrometeoizdat, Leningrad, 1948), 696 pp.
11. A.S. Zverev, *Synoptic Meteorology* (Gidrometeoizdat, Leningrad, 1977), 712 pp.
12. M.A. Lokoshchenko, B.A. Semenchenko, M.A. Kallistratova, and M.S. Pekur, Atmos. Oceanic Opt. **7**, No. 7, 522–528 (1994).
13. V.F. Romanov, N.V. Ariskina, V.F. Vasil'ev, and V.E. Lagun, *Energy of the Atmosphere in Polar Regions* (Gidrometeoizdat, Leningrad, 1987), 296 pp.