On the role of turbulent mixing in formation of ground-level ozone concentration in the Kola Peninsula

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The monthly averaged maximal ground-level ozone concentrations are calculated based on the climatic values of maximal altitudes of the mixing layer above Apatity town and the data of the local ozone-sensing station (Sodankyla, Finland). In the Kola Peninsula, they are shown do not exceed the average ozone concentrations at the top boundary of the mixing layer. This is indicative of the turbulent mechanism of formation of the ground-level ozone field in the Arctic.

Introduction

According to classical concepts, ozone comes to the atmospheric ground level due to its turbulent transport from upper layers. Besides, under the influence of UV radiation, it can be photochemically generated from hydrocarbons and nitrogen oxides of natural and anthropogenic origins. The role of the dynamic and photochemical mechanisms of the ground-level ozone field formation in the Arctic, as well as the relationship between them largely remain unclear.

According to high-latitude observations of background concentrations of nitrogen-containing gases, the NO_x concentration does not exceed 0.01–0.05 ppb (Ref. 1). In such conditions, photogeneration of ozone in the surface layer is essentially balanced by chemical decomposition,[2] and the role of turbulent ozone influx from upper levels grows and perhaps becomes prevailing. However, the authors of the one-dimensional chemical model[3] believe that ozone in the lower troposphere has mostly a photochemical origin. Authors of another one-dimensional chemical model[4,5] hold the viewpoint about a significant role of photochemical origin of ozone in the Kola Peninsula as well.

However, the results of parallel measurements conducted in 2002–2004 show that the maximal ozone concentrations in the center and immediate outskirts of Apatity, as well as in the background region are almost equal despite different levels of anthropogenic pollution.[6,7] The presence in air of ozone precursors does not affect its maximal values even during the polar day period and other days favorable for photochemical formation of the ground-level ozone. This allows us to infer about a minor role of photochemical ozone generation in the Arctic because of unfavorable meteorological conditions (e.g., low temperatures) and a low concentration of precursors. In this case, the main source of ozone in the ground layer is its turbulent transport from the top down.[6,7]

In this paper, average maximum ground-level ozone concentrations in the Kola Peninsula, which are possible due to the turbulent exchange, are estimated taking into account peculiarities of the vertical ozone distribution in this region. The obtained values are compared with the results of long-term measurements.

Research method and data involved

It is known from the vertical ozone sensing data (http://www.fmi.fi/research_atmosphere/atmosphere_4.html, for example) that the ozone mixture ratio (OMR) nearly always grows several times from the Earth's surface to the boundary layer top (1–2 km) up to 50–60 ppb. A typical vertical distribution of tropospheric ozone is plotted in Fig. 1.

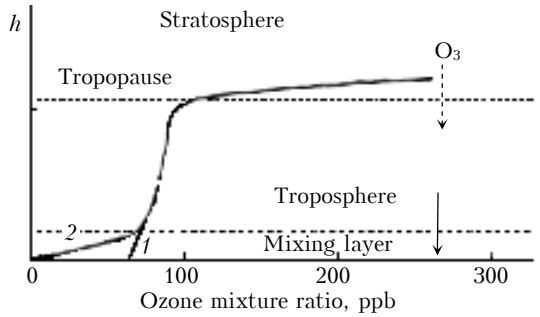

Fig. 1. Vertical distribution of ozone in the lower atmosphere in mixture ratio units.

The intensive turbulent mixing smoothes the vertical ozone profile within the mixing layer (ML) in such a way that maximal surface ozone concentrations approach those at the ML top boundary (profile *1* in Fig. 1). The mixing can be created by the thermal turbulence in the case of unstable stratification, and by a dynamic turbulence in case of a stable one, which in its turn is caused by peculiarities of the vertical wind profile. Curve *2* in Fig. 1 corresponds to conditions of a weaker turbulent exchange. The given pattern is experimentally proved by parallel measurements of stratification parameters and vertical ozone distribution in the atmospheric boundary layer (see, for example Ref. 8).

It is quite evident that the highest ozone concentrations, possible in the ground layer only due

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to turbulent mixing, must not exceed ozone concentrations at the ML top boundary (ozone flux is directed downward only under these condition). Otherwise, there must be a ground-layer source of ozone (its photochemical generation).

Therefore, having the data on the ML heights and vertical ozone distribution, we can estimate the contribution of turbulent exchange into formation of the maximal values of OMR.

The monthly average maximal ML heights were calculated based on the boundary layer model[9,10] and the average long-term values of the turbulent exchange coefficient for the town of Apatity ($\varphi = 67.57°$N, $\lambda = 33.40°$E) obtained from the processing of gradient measurements.[10]

For the measurements were short-term (December 2002 – March 2004), we used the data for Lovozero ($\varphi = 67.97°$N, $\lambda = 35.02°$E) instead of average long-term OMR for Apatity, because, according to parallel observations,[7] in these sites the monthly average OMR differ not more than by 2 ppb (or we suppose that the 80-km-spaced average ML heights over Apatity and Lovozero differ negligibly).

The vertical ozone sensing station nearest to Apatity and the Lovozero observatory is the Sodankyla observatory located 300 km to the south-west (Finland, $\varphi = 67.39°$N, $\lambda = 26.65°$E). The average ozone concentrations at the ML upper boundary in Apatity (and over Lovozero) were assumed equal to those in Sodankyla at the levels corresponding to the average maximal ML heights over Apatity for this month.

Results and discussion

The monthly average OMR obtained by the above method at the ML top boundary are shown in Fig. 2 together with monthly averaged OMR peaks for Lovozero.

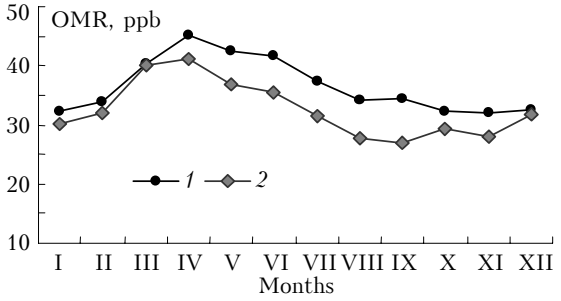

Fig. 2. Monthly average OMR over Sodankyla at the heights corresponding to the ML monthly average maximal heights over Apatity (*1*), as well as the monthly average maximal OMR for Lovozero (*2*).

On the whole, the calculated curve well enough reproduces the OMR annual trend in the Kola Peninsula. The least disagreement between the calculated and measured values is observed during the colder six months (from November to March), and the greatest one – in summer. The reason is that in winter period the vertical ozone profile in the ground layer is smoother due to slow ozone destruction rates above the snow cover, while in summer ozone largely sinks to the surface and to the level of a few meters above the surface (the leftward knee of curve *1* in Fig. 1).

Figure 2 shows also that the average maximal OMR values fixed in the Kola Peninsula do not exceed analogous values at the ML top boundary.

This inference is also supported by the comparison of OMR data obtained over Lovozero and at the top of the Lovchorr Mountain (1095 m, the Khibini mountains, $\varphi = 67.6°$N, $\lambda = 33.7°$E, horizontal distance between Lovozero and the Lovchorr Mountain is 60 km, between Apatity and the station on the Lovchorr top – 20 km).

Our estimates show that maximal monthly averaged ML heights in the region change from 300 m in winter to 900–1050 m in summer. In June (polar day) the Lovchorr monitoring station is at the height, which approximately corresponds to the ML upper boundary (1050 m) above the surrounding plains. During the polar day the mountain-valley circulation in Khibini is not developed[12] and ozone dynamics on the Lovchorr Mountain is largely determined by dynamical processes in free atmosphere (the OMR diurnal behavior, typical for ground and boundary layers, is absent on the Lovchorr Mountain). As is known, when a flow moves across a barrier, there appears a vertical component. Therefore, the ozone-lean air from below comes to upper parts of mountains. Therefore, OMR on the Lovchorr top is somewhat lower than at the same height in the free atmosphere (by ozone-sonde data, on the average, monthly averaged OMR on the Lovchorr Mountain are lower by 3.4 ppb per year than monthly averaged OMR at a height of 1095 m above Sodankyla).

However, even at such undervaluing the hourly averaged OMR values for Lovozero (Fig. 3), as a rule, do not exceed those for the Lovchorr Mountain (a few events of overvaluing not exceeding 1–2 ppb, fall on periods of severe fogs with a visibility less 100 m on the Lovchorr Mountain, when there appears an additional ozone sink due to interaction with the droplet aerosol).

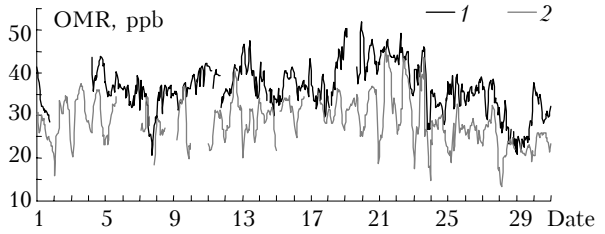

Fig. 3. Hourly averaged OMR for the Lovchorr Mountain (*1*) and Lovozero (*2*) in June, 2005.

The most OMR difference between these two sites is observed at night hours at a low sun elevation (polar day) and the least one – in post-noon time, when the turbulent exchange in the boundary layer is maximal.[13] Natural diurnal variations of turbulent fluxes, most possible, determine also the ozone diurnal behavior in the ground layer.[6,7]

As it was mentioned above, somewhat noticeable photochemical ozone generation in the Kola Peninsula was not found.[6,7] It was also marked[6,7,14] that diurnal variations of ozone in the region all the year round qualitatively well agree with the commonly accepted notion of the diurnal variations of dynamical processes in ground and boundary layers. Estimates presented here, which show that maximal near-ground ozone concentrations in the region do not exceed values characteristic of the ML top boundary, are indicative of the dominating role of low-troposphere dynamical processes (turbulent exchange) in generation of near-ground ozone field in the Arctic.

Conclusions

1. Based on data of the local station of ozone vertical sensing in Sodankyla (Finland), the monthly averaged maximal ML heights in the central Kola Peninsula, as well as monthly averaged OMR values at the ML top boundary have been calculated.

2. The monthly averaged maximal OMR observed (including the polar day period) in the region, are shown to not exceed mean ozone concentrations at the ML top boundary, which testifies that the turbulent mechanism of the near-ground ozone field formation dominates in Arctic conditions.

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