Foehn effects above the Khibiny in changes of the surface ozone concentration

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We present some results on the surface ozone concentration (SOC) measured on Lovchorr Mountain (at 1089 meters height above sea level (a.s.l.) in the Khibiny mountains) during free foehn periods. It is shown that the foehn occurrence at the observation site is accompanied by synchronous variations of SOC, relative humidity and, to a lesser degree, air temperature. The SOC increase in foehn situations can amount to 10 to 20 ppb and is caused by the intrusion of the air enriched with ozone from the upper atmospheric layers into the surface layer at downwelling airflows in an anticyclone.

Introduction

Since March, 2004 the Polar Geophysical Institute (PGI) has launched the program on monitoring the surface ozone concentration (SOC) on the Lovchorr Mountain ($\varphi = 67°36'$, $\lambda = 33°51'$, 1089 meters a.s.l.) – one of the tops of the Khibiny massif. The measurements are carried out with an "ML9810B" UV-ozonometer (Great Britain) at "Tsentralnaya" mountain avalanche station of "Apatity Ltd." along with the full complex of meteorological observations.

One of the tasks of the monitoring is the study of the effects of mesoscale processes of mountain circulation, such as foehn effects, on the SOC variations.

According to definition, foehn is a katabatic wind in a mountain region yielding the rise of air temperature while decreasing relative humidity of the air. The classic model of the foehn origin is as follows. Humid air is first forced upward over the windward mountainsides accompanied by production of clouds and precipitation. As the air flows downward over the leeward sides with dry-adiabatic gradient, it is warmed up and clouds dissipate. In reality, the pattern is more complicated. Few types of the foehn are being distinguished in the literature[1–3] depending on the mechanism of katabatic wind.

As follows from data of sounding the vertical ozone distribution (see, e.g., http://www.fmi.fi/research_atmosphere/atmosphere_4.html), ozone concentration increases with height. Hence, the airflows moving down along the mountain slopes and resulting in the foehn phenomenon should manifest themselves not only in different behavior of meteorological parameters observed at mountain and foothills stations, but in SOC dynamics as well. From this viewpoint, foehn effects well known in meteorology can serve an indicator of the katafront mechanism of SOC changes.

Diagnostics of the Foehn effects

It is known, that the foehn resulting from even lofty mountains practically has no effect in valleys already at the distances over 20 to 30 km. The Khibiny massif has elevations about 1000 to 1100 m (with maximum height of 1200 m) and is only 800 to 900 m higher than the surrounding plains. Lateral dimensions of the Khibiny massif is not large as well, 30×50 km approximately. Under these conditions, air mass transfer does not produce foehn effects at surface ozone monitoring stations of PGI in Apatity, 10 km to the southwestward from the Khibiny (i.e., windward side predominantly). The same is true for "Lovozero" geophysical observatory also 10 km far but to the northeastward from the Lovozero Mountains with similar to the Khibiny altitude and horizontal measures. In fact, the foehn effects were revealed neither in Apatity, nor in Lovozero during all the observation period (1999–2005). At the same time, the foehn effects are clearly seen in traces of thermo- and hygrograms at "Vostochnaya" mountain avalanche station (located within 3 km from the southeast mountainside of Khibiny). Those appear as an abrupt temperature rise up to 6 to 10°C and synchronous relative humidity decrease by 20 to 40%.

The foehn effects resulting from air mass transfer are impossible at the station at the Lovchorr Mountain, as it is only 10 km far from the top. However, the so-called free foehn (foehn from the free atmosphere) due to concretion inversion into an anticyclone is possible. Such foehns reach the Earth's surface very seldom but mountainsides and tops at the altitude of 1000–3000 m can be crossed with inversions very often resulting in changes of temperature and relative humidity of the air. This type of the foehn is characteristic for all the mountain systems including Khibiny,[3] but often is missed because of the absence of observations at the mountaintops.

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As known, the foehn manifests itself in temperature rise and relative humidity decrease. The mechanism is the following: the descending air is warmed up while transporting the specific humidity from its starting point. However, meteorological parameters of foehn-like situations in mountain regions are different from meteorological parameters of foehns in valleys. The free foehns are often observed under calm conditions and are characterized by a peculiar behavior of the temperature and humidity. Thus, for example, the temperature effect of the foehn (i.e., temperature rise at a station) can be revealed only if the descending air is warmer than the displaced air, i.e., the effect depends both on the vertical temperature distribution and the displaced air temperature. In certain cases, the temperature can keep unchanged or rises only a little under the foehn.[2]

The weakened temperature effect or its absence sometimes is characteristic of the free foehn. This makes one to change the diagnostic criteria. In contrast to the foehns of foothills regions, we take into account neither wind velocity, nor the temperature rise. The main feature of the foehn-like situation is the relative humidity decrease.[2] In so doing, we proceed from the fact, that the sign of relative humidity change always coincides with the sign of vertical velocity under stable stratification, i.e., the relative humidity decrease is always observed in downwelling airflow.[2]

Different criteria of the free foehn by the dynamics of relative humidity have been suggested in literature. For example, Bernhard[2] determines the foehn by relative humidity not higher than 40%. However, considering daily variation, when cases of low air humidity due to the daytime temperature rise at a mountain station are excluded, the relative humidity decrease to 60% and less can be taken as the free foehn criterion.[2] Thus, the Flohn foehn criterion, obtained in studying anticyclone foehns in Alps, is relative humidity of 40% and less in daytime and not more then 60–65% in other time.[4] Similar criterion was used to reveal the foehn-like situations in Caucasus.[5]

In the work, to diagnose a foehn process, we used the location over the region of an anticyclone with down moving airflows (the sign was determined according to techniques from Refs. 6 and 7); the appearance of concretion inversion based on aerological sounding data from the nearest stations (Kandalaksha and Murmansk) with the bottom boundary of the inversion layer lower than the station at the Lovchorr Mountain; and the relative humidity decrease to 40–60% uncharacteristic of the region. The absence of considerable wind and low clouds, increase of horizontal visibility range, and, if occurred, synchronous changes of air temperature served as an additional criterion.

Measurement results and discussion

The free foehn at the Lovchorr station was revealed in traces of thermo- and hygrograms on September 3–4, 2004. In this period, sufficiently strong anticyclone was located over Kola Peninsula and the White Sea. Lower tropospheric downwelling airflows (in the layer up to 850 hPa) manifested themselves in the dynamics of the surface pressure in accordance with the observations in Refs. 6 and 7. Rapid deformation of the vertical profile of temperature and humidity as well as appearance of characteristic concretion inversion in the layer of 900 to 1160 m served as visual proofs. The concretion inversion was detected using data of vertical aerological sounding at 00 UT on September 4 in Kandalaksha, which is 70 km far to the southwest from the Lovchorr Mountain. When the bottom boundary of such an inversion crossed the station level (1089 m a.s.l.), the necessary conditions for the free foehn appearance were evidently produced.

Indeed, according to the parallel traces of the hygrograph and thermograph (Fig. 1), rapid decrease of relative humidity from 90 to 26% and synchronous temperature rise by 1.5°C began at 22:20 (hereinafter the time is Moscow winter time) against the almost clear sky (cirrus cloud amount of 2) and light breeze (less than 2 m/s).

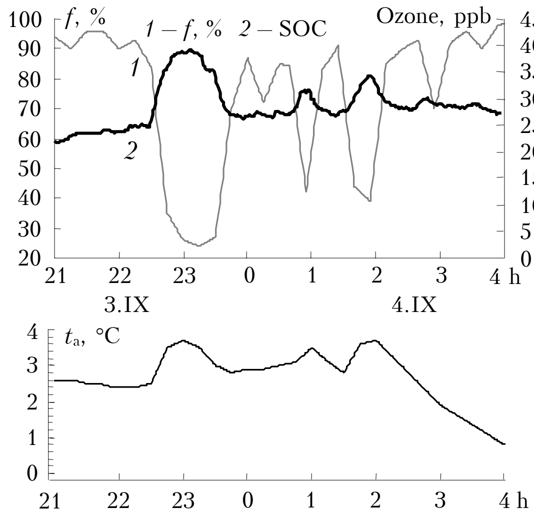

Fig. 1. The behavior of relative humidity (f, %), ozone concentration (ppb), and air temperature (t_a) on the Lovchorr Mountain on September 3–4, 2004.

The stable weather according to the surface observations (http://www.met.fu-berlin.de) and the absence of sudden changes in usual daily behavior of the meteorological parameters in the same period at the nearest meteorological stations "Apatity," "Monchegorsk," and "Lovozero" (Table 1) exclude the advection mechanism of the changes occurred on the Lovchorr Mountain and allow us to consider them as the result of the foehn process over Khibiny due to the descending air mass in the anticyclone.

As the ozone concentration in the troposphere increases with height, the descending air resulted not only in the foehn on the Lovchorr Mountain, but in a significant ozone content growth from 20–22 to 33–34 ppb. It is important that the ozone concentration and relative humidity changed synchronously but in antiphase. The temperature change was little in accordance with the above free foehn properties.

Table 1. Values of the main meteorological parameters in Lovozero on September 3–4, 2004

Period	3.IX		4.IX		
	18 h	21 h	00 h	03 h	06 h
Wind direction, compass point	ESE	ESE	SSE		NNW
Wind speed/gust, m/s	1–2	2–3	2–3	calm	1–2
Weather	fair	fair	fair	fair	haze
Cloud amount:					
total/lower	4/0	5/0	0/0	3/3	4/0
altitude of bottom boundary	–	–	–	600 m	–
Type of clouds	Ci. fib	Ci. fib		Sc. diur, vesp	Ci.fib
Air temperature, °C	11.6	5.9	5.8	–0.1	–0.3
Relative humidity, %	57	86	96	96	100
Atmospheric pressure, hPa	1032	1032	1032	1033	1033

Table 2. Values of the main meteorological parameters and SOC on the Lovchorr Mountain in the foehn period on October 3–4, 2004 (*dd* and *V* are wind direction and speed, t_a is air temperature, *f* is relative humidity, and N_{tot}/N_{bot} is the total and bottom cloud amount)

Date	Period, h	*dd*, point	*V*, m/s	T_a, °C	*f*, %	N_{tot}/N_{bot}, number	SOC, ppb
10.02.2004	15	SW	2	–0.9	100	10/10	27.2
10.02.2004	18	SW	2	–1.8	100	10/10	24.2
10.02.2004	21	SW	2	–1.3	100	9/9	24.9
10.03.2004	00	SW	2	–0.6	95	4/0	25.9
10.03.2004	03	W	2	–0.5	89	3/0	24.5
10.03.2004	06	WNW	2	0.7	74	2/0	34.8
10.03.2004	09	NW	3	3.2	50	1/0	42
10.03.2004	12	NW	2	6.0	51	0/0	42.9
10.03.2004	15	NW	4	7.5	49	0/0	40.9
10.03.2004	18	WW	6	6.2	47	0/0	42.5
10.03.2004	21	W	8	5.1	45	0/0	44.4
10.04.2004	00	WNW	4	5.0	43	0/0	41.5
10.04.2004	03	calm	0	2.6	50	7/0	37.5
10.04.2004	06	WNW	4	2.5	50	4/0	36.8
10.04.2004	09	WNW	9	1.7	69	3/0	31
10.04.2004	12	WNW	7	1.2	81	2/0	32.4
10.04.2004	15	NW	5	1.3	87	4/1	29.6

The second and third foehn events, the heavier ones, were recorded at about 01:00 and 02:00 on September 4. They were accompanied by synchronous changes of temperature, relative humidity, and ozone concentration and evidenced of instability of the vertical velocity in the foehn zone.[2,8] Such an instability can be caused by the alternation of vertical motion direction to the boundary layer under wave processes due to thermal stratification of the atmosphere.[2]

The instability took place in the foehn period on February 7–8, 2005, when the strong anticyclone located over the East Europe with the ridge to Northland and Kola Peninsula. The behavior of relative humidity, air temperature, and ozone concentration on the Lovchorr Mountain in the above period are shown in Fig. 2.

The descending airflows resulted in the decrease of relative humidity from 80 down to 40%, synchronous temperature rise by 3°C and the growth of the ozone content from 35 to 40 ppb in the period from 21:00 to 05:00. The second foehn outbreak was observed after 07:00 and it was accompanied by the synchronous relative humidity decrease down to 35%, temperature rise by 1°C, and SOC increase from 32 to 42 ppb. All the changes occurred against the practically clear sky (high-level cloud amount of not more than 3). As was mentioned above, such a foehn could not reach the Earth surface. No similarly anomalous variations of the meteorological parameters and SOC were observed in Apatity and Lovozero at this period.

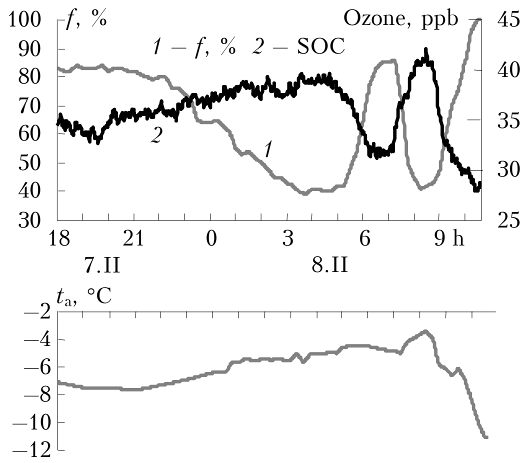

Fig. 2. The behavior of relative humidity (*f*, %), ozone concentration (ppb), and air temperature (t_a) on the Lovchorr Mountain on February 7–8, 2005.

The meteorological parameters and SOC had the foehn nature on the Lovchorr Mountain on October 3–4, 2004. Meteorological data at "Tsentralnaya" mountain avalanche station for this period are presented in Table 2. In this period, the anticyclone was located over Kola Peninsula. The descending

Table 3. Values of main meteorological parameters and SOC on the Lovchorr Mountain in the foehn period on April 23–24, 2004 (notation conventions are the same as for Table 2)

Date	Period, h	*dd*, point	*V*, m/s	T_a, °C	*f*, %	N_{tot}/N_{bot}, number	SOC, ppb
04.23.2004	09	calm	0	–11.9	100	3/1	25.6
04.23.2004	12	S	3	–12.4	100	2/1	27.5
04.23.2004	15	SSE	4	–12.2	90	2/0	31.6
04.23.2004	18	S	4	–11.8	70	0/0	42.8
04.23.2004	21	S	3	–12.4	54	0/0	46.3
04.24.2004	00	S	2	–11.5	55	0/0	45.8
04.24.2004	03	S	2	–10.4	56	0/0	45
04.24.2004	06	calm	0	–9.2	51	0/0	47
04.24.2004	09	calm	0	–6.7	51	0/0	43.4
04.24.2004	12	calm	0	–6.8	48	0/0	46.3
04.24.2004	15	calm	0	–8.1	52	7/0	41.5
04.24.2004	18	N	4	–9.2	54	9/0	40.7
04.24.2004	21	calm	0	–10.4	71	5/0	35.3

airflow caused concretion inversion forming in the layer from 812 to 1345 m (according to aerological sounding data at 12 UT on October 3 in Kandalaksha), which evidences of the presence of conditions favorable for the free foehn origin on the top of the Lovchorr Mountain. Until 20:00 on October 2 thick fog had been recorded. During the next 4 hours clouds practically dissipated, including those at the mountain top level, under the light breeze (1–2 m/s).

Dramatic humidity decrease due to the foehn was recorded; according to current data, it kept on the level of 40–50% until 05:00 on October 4, and, according to hygrograph records, decreased to 30% sometimes. At that, the mean long-term values of the relative humidity at the Lovchorr Mountain for this season amounts to more than 90% without any daily variations. Synchronously air temperature rose by 2°C by 06:00. Further temperature rise could well be caused by daytime warming-up under the fair weather that distorted the foehn temperature effect.

The descending airflow caused synchronous SOC increase from 25 to 45 ppb (see Table 2). Inverse processes (relative humidity increase and SOC decrease) began practically simultaneously, at about 01:00 on October 4. By this time, the meteorological situation changed: the anticyclone came to the south, the Atlantic cyclone had more strong effect, and ascending motions changed the descending ones.

One more example is the foehn occurrences on April 23–24, 2004, when at the periphery of the anticyclone under the calm and fair weather, after 17:30 on April 23 and at night relative humidity began to decrease from 100 to 47% and ozone concentration correspondingly increased from 26 to 46 ppb (Table 3). The foehn temperature effect made up 3°C growth by 06:00 on April 24. Later the temperature continued to rise, but this could be caused by usual daily variation.

Conclusion

1. The measurement on the surface ozone concentration (SOC) at the Lovchorr Mountain (altitude of 1089 meters a.s.l. in the Khibiny massif) acquired in the free foehn periods were analyzed.

2. It was shown that the foehn occurrence at the observation site is accompanied by synchronous variations of SOC, relative humidity and, to a lesser degree, of the air temperature. The SOC increase in the foehn situations can amount to 10 to 20 ppb and this is caused by the invasion of the air enriched with ozone from the upper atmospheric layers.

3. Synchronous appearance of the foehn effects in the records of meteorological parameters can be used to reveal the SOC changes due to descending air motions in the mountain regions.

Acknowledgments

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