Vertical profile of ozone concentration and temperature in the atmospheric surface layer over the southeastern coast of Lake Baikal

V.P. Butukhanov, G.S. Zhamsueva, A.S. Zayakhanov,
Yu.L. Lomukhin, and B.Z. Tsydypov

Department of Physical Problems,
Presidium of Buryat Scientific Center of Siberian Branch of the Russian Academy of Sciences, Ulan-Ude

Received June 24, 2002

Measurements of the vertical profiles of air temperature and ozone concentration in the atmospheric surface layer over the southeastern coast of Lake Baikal are presented. It is shown that ozone accumulates above the inversion layer, while under the bottom of this layer its significant depletion is observed at the inversion type of atmospheric temperature stratification.

The main channel of ozone sink is its interaction with the surface (chemical and physical sorption). The important role of the surface for the ozone sink follows, first of all, from the character of the vertical ozone profile in the troposphere − ozone concentration in the troposphere decreases when approaching the surface.[1] Deviations from this vertical ozone profile are explained by the effect of local ozone sources and sinks, as well as by the stratification of the surface atmosphere. However, the studies in Ref. 2 have shown that blocking inversion layers in the atmosphere, wind, and stability of the boundary layer do not play the decisive role in ozone accumulation. In experiments,[1] it was shown that the maximum of the near-surface ozone concentration is established above the inversion layer in the case of its transport from higher atmospheric layers (natural source). In the presence of anthropogenic ozone sources, its maximum concentration is observed under the inversion layer.

Experimental investigations and analysis of the dynamics of the vertical ozone profile along with the investigation of meteorological parameters can give information on the causes for variations of the ozone concentration and its sources in the atmospheric surface layer for every particular site (region).

To study the effect of atmospheric stability on the ozone profile, we have conducted simultaneous measurements of the near-surface ozone concentration and temperature in the 12-m atmospheric layer over the southeastern coast of Lake Baikal in the summer period (July 13–28) of 2001.

Observations

The observation site was located in the Boyarsk village at the research facility of BSC SB RAS with the coordinates: 51°40′N, 103°40′E, 500 m along the normal to the shoreline at the altitude of 200 m above the Lake Baikal level. The ozone concentration and temperature were measured with a meteorological mast on an open ground with the grass cover roughly 50 mm high. A probe with a temperature sensor and a Teflon sampling tube was lifted by a rope with 2-min intervals to the altitudes of 2, 4, 6, 8, 10, and 12 m four times a day on the average (morning, day, evening, night). The maximum altitude 12 m was chosen based on technical capabilities of sensing of the atmospheric surface layer.

The O_3 concentration was measured with a 3-02P1 gas analyzer of the OPTEK company. The gas analyzer has the following characteristics: concentration range from 1 to 1000 $\mu g/m^3$, relative measurement error of 15%, and response time no more than 1 s.

The gas analyzer is equipped with the built-in ozone calibrator providing for automatic calibration, as well as with analog and digital output. Air is sampled through the Teflon tube 13 m long.

The temperature was measured with an E7-11 device based on the bridge method of measuring the electrical resistance of a thermoresistor (temperature sensor) with the following conversion of the sensor resistance into temperature by the calibration curve.

The wind velocity was measured with an M-49 weather station at the altitudes of 4, 6, and 8 m. For analysis, we used the temperature and the ozone concentration averaged over 2-min intervals for each of the altitudes.

Figure 1 depicts the average curves of the vertical profile of the ozone concentration and temperature depending on the parameter B − an analog of the Richardson number characterizing the turbulent conditions in the surface layer[3]:

$$B = \frac{g}{T_1}\frac{z_3\,\Delta T}{C_3^2}, \qquad (1)$$

where $\Delta T = T_2 - T_1$, T_1 is the temperature at the altitude z_1, T_2 is the temperature at the altitude z_2; C_3 is the wind velocity at the altitude z_3, $z_1 = z_3/2 = 2$ m, $z_2 = 2z_3 = 8$ m, $z_3 = 4$ m; $g = 9.8$ m/s^2. The value and sign of the parameter B are determined by the effect of stratification on the turbulent conditions.

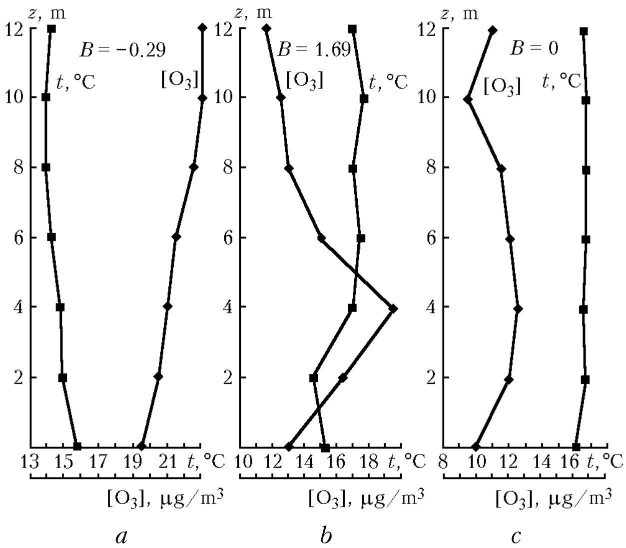

Fig. 1. Vertical profile of the ozone concentration and temperature in the atmospheric surface layer over the southeastern coast of Lake Baikal (Boyarsk, July 13–28, 2001).

The curve of the vertical temperature profile in Fig. 1*a* is characteristic of unstable stratification, as indicated by the parameter $B = -0.29$. This type of stratification was usually observed in the first half of a day (11–12 a.m. LT) in 21 cases for the entire observation period. In this case, $\Delta[O_3]$ at the level of 10 m was 3.5 µg/m^3.

At unstable stratification in the morning, as the surface becomes warmer, development of upward convective fluxes begins, and these fluxes favor a more intense turbulent mixing of air masses in the atmospheric layer from 2 to 10 m. With the top boundary of the mixing layer lying at the height of 10 m, the O_3 concentration was equal to 23 µg/m^3, while $[O_3]$ just near the surface decreased insignificantly (down to 19 µg/m^3). Thus, the convective flux at unstable stratification creates the conditions favorable for turbulent exchange of O_3 molecules, and thus its concentration at different altitudes is equalized. It should be noted that this stratification was accompanied by high insolation favoring the ozone generation.

In Fig. 1*b* the curve of the vertical temperature profile characterizes the inversion type of stratification in combination with calm conditions in the lower atmospheric surface layer. In this case, the parameter B equals 1.69, thus indicating toward strong stability of this layer. In the inversion layer, turbulence and vertical motions are weak or completely absent, and in the case of a very strong inversion the so-called blocking layer is formed. The wind velocity measured at the altitudes of 4 and 8 m was equal to 2 and 1 m/s, respectively. This type of stratification was observed in the evening (09–10 p.m. LT) in 14 cases over the entire observation period at the air temperature of +17 °C and the southeastern wind.

In Ref. 4 it was shown that the occurrence of ground inversions on the southern coast of Lake Baikal in summer is 44%, and they are mostly observed in the evening and night hours and connected with surface cooling.

Besides, it is necessary to take into account the effect of breeze, which is observed rather often at such a big lake like Lake Baikal. According to Ref. 5, the occurrence of the breeze circulation and other local periodic winds in summer reaches 50–70%.

In evening and at night hours with no ozone generation, its destruction occurs in dark reactions with nitrogen oxides and other trace gases. Comparing the $[O_3]$ profiles in Figs. 1*a* and *b*, we can see that the ozone concentration at the altitude $z = 12$ m in the evening (09–10 p.m. LT) is halved as compared to $[O_3]$ in the period of intense ozone generation (see Fig. 1*a*).

On the other hand, the interaction of local circulations with the common flux in this period often gives rise to calm layers, in which the wind velocity decreases down to 0–1 m/s. These layers concentrate atmospheric trace gases under the effect of diffusion processes.[5] It is seen from Fig. 1*b* that the ozone concentration in this layer begins to increase smoothly starting from the altitude 12 m and reaching $\Delta[O_3] = 4$ µg/m^3 at the altitude $z = 6$ m at the wind velocity of 1 m/s. Then, falling in the fluxes of local winds, ozone is transported to the lake area, where it is accumulated. At the development of the land breeze, cold air masses with accumulated ozone in its counterflow come to the ground layer of the observation site. As a result, an internal layer is formed on the coast, and air within this layer appears to be cooler than above it. The air temperature here decreases with height, but it may increase on top of the layer. Thus, the ground inversion arises, whose altitude and intensity depend on the local time, the distance from the shoreline, and the temperature difference between the water and land surfaces. The bottom of such an inversion lies at relatively low altitudes.[6] To assess the height of the inversion layer on the southeastern coast of Lake Baikal, we used the following empirical equation[7]:

$$H = \frac{u_*}{u}\sqrt{\frac{x\Delta T}{\partial T/\partial z}}, \qquad (2)$$

where $u = 2$ m/s is the mean wind velocity, $u_* = 0.3$ m/s is the dynamic or friction velocity; $x = 500$ m is the distance from the coast to the observation site; $\Delta T = -2$°C is the water/land temperature difference, $\partial T/\partial z = -1.1$°C/m is the mean air temperature gradient on the coast.

Having substituted the parameter values into Eq. (2), we got the layer height $H \approx 4.5$ m. Comparing calculated H with the experimental one, we can see that a minor difference between these heights (see Fig. 1*b*) is caused by the rough value of the friction velocity u_*. To determine H more correctly, we should measure this parameter.

In the inversion layer, the process of ozone accumulation intensifies. The ozone concentration peaks at $z = 4$ m. In this case $\Delta[O_3] = 8$ μg/m^3. Below the inversion bottom at $z < 4$ m, the decrease of the ozone concentration and its sink occur with intensification of turbulent diffusion from the surface.

As known, at the neutral stratification, the temperature varies adiabatically with height; the parameter $B = 0$ in this case. Taking into account that the vertical size of the surface layer is rather small, a particular case of the stable stratification, namely, isothermia, can be classified as neutral stratification. In this case, as in the case of inversion stratification, any vertical fluxes are very weak. The temperature profile shown in Fig. 1*c* almost does not change with height, $\Delta[O_3]$ is also insignificant, and its mean value is 1.7 μg/m^3. Some decrease of $[O_3]$ is observed at the height of 10 m, and this can be apparently explained by the effect of forest near the observation site, as forest is an efficient ozone sink. The mean tree height is roughly equal to the sampling height, at which deviation of the ozone concentration is observed. To reveal the forest effect on ozone variations, further observations are needed.

Thus, for summer period of observations of the vertical $[O_3]$ and temperature distributions in the atmospheric surface layer over the southeastern coast of Lake Baikal, we have obtained three types of stratification and assessed their effect on the vertical ozone profile. In daytime the ozone concentration at the height of 10 m (see Fig. 1*a*) is twice as large as $[O_3]$ at other stratifications due to intense turbulent mixing. It should be noted that the types of stratification in Figs. 1*a* and *c* agree with theoretical and experimental data of other investigations.[7,8] In the case of inversion, it was shown that the blocking layers in the coastal atmosphere of Lake Baikal play a significant role in the ozone accumulation in this layer.

For a more detailed investigation of the effect of atmospheric stability on the vertical ozone profile, additional long-term observations with the use of modern vertical sensing instrumentation are needed.

Acknowledgments

Support form the Russian Foundation for Basic Research (Grant No. 01–05–97240) is acknowledged.

References

1. F.Ya. Rovinskii and V.I. Egorov, *Ozone, Nitrogen and Sulfur Oxides in the Lower Atmosphere* (Gidrometeoizdat, Leningrad, 1986), 184 pp.
2. N.P. Krasnenko and M.G. Fursov, Atmos. Oceanic Opt. **7**, Nos. 11–12, 874–875 (1994).
3. A.T. Matveev, *Course of General Meteorology. Atmospheric Physics* (Gidrometeoizdat, Leningrad, 1976), 639 pp.
4. Yu.A. Israel and Yu.A. Anokhin, eds., *Regional Monitoring of Lake Baikal* (Gidrometeoizdat, Leningrad, 1987), 303 pp.
5. V.V. Vlasenko, *Climate and Plants of Southern Cisbaikalian.* Collection of research papers (Nauka, Novosibirsk, 1989), pp. 32–43.
6. M.E. Berlyand, *Prediction and Management of Atmospheric Pollution* (Gidrometeoizdat, Leningrad, 1985), 272 pp.
7. G.S. Reynor, Boundary-Layer Meteorol. **16**, No. 4, 487–514 (1979).
8. V.I. Yegorov and F.Ya. Rovinsky, J. Ecol. Chem., No. 1, 41–45 (1993).