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Measurements of the Tropospheric Ozone Concentration over the Kislovodsk High-Altitude Scientific Station: Synoptic-Scale Meteorological Processes As a Cause of Ozone Variations

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Abstract—Variations in the surface ozone concentration within atmospheric fronts, cyclones, and anticyclones are studied at the Kislovodsk high-mountain scientific station (KVNS), 2070 m above sea level, on the basis of observations from March 1998 to February 1999. The following regularities are revealed: (1) In anticyclones moving only slightly and in low-gradient pressure fields, the daily surface-ozone behavior formed by local and seasonal conditions and characterized by a noon minimum and nighttime (or evening) maximum typical of the KVNS reveals itself most clearly. (2) The anomalous daily behavior of the ozone concentration, namely, abrupt, short-term spikes and a daily variability exceeding the background one are associated with atmospheric circulation. (3) The strongest ozone variations are associated with cold atmospheric fronts. (4) The lowest ozone concentration is characteristic of highly humid cyclones and zones of quasi-stationary atmospheric fronts moving only slightly. (5) The ozone concentration tends to decrease in cyclones containing air masses of different origin in their warm zones. Several episodes that can be explained by different causes, such as the advection of continental tropical air, atmospheric fronts and centers of cyclones, and pollutants resulting from long-range transport, are considered. The overall conclusion is that large-scale atmospheric processes should be taken into account when trends are estimated.

INTRODUCTION

The surface ozone concentration in the region of Kavkazskie Mineralnye Vody has been monitored at the Kislovodsk high-mountain scientific station (KVNS) since 1989. The station is located 2070 m above sea level, 18 km south of the town of Kislovodsk. It is located in a region characterized by a stable climate and weak sources of natural and anthropogenic ozone precursors. No clearly pronounced uphill-downhill circulation occurs there, and thus the transport of pollutants from the foothills is not intense. The ozone behavior at the KVNS is characterized by small seasonal variations, stable daily behavior with a minimum around noon, and slight or no daytime chemical ozone generation. These circumstances give grounds to treat the meteorological conditions at the station as approximating the free-troposphere conditions.

As is noted in [1-3], in the observation period, the ozone concentration at the KVNS experienced a small negative trend. Additionally, significant interannual variations in the surface ozone concentration occur. Against the overall pattern of the observations, two years (1991 and 1996) manifest themselves by unusual annual mean ozone concentrations. Up to now, the causes of these significant peculiarities are unknown. Meanwhile, it is obvious that day-to-day and long-term ozone variations are caused by peculiarities in the atmospheric circulation and are associated with large-scale atmospheric processes and synoptic-scale disturbances. The latter disturbances predetermine the properties and photochemical prehistory of incoming air masses, the intensity of vertical air transfer, and the advection of ozone and of minor species reacting with it.

Most of the time, the KVNS is located over the planetary boundary layer. This fact determines the variability of the surface ozone concentration at the station. Namely, according to our estimations, the ozone variability is influenced by the peculiarities in the large-scale atmospheric circulation to a significantly greater extent than by the daily and seasonal behavior of the meteorological parameters and by the emission of ozone precursors.

Monograph [4] was among the first to generalize the available data on the influence of large-scale atmospheric processes to variations in the total content and surface concentration of ozone. In [4], pronounced effects of pressure fields, jet streams, and planetary waves on ozone behavior were indicated. In the mono-

Table 1. Number of cyclones influencing the region of the KVNS over the period from March 1998 to February 1999

Month	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
Number of cyclones	4	4	3	2	2	1	3	3	4	3	3	4

graph, ozone dynamics in warm and cold fronts and the behavior of the ozone concentration in surface air of different origin are considered. In [5], it is shown that variations in the ozone content can be used as an indicator of the propagation of the southern cyclone over European Russia. Let a minimum in the spatial distribution of tropospheric ozone arise in the space over a region. With a probability of 85%, a southern cyclone should fill this space two to three days later. The center of such a cyclone is located 300-400 km away from the space of the precyclone ozone minimum. In [6], the changes in the surface concentrations of gases (including ozone) that are due to the passage of atmospheric fronts in the vicinity of Tomsk are described. In the European free troposphere, the authors of [7] observed the simultaneous inflowing of ozone from two sources: from the stratosphere and from North America; the latter was produced photochemically in the atmospheric surface layer. The stratospheric ozone inflow was observed for at least 36 h and was associated with an increase in the ^{7}Be concentration. Thus, a number of studies lead to the conclusion that synoptic and trajectory analyses can partially explain variations in the concentrations of minor gases.

On our opinion, the conclusion that variations in the ozone concentration are associated with the types of air masses and pollution transport has sufficient grounds. For example, in [8], it is shown that ozone variations at Bermuda are characterized by semiannual cycles similar to the pollutant content behavior. These authors associate the spring and fall aerosol maxima, the summer pollutant maximum, and the winter pollutant minimum with air transport from North America, from the Eastern Atlantic and Africa, and with the transport of humid northeastern air, respectively. The synoptic method was one of the techniques applied to the analysis of the ozone variations at a high-altitude station located more than 1000 m above sea level in the eastern United States [9]. The authors of [9] studied the response of the ozone concentration to changes in the meteorological parameters and the movement of atmospheric fronts.

The peculiarities of air mass distribution influenced by the synoptic situation determine the regional distribution of the tropospheric ozone content, which can be computed from satellite data [10]. Maximum ozone contents are usually observed over the Atlantic Ocean near the coast of North Carolina. This feature is caused by the accumulation of ozone transported from the northeastern United States. The authors of [10] note that, under conditions of stable anticyclonic circulation, this maximum gradually shifts to the southeastern United States. Such a shift frequently leads to episodic enhancements of the surface ozone concentration over the allowable level. Within several days after the anticyclone's destruction, less polluted tropical air is transported into the space and the tropospheric ozone content decreases.

In this work, an attempt is made to estimate the contribution of synoptic-scale atmospheric processes to the variability of the surface ozone concentration. The observations are performed under conditions close to free-troposphere conditions, at a KVNS located in a region with no intense sources of emissions. We take into account that, under high-mountain conditions, synoptic processes are influenced by specific factors associated with mountain relief and a complicated system of the local uphill-downhill winds (the so-called uphill-downhill circulation).

PECULIARITIES OF THE REGIONAL CIRCULATION

The North-Caucasian region, unlike midlatitude plain regions, is characterized by a relatively low frequency of occurrence of cyclones (about **4%)** and anticyclones (about 6%) with closed circulation. The frequencies of occurrence of low-gradient high-pressure and low-pressure fields are equal to 14 and 11%, respectively. Pressure lows (36%) and highs (29%) with weakened air transport are predominant [11].

In the region of the North Caucasian foothills, the yearly mean distribution of the air masses transported from different directions is as follows: 73.3% midlatitudinal continental air; 9.4% midlatitudinal marine air; 7.6% tropical continental air; 6.4% tropical marine air; Arctic air is transported most seldom, with the portions of continental and marine air equal to 1.4 and 1.9%, respectively. It is seen that midlatitudinal air is most frequently transported to this region.

OBSERVATIONAL DATA AND THE SYNOPTIC FEATURE OF THE OBSERVATION PERIOD

We use the results of observations performed between March 1998 and February 1999. These data are used to reveal the dependence of ozone concentration variations on the synoptic situation in the region. In order to reveal the ozone concentration variations caused by short-term structural changes in pressure fields, information on the 10-min mean concentrations of surface ozone was used. We analyzed 17 situations in which the station was influenced by anticyclones. Over the observation period, the KVNS was influenced

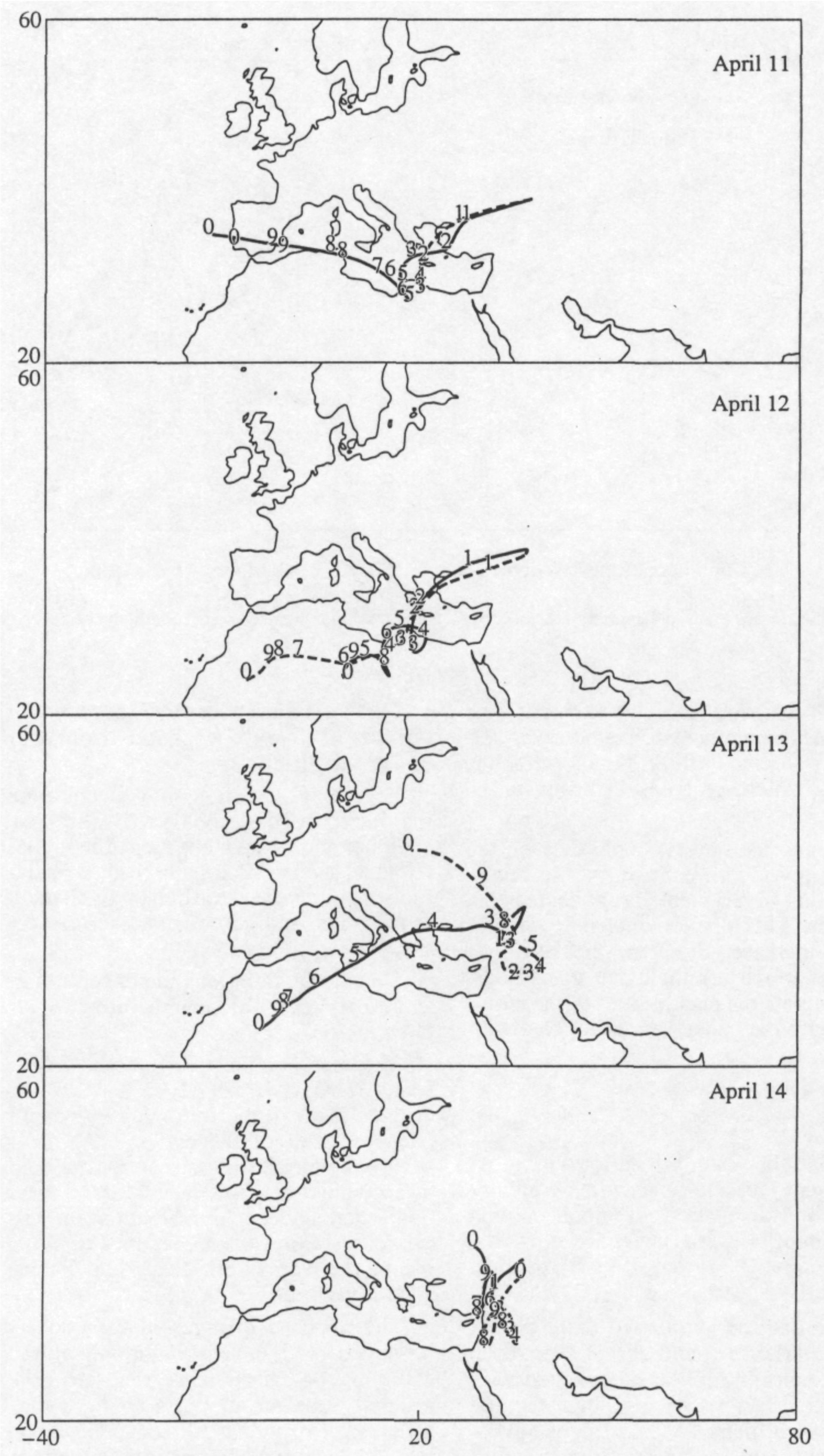

Fig. 1. Back isentropic trajectories of the tropical air mass included in the Mediterranean cyclone (numbers near the trajectories specify the time period (days) before arrival of the air mass in the space over the KVNS).

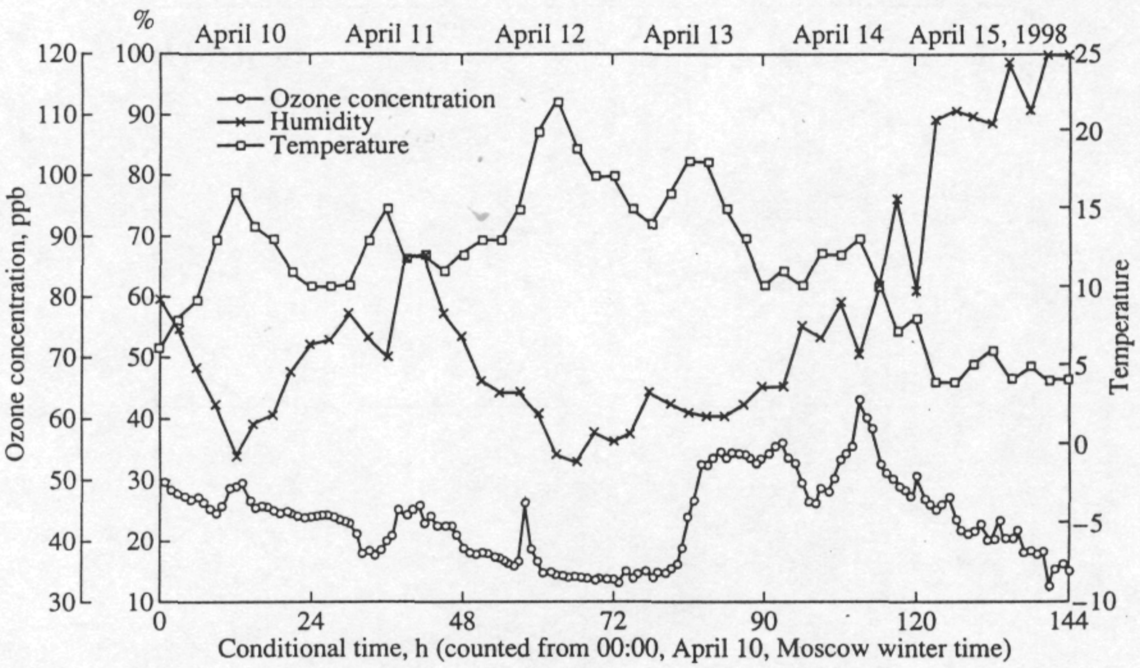

Fig. 2. Variations in the surface ozone concentration, temperature, and humidity influenced by the Mediterranean cyclone measured at the KVNS.

by 36 cyclones. Table 1 shows that, in winter, cyclonic situations dominated. In summer, this region was seldom influenced by cyclones; in three summer months, only five events in which cyclones determined the weather were identified.

For transitional seasons, observational data on the ozone concentration revealed repetitive five- to seven-day periods terminating in a typical abrupt decrease in ozone concentrations. This phenomenon is evidently associated with an increased frequency of cyclones during these seasons. Such a conclusion gives additional grounds to correlate the peculiarities of the atmospheric circulation with the ozone variability on different time scales.

RESULTS

An analysis showed that, in quasi-stationary anticyclones and low-gradient pressure fields with no intense air transport, under high insolation, the noon minima and nighttime (or evening) maxima characteristic of the surface ozone concentration at the KVNS manifest themselves most clearly.

It was established that the anomalous daily behavior, significant daily variability, and abrupt short-term spikes in the ozone concentration are associated with dynamic and circulation factors. Among these factors, we can distinguish two principal ones, namely, advection, which is a mechanism for transporting different air masses and pollutants, and the intense air exchange in the zone of atmospheric fronts. The surface ozone variations due to advection are as follows.

(1) A rise in concentration occurs in anticyclones due to the free-tropospheric ozone transported with downward air flows.

(2) Abrupt variations in concentration occur due to the interchange of cold and warm sectors in both cyclones and anticyclones and due to the arrival of new air masses that significantly change the temperature, moisture content, stratification, character of vertical movements, and gaseous and aerosol compositions of the air over the station.

(3) Abrupt variations in concentration occur within an air mass as anthropogenic products arrive from pol luted regions.

The arrival of dry air masses from Central Asia, Iran, Arabia, or North Africa in the warm sector of any cyclone leads to the following two-step change in the ozone content of the cyclone. At the first step, the slowly moving air masses are humidified up to a relative humidity of 40-50% and fill the space over the station. Then, under high insolation, intense photochemical generation of ozone occurs and, thus, immediately behind the warm front, the ozone concentration in the air is increased.

The opposite changes in the ozone concentration were observed under conditions of rapid advection within a tropical air mass stratified in a rather stable manner. Such an air mass changes the typical daily behavior of ozone, and its concentration is established at a low level unusual for high-mountain regions. The original properties of the air mass do not change: its relative humidity is equal to 30% or less. Most often, such conditions occur in spring and early summer. Among four episodes of tropical air masses arriving in the region of the KVNS, the episode observed in April 1998 was most prominent. In addition, it illustrates a rather rare effect, namely, the response of the tropospheric ozone content to the transboundary plume of polluted air.

Trajectory analysis showed that, during the period from April 10 to April 13, a quickly moving North African air mass came at heights of *2-4* km into the space over the Caucasus within the warm sector of the Mediterranean cyclone (Fig. 1). The temperature increased within the range 16-22°C (at the KVNS, such warm weather is rare, even in summer). During these four days, the ozone concentration ranged between 33 and 45 ppb (Fig- 2).

Beginning with the first day of tropical air advection on April 10, the usual daily behavior of the ozone concentration was disrupted: namely, a near-noon maximum concentration of 53 ppb was observed. The trajectories allow us to conclude that this maximum was caused by ozone generation influenced by pollutants transported from the southern Balkan Peninsula. However, the narrow plume revealed itself for a very short period. On subsequent days, in this African air, which was dry and evidently dust-laden and depleted in ozone, the process of intense ozone destruction dominated. By the evening of April 11, the ozone concentration had fallen to 38 ppb.

In [4], it was shown that ozone decomposes on the surface of aerosol particles of mineral origin. This process is significant even at ozone concentrations close to the background levels. Aerosol characterized by an ozone decomposition coefficient $y > 10^{-5}$ participates significantly in atmospheric ozone decomposition; the aerosol and oxygen mechanisms of ozone decomposition are comparable in their efficiency [12]. Ozone decomposition on the aerosol carried up by intense convective flows over the African and Asian desert areas could justify our assumption that the low ozone concentration in the region of the KVNS is caused by the advection of a tropical air mass.

One more short-term spike in the ozone concentration was observed for 30-40 minutes on April 12 after 9:00; the ozone concentration increased by 17 ppb and reached 52 ppb. This spike can be explained by the transport of a plume of anthropogenic pollutants from southern Greece to the KVNS over a period not exceeding a day. This pulsating plume propagated over the KVNS at the nighttime as well; however, it could not transform the ozone background in the absence of solar radiation. After this spike, the ozone concentration decreased quickly, much as it had increased just before, and 30 minutes later it was equal to 35 ppb. Simultaneously, the air humidity began to decrease. In the afternoon, it reached 32%, by which time the temperature had increased to 22°C. Until the following noon, the North African air mass propagated with the cyclone over the KVNS. The trajectories give grounds to conclude that the air mass propagated at heights of 2-3 km and therefore was not saturated with moisture and ozone-generating species.

Until the morning of the fourth day of tropical air advection, the ozone concentration remained at a level of about 35 ppb until a turn of the air flow occurred. The southern cyclone turned in the northeasterly direction and joined with the polluted air masses that had passed over southern Greece and the countries of the Middle East. When the plume of pollutants originating in these regions reached the North Caucasus, intense ozone generation began at a humidity of about 40%. By 13:00, the ozone concentration exceeded 50 ppb. It remained at this level until midnight. In this event, the data on the ozone concentration could be regarded as a sensitive source of information on impurities occurring in different tropical air masses of similar origin.

The character of ozone concentration changes initiated by air masses transported from the east to the space over the station confirms our interpretations given in the preceding paragraphs. From May 1 to May 4, 1998, the areas around the station were subsequently influenced by the southern and western peripheries of a cold midlatitudinal anticyclone moving towards the Aral Sea. As long as the air masses were coming into the space over the station from Kazakhstan, the ozone concentration was usually within 40-50 ppb. By noon on May 3, the humidity decreased to 38% as a result of the arrival of an air mass from the deserts of Central Asia. This air mass caused an anomalous daily behavior of the ozone concentration. Namely, at 19:00, instead of a typical maximum, a minimum of 39 ppb was observed. The following sequence of wind directions was observed: easterly-southerly-easterly. This fact allows us to assume that the air flow meandered. Prior to noon on May 4, a maximum ozone concentration of 60 ppb was observed. The maximum at this time of day is uncommon in high-mountain areas. This maximum was caused by a plume of ozone-generating pollutants transported by the southerly air flow from the atmosphere over the Caspian oil and gas fields. On June 11-12, under the conditions of advection of the Central Asian air, the daytime ozone concentration decreased to 31-38 ppb.

Thus, the long-range transport of ozone precursors significantly influences the background ozone concentration, since these precursors cannot be transported in the unchanged chemical state. The consequences of the frequent arrival of tropical air masses may be more significant. Evidently, the procedure for analyzing ozone trends should take this conclusion into account. However, this statement requires more comprehensive studies, including sampling and analyzing of aerosols.

Cold atmospheric fronts usually result in a decrease in the ozone concentration. Table 2 presents the synoptic information on the days of passage of atmospheric fronts over the KVNS, some meteorological characteristics measured at the Shadzhatmaz meteorological station during these days, and data on changes in the surface ozone concentration measured at the KVNS during these days.

We assumed that a surface-air temperature drop of 4°C or more meant that a cold atmospheric front was over the station. Table 2 shows that cold fronts are usually accompanied by a decrease in the ozone concentration. This decrease ranges from 15 to 35 ppb. In 70% of such events, it is no less than 25 ppb, and these events correspond to abrupt temperature drops of no less than 6°C. Sometimes, under the condition of a high ozone concentration (around 70 ppb) ahead of the front, the "frontal" decrease in the ozone concentration exceeds 40 ppb. In April-May and from late August to early October, the ozone concentration in the cold-front zone began to drop, as a rule, after an increase to a level of about 70 ppb. In the spring, the drop was not as deep as in the fall, and the ozone concentration in the air following the front remained at a level of 45 ppb. In the fall, the ozone frontal drop was extremely deep, dropping by 36-42 ppb, and the ozone concentration in the air following the front was low, namely, at a level of 25-32 ppb. Evidently, such ozone behavior is caused by the latitudinal migration of the high frontal zone. Within the frontal zone, observations revealed short-term ozone spikes ranging between ten minutes and several hours. These spikes were associated with upper troposphere ozone transported by downward convective jet streams under powerful cumulonimbus cloudiness. The intensity of vertical mixing within the baroclinic zone of the atmospheric front influences the ozone concentration in the air following the front.

Table 2 shows that the value of the temperature drop within the cold front cannot be viewed as a quantitative criterion of ozone depletion. The correlation coefficient computed for these two parameters on the basis of the total sample is equal to 0.22.

Within the cyclone areas, no ozone concentration rise due to stratospheric intrusion is revealed. Evidently, such inefficiency of intrusion in the observation period is associated with the absence of deep folds and descents of the tropopause over the KVNS region. The stratospheric inflow into the lower atmosphere caused by such tropopause peculiarities is more characteristic of high and middle latitudes [13].

Our investigations showed that the primary cause of the drop in the ozone concentration within cold atmospheric fronts is a high relative humidity always exceeding 80%. Possibly, water aerosol adsorbs ozone intensely. The "frontal" drop in the ozone concentration depends on the width of the frontal cloud system and on the velocity of front movement. In other words, it depends on the duration of the period when the atmospheric humidity in the vicinity of the station is near saturation and on the characteristics of the cold air mass following the atmospheric front. The subpolar dry air mass that arrives after passing over the Volga basin is ozone-depleted in comparison with the air mass arriving from the northwest after passing over the polluted eastern Ukrainian regions. In such air masses, the ozone concentration varies significantly from season to season.

Table 2. Variations in the ozone concentration (ppb) influenced by cold atmospheric fronts (O_3 and O_3* are the ozone concentrations in the air ahead of the cold front and in the air following it, respectively)

Date		Relative humidity, %	$0_3/0_3$* , ppb	Ozone drop AO_3, ppb	Temperature drop ДТ; ^{0}C
March	6-7	100	48/34	14	10
	12-13	100	52/18	34	13
	17-18	100	48/22	26	5
	20	100	46/23	23	4
	23-24	100	62/35	27	9
April	14-15	90	64/45	19	6
May	20-21	100	77/44	33	8
	28-29	100	65/38	27	4
June	14-15	100	58/32	26	4
	22-23	100	38/23	15	10
July	5-6	100	60/28	32	8
	18	100	52/25	27	12
Aug.	11	100	58/28	30	9
	31	100	72/30	42	6
Sept.	17	90-100	68/32	36	8
	24	100	50/30	20	5
Oct.	16-17	100	70/25	45	12
	21	100	55/30	25	10
	31	98	48/25	23	9
Nov.	19	100	43/27	26	8
Dec.	10	98	45/30	15	7
	23	100	46/14	32	9
Feb.	8	85-100	50/35	25	7
	21	80-100	58/25	33	5
	25	90-100	54/37	17	5

In many respects, it is interesting to consider the synoptic situation, air-mass trajectories, and changes in the meteorological parameters and surface ozone concentration at the center of a small-scale Black-Sea cyclone at the stage of occlusion of atmospheric fronts. Such a consideration is based on the observational data obtained on May 20, 1998 (Figs. 3a, 3b). During this event, the daily variability in the ozone concentration was equal to 44 ppb.

On May 20, early in the morning and at 14:00, ozone spikes up to 53 and 52 ppb, respectively, were observed. Between these spikes, the ozone concentration dropped to 33 ppb. Until 15:00, the air temperature was within the narrow range of 10-13°C, and the relative humidity was

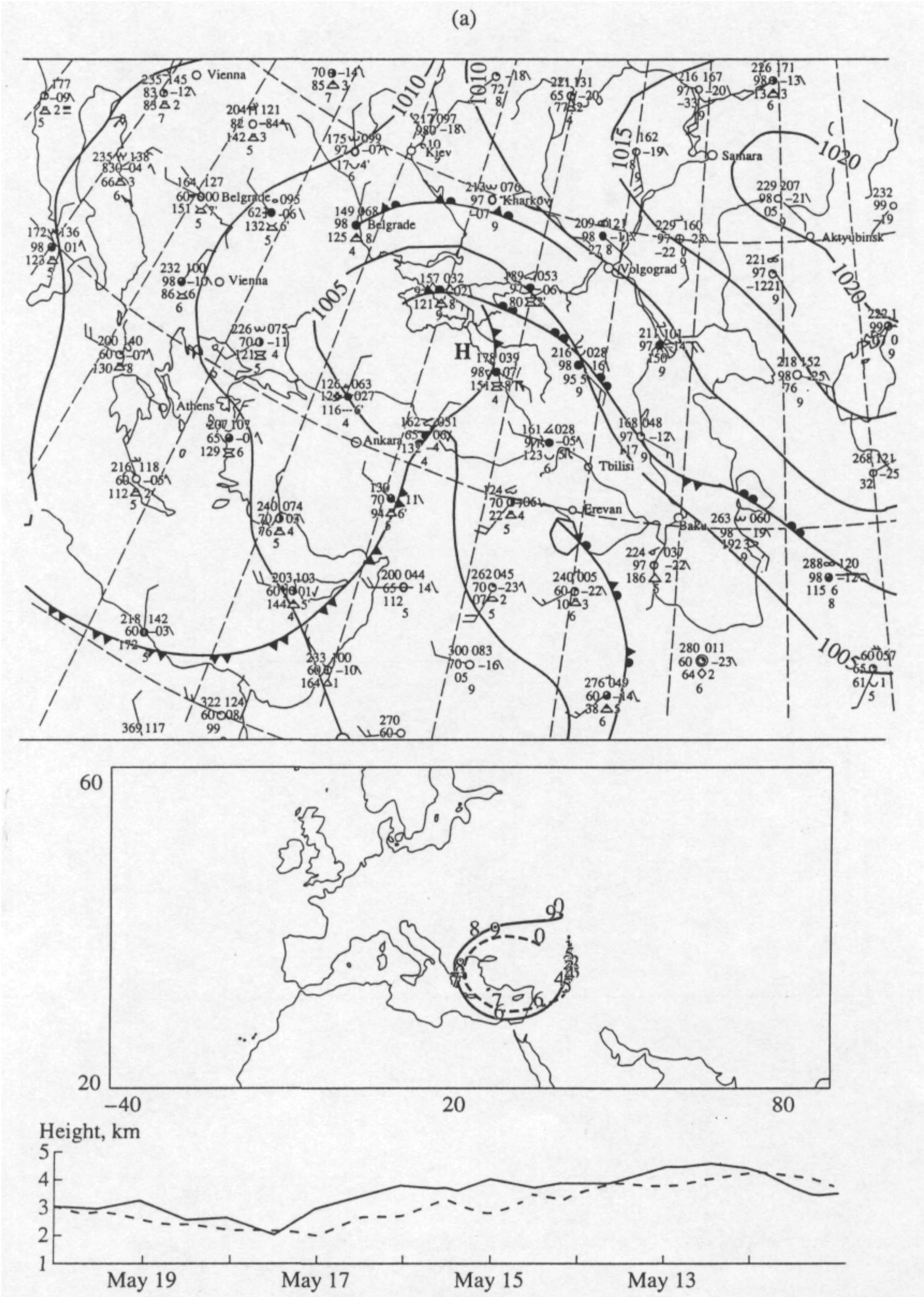

Fig. 3. (a) Synoptic situation and trajectories and (b) variations in the surface ozone concentration, temperature, and humidity influenced by the Black Sea cyclone measured at the KVNS.

within 60-76%. During the following three hours, the KVNS was influenced by a cold rainy atmospheric front; the te.mne.rnrnrp. drnnne.rl hv 7°Γ! *find* the. hnmidirv rnsp. to 90%. Prior to the rain, an ozone spike up to 52 ppb was observed. When the rain began, the ozone concentration dropped to 36 ppb; possibly, this drop was caused by an

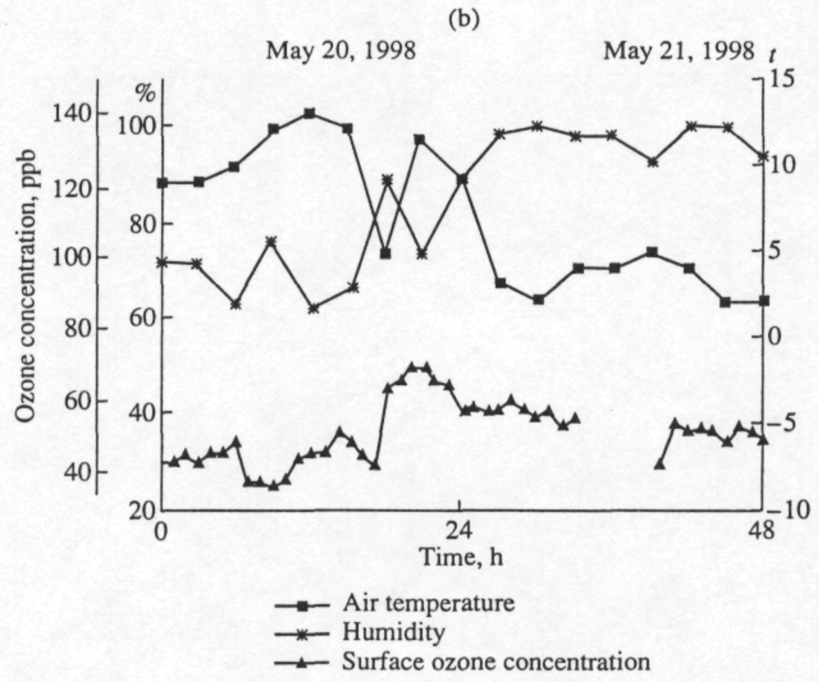

Fig. 3. (Contd.)

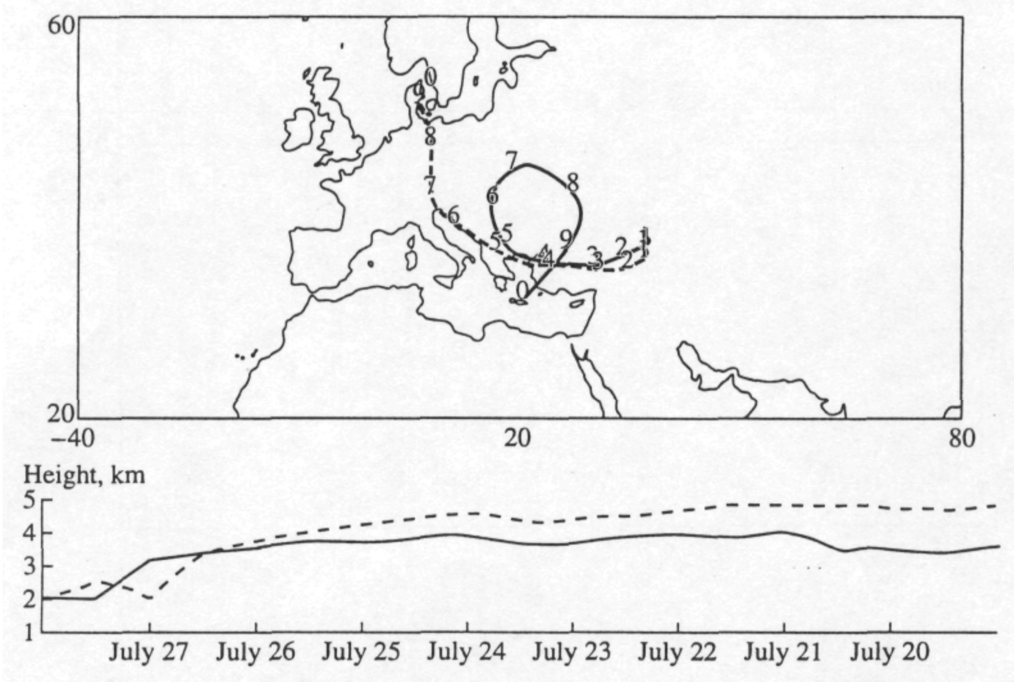

Fig. 4. Air transport within the anticyclone: isentropic trajectories and their vertical profiles.

ozone-poor air inflow with upward jet streams within the cumulonimbus clouds. Later, due to the arrival of ozone from the upper atmosphere, the surface ozone concentration in the cold air rose rapidly up to 77 ppb. Then, the ozone concentration dropped by almost 20 ppb in one hour. At 20:30, one more ozone maximum of 77 ppb was observed. This ozone concentration is comparable with that in the upper troposphere. By 21:00, the temperature rose rapidly up to 11°C; at the midnight, it was equal t 9°C. Therefore, we assume that the warm sector of th cyclone filled the space over the station again. The sta tionary cold air mass filled the space over the station onl at night. On May 21, the temperature was within 2-5°< and the relative humidity was within 90-100%. The anl emeridian ozone concentration was rather high, nameh

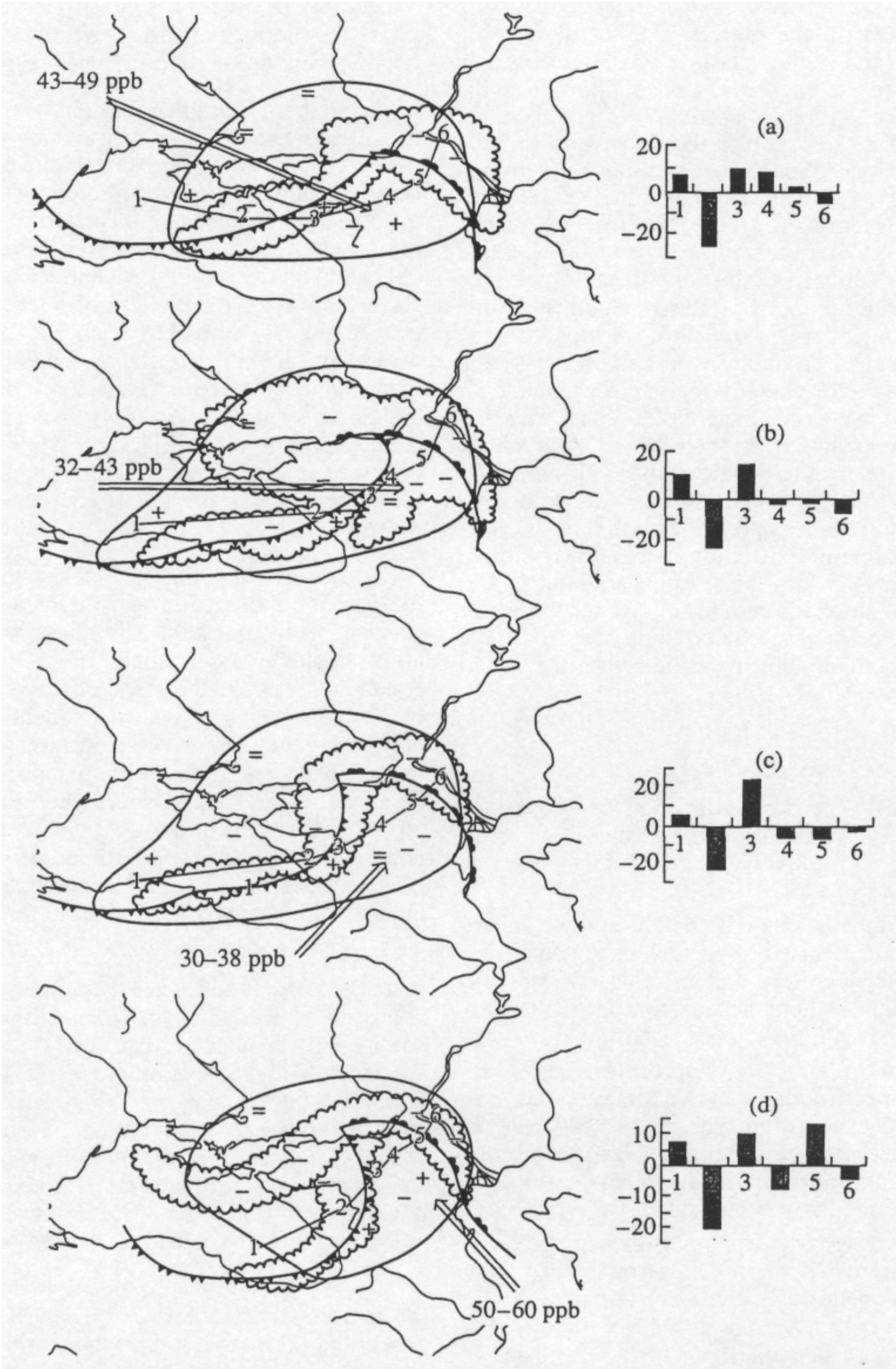

Fig. 5. Schematic patterns of ozone variations within cyclones: (a) midlatitudinal cyclone, (b) Black Sea cyclone moving slowly; (c) advection of tropical continental air; and (d) advection of polluted air; in the inserts, the ozone concentration (ppb) is given along the ordinate.

54-61 ppb. These results indicate that the cold air mass following the atmospheric front was ozone-enriched.

These observations characterize the complicated atmospheric processes proceeding in the center of the cyclone and in the baroclinic zone of the atmospheric front. The results of continuous measurements of the surface ozone concentration clarify the participation of air masses and atmospheric layers in cyclone formation.

As was shown in the preceding text, the evening ozone maxima and high nighttime levels observed in mountain regions are caused by ozone inflow from the free troposphere. A more powerful mechanism for ozone-enriched air transport is the downward ordered flows in anticyclones. Such processes can be identified using the method of three-dimensional trajectories [13]. Ozone advection from the free troposphere can manifest itself either in a significant rise in the usual maximum or in a change of the daily behavior with the initiation of an additional maximum at an unusual time of day. Two examples are given below. On July 28, at the southern outskirts of an anticyclone localized over the lower Volga and the black-earth region, tropospheric air began to come down from a height of *3-4* km. This air-mass migration resulted in an intense rise in the ozone concentration over the Caucasian high-mountain region. Namely, on July 29, the surface ozone concentration was within 58-69 ppb. On May 27, in the anticyclone, the ozone-enriched air came down slowly from a height of 4—5 km. As a result, at about 10:00, instead of the ozone minimum usually observed, a rise in the ozone concentration up to 61 ppb occurred. This maximum is comparable in value with the usual evening maximum (Fig. 4).

DISCUSSION

An analysis of the correlation between synoptic-scale processes and variations in the surface ozone concentration in the high-mountain region led us to the following conclusions.

The most dramatic changes in the surface ozone concentration are caused by cyclones containing clearly pronounced sectors and by cold atmospheric fronts. The general schematic description of the processes proceeding within cyclones is given below.

If a warm atmospheric front approaches the region, the phenomenon of frontal inversion arises, cloudiness intensifies, and the atmospheric water content increases. These factors reveal themselves in a drop of the ozone concentration and, on frequent occasions, in the disruption of the daily ozone behavior (Fig. 5).

Once the atmospheric front has passed over the region, the ozone behavior in the warm sector of the cyclone over it depends on the characteristics of the air masses participating in cyclone formation.

(1) In warm midlatitudinal and marine tropical air masses characterized by a relative humidity far from saturation, the insolation increases, the clouds are scattered, and the usual daily ozone behavior with its characteristic concentration extrema occurs (Fig. 5a).

(2) In warm and humid air masses (marine tropical or temperate continental), the vertical air exchange is intensified in comparison with that within the frontal zone. When cloudiness occurs in the lower and middle atmospheric layers and the relative humidity exceeds 80%, the inflow of tropospheric ozone does not make up for the shortage of surface ozone, and dry and humid ozone precipitation predominates (Fig. 5b).

(3) In the sector filled with dry tropical air, which is identified by its low humidity and high temperature, the ozone concentration drops to the level of 40 ppb characteristic of the region and remains at this level until the air mass is replaced. Air arriving from the desert regions of Central Asia, Arabia, and North Africa is characterized by a high concentration of mineral aerosol, which is the main cause of intense ozone destruction in the daytime. For such air masses, nighttime inversions blocking the downward flow of tropospheric ozone are characteristic. Therefore, for a period of several days, aerosol of desert origin causes a low level of ozone concentration (Fig. 5c). A similar pattern was observed in the dry season at the KVNS as a result of the arrival of air masses from the Kuma basin and Kalmykiya.

(4) The arrival of polluted air masses from industrial regions of southern Europe, the Middle East, and the Caspian oil and gas fields stimulates local ozone-generating processes. On sunny days, short-term ozone spikes that disrupt the standard daily behavior of the ozone concentration occur frequently (Fig. 5d). At nighttime, the ozone concentration rise that results from ozone generation within the air mass can be used as an indicator to determine whether the air mass is advected from one of these regions. Such identification is possible under stable stratification with insignificant or no vertical transport. Unlike stable tropical-air flows, the arrival of narrow plumes of anthropogenic pollutants is a rare occurrence in the high-mountain region.

(5) If a pronounced cold atmospheric front approaches the region, the ozone concentration rises, and its daily behavior is disturbed by short-term spikes associated with convection processes, frontal precipitation, and thunderstorms. When a cold atmospheric front covers the region, an intense vertical air exchange occurs. Therefore, the increased ozone concentration can be observed for some time. Then, an intense drop in ozone begins. Such a tendency reveals itself as long as the air humidity is close to saturation.

(6) As a cold atmospheric front moves away from the region, the standard daily behavior of the ozone concentration is reset within the rear of cyclone. However, the air mass that is moving away is cooled and is characterized by a reduced ozone concentration.

(7) If an aging cyclone fills the region over the station, no abrupt change in the surface ozone concentration occurs. Low-level clouds and high humidity promote ozone concentration stabilization. In an atmosphere with high humidity, the daily amplitudes of the surface ozone concentration are almost independent of the season. They are limited by values of 10 and 15 ppb during the cold and warm seasons, respectively.

CONCLUSIONS

In this work, the responses of the surface ozone concentration to synoptic-scale processes are clarified. It is obvious that, in order to improve statistically significant quantitative characteristics, it is necessary to use a more representative data selection and to supplement it with information on the state of the lower and upper troposphere. In addition, the authors believe that the analyzed data should be supplemented with observational results that could be obtained at a second station located in the park zone of the town of Kislovodsk at about 900 m above sea level.

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