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THE FREE AIR FOEHN EFFECT ON OZONE CONCENTRATION IN THE KHIBINY AND THE CAUCASUS MOUNTAINS

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Abstract. The results of ozone concentration measurements at the top of Lovchorr mountain (1095 m asl, the Khibiny Mountain range) and at Kislovodsk high-altitude scientific station of the Institute of Atmospheric Physics (2070 m asl, the Shadzhatmaz Plateau, Caucasus) during foehn periods are presented. The analysis shows that the foehn occurrence, indicated by meteorological parameters, is accompanied by a synchronous increase in the ozone concentration. The increase results from the air, enriched with ozone, coming from the upper layers of the atmosphere.

Introduction

The foehn is a warm and dry downslope wind, which occurs on the leeward side when the air mass crosses a mountainous obstacle. The classical mechanism used to explain the foehn effect suggests a forced rise of the moist air along the windward slope of mountain ridge and lowering along the leeward slope. However, the real picture appears to be more complicated. There are some types of the foehns related to the catabatic motions (see, e.g., [1-4]). However, it should be recognized that none of the known approaches are quite satisfactory. Unified criteria for detection of the foehn have not been presented either. The reason is a great variety of the local foehn situations.
Therefore, we have to take into account nearly the whole complex of meteorological factors: the direction and speed of the wind, total and low-level overcast, cloud formation, air temperature and humidity, atmospheric phenomena. The regional foehn synoptic situation implies a definite direction of the wind, i.e. from the mountains in the lower troposphere, an increase in the air temperature and a simultaneous decrease in the relative humidity distorted the usual diurnal variation and the absence of low-level clouds and precipitation. The air subsides during the foehn.

In fact, when there is no horizontal advection, the local changes in the air temperature and saturation specific humidity at the station level are given by

$$\begin{aligned} &\frac{\partial T}{\partial t} + \omega(\gamma_a - \gamma) = 0, \\ &\frac{\partial q}{\partial t} + \omega \frac{\partial q}{\partial z} = 0, \end{aligned} \tag{1}$$

where ω is the vertical velocity, γ the vertical temperature gradient, γ_a the dry-adiabatic gradient.

The relative humidity is $f = f(q,T) = \frac{q}{Q(T)}$

Here *Q(T)* is the maximum saturation specific humidity at temperature *T*.
The local change in the relative humidity can be written as

$$\frac{\partial f}{\partial t} = \frac{\partial f}{\partial q}\frac{\partial q}{\partial t} + \frac{\partial f}{\partial T}\frac{\partial T}{\partial t} \tag{2}$$

By substituting equation (1) into equation (2) we find

$$\frac{\partial f}{\partial t} = -\omega\left[\frac{1}{Q(T)}\frac{\partial q}{\partial z} + \frac{\partial f}{\partial T}(\gamma_a - \gamma)\right] \tag{3}$$

The vertical distribution of the saturation specific humidity *q(z)* can be expressed as $q(z)=q_0 * 10^{-\alpha z}$. Then

$$\frac{\partial q}{\partial z} = -2.3\alpha q_0 \cdot 10^{-\alpha z}$$

As $f = \frac{e}{E}$ and $\frac{\partial f}{\partial t} = -\frac{e}{E^2}\frac{\partial E}{\partial T}$, then using the Mendeleev-Claypeyron equation of gas state $\frac{\partial E}{\partial T} = \frac{LE}{AR_{\Pi}T^2}$, expression (3) can be written as

$$\frac{\partial f}{\partial t} = \omega\left[\frac{2.3\alpha q_0}{Q(T)} \cdot 10^{-\alpha z} + \frac{eL}{AR_{\Pi}T^2}(\gamma_a - \gamma)\right] \tag{4}$$

Consequently, the sign of the change in the relative humidity at a given station coincides with the sign of the vertical speed, provided that $\gamma<\gamma_a$. That is, the descending motions in the mountain regions are detected by specific foehn variations of the relative humidity at the stable stratification.

The ozone concentration increases with height and the descending air, enriched with ozone, enters the lower layers. If a monitoring station gets into the layer of intense descending motions, a free foehn emerges and the ozone concentration increases. Thus, the foehn effects, well-known in meteorology, can serve an indicator of the catabatic mechanism of changes in the ozone concentration.

The free air foehns

The altitude of the station located at the top of the Lovchorr Mountain (the Khibiny Mountain massive) is 1095 m asl, where there are free air foehns. These foehns are caused by subsidence inversions in an anticyclone and accompanied by temperature and humidity effects, provided the inversion layer crosses the station level. The free foehns reach the surface layer very infrequently. However, the inversions cross the slopes and tops at the altitude of 1000-3000 m frequently enough. They cause an increase in the air temperature and a decrease in the relative humidity. This type of the foehns is typical for all mountainous regions, including the Khibiny, but, as a rule, it is not registered because of a small number of meteorological stations in the mountains.

It is known that the foehn emerges in the conditions of increased temperature and decreased relative humidity. The mechanism of this phenomenon is the following: the descending air gets warmer but keeps the saturation specific humidity corresponding to the altitude, from which the air movement begins.

However, the meteorological characteristics of the free foehns and valley foehns are different. The free foehns are observed in nearly perfect absence of the wind and characterized by the original variations of the temperature and relative humidity. Thus, for example, the temperature effect of the free foehn (an increase in the temperature at the station) takes place only if subsiding air is warmer than the displaced air, i.e. the temperature effect of the free foehn depends on the vertical temperature distribution and the temperature of the displaced air. In certain situations, the free foehn can be observed when the temperature increase is small or absent [2].

The absence or weakening of temperature effects is a characteristic feature of the free foehns, meaning that the diagnostics of the free foehn should be changed. As the sign of the change in the relative humidity under stable stratification is always coincident with the sign of the vertical speed (a decrease in the relative humidity can be observed only in the presence of descending air), a decrease in the relative humidity is a major signature of the free foehns [2].

Various criteria of the free air foehns have been proposed. Bernhard [2] relates the free air foehn to the relative humidity below 40%. A signature of the free foehn can be a decrease in the relative humidity to 60 % and smaller [6], when the diurnal variation in the relative humidity is excluded. The foehn criteria of Flon [5] in the Alps are the values of the relative humidity smaller than 40 % in the afternoon and not more than 60-65 % for other time. Similar criteria were used as signatures of foehn situations in the Caucasus [6]. Such a variety of signatures essentially complicate the analysis.

For the diagnostics of the free air foehn in the Khibiny, a decrease in the relative humidity to 40 – 60 % (which is not typical for our region) and an appropriate foehn synoptic situation (descending motions in the anticyclone and the position of the lower boundary of subsidence inversion below the top of the Khibiny mountains) have been used [7, 8]. The qualitative estimation of the sign of vertical movements is obtained from the dynamics of the ground pressure with the use of the technique described in [9, 10]. The absence of a noticeable wind and the lower cloudiness, an increase in the horizontal visibility and, sometimes synchronous fluctuations in the air temperature are additional criteria.

Free air foehns and variation in the ozone concentration at the mountain stations

A free foehn at the top of the mount Lovchorr was detected by the thermograph and hygrograph records on October, 3-4 2004, in the period of anticyclone above the Kola Peninsula. The presence of descending motions in the lower troposphere (in the layer up to 850 gPa) was established from the pressure dynamics [9,10]. The deformation of the temperature vertical distribution, humidity values and the occurrence of subsidence inversion (Fig. 1) are an obvious evidence of the catabatic motions (in accordance with the sounding data in Murmansk). The descent of the layer lower border of the subsidence inversion below the station level (1095 m) provided the necessary conditions for free foehn occurrence. The synoptic situations, namely, the weak wind, rapid dispersion of fog and clouds and decrease in the relative humidity down to 40-50 % (Table 1) was appropriate for the foehn occurrence at the station. The ozone concentration increased from 25 to 45 ppb during the same period (Fig. 2).

The preservation of the synoptic situation, as indicated by the maps of the surface analysis (http://www.met.fu-berlin.de), and the absence of abrupt changes in the meteorological parameters at the nearest meteorological stations "Apatity", "Monchegorsk", "Lovozero" in the period under study, rule out the advection as a mechanism of the above variations. The changes in the ozone concentration and relative humidity at the top of the Lovchorr mountain, referring to the time-dependent foehns on September, 3-4 2004 [7, 8], are shown in Fig. 3. The time dependence can result e.g. from the change of the sign of the vertical motions in the boundary layer in the wave processes caused by atmosphere thermal stratification [2, 4]. The growth of the relative humidity and decrease in the ozone concentration started nearly synchronously on October 4. The synoptic situation had changed earlier, namely, the anticyclone shifted to the south and the Atlantic cyclone started approaching the Kola Peninsula.

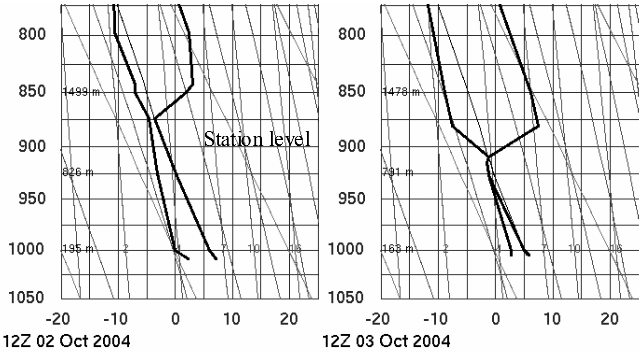

Figure 1. Skew-T diagram of aero-sounding in Murmansk on 02.10.2004 at 12 UT and on 03.10.2004 at 12 UT

Table 1. The value of some of the meteorology parameters at the Lovchorr mountain on October, 2-4 2004

Data	MT	T°C	f%	dd°	V m/s	Cloud amount	
						Total	Low-level
02.10.2004	15	-0.9	100	225	2	10	10
02.10.2004	18	-1.8	100	225	2	10	10
02.10.2004	21	-1.3	100	225	2	9	9
03.10.2004	0	-0.6	95	225	2	4	0
03.10.2004	3	-0.5	89	270	2	3	0
03.10.2004	6	0.7	74	290	2	2	0
03.10.2004	9	3.2	50	315	3	1	0
03.10.2004	12	6	51	315	2	0	0
03.10.2004	15	7.5	49	315	4	0	0
03.10.2004	18	6.2	47	270	6	0	0
03.10.2004	21	5.1	45	270	8	0	0
04.10.2004	0	5	43	290	4	0	0
04.10.2004	3	2.6	50		0	7	0
04.10.2004	6	2.5	50	290	4	4	0
04.10.2004	9	1.7	69	290	9	3	0
04.10.2004	12	1.2	81	290	7	2	0
04.10.2004	15	1.3	87	315	5	4	1

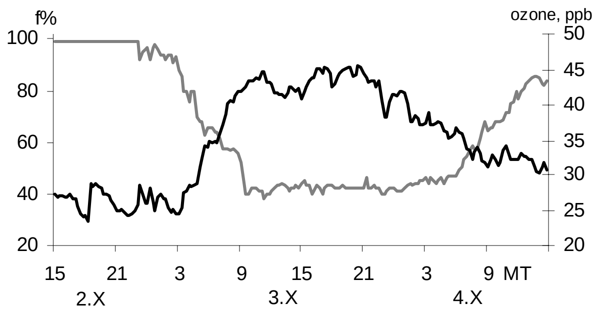

Figure 2. The temporal changes of the ozone concentration and the relative humidity at the Lovchorr mountain on October, 2-4 2004

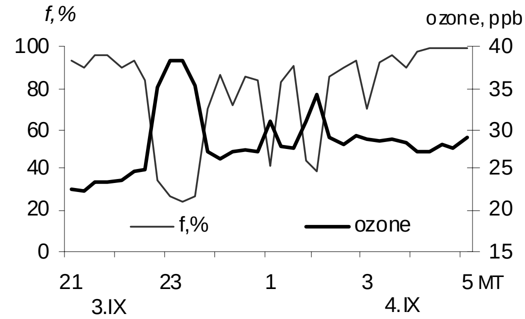

Figure 3. The temporal changes of the ozone concentration and the relative humidity at the Lovchorr mountain on September, 3-4 2004

The free air foehns are also observed in the Caucasus. For example, on April, 28 2003 the free foehn was observed at KVNS (Table 2), when the region of Caucasus Mineral Waters was under the influence of anticyclone (at its southwest periphery). A rapid deformation of the vertical profiles of temperature and humidity was also observed (Fig. 4). A dry layer (the relative humidity smaller than 30 %) was at the altitude of 2.7 km above the aerological station “Mineralnye Vody” at 00 UT April, 28 but its lower boundary moved down by 12 UT to the altitude less than 2 km, i.e. the layer of descending motions crossed the level of the KVNS.

The preservation of the synoptic situation and the absence of appreciable wind in the middle troposphere suggest the absence of advection in the described events. The ozone concentration increased by 20 ppb during the foehn period (Fig. 5). Thus no peculiar variations in the meteorological parameters were observed at the foothill meteorological stations (“Pyatigorsk”, “Vladicavcas”, “Mineralnye Vody”, “Mozdok”, “Nalchik”) because the free foehns did not reach the surface layer. The subsiding air spread aflat at the altitudes larger than 1 km, having formed a strong subsidence inversion.

Table 2. Some meteorological parameters at KVNS on April 27-29 2003

Data	UT	T°C	f%	dd°	V m/s	Cloud amount/form Total	Low-level
27.04.2003	15	-5	100	360	2	-	fog
27.04.2003	18	-6	100	360	2	-	fog
27.04.2003	21	-6.1	100	45	2	-	fog
28.04.2003	0	-7.4	93	157	2	4 (Ci)	0
28.04.2003	3	-9	92	157	2	3 (Ci)	0
28.04.2003	6	-4.7	86	0	0	3 (Ci)	0
28.04.2003	9	-0.3	50	135	2	2 (Ci)	0
28.04.2003	12	1.5	25	157	2	2 (Ci)	0
28.04.2003	15	0.9	37	135	2	2 (Ci)	0
28.04.2003	18	-0.9	65	157	2	3 (Ci)	0
28.04.2003	21	-1.3	47	180	2	3 (Ci)	0
29.04.2003	0	0.2	29	180	2	3 (Ci)	0
29.04.2003	3	0.2	20	180	2	4 (Ci, Ac)	0
29.04.2003	6	1.6	28	0	0	3 (Ci)	0
29.04.2003	9	3	59	360	2	3 (Ci)	0
29.04.2003	12	3.5	58	22	2	4 (Ci, Ac)	0

The instability of the vertical speed in the foehn zone has caused time-dependent character of ozone concentration variations.

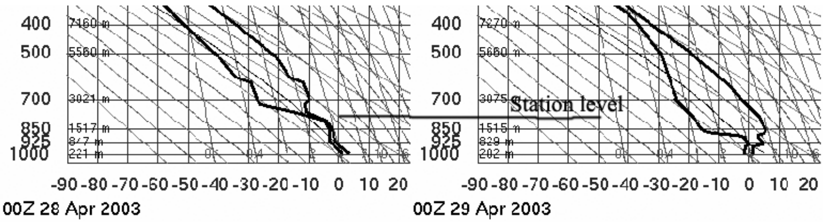

Figure 4. Skew-T diagram of aerological sounding in Mineralnye Vody at 00 UT on 28.04.2003 and at 00 UT on 29.04.2003

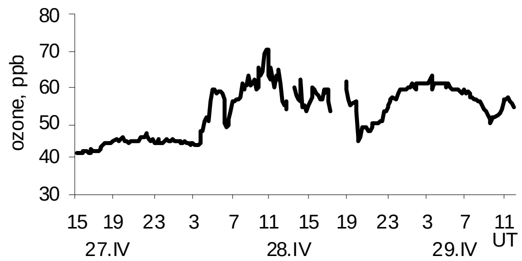

Figure 5. The temporal changes of the ozone concentration and the relative humidity at KVNS on April, 27-29 2003

Conclusions

The analysis of ozone concentration dynamics during free foehn events at the Lovchorr mountain (1095 m, the Khibiny Mountain range) and at the Kislovodsk high-altitude scientific station of the Institute of Atmosphere Physics (2070 m, the Shadzhatmaz Plateau, Caucasus) has been performed. It is shown that the occurrence of the foehn in the point of observations is accompanied by simultaneous increase in the ozone concentration by 10-20 ppb. The increase is caused by descending motions and receipt of the air enriched with ozone from higher atmospheric layers.

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