

RUSSIAN GEOGRAPHICAL SOCIETY

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No. 01 [v. 05]
2012

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SOILS AS INDICATORS OF CLIMATIC CHANGES

ABSTRACT. A number of examples for the reaction of chernozems in the center of the East European Plain and their relation to different periodical climatic changes are examined. According to unequal-age chernozems properties, the transition from the Middle Holocene arid conditions to the Late Holocene wet conditions occurred at 4000 yr BP. Using data on changes of soil properties, the position of boundary between steppe and forest-steppe and the annual amount of precipitation at approximately 4000 yr BP were reconstructed. The change from warm-dry to cool-moist climatic phases, which occurred at the end of the XX century as a reflection of intra-age-long climatic cyclic recurrence, led to the strengthening of dehumification over the profile of automorphic chernozems and to the reduction of its content in the upper meter of the soils. The leaching of carbonates and of readily soluble salts contributed to the decrease in soil areas occupied by typical and solonchic chernozems, and to the increase in areas occupied by leached chernozems.

KEY WORDS: chernozems, climate change, Holocene, forest-steppe, steppe.

INTRODUCTION

Among the diverse objects in the natural environment, the soils are rightfully considered one of the most informative components. They contain the records not only of contemporary, but also of past physical-geographical and climatic conditions. At the same time, the soil is a rapidly changing

system, which sensitively reacts to changes in natural conditions and, in the first place, to climate change. Therefore, in scientific literature in connection with soils, arose such concepts as "soil-moment" and "soil-memory", "urgent" and "relict" characteristics of soils, and "sensitivity" and "reflectivity" of soil properties [Aleksandrovskii, 1983; Gennadiyev, 1990; Sokolov and Targul'yan, 1976; Sokolov, et al., 1986; and others].

In contemporary world geography, there still remains a paucity of information on the many-sided interrelations of soils with the other components of the natural environment. This is extremely important aspect in light of current global ecological problems, studies, and policy decisions, one of which is the problem of climate change.

While these have been long discussed by scientists, this problem during the last few years acquired new urgency in connection with new data, reflecting "long" sequences in paleoclimatic reconstructions and a comparatively short, but detailed series of instrumental observations [Climate..., 2002; Climate..., 2008; Global..., 2000; and others]. We will continue the discussion on the following questions: "In what direction might the change in global climate go?" and "Is this change subordinated by trend dependence or does it occur within cyclic climatic dynamics?" [Bunyard, 2001; Lupo, 2008; and others]. It seems that in finding new ways and approaches to this problem it may be possible to find a solution to a number of other problems and the solution

must be connected with a thorough study of soils as indicators of climate change.

The role of soils in the study of chronological variations of climate is reflected in a number of publications, many of which are oriented toward the use of soils in reconstructions of long-term climate changes [Aleksandrovskii and Aleksandrovskaya, 2005; Buol et al., 1997; Chendev, 2008; Climate..., 2009; Felix-Henningsen, 2000; Gennadiev, 1990; Ivanov, 1992; Jenny, 1941; and others]. There are fewer references on the study of soils as indicators of contemporary climate change [Ovechkin and Isaev, 1985; Savin, 1990; Solovyov, 1989; and some others].

The main purpose of this paper is identification of forest-steppe and steppe chernozems reactions to climate change with different periodicities.

The stated purpose assumed solution of the following objectives:

- using a number of examples, to show the effectiveness of unequal-age chernozems properties in paleoclimatic reconstructions;
- to discuss the influence of short-term climate changes on properties and areas of chernozems dynamics.

DISCUSSION OF THE PROBLEM, OBJECTIVES, AND METHODS

Contemporary soil cover within the territory of East European forest-steppe and steppe began to form in the Early Holocene – approximately 10000 years ago [Aleksandrovskii, 1983; Gennadiev, 1990; Ivanov, 1992]. In the study region, climate repeatedly changed during the Holocene, which led to the time-spatial changes of the boundaries for natural and soil zones. The natural-climatic periodization of the Holocene for East Europe according to Blytt-Sernander [Aleksandrovskii, 1983; Ivanov, 1992] is widely known. However recently, the appropriateness for wide interpretation of this

scheme, originally created for Scandinavia, is open for discussion [Aleksandrovskii and Aleksandrovskaya, 2005; Aleksandrovskii and Chendev, 2009]. In our understanding, from the point of view of age-long (long-periodical) climate change in the territory of the forest-steppe and steppe zones of the central part of the East European Plain, it is better to use division of the Holocene into Early, Middle, and Late period. According to contemporary ideas, the Early Holocene (10000–8000 yr BP) was characterized by a cool-cold and dry climate. The Middle Holocene (8000–4000 (3500) yr BP) had alternation of temperature drops and rises in conditions of dry, in general, climate; and the Late Holocene (last 4000–3500 yr) was characterized by a reduction in the degree of continentality and an increase of the climate humidity [Aleksandrovskii and Aleksandrovskaya, 2005; Aleksandrovskii and Chendev, 2009; Chendev, 2008]. In respect to evolution of chernozems in the Holocene in the East European Plain, there remain a number of only weakly illuminated questions. Among these questions: the determination of the exact chronological boundary between the Middle and the Late Holocene and identification of the distance of the shift of climatic border between forest-steppe and steppe that occurred at the beginning of the Late Holocene. The answers to these questions are discussed in this paper.

The well-known ideas of the Holocene natural periodization consider only long-term fluctuations in climate, whose tracks can be revealed in soil profiles. However, for secular variations in the climate background, there were short-term variations whose influence on soils and soil cover is studied rarely at present. L.V. Klimenko [1992] analyzed seasonal behavior of temperatures, using the data provided by a meteorological network, located in the southern half of the East European Plain (45°–55°N 30°–50°E) for 1891–1990. In the researcher's opinion, the natural fluctuations of the temperature in both the summer and winter seasons for the past 100 years show the presence of two large waves of temperature decrease

during the summer time (1920s–1930s and 1970s–1980s); coincident with them were temperature increases during the winter seasons. L.V. Klimenko explains these by finding that similar atmospheric processes occurring in different seasons can lead to different climatic effects. For example, since the beginning of the 1970s, cyclonic activity increased sharply, and in the cold season, positive anomalies of temperature began to appear more frequently, but, in the warm season, negative anomalies appeared. The latter result is reflected by an increase in cloudy weather with precipitation [Klimenko, 1992].

According to A.N. Sazhin and O.V. Kosina [2000], in the Northern Hemisphere during the atmosphere circulation epoch of the 1890s–1920s, the annual amount of precipitation exceeded the long-term climatic norm. In the 1920s, a new atmospheric regime became established, and this continued into the middle 1950s. During this epoch, global temperatures rose, precipitation decreased, which caused more frequent droughts and these occurred repeatedly in the ordinary-steppe and dry-steppe regions of East Europe. From the beginning of the middle 1950s, in the extreme southeast of Russia's European territory, the climate steadily moistened and reached its maximum in the 1990s–2000s. With increasing precipitation, the character of many natural processes significantly changed: within the chernozem zone, the level of the ground water increased; the composition of natural vegetation changed sharply. Hygrophilous forms of plants appeared and the activity of wind-erosion processes decreased. The authors suggested that during the first half of the XXI century, changes in climate and the connected changes in the regime of temperature-moisture potential will occur in a manner similar to the period of the 1920s–1950s. This will lead to a sharp worsening in the natural climatic conditions for the development of agriculture within the southern East European Plain [Sazhin and Kosina, 2000].

The main subjects of our study are the chernozem soils, situated in the center of the East European Plain.

For climate change, the following properties of chernozems were examined: their humus horizons thickness and depth of effervescence (depth of the upper boundary of carbonates in the soil profile). Also, we analyzed temporal change in the areas of different genetic groups of chernozems (leached, typical, solonetzic) as the reflection of climate change.

According to the existing ideas, with an increase in climatic continentality (strengthening aridization of climate), the humus horizon thickness and the depth of effervescence decrease, while the area of chernozems, characteristic for more arid climatic conditions, increase. A decrease in climate continentality (during moistening of climate) causes the opposite processes: the humus horizon thickness and the depth of effervescence grow and the area of chernozems, formed under more dry climatic conditions, decreases.

Paleoclimatic reconstructions based on data on temporal changes of soil properties were done by the method of soil chronosequences. This method can be described as the study of chernozems covered by unequal-age burial mounds, with a subsequent comparative analysis of their humus horizon thickness and depths of effervescence. Additionally, the method uses a comparison of the ancient chernozems properties together with the properties of modern (background) chernozems formed on the natural topographic surface of the adjacent mounds. The results of the examination of soils as the objects of the paleoclimatic reconstructions were compared with the conclusions of other studies based on the use of other paleoclimatic indicators. Specifically, pollen spectra of the Holocene deposits and soils were used in earlier studies and here. In this article, one of the methods of soil chronosequences applications was the identification of climatic boundary position between the steppe and the forest steppe zones 4000 yr BP and its comparison with the modern position.

Repeated measurements (observations) and repeated cartography (comparison of maps for different years) were used to study the influence of short-term climate change (for the end of the XX – the beginning of the XXI centuries) on the properties and areas of chernozems. Using the Belgorod Region as an example, short-term climatically induced changes were mapped for the periods 1951–1980 and 1971–2000. These maps and literature data were the basis of our discussion on causes of relatively fast changes of soil properties and soil areas. In this discussion, we used observations and the large-scale soil surveys, which were conducted at 20–30-yr-long intervals.

RESULTS AND DISCUSSION

Using literature data and the results of our own field studies, the authors produced calculations of change in the thickness of the humus horizons (A1 + A1B) for the chernozems of the steppe zone (a subtype of ordinary chernozems) formed on flat watersheds and on loess carbonated loams, for the time-interval from 5200 yr BP to the present (Fig. 1).

The study region is delineated by the coordinates 49°–51°N and 35°–37°E. The graph of the soil type (Fig. 1B) was constructed and then correlated with the curve of chronological variation of the natural zones boundaries within southern forest-steppe of the river Don basin (data obtained from E.A. Spiridonova [1991]) (Fig. 1A). The data from [Spiridonova, 1991] are based on the analysis of the pollen spectra from the Holocene deposits; soils have been dated by the radio-carbon method.

As can be seen in Fig. 1, the basic extrema during the end of the Middle Holocene to the beginning of the Late Holocene, which were discovered through changes in the chernozems humus horizon thickness, are the same as on the pollen spectra variations. These were coincident with increases in the hydrothermal coefficient (during episodes of forest invasion to steppe). Then there was a decrease in their thickness observed to take place in the stages of climatic aridization (during reduction in hydrothermal coefficient values and advance of steppes to the north).

The smoothed row of the chernozems humus horizons thickness chronological variation (Fig. 1C) clearly reflects the presence of two large climatic epochs: the epoch of climate aridization, during which the humus horizons thickness was reduced, and the epoch of climate moistening, during which an increase in the humus horizons thickness occurred. The boundary between these epochs corresponds to 4000 yr BP. Specifically, this boundary should be considered as the beginning of the Late Holocene in the territory of the steppe and forest-steppe zones within the Central East European Plain. A trend toward improvement in the soil characteristics (an increase in the humus horizons thickness and the growth of the upper boundary of carbonates depth in soil profiles) as a consequence of humidity increase, was also observed for the first half of the Late Holocene within the East Europe chernozem area. This is reflected in Table 1.

In accordance with the existing ideas about the climatically induced shift of the

Table 1. Changes in the morpho-genetic properties of typical chernozems within the East European Plain forest-steppe area during the last 4000 years, % of modern values (based on [Chendev, 2008])

Soil index	Chrono-interval		
	4000 yr BP <i>n</i> = 3	3500–3000 yr BP <i>n</i> = 8	2600–2200 yr BP <i>n</i> = 15
Thickness of A1 + A1B	71.67 ± 2.92	76.50 ± 1.93	103.33 ± 2.80
Depth of effervescence	0	55.00 ± 4.73	64.73 ± 7.18

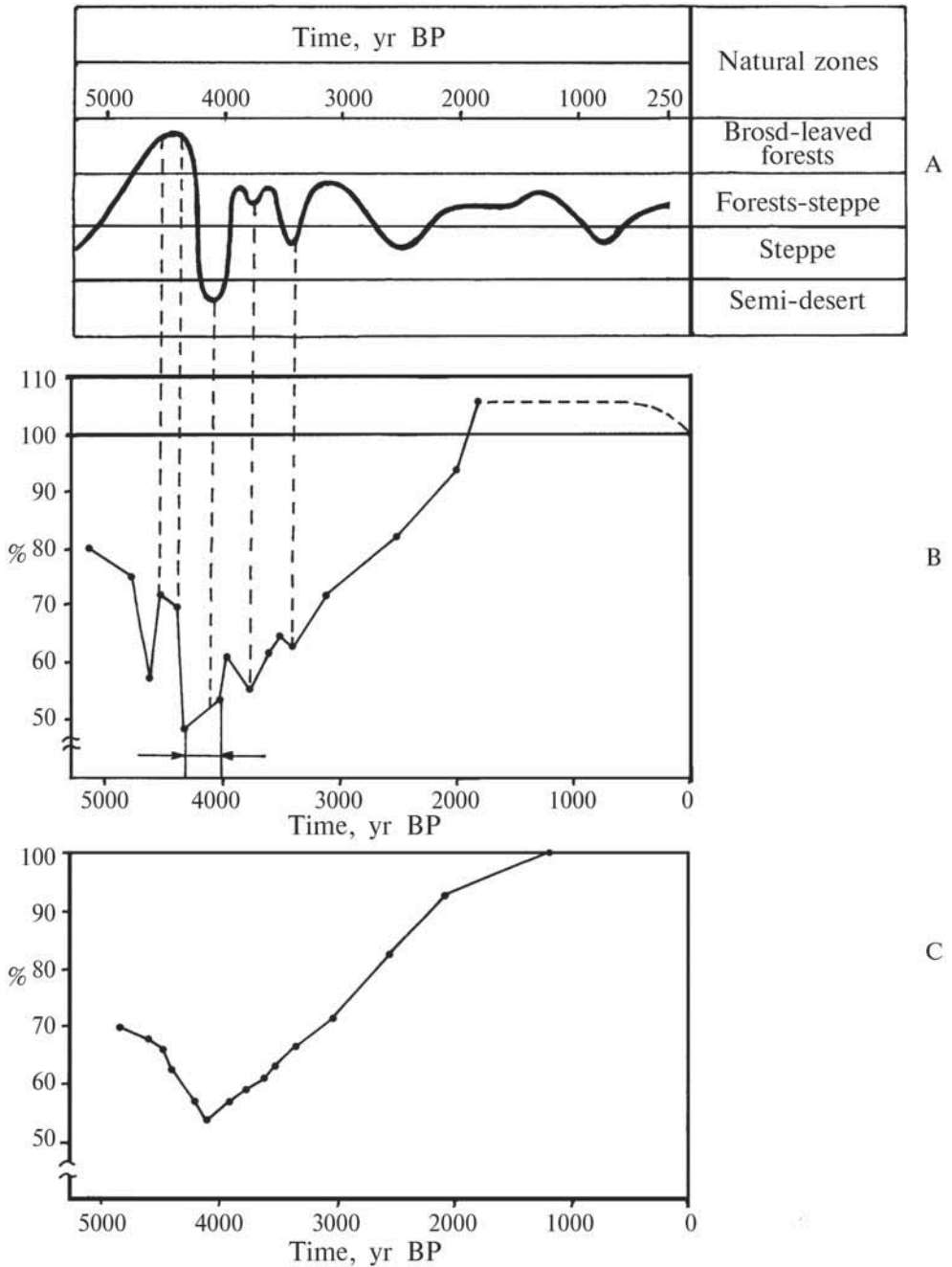


Fig. 1. Evolution of natural zones within southern forest-steppe of the river Don basin (according to [Spiridonova, 1991]) (A), and the chronological variation of chernozems humus horizons (A1 + A1B) within the steppe zone of the Central East European Plain,% from contemporary values (B – empirical row, C – smoothed row (based on the data of [Aleksandrovskii, 1983; Aleksandrovskii and Aleksandrovskaya, 2005; ChendeV, 2008; Ivanov, 1992] and the results of field studies of the authors)

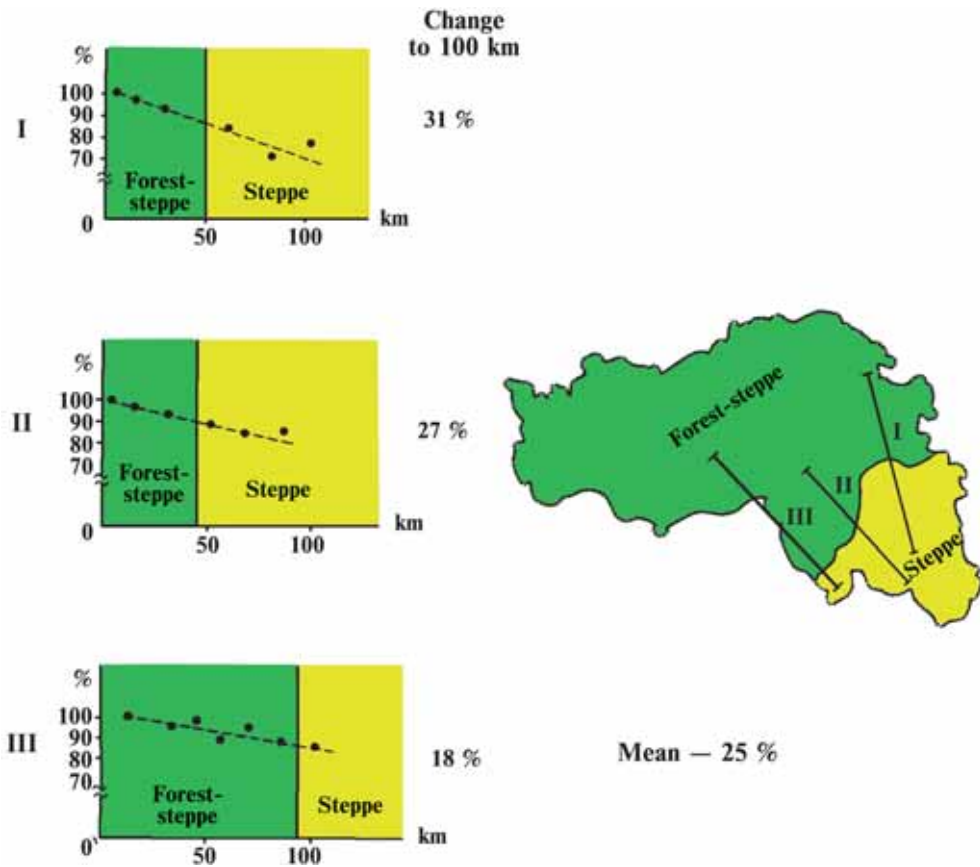


Fig. 2. Linear changes of the chernozems humus horizons (A1+A1B) thickness near the modern boundary between forest-steppe and steppe (the authors' data)

southern boundary of the forest-steppe zone at the beginning of the Late Holocene [Aleksandrovskii, 1983; Aleksandrovskii and Aleksandrovskaya, 2005; Spiridonova, 1991], we set our goal to determine where the location of the boundary between the steppe and the forest-steppe zones existed at approximately 4000 yr BP. The method utilized here consisted of the calculation of the spatial change gradient of the humus horizons thickness for the watershed chernozems in the direction from a more humid forest-steppe to a more arid steppe chernozems (Fig. 2, transects I–III). The data from the morpho-genetic properties of contemporary chernozems were generated from the materials of the large-scale soil survey of the Belgorod region (archive information). Each point of the transects characterizes the mean arithmetic thickness of the humus profiles from 10–15 locations that are situated within a

radius of 5 km from the point of determination. The thickness of the northernmost chernozems was accepted as 100%.

As can be seen from Fig. 2, under contemporary conditions, the value of the thickness decreases for every 100 km and varies from 18 to 31% (25% on average). If the 4000-yr-BP's thickness of the humus profiles for paleochernozems in the southern part of the forest-steppe zone was equal to about 72% of the background (modern) values (Table 1), then, according to our calculations, the steppe zone, at this time, could be found about 112 km to the northwest of its contemporary position. In the southeastern direction, the annual amount of precipitation at the indicated distance decreased by 80 mm. Consequently, near the contemporary boundary of forest-steppe and steppe,

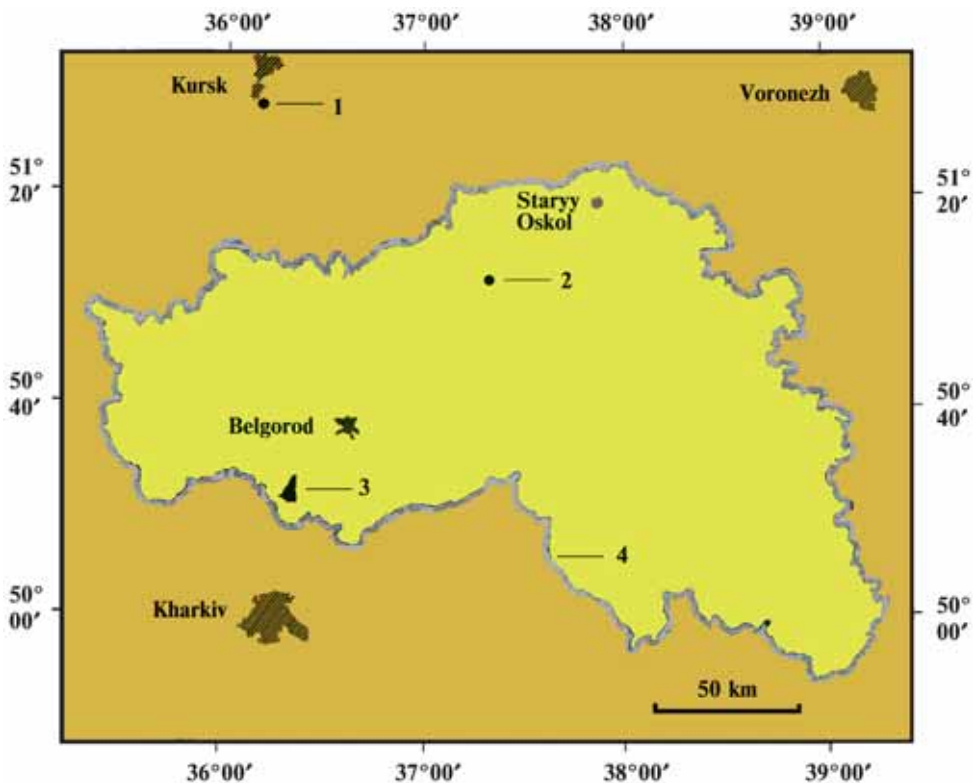


Fig. 3. The location of the study plots used to assess the short-term periodic climate change influence on soils and soil cover dynamics.

Plots: 1 – “Streletsкая Step”; 2 – “Yur’evka”; 3 – “Octyabr’skii” (plots 1 and 2 are shown not to scale); 4 – administrative border of the Belgorod Region

the climate of 4000 yr BP was more arid than contemporary (probably, 80 mm less precipitation); the annual precipitation, at this time, could have been approximately 430–450 mm.

The influence of the short-term climate change on the properties and areas of forest-steppe chernozems have been examined based on the example of three key plots. Two of these plots are located in the territory of the Belgorod Region, and one is within the territory of the Kursk Region (Fig. 3).

The periods of observations corresponded to different phases of short-term helioclimatic cycle – warm-dry and cool-wet. The presence of the indicated climatic phases is confirmed by a comparison of the climatic maps for the Belgorod Region created at different time-

points (Fig. 4). The comparison of the maps, which reflect average climatic indices during 1971–2000, with the maps that characterize climatic indices during the earlier thirty-year period (1951–1980) showed that, for last quarter of the XX century, there were a distinct increase in the annual amount of precipitation and the evolution toward a less continental temperature regime. This was reflected by the shift to the north of the January isotherms and to the south of the July isotherms (Fig. 4).

According to the observed data obtained for the Kursk Region, L.A. Bashkakova et al. [1984] established that there was a reduction in the humus content both in arable and in virgin chernozems of the Streletsкая Steppe Preserve (Table 2; key plot No. 1 on Fig. 3). As has been discovered, during the period from

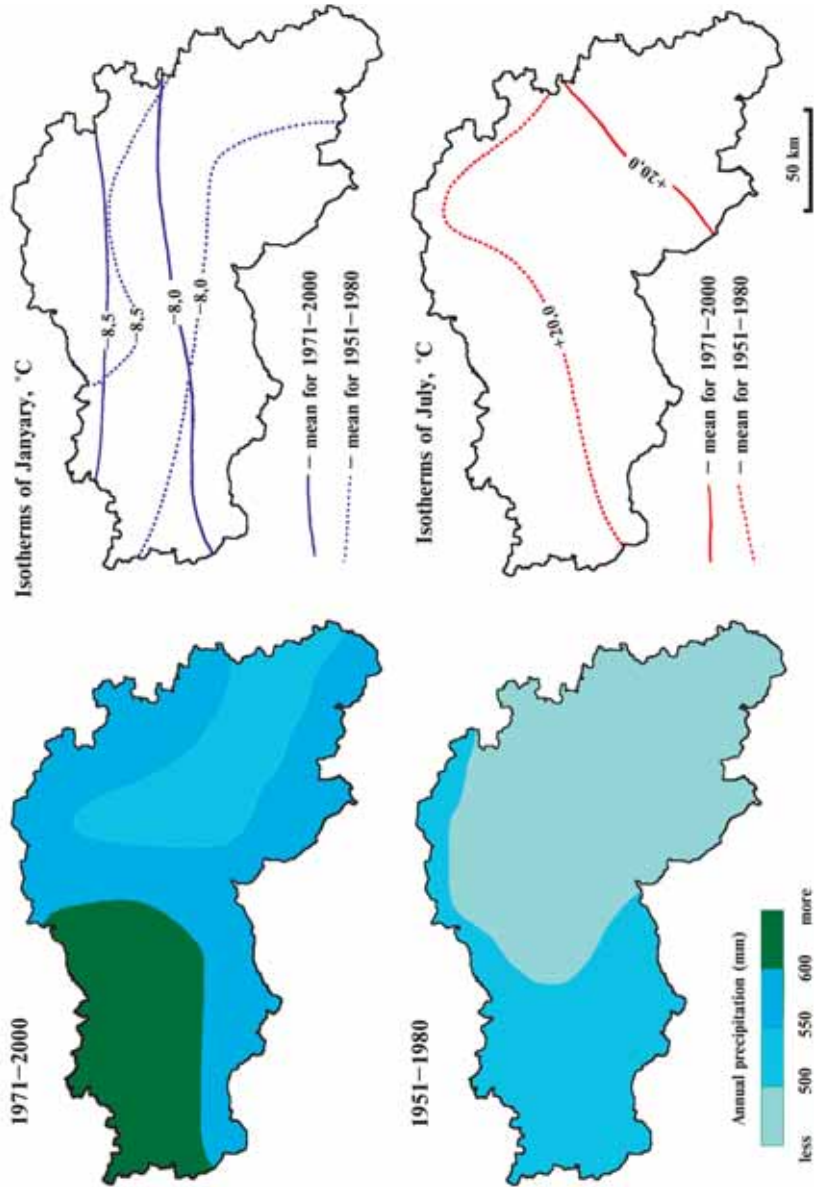


Fig. 4. Climatic indices of the Belgorod Region for the periods 1951–1980 and 1971–2000 (adapted from the data of [Climatic..., 1982; Grigoryev and Krymskaya, 2005])

Table 2. Humus content (% at mass of soil) in arable and virgin typical chernozems of northern forest-steppe observed in different periods (based on data [Bashkakova et al., 1984])

Depth. cm	Arable land since 1927		Virgin steppe		Mown steppe	
	1963	1981	1958	1981	1958	1981
0–5	8.8	7.1	11.17	9.1	11.12	8.7
5–10	8.5	7.1	8.76	7.3	7.88	7.2
10–20	8.5	6.7	7.72	6.4	6.76	6.5
20–30	7.5	5.7	6.57	5.4	5.58	6.5
30–40	6.8	4.9	6.03	4.8	5.02	6.0
40–50	6.0	4.1	4.95	4.3	4.62	4.6
50–60	5.7	3.8	4.29	3.3	4.03	4.2
60–70	5.2	3.2	3.72	2.8	3.69	4.0
70–80	4.4	3.1	2.98	2.6	3.23	3.3
80–90	3.7	2.5	2.60	2.2	3.08	2.5
90–100	3.6	2.1	2.28	2.0	2.84	2.3

1958 to 1981, dehumification under virgin steppe was occurring in the soil profile to a depth of 100 cm. For the study period, the intensity of dehumification in the arable land in 1927 was even less than under virgin steppe without grass mowing (Table 2). Researchers now explain that the reduction of the contents of humus and of exchangeable bases in automorphic meadow-steppe chernozems is associated with changes in conditions of soil formation and nature of vegetation. These changes occurred as a result of the recent cycle of moistening climate influence, which begun at the end of the 1960s and the beginning of the 1970s. In this case, the dynamic equilibrium moved toward leaching of exchangeable bases and the increase in humus mineralization above humification of organic matter [Bashkakova et al., 1984].

The influence of short-term climate changes on soils and the soil cover can be studied by analysis of large-scale soil maps, as discussed above, compiled through identical procedures but for different periods. Suitable for this purpose are 1:10000 scale soil maps

of agricultural enterprises created by large-scale soil surveys at different times-points. For example, we have carried out the temporal-spatial analysis of the soil cover conditions in 1970 and 2001 within the territory of the state farm in the "Stepnoe" in the Gubkin District of the Belgorod Region (key plot "Yur'evka", Fig. 3). Also, in 1976 and 1996, the same analysis was done within the territory of the state farm "Dmitrotaranovskiy" in the Belgorod District of the Belgorod Region (key plot "Octyabr'skii", Fig. 3).

As has been shown in the comparative analysis, the areas occupied by typical and leached chernozems on the maps of 1970–1976 and 1996–2001 differ significantly (Fig. 5). In the contemporary period, the area of leached chernozems generally increased while the area of typical chernozems decreased. Furthermore, the obvious tendency was a reduction of the areas with solonetzic chernozems (plot "Yur'evka", Fig. 5).

It is possible to assume that the discovered changes have been, in many respects, caused by climatic dynamics. For example, it

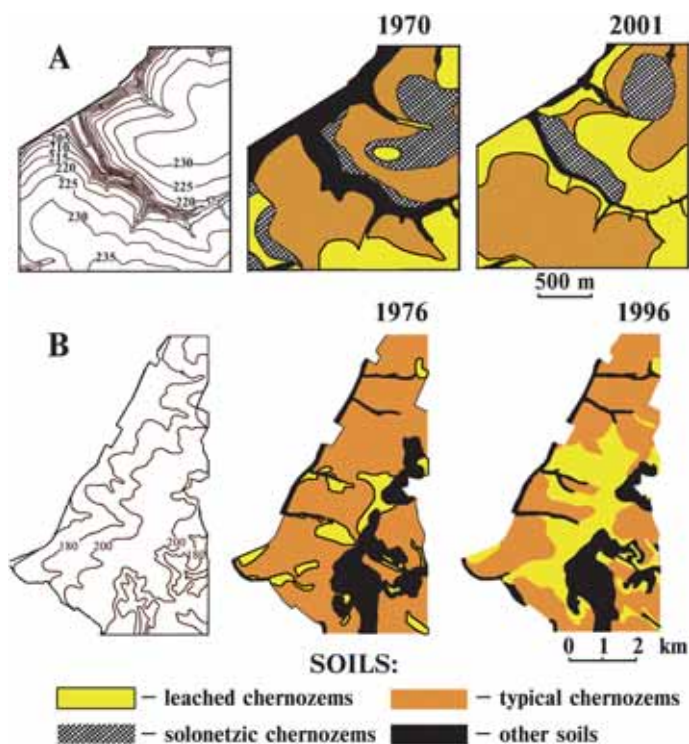


Fig. 5. Orographic maps (left figures, absolute heights are indicated in m) and the soil cover of key plots “Yur’evka” (A) and “Octyabr’skii” (B) for different soil surveys periods (based on the data from [Soils..., 1976; Soils..., 1996; Soils..., 1970; Soils..., 2001])

is known that in the territory of the Belgorod Region during 1971–2000, the total annual precipitation grew substantially (Fig. 4). According to L. V. Klimenko [1992], during the last quarter of the XX century, there has been increased moistening of the climate in winter. During this period, the frequency of thaws increased. According to the observed meteorological data in the Belgorod Region from the 1990s to the beginning of the 2000s, the steady snow cover frequently appeared only at the end of the winter periods and persisted only for 2–4 weeks. We considered that during the periods of winter thaws, precipitation in the form of wet snow or rain with the absence of soil freezing could initiate leaching of soils. In our opinion, this process was one of the main reasons for the rapid (years to decades) evolutionary dynamic transformation of typical chernozems into leached chernozems, and, probably, of solonetzic chernozems into chernozems typical or leached (Fig. 5).

CONCLUSIONS

In the course of this research, it has been established that chernozems are sensitive indicators of both long-term and short-term climatic changes.

For the territory of the Central East-European Plain, the existence of two large climatic epochs with the opposing tendencies in the climatic processes have been revealed with respect to changes in the humus horizons thicknesses in automorphic steppe chernozems in the second-half of the Holocene: the earlier part of the period was arid and the contemporary is moist. Transition from the arid to the moist epochs took place near 4000 yr BP. The duration of the Late Holocene within the study territory was 4000 years. The 4000-yr-BP boundary between steppe and forest-steppe was approximately 100–120 km to the northwest of its contemporary position. Near the boundary of “steppe – forest-steppe», the

annual amounts of precipitation were, on average, 80 mm lower than contemporary values (16% of the modern annual sum).

The change from the warm-dry to the cool-wet phases inside the age-long helioclimatic cycles was reflected noticeably in the properties and areas of chernozem soils. In the last quarter of the XX century, climate moistening contributed to strengthening of the dehumification in the profiles of automorphic chernozems and to the reduction of humus content in the upper meter of soils. The leaching of carbonates and of readily soluble salts contributed to the decrease in the areas occupied by typical and solonchic chernozems and to the increase in the areas occupied by leached chernozems. The discovery that these changes are cyclically repetitive events should be considered in the development of plans for the economic management of lands for the next few years and decades

It is feasible to conduct joint international scientific research within the territories of the continents of the Northern Hemisphere for the understanding of similarities and differences in the nature of prolonged and short-term climate changes and of how they influence the properties of soils and of the soil cover. According to available data, in the territories of the northeastern part of the USA Central Plains and the center of the East European Plain, climate change is currently subordinate to regular climate variations. In the Middle Holocene, the climate of these territories was more arid than the contemporary [Aleksandrovskii and Chendev, 2009; Denniston et al. 2000; Ruhe, 1974; Woodhouse and Overpeck, 2008; and references within]. At the end of the XX century within the two indicated regions, the atmospheric moisture increased [Chendev and Petin, 2009; Sauer, et al., 2009] as a reflection of climatic intra-secular cyclic recurrence. ■

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INTERNATIONAL PASSENGER RAILWAY COMMUNICATION IN UKRAINE

Abstract. The longer the distance that separates Ukraine from a state – object of international passenger communication, the higher is the administrative rank of the city-terminus of this communication. In 2007, 139 international passenger trains and 76 direct carriages ran through the country. Owing to the effect of historical inertia, Ukrainian cities are predominantly connected by international passenger service with Russian cities, especially with Moscow.

Key words: international passenger railway communication of Ukraine, metropolization, polarization, geo-economy, geopolitics, geo-history.

INTRODUCTION

Railway transport is the most stable in time and space among all kinds of transport because its functioning expensive transport infrastructure – railway equipment and rolling stock – is needed. It is the most inertial kind of international passenger service, for it requires not only coordination of train routes between two countries, but also the proper state of the entire necessary transport infrastructure. On the contrary, air and bus traffic do not need substantial funding, they are more mobile as far as the choice of the route is concerned unlike railway carriages, the coursing of which is strictly determined. That is why many present-day routes are the “relics” of earlier relations, formed in the preceding periods of the railway network’s development.

STATISTICS

The research is based on public data on station-by-station traffic of international

passenger railway trains and through carriages available on the official website of AS *Ukrzaliznytsia* <http://www.uz.gov.ua> as of 10.01.2007. The author analyses international passenger trains and through carriages running according to winter schedule exclusively, and does not discuss temporary or summer passenger trains and carriages, with the exception of the characteristic of transit trains and through carriages traffic.

THEORY AND METHODOLOGY OF RESEARCH

International passenger railway traffic is subjected to regulation within the framework of the state’s foreign policy and is also determined by political, economic, and social processes. Thus, it carries out the following functions: symbolic (the expediency of foreign relations development for the policy of the country), economic (the participation in foreign trade of the countries, particularly between the regions, in which the terminal stations of the international passenger trains and through carriages are located) and socio-communicative (the presence of such kind of communication makes possible stable international personal relations and international migration).

Alternative kinds of passenger international communication – motor and air traffic – possess both certain advantages (the speedier movement in space and time) and significant drawbacks (bigger fees, less comfort, notable restrictions in the parameters and weight of the luggage etc.). However the speed of trains is essential and it depends not only on the technical state of the rolling stock and station and railway equipment, but also on the time spent on

passport and customs control at the check points on the state border.

The *border effect* is an important factor restraining railway communication. Substantial differences in customs and technical documentation of various countries result in drastic cut in the trade between them [Kunth, 2002, p. 23]. The more strained are political and economic relations between the neighboring countries, the more expressed will the border effect be. It is the consequence of the *neighborhood effect* – with the expansion of distance between certain points, the interaction between them declines. The effect of historical inertia largely impacts the manifestation of the neighborhood effect in socio-economic relations – long-term unidirectional use of industrial objects and objects of infrastructure, determined by the need to recover of the capital spent on them [Blij&Muller, 2004, p. 272]. Capital-intensive railway construction is one of the good examples of the effect's manifestation. Thus, notwithstanding the formation of new states and the emergence and/or change of state border lines, many of the earlier train routes are still functioning.

The crossing by international passenger trains of several state borders testifies, in our opinion, to the fact of existence of strong ties between the cities-terminuses and their affected areas in different countries. To a great extent it is determined by the concentration of human and economic potential predominantly in the main cities of the country (*metropolis effect*) [Benko, 1999, p. 128], which mainly are the terminal stations of the international passenger trains' courses.

The *capital city effect* has a similar mechanism of spatial manifestation, implying the prevalence of centripetal movement towards a capital, which forms economic and political space on the subordinated territory. It is based on the centralized structure of state power. No wonder that this effect manifests itself vividly in the most

centralized countries (such were the Russian Empire and the USSR), where the bulk of the issues is dealt with in the capital. The latter had the evident prerogative to carry out international communication; besides, it sanctioned, in the case of impossibility of direct communication, the alternative functioning of separate privileged centers on the periphery of the state. This led to the emergence of a radial railway network spreading from the capital of the big state to its outskirts (*theoretical model* *toile de Legrand*) [Guigou, 1993, p. 16–20].

Among the peripheral regions of such a state, littoral southern outskirts play the most important part, as a result of *SSS¹ effect* (the concentration of population and economy in the regions with favorable climatic conditions) [Brunet, 1990, p. 19]. Direct railway routes are laid to connect such regions with the central regions in order to satisfy the need of the latter's (and mainly the capital's) inhabitants in sea-side holidays during summer time and also for carrying out of maritime trade.

The traffic of foreign passengers and cargo within the framework of international cooperation has a positive impact on the economic development of a certain territory in case when there is economic interaction between the administrative bodies of the states, through the territory of which traffic flows pass, and not only run through (*tunnel effect*). In the latter case one can view such trains as transit only. In this case railway lines have no significant economic impact on the territory they run through, as they serve for connecting metropolises only. The combination of tunnel effect with the metropolis effect leads to *Morvan's effect* – the emergence of a poorly developed, in the economic sense, territory, which lies between the peripheral regions of the adjoining economic centers [Brunet, 1993, pp. 121–122].

Official schedule of international passenger trains and through carriages has been systematized by railroad hauls. Then we counted the number and frequency of the

runs per week (the intensity of traffic) by each of the hauls and by railway stations.

We have singled out such types of international passenger trains and direct carriages passing through Ukraine:

- 1) passing – connecting the localities of one state and passing without stops the territory of another state;
- 2) transit – connecting the localities of different states and making stops on the territory of the third country;
- 3) of internal makeup – with one of the terminal stations in the territory of Ukraine, and the other – on the territory of another state.

In order to understand the importance of international passenger railway communication for the regions of a country, one should single out the cities, which are the terminal stations of the routes of such kinds of trains, especially in the main metropolises of the state. It will let us determine transport accessibility of these cities in the system of international relations, which facilitates their competitive advantages.

GENERAL TENDENCIES OF RAILWAY TRANSPORT DEVELOPMENT IN UKRAINE

Railway communication in the CIS countries is strategically important for national economies. The exploitation of one of the biggest in the world network of stations and tracks together with rolling stock, inherited by Ukraine after the break down of the USSR [Railway Statistics – Synopsis, 2009] allowed the country to increase annually the volumes of export and transit rail-freight traffic. To a large extent the fact can be explained by favorable economic situation on export markets of raw materials and prefabricated products of the CIS countries, by which the rail-freight of the country is mainly represented.

Ukraine does not fully exploit its existing potential in international passenger railway

communication, although through its territory six out of thirteen RCO railway corridors and three out of ten European transport railway corridors pass. Maximum concentration of the railway network in two diametrically located border regions, Donetsk and Lviv – respectively, 60.2 and 58.8 km per 1000 km² [Statistical yearbook of Ukraine 2009, 2010, p. 236] – is an important factor facilitating the development of international passenger transit in Ukraine.

Ukraine remains one of the world leaders in regard to the development of railway network and the volumes of passenger and cargo rail-freight traffic [Railway Statistics – Synopsis, 2009]. Nevertheless, such factors hinder further growth: depreciation of the branch's fixed assets, reduction of the operational length of public service railway tracks, and full use of the trunks' carrying capacity [Russian-Ukrainian borderland..., 2009, pp. 145–147].

High level of amortization of the exploited rolling stock inhibits the return to the pre-crisis volumes of passenger and cargo rail-freight traffic. As E.A. Petrenko notes, "by the beginning of 2010, the operating life of 83 per cent of passenger carriages, 71 per cent of freight stock, 89 per cent of main-line electric locomotives, and 92 per cent of diesel locomotives was over" in Ukraine [Petrenko, 2010, p. 53]. That is why the fleet of passenger carriages is constantly decreasing. If in 2000, 9.0 ths of passenger carriages had been exploited [Statistical yearbook of Ukraine 2007, 2008], in 2009, only 7.3 ths of them were in use, the average operating age of which constituted 26.8 years [Serhienko, 2010, pp. 39–40]. This data allow us to state that without high investments into rolling stock (in 2009 only four locomotives were purchased! [Petrenko, 2010, p. 53]), further development and normal functioning of the country's railway transport is impossible.

The present-day state of the railway transport in Ukraine directly affects its volumes of passenger traffic, internal as well as international. That is why the Ukrainian railway transport carried 426 bln people

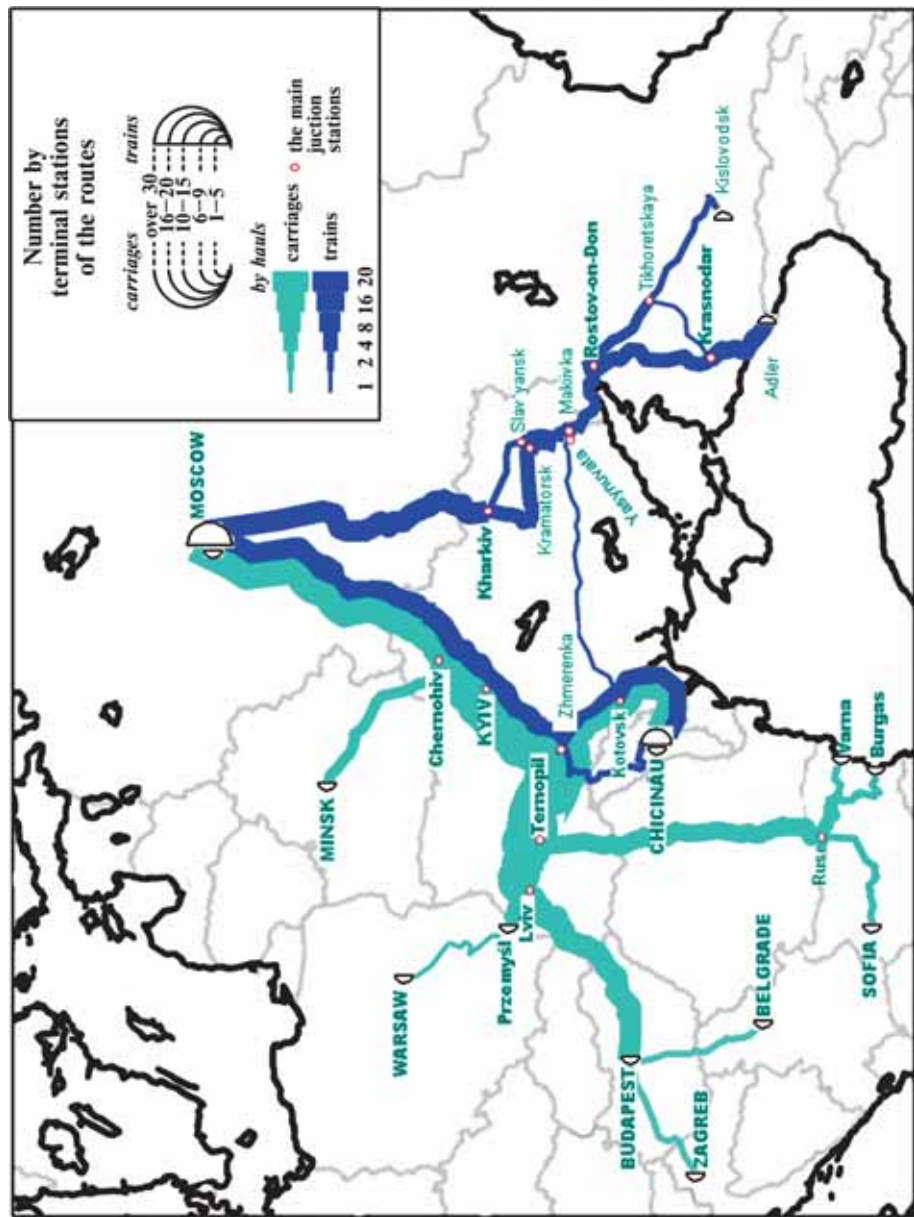


Fig. 1. Traffic of transit international passenger railway trains and direct carriages, passing through the territory of Ukraine (as of 01.01.2007)

in 2009, which only slightly exceeds the figure of 1971 (419 bln people) [Year book statistics of Ukraine 2009, 2010, p. 236; National economy of the Ukrainian SSR in 1974, 1975, p. 347]. However, the share of railway transport in long-distance passenger transportation increased during the period of Ukraine's independence from 27.5 to 47.7 per cent (calculated by [Statistical yearbook of Ukraine 2009, 2010, p. 236]). Thus, there are good reasons to say that international passenger railway communication is one of the main economic profiles of AS *Ukrzaliznytsia*. Since the end of the 1990s, railway transport of the country "makes up about 60 per cent of its freight turn-over due to (export, import, and transit) cargo traffic in direct and mixed communication" [Rail transport of Ukraine and Russia..., 2008, p. 7]. Over the period of 2000–2009, the cost of export of railway passenger service increased 4.4 times and freight transportation cost grew 2.2 times (calculated by [Dynamics of export-import services (2005–2009); Official average exchange rate of hrivnyia; Rail transport of Ukraine and Russia..., 2008, pp. 43, 173]). Stable growth of these indices, together with the increase of the rate of long-distance passenger transportation, allows us to state that AS *Ukrzaliznytsia* is an export-oriented company.

Export of international passenger services in 2009 brought 280.56 bln USD (calculated by [Dynamics of export-import services (2005–2009); Rail transport of Ukraine and Russia..., 2008, pp. 43, 173]), i.e., 41.80 per cent of the total benefit gained by all kinds of passenger traffic by the Ukrainian railways (calculated by [Dynamic of export-import services (2005–2009); Official average exchange rate for UAH]).

Transit railway international communication of Ukraine is directed predominantly westward and crosses the bigger part of the country's territory. Trains mainly proceed from Russia to the countries of Central and Eastern Europe. Thus, about $\frac{1}{3}$ of all transit freight and passengers is carried by Southwestern Railways (calculated by [Rail transport of Ukraine and Russia: development tendencies and reformation issues, 2008, pp. 162, 164].

It operates on the busiest, in terms of transit, international communication railway line of the country – Moscow–Kyiv–Zhmerynka (Fig. 1).

In 2007, 139 international passenger trains and 76 direct carriages ran through the country. Most of them were trains (89.3 per cent) and direct carriages (60.0 per cent of the total) of *internal make up*. This is precisely why we paid so much attention to them in our research.

TYPES OF PASSENGER RAILWAY COMMUNICATION OF UKRAINE

Transit passenger trains and direct carriages cross the territory of Milovskyi raion of Luhanska oblast of Ukraine along one of the busiest trunk railways *RZhD* Moscow–Rostov-on-Don. They do not pass customs and border control in Ukraine and that is why we excluded them from the object of our research. These trains and direct carriages do not stop on the territory of Ukraine, which leads to the manifestation of the *Morvan's effect* in the regions owing to the fact that the local population and the economy are not involved into provision of services for railway communication.

The launch of one of the speedy trains on this part of the Southeastern Railway of *RZhD* on the route Moscow–Ryazan–Michurinsk–Voronezh–Likhaya–Rostov (Mineralnye Vody, Tuapse) [Coordination of rail transport..., 2002, p. 46] will reinforce its barrier function. If protective structures are built along the roadway, the latter turns into a delimitative line with strictly determined crossing points (*the border effect*). Thus, speedy railway traffic will increase the rate of transport isolation of Milovskyi raion of Luhanska oblast from the adjacent territories of the neighboring countries (*tunnel effect*). We should not forget about the discomfort caused by drastic increase of noise and light disturbances in the area along the roadway, which would lead to the emergence of "lifeless desert" on both sides of the speedy railway track, where the presence of humans and animals is minimal.

Transit international passenger trains and direct carriages, passing through the territory

of Ukraine, beyond its limits connect only the cities of Russia and Moldova (Fig. 1). Except for train No120 Adler–Chişinău², the rest of the trains run back and forth. Altogether in 2007, four terminal stations of transit international passenger trains existed (Fig. 1). Such trains mainly run in summer (e.g., No24C Adler–Moscow and No27C Kislovodsk–Moscow), and that is ineffective use of the Ukrainian transit potential. They cross the country along its main busy trunk railways. All regional railways of AS *Ukrzaliznytsia* provide services to them (Fig. 1).

Transit international passenger direct carriages, passing through the territory of Ukraine, connected ten cities of eight states in 2007 (Fig. 1). With the exception of Burgas, Varna (Bulgaria), and Przemyśl (Poland), all the cities are the terminuses of the given type of carriages, which, in our opinion, points to the decisive role of the *capital effect* in their functioning. The makeup of direct carriages for the directions Moscow–Budapest–Belgrade/Zagreb and Moscow–Bucharest/Sofia instead of earlier regular train routes can be viewed as a geopolitical “relic” of the Soviet bloc times (see Fig. 1). In 2009–2010, such carriages had been launched from Moscow to such cities as Bar (Montenegro), Thessaloniki (Greece), and Venice (Italy). All of them run exclusively in summer, serving recreational needs of Russians (*SSS-effect*). Part of transit international passenger trains and direct carriages crosses the Carpathians. “For the Ukrainian railway transit, the one-gauge tunnel of Beskids, built as early as in 1886 in the times of Austro-Hungarian rule, is a sore spot. The issue of this tunnel’s exploitation had arisen long time ago, however *Ukrzaliznytsia* declared the start of drafting of its reconstruction only in June of 2000», planning to attract the loan of EBRD amounting to 40 bln USD for the implementation of the project [Petrenko, 2010, p. 60].

In our opinion, transit international passenger trains and direct carriages served, in the times of the Russian Empire and the USSR, the needs of the inhabitants of predominantly the capital of the state in sea-

side recreation (*SSS effect*). This is precisely why they are oriented from north to south, whereas transit international passenger direct carriages, made up beyond the limits of Ukraine, with the exception of route No51 Chişinău–Warsaw, run in the direction east – west. This policy of the railway routes makeup is a direct consequence of tsarist and the Soviet geopolitics, based on *étoile de Legrand* principle.

International railway passenger trains of internal makeup. Terminal stations of such trains’ routes within the limits of Ukraine (Fig. 2, 3) are concentrated in 20 cities, 15 of them are the capitals of administrative and territorial units of Ukraine of the first level. Consequently, the population of the larger part of the country’s territory can employ their services. With the exception of such important junction stations as Zhmerynka and Kovel, and also the resort of Berdiansk, all terminuses of international railway passenger trains of internal makeup are in the centers of interregional systems of settlement of Ukraine (*metropolis effect*).

Pronounced *macrocephaly* of Kyiv, where 30 international railway passenger trains of internal makeup are made up, is leading. Regional metropolises of the country follow the state capital in regard to this factor (Fig. 2). Such distinct hierarchy of terminal stations placement in certain cities allows us to suggest that it has been formed in accordance with the provisions of Central Place Theory. However, only four cities of the country are the terminal stations of the international railway passenger trains of internal makeup, which run westwards, whereas such trains run eastwards from 20 cities of the country (Fig. 2, 3).

Clear East – West asymmetry in the territorial structure of the international railway passenger communication of internal makeup was inherited by Ukraine from the USSR, where the connections with foreign countries had been limited and were regulated from the capital.

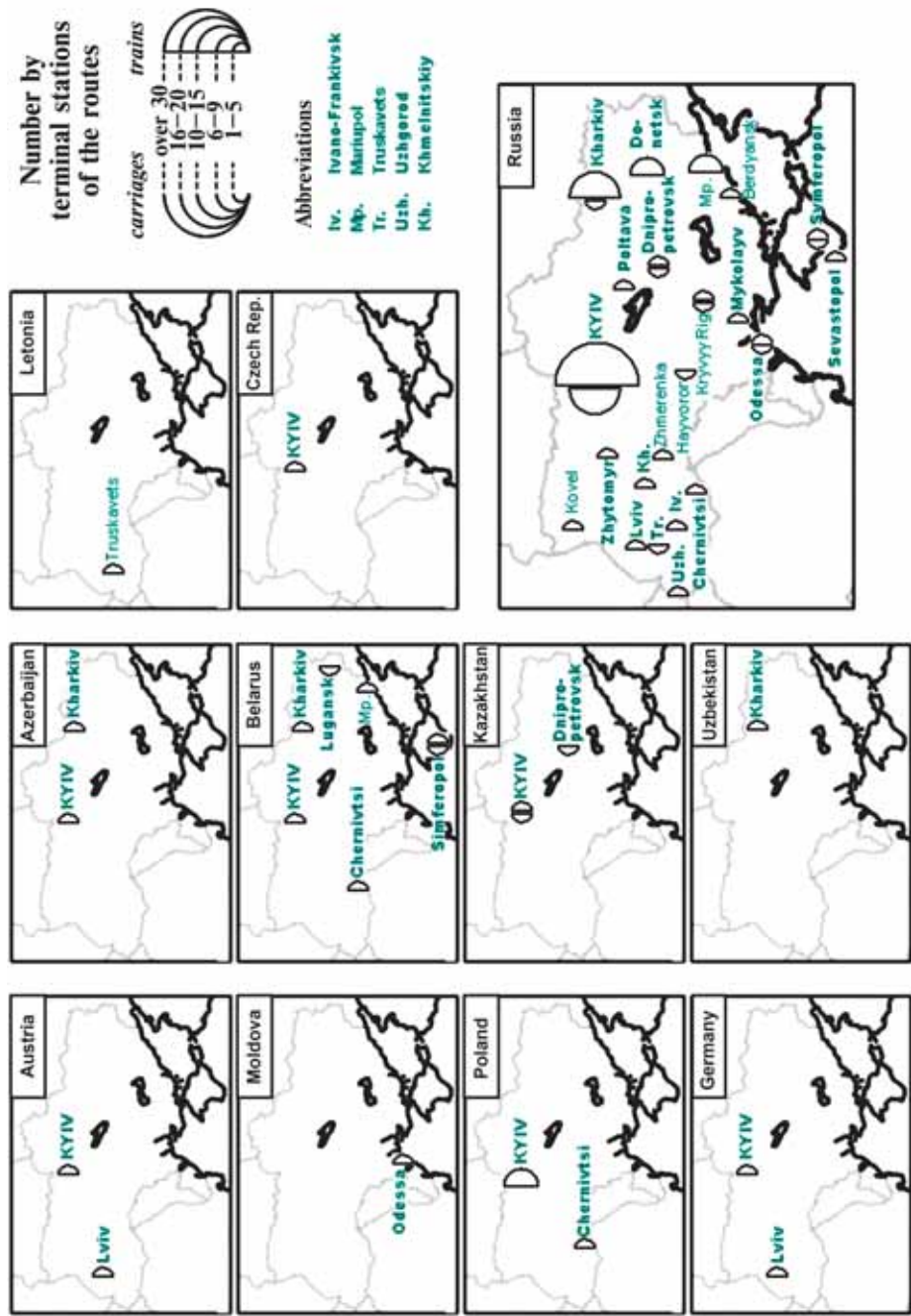


Fig. 2. Distribution by country of international passenger railway trains and direct carriages of internal makeup (as of 01.01.2007)

The dominance of the *eastward direction* international railway passenger trains of internal makeup (90 trains from 20 cities), in our opinion, is the result of the *historical inertia effect*. The existing distribution of terminal stations of international railway passenger trains of internal makeup, to a big measure, is the consequence of historical development of railway network before the WWI and partially in the period in-between the two World Wars. Here owing to the *capital effect*, by a finger's breadth lead two cities: the present-day capital of the state Kyiv (22) and Kharkiv, the capital of the Ukrainian SSR from 1918 till 1933 (19 trains). Then, predominantly the cities of the east of Ukraine follow (Fig. 2).

The analysis of the traffic of international railway passenger trains and direct carriages of internal makeup proved that eastern direction is predominant. 58.1 per cent (2007) and 51.5 per cent (2000) of their total number (calculated according to [Transport and communication of Ukraine – 2007. Statistical Proceedings, 2008, p. 167]) crossed the state land border of Ukraine with Russia. By the number of trains of internal makeup (Fig. 3), precisely this direction dominates in the international passenger railway communication of Ukraine. Inherited strategies of the unified big transcontinental railway system's formation with its center in Moscow explain the prevalence of the cities–terminuses of such trains to Russia in the present-day railway communication of Ukraine running in the eastern direction and the presence of continuous communication of this type with its ultimate biggest junction stations: Baku, Vladivostok, and Tashkent (Fig. 3).

All the cities–terminuses of the above mentioned trains in the eastern direction are the administrative centers of administrative and territorial units of the first level (with the exception of Adler and Kislovodsk in Russia, which, in our opinion, is predetermined by their status of recreation zones of the interstate significance).

63.2 per cent of the cities–terminuses of the routes of international passenger trains with one of the terminal stations located in Ukraine, are situated in Russia. Under the influence of *the historical inertia effect*, all the metropolises – the interregional centers of settlement of Ukraine – have international passenger communications predominantly with the cities in Russia. The strongest of the existing ties are with Moscow. The formation of the present-day railway network on the territory of the CIS countries in the times of the Russian Empire and the USSR explains pronounced dominance of the capitals of the aforementioned states – Moscow (37) and Saint Petersburg (11 of such trains) in the distribution of the international passenger communication in Ukraine in the eastern direction. As Fig. 3 shows, among other states of the eastward direction, Belarus (2) and Kazakhstan (3 cities) stand out.

Only 19 international passenger trains of internal makeup run westwards. They depart from four cities of Ukraine (Fig. 2, 3). As Fig. 2 shows, 10 of such trains are made up in Kyiv, four – in Odessa, three – in Lviv, and two – in Chernivtsi. Such a graded way of trains' distribution by the biggest cities of Ukraine, located nearby the western segment of its state border, is suggestive of the advantages of their location, and, to a great extent, is the result of the *effect of historical inertia* and *the metropolis effect*. Therefore, Kyiv and Lviv have the most multidirectional passenger communication of this type, although the biggest number of trains runs between closely situated Odessa and Chişinău.

The use of the advantages of the near-border location of the aforementioned cities allows them to have rather intensive connections with the neighboring states. Terminal stations of such trains are situated in seven cities of four states (Fig. 3). With the exception of Poland (Warsaw, Wrocław, Cracow, Przemyśl), European countries have only one such city each (Fig. 3), and all of them are the capitals.

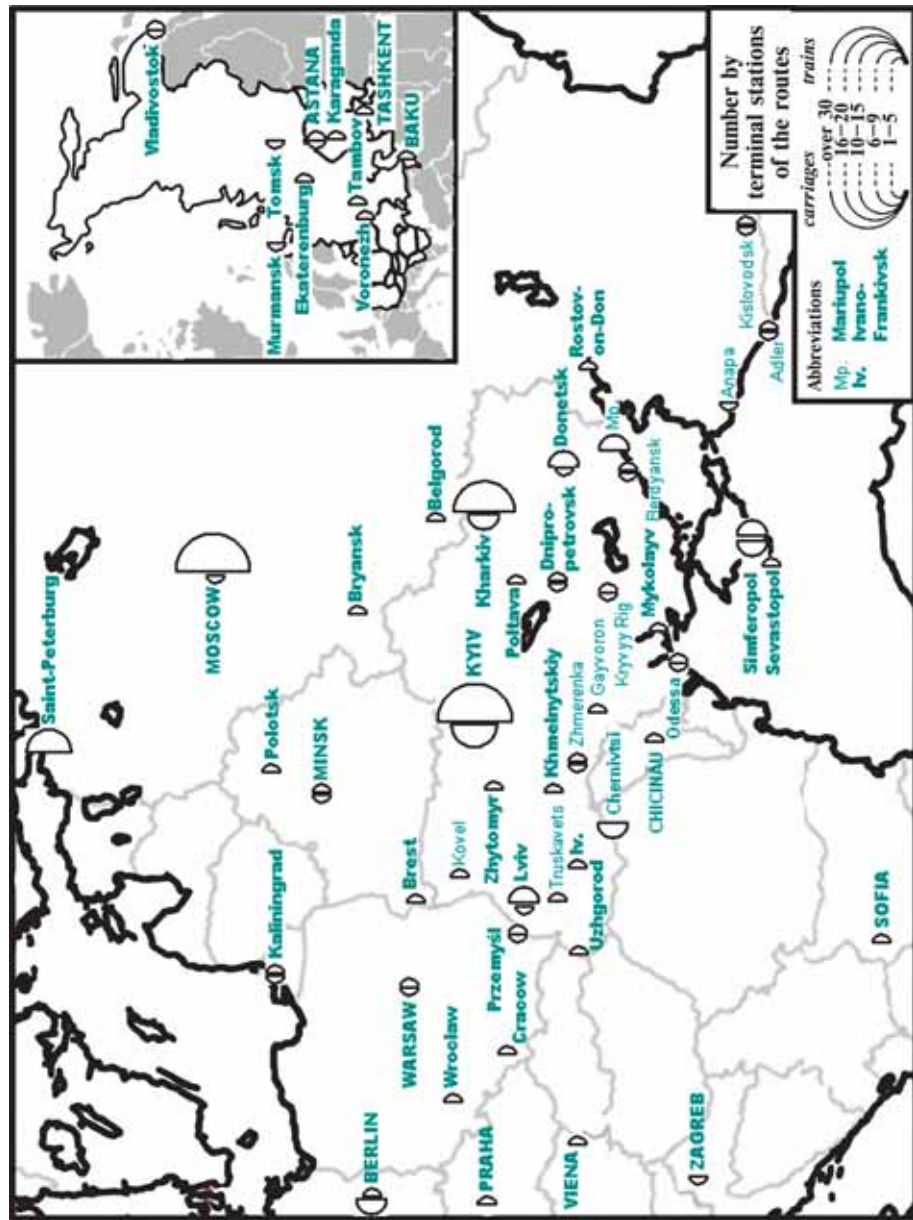


Fig. 3. Distribution by terminus of international passenger railway trains and direct carriages of internal makeup (as of 01.01.2007)

Many of today's functioning railway routes have been inherited from the times of the railway network formation in the reviewed regions in the end of the 19th – the beginning of the 20th c. in the period of existence of the Austro-Hungarian and the Russian Empires. E.g., route Chernivtsi–Przemyśl is a part of old route Chernivtsi–Lviv–Przemyśl–Cracow–Vienna, functioning with the aim of connecting the Austro-Hungarian outskirts with the capital of the Empire. Train Odessa–Chişinău, is a similar relic, running since the time of the emergence of *Odessa Railways* in the Russian Empire. In those days, regular international railway communication between the two Empires was carried out mainly along the trunk railway Saint Petersburg–Vilnius–Warsaw–Vienna and was aimed at the connection of the two capitals, and not at the creation of the susceptible transport link between the periphery parts of the states. Precisely these inherited spatial structures explain the existing irregularity in the intensity and orientation of the international passenger railway communication of Ukraine (*effect of historical inertia*).

The aforementioned facts allow us to establish the following consistent pattern: the longer the distance that separates Ukraine from a state-object of international passenger communication, the higher is the administrative rank of the city-terminus of this communication (Fig. 3).

CONCLUSION

Ukraine is one of the world leaders as far as the level of development of railway network and the volumes of freight and passenger transportation are concerned. Depreciation of the branch's fixed assets and the reduction of the length of public service railway tracks hinder further growth.

In 2007 through Ukraine ran 139 international passenger trains and 76 direct carriages (89.3 per cent of them were trains of internal makeup and 60.0 per cent were direct carriages of internal makeup).

Passing passenger trains and direct carriages cross the territory of Milovskyi raion of Luhanska oblast without any stops along one of the busiest, in terms of passenger and freight traffic, trunk railways *RZhD* – Moscow–Rostov-on-Don, which results in the manifestation of the *Morvan's effect* in this region.

Transit international passenger railway trains, passing through the Ukrainian territory, beyond its limits, connect only the cities of Russia and Moldova. Such trains mainly run in summer along the busiest, in terms of passenger and freight traffic trunk railways, of Ukraine. Direct carriages of such kind connect mainly the capitals of the countries. Such trains and carriages are oriented from the north to the south to satisfy the needs of Russians in sea-side recreation, whereas transit international passenger railway direct carriages, going beyond the limits of Ukraine, predominantly have east-west orientation.

Terminal stations of the routes of international passenger railway trains of internal makeup within the limits of Ukraine are located in 20 cities, 15 of which are the capitals of administrative units of the first level.

Eastward orientation dominates in international passenger railway communication in Ukraine. In this direction 4.7 times more trains pass, than westwards. Only four cities of the country are the terminal stations, from which such trains depart in the western direction, whereas eastward directed trains depart from 20 Ukrainian cities. As a consequence of the effect of historical inertia, all Ukrainian metropolises have passenger railway communication mainly with Russian cities, especially with Moscow.

We have discovered the following consistent pattern of international passenger railway communication's development: the longer the distance that separates Ukraine from a state-object of international passenger communication, the higher is the administrative rank of the city-terminus of this communication. ■

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LANDSCAPE METRICS FROM THE POINT OF VIEW OF MATHEMATICAL LANDSCAPE MORPHOLOGY

ABSTRACT. This paper discusses potential of obtaining answers to key issues related to the use of landscape metrics by applying approaches of mathematical landscape morphology. Mathematical landscape morphology that has emerged in Russia's geography in recent years serves as the basis of the new scientific direction in landscape science. Mathematical landscape morphology deals with quantitative regularities of the development of landscape patterns and methods of mathematical analysis.

The results of the research conducted have demonstrated that landscape metrics are subjected to stochastic laws specific to genetic types of territories; furthermore, these laws may be derived through mathematical analysis. It has been also shown that the informational value of different landscape metrics differs and can be predicted. Finally, some landscape metrics, based on the values derived from single observations, nevertheless allow one to provide assessment of dynamic parameters of existing processes; thus, the volume of repeated monitoring observations could be reduced. Other metrics do not possess this characteristic. All results have been obtained by applying mathematical landscape modeling.

KEY WORDS: landscape metrics, mathematical landscape morphology, landscape pattern, mathematical models.

INTRODUCTION

Nowadays, quantitative parameters that characterize landscape mosaics formed at the Earth's surface are widely used [Vinogradov, 1966; Nikolayev, 1978; Victorov, 1966, 1998; Leitao, et al., 2006; Riitters, et al., 1995, etc.] These parameters are called landscape metrics; earlier in the Russian literature, terms "quantitative indicators of landscape structure of the territory" were used [Ivashutin and Nikolayev, 1969; Nikolayev, 1975; etc.]. Currently, a large number of such parameters exist both in literature [Victorov, 1998; Leitao, et al., 2006] and in software tools for analysis of mosaics [McGarigal, et al., 2002; Pshenichnikov, 2003]. Furthermore, the number of possible metrics is infinite. Finding new metrics is precisely the direction that the efforts of many researchers are focused.

Landscape metrics are used in a variety of geographic tasks – in landscape analysis and planning, definition of geological conditions, analysis of changes in the environment, risk assessment, and in other areas [Nikolaev, 1975; Leitao, et al., 2006; Riitters, et al., 1995; Victorov, 2005a, b; Moser, et al., 2007; etc.]. At the same time, undertaken studies have omitted a number of important issues related to landscape metrics. These are:

- Are the values of landscape metrics subjected to any laws and can we predict them?

- What is the relative informational value of different landscape metrics and of their combinations?
- To what extent do landscape metrics reflect the dynamics of landscape structure of the territory?

The answers to these questions are crucial because they determine the effectiveness of landscape metrics in addressing problems of landscape planning, of defining geological conditions, and of environmental monitoring.

RESEARCH METHODS

The modern level of landscape science provides solution to these issues on the exact theoretical basis. Mathematical landscape morphology that has emerged in Russia's geography in recent years serves as the basis of the new scientific direction in landscape science [Victorov, 1998, 2006; Victorov and Trapeznikova, 2000; Kapralova, 2007]. Mathematical landscape morphology deals with quantitative regularities of the development of landscape patterns and methods of mathematical analysis. The object of study is a landscape pattern (morphological structure), i.e., the spatial mosaic formed on the surface by the areas corresponding to the natural-territorial complexes developed in this territory.

One of the main outcomes of the mathematical landscape morphology is mathematical models of landscape patterns [Victorov, 1998, 2006]. A mathematical model of a landscape pattern based on existing models is the theory of stochastic processes and is a collection of mathematical relationships that reflect the landscape's most important geometric properties. A special role is played by the so-called canonical mathematical models of landscape patterns. The canonical mathematical models of the morphological structures of a particular genetic type are the mathematical models of the morphological structures formed under the impact of one process under homogeneous

physiographic conditions, i.e., the models of simple landscape patterns. The requirement of uniformity includes absence, in the area, of faults, buried hollows, abrupt changes in chemical composition of surface sediments, etc., but at the same time does not limit composition and amount of rainfall, temperature, etc. Thus, a canonical mathematical model of morphological structures represents such elements that can be used to create a mathematical model of a landscape pattern anywhere. For example, to date, there have been established canonical mathematical models of morphological structures of alluvial plains, of plains with the development of karst, of subsidence-suffusion processes, of erosion plains, etc. [Victorov, 2006].

The method of mathematical landscape morphology is based on the fact that equations of mathematical models are valid for the same genetic type of landscape in a very wide range of physical and geographical conditions (composition of deposits, sediments, age, etc.). This remarkable stability is explained by similarities of features in the course of the main processes (erosion, karst, etc.) in different natural conditions and has been noticed previously in a qualitative form as the phenomenon of isomorphism of landscape patterns [Nikolaev, 1975]. Due to this property specifically, mathematical models of landscape patterns can be created without reference to a specific composition of sediments, precipitation, etc., for the territory of a given genetic type; specific conditions only affect the values of parameters in the model.

Mathematical models of complex morphological structures can be obtained theoretically on the basis of canonical models.

ANALYSIS OF RESULTS

The usage of mathematical models of landscape patterns provides answers to the aforementioned key issues of landscape metrics application.

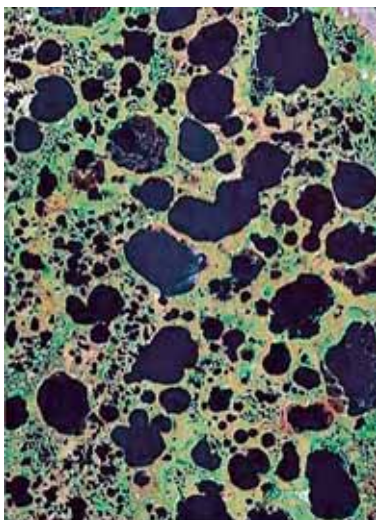


Fig. 1. A typical representation of the landscape pattern of thermokarst-lake plains on satellite imagery (West Siberia)

Values calculated from different metrics depend on their properties. However, little is known about whether parameters of landscape metrics are subjected to any laws and whether it is possible to forecast these parameters. Using mathematical models of landscape patterns allows one to predict what laws will govern the value of one or another landscape metric. We will demonstrate this by using the example of such a widespread metric as the area of the contour of a lake on a thermokarst-lake plain.

Let us consider the area of a thermokarst-lake plain uniform in soil and geomorphological conditions. The test area has a low-hilly sub-horizontal surface with the predominance of tundra vegetation (cotton-grass tundra, sedge-cotton-grass tundra, etc.) and with interspersed thermokarst lakes (Fig. 1). Lakes are isometric, frequently round in shape, and are randomly scattered over the plain.

The model can be based on the following assumptions:

1. The process of formation of the primary depressions is probabilistic and occurs independently in non-intersecting areas;

2. Thermokarst depressions generation occurs simultaneously; the likelihood of the formation of one depression in the test area depends only on its size (Δs) and it is much greater than the likelihood of the formation of multiple depressions, that is,

$$p_1 = \mu \Delta s + o(\Delta s) \quad (1)$$

where μ is the average number of depressions per unit area;

3. The growth of the radii of lakes due to thermoabrasive impact occurs independently of each other, it is directly proportional to the amount of heat in the lake, and it is inversely proportional to the lateral surface area of the lake basin;

4. The depth of the lake is proportional to the radius.

The first assumptions seem natural, as derived from the homogeneity of the study area, and reflect the relative rarity of thermokarst depressions. The third assumption comes from the fact that the thermal effect is proportional to the heat flow through unit surface area. Finally, the fourth assumption reflects the fact that, along with increasing diameter of the lake, there is vertical thawing, though slow (this notion can substituted with the assumption of a constant depth).

The foundation of the model compiled allows one, through rigorous mathematical analysis of the assumptions, to arrive at the laws for such a widespread metric, as the area of the contour of a thermokarst lake on a thermokarst plain. It is possible to demonstrate that lognormal distribution of a thermokarst lake's radius follows strictly from the model assumptions [Victorov, 2006]. Since the logarithm of the lake area and the logarithm of its radius are in linear relation, it follows that the area of the lake will also be subjected to the lognormal distribution, i.e., for the density distribution of the lakes areas at any time (t) over the course of development of the site it is true

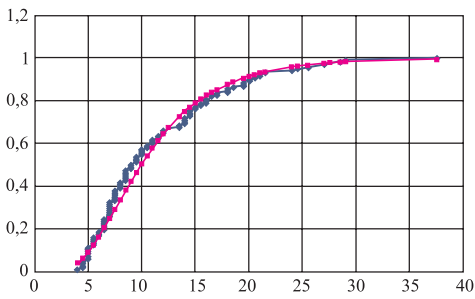


Fig. 2. An example of the comparison of the theoretical lognormal (magenta) and of the empirical (dark blue) distribution of the area of the thermokarst lakes (the experimental site)

$$f_s(x, t) = \frac{1}{\sqrt{2\pi}\sigma x\sqrt{t}} e^{-\frac{(\ln x - at)^2}{2\sigma^2 t}} \quad (3)$$

where a , σ are the model parameters.

The conclusion has been empirically validated in real measurements based on remote sensing surveys for the sites in West Siberia, Alaska, and other areas [Victorov, 1995, 2006; Kapralova 2008 (Fig. 2).

Thus, although each lake area has its own value, their combination is subjected to a certain stochastic pattern; this pattern was obtained by mathematical analysis of the model. In general, we can conclude that the use of the mathematical landscape morphology approach to predict landscape behavior allowed forecasting values of landscape metrics for homogeneous physiographic conditions for the areas of thermokarst-lake plains. The type of distribution is lognormal and remains constant; the values of the distribution parameters vary depending on the specific physical and geographical conditions of each site.

Another key issue of development of the theory of landscape metrics is the relative informational content of different landscape metrics and of their combinations in problem solution. Typically, a researcher does not entertain the question and uses more or less suitable metrics contained in the well-known software tools and references [McGarigal, et al., 2002; Leitao, et al., 2006; etc.]. However, the analysis shows that, if

some of the metrics are interrelated, sharing them is not rational, because it does not add information – a metric automatically confirms the differences identified by the other metrics. The interconnectedness of the metrics most often is not visible in advance and its detection is one of the main problems of using landscape metrics.

Approaches of mathematical landscape morphology can reveal hidden, at first glance, relationships of landscape metrics and, thus, evaluate their joint informational content. We will demonstrate this by the assessment of the joint informational content of three landscape metrics:

- the average area of a contour,
- the density of contours, and
- the share of the area under one type of contours.

Let us evaluate interrelationships of these metrics for a plain territory with the dominance of karst and subsidence-suffusion processes. Such territories develop in homogenous geological and geomorphological conditions and usually represent homogeneous landscape background with randomly scattered subsidings and rounded suffusion (or karst) depressions (Fig. 3).

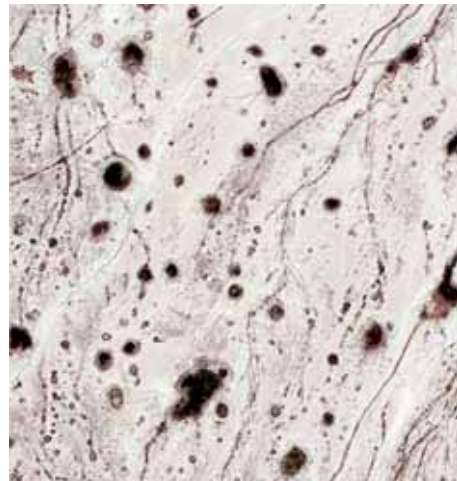


Fig. 3. A typical representation of a landscape pattern of the plains with subsidence-suffusion processes on satellite imagery (the foothill plain of Kopet-Dag)

The task of assessment of metrics relationships was solved not only for the genetic types of the territories, but also for a wide class of dangerous geological processes, with the centers of circular shapes, on the basis of mathematical models of landscape patterns. The assessment was based on the fact that processes prevalence, expressed by the average share of land area occupied by the centers of subsidence-suffusion processes, is equal to the probability of a point, randomly selected on a site of being within the limits of the center of the process. This, in turn, is a problem of the probability of subsidence-suffusion processes impact on small-size structures. According to the obtained solution for this problem [Victorov 2007b; Victorov, 2006], the following relation describes the impact:

$$P_d = 1 - e^{-\mu\bar{s}} \quad (4)$$

where μ is the mean density of the depressions locations; \bar{s} is the average area of the depressions. The outcome has been subjected to the primary empirical test (Table).

Thus, the three metrics analyzed are in a hidden relationship, described by the expression provided above. Consequently,

the use of the third metric (processes prevalence) does not add additional information for the mean density of the depressions locations and their average area. We emphasize that the evaluation of the informational content of the metrics has been conducted by the theoretical means; the experimental data have only confirmed the findings. The forecast of the relationships has been done using the models of landscape patterns.

One of the key questions in the theory of landscape metrics is the following: the extent to which landscape metrics reflect the dynamics of the landscape structure of the territory.

Let us examine this issue using the example of the plains dominated by thermokarst processes. Referring to the analysis presented above, it is easy to see that, for the thermokarst-lake plains, the average area of thermokarst lakes increases, reflecting the general dynamics of the landscape due to the degradation of permafrost on the edges of thermokarst lakes. However, let us consider the development of erosion-thermokarst plains in a situation where continued generation of new centers of thermokarst occurs.

The comparison between theoretical dependence of m1, m2, and m3 metrics and the empirical data

Locations of the test sites	Metric 1 (average density of depressions) km ⁻²	Metric 2 (average area of depressions) km ²	Metric 3 (processes prevalence)	
			Empirical values	Theoretical values
Turgai tableland (southern part)	0.111	0.820	0.106	0.087
Caspian lowland	1388.889	0.0002	0.209	0.188
Baraba steppe	0.899	0.307	0.198	0.241
Caspian lowland	11.364	0.008	0.070	0.090
Foothill plain of Kopet-Dag	81.439	0.001	0.053	0.073
Russian plain (Belarus)	148.448	0.002	0.250	0.224
West Siberia (South)	0.272	0.434	0.093	0.111
Turgai tableland (northern part)	0.364	0.354	0.053	0.129

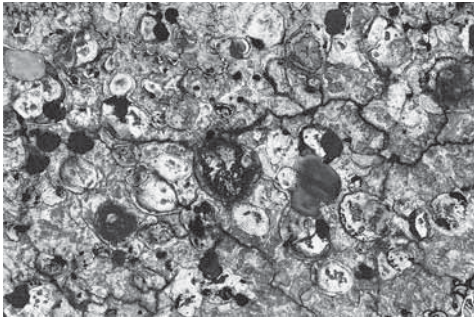


Fig. 4. A typical representation of the landscape pattern of erosion and thermokarst plains on satellite imagery

The test area has a low-hilly sub-horizontal surface with the predominance of tundra vegetation (cotton-grass tundra, sedge-cotton-grass tundra, etc.), which is interspersed with lakes and hasyreis and with infrequent erosion network. Lakes are isometric, frequently round in shape, and are randomly scattered over the plain. Hasyreis are flat depressions, also of isometric form, occupied with the meadow or marsh vegetation and, similar to the lakes, located on a plain in a random pattern (Fig. 4).

The basic assumptions of the model of the morphological structure of erosion and thermokarst plains satisfy the model of the thermokarst-lake plains presented above in the first positions, but are supplemented by two further assumptions that describe the interaction of thermokarst and erosion processes:

4. In the process of growth, a lake can transition to a hasyrei if it is drained by the erosion network; the probability of this even is independent of the other lakes; with it, the growth of the lake is terminated;

5. The location of the sources of erosion forms on a randomly selected site is a random event and its probability is proportional to the size of this site.

Also, the first assumption is modified, given the situation of a constant generation of new thermokarst lakes.

Thermokarst depressions generation is a random process; the likelihood of the formation of one depression on the test sites is independent and depends only on the area of the site (Δs) and the considered time interval (Δt); it is much greater than the likelihood of the formation of multiple depressions; that is,

$$p_1 = \lambda \Delta s \Delta t + o(\Delta s \Delta t) \quad (5)$$

where λ is the average number of depressions that occur per unit area per unit time.

The complexity of analyzing the dynamics of this area is associated with the fact that there are two opposing trends on the site: the growth and the formation of new lakes on the one hand, and disappearance of lakes due to drainage through erosion processes and their transition to hasyreis, on the other hand. What is the dynamics of the territory after a considerable time?

Mathematical analysis of the model allows us to demonstrate [Victorov 2005b], that after a considerable time in a wide range of conditions on erosion-thermokarst plains, the dynamic equilibrium in the processes of generation of thermokarst lakes and their transformation to hasyreis is established. This dynamic equilibrium is characterized by the following dependencies in the morphological structure of erosion-thermokarst plains:

the density of the radii distribution of thermokarst lakes

$$f(x, \infty) = \frac{2}{x \text{Ei}(-\pi\gamma)} e^{-\pi x^2}, \quad x > 1, \quad (6)$$

the average density of the locations of lakes

$$\eta(\infty) = -\frac{1}{2a} \text{Ei}(-\pi\gamma) \quad (7)$$

the average area of a lake

$$\bar{s}(\infty) = -\frac{1}{\gamma \text{Ei}(-\pi\gamma)} e^{-\pi\gamma} \quad (8)$$

the level of the processes prevalence, taking into account the incidence of thermokarst depressions generation, the growth of lakes, and their transformation into hasyreis

$$P_i(\infty) = 1 - \exp\left(-\frac{\lambda}{2a\gamma} e^{-\pi\gamma}\right) \quad (9)$$

the distribution of hasyreis radii

$$F_h(x, \infty) = 1 - e^{-\pi\gamma x^2} \quad (10)$$

where γ is the average density of the locations of the sources of erosion forms; a , σ are the model parameters; $Ei(x)$ is the integral exponential function.

The findings obtained have also been subjected to the empirical test, which is shown in Fig. 5.

Thus, the analysis shows that such landscape metrics as the average area, density of locations, and share of the area of thermokarst lakes on erosion-thermokarst plains do not reflect the dynamics of the area. The reason is the state of the dynamic equilibrium with local changes (possibly intense) when the overall parameters remain constant and, thus, are not suitable for trend analysis.

The problem of capturing the dynamics of landscape metrics has another very interesting aspect. Above, we have discussed

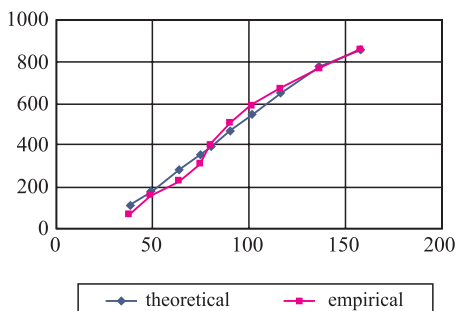


Fig. 5. The correspondence between the theoretical and empirical size distribution of the hasyreis (a part of the Yamburgskoye Gas condensate field)

the question of controlling the dynamics of the territory by recalculating the values of the metrics over time. One may ask whether the values of landscape metrics *obtained at a single point of time* can carry information about the characteristics of the dynamics of the territory (the rate of development, the relationship of the rates, the probability of change, the duration of stages and their relation to each other, etc.). Such a formulation is of great practical importance, since it can dramatically reduce time-consuming stationary observations in predictions.

Let us examine this question using an example of the landscape of alluvial plains. The principal elements of alluvial plains are oxbow (ancient oxbow) depressions and former riverbed elevations. The depressions have an arcuate shape, inherited from the former meanders, and are occupied by lakes, swamps, salt marshes, wetland forest vegetation, and tugai vegetation. The elevations, also of an arcuate shape, are occupied by more xeromorphic systems in accordance with the zonal, climatic, geological, and geomorphological conditions. The elevations and the depressions, adjoining each other, form patches coherent in shape and orientation. The patches of different generations adjoin each other, often "eating" parts of each other and, thus, forming the landscape pattern of the alluvial plains (Fig. 6).

A number of assumptions formed the basis of the mathematical landscape pattern models for the alluvial plains [Victorov, 1998;



Fig. 6. A typical representation of the alluvial plain on satellite imagery

2006], of which the most important for the solution of this task are:

The probability of the straightening of the bend over a certain time-interval depends on the duration of this interval and does not depend on the behavior of other bends;

$$p_d = \lambda \Delta t + o(\Delta t) \quad (11)$$

where λ is the parameter; the probability of more than one straightening over a short time-interval is much smaller than the probability of a single one.

The formation of ridges occurs isochronously with the period φ .

The correctness of the model may be verified by validating the conclusion on the distribution of patch arrows¹. The analysis of the model implies that the distribution of the cycle of the development of the bend and, correspondingly, the size of the patch in the direction perpendicular to the chord (i.e., the arrow) must meet the exponential distribution. This conclusion considers the fact that the straightening of the bend occurs repeatedly and that is why each younger patch "erases" the corresponding part of the preceding patch or the entire patch (Viktorov, 2007a). Several consecutive patches can be erased completely.

This conclusion was validated by processing remote sensing data for the alluvial sites of the valleys of the rivers Vakh and Taz. Satellite images of 5-m and 15-m resolution were georeferenced using GIS MapInfo. The arrows of the fragments of the patches were drawn reflected their size. The arrows in the young developing patches were drawn as a perpendicular between the patch base (a straight line) and the parallel line tangent to the top of the patch. The arrows in the fragments of the old patches were drawn as a perpendicular between the line tangent to the top of the arc of the fragment base

and the parallel line tangent to the top of the arc that delimited the patch fragment on the outside. In some cases, there were difficulties associated with the erasure of the side parts of the fragments due to the shift of the channel, but in general, despite these uncertainties, in most cases, it was possible to draw the arrows. Adjacent fragments of the patches were isolated on the basis of angular unconformities.

The curves of the empirical distributions were constructed from the measurements results:

- the size of the young growing patches;
- the size of the entire set of the patches.

Further, the average values for the samples was determined and the empirical distributions were compared with the theoretical exponential distribution with the shift, according to the results obtained. The use of the distributions with the shift was connected with the fact that the analysis of the images showed fragments of the patches consisting of at least two ridges and one inter-ridge depression; there were no fragments consisting of one ridge only. The comparison (Fig. 7) shows that the results of the model are supported by the empirical data by both the relationship of distribution curves and the Pearson criterion at a significance level of 0.95. However, more reliable results are obtained when applying the criterion for the sample-size of more than 50.

The use of the obtained conclusion on the distribution of the duration of the cycle of development of the bend allows obtaining the distribution of the number of ridges in the patch. Considering steady generation of the ridges in time, it is possible to see that it is described by the expression

$$P_v(m) = e^{-m \frac{\varphi}{\mu}} \left(1 - e^{-\frac{\varphi}{\mu}} \right) \quad (12)$$

where φ is the average period of the formation of a ridge; μ is the average duration of the formation of the bend.

¹ By analogy with the rise of an arc, which is the line perpendicular to the chord that goes from the center to the apex of the arc.

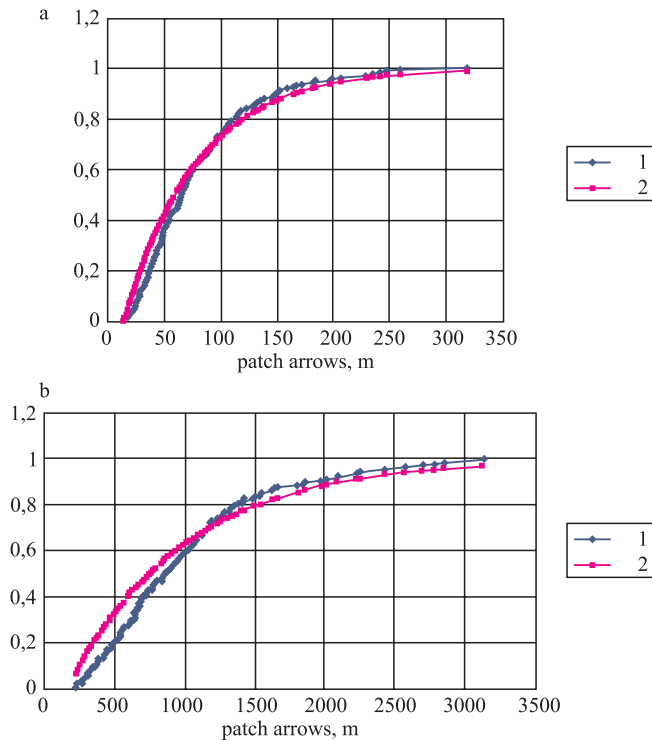


Fig. 7. The comparison of the experimental curve of the distribution of the sizes of the arrows of the preserved fragment of the formed patch (1) and of the theoretical curve of the exponential distribution with a shift (2) for the areas of the alluvial plains of Western Siberia:

a – the valley of the river Vakh; b – the valley of the river Taz

It follows that the average number of the ridges in the patch may be given by the expression

$$\bar{v} = -\frac{e^{-\frac{\varphi}{\mu}}}{1 - e^{-\frac{\varphi}{\mu}}}. \quad (13)$$

The latter expression makes it possible to obtain the value for the dynamic parameter, which is the ratio between the period of the straightening of the bend and the period of the formation of the ridge

$$\frac{\varphi}{\mu} = \ln\left(1 + \frac{1}{\bar{v}}\right). \quad (14)$$

Thus, the dynamic parameter of the alluvial plains that describes the relation between the period of the bend straightening and the period of ridge formation may be defined by using such landscape metric as the average number of ridges in the patch. We emphasize that the metrics values are determined from a single period of observations.

CONCLUSIONS

Thus, this study suggests the following conclusions.

The values of landscape metrics are subjected to stochastic patterns specific to each landscape.

The joint informational content of various combinations of landscape metrics varies and can be predicted.

Landscape metrics in different landscapes reflect their dynamics to varying degrees and this can be forecasted; the values of some landscape metrics obtained for one period, however, reflect temporal parameters of the landscape dynamics of the area.

The key issues in the use of landscape metrics can be addressed using theoretical approaches based on mathematical landscape morphology. ■

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THE INFLUENCE OF CHANGING CLIMATE AND GEOCRYOLOGICAL CONDITIONS ON THE REGIME OF REGIONAL DISCHARGE AND ICING IN THE UPPER PART OF LENA RIVER'S BASIN

ABSTRACT. Using the balance method authors showed for the case of 1990 that the reaction of the river discharge on the climate change is different in the regions with continuous and sporadic permafrost extent. In mountain with continuous permafrost extent the climate warming has no strong influence on the river discharge but affects on the ice-mounds' volume. In case of sporadic permafrost extent the decreasing of permafrost area to 30% leads to decreasing of snow-melting overflow up to 38%. Also the period of the flood became longer because the underground storage increasing that takes away the precipitation, snow-melting and condensation water from surface discharge.

KEY WORDS: permafrost, underground water, river run-off, climate change, numerical simulation.

INTRODUCTION

The climatic and hydrologic regimes of Arctic and Subarctic rivers are strongly impacted by the permafrost distribution within their watersheds. Rivers that collect their waters entirely from watersheds with continuous permafrost distribution (i.e. permafrost is everywhere, drastically limiting the influence of groundwater in the water balance), such as the Kuparuk and Colville Rivers in Alaska or the Yana and Indigirka Rivers in East Siberia, practically cease their discharge into the Arctic Ocean during the winter. In contrast, the larger arctic rivers, which extend their watersheds into the regions with discontinuous permafrost or even into the permafrost-free areas (Ob', Yenisei, Lena, Mackenzie), continue to discharge a significant amount of water into the Arctic Ocean during the entire winter. Moreover, the ratio of "winter" to "summer" discharge decrease among

the Great Siberian Rivers (Ob', Yenisei, Lena) accordingly to the extend of permafrost in their watersheds [Savelieva et al., 2001].

Based on this observation, it becomes obvious that the seasonality in the arctic river discharge can change significantly with a warmer climate. The predicted warming in this century will be significant enough to start the permafrost degradation in many areas in the Northern Hemisphere [Anisimov et al., 2001; Sazonova et al., 2001]. Degradation of permafrost will significantly change the permafrost spatial extent and can affect its vertical thickness. As a result, conditions of groundwater recharge, flow, discharge and storage will be altered considerably, increasing the role of subsurface flow in the water balance. Altogether, it will change the seasonality of the arctic river discharge into the Arctic Ocean, increasing winter flow, it will probably increase the total discharge as well. We already see the changes. With practically no increase in precipitation over the Siberian river watersheds [Savelieva et al., 2000 and 2001], there was observed a slight increase in these rivers total discharge during the last three decades and, most importantly, this increase is much more noticeable during the winter months [Savelieva et al., 2000 and 2001]. During winter, all other sources of river discharge but groundwater accumulated in unfrozen zones within permafrost (taliks) are locked in temporary storage as snow or ice. Taking into account the observed increase in permafrost temperatures in Siberia over the same period of time [Pavlov, 1994; Romanovsky et al., 2001a and 2001b], the most reasonable explanation of changes in the winter river discharge is the permafrost dynamics within the Siberian river watersheds and especially in the upper parts of their basins where permafrost is the warmest and already discontinuous.

An increase in thickness of the active layer (the layer of soil above the permafrost that experiences thawing every summer) alone cannot explain the observed increase in the winter discharge. Though the active layer dynamics can explain changes in

stream recessions in the Arctic and Subarctic [Dingman, 1973; McNamara et al., 1998], the effect of increased active layer thickness on winter river discharge is minimal. Even within discontinuous permafrost the active layer freeze-up is usually complete by the end of January. In the continuous permafrost zone the complete freeze-up occurs in late October – November [Romanovsky and Osterkamp, 1995 and 2000; Osterkamp and Romanovsky, 1997]. As numerous data from the permafrost research in Siberia show, long before this time, about two to three weeks after onset of the freezing, the excess groundwater in the active layer on slopes drains away completely [Romanovskiy, 1983]. The active layer within the flat surfaces in uplands, river terraces, and floodplains continues to hold a significant amount of groundwater until its complete freeze-up. However, this water does not contribute significantly to the streamflow and freezes in the active layer with some small local redistribution. Any natural increase in the base flow of the arctic rivers in the late winter and early spring (before snowmelt started) should be related to changes in subsurface flow and storage volume in the talik zones within the permafrost.

The most dramatic changes in subsurface flow occur when permafrost starts to thaw from its surface and the active layer fails to freeze back completely (in this case a talik will be formed over the permafrost) [Kane, 1997]. However, significant changes in subsurface storage and flow could happen even without widespread permafrost degradation. Relatively small increases in the size of the inter-permafrost taliks, which are usually related to the fractured tectonics zones [Romanovsky and Afanasenko, 1980; Romanovsky and Romanovskiy, 1984] or to the layers of coarse-grained sediments with increased hydraulic conductivity, will lead to significant changes in subsurface flow and storage with subsequent changes in river discharge, especially in its seasonality. These changes will be the most noticeable in the uplands and mountain regions in the upper parts of the northern rivers where all thermal

subsurface processes are coupled very tightly with subsurface water movements (subsurface hydrology or hydrogeology) and where the permafrost is the most dynamic.

It is obvious from the previous discussion that some very important processes are already happening in the “Hydrology-Hydrogeology-Permafrost” system in Siberia, resulting in unexplained increases in the Siberian river discharge (especially its winter component). In an attempt to properly describe the arctic river discharge into the Arctic Ocean (especially its seasonality), the Regional and Pan-Arctic Hydrological models have to take into account changes in subsurface storage, fluxes, and changes in partitioning of water movement between surface (or near-surface) and deeper subsurface flow. In other words, these models have to include the permafrost-hydrogeological conditions and changes in these conditions that will occur as a result of climate warming and permafrost degradation.

The overall goal of the proposed research is to obtain a deeper understanding of coupled thermal and hydrogeological processes of heat and water exchange within different permafrost zones along the Lena River and to use this understanding for prediction of changes in arctic river discharge into the Arctic Ocean as a result of climate warming and permafrost degradation.

This investigation will be based on analysis, synthesis, and integration of the existing data on the Lena River hydrology and available permafrost dynamics data within the Lena River basin. In addition, extensive field studies will be conducted to quantify changes in hydrological and permafrost regimes during the last 100 years. Remote sensing studies will be applied to detect geomorphological changes that may be attributed to degradation of permafrost (thermokarst) or changes in ground water dynamics (icing formation and extent). Intensive use of physically based two- and three-dimensional coupled permafrost-hydrogeological numerical models for

sensitivity analysis and for predictions of permafrost-hydrogeological system dynamics will be the key methods employed to achieve this goal. Field research, including application of geophysical methods, will be also performed to obtain specific permafrost-hydrogeological information for the specific sites. This information will be used as input data for our numerical modeling. Image analyses will provide key input parameters for model initiation and verification.

To accomplish this goal there are four possible perspective objectives to meet:

1. Developing the physically based numerical models of ground water recharge/discharge, and subsurface flow and storage in the permafrost affected hydrostratigraphic units at typical locations within the principal parts of Lena River basin.
2. Estimate the two- and three-dimensional permafrost dynamics within these units as a response to climate change during the 21st century.
3. Assess the effect of these changes in permafrost characteristics on the hydrology and hydrogeology within the Lena River basin and as a result on the Lena River discharge patterns.
4. Assess and quantify the impact of these changes across Siberia and throughout the Arctic.

RELIEF, GEOLOGICAL AND PERMAFROST CONDITIONS

The areas of investigation are located at the upper part of Lena Basin on the Chulman River (the tributary of Aldan River with the area 3840 km²) and Chara River (the tributary of Olyokma River with the area 4150 km²). The head water of Chulman River is located in the Stanovoy Ridge and the middle part of the stream cross the middle part of Mesozoic Chulman Depression. This territory is well studied by hydrogeologists and permafrost scientists.

The permafrost here is discontinuous [Fotiev, 1965; Southern Yakutia, 1975, pp. 291–311]. The Chulman Depression as tectonic region has a plateau relief with the typical heights above sea level from 150 m (valleys) to 950 m (watershed divides). The watershed divides are wide and have the flat shape. The slopes are steep (10–20°). The permafrost exists on the lower part of the slopes and on the bottoms of valleys. The flat watershed divide are the area of infiltration of atmospheric precipitation. In winter the deep seasonal cooling of the rocks takes place here (up to 5 m depth).

Chara River has the sources in Kodar and Udokan Ridges with ancient crystalline rocks. Kodar Ridge has the alpine relief with up to 2999 m altitude and living glaciation. Udokan Ridge has the smooth bald mountain relief with up to 2174 m altitude. The upper part of Chara Basin is located in Chara Rift Depression that has the 40 km width. Here the permafrost is continuous.

METEOROLOGICAL AND HYDROLOGICAL CONDITIONS

The comparison of long term tendencies of meteo- and hydrological characteristics showed the difference between Chara's and Chulman's basins. In Chulman we saw the opposite trends of the air temperature and precipitation in one hand and the river discharge in the other hand (see Fig. 2a). It's noticeable the synchronism of precipitation's and river discharge's anomalies in several periods (1950–58, 1967–70, 1982–90, or 19 years from 45) and abrupt anomalies' lack of coincidence in the other periods.

In Chara Basin we did not saw the evident trends of precipitation and river discharge despite the similar air temperature warming (see Fig. 2b). The synchronism of anomalies here existed during longer period of time (1957–59, 1963–69, 1972–75, 1979–95, or 25 years from 38).



**Fig. 1. The discharge of open talik pressure water in the valley bottom (Southern Yakutia).
This head water forms the icing in the winter**

METHODS AND ASSUMPTIONS

Authors formed hypothesis that the major ground of the ambiguous river discharge's response to precipitation trend is the underground water dynamics linked with permafrost condition [Vsevoljskiy, Kurinova, 1989]. To estimate the role of permafrost change in the river discharge variation the method of balances was used. We took into account in the balance equation the water amount from melting snow, icing and glacier, the liquid precipitations, the evaporation, regional underground discharge, condensation in the active layer.

Chulman Basin was divided on two parts: plateau (40% of area) and high mountain (60% of area). In 1976 Permafrost Department of Moscow State University drew-up the permafrost map of this region with the scale 1:200 000.

This map helped us calculate the ratio of permafrost and taliks areas. In seventies on the plateaus the permafrost was located at 69% of the territory. In the southern part of Chulman Basin the permafrost occupied 97% of the territory.

Climatic data was obtained from Chulman meteorological station. In the Stanovoy Ridge the amount of precipitation is more up to 1.5 times than in Chulman depression was assumed (no direct data about it).

The magnitude of precipitation did not take in account. Authors assumed that the precipitation water was going without any delay from permafrost areas to the rivers' channels.

However in the plateau surface without permafrost the precipitation water was going to underground space using the zone of high fissuring (tectonic or cryogenic) and was reaching the river bed in the next month that was following the month of precipitation. This assumption was supported by the hydrogeological observations of head water level and discharge dynamics (Fig. 1).

We supposed that all underground water was discharging in the river within each subdivision of the basin, in other words the underground water in Stanovoy Ridge was discharging in rivers within Stanovoy Ridge. Snowfalls was starting in October, 10% of snow was melting in April, consequently 70% – in May, and 20% – in June. Also we supposed that the water from snow melting was flowing as the water from liquid precipitations.

RESULTS AND DISCUSSION

Reconstructed water balance for each month of 1990 was reflected in calculation annual hydrographs (Fig. 2). In Chulman the calculated and real hydrograph showed the noticeable trace difference. That was concerned the time of spring tide and the existing of the second peak of discharging in September (Fig. 2a). We expected that the dynamics of river discharge should be corresponded to precipitation regime but in 1990 it was not show up.

Authors explain this phenomenon by the large underground collectors that adsorb the surplus of atmospheric water. In Chara this difference was not be showed though the amount of the spring tide was be overrated as well as the August's peak and September's discharge was be unappreciated (Fig. 2b). This fact corresponds to continuous permafrost extent in Northern Transbaykalia and low importance of underground discharge in this region.

The maximum of monthly discharge showed the gradual decreasing in long-term aspect (Fig. 3). The regional evaporation in both regions did not show the significant change in the 50-year period. Only in the early seventies this parameter slightly decreased that was compensated later [Berezovskaya et al., 2005].

The change of permafrost extent brings to change the river discharge regime. In Chulman region this link is significant because

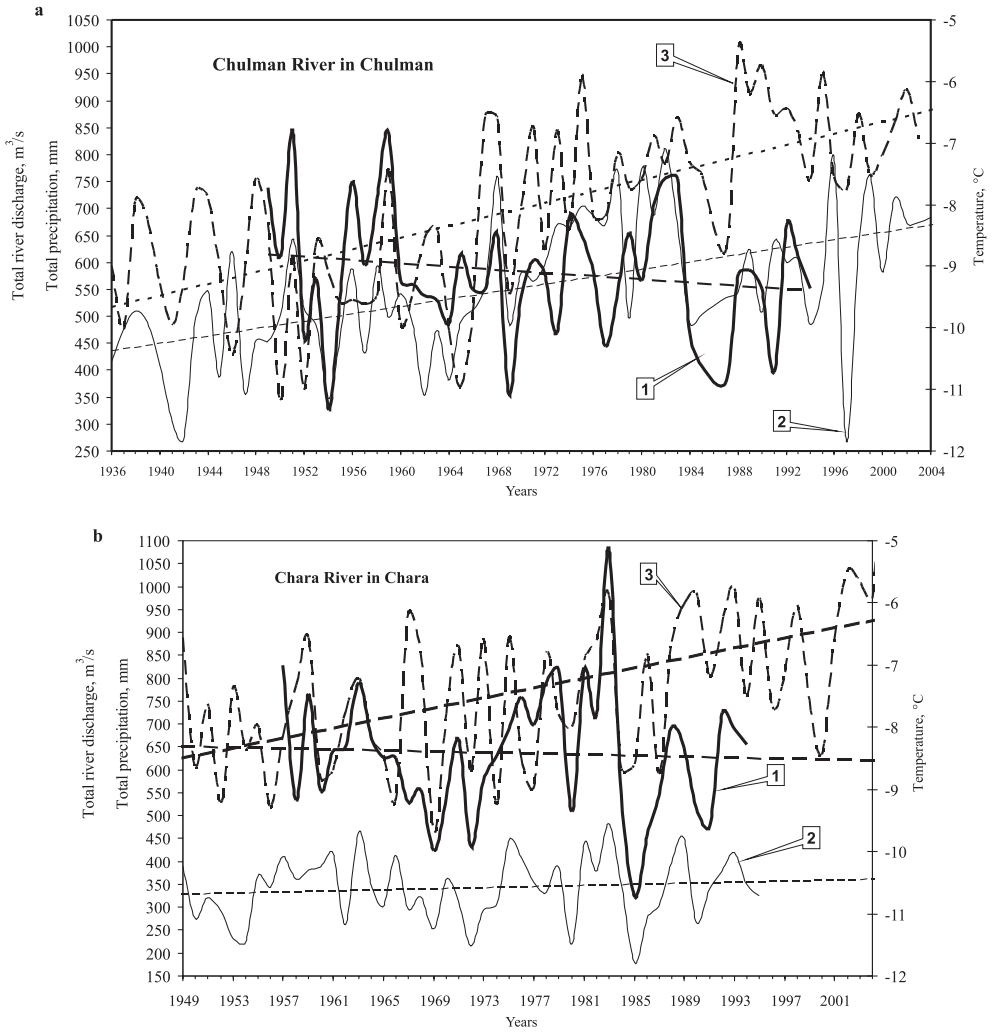


Fig. 2. The dynamics of mean annual values of climate and river discharge characteristics in Chulman (a) and Chara (b):

1 – river discharge (left scale), 2 – precipitation (left scale), 3 – air temperature (right scale)

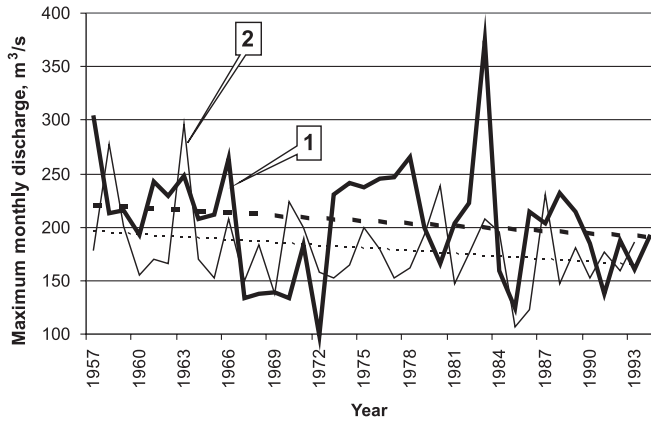


Fig. 3. The dynamics of maximum monthly discharge in Chara (1) and Chulman (2). The dashed lines show the corresponding linear trends

the dependency of water sink areas from permafrost distribution change. In Chara the climate change bring to permafrost temperature shift only because the low regional level of ground temperature (up to $-7 \div -9^{\circ}\text{C}$). In Chulman Region the increasing of talik underground water feeding zones up to 10% brings to decreasing of the peak of river flooding up to 15%. The consecutive increasing of the first one brings to shrinking

of spring tide up to 38% and to prolongation of the flooding to the end of June. The summer-end peak decreased and extended also but did not disappeared completely. These changes were linked with the water flow splitting when the part of atmospheric precipitation goes to underground taliks through watershed divide. If the permafrost extent will increase then the discharge delay will increase too.

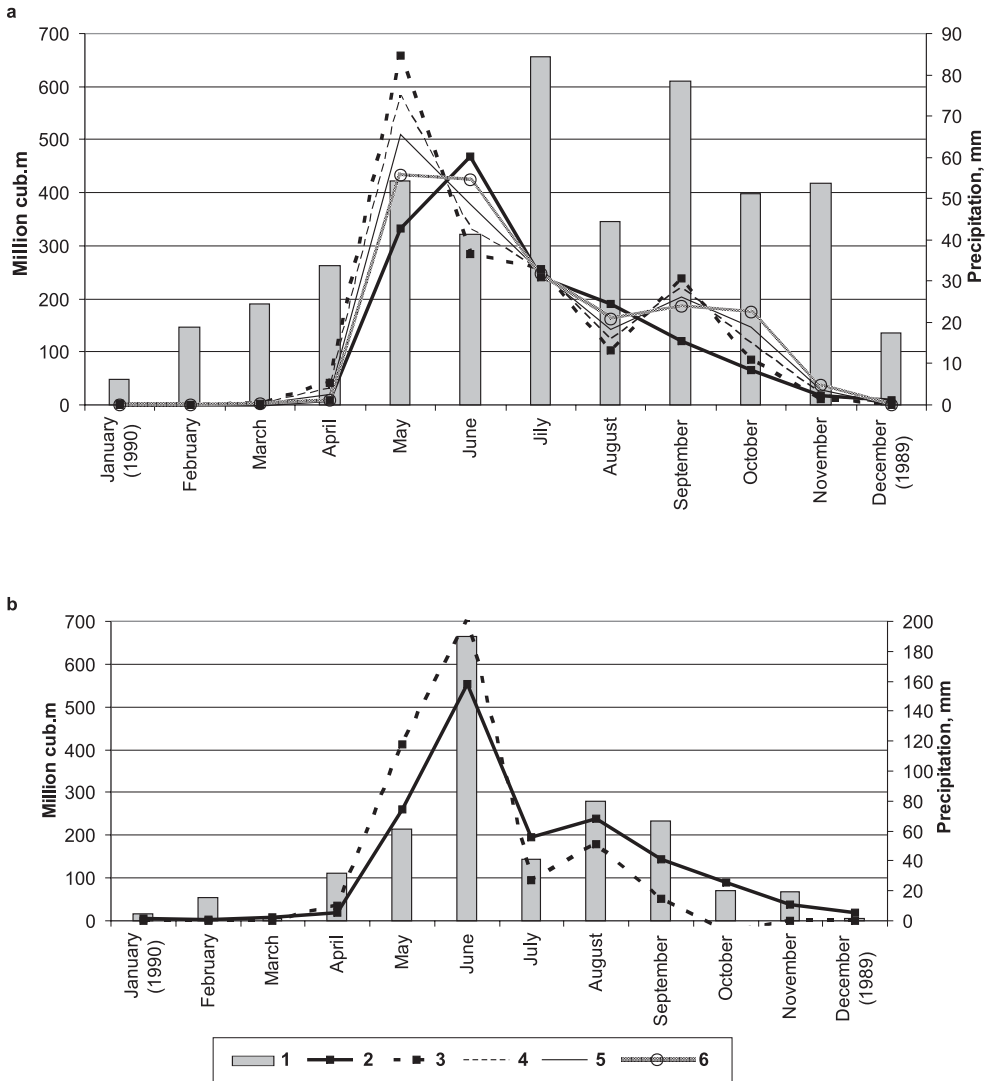


Fig. 4. The comparison of real and calculated river discharge for 1990 in Chulman (a) and Chara (b): 1 – Liquid precipitation equivalent (bar chart, the right scale), 2 – Real river discharge in the river bed (left scale), 3 – Calculated river discharge (left scale), 4 – Calculated river discharge with the talik areas increased up to 10% (left scale), 5 – Calculated river discharge with the talik areas increased up to 20% (left scale), 6 – Calculated river discharge with the talik areas increased up to 30% (left scale)

It is noticeable that the permafrost extent estimation was obtained from old permafrost map (1976). We have no precise data about actual permafrost distribution. So the underestimation of taliks' areas cannot be the cause of the discrepancy between observed and calculated hydrographs of Chulman River. Thus the climate warming brings to enlargement of underground water feeding zones and to increasing of hydrogeological collectors' volume.

In Northern type of cryolithozone (e.g. Northern Transbaykalia, Chara) the permafrost temperatures are low and the volume of talik collectors is less than permafrost massifs' volume. In this case the climate warming influences on local springs' flow-rate, on the volume of underbed river taliks and therefore on the intensity of ice mound formation. The volume of ice mounds in Chara Region was strongly decreased the last 20 years [Shesternyov, Verkhoturov, 2006].

In Southern type of cryolithozone the climate warming influences on the regime of river discharge and brings to softening of river hydrograph shape (Fig. 4a). This phenomenon is linked with the increasing of part of atmospheric water that flows from watershed areas under surface and under permafrost massifs with monthly delay.

CONCLUSION

Using the balance method authors showed for the case of 1990 that the

reaction of the river discharge on the climate change is different in the regions with continuous and sporadic permafrost extent. In mountain in case of continuous permafrost extent the climate warming has no strong influence on the river discharge but affects on the ice-mounds' volume. In case of sporadic permafrost extent the decreasing of permafrost area to 30% leads to decreasing of snow-melting overflow up to 38%. Also the period of the flood became longer because the underground storage increasing that takes away the precipitation, snow-melting and condensation water from superficial discharge.

Practical importance of fulfilled study is evident for the more accurate prediction of hydrological regime of Siberian rivers.

ACKNOWLEDGEMENT

This work was completed with the support of NASA "Current Climate Change over Eastern Siberia and their Impact on Permafrost Landscape, Ecosystem Dynamics, and Hydrological Regime", as well as support of Russian Fund of Basic Research grant 06-05-64959a "The influence of the climate change and geocryological conditions on the regime of regional discharge and icing regime at typical mountain catchments' areas in Lena River's basin". Authors also appreciate S.L.Berezovskaya and M.V.Kasimskaya for the effective helping with data processing and interpretation. ■

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DETECTION AND ASSESSMENT OF ABIOTIC STRESS OF CONIFEROUS LANDSCAPES CAUSED BY URANIUM MINING (USING MULTITEMPORAL HIGH RESOLUTION LANDSAT DATA)

ABSTRACT. Remote sensing have become one of decisive technologies for detection and assessment of abiotic stress situations, such as snowstorms, forest fires, drought, frost, technogenic pollution etc. Present work is aiming at detection and assessment of abiotic stress of coniferous landscapes caused by uranium mining using high resolution satellite data from Landsat. To achieve the aim, ground-based geochemical data and were coupled with the satellite data for two periods, i.e. prior and after uranium mining decommissioning, into a file geodatabase in ArcGIS/ArcInfo 9.2, where spatial analyses were carried out. As a result, weak and very weak relationships were found between the factor of technogenic pollution – Z_c and vegetation indices NDVI, NDWI, MSAVI, TVI, and VCI. The TVI performs better compared to other indices in terms of separability among classes, whereas the NDVI and VCI correlate well than other indices with Z_c .

KEY WORDS: remote sensing, high resolution satellite data, abiotic stress, coniferous landscapes, uranium mining, Landsat.

INTRODUCTION

The importance of remote sensing (RS) is noted in a number of key documents and programs such as Global Monitoring for Environment and Security (GMES) of the European Union (EU), Global Earth Observation System (GEOS), Commission for Earth Observation Satellites (CEOS) and networks for calibration and validation of satellite data and satellite products – (Cal/Val). The importance of RS data for governance is underscored also in several EU framework directives, such as INSPIRE (2007/2/EC), Water Framework Directive (2000/60/EC). Forest resources that are part of the European ecological network of habitats – NATURA 2000, which establishment is based on the directives of the European Union (EU) – Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (the Habitats Directive in brief) and Directive 79/409/EEC on the conservation of wild birds (usually called the birds Directive), are subject to conservation measures and restrictions on anthropogenic loading in order to protect habitats and biodiversity.

The importance of stress situations of forest resources for science and society in Europe is outlined in current COST FP0903 action entitled “Climate Change and Forest Mitigation and Adaptation in Polluted Environment” [About COST, 2011]. As noted by [Franklin, 2001] the criteria and indicators for sustainable forest management prepared by the Food and Agriculture Organization (FAO) of the United Nations (UN), and several national criteria – Canada, Criteria 2 – Element 2.1 “The occurrence of forest disturbances and stress” appear with 8 indicators, which underscore the international importance of monitoring the vegetation stress for sustainable use and conservation of natural resources. In Bulgaria, the adopted National Forest Policy and Strategy “Sustainable Development of Forestry Sector in Bulgaria 2003–2013”, subsequently revised and adopted under name “National Strategy for Sustainable Development of Forestry Sector in Bulgaria 2006–2015”, outlines three strategic actions, i.e. 2, 4 and 5, which define measures for protection of forests affected by various abiotic and biotic stressors.

On an international level several international organizations, such as the International Atomic Energy Agency (IAEA) and European Commission (EC) are dealing with the determination of Threshold Limit Values (TLVs) for human and nonhuman part of the biota, as a reflection of the guidelines set out in their recommendations and regulations and directives. Some countries have already adopted rules to protect the nonhuman part of the biota, such as UK – England and Wales, which requirements for Environmental Impact Assessment (EIA) concerning NATURA 2000 habitats include ionizing radiation. In United States of America (USA), guidelines for the protection of biota and minimum levels of toxicity are given by the USDOE Orders 5400.5 and 450.1.

In the late 90s of the 20th century, problems with acidification of soil and acid rain have led to the emergence of so-called “New forest decline”. For example, as a result of

soil acidification in the Ore Mountains in the Sudetenland area, about 8000 ha has developed Mg deficiency [Omasa, Nouchi et al., 2005]. In Bulgaria the proportion of contaminated soils with heavy metals from industrial plants is approximately 90% of total contaminated land, which are about 1% of the total area of the republic [Stoyanov, 1999]. Contaminated agricultural land with heavy metals and metalloids from industrial activities cover an area of 44,900 ha, 61.3% of them are close to industrial enterprises, of which 8160 ha are contaminated five times the TLVs. The most affected are lands into three to four kilometres off the areas around large industrial sites [Staykova, Naydenova, 2008]. Fires and droughts are other stressful situations, which are quoted using RS methods. With low resolution spectrometers from series EOS-MODIS - TERRA and AQUA, NOAA-AVHRR of National Aeronautics and Space Administration (NASA), Medium Resolution Imaging Spectrometer (MERIS) and the Along-Track Scanning Radiometer (ATSR-1) (ATSR-2) aboard the ERS-1 and ERS-2, Advanced Along-Track Scanning Radiometer (AATSR) on board Envisat of European Space Agency (ESA), and SPOT VEGETATION 1 and 2 on board of SPOT 4 and 5 is made the global monitoring of forest fires and their consequences [Garbuk, Gershenson, 1997; Mardirossian, 2000; Chuvieco, 2008].

The aim of the study is to detect and assess the abiotic stress of coniferous landscapes using High Resolution (HR) Landsat satellite data. The subject of study is coniferous landscapes in Teyna River basin, Novi Iskar Municipality, Sofia-city, Bulgaria.

MATERIALS AND METHODS

Two groups of data have been used to identify the abiotic stress in coniferous plants in the examined regions. The first includes data obtained from independent information sources – field geochemical data, and the second is HR Landsat satellite data.

Field Data

During the ground-based studies conducted in the *Iskra* uranium mining section in 2010 and 2011, the following ground truthing were collected and stored in table.dbf format into a file geodatabase in ArcGIS/ArcCatalog 9.2: 1) GPS measurements; 2) contents of heavy metals and metalloids (Cu, Zn, Pb, Ni, Co, Mn, Cr) and natural and artificial radionuclides (^{235}U , ^{234}Th , ^{226}Ra , ^{40}K) in soils, measured in licensed after the international standards laboratories for the respective elements (Fig. 1). The data collection and sampling scheme is carried out in accordance with Bulgarian Institute for Standardization (BDS) 17.4.5.01 and BDS ISO 18589–2 standards. The content of natural radionuclides is determined by gamma-spectrometric analysis with multichannel analyzer DSA 1000, made by CANBERRA and hyper clean Ge-detector. Analyses were performed in “Accredited Reference Laboratory of Radioecology and

Radioisotope Studies” at the Institute of Soil Science “N. Pushkarov” in accordance with IEC 61452 and ISO 18589–3 [Naydenov, Misheva, et al. 2001].

Satellite data

In order to be able to store, visualize and manage the geospatial information required for the purposes of this study, a raster catalog in a file geodatabase was composed. The raster catalog includes images of Landsat 5 TM from the following years (Table 1).

The data stored in the geo-database of Landsat 5 TM, is in GeoTIFF file format for level of processing – Level 1T (terrain corrected), Level 1Gt (systematic terrain corrected) or Level 1G (systematic corrected). QUICK Atmospheric Correction (QUAC) algorithm was applied on the selected channels in the respective spectral range using the licensed module QUAC in ENVI [ENVI Atmospheric

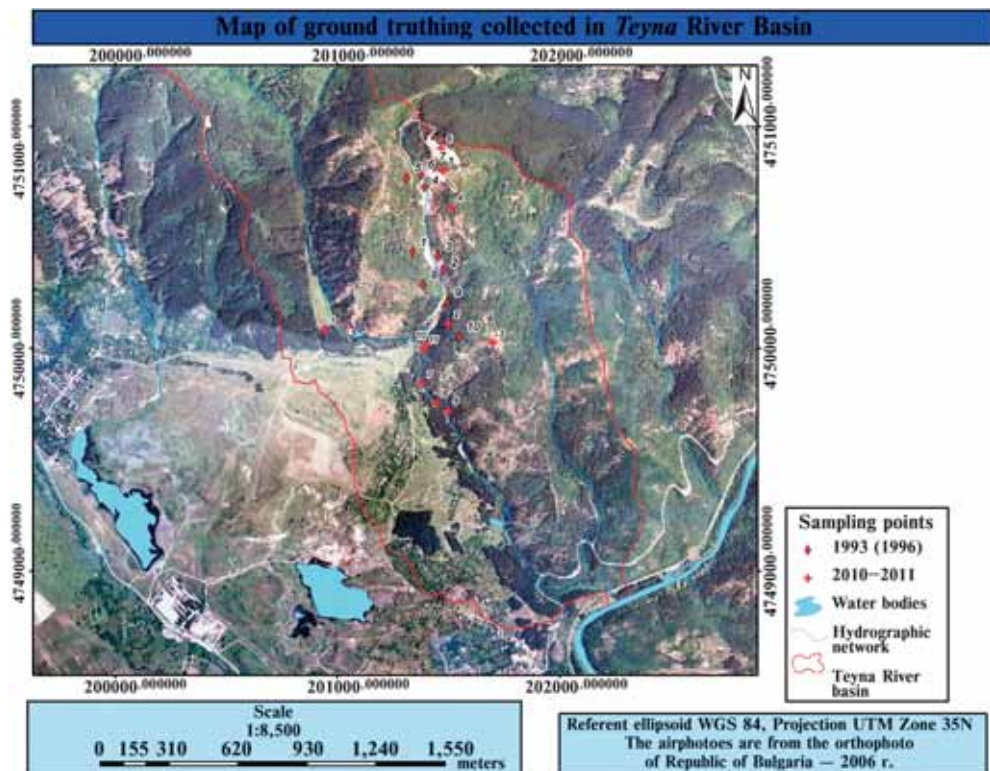


Fig. 1. Map of ground truthing from the catchment area of Teyna River basin

Table 1. List of Landsat images stored into the geo-database

No	Satellite/ radiometer	Date	Solar azimuth	Calibration parameters	Source
1	Landsat 5/TM	11 June 1990	57.07°	In the.MTL file	LPDAAC, USGS
2	Landsat 5/TM	28 June 1991	58.76°	In the.MTL file	LPDAAC, USGS
3	Landsat 5/TM	16 August 2003	53.11°	In the.MTL file	LPDAAC, USGS
4	Landsat 5/TM	23 July 2006	60.18°	In the.MTL file	LPDAAC, USGS
5	Landsat 5/TM	26 July 2007	59.73°	In the.MTL file	LPDAAC, USGS
6	Landsat 5/TM	15 July 2009	60.81°	In the.MTL file	LPDAAC, USGS
7	Landsat 5/TM	3 August 2010	57.69°	In the.MTL file	LPDAAC, USGS
8	Landsat 5/TM	19 June 2011	63.07°	In the.MTL file	LPDAAC, USGS

Correction Module – User’s Guide, 2010]. The satellite data is then subdivided and bundled into two time series, i.e. 1990–1991 and 2003–2011, in order to correlate the respective field measurements and geochemical assessments in 1993 (1996) and 2010–2011 with the satellite data.

Methods

In order to establish the heavy metal and radionuclide pollution distribution fields in the examined study area, the landscape approach is adopted. A Digital Landscape Model (DLM) for the river basin of the Teyna River [Filchev, 2009] was created as a result of the unification of the thematic layers according to the LANMAP methodology [Mücher et al., 2010]: 1) Geology – lithology; 2) Relief – aspect and inclination of the slope, geochemical types of landscapes; 3) Climate – climatic type after the climate classification of Koppen-Kottek, [Kottek et al., 2006]; 4) Vegetation – forest types; 5) Soils – main soil types after the soil classification of the FAO, which comprises 452 elementary landscapes united in 98 landscapes after the linear combination method [Filchev, 2009]. The landscapes of coniferous plants were subsequently extracted and a stratified random sampling was made within them to determine the sample sites [McCoy, 2005]. The assessment of the technogeochemical state for 1993 and 2011

was made using the total contamination factor of technogenic pollution with respect to the background – Z_c [Saet et al., 1990]:

$$Z_c = \sum_{i=1}^n K_c - (n - 1) \quad (1)$$

where K_c is the technogenic concentration coefficient > 1 (or 1.5) representing the ratio of heavy metal and metalloid concentrations and the specific activities of natural radionuclides in surface soil horizon to the background concentrations and specific activities determined for the examined region; and n – the number of chemical elements with $K_c > 1$ (or 1.5).

$$K_c = C/C_{\text{background}} \quad (2)$$

where C is the concentration of the chemical element in the soil sample and $C_{\text{background}}$ is the background concentration. The Z_c index is reclassified according to the following classification system: 1) 0–10; 2) 10–20; 3) 20–30; 4) 30–50; 5) 50–60, and 6) > 60 . The Z_c values above 50–60 are found to indicate technogeochemical pollution [Penin, 1997]. According to previous research carried out by [Filchev & Yordanova, 2011], it is found that the Z_c values are ranging from 3.13 to 129.24 for 1993 (1996), whereas for 2010–2011 the range is: 2.29–32.18, which indicates fourfold decline in Z_c values between two observation

Table 2. Vegetation indices used for detection and assessment of abiotic stress

Vegetation index	Equation	Source
Normalized Difference Vegetation Index (NDVI)	$NDVI = (RNIR - Rred)/(RNIR + Rred)$	Rouse et al., 1974
Normalized Difference Water Index (NDWI)	$NDWI = \frac{(R_{NIR} - R_{SWIR})}{(R_{NIR} + R_{SWIR})}$	Gao, 1996
Modified Soil Adjusted Vegetation Index (MSAVI)	$MSAVI = \frac{1}{2} \left[2R_{800} + 1 - \sqrt{(2R_{800} + 1) - (R_{800} - R_{680})} \right]$	Qi et al., 1994
Triangular Vegetation Index (TVI)	$TVI = \frac{1}{2} \left[120(R_{720} - R_{550}) - 200(R_{670} - R_{550}) \right]$	Broge, Leblanc, 2000

periods. This is attributed to the reclamation and restoration measures for mitigation of the anthropogenic impacts from uranium mining activities.

The estimated vegetation indices from Landsat 5 TM dataset used in this study are presented on (Table 2).

The Vegetation Condition Index (VCI), characterize the vegetation condition using the ratio of the differences between the maximum and the minimum value of NDVI, for a period of observation or a certain phenophase. To monitor the signals of abiotic stress caused by drought a multitemporal NDVI data is derived index of vegetation condition – (VCI) [Kogan, 1987; Seiler, Kogan et al., 1998; Unganai, Kogan, 1998]. The formula for calculating the VCI is:

$$VCI = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (3)$$

The VCI is based on the concept of the ecological potential on natural resources, climate, soil diversity, type and amount of vegetation, and topography of the region [Seiler, Kogan et al., 1998]. Index values range from 0 to extremely adverse conditions to 100 – optimum conditions.

The reclassified thematic layers of Z_c are combined with coniferous landscapes derived from DLM, which new landscapes serve as a

basis for the derivation of descriptive statistics from the classes contaminated coniferous landscapes. This statistics is based on the comparison of classes' polluted landscapes and search for similarities and differences in them. Theoretically constructed classes of polluted landscapes are compared in terms of their separability using the VIs of HR satellite data. Then using hierarchical clustering, groups of values of vegetation indices are analyzed for similarities and differences with the theoretical classes of polluted landscapes. Dendrograms are compiled on the basis of the signatures of classes derived from the multitemporal VIs of Landsat 5 TM. The tool "Dendrogram" in ArcGIS/ArcInfo 9.2 (Academic license) use hierarchical clustering algorithm. The construction of the dendrogram begins with the estimation of distances between each pair of classes from the input signature file and iterative collection of all pairs of classes closest to the outermost. Each iteration is merging classes, based on the updated values of the distances, and the average coefficient of variation. The two approaches for construction of a dendrogram in ArcGIS/ArcMap 9.2 are based on: 1) calculating distances based on the class average, and 2) calculating distances using the mean and variance of the values in each class [ArcGIS Desktop Help, 2008]. For purposes of present work the second approach is chosen, as more reliable, as there is no prior knowledge of the statistical distribution of VIs values within each class. In case of

coincidence of VIs classes with the Z_c classes, correlations and regression model of dose-effect relationships of the values of Z_c and VIs is built.

RESULTS AND DISCUSSIONS

The comparison of data on the current state of the coniferous landscapes is done in by the Landsat satellite data for the years 1990 and 1991 with modelled environmental fields of total contamination factor of tehnogetic pollution- Z_c for the corresponding period of the ground-based measurements of heavy metals and radionuclides – 1993 (1996). The values of NDVI, NDWI, MSAVI, and TVI for the

1990–1991 are presented on, (Table 3). The table shows that the average between the classes 2 and 3 do not differ significantly for NDWI, the NDVI, indices MSAVI-of the order of 0.03–0.02% of the values of. In TVI the difference in the average of the 2nd and 3rd class is of the order of 0.12.

Differences in the standard deviations (SDs) of the previous group are not a quite bigger 0.003–0.008, while in TVI this difference is 0.12. The grouping of classes in their values (s) from one another is presented (Fig. 2).

The 1990–1991 period shows that the average values of NDVI in the Z_c classes

Table 3. Descriptive zonal statistics of classes contaminated landscapes from time series of NDVI, NDWI, MSAVI, TVI (1990-1991).

No	Z _c (classes)	Pixels	Area(m ²)	Min	Max	Range	Average	Standard Deviation (SD)
NDVI								
2	10–20	14	12600	0.524	0.655	0.131	0.576	0.033
3	20–30	16	14400	0.420	0.717	0.297	0.533	0.078
4	30–50	35	31500	0.426	0.660	0.234	0.564	0.060
5	50–60	3	2700	0.458	0.641	0.183	0.568	0.079
NDWI								
2	10–20	14	12600	0.205	0.361	0.155	0.280	0.049
3	20–30	16	14400	0.196	0.408	0.212	0.311	0.048
4	30–50	35	31500	0.183	0.420	0.237	0.306	0.070
5	50–60	3	2700	0.196	0.278	0.082	0.251	0.038
MSAVI								
2	10–20	14	12600	0.687	0.793	0.105	0.730	0.027
3	20–30	16	14400	0.593	0.836	0.243	0.693	0.063
4	30–50	35	31500	0.595	0.798	0.202	0.719	0.052
5	50–60	3	2700	0.627	0.786	0.159	0.725	0.070
TVI								
2	10–20	14	12600	0.673	1.032	0.359	0.907	0.110
3	20–30	16	14400	0.787	1.035	0.248	0.879	0.065
4	30–50	35	31500	–0.236	1.096	1.332	0.819	0.279
5	50–60	3	2700	0.153	1.086	0.933	0.770	0.437

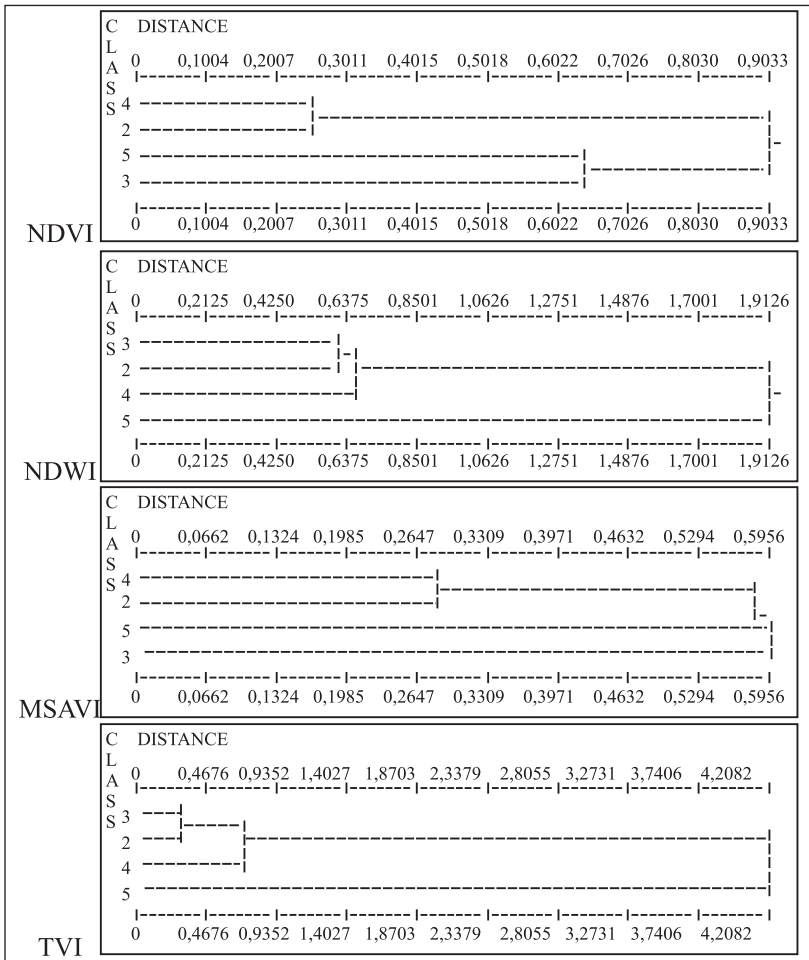


Fig. 2. Dendrograms of zonal statistics extracted from Landsat 5 TM VIs images: NDVI, NDWI, MSAVI, TVI. (1990–1991)

change relatively smoothly in ascending order. The same is for the standard deviation in the class, which is smallest in the 2nd class of relatively uncontaminated landscapes and the highest in the 5th class of technological contaminated landscapes. The grouping of classes of values of NDVI is presented (Fig. 2). The figure shows that hierarchical k-means clustering groups the values of the 4th and 2nd class at a distance of 0.26, 5th and 3rd class at 0.65, and the two merged clusters at 0.90. The grouping on the basis of the average and standard deviation of the groups is not sufficiently reliable method for the separation of the groups, and the reliability of NDVI in the determination of stress in one and two-year multispectral satellite data is

not that large, which affect the speed and timeliness of detection of abiotic stress with the use of this data type.

The spectral vegetation index MSAVI, which is generally a derivative of NDVI with corrections for topsoil reflectance, shows relative stability in ascending and descending order of the classes. The standard deviation oscillates in increasing order of class 2 to class 5.

The grouping of classes is shown in (Fig. 2) that shows that the classes are grouped similarly to the values of NDVI. This is at distances respectively: 0.28, 0.59, and 0.58. The difference in MSAVI in comparison with the NDVI is that the grouping of the 5th and

3rd class is at a relatively large distance, which indicates that they are more easily separable rather than 2nd and 4th class. However, similarly to the NDVI, classes of pollution do not follow the course of an increase in the values, which witnesses for non-linear dependence of stress effects caused by pollution with heavy metals, metalloids, and radionuclides or non-enforceability of the MSAVI, as an indicator of stressful situations.

In the NDWI average values also increase relatively slowly, along with some of the increase of the SD with the increase of pollution, from class 2 to class 5 (Table 3). (Fig. 2). From the shape of the dendrogramme can be seen that the first two classes, i.e. 2 and 3, group at a distance of 0.61, and then to the first cluster by adding the values of class 4 at a distance of 0.67 and finally the class 5 at a distance of 1.91. This group follows the course of increase in the values of NDWI, proving that the class with the most contaminated landscapes, i.e. 5, is well separated by using NDWI values. As the index is used for assessment of the water status of vegetation, it follows that the total water content of coniferous vegetation in the classes of polluted landscapes is significantly larger, which may be attributed, both to the total water content and the level of the groundwater seepage in landscapes, as well as to the total contamination factor of technogenic pollution – Z_c .

The average values of the TVI unlike other indices decline in descending order with the increase in pollution from 2nd to 5th class. It is seen also that with the declining average values the SD increase, although the small sample for class 5, i.e. 3 pixels. The grouping of the values of the TVI classes (Fig. 2), shows that TVI first join the 2nd and 3rd class at a distance of 0.33, and then 4th in 0.75, and finally 5th class at 4.20 similarly to NDWI. The difference of the discriminative power for distinguishing classes of contaminated landscapes in TVI to NDWI is due to the sharp separation of adjacent classes 2 and 3, while the most contaminated landscapes – 5th class is grouped at 4.20.

The time series of NDVI, NDWI, TVI, MSAVI, and VCI VIs from Landsat 5 TM is spanning 9 years, i.e. 2003–2011. Using the so created time series a descriptive statistics on a zone level is retrieved: average, median, minimum and maximum values, range, SD, characterizing the distribution of values in the technogenic contaminated landscape units. The zones are created on the basis of coniferous landscapes of the black pine, in the middle and lower part of Teyna River basin, which are merged with the areas of technogenic pollution, which in turn are derived by reclassifying the values of Z_c (Table 3). The zonal statistics for the 1st and 2nd class is not extracted due to the small size of the test sites of the zones (i.e. about 1 pixel) and due to ignoring zero values in the calculation.

The dendrograms for 2003–2011 VIs, which are built using the extracted signatures from the overlaid reclassified Z_c and coniferous landscapes, are presented on (Fig. 3). From the grouping of the NDVI values, can be inferred that the average of the 2nd and 3rd class resemble one another. The only ungrouped classes remain the 1st and 4th class. The point of clustering of dendrogram is at the distance between the classes 0.780.

The MSAVI shows approximately the same weak distinction between classes, i.e. 0.01 to the average of the classes. Comparing to the NDVI, MSAVI has smaller values of the SD, which shows relatively more stable behavior of the index for registration of changes in the coniferous vegetation. Clusters of signatures of classes of MSAVI are shown in (Fig. 3). The figure shows that clustering of the classes is again at a distance of 0.780 and is similar to the values of NDVI, which indicates that the index has almost the same presentation as regards the discrimination of the classes of landscapes subject to abiotic stress.

Similarly to the dendrogram of the NDVI, NDWI is grouped in 3 classes: 1, 2 and 3, and 4 (Fig. 3). The NDWI values of the 3rd and 4th class approaches one another at 0.816, which shows relatively better representation

Table 4. Descriptive zonal statistics of classes contaminated landscapes from the time series of NDVI, NDWI, MSAVI, and TVI. (2003-2011)

No	Z _c (classes)	Pixels	Area(m ²)	Min	Max	Range	Average	Standard Deviation (SD)
NDVI								
1	8,29-10	–	–	–	–	–	–	–
2	10-20	59	53100	0.466	0.816	0.350	0.699	0.070
3	20-30	9	8100	0.504	0.838	0.333	0.721	0.087
4	30-32.18	–	–	–	–	–	–	–
NDWI								
1	8,29-10	–	–	–	–	–	–	–
2	10-20	59	53100	0.109	0.479	0.369	0.293	0.293
3	20-30	9	8100	0.175	0.429	0.254	0.328	0.328
4	30-32.18	–	–	–	–	–	–	–
MSAVI								
1	8,29-10	–	–	–	–	–	–	–
2	10-20	59	53100	0.642	0.901	0.259	0.821	0.051
3	20-30	9	8100	0.658	0.914	0.257	0.834	0.068
4	30-32.18	–	–	–	–	–	–	–
TVI								
1	8,29-10	–	–	–	–	–	–	–
2	10-20	59	53100	-0.340	1.231	1.571	0.576	0.447
3	20-30	9	8100	0.142	1.048	0.906	0.763	0.269
4	30-32.18	–	–	–	–	–	–	–
VCI								
1	8,29-10	–	–	–	–	–	–	–
2	10-20	59	53100	0	76.436	76.436	14.326	17.892
3	20-30	9	8100	0	94.248	94.248	22.576	32.777
4	30-32.18	–	–	–	–	–	–	–

of NDWI in comparison with the NDVI for the separation of contaminated and stressed of heavy metals and radionuclides coniferous landscapes.

Unlike the other indices, TVI shows considerably larger differences of the average values of the Z_c between the 3rd and 4th

class – nearly 0.2 (Fig. 3). Grouping in a single cluster of the 1st and 2nd class is at distance between the classes 0.627. The grouping of 3rd and 4th class is logical because there are subtle differences in their values. Lower values of 1st and 2nd class are separated at a little distance of the classes, which shows a better presentation of the TVI in comparison

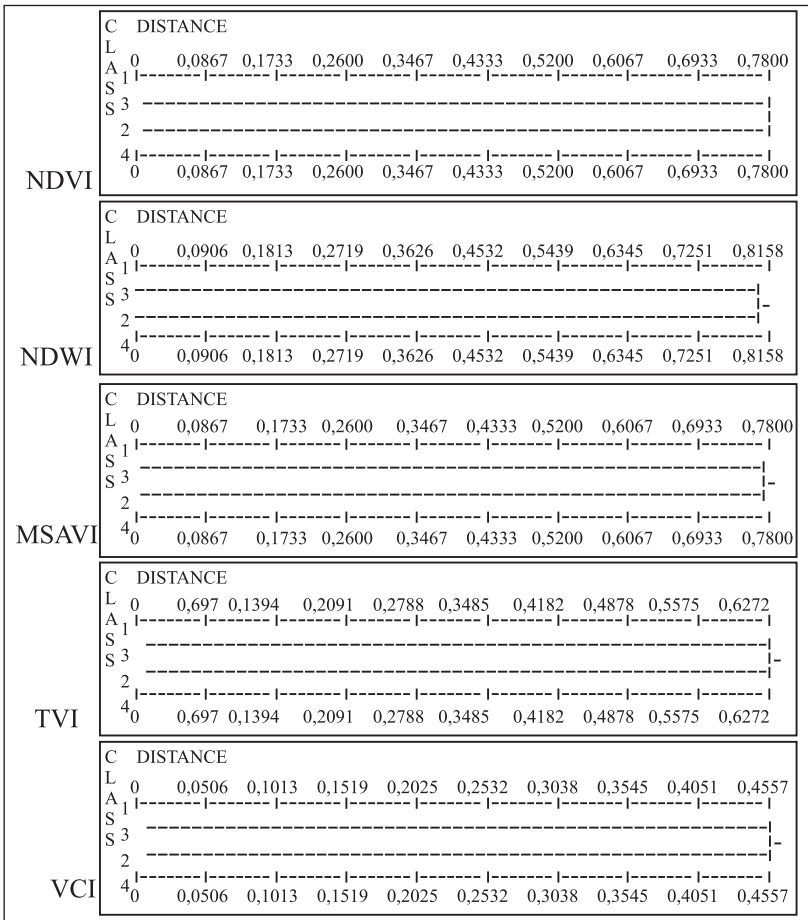


Fig. 3. Dendrograms of zonal statistics extracted from Landsat 5 TM VIs images: NDVI, NDWI, MSAVI, TVI, and VCI. (2003–2011)

with previous indices. This is due to the fact that the index uses the information from 1 additional channel in the green zone of the visible area of the spectrum.

The overall vegetation condition of coniferous landscapes according to preserve VCI index is poor – 2nd grade to 3rd grade on average, which reflects the the NDVI sensitivity regarding the vegetation greenness, which as was noted, is increased by increasing the concentration of tehnogenic pollution in the soil. The phenophase under investigation shows a difference in the average values for the two classes from 14.32 to 22.57 (Table 3). The SD for the same classes varies from 18 to 33, which shows the large variation of values in the 3rd class. The grouping of these

classes is at 0.45, which is fairly close to the grouping of the 2nd and 3rd class in the NDVI, and shows greater similarity than difference in classes.

The relationship between the values of VIs for 1990–1991 and the values of the total factor of tehnogeochemical pollution – Z_c are shown in Fig. 4.

The figure shows that between the values of the total index Z_c and VIs, there is a low linear positive correlation, which does not permit the creation of a linear regression model as well as its inversion between the rate of contamination VIs. Correlation of NDVI and Z_c has $R^2 = 0.74$ (Pearson) and $R^2 = 0.675$ (Spearman) with the level of significance,

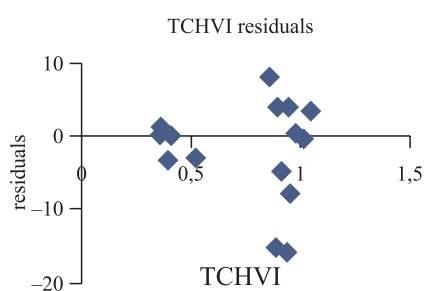
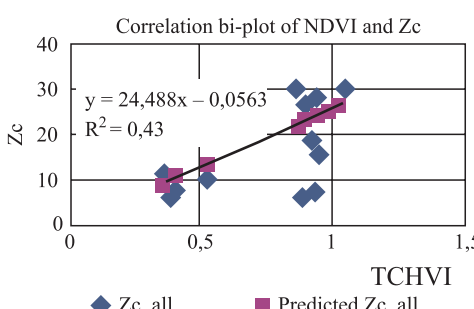
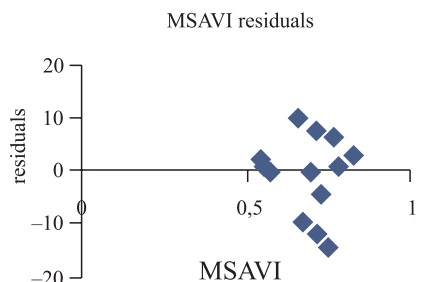
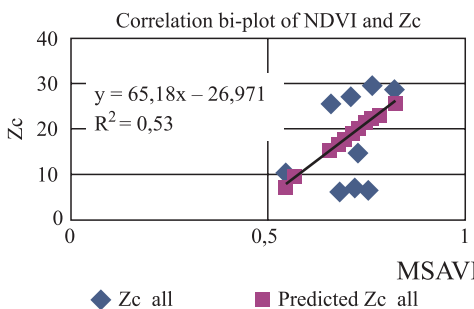
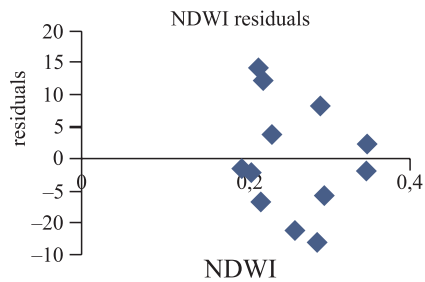
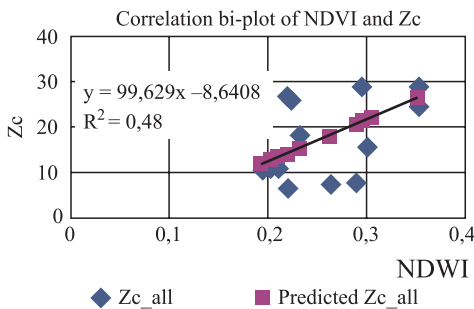
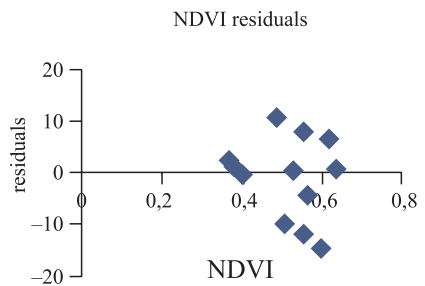
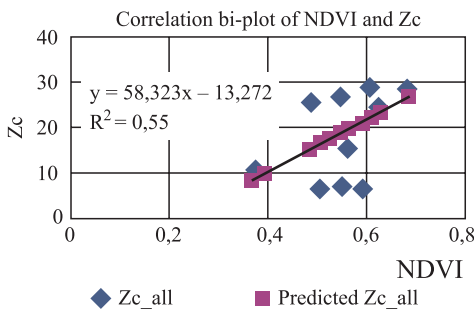


Fig. 4. Correlation bi-plots and residuals of the actual values of NDVI, NDWI, MSAVI, TVI from Landsat and Zc. (1990–1991)

21.789 for $F: < 0.001$. Correlation of NDWI and the Z_c has $R^2 = 0.695$ (Pearson) and $R^2 = 0.662$ (Spearman) with $F = 17.791$ for $F: < 0.001$. For MSAVI and Z_c : $R^2 = 0.73$ (Pearson) and $R^2 = 0.675$ (Spearman) at levels of significance $F: 20.508$ for $F < 0.001$. For the TVI they are $R^2 = 0.658$ and $R^2 = F: 0.373$ for $F: 13.78$ and $F: 0.002$ respectively.

The relationships between the VIs values of the Landsat TM (2003–2010) and the values of the total factor of technogeochemical pollution – Z_c are shown in Fig. 5. The figure shows that the values of the coefficient of correlation are very low, such as the highest correlation is with VCI, which is derived from the NDVI and NDVI with Z_c . All other indices do not have, or have a very weak correlation with a total coefficient of technogenic pollution. This low value of R^2 is explained by the variation of seasonal dynamics of vegetation during the period of observation by Landsat TM, which dynamics should be tested separately in time, and compared with the dynamics of the Z_c , for the same periods of observation which is beyond the scope of this study. Correlation

of NDVI and Z_c has $R^2 = 0.41$ with level of significance $F: 12.60$ for $F: < 0.002$. Correlation of NDWI and the Z_c is $R^2 = 0.18$ with $F = 4.19$ for $F: < 0.05$. For MSAVI and Z_c : $R^2 = 0.15$ with $F: 3.29$ in $F < 0.08$. For the coefficients TVI the R^2 is respectively 0.01 at $F: 0.28$ and $F: 0.60$ or lack of correlation.

CONCLUSIONS

In conclusion, it was found that the HR multispectral satellite data from Landsat can be used for detection and assessment of abiotic stress of coniferous landscapes caused by uranium mining. This is based on the established weak relationships between the Z_c and VIs, which however, do not permit for inversion of the derived regression equations between the indices and Z_c . From the analysis of the results it was found also that NDVI and VCI perform better than the index MSAVI. Due to a better presentation of the NDWI in relation to the water content in vegetation, and the resulting physiological abiotic stress, it could be concluded that the water content of the plants is not diminished drastically, while the vegetation greenness is

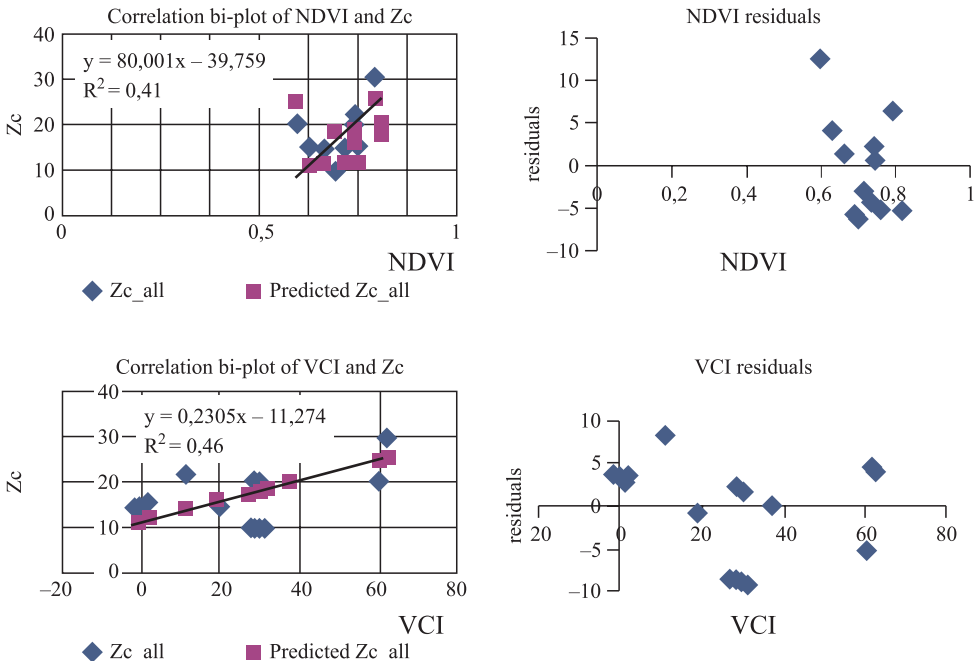


Fig. 5. Correlation bi-plots and residuals of NDVI, VCI from Landsat and Z_c (2003–2011)

more sensitive to this type of stress. As noted, the observed abiotic stress is most likely to be on a physiological level, and one of its manifestations is linked to the increase in the total water content, but also to increase the vegetation greenness of plants. This is better observed by using TVI as an indicator, as it incorporates the green channel in its formula. This argument supports the conclusion of a non-specific reaction of the vegetation renewal and increase in the total water content of conifers discovered in the 1980s of the 20th century [Aronoff et al., 1985]. It can be concluded also that VCI could serve as a relatively good tool for assessment of abiotic stress of coniferous landscapes, in case of availability of a full time series of multispectral HR data.

ACKNOWLEDGEMENTS

Present study uses geochemical analyses for heavy metals, metalloids and natural

radionuclide in soils financed under the “Enhancing the Qualification and Retaining a Young Scholars’ Team in the Field of Aerospace Technologies as a Prerequisite for Monitoring and Preservation of the Environment and Prevention of Damages Caused by Natural Disasters” Project under Contract No.BG051PO001/07/3.3-02/63/170608 within the “Human Resource Development” OP of the Ministry of Education, Youth and Science of the Republic of Bulgaria, of which Chief Assistant L. Filchev is a beneficiary. The authors are deeply appreciated to their colleagues from “Accredited Reference Laboratory of Radioecology and Radioisotope Studies” at the Institute of Soil Science “N. Pushkarov” for making the geochemical analyses of soils for the years 2010–2011 and their comments and valuable discussions on the research. The ArcGIS/ArcInfo 9.2 academic license software is granted to RS and GIS Department, SRTI-BAS by ESRI Inc. and SCGIS. ■

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LONG-TERM CHANGES IN THE LARGE LAKE ECOSYSTEMS UNDER POLLUTION: THE CASE OF THE NORTH-EAST EUROPEAN LAKES

ABSTRACT. A retrospective analysis of aquatic ecosystem long-term changes in the Russian large lakes: Ladoga, Onega, and Imandra, is given. The lakes in the past were oligotrophic and similar in their origin, water chemistry and fauna. The ecosystems transformed under the impact of pollution with toxic substances and nutrients. There are three stages of ecosystem quality: background parameters and degradation and recovery trends after the decrease of the toxic stress. On the stage of degradation, species abundance and community biodiversity were decreased. Eurybiontic species abundance and biomass were increased due to lack of competitive connections in toxic conditions and biogenic inflow. Small forms of organisms (*r*-strategists), providing more rapid biomass turnover in ecosystem, dominated in the formed plankton communities. On the stage of decrease of the toxic pollution, the lakes recolonization with northern species occurs, which is confirmed by replacement of dominating complexes, increasing index of plankton community biodiversity, and the rise of the mass of individual organisms

of the communities. Accumulated nutrients in ecosystems are efficiently utilized at the upper trophic level. The ecosystem state after decrease of the toxic impact indicates formation of its mature and more stable modification, which differs from a natural one.

KEY WORDS: long-term pollution, aquatic ecosystem, reference condition, disturbance, recovery.

INTRODUCTION

Prolonged anthropogenic pollution of the environment, which dates back to the period of industrial revolution in the 18th century, dramatically manifested itself in negative environmental changes in the mid-19th century. Numerous investigations have given insight into the regularities of the anthropogenic environmental transformations and the responses of biologic systems to anthropogenic stress and revealed the severe hazard of environmental pollution by toxic substances.

In view of the cardinal importance of fresh water for the survival of the Earth's population and its species diversity, the importance of the recovery of aquatic ecosystems and the preservation of their habitat is also evident.

It is worth mentioning that, as a rule, aquatic ecosystems experience a multi-contaminant stress. Hence, their degradation and recovery develop in a complicated, non-linear, and often unpredictable way. The ecological theory plays a key role in understanding the anthropogenic successions and the regularities of recovery. If the trajectories of successions of communities and ecosystems under the conditions of increasing and decreasing anthropogenic loads are known, it is possible to efficiently accelerate the processes of ecosystems recovery. The recovery of aquatic ecosystems due to decreasing anthropogenic inputs, including toxic pollutants, has been well documented in the scientific literature [Cairns, 2005; Harris, 2006; Palmer *et al.*, 2007]. During the latest years, there has been a distinct tendency towards the decline of dangerous pollutants' stream into environment, including water. Science has been compiling information on ecosystems recovery after the contaminating disturbance. However, only recently scientists have been attempting to predict all the scenarios of ecosystems recovery, including their successions after toxic disturbance [Cairns, 2005]. Many scientists raise a question: is it possible for ecosystems to recover after toxic disturbance, or they attain a new configuration?

Water ecosystems, as a rule, suffer multi-contaminating disturbance and that is why such processes as degradations and recoveries proceed completely, nonlinearly, and often incalculably. The ecology theory plays a key role in understanding of anthropogenic successions and recovery mechanism. Knowing trajectory of successions of communities and ecosystems in conditions of increasing and decreasing pressure, one can coordinate actions aimed at acceleration of ecosystem recovery processes [Depledge, 1999; Palmer *et al.*, 2007].

The representative example of long-term multi-contaminating pollution is the large Russian lakes: Lake Ladoga, Lake Onega and the subarctic lake of Imandra (Fig. 1). These three lakes, situated in the North-West of Russia, are characterized by one genesis of ecosystem formation during the postglacier period; for this reason they have common characteristics of water chemistry, as well as of fauna.

Objectives:

to make a retrospective analysis of conditions of ecosystem elements and estimate their reference conditions on the base of a time-space analysis of dominant characteristics of the ecosystems;

to reveal the main consistent patterns of successions of water ecosystems of northern lakes under anthropogenic load and their reduction: from background characteristics – through degradation – to recovery;

to explain the trajectory of these changes according to the ecology theory and to estimate the ability of ecosystems to recover after toxic disturbance.

This paper is based on an analytical review of the relevant published results and also on more than 30-year investigations of the authors in this region [Krokhin, Semenovich, 1940; Moiseenko *et al.*, 1996; Moiseenko, Yakovlev, 1990; Moiseenko, Kudrjatzeva, 2002; Antopogenic Modification, 2002]. Although much information is available, there has been no continuous long-term monitoring of the lakes and, therefore, this paper is based on discontinuous information. In this review, attention is focused on the main parameters of water chemistry and key indicators of phytoplankton, zooplankton, benthos, and fish conditions that reflect ecosystem changes during different periods for Volkhov Bay of Ladoga Lake, Kondopoga Bay of Onega Lake and the Bol'shaya Imandra basin that suffered from the pollution of water with toxic agents and nutrients.

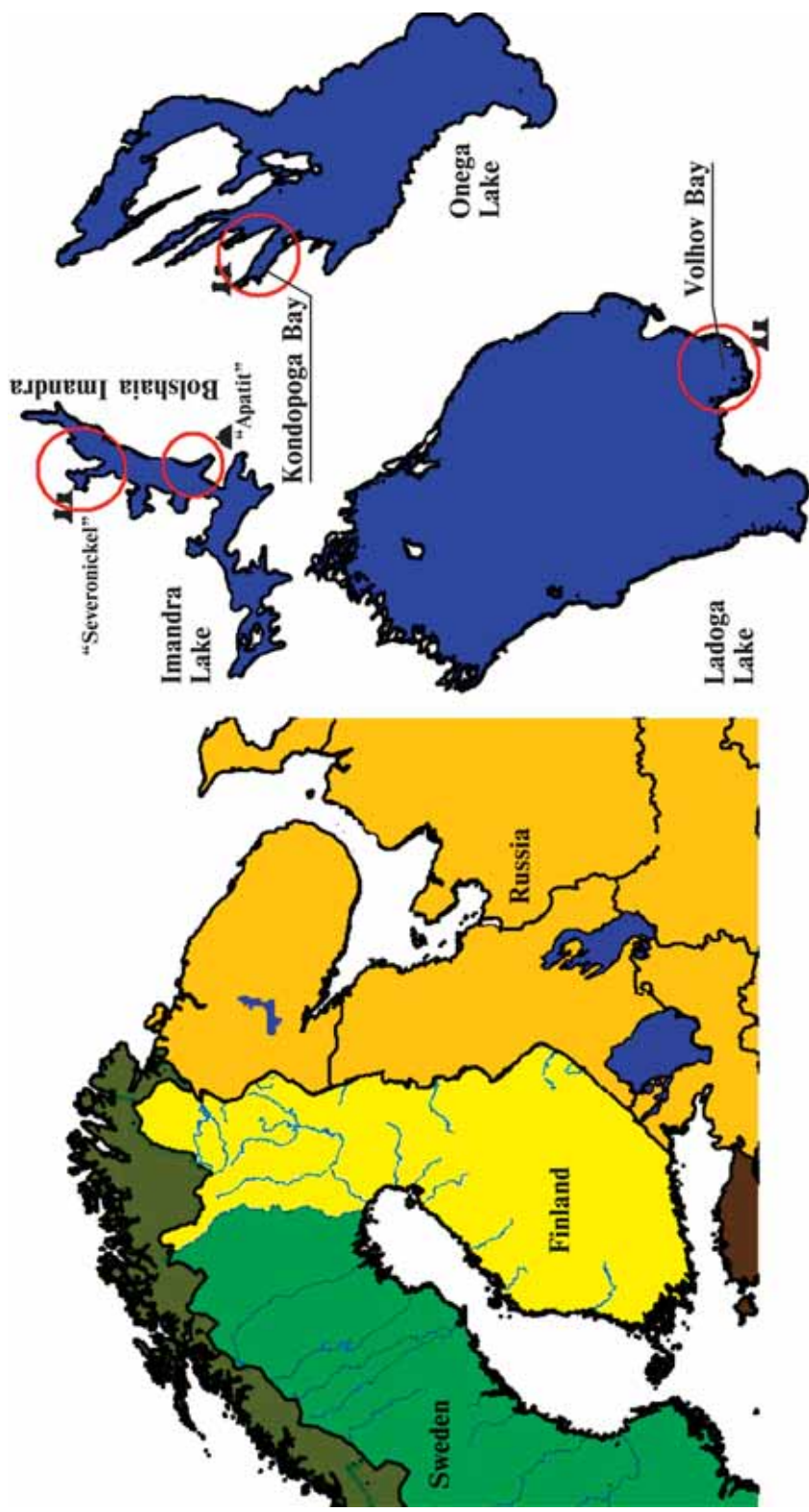


Fig. 1. Map of Imandra, Onega, and Ladoga lakes and locations of the main industries on their shores

CHARACTERISTICS AND REFERENCE CONDITIONS OF THE LAKES

Lakes of Ladoga, Onega, and Imandra are situated in the North-Taiga ecoregion in the European part of Russia; Imandra lake is above the Polar cycle. Knowledge of reference conditions (ecological conditions found at undisturbed or minimally disturbed sites) is important when trying to manage anthropogenic stress [Falk *et al.*, 2006]. The background conditions of the lake prior to industrialization provide a benchmark for water quality and ecosystem recovery.

Ladoga, which is the largest lake of Europe, is one of the 15 largest freshwater reservoirs in the world. The state of the environment in the Ladoga area affects the life standard of several million people living in 258 300 km² of the lake watershed area, which includes a great part of the Russian north-west and eastern Finland. Lake Ladoga covers an area of 17 700 km² (with its islands, 18 135 km²). The main feeder rivers are the Volkhov, Svir, and Vuoksa, and the lake's outlet is by way of the Neva River into the Gulf of Finland. Its maximum depth is 230 m.

Onega is the second largest lake in Europe after Lake Ladoga. The area of the lake is 9800 km², and the volume is 262 km³, with average and maximum depths of 30 and 120 m, respectively. Its watershed covers about 56 300 km² (including the lake itself), equaling to a quarter of the Lake Ladoga watershed area.

Imandra is situated within the Arctic Circle in the Kola Peninsula, Russia. The lake has an area of 813 km² (with its islands, 880 km²) with a catchment area of 12 300 km² and the volume of 11 km³. The lake has a complex shoreline and consists of three main basins connected by narrow passages, with maximum and average depths of 67 and 13 m, respectively.

The climatic factors of the North (high influence of atmospheric inputs, low temperatures, thin layer of soil, slow

chemical weathering processes, and slow element cycling) form clear waters (the sum of ions is 20–55 mg/l). Prior to the 1930s, the lakes were typically oligotrophic with hydrocarbonate–calcium salt contents, low concentrations of suspended material and microelements; phosphorus content (especially its bioavailable phosphates) was too low. High N/P ratio (43–45) limit productional processes by phosphorus content. In general, nutrients and organic substances increase from arctic Imandra Lake to Ladoga, located in the Northern Taiga. Water inhabitants of the three lakes are typical oligotrophic cold-water species. Content and structure of phytoplankton from the investigated lakes is mainly similar to the content and structure of deep oligotrophic lakes [Lake Onega..., 1999; Lake Ladoga..., 2002; Anthropogenic modification..., 2002]. Dominant species in the three lakes are shown in Table 1, basic quantitative indexes, describing condition of natural ecosystems of these lakes during the pre-industrial period, are shown in Table 2.

The table is compiled using data from: Voronikhin (1935); Poretskij *et al.* (1934); Krokhin and Semenovich (1940); Berg and Pravdin (1948); Sokolova (1956); Petrova (1987, 1971); Moiseenko and Yakovlev (1990), Petrovskaya (1966); Nikolayev (1972); Vandish (2002); Anthropogenic eutrophication... (1982); Sabylina (1999); Yakovlev (1998); Iliyashuk, B.P. (2002), Lake Onega... 1999; Lake Ladoga... 2002; Anthropogenic modification... 2002.

In the middle of the last century (1940s) diatoms, in particular *Aulacoseira islandica*, predominate in phytoplankton of Imandra, Ladoga, and Onega. Values of phytoplankton biomass were low, which is typical of oligotrophic northern lakes [Petrova, 1987]. Crustacea Cladocera and Copepoda typically dominated in zooplankton of Ladoga, Onega, and Imandra [Sokolova, 1956; Petrovskaya, 1966; Nikolayev, 1972; Vandysh, 2002]. Midge larvae (Chironomidae), bivalves (*Euglesa spp.*) and crustacea (*Monoporeia affinis*, *M. relict*, *Pallasiola quadrispinosa*) dominated in zoobenthos of the lakes. Oligochaeta

Table 1. Dominating complexes of community structure of the Russian large lakes: Imandra, Onega, and Ladoga during the key periods of ecosystem modification

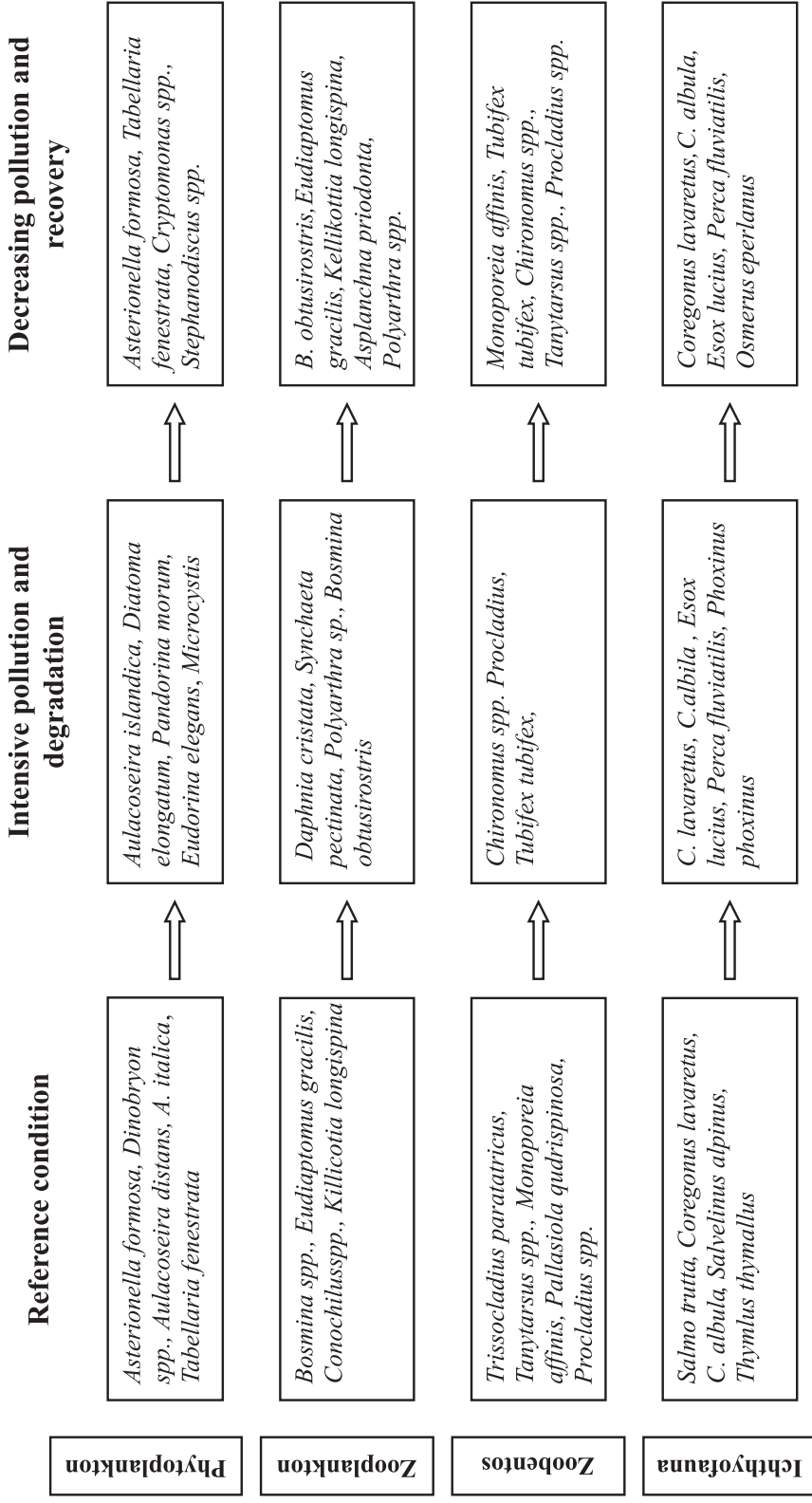


Table 2. The main indicators* of water quality and community conditions of Russian large lakes during the key periods of ecosystem changes:

1 – reference condition, 2 – intensive pollution and degradation, 3 – decreasing pollution and recovery

Variable	Periods	Lakes		
		Imandra	Onega	Ladoga
Ptot/PO ₄ , µg/l	1	6/1	8/1	10/3
	2	26/21	54/30	178/100
	3	26/2	24/5	34/9
Ntot/NO ₃ , µg/l	1	260/17	350/110	450/130
	2	436/102	750/120	920/240
	3	395/19	648/85	890/230
Si, mg/l	1	1	2	1
	2	1.1	1.2	0.5
	3	0.42	0.1	0.2
Chl "a", mg/m ³	1	0.3	0.7	0.7
	2	3.8	8.4	8.0
	3	3.6	6.8	7.9
Toxic loads (ΣCi/MPCi)**	1	0.1	0.1	0.1
	2	3.2	0.7	0.8
	3	1.0	0.6	0.5
Phytoplankton				
Biomass, g/m ³	1	0.1	0.1	0.5
	2	3.6	2.4	5.5
	3	3.4	1.7	2.1
Number, cell 10 ⁶ /l	1	0.1	0.1	0.4
	2	3.8	3.6	12.3
	3	3.2	2.5	3.4
H (Shannon's index), bit/spec.	1	3.2	3.7	3.4
	2	2.5	3.3	3.1
	3	3.1	3.8	3.6
Zooplankton				
Biomass, g/m ³	1	0.3	0.1	0.6
	2	1.7	2.9	2.8
	3	1.2	1.1	0.9
Number, spec. 10 ³ /m ³	1	15	3	13
	2	271	110	143
	3	107	80	34

Variable	Periods	Lakes		
		Imandra	Onega	Ladoga
H (Shannon's index), bit/spec.	1	2.8	2.3	–
	2	1.9	1.7	–
	3	2.5	2.5	2.7
Macrozoobenthos				
Biomass, g/m ²	1	0.6	0.6	1.6
	2	35	3.2	4.8
	3	13	12.0	12.6
Number, spec. 10 ³ /m ²	1	0.5	0.2	0.8
	2	43	2.4	1.1
	3	6.2	7.0	3.5
H (Shannon's index), bit/spec.	1	3.5	2.6	–
	2	1.6	2.0	–
	3	1.1	1.4	–

* Numerical values of indicators are taken from the literature cited below;

** Toxic loads: $\Sigma Ci/MPCi$ – the total concentration of pollutants (Ni, Cu, Pb, phenol and lignosulphonate) normalized, to maximum permissible concentrations (MPC) for aquatic life in Russia [List of Fishery Standards..., 1999].

The table is compiled using data from: Voronikhin (1935); Poretskij et al. (1934); Krokhin and Semenovich (1940); Berg and Pravdin (1948); Sokolova (1956); Petrova (1987, 1971); Moiseenko and Yakovlev (1990); Petrovskaya (1966); Nikolayev (1972); Vandish (2002); Anthropogenic eutrophication... (1982); Sabylina (1999); Yakovlev (1998); Iliyashuk, B.P. (2002), Lake Onega... 1999; Lake Ladoga... 2002; Anthropogenic modification... 2002.

were represented by the Lumbriculidae and Naididae families [Krokhin and Semenovich, 1940; Gerd, 1949; Sokolov, 1956; Alexandrov, 1968]. These lakes were typical whitefish lakes with the presence of trout and loach: *Coregonus albula* (L) is the main plankton feeder; *Coregonus lavaretus* (L) is the main benthophage. Among carnivorous fish lake salmon (*Salmo trutta trutta* (L)) dominates in Ladoga and Onega lakes; arctic char (*Salvelinus alpinus* (L)) dominates in Imandra lake [Galkin, 1966].

ANTHROPOGENIC LOADS AND ECOSYSTEMS DISTURBANCE

Considerable industrial expansion in the 1930s resulted in the building of large industrial enterprises in the lake catchments. In the beginning of the last

century, the first aluminum plant, pulp and paper factory and other plants were built on the shore of Ladoga Lake (Volkhov Bay). Plant pollution with phenols, lignosulfate, benzopyrene, and other toxic agents reached its maximum by the end of the 1960s. Phosphor load was associated with flux of toxic agents with industry wastewater (especially after using new raw materials by the aluminum plant: phosphorus-containing apatite-nepheline ores) and with wastewaters of the Volkhov town. According to scientists' estimates phosphor flux into the lake increased a hundred times: in the 1970s–1980s, phosphor load was 6–7 thousand ton/year (Volkhov Bay's part was 50–60% of the total value) [Lake Ladoga..., 2002]. It should be noted, that the area of this bay amounts only to 8% of the whole lake.

Lake Onega is polluted by wastewater of the largest in the country pulp-and-paper plant. The Kondopoga Bay receives large amounts of industrial wastewater and domestic sewage, which contains toxic pollutant and nutrients. Its area is less than 3% of the lake. The plant operated without waste-water treatment facility for 30 years. Wastewater treatment system was forced into application in the 1980s, however phosphor and nitrogen compounds were additionally applied as agents. Phosphor load to the Bay area increased to 0.56 g/m^2 per year and the nitrogen load reached 11.1 g/m^2 per year. However total phosphor load to the lake was 0.1 g/m^2 per year [Sabylina, 1999].

Lake Imandra has been subjected to more severe pollution than many Arctic lakes. Industrial development of copper- and nickel-rich, apatite-nephelinite, and iron deposits in the catchment area of Lake Imandra began in the 1930s. Anthropogenic pressure on the Imandra Lake began in the 1940s and reached its peak in the 1980s. Data are available for 1983–1992, when the effects of pollution were most evident. The lake was subjected to pollution by a number of contaminants including heavy metals, nutrients, sulphates, and chlorides. The main pollution occurred in the northern part of the lake (i.e., Bol'shaya Imandra) (38% of the all lake area).

Pollution of the lakes with toxic mixture of substances was dramatic. It is difficult to estimate exact dimensions of toxic flow into the ecosystems, but even available limited information is indicative of high toxic stress for water dwellers in the period of intense water pollution. In this period, industrial activity went with uncontrollable toxic wastewater and sewage bled-off into sections of the lakes. Thus, toxic pollution of the lakes went with the bulk input of nutrients (phosphor and nitrogen). Polluted bays (in Ladoga – Volkhov Bay; in Onega – Kondopoga Bay; in Imandra – White Bay) satisfy eutrophic condition by phosphor content (according to the R.A. Vollenweider classification,

1979) and adjacent large areas satisfy mesotrophic condition.

Water chemistry changes in all three lakes in the period of pollution were similar in type: water clarity has decreased; pH level, sulphates, chlorides, and biogenic elements content has increased; change in contaminants with toxic properties have also occurred. Thus, in the period of intense pollution habitat conditions for aquatic organisms in the analyzed bays became different from their native characteristics, and new property – water toxicity – has occurred and involved changes of structure of all ecosystem units (see Table 2).

During the summer period, phytoplankton biomass in polluted lake bays increased 20–30-fold because of large dimensions of nutrients input. Intensive cyanobacterial blooms were observed in Ladoga and Onega Lakes; in the arctic lake of Imandra they occurred to a lesser degree. Structural changes of phytoplankton community promoted intensive development of species, typical of eutrophic waters: blue-green, green, and cryptophyte algae dominated in that period (see Table 1).

In the period of intensive pollution of the lakes, zooplankton structure changed towards the dominance of eurybiontic species. Percentage of rotifers in the zooplankton structure in Imandra increased to 60%, which occurs because of rotifers' high resistance to the impact of contaminants. At the same time, percentage of such specific northern water dwellers as *Collotheca sp.*, *Conochilus sp.*, *Holopedium gibberum* decreased. According to the data from [Vandish, 2002], total biomass of zooplankton community increased, whereas species diversity index decreased. Abundance of rotifers in Ladoga and Onega increased, whereas abundance of typical northern crustacean species decreased.

The total abundance and biomass of zoobenthos in the pollution zones of all lakes have steeply risen while their biodiversity

have decreased. Communities with high abundance and restricted biodiversity of Chironomus, Procladius, Nematoda, *Tubifex tubifex*, *Limnodrilus hoffmeisteri* developed in the contamination area. Species diversity index in the severely polluted zones was less than 1–2 bit/spec. Oligochaetes (up to 200 g/m²) and Chironomidae (up to 50g/m²) abundance dominated in benthos of Imandra Lake. At the same time, the ratio of pollution-sensitive Chironomidae larvae and bivalve mollusks decreased by more than 50%. One of two epibiotic crustaceans seen in Imandra Lake before (i.e., *M. relicta*) has probably petered out of the fauna. *M. affinis* appeared to be more resistant to heavy metals and biogenic elements polluting the lake [Moiseenko and Yakovlev, 1990].

Dramatic pollution of Ladoga and Onega lakes occurred in the period of flood-release outlet from the pulp-and-paper production and the total annihilation of bottom communities was observed [Polyakova, 1999; Slepukhina, 1992; Belkina *et al.*, 2003]. Communities of some resistant species of chironomid-oligochaete complex were formed in conditions of moderate pollution. Rather large-size chironomids formed 10–50-fold higher biomasses in comparison with natural values thriving on organic substances and nutrients. Oligochaetes dominated in the zones with decreased toxicity and high accumulation of organic matter in the bottom silt.

Abundance of trout and loach in fish community significantly decreased because of their high water pollution sensitivity. These species completely disappeared in commercial catches of Imandra. Whitefish abundance decreased. Such diseases of whitefish as nephrocalcosis (kidney stones), lipid liver, cirrhosis, etc. were recorded also. Case frequency rate (% of those surveyed) was closely related to nickel concentration in water and its accumulation in kidneys [Moiseenko and Kudriavtseva, 2002]. Lake salmon abundance in Ladoga and Onega had decreased dramatically [Lake Onega..., 1999; Lake Ladoga..., 2002].

Productive areas of benthic communities developed and zoobenthos biomass increased, which attracted whitefish. By migrating to these food-rich areas, fish were exposed to the effects of toxic contaminants [Moiseenko and Yakovlev, 1990]. Disease occurrence of fish in these areas was dramatic, and the lethal outcome for the fish after staying was high. Criteria to determine fish conditions (by physiological indicators of intoxication) are important for assessing toxic effects and are used as integral parameter of ecosystem health [Adams and Ryon, 1994]. Using these criteria, fish diseases indicated the dramatic state of ecosystem health in Lake Imandra during the period of intensive pollution.

TENDENCY TO RECOVERY

In the 1990s, the anthropogenic load on the lakes decreased. Tendency to improvement of water quality and ecosystem recovery occurred in response to decreasing anthropogenic load to the Volkhov (Ladoga) and Kondopoga (Onega) Bays and reaches of Imandra.

Toxic matter concentration in water of the analyzed bays decreased: concentration of nickel as a major marker of pollution in Imandra decreased from 150 to 10 µg/l; concentration of lignosulphates and phenols, as markers of pulp-and-paper industry pollution, decreased in the Kondopoga Bay of Onega; concentrations of lignosulphates and phenols in Ladoga also decreased (see Table 2).

Concentration of common phosphorus forms in Ladoga and Onega decreased; whereas in Imandra, they remained at the same level; concentration of common nitrogen decreased in all three lakes only slightly. Concentrations of bioavailable phosphates and nitrates significantly decreased (6–20-fold), which indicates their more active utilization in the changed trophic ecosystem structure. Dynamics of silicon is of particular interest; its concentration did not improve and kept decreasing steadily, due to more

active absorption of it by developing diatoms.

Phytoplankton abundance decreased in the Volkhov Bay of Ladoga and the Kondopoga Bay of Onega; phytoplankton abundance in Imandra remained the same. Average biomass values in the lakes varied from 1.7 to 3.4 g/m³; chlorophyll "a" concentrations varied from 3.6 to 7.9 mg/m³. There was still a high abundance of species of the genera *Cryptomonas*, *Stephanodiscus* *u* *Aulacoseira islandica*. Relative abundance of cryptomonades, bluegreen, and green algae was still high in the phytoplankton structure.

In spite of the decrease of phosphorus load in the bays of Ladoga and Onega in the period of recovery, maximal and average indexes of biomass and chlorophyll content remained very high in comparison with natural values. From the end of the 1990s to the beginning of the 2000s, the index of zooplankton community abundance had decreased and the biodiversity index had increased in the analyzed bays of Ladoga, Onega, and Imandra lakes (Table 2). Biomass had also decreased, but not so greatly, because of increasing abundance of larger Cladocerae (*Bosmina obtusirostris*) and Copepoda (*Cyclops* *sp.*, *Cyclops*, *Mesocyclops leuckarti*) and depletion of ratio of small rotifers, typical pollution indicators. Valuable food Cladocerae (*Holopedium gibberum*, *Daphnia* *sp.*, *L. kindtii*), which used to affect the lake before the peak of pollution, recovered. However, there was still only a trace amount of the most pollution-sensitive crustaceans (*Leptodora kindtii*, *Polyphemus pediculus*, *Eudiaptomus graciloides*, *Heterocope appendiculata*). Cladocera and Copepoda dominated in zooplankton in the Volkhov Bay of Ladoga lake [Lake Onega., 1999, Lake Ladoga..., 2002, Anthropogenic modification, 2002].

Zoobenthos was very slow to recovery. Its biomass in Imandra decreased, but it kept rising in Ladoga and Onega. Oligochaete-Chironomidae complex with the dominance

of worms still dominated in benthos of the northern part of the Kondopoga Bay of Onega Lake, but epibiotic Amphipoda was not found there. During a 30-year period of operation of the wastewater treatment facilities that promoted dissipation of polluted waters, the conditions of benthos in the Kondopoga Bay improved; the number of species rose more than forty-fold and its biomass increased over twenty-fold, on average, compared to 1964 (the beginning of the observations.) In conditions of a significant decrease of toxic load and of good nutrients supply, epibiotic crustaceans *M. Affinis* dominated among invertebrates in profundal benthos of the arctic lake (the stretch of Bol'shaya Imandra). Their relative abundance grew almost twice – from 36% to 60% [Iliayashuk, 2002].

Abundance of valuable Salmonidae and Corigonidae did not grow in fish fauna, whereas pike and perch abundance increased. In response to the toxic load decrease, the incidence of fish diseases in Imandra Lake fell. According to the findings of 2003, fish's physiological state improved [Moiseenko *et al.*, 2006]. There are no such data about the other lakes. It should be noted, that during this period, there was an increase of illegal catch volume, which together with pollution and eutrophication could impact fish communities structure. It is complicated to define the determining factor of successions of fish communities, since it is impossible to take a proper account of real numbers of fish caught from the lake.

SIMILARITIES OF LAKE ECOSYSTEMS DEGRADATION AND RECOVERY

Often, modern changes of ecosystems under the impact of anthropogenic load do not have analogues in the past; that is why, in order to understand ecosystems recovery processes, it is necessary to apply theoretical principles of ecology to investigations of processes of community development and structure occurring with time [O'Neil, 1999; Falk *et al.*, 2006; Palmer *et al.*, 2007]. Ecosystems are self-regulating

systems that have developed mechanisms for self-repair [Odum, 1985]. Following a decrease or removal of anthropogenic stress, natural processes bring the system back to the near equilibrium state [O’Neil, 1999]. The investigation of long-term pollution of the bays in the large lakes in the North of the European part of Russia has revealed common characteristics of ecosystems degradation and similarities of recovery processes after the anthropogenic stress decrease. All three lakes were characterized as oligotrophic with low concentrations of nutrients, suspended matter, and microelements. Dominant ichthyofauna consisted of psychrophilic stenoecic species typical of cold oligotrophic water in the North.

For more than half a century, industrial activity on the shores of the lakes had resulted in release of toxic elements and sewage into the ecosystems of the same zones of the lakes. According to [Odum, 1985], a limited influx of organic matter and nutrients into ecosystems represents an additional energy input, whereas a toxic contaminant is a stress factor, intensifying energy dissipation. The lakes’ ecosystems changed under the impact of two factors – energy input of nutrients influx and stress of toxic contamination. Applying Odum’s theory of the early succession stages of development and of unstable stressed ecosystems [1985] to the key indicators observed in the ecosystems of all three bays in the period of intensive pollution, it becomes clear that the lakes’ ecosystems have transformed from their stable natural state to a new phase that may be considered as a development stage. Let us now discuss attributes, characterizing water ecosystems of the three lakes in the period of their disturbance under the impact of multi-pollution.

Together with the growth of content of total phosphor, bioavailable forms (orthophosphate) grow too; the ecosystems are not able to utilize bioavailable forms at this stage of transformation and they become reserves of intensification of the

production processes and biomass growth. Due to a high phosphor concentration, growth of biomass of primary producers (phytoplankton) occurs. The structure of the phytoplankton biomass changes towards the dominance of blue-green, green, and cryptophyte algae, as well as of pollution resistant algae. It is known, that mixotrophic nutrition is a feature of cryptophyte algae, and they provide rapid biomass turnover in ecosystems due to their small size.

The abundance of typical northern species, vulnerable to toxicants (see Tables 1 and 2), in zooplankton and benthos communities falls, that results in decrease of the total species diversity. The abundance of eurybiontic species in zooplankton and benthos communities grows owing to high concentrations of nutrients and lack of competitive connections with the typical dwellers of the northern water, vulnerable to toxic impact. Eurybiontic species dominance in all communities increases. Small size rotifers dominate in zooplankton communities. It is possible to retrace the process of formation of the high biomass of organisms of the chironomids-oligochaete complex in the benthos community in conditions of integrated pollution. Decrease of the *nominal* individual mass, typical for phyto- and zooplankton communities, indicates the dominance of small forms (*r*-strategists), providing more rapid biomass turnover in the ecosystem and utilization of energy subsidies, received additionally. Percentage of predatory species in zooplankton and fish decreases. The observed features indicate the critical state of the ecosystems of the three lakes in the zones of intensive pollution and correspond to the characteristics of their unstable stress state.

Let us consider, what kind of configuration ecosystems have after decrease of toxic pollution and to what extent they conform with a more stable (mature) modification in compliance with Odum’s ecology theory [1985].

At the background of high concentrations of total phosphor in the three lakes, the concentration of bioavailable phosphates decreases because of their rapid utilization in a new trophic structure of the ecosystems. In spite of decrease of phosphor flux into the ecosystems of Ladoga and Onega (in the polluted bays), the values of maximal and average biomass and the chlorophyll content during the period of pollution decrease are almost as high as during the period of intensive pollution.

A similar phenomenon occurred in the Great Lakes, i.e. the delayed response of phytoplankton to the decrease of phosphor load. For example, from 1968 to 1985, phosphor concentrations had been slowly decreasing in Ontario, and, by the 1985, they have decreased two-fold. However, the production of phytoplankton and chlorophyll "a" did not change before the beginning of the 1980s, and the tendency of the lake's oligotrophication appeared only in the subsequent years [Grey *et al.*, 1994; Great Lake Ecosystem report, 2000]. The dominance of the blue-green algae was replaced by the dominance of the cryptophyte algae along with the decrease of the phosphor concentration and increase of the N/P ratio during the recovery period. This phenomenon also occurred in response to the decrease of phosphor load in a number of lakes in Sweden [Willen, 1987]. In Ladoga, cryptophytes algae have progressively developed during the recovery period. They have a high P/B ratio with a high rate of biomass turnover [Lake Ladoga..., 2002].

The species structure of the communities differed from the natural state: a number of species, typical for the natural conditions, did not recover or the recovery occurred only in isolated cases; dominance in the communities changed, e.g. species, which are solitary in nature, greatly increased in numbers; introducents appeared. At the same time, the biomass of zooplankton decreased, which can be explained by two factors: 1) an increase in the predominance of predatory forms in these zooplankton communities

and 2) the increase in a number of fish due to reduced pressure on the population.

The species diversity of zooplankton communities grew, and the number of large forms (K-strategists) and prey organisms in its structure rose also; the nominal individual mass of the organisms increased respectively. Benthos communities were less active in recovery; their biodiversity was still low. However, large growth of prey species – relict crustacean *M. affinis* – in Imandra Lake indicates formation of a new structure. This species has an advantage in its development in conditions of the decrease of toxic load and favorable feeding. Water communities of Ladoga and Onega have also undergone considerable structural transformations under the impact of invasions of the Baikal amphipod *Gmelinoides fasciatus* (Stebbing) [Ladoga Lake..., 2002; Berezina and Panov, 2003]. Due to high numbers and rates of production, it rapidly gets involved in the ecosystems' processes of transformation of matter and energy.

CONCLUSION

The information presented above indicates that recovery of an ecosystem depends not only on improvement of habitats, but also on complicated ecological mechanisms. One of these mechanisms is the maintenance of stability of a newly formed ecosystem and the complexity of a return to the early succession conditions. It is known that in any disturbed ecosystem, the processes of energy regulation and reorganization turn to the near equilibrium stable condition [Chapman, 1999; Power, 1999]. The important questions are: Which features characterize ecosystems trajectory and their new structure? To what extent they correspond with mature (climax) conditions?

The features of the ecosystem state after the decrease of toxic pressure, specifically, recolonization of the lakes with individual northern species, appearance of new introducents, increase of the role of the upper levels of the ecosystem trophic

structure, successful utilization of mineral forms of biogenic elements, and increase of the share of K-strategists – all these features of the ecosystem state after decrease of the toxic pressure, discussed in this paper, indicate formation of a mature and a more stable modification, which differs from the natural one. This trajectory of transformation from a natural state through disturbance to recovery corresponds to the mechanisms of ecosystem successions: from a natural state through development to a more stable mature (climax) modification according to Odum's theory [1985].

The analyzed example of the anthropogenic modifications of the northern water ecosystems (polluted bays of Imandra, Ladoga, and Onega lakes) showed that ecosystems, after their disturbance, do not revert to the natural state. The theoretical trajectory of the ecosystem modification is presented in Fig. 2. Therefore in this case, the term "recovery of ecosystems" can't be identified with the notion of reversion to the natural state.

Since the scientific community is anxious about climate warming, in conclusion, we

will note obvious phenomena that may take place in the northern ecosystems due to climate warming.

It is probable that increasing water temperature as a result of global warming will make a return to reference conditions impossible [Harris *et al.*, 2006]. Temperature influences the following ecosystem functions: (1) rate of carbon fixation, (2) rate of nutrient increase/decrease, (3) rate of detritus processing and storage, (4) rate of suspended-solid trapping, and (5) nutrient trapping and storage [Cairns, 2005]. Accumulated nutrients will be more actively utilized in trophic chains, because in warmer conditions communities will move towards the predominant development of eurybiontic species. The influx of biogenic elements from the catchment areas is likely to increase with rising temperature and it will provide increasing productivity for pollution-resistant species. Climate warming is unlikely to favor fish species such as arctic char and trout, although other species such as whitefish, perch, minnow, and smelt may benefit from advantageous ecosystem changes. For example, higher bioproductivity of amphipods in warmer temperatures will

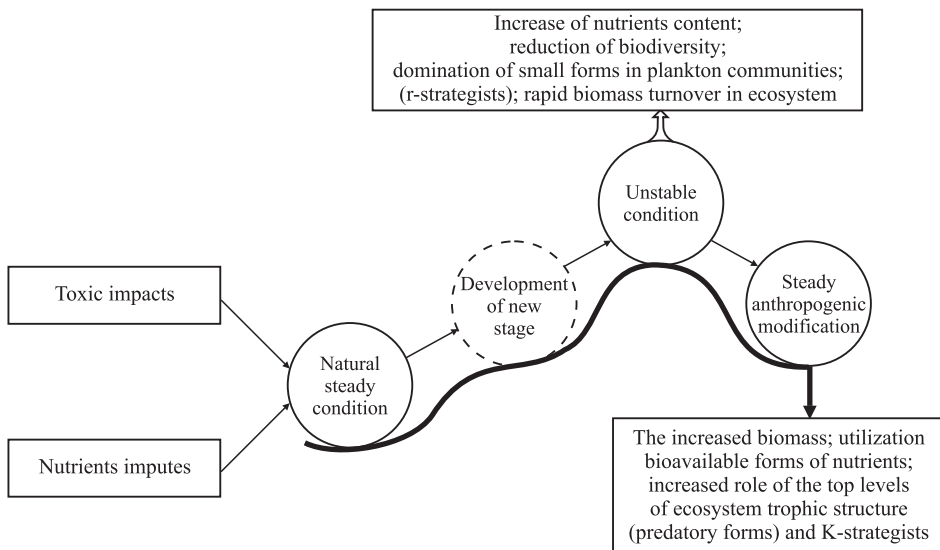


Fig. 2. A theoretical trajectory of an ecosystem modification under toxic and nutrients impacts: the attributes of the disturbance unstable stage and of the new stable stage, after a decrease in toxic impacts

create more favorable conditions for feeding and growth of whitefish and will lead to an increase in their numbers. The lake is likely to change from mesotrophic to eutrophic in some areas, which is observed in present conditions of biogenic pollution.

Studies reviewed in this paper show the changing effects of man's impact on northern water ecosystems under varying conditions of anthropogenic pollution and impossible

return to natural conditions after a period of heavy anthropogenic stress (toxins and nutrients), because aquatic ecosystems with new parameters attain stability.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (Projects no 10-05-00854) and by a grant from the Government of Russia (№ 11G34.31.0036). ■

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RISK ASSESSMENT OF ENCOUNTERING KILLER WAVES IN THE BLACK SEA

ABSTRACT. The problem of assessing the risk for a vessel to encounter a killer wave in the Black Sea is considered. Analysis of in situ wave data obtained from the platform of Marine Hydrophysical Institute in the autumn of 2009 shows that occurrence frequency of abnormally high waves (freak, rogue, or killer waves) varies considerably on the time scale of several hours. It is shown that the formation of such waves is associated with nonlinear processes in the wave field, presumably, with the development of modulational instability. Ninety percent of the total number of killer waves was observed in the swell wave system, and 70% of them propagated approximately in wind direction. We propose a scenario of the killer waves formation in the Black Sea. The scenario was confirmed by numerical reconstruction of the wind and wave fields in the Black Sea for the history of storms on Oct. 14, 2009 in Katsiveli and on Feb. 01, 2003 in Gelendzhik, using the MM5 mesoscale atmospheric model and the WAM-C4 wave model. A practical approach to assessing the risk for a vessel to encounter a killer wave in the Black Sea is presented.

KEY WORDS: storm seas, killer/freak/rogue waves, Benjamin-Feir instability, field study in the Black Sea, numerical recovery of wind and wave fields, risk assessment for extreme maritime events.

INTRODUCTION

Extreme high sea waves have long been known legends and folklore of many countries. In English literature, the most

common names are “freak waves” and “rogue waves”, i.e., the unusual, bizarre, wondering waves, which appear “from nowhere”, even in the absence of strong wind, and stand out from the surrounding wind waves because of their abnormal height and steepness. In Russian literature, they are called “killer waves”. Encounters with killer waves may cause damage or loss of a vessel or life. A description of such incidents is the subject of numerous publications (see e.g., [Kurkin and Pelinovsky, 2004; Dotsenko and Ivanov, 2006; Kharif, et al., 2009]). To date, forecast of occurrence of killer waves and risk assessment of vessels' encounters with killer waves remain pressing problems of environmental safety.

In recent decades, there has been steadily increasing interest in the extremely high waves on the sea surface and, consequently, a growing number of publications on various issues related to killer waves. This is due to recognition of the fact that killer waves are not extremely rare, and they, apparently, can be found in all regions of the world ocean [Kharif, et al., 2009]. Moreover, there is a point of view that, in the future, frequency of encounters with killer waves will increase due to climate change [Osborne, et al., 2005]. In the Black Sea, for the first time, a killer wave was recorded by a wave-monitoring buoy in 2001 near Gelendzhik [Divinsky, et al., 2003]. Since then, the number of instrumental observations of the anomalous high waves in the Black Sea has increased significantly [Kuznetsov, et al, 2006; Dotsenko, et al., 2009,

2010; Saprykina, et al., 2010; Kuznetsov, et al., 2011].

To date, a number of possible physical mechanisms of the killer wave formation are known. Their detailed description with a broad review of the literature is given in the book by Kharif, Pelinovsky, and Slunyaev [2009]. The most common point of view is that the concentration of wave energy, necessary to form extremely high waves, is the result of wave focusing. There are different types of wave focusing: spatial (geometrical) focusing caused by inhomogeneities of the marine environment, currents, topography, and weather conditions; temporal focusing (or “dispersion compression”) associated with nonstationarity of the medium or with a special character of wave generation; and “non-linear focusing” during the development of modulational instability of a homogeneous train of waves, also known as the Benjamin-Feir instability. The possibility of the formation of the abnormally high waves as a result of these mechanisms is confirmed by numerical simulations and in laboratory experiments.

For a “purely” nonlinear mechanism associated with modulational instability, in order for killer waves to form, it is not necessary to have special focusing properties of the marine environment in the form of spatial or temporal inhomogeneities. The efficiency of the nonlinear mechanism is determined by the steepness or the “nonlinearity parameter” of the waves $\varepsilon = \varepsilon / ak$, where a is the amplitude, and k is the wave number. Several authors have given a possible explanation of the killer waves’ properties being a result of modulational instability ([Onorato, et al., 2001; Janssen, 2003; Socquet-Juglard, et al., 2005; Chalikov, 2007; Zakharov, et al., 2008], etc.). Under this interpretation, the following theory for the killer wave prediction was proposed [Janssen, 2003; Mori and Janssen, 2006]. The result of this prediction is the probability of wave occurrence with a height H exceeding

the significant wave height H_s by a specified number of times $n = H/H_s$:

$$P_H(n) = \exp(-2n^2) \times \left[1 + 2n^2(n^2 - 1) \frac{\pi}{3\sqrt{3}} BFI^2 \right].$$

This probability can be calculated using the Benjamin-Feir index (*BFI*):

$$BFI = \sqrt{2} \varepsilon f_p / \Delta f \quad (1),$$

where f_p is the frequency of the wave spectral peak, ε and Δf is steepness of waves and the width of the frequency spectrum defined, in one way or another, from the wave spectrum.

The wave spectrum can be predicted traditionally using the WAM-models and wind field forecast (see, e.g., [Komen, et al., 1994]). Under this approach and beginning in 2003, the ECMWF (European Center for Medium Range Weather Forecast) has been producing the *BFI* among formal parameters of prediction of the probability of extremely dangerous sea waves: if *BFI* is close to 1, the situation may be considered hazardous. To date, however, there are apparently no known facts that support the usefulness of such a forecast for the prevention of ship encounters with killer waves (see also extensive discussion of the problem in [Kharif, et al., 2009, pp 162–164]).

Focusing of the wave field by all of the abovementioned physical mechanisms is only effective if a wave is quasi-monochromatic, i.e., when the spectrum is narrow enough both in frequency and direction of wave propagation (see, e.g., [Kharif, et al., 2009]). This condition for the width of the spectrum in the frequency domain is shown in Equation (1) for *BFI*: decrease of Δf causes increase of *BFI* and, accordingly, the probability of occurrence of extremely high waves. However, the condition of a sufficiently small angular width of the spectrum is definitely not the

case for the well-known empirical models of the wind wave spectra [Onorato, et al., 2009]. Thus, one can expect that modulational instability in the real seas will develop only at a special shape of the wind wave spectrum that differs significantly from what is usually observed. On the other hand, waves of swell coming from a remote area of a storm and not related to local winds have a relatively narrow spectrum. As it follows from (1), the system of swell waves with sufficient steepness would have BFI close to 1 and, thus, could produce killer waves. In the Black Sea, as a rule, there are a system of wind waves and a system (or multiple systems) of swell observed simultaneously. Most often, the system of swell dominates and the waves of the spectrum peak relate specifically to this system.

Professional sailors are well aware of high-risk situations when wind increases in the same direction as the swell. In particular, in such circumstances, the inhabitants of the Crimean coast, for fear of accidents, do not go out to sea on small vessels. Considering the arguments presented above, the following possible explanation of this tradition may be suggested. A collinear wind enhances the swell. Upon swell waves reaching a sufficiently steep slope, modulational instability develops and produces sporadically the abnormally high waves. As a result, the wave situation at sea becomes dangerous.

This scenario is supported by [Tamura, et al., 2009], where a model reconstruction of the wind and wave conditions for the time of the accident in the Kuroshio region has been performed; specifically, a fishing boat with twenty crewmembers sank as a result of an encounter with killer waves. Note also that there are publications discussing the swell effect on occurrence of killer waves in the wind-driven wave system ([Donelan and Magnusson, 2005; Gramstad and Trulsen, 2010], etc.). In these papers, it was assumed that killer waves are unlikely to occur in the swell system due to lack of sufficient steepness of swell waves.

The issues discussed above provide motivation for writing this paper. Its main purpose is to show the applicability of the viewpoint that the formation of killer waves in the Black Sea is mainly the result of modulational instability of swell waves and that a particular danger is associated with the situation when swell waves propagate in the direction of wind. The work is based on the analysis of the experimental data obtained in the joint field experiment of the Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine (MHI) and P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO) in 2009 [Saprykina, et al., 2010; Kuznetsov, et al., 2011].

The paper is organized to present these data and to consistently answer the following questions: i) whether it is possible to interpret the field observations of anomalously high waves in the Black Sea as the development of modulational instability, ii) whether the abnormally high waves in the Black Sea are associated with swell waves, and iii) whether collinear wind and swell waves lead to the emergence of killer waves. In conclusion, the paper presents a simple procedure of estimating the risk of a ship encountering a killer wave in the Black Sea built on the assumption that all answers to the questions posted above are positive. The procedure may be applied in the practice of navigation.

THE FIELD EXPERIMENT

The joint field experiments of IO and MHI [Saprykina, et al., 2010] was carried out from Oct. 12 to Nov. 6, 2009, at the stationary oceanographic platform of the Experimental Department of MHI (the settlement Katsiveli, the southern coast of Crimea, located at 44°23'N 33°59'E). The photo of the platform and the schematic representation of its location relative to the coastline are shown in Fig. 1. The distance to the nearest coastal point is approximately 0.5 km. The sea depth at the platform location is 28 m.

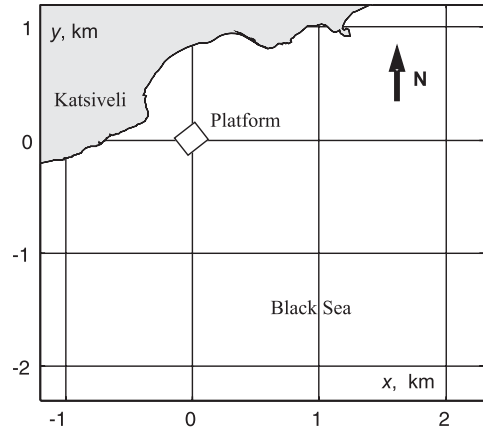


Fig. 1. The research platform of MHI near the settlement Katsiveli. The general view and the layout

For a complete spatial recording of surface waves, two wave gauge arrays (WGAs) were used simultaneously. The “small” WGA was composed of five string resistance sensors located at the vertices of a regular pentagon at a distance of 25 cm from the center and of one at its center. The whole construction was suspended on a lifting boom at a distance of 10 m from the nearest platform column. The suspension system allows through-calibration of the measuring by the vertical displacement of the sensors at accurately measured distances. With this well-controlled linearity of the sensor, a fundamentally important property in evaluating characteristics of nonlinear waves was achieved.

The “large” WGA included four string capacitive sensors, spaced at distances from 3 to 16 m in order to increase the angular resolution of the sensor system for the longest surface waves. The “large” WGA operated during Oct. 12–24; the “small” WGA operated through the entire duration of the experiment. Each WGA had its own recording equipment with a sampling frequency of 10 Hz or greater. Continuous wave recordings were conducted for periods ranging from several hours to several days. In addition, a meteorological complex operated continuously with an autonomous registration system, which recorded meteorological parameters every minute, including wind speed and direction

at the horizon of 23 m. In order to avoid false alarms associated with ship waves, only those records where the significant wave height exceeded 0.5 m were selected for processing. The total length of the records was 217 hours.

To calculate wave characteristics, the data sets were broken down into non-overlapping twenty-minute intervals. For each interval, the maximum wave height H_{\max} , the variance $\sigma^2 = \langle \zeta^2 \rangle$, and the fourth central moment $\mu_4 = \langle \zeta^4 \rangle$, where ζ is the elevation of the sea surface relative to the average level, as well as the significant wave height $H_5 = 4\sigma$ and kurtosis of distributions of elevations $K_t = \mu_4/\sigma^4$, which characterizes the intensity of nonlinear interactions in the wave field [Janssen, 2003], were determined.

To identify killer waves in the instrumental records of the surface waves, there are a number of criteria based on the characteristics of individual waves (see, e.g., [Guedes Soares, et al., 2004; Kurkin and Pelinovsky, 2004; Kharif, et al., 2009]). Typically, these definitions are descriptive in nature and not related to the physical mechanisms and conditions of the formation of killer waves. At the same time the results of laboratory studies of killer waves can be extended to natural conditions using dimensional consideration. If period of the waves in an experimental tank is m times less than in natural conditions, then,

in the transition to the field conditions, all geometric dimensions of the waves must be multiplied by m^2 . This follows from the linear dispersion relation for the surface waves in deep water. It is essential to keep constant the steepness of the waves at the transition, as a parameter that determines the intensity of nonlinear processes. For this reason, the most widely used simple criterion for the selection of killer waves in practice is the height of the abnormally high waves that is two or more times greater than the significant wave height [Kharif, et al., 2009]:

$$H > 2H_s, \quad (2)$$

In this case, the definition of killer waves includes relatively low waves, for example, with a height of about two meters that, in the usual sense, are not dangerous. However, the records of such waves can be used to study physical mechanisms of the formation of real killer waves.

Using criterion (2), 40 abnormally high waves were identified. Fig. 2 shows an example of such a wave. The fact that killer waves are not very rare events is consistent with earlier research (see, e.g., [Liu and Pinho, 2004; Kharif, et al., 2009]). However, the moments of their appearance are clearly not associated with local wind speed and wave height. These points are non-uniformly distributed over time.

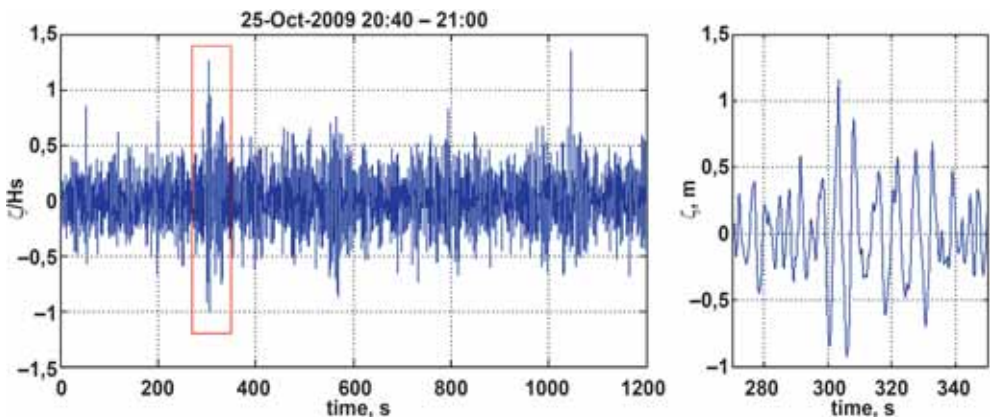


Fig. 2. A fragment of a record of the sea surface elevations containing a wave of the anomalous height. This wave and its neighborhood are marked by the rectangle and are shown, in detail, on the right

Fig. 3 illustrates non-uniformity of frequency of occurrence of killer waves on a time-scale of about an hour during the storm in Katsiveli on Oct. 14, 2009. The figure shows wind speed, its direction, and the significant wave height as the functions of time. In addition, frequency of occurrence of anomalous waves N , selected according to the criterion (2) for the time interval of one hour and summed over all nine sensors, are shown. In the intervals 04:00–08:00 and 09:00–13:30, the anomalous wave heights were observed quite frequently; in the interval 13:30–16:40, they were entirely absent. Variability of N in Fig. 3, obviously, does not follow any changes of wind speed or the significant wave height.

Fig. 4 shows the probability density function (*PDF*) of elevations of the sea surface from the mean sea level, normalized at H_s that was obtained from the combined data of nine sensors for the time-intervals 10:00–11:00 and 13:40–14:40. It also shows the Gaussian curve corresponding to the linear, i.e., non-interacting, waves. As can be seen from the figure, during the time of observation of abnormally high waves, the shape of *PDF* is very different from the Gaussian. That is in this case, the wave field has clearly nonlinear properties [Janssen, 2003; Onorato, et al., 2009].

Fig. 5 shows dependency of the index of abnormality, $A_i = H_{\max}/H_s$ [Kharif, et al., 2009],

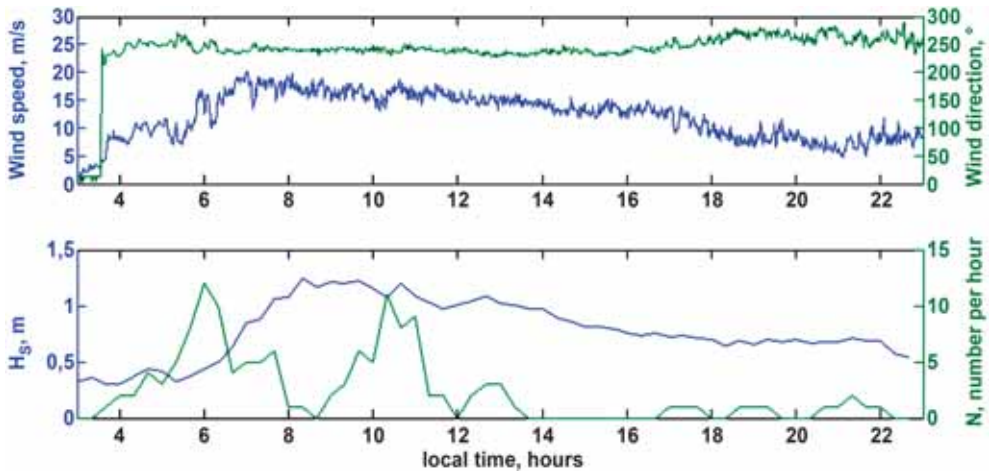


Fig. 3. The observations from the platform in Katsiveli on Oct. 14, 2009: wind speed and direction (top), the significant wave height H_s and frequency of occurrence of waves of the anomalous height (bottom)

on the value of kurtosis for all recordings of the experiment. The value of kurtosis is three for the linear waves, and the kurtosis deviation from three characterizes the nonlinear processes in the wave field [Janssen, 2003]. The graph shows a clear relation between the degree of waves' abnormality and nonlinear interactions. A similar relationship was reported in [Shin

and Hong, 2009] for a three-year long registration of waves in the open part of the Yellow Sea. Three blue dashed lines in Fig. 5 show the logarithmic approximation of this dependence obtained for the data for 2004, 2005, and 2006 by Shin and Hong [2009]. The same form of approximation of our data reads $A_i = 1,82 \ln(\kappa_i) - 0,27$. The corresponding curve is shown in the figure in red.

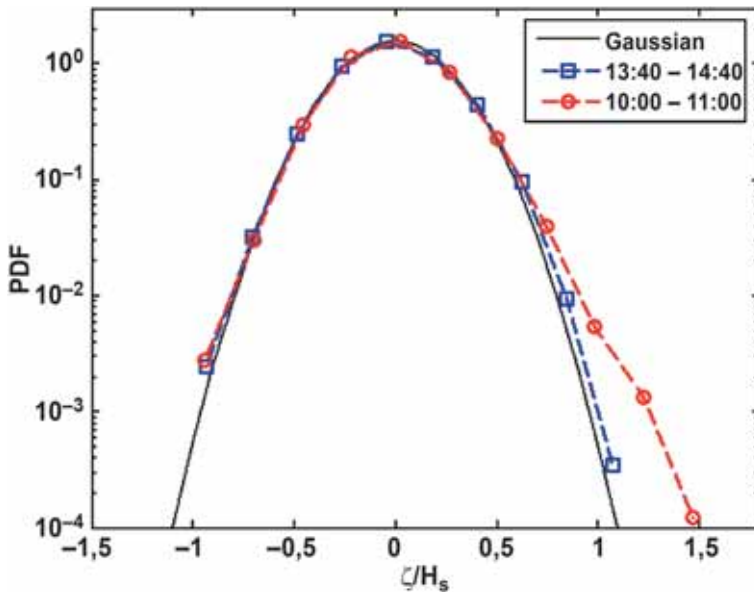


Fig. 4. PDF of the normalized sea surface elevations for the time intervals of higher and lower occurrence frequency of waves of the anomalous height. Solid line shows the normal distribution

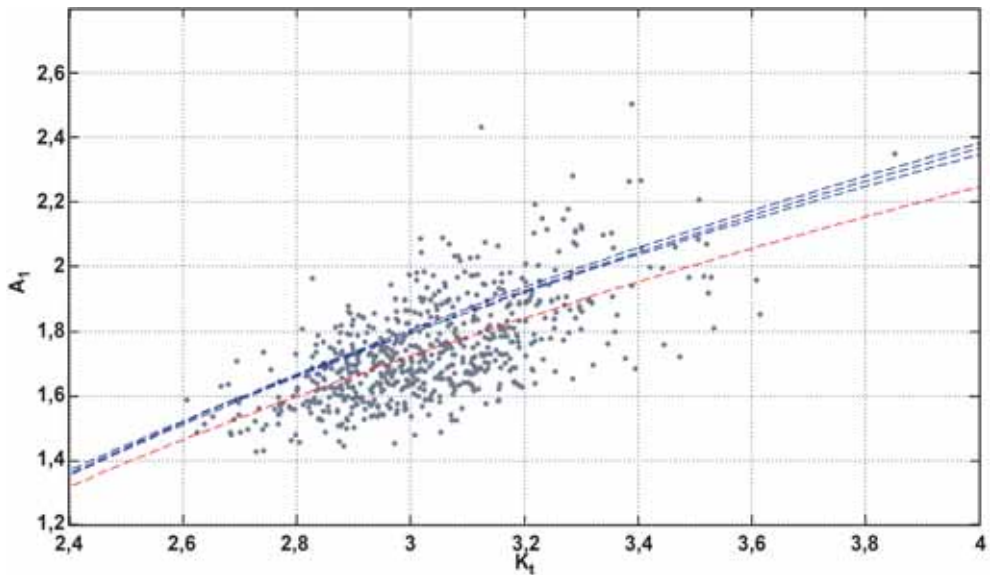


Fig. 5. The relation between the abnormality index and kurtosis. The points represent the experimental data; the red line is the average dependence; the blue lines are the results of Shin and Hong [2009]

It demonstrates the agreement between the observations in the Black Sea and the Yellow Sea. The absence of an exact correspondence between the approximating curves may be due to differences in measurement techniques [Shin and Hong, 2009]. Note also that our data allow the estimation of BFI from the wave spectra, but we, like Shin and Hong [2009], were not able to identify its connection with the abnormally high waves.

Review of the experimental results shows that formation of the anomalously high waves is connected with nonlinear processes in the sea wave field. The index of abnormality A_1 is related to kurtosis on average, and this interrelationship is similar to the one obtained in the Yellow Sea. The frequency of occurrence of the abnormally high waves varies considerably over a time scale of several hours. It follows that the most favorable conditions for the formation of killer waves in the Black Sea are realized at such time scales. The search for these conditions is the natural approach to predict the most dangerous storm situations when encounters of ships with killer waves are possible.

THE ANALYSIS OF WIND AND WAVE CONDITIONS OF THE OCCURRENCE OF ABNORMAL WAVES

The definite separation of sea surface waves into the swell and the wind systems, as a rule, is associated with a certain difficulty, especially when the directions of propagation of the waves of both systems are similar. Therefore, below, we will describe, in detail, the procedure for the spectral partitioning that is applied in this paper. Fig. 6 shows an example of the wave spectrum on Oct. 14, 2009, estimated from the measurements of the "big" and "small" WGAs. The figure also shows wind speed and direction, averaged over the time-period for which the spectrum was estimated. The frequency spectra $S_1(f)$ were estimated by the Welch's method (averaging the spectra estimations obtained from half-overlapping segments of realizations). The frequency-angular spectra $S_2(f, \phi)$ were estimated by the maximum-likelihood method [Johnson, 1999]. The vertical axes represent the direction of the waves, i.e., the geographical azimuth from which the waves come. This manner of presentation of the spectra is useful for comparison with wind direction, indicating "where from". Fig. 6 shows two two-dimensional spectra of the sea

surface elevations obtained from the data of the “big” and “small” WGAs. Both spectra give the same overall pattern, but the data of the “big” WGA reveal details of the angular distribution of energy for the waves with the greatest lengths (in Fig. 6, 0.1–0.2 Hz frequencies correspond to the wavelengths of up to 70 m).

Since the wave spectra subside rapidly with increasing frequency, only the region of the spectral peak is clearly visible in a linear scale. To get an idea of the spectrum of higher frequencies, which is usually associated with local wind, it is convenient to consider a two-dimensional slope spectrum, which is, in the angular-frequency representation, proportional to the value of $f^4 S_2(f, \phi)$. Specifically this quantity estimated from the data of the “small” WGA is shown in Fig. 6 as the spectrum of the slopes. As Fig. 6 shows, propagation direction of the short-wave part of the spectrum corresponds to the direction of wind.

It should be noted that traditional methods for evaluating a two-dimensional wave spectrum from measurements by the WGA (the maximum likelihood estimation and the maximum entropy estimation) overestimate the angular width of the spectrum [Young, 1994]. Therefore, our data do not allow using the angular width of the spectrum to separate swell and wind waves. In the plot of the frequency spectrum (Fig. 6, left sub-plot), the vertical line marks the Pierson-Moskowitz spectral peak frequency calculated using the local wind speed U : $f_{PM} = 0,83g/(2\pi U)$ [Komen, et al., 1994]. If we consider the Pierson-Moskowitz spectrum as fully developed, then the waves of the spectral peak can be attributed to the swell when the spectral peak has a frequency of less than f_{PM} . In our case, this method of separation of swell and wind waves is not suitable. A more effective approach proposed by Hanson and Phillips [1999] is based on the theory of the equilibrium range of Phillips [1985]. To explain it, the plot of the frequency spectrum shows the Toba spectra as two dotted lines $S(\omega) = \alpha g u_* \omega^{-4}$, where $\omega = 2\pi f$,

u_* is the friction velocity in the air, while the coefficient α for the two lines is equal to 0.06 and 0.11. According to Hanson and Phillips [1999], the frequency spectrum of the wind system associated with local wind in the area to the right of its spectral peak must lie in the band formed by these lines. This is exactly what we see in Fig. 6. The spectral peak of the wind system defined in the frequency spectrum by means of this criterion is clearly seen on the frequency-angular spectrum of the slopes and the direction of the waves of this peak area corresponds to the direction of local wind. We emphasize that, in this case, separation is possible, despite the fact that the spectrum, at first glance, looks like having a single peak and the directions of the wind system and of the swell waves are similar.

Having relatively long-time records of sea waves, one can confirm the verity of the separation considering the history of the wave spectrum. Often, in such situations, swell waves are clearly distinguished by comparing their peak with the Pierson-Moskowitz spectral peak frequency. Then, with increasing wind speed, the frequency peak of swell waves remains practically invariable, while the peak of developing wind systems, isolated in the frequency-angular spectrum using the Hanson and Phillips method, evolves in the direction of decreasing frequency. Note, that for the application of this approach, it is sufficient to know the Toba spectrum level only approximately. Therefore, in our analysis, the value of the friction velocity was estimated by the aerodynamic bulk formula $u_* = \sqrt{C_D} U$, where drag coefficient was set to $C_D = 1.5 \cdot 10^{-3}$.

Fig. 7 illustrates the analysis of the wind and wave conditions for Oct. 14 based on the approach described above, when the frequency spectrum and the frequency-angular spectra of elevations and slopes of the waves were considered together. In the time interval 00:00–02:00, light swell waves, arriving from the east, were observed ($f_p = 0.22$ – 0.25 Hz, $H_s < 0.5$ m). A moderate east wind ($U = 7$ – 9 m/s) was accompanied by

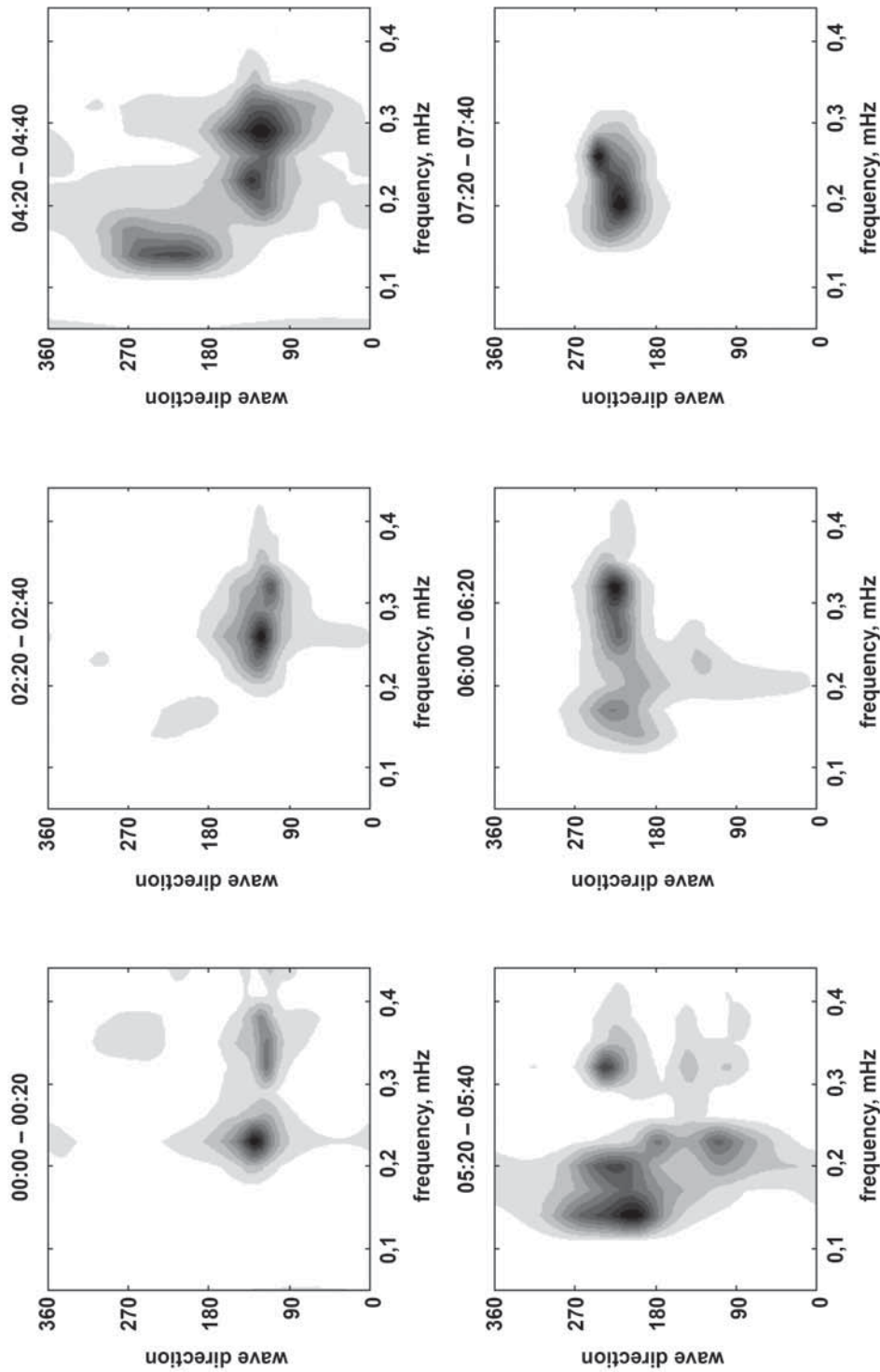


Fig. 7. Evolution of the frequency-angular spectra of the sea elevations on Oct. 14, 2009

the wind-wave system ($f_p = 0.33\text{--}0.35$ Hz). At 2:20, a weak swell system arriving from the southwest appeared on the wave spectrum. Frequency of this system's peak was 0.14 Hz; it did not change the significant wave height H_s . At the same time, wind speed began to decay and wind direction to rotate. From 2:20 to 04:00, wind speed was weak ($U < 3$ m/s) and wind direction changed from east to north and further west. The wave heights remained low ($H_s < 0.5$ m) and the same wave systems dominated. There was also a new weak southwestern wave system with a persistent frequency peak.

At about 4:00, wind speed increased to 7–9 m/s and its direction was set at the azimuths of $230^\circ\text{--}250^\circ$. Between 04:00–05:00, there was strengthening of the southwestern swell waves and weakening of the eastern swell waves. Around 5:00, the spectral levels of these systems were already similar. During this period, the southeastern wind system with a peak frequency of 0.33 Hz emerged.

By 6:00, wind speed continued to increase and there was an increase of the wave heights due to increased spectral levels, both of the southwestern swell waves and of the wind system. On the frequency-angular spectra of the wave elevations, the eastern wave systems became indistinguishable. Wind speed continued to increase and the wind system continued to develop – its spectrum level increased and the peak frequency decreased. The spectral level of the swell-wave peak increased also, and its frequency decreased – there was a convergence of the peaks of the swell waves and the wind waves. By 8:00, it was already not possible to isolate the swell system from the wind system in the spectrum of the merged wave systems with a peak at 0.2 Hz frequency. This situation continued until 09:00. Note, that at 05:00–08:00, when there was development of the wind systems on the background of already existing swell waves of the same direction, there was intensification of occurrences of the abnormally high waves (see Fig. 3).

After 9:00, a new peak of the wind system, corresponding to 0.5–0.6 Hz frequencies, became visible in the spectra. The new wind system was isolated based on the Hanson and Phillips technique: its spectral level fell into the band of the “Toba spectra», while the spectral level of the “old” wave system was lower. This situation was shown on Fig. 6 above, where seas consisted of the energy-carrying long-wave (“old”) system and of developing wind system. Although the energy-carrying system cannot be attributed to swell waves formally, in this case, physical situation was the same as at 05:00–08:00, when there was development of the wind system on the background of already existing swell waves of the same direction. Again, there was more frequent occurrence of the abnormally high waves. From 10:00, there was a gradual decrease in frequency of the spectral peak of swell waves and a fall of its spectral level that apparently led to the disappearance of the abnormally high waves by 14:00.

The waves of abnormal heights observed in this case had periods of 6 s or longer corresponding to swell waves (see Fig. 3), i.e., the conditions for realization of modulational instability appear to have been satisfied. Therefore, let us consider whether we can interpret this case as realization of modulational instability.

According to theoretical concepts [Janssen, 2003; Kharif, et al., 2009; Kartashova and Shugan, 2011], modulational instability represents a discrete energy cascade, in which the wave spectrum have additional peaks corresponding to resonance conditions. An important feature of the manifestation of modulational instability is discrete changes in the spectrum as it evolves. This phenomenon can be seen in a long lab tank, where sequential stages of the cascade occur at various distances from the wavemaker [Kuznetsov and Saprykina, 2009]. As was demonstrated in the laboratory studies under conditions of modulational instability, a shift of frequency of the spectral peak into the low-frequency region is discrete,

both in frequency and in the distance from the wavemaker (see Fig. 6 in [Kuznetsov and Saprykina, 2009]). At the same time, as instability develops, regular groups of waves are transformed into rather irregular wave pattern with clear-distinguished “freaks” of the form of abnormally high waves. The higher the initial steepness of the waves, the faster (the closer to the wavemaker) the new killer waves appear, but evolution of the spectrum for different initial wave steepness proceeds under approximately the same scenario.

Fig. 8 shows evolution of the frequency spectrum of the waves observed in the experiment in Katsiveli on Oct. 14, from 07:00 to 14:00. The spectra are presented in three dimensions as a function of frequency and time. Each spectrum was estimated for a one hour interval that corresponds to 38 degrees of freedom. One can see edges on the surface $S(f, t)$. The height of the high-frequency edges decreases with time while the height of the low-frequency edges grows. As a result, spectral peak downshifting takes place. At the same time, the edges are parallel to the axis of time, indicating the discrete pattern of energy transfer into the low-frequency region. It was during this time-period that killer waves were observed, as discussed above. Note that the wave recording shown in Fig.

2 refers to the time-period under discussion. The pattern of irregularity of the waves on this figure is similar to that observed in laboratory experiments when modulational instability occurred (see Fig.6 in [Kuznetsov and Saprykina, 2009]). Thus, it is reasonable to treat the situation recorded on Oct. 14 as modulational instability, which was accompanied by the formation of waves with abnormal heights.

Let us discuss the issue of strengthening of swell waves by local wind. The area of the storm is a source of swell waves propagating in the direction of wind in the storm area. Further, due to the angular and dispersion divergence of the waves, the swell wave spectrum becomes narrow, both in frequency and direction. It is exactly this feature of swell waves that could result in modulational instability [Onorato, et al., 2009] in the area remote from the zone of the storm. However, due to divergence and attenuation of the waves, their steepness decreases and, therefore, intensity of nonlinear processes decreases also. In order to instability to occur, the strengthening of swell waves is necessary. It can be assumed that strengthening of swell waves on Oct. 14 was due to the wind that blew in the direction of swell waves. Note that different versions of the traditional wave models WAM correctly describe evolution of waves only for long (an

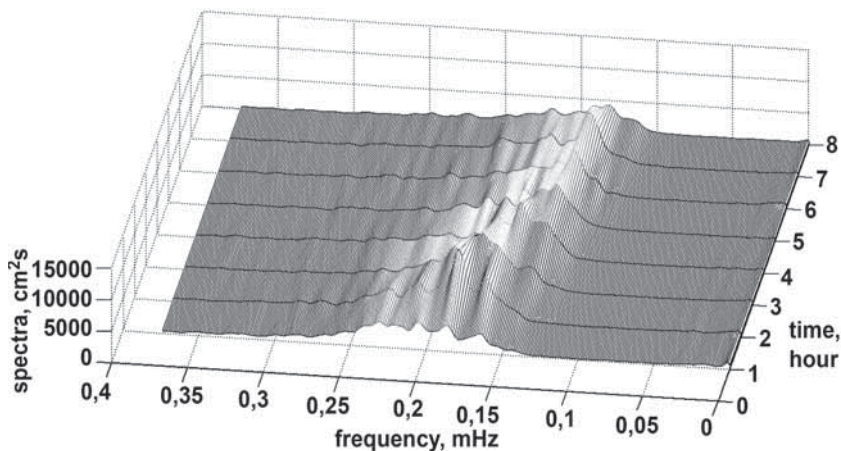


Fig. 8. Evolution of the wave spectrum from 07:00 to 14:00 on Oct. 14, 2009.
Label 1 on the time axis corresponds to 07:00

hour or more) time-periods. This is due to the fact that they treat four-wave interactions just as resonant [Komen, et al., 1994]. At the same time, "quasi-resonant" four-wave interactions lead to a much more rapid evolution of the spectra [Annenkov and Shrira, 2009; Badulin, et al., 2009]. In [Badulin, et al., 2009] the mechanism of amplification of swell waves due to "fast" quasi-resonant four-wave interaction with wind waves propagating in the same direction has been simulated. As the result of this interaction, there was a rapid transfer of energy from the wind waves to the swell, while the development of wind waves practically ceased. It is possible that precisely this situation was observed on Oct. 14, 2009.

The procedure of separation of swell and wind waves described above was applied to all processed records. Wind-wave situations were divided into three classes: "1" – the main spectral peak corresponds to the system of wind waves, "2" – the main spectral peak is due to the system of swell waves and swell direction corresponds to wind direction within 45 degrees; "3" – mixed seas with prevailing swell waves, including calm conditions when the system of wind waves was absent.

Only four (10%) of the 40 recorded abnormally high waves were observed in the situation with purely wind seas; the rest of the abnormally high waves appeared in the swell system. Of these, 28 (70%) were observed in situation "2" when the direction of propagation of swell waves was close to that of wind.

Thus, on Oct. 14, 2009, there was amplification of swell waves by wind of the same direction. This resulted in a narrow spectrum of relatively steep swell and high frequency of occurrence of the abnormally high waves. These waves presumably formed as the result of modulational instability. This scenario of higher occurrence frequency of killer waves (high-risk situations) dominated through the entire experiment.

THE SIMULATION OF WIND-WAVE CONDITIONS OF THE KILLER WAVES FORMATION

Let us consider what the synoptic conditions are conducive to the local wind-wave situations of higher occurrence frequency of the abnormally high waves. For this, we will perform a model reconstruction of the storms on Oct. 14, 2009 (discussed above) and on Feb. 1, 2003, when there were abnormal waves in the area of Gelendzhik (as described in [Divinsky, et al., 2004; Kuznetsov, et al., 2006; Kuznetsov and Saprykina, 2009]). That is we will analyze the wind-wave fields in the Black Sea for the periods corresponding to these instrumental observations.

For the reconstruction of the wave field, the wind fields at the 6-km grid with a time-step of one hour were calculated with the help of the regional mesoscale atmospheric model MM5 [Dudhia, 1993], developed by the US National Center for Environmental Prediction/National Centers of Atmospheric Research (NCEP/NCAR). To set the boundary conditions, reanalysis data NCEP/NCAR, presented in the public domain, were used. The wave spectra were calculated using the wind fields and the model WAM-C4 [The WAMDI group, 1998; Yefimov, et al., 1998].

At night on Oct. 13, preceding the formation of the abnormally high waves at the platform in Katsiveli, an atmospheric cold front passed across the Black Sea. Fig. 9 illustrates the wind speed field at 21:00 and 24:00, local time, on Oct. 13. The wind speed in the front area exceeded 16 m/s and wind was primarily of the northern direction. Accordingly, the zone of the storm was moving with the zone of the strongest wind. Fig. 10 shows the fields of wind speed and waves at 3:00, local time, on Oct. 14. It can be concluded from the figure that in the neighborhood of a point with the coordinates 43°N 33°E, there had already been waves with the period of about 6 s. Their group velocity was about 5 m/s. Therefore, propagating in the direction of Katsiveli, they were able to reach the platform after 6 hours in the form of

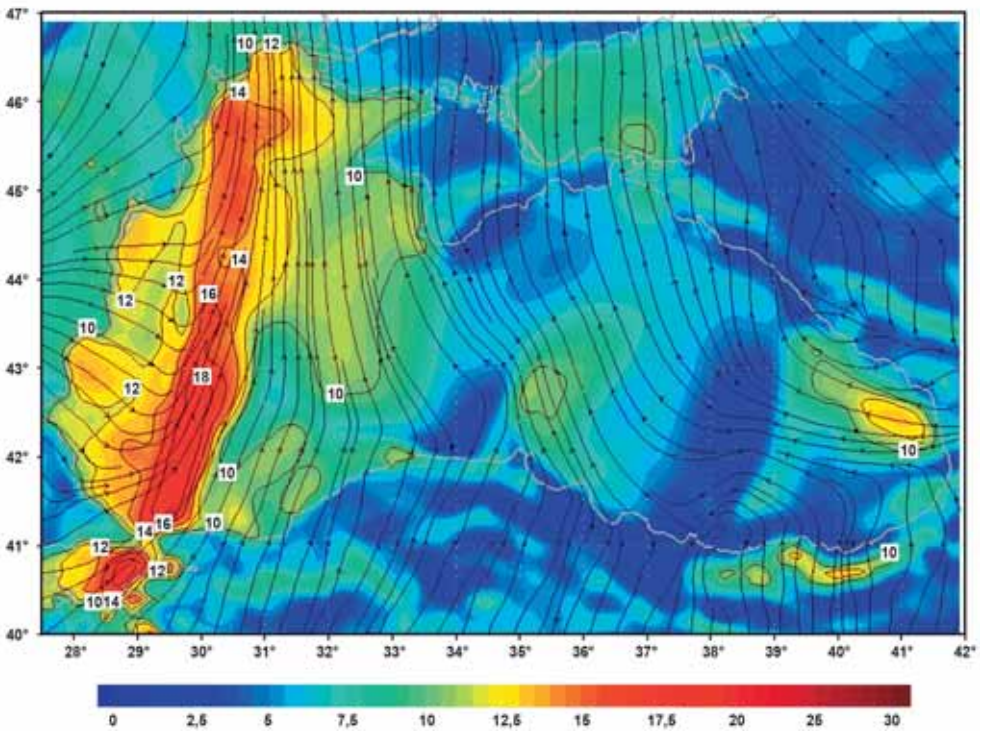
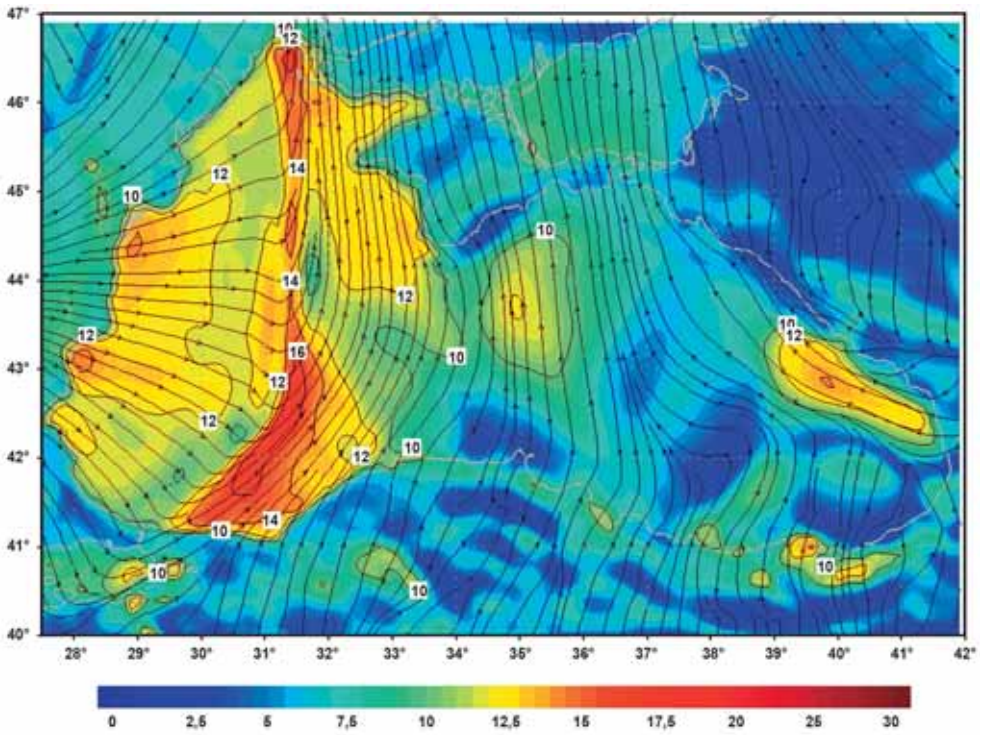


Fig. 9. The results of the simulation. Movement of the atmospheric front over the Black Sea. The fields of wind speed and direction at 21:00 (top) and 24:00 (bottom) on Oct. 13, 2009, local time. The color scale gives wind speed in m/s

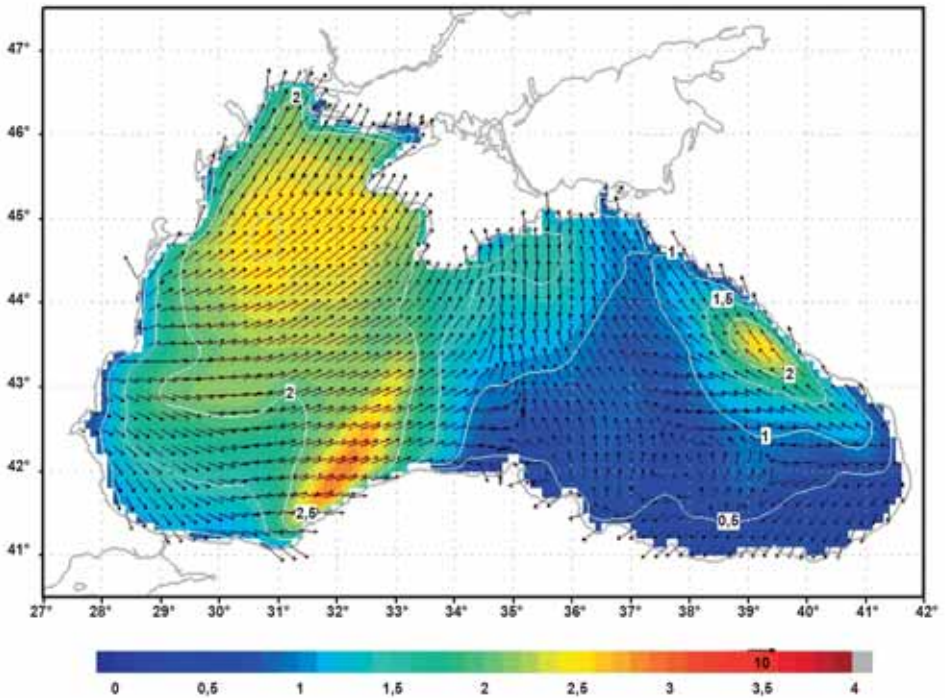
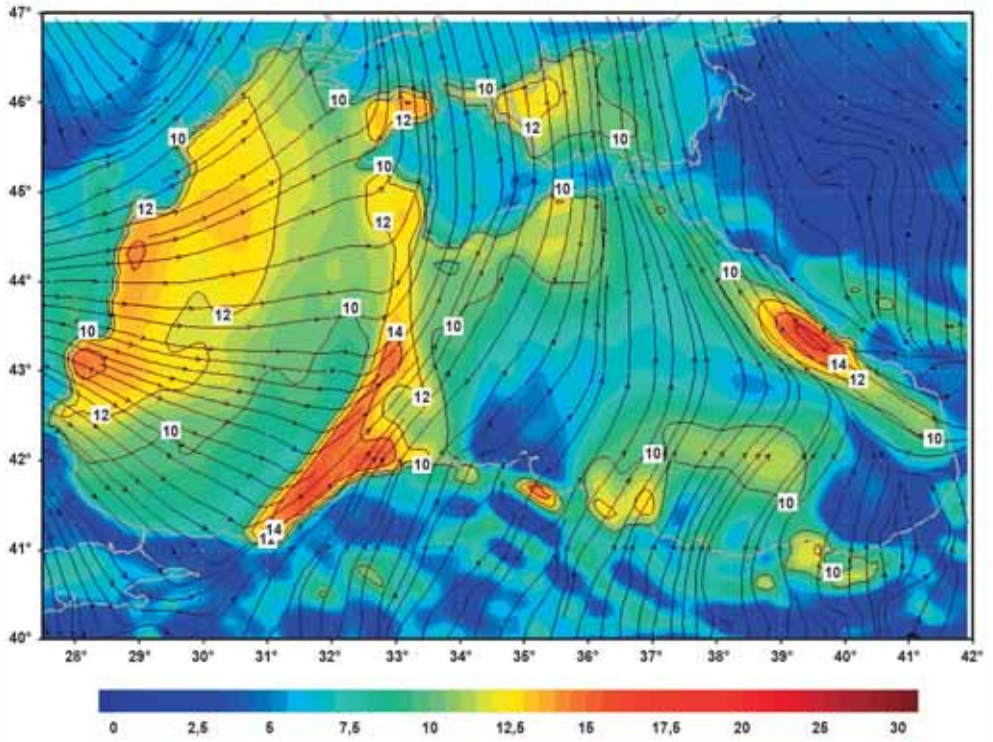


Fig. 10. The results of the simulation. The field of wind (top) and waves (bottom) on Oct. 14, at 3:00, local time. The color scales represent wind speed in m/s and wave height in m ; the arrows indicate the direction of the waves; the length of the arrows shows the wave period in s when compared to the scale of $10 s$ given in the area of the color scale

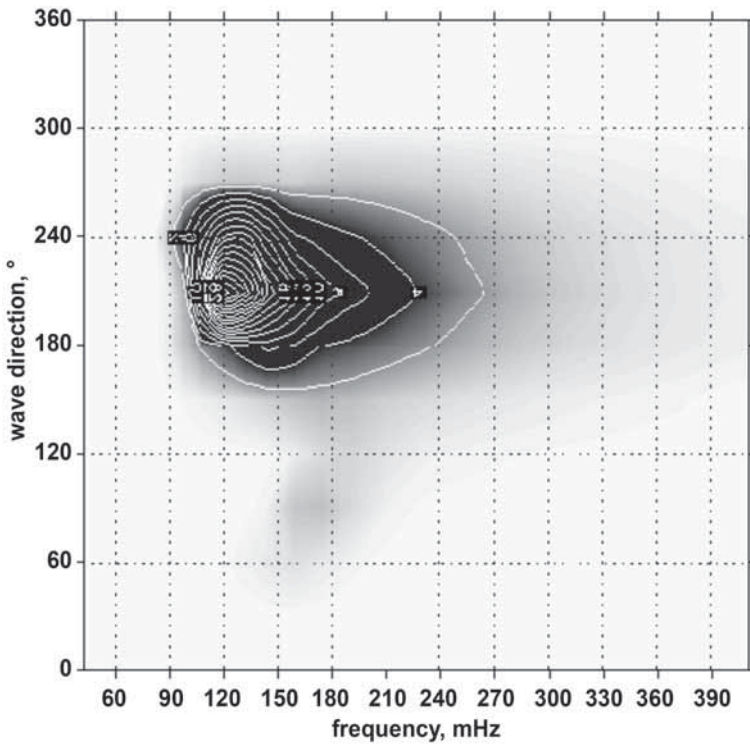


Fig. 11. The simulated spectrum of the waves at 12:00, local time, on Oct. 14, 2009

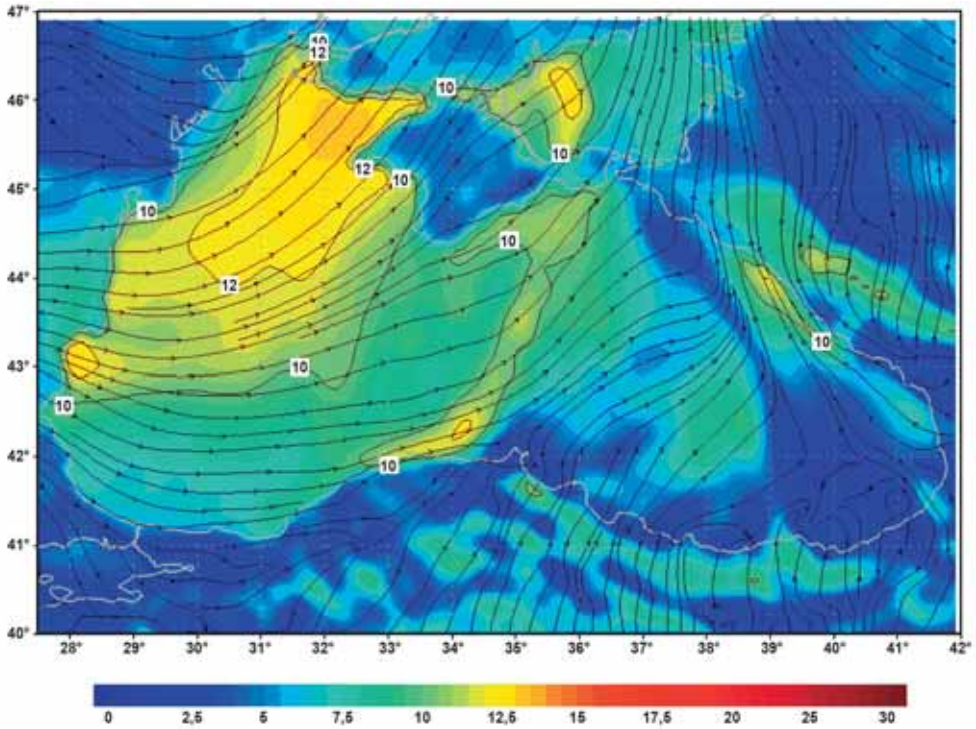


Fig. 12. The simulated wind field at 9:00, local time, on Oct. 14, 2009

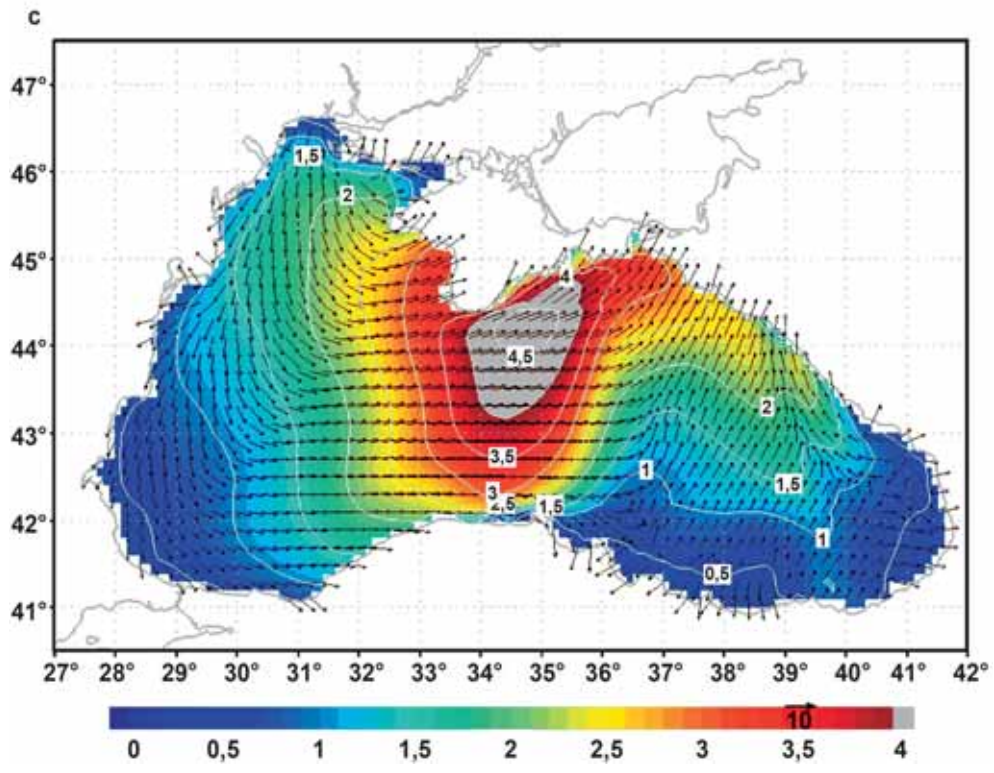
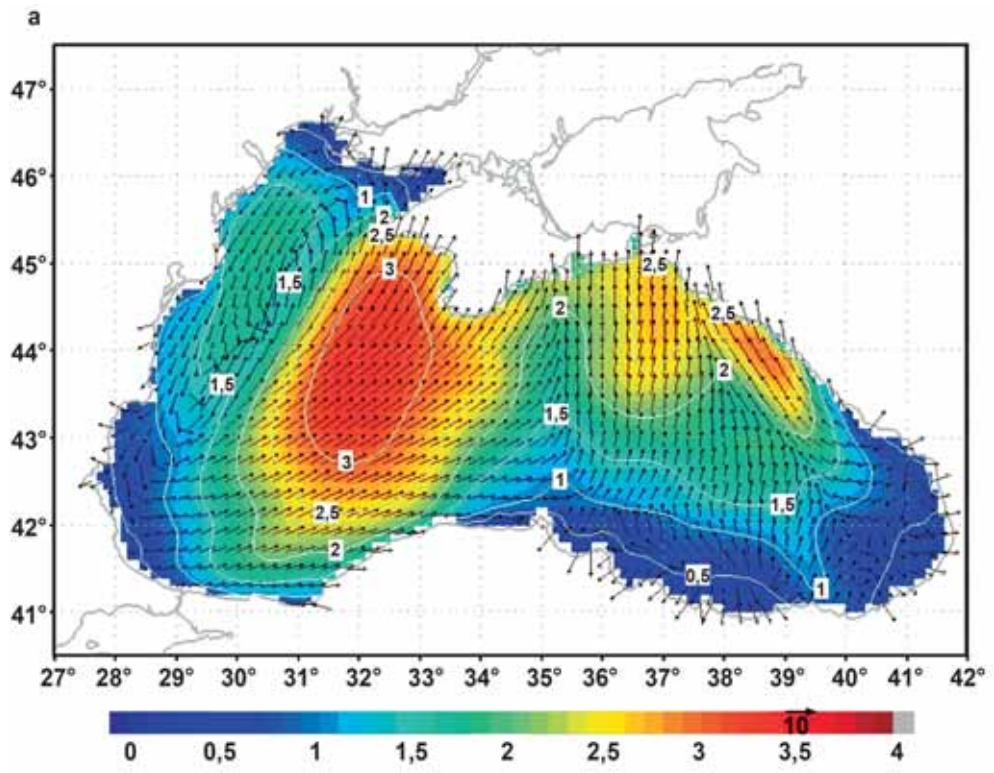
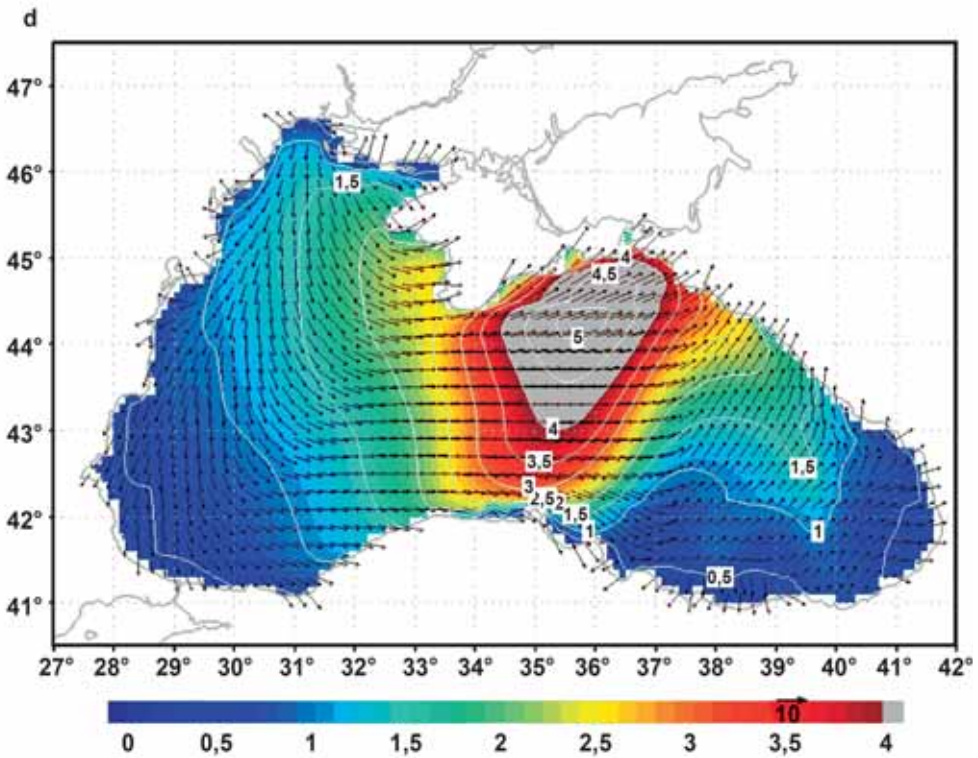
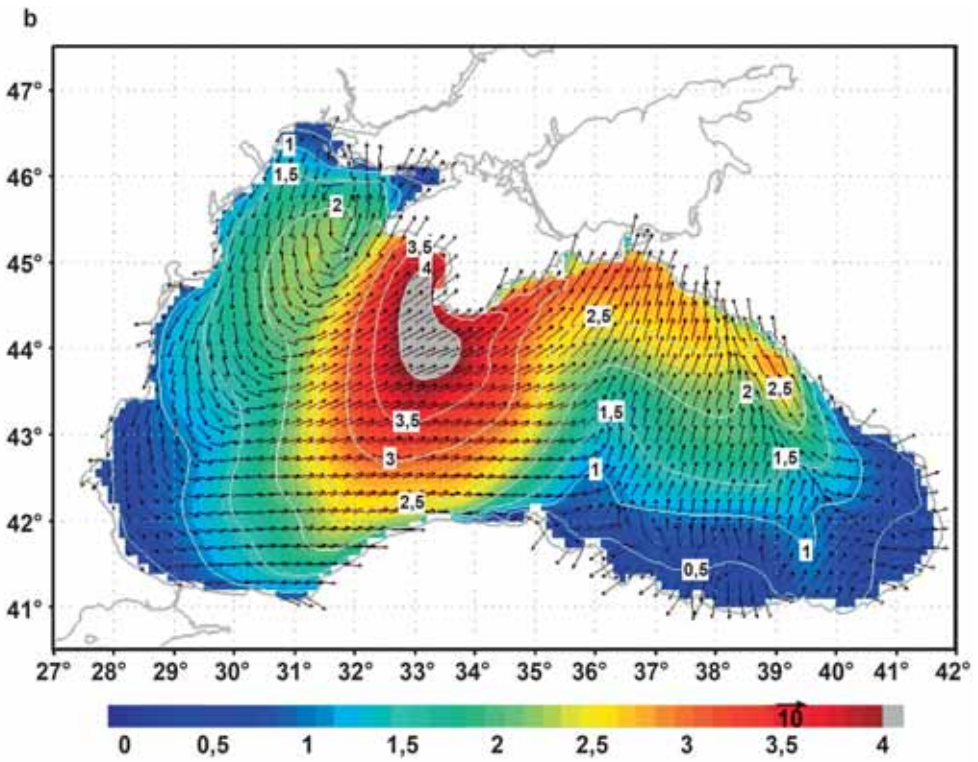


Fig. 13. The background conditions of the formation of the 12-meter killer wave in the area near Gelendzhik. ⇒



The simulated field of waves for 1:00 (a), 4:00 (b), 7:00 (c), and 10:00 (d) hours, local time, on Feb. 1, 2003. The notation is the same as in Fig. 10

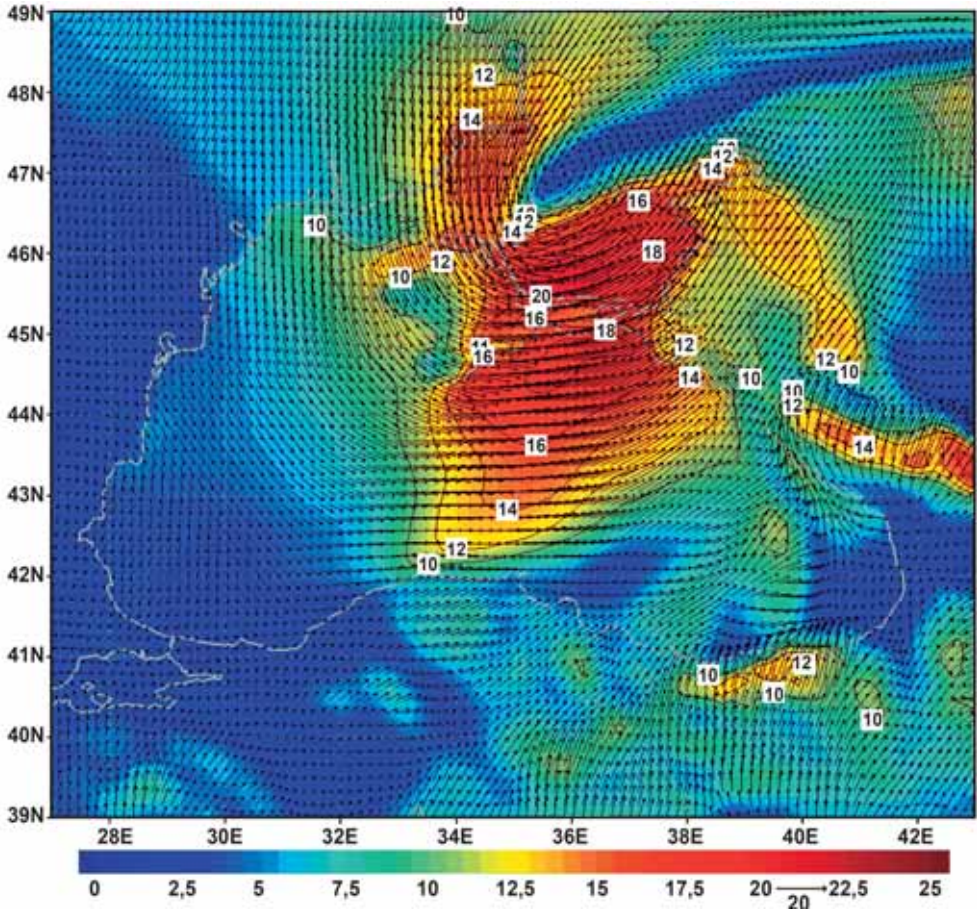


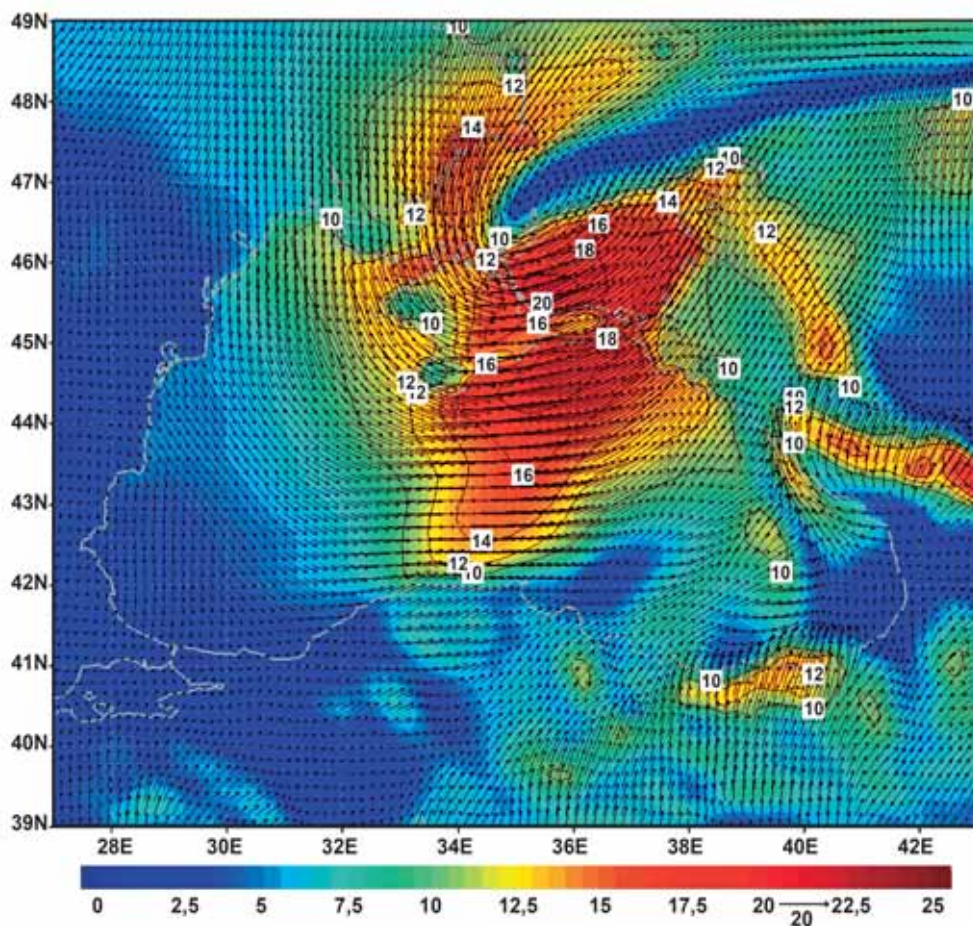
Fig. 14. The simulated wind field at 8:00 and 10:00 (opposite page), local time, on Feb. 1, 2003

swell waves with the observed, at the time, frequency and direction (see Fig. 7).

Fig. 11 shows the simulated spectrum of the waves for the region of the platform at 12:00 on Oct. 14. Comparing it with the spectrum in Fig. 7, estimated from the in situ data of the time interval 12:20–12:40, one can see the correspondence of the spectral peaks, both in direction of the waves and frequency: frequency of the peak for the simulated spectrum and the measured spectra are 0.12 Hz and 0.13 Hz, respectively. Thus, in the situation discussed above, there were indeed swell waves coming from the storm area of the central part of the Black Sea.

Fig. 12 shows the wind speed field at 9:00 on Oct. 14. The simulated and observed wind directions coincide (220° – 230° , compare with Fig. 3). Thus, the model simulation of the wind and wave fields in the Black Sea allows one to conclude that the interpretation of the wind-wave situation, made based on the field measurements at the location of the platform, corresponds to the synoptic situation. There were the abnormally high swell waves when the direction of their propagation was close to that of wind.

Now, let us consider the situation on Feb. 1, 2003, when, in the area of the recording buoy of the Southern Branch of the IO, a 12-m high killer wave, discussed in [Divinsky, et al.,



Continued Fig. 14

2004; Kuznetsov, et al., 2006; Kuznetsov and Saprykina, 2009], was observed. We should emphasize that, in contrast to the abnormally high waves on Oct. 14, 2009, examined for research purposes, the Gelendzhik killer-wave represented a real danger. Details of the wave situation, obtained with the Datawell buoy, including frequency and the frequency-angular spectra of waves, are given in the papers cited. Period of this wave was 11–12 s and the group velocity of the waves of this frequency was 9–10 m/s, i.e., almost two times higher than for the swell waves on Oct. 14, 2009. Therefore, we can expect that the formation of killer waves is associated with the previous synoptic situation during the period of time of less

than 10 hrs, i.e., two times shorter than in the previous case.

Analysis of the calculated wind field showed that, during this period, the western and central parts of the Black Sea were in the zone of intense local cyclone moving northeast. In these parts of the sea, there was an extensive area of a violent storm with wind speed exceeding 20 m/s and of a primarily northeastern direction. Fig. 13 shows the calculated wave fields, demonstrating the background for the formation of a killer wave up to the time of its registration. As can be seen from the Fig. 13, the region of strong storm was, over time, approaching the location of the buoy. In this region, wave

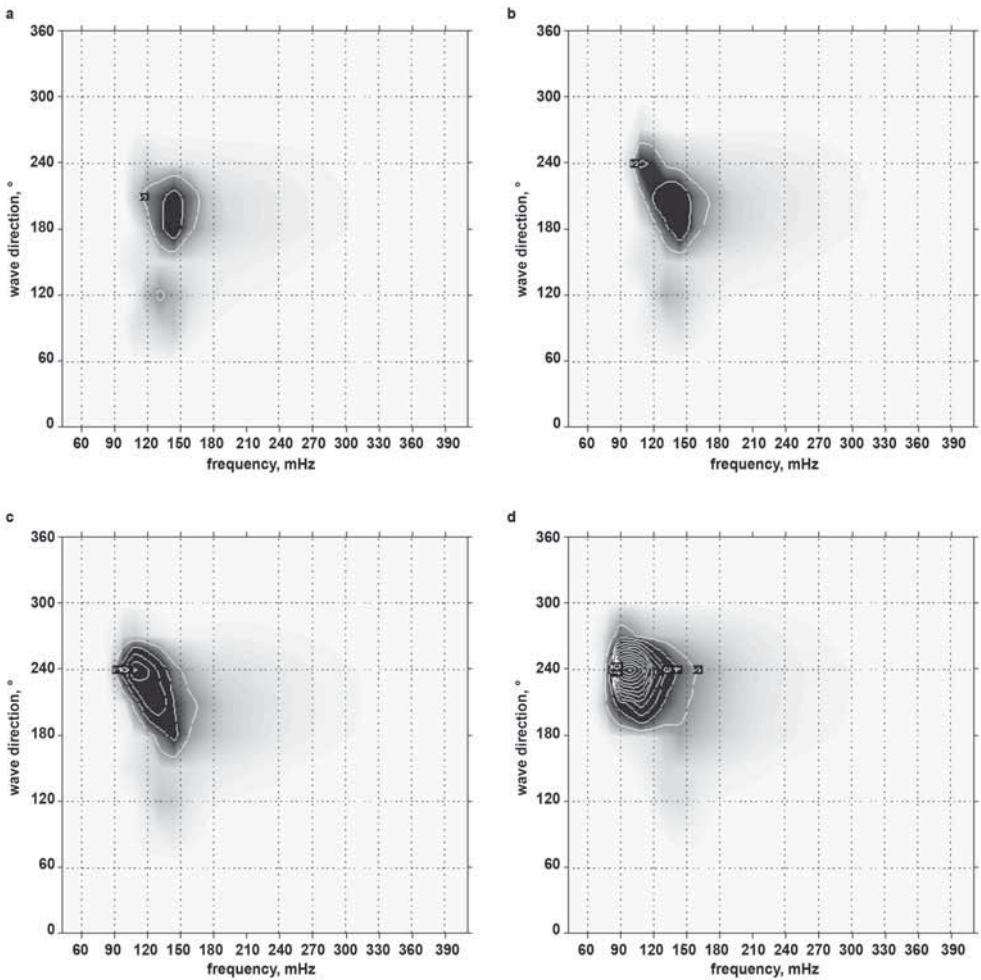


Fig. 15. The simulated spectra of the waves at 7:00 (a), 10:00 (b), 11:00 (c), and 13:00 (d), local time, on Feb. 1, 2003

height reached 5 m, period was approaching 10 s, and wave direction was approximately in the direction to the location of the buoy. We emphasize that, at the time of the observation of the killer wave (between 9:00 and 10:00), the storm area had not yet reached the longitude of Gelendzhik (38°E). Therefore, the waves with periods longer than 11 s registered by the buoy should be referred to swell waves propagating in the direction of the buoy from the region of the intense storm.

The fields of wind speed at 8:00 and 10:00 hrs (Fig. 14) show that, at the point of the measurements during this time-period, wind

retained its velocity at 12–14 m/s and its direction at 220°–240° (“from”), corresponding to the direction of swell waves.

Figures 15 a-c present the calculated wave spectra for the point of the buoy location, which show the wave history prior to the observed killer wave. Fig. 15a shows that, six hours prior, there had already been the swell wave system with basic frequency of 0.15 Hz and the general direction of 200°. The waves of the swell wave system that corresponded to the killer wave (15c) had appeared three hours prior to its observation and, at this moment, their basic frequency was 0.1 Hz, and the general direction was 240°

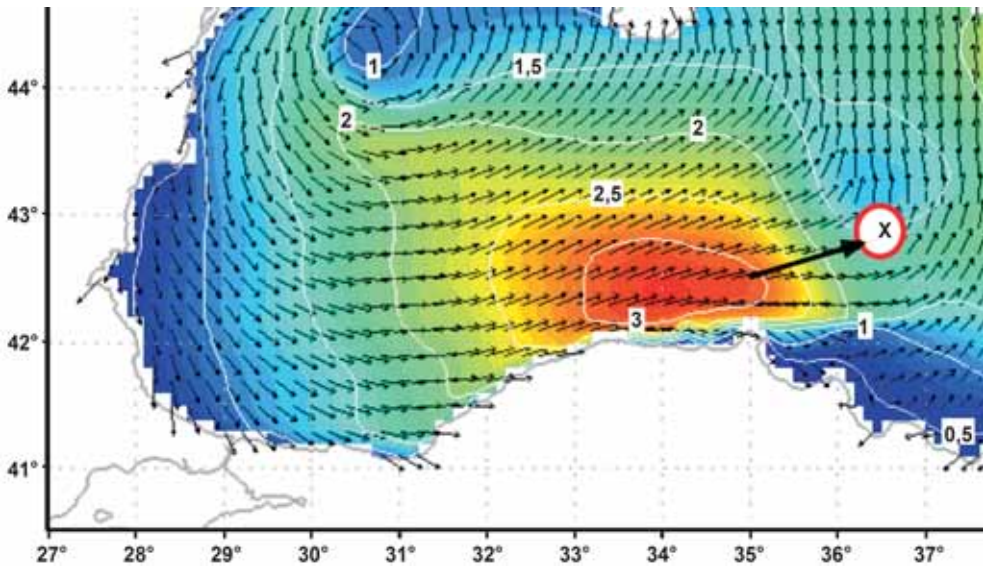


Fig. 16. Example of the implementation of the risk assessment of an encounter with a killer wave.
See explanation in the text

(Fig. 15b). This interpretation corresponds to the concept of a moving source of the waves of the swell wave system (localized in the storm zone) and to the instrumental measurement of the height and frequency of the waves. The new wave system had higher wave energy (see Fig. 2a in [Kuznetsov and Saprykina, 2009]) and direction of the waves coincided with wind direction (see Fig. 14). Fig. 15d allows assessing the quality of the model reconstruction of the spectra. Comparing it with the instrumental estimation of the spectrum for the same time (see Fig. 1 in [Kuznetsov and Saprykina, 2009]), we can conclude that the model reproduces correctly the main features of the wave field, i.e., general direction and period of the energy-carrying waves.

Thus, the synoptic situation prior to the formation of the killer wave on Feb. 1, 2003, was almost similar to the situation on Oct. 14, 2009, when, at the platform in Katsiveli, there were relatively frequently observed waves of the abnormal height. This gives grounds to assert that the scenarios of the formation of these killer waves were similar too.

CONCLUSIONS

This paper presents analysis of the field data collected in the Black Sea from the research platform in Katsiveli, in the autumn of 2009. The abnormally high waves, exceeding two times or more the significant wave height, were revealed in the data of wave staff array. It has been shown that the anomalously high waves are due to nonlinear processes in the wave field. The obtained relationship of the index of abnormality and kurtosis – the characteristics of the intensity of nonlinear processes, is in agreement with the previously published results [Shin and Hong, 2009]. Frequency of occurrence of the abnormally high waves (killer/freak/rogue waves) varies considerably on the time scale of several hours. In 90% of all cases, killer waves were observed in the swell wave system, whereas in 70% of all cases, the swell waves that formed killer waves propagated in approximately same direction as wind.

One of the fragments of the observations of higher occurrence frequency of the abnormally high waves (Oct. 14, 2009) was described in detail to identify the wind and wave conditions specific to the formation of

killer waves. Evolution of the wave spectrum in this fragment was similar to that observed in the laboratory, where the formation of killer waves due to modulational instability was studied [Kuznetsov and Saprykina, 2009]. The data can be interpreted as the field observations of the energy cascade discrete in frequency and time, which is inherent in the development of modulational instability [Kartashova and Shugan, 2011].

From the analysis of the records on Oct. 14, 2009, the following scenario of the killer wave formation can be derived. Swell waves with a narrow spectrum (both in frequency and direction of propagation) are amplified in the conditions when wind direction is close to that of swell waves. Upon swell waves reaching the sufficient steepness, modulational instability develops, which leads to the formation of the abnormally high waves. This scenario agreed well with the reconstruction simulation of the wind and wave fields in the Black Sea, showing the background conditions of the storm on Oct. 14, 2009, in Katsiveli. A similar reconstruction was performed for Feb. 1, 2003, when a 12-meter killer wave was recorded with the Datawell wave buoy near Gelendzhik. These estimates have also supported the proposed scenario.

The findings of this study are supported by a number of results reported earlier. For example, in [Dotsenko, et al., 2009, 2010], the observations of killer-waves in the northwestern part of the Black Sea were described and it was concluded that frequency of occurrence of killer waves is distributed nonuniformly in time and is not explicitly linked with wind speed, its direction, and wave height. Figures 2 and 3, in [Dotsenko, et al., 2010], indicate that the abnormally high waves shown there were observed in the swell wave systems. Young [2006], analyzing data of the Datawell directional wave buoys offshore Australia, showed enhancing of swell waves due to wind of the same direction. Tamura, Waseda, and Miyazawa [2009] reconstructed wave conditions for the time of the accident in

the Kuroshio region in 2008, when a fishing boat with 20 crewmembers sank because of an encounter with killer waves. Model calculations of the wave field have shown that swell waves existed in this region. These waves were intensified during interaction with wind waves that were propagating in approximately same direction. Thus, the scenario, which we proposed for the development of extremely hazardous situation, was also obtained in the paper of Tamura, Waseda and Miyazawa [2009].

Apparently, the scenario discussed is often realized in natural conditions. At least, it is possible to attribute 70% of the extremely high waves observed in our experiment to this scenario. If this is true, the operational monitoring of the wind-wave situations could serve as a basis for the killer wave forecast.

At this point, it is already possible to offer, based on this approach, the following simple practical strategy to risk assessment of a ship encounter with a killer wave in the Black Sea. The assessment is made for a given point X and for a given time T as follows:

1. Analysis of the wind-wave forecast several hours prior to the time T is performed. It should be noted that the regional operational forecast of the wind situation over the Black Sea for three days, as well as the regional operational forecast of the wave situation for three days for a grid of 10 km \times 10 km is conducted consistently at the Department of Atmosphere-Ocean Interaction of MHI. The results of the forecasts can be found at the site <http://vao.hydrophys.org/> in the public domain. Because the real danger is associated with the waves of the height of several meters, reviewing the data allows identification of the zone of intensive storm. The corresponding wind field must also be characterized by storm wind speed. If, within the Black Sea region, there is a zone of intense storm, then the second step of the risk assessment is performed.

2. The purpose of this step is to determine whether swell waves will come from the

storm zone to point X at time T . In a real situation, instead of a single point, it is feasible to consider region X , chosen in accordance with the practical purposes of risk assessment. Fig. 16 explains how to perform this assessment. In this case, the forecast of the wave field shows that, in the storm zone, there are waves with period $\tau = 9$ s (the wave period is presented by lengths of the small arrows). The large black arrow in Fig. 16 is drawn to connect the storm area with region X in the direction that corresponds approximately to the direction of wave propagation. The length of this arrow is the distance R that the waves must cover (it can be determined, for example, by putting the arrow to the latitudinal axis; in Fig. 16, $R = 110$ km). Time t , which is required for waves to travel this distance is determined by the formula $t = 0.18R/\tau$, where R is expressed in km, τ is in seconds, t is in hours (in our example, $t = 2.2$ hours). If the waves reach region X at time T , then the third step of the risk assessment is performed.

3. The purpose of this step is to determine whether swell waves will be amplified when approaching region X . For this purpose, the forecast of the wind field at time T is reviewed. If, in and around X at time T , a strong wind from the direction corresponding to the direction of the large black arrow is expected, there exists a real danger of encountering killer waves.

ACKNOWLEDGEMENTS

This work was performed under the joint project of the Russian Foundation for Basic Research (09-05-90430-Ukr-f-a) and the State Fund for Fundamental Research of Ukraine (F25/438) and has been partially supported by the EC FP7 ERC (Grant No. 227915 "Atmospheric planetary boundary layers – physics, modeling, and role in the Earth system") and by the State Agency for Science, Innovation, and Informatization of Ukraine (Contract M/412-2011). ■

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EXPORT-ORIENTED MODEL OF SUSTAINABLE DEVELOPMENT IN RUSSIA (FROM THE “DUTCH DISEASE” TO INNOVATIVE DEVELOPMENT)

ABSTRACT. This article analyzes the “Dutch disease” as a significant barrier to sustainable development associated with the presence in the country of large hydrocarbon resources and their enhanced export. Rybczynski’s theorem was used to demonstrate negative effects of the “Dutch disease” in advancement of processing industrial sectors. The “oil-shale revolution” that occurs mainly in the U.S. and represents a threat even for the Russian export of natural gas and oil, has been analyzed. A liberal export-oriented model of Russia’s participation in the international division of labor may help overcoming this unstable situation.

Key words: “Dutch disease”, “oil-shale revolution”, export-oriented model, sustainable economic development, Russia

INTRODUCTION

Russia’s economic development and effective reintegration into the global economy after the collapse of the military-industrial structure (in terms of the territorial-sectoral organization and the composition of products) during the period of perestroika and the collapse of the former Soviet Union, was based on the exploitation of considerable reserves of fuel and raw materials diverse in composition. There have been massive changes in the macrostructure

of both production and exports. The country has been taken in the toils of the hard-to-treat (but still curable) “Dutch disease” that has been relevantly described by the theorem of an English economist T.M. Rybczynski [1955] that has become the “classics” of economic thought. Its meaning is quite simple and is based on the notion that the transfer of resources (investment, labor, and other production factors) from the manufacturing sector to the secondary (raw) and to the tertiary (non-productive sphere) lowers the added value. Rybczynski has logically and mathematically proven and has illustrated graphically that the sector of the economy where the cheapened production factor is most intensively used “drains” mobile production factors away from another sector. At constant prices and availability in the economy of only two sectors (theoretical assumption), the growth of one of the production factors leads to the reduced production of the other commodity. Expansion of the “hydrocarbon” areas (as a redundant factor of production and, hence, of exports) leads to drop in the rate of growth in other sectors and increases the instability of the economy as a whole. This is expressed primarily in de-industrialization. Further empirical studies have shown that the higher the proportion of the resource component in the GDP, the less incentive there is to move forward – to

the development of an innovative economy. The “Dutch disease” in Russia takes a long course and a serious form: with a focus on growth in the world prices for hydrocarbons and a manifestation of the “narrow-minded” mentality, whose attributes are complacency and underestimation of the need for fundamental changes in the nature of Russia’s participation in the international division of labor. There is another threat to economic stability in Russia, which the country can face even in the near future – the “oil-shale revolution” taking place rapidly in the U.S., which may allow moving away from the traditional paradigm of oil and gas production. Shale hydrocarbon reserves may change both the geoeconomic and geopolitical structure of the world. The way out of the emerging world situation can be a model of sustainable economic development in the international and transnational division of labor. A break from a “vicious circle” can be found in historical and geographical study of similar processes and methods of overcoming them. The paper proposes a purely preliminary idea of Russia’s preferred orientation for a gradual engagement with countries-leaders/innovators in the modern economy of the world system. A logical scheme of the implementation stages of the process of integrating the Russian economy into the global economy is provided in support of this approach.

DATA AND METHODS

Material for this article is based on discussions of the future of sustainable world economy, including Russia, in national and foreign scientific publications and periodicals that are becoming increasingly intense in the time of crisis. The basic method is a set of logical arguments arising from the experience of observing reality and adhering to the rules of theoretical approaches prevailing in the social geography used to test different positions towards occurring events and potential to determine their possible development at least in the short term.

RESULTS AND DISCUSSION

The history of economic development shows that individual countries can get rich quick by a sudden discovery of large reserves of raw materials and energy resources. It is possible to increase the level of exports with significant growth of the world prices for resources already developed. This situation, for example, was characteristic of OPEC in the 1970s and the subsequent crisis “peaks” of supply and demand for oil in the world markets.

The effect of large changes due to the discovery of new reserves and increase of their prices have such a negative effect on the macrostructure of the economy, on the level and direction of foreign investment, on the composition of exports, and on the exchange rate of the country, that the magazine “Economist” in 1977 [Economist, 2010] named this effect the “Dutch disease”. The name is associated with the discovery in the Netherlands in 1959, of several fields of natural gas. This was followed by the decline in manufacturing exports and the increase in inflation and unemployment. The additional foreign exchange inflow in the mining sector has eventually led to real currency appreciation and, consequently, increased domestic and export prices. In the long term, the “Dutch disease” leads to a transfer of resources from the manufacturing sector to the raw materials sector and to the tertiary sector. The latter sectors create less added value, which lowers the total GDP of a country.

A more intuitive explanation of the mechanism of the “Dutch disease” can be obtained using Rybczynski’s theorem and the following assumptions: constant prices and the availability of only two sectors of the economy. Based on these assumptions, the quantitative growth of one of the factors of production (capital, labor, land) leads to the reduced production volumes of the other sector of the economy [Rybczynski, 1955; Kireev, 1997; Zabelina, 2004]. Moving the economic resources to oil and gas production over a certain time-period results in increase

in income of the population. The subsequent growth of prices for oil and gas leads to a new phase of the “Dutch disease” associated with reduction in personal income, with transfer of resources from the fuel sector, and, once again, with strengthening of the positions of the traditional export sectors of manufacturing industry.

Thus, according to Rybczynski’s theorem, the “Dutch disease” leads, over one time-interval or another, to a reduction of the production of non-resource goods export. As already noted, this is due to the fact that the GDP growth during the boom in the extraction of natural resources leads to an outflow of capital (investment) from the earlier traditional, for the country, export manufacturing activity and its inflow to the primary (resource) sector. In 1981, this phenomenon was investigated in detail by Ellman [Ellman, 1981] whose work has been devoted not so much to the problems of connection of the discovery of large deposits of oil and gas with the increase in foreign exchange rates, but rather to inefficient investments by the state petroleum revenues into the social sphere. Empirical analysis of the U.S. researchers J. Sachs, A. Warner, and F. Larrain [Sachs and Warner, 1995; Sachs and Larrain, 1996] of the correlation between the share of the resource sectors in the GDP and the rate of economic growth (over a period of a very high growth in the world trade due to lower prices for goods transportation in 1970–1990) have established the presence of feedback and arrived at the conclusion that the greater the share of the resource component of the GDP, the less incentive there is to move forward. Later, such terms as “resource curse” and “paradox of plenty” have entered even in the economic literature.

Russia is a “hydrocarbon” country based on its economic structure. It is only natural that the Russian economy was struck by the “Dutch disease”. The GDP growth is mainly provided by higher energy prices, which reduces Russia’s competitiveness in the international division of labor and leads to significant risks to economic security. And

the risks are increasing due to Russia’s role as a superpower in the global geopolitics (with some reservations); the country, along with the U.S., determines the balance of forces in the system of the global order.

The “Dutch disease” in Russia is long-drawn and very severe (the Netherlands were “sick” for a shorter time in comparison with Russia – for slightly less than a decade). The pressure of hydrocarbon exports on the domestic economy significantly reduces its competitiveness in the world economy. Moreover, a severe form of the disease leads to the degradation and even loss of propulsive high-tech industries. Drop in profitability in high-end industries due to increasing pressure of hydrocarbon exports leads not only to technological backwardness, but also to preservation of the necroeconomy that brings irrelevant or even unwanted goods to market and is not in need of a major upgrade of technology and of inflow of foreign investment [Papava, 2009]. Given the current situation, which has long-term inertia, there is an acute problem of scenarios (models) of the development of the Russian economy in the next 15–20 years.

Another factor threatening the economic stability of Russia may be the so-called “oil-shale revolution” widely discussed in scientific publications and the media. This revolution (sometimes it is called the “oil-shale rush” by analogy with the largest “gold rush” in the U.S. in the XIXth century in Northern California and Alaska). The “shale revolution” is primarily associated with the territory of the U.S. and more precisely, with the Bakken formation (Wyoming, Montana, and North Dakota). The second largest oil-shale field is the Niobrara formation (in the borderlands of Dakota and Nebraska). The total potential reserves of oil-shale is estimated at 650 trillion tons, of which 430–450 trillion tons are in the United States (Colorado, Utah, Wyoming) [Shale industry in Russia, 2011].

Russia occupies the second place, followed by Brazil. Russia has 12–13% of the world oil reserves, 42% of natural gas, about 20%

of black coal, and 32% of other coals, not considering the huge stocks of alternative fuels, which include oil-shale [Shale industry in Russia, 2011]. In Russia, the largest known oil-shale deposits are located in the Leningrad region, the Volga region, and in the Timan-Pechora and the Vychegda Basins. However, their development needs investment, especially in exploration and new technologies.

In the U.S., technology that increases profitability of oil and gas extraction is being intensively developed. Great potential, partly implemented, in the oil and natural gas sector in the U.S. may prevent hydrocarbons produced in Russia from entering largest markets in North America, Canada, and possibly, in Europe. While there are discussions about the “shale revolution”, the flow of information in press on the intensive exploration of the Bakken oil formation and on a sharp decline of its cost of production is gaining momentum. A possibility that companies specializing in oil and gas production from shale will become largest players in the world hydrocarbon market should not be excluded. With the sharp growth of supply, prices will drop dramatically.

Many well-founded models are built on the ideas of moderate liberalism. They are based on the notion of self-development of the national economy in transition (transformation) to the highest and best forms with full participation in global and regional processes of the international division of labor. As noted by V.L. Tsybursky, a liberal (*great* in his account) worldview is: “The world, as it is, has originated by some coincidence. Disrupting the balance of this world, interfering with its operation, we run the risk of plunging it into chaos and disintegration”. This is absolutely the opposite thesis to the one that the socialists and a number of liberals, or rather, liberals of Keynesian persuasion, conform to. “From the standpoint of socialism, nothing good will become of this world, if we do not construct and do not build it” [Tsybursky, 2001].

The way out of this situation, out of the “vicious circle” of different world’s views, in our opinion, is historical-geographical study of specific processes of progress in specific countries and regions. All countries that have made significant strides in the progress of the economy and society as a whole, with all the nuances of the methods of achieving them adhere, to some extent, to the ideas of liberalism and have certainly participated in the international division of labor. For Japan and newly industrialized countries that do not have on their territories a variety of significant stocks of raw materials and fuel (and therefore free from the “Dutch disease”), a leading factor in the progress of their policy is the successive (cascade) integration into such a powerful planetary process as the international geographic division of labor. In order to fully participate in the process of internationalization/globalization on the basis of division of labor, these countries (and now their followers that have rejected the anti-liberal protectionism and import substitution) have conducted a major anti-feudal reform, have created the institution of private property, and have entered the democratic principles of the functioning of society.

Their preferred orientation towards foreign economic cooperation with leading countries/economic innovators in the world economy has become the main road of progress (modernization). Analysis of the experience of integration into the global economy of Japan shows that a country-follower (at the start, a country of imitation) consistently exports, to countries-leaders, goods whose production in the country-follower is cheaper and the quality is equal and sometimes is better than the in the countries-leaders.

If a country-follower chooses a different path, i.e. the orientation of its economy towards markets of economically less developed countries that impose the demand for cheap and outdated products, modernization of society and technological progress in this country-follower are virtually impossible [Maksakovskiy, 2003; Portnoy, 1996].

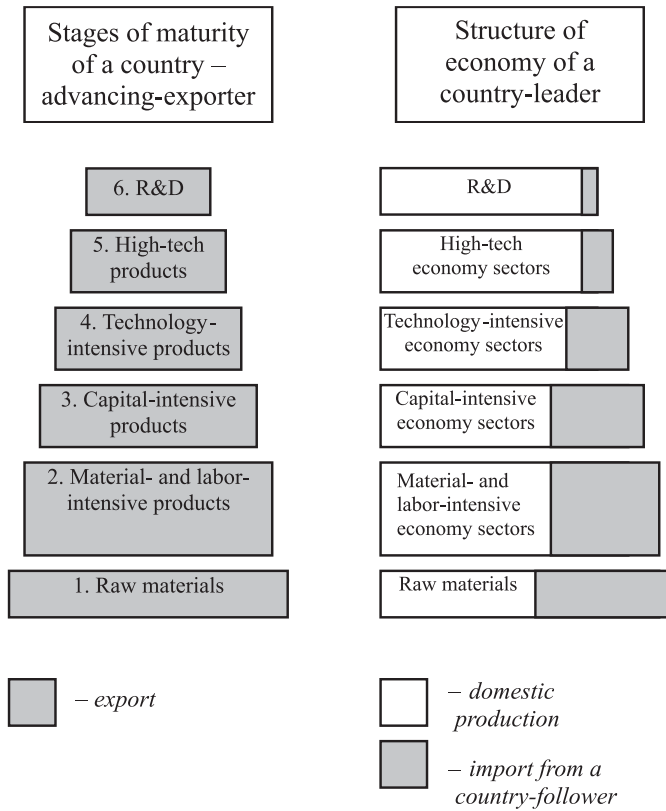


Fig. 1. Schematic representation of the implementation of the process of integration of a country-follower's economy into the world's economy (R&D stands for research and development). The export-oriented model of development (based on [Portnoy, 1996])

Based on the "ideology" of foreign economic cooperation with leading countries, a country-follower acts in time with the principles of liberalization, finding its place in the self-development of the world "to the highest and best forms". The scheme of implementation of the integration of a country-follower's economy into the world economy is presented in Fig. 1 with a brief explanation afterwards.

The first stage. A country does not have goods competitive on the world commodity market or has inadequately competitive goods. However, it has raw and primary materials. Such countries include Russia, with its diverse and vast potential of natural resources. The raw materials and fuel exports at this country's early state of the reintegration into the global economy

is inevitable. However, this type of exports in the overall strategy of participation in the international division of labor should be considered as the first step in cooperation with foreign countries and multinational corporations; major stages of production are in those countries. Since the revenue from the industries of the primary sector and foreign direct investment are the main sources of modernizing the subsequent (according to the rank) industries (manufacturing in the broadest sense), such approach is a strong argument in favor of this idea.

The second stage. At this stage, the country becomes an exporter of material- and labor-intensive goods that outcompete the raw material component for the important position in the economy. The most common

goods of exports: oil, high quality building materials, textiles, chemical products, clothing, shoes, etc.

The third stage. By modernizing the subsequent, according to the ranking, industrial sectors, the country is becoming an exporter of capital-intensive goods. Typical products: steel rolling, forge-and-pressing equipment, construction machinery, and ships.

The fourth stage. The country exports technology-intensive products: machine tools, production lines, turbines, automobiles, buses, and measuring tools and instruments.

The fifth stage. The country is exporting a wide range of high technology products: electrical, electronic, and aerotechnics products, communication equipment, new construction materials, etc.

The sixth stage. As a final step - cooperation in research and development.

This scheme is not straight-lined, but quite logical. Without strong modern metallurgy and engine building, it is impossible to become a producer and an exporter of domestic cars. The logic nature of the scheme is supported by the experience of postwar Japan and the Republic of Korea. However, the specifics of these two countries, unlike in Russia, is in the fact that, in the absence of any significant stocks of raw materials and fuel, they do not have to overcome huge diseconomies associated with the “Dutch disease”. Therefore, the advancement of the Japanese and the South Korean exports up the steps of the technological ladder went from light industry to the prevailing export of machinery and equipment. Such a rise took fifteen to twenty years in Japan and, as a country-follower, it went through the stages of “textile”, “steel”, “car”, and “semiconductor” “wars” with the countries-leaders; with the renovation of its automobile construction section beginning

in the 1990s, it entered into a new “car war” till it carried out a widespread penetration into the U.S. of its transnational corporations in the form of “trans-plant” corridors [Philip and North, 1991].

Interaction of Japan (a country-imitator of advanced technologies and institutional infrastructure) with the U.S. (an innovative leading country) contributed to the restructuring and to the socioeconomic sustainability of both countries.

CONCLUSIONS

1. A public policy aimed at overcoming the “Dutch disease” associated with the marked predominance (40%) in domestic exports of fuel and commodities may become a real catalyst for transformation in achieving sustainable economic structures in Russia. The so-called “shale revolution” predicted by scientists can contribute to restructuring of the economy in general and of its export component in particular. It can produce a significant supply of energy to the world market, which will inevitably lead to a reduction in its prices. This, in turn, can lead to a dramatic reduction in the quality of life of the Russian population.

2. If earlier, the “Dutch disease” has spread to individual, mainly small and medium advanced countries in the context of regional-scale discovery of oil and gas fields, the “shale revolution” could become a disease of global proportions. This may break the existing relative balance of supply and demand in this sector, which plays a major role in the alignment of the geoeconomic and geopolitical balance of power in the world.

3. Rybczynski’s theorem has been repeatedly confirmed (with certain deviations). The case of the deindustrialization of the Netherlands and other countries has become a textbook example. Therefore, the principles of this theorem can spread practically to the entire world and have negative consequences at the level of so-called large spaces.

4. As a proposal of overcoming the state of anxiety and uncertainty about the threat of instability, the experience of the countries that have overcome the “Dutch disease” should certainly be taken into account. However, alone that is not sufficient. Here, the scheme of creation of the export-oriented model of Russia’s entry into the international division of labor is suggested. In the authors’ opinion, a step-by-step progression up the larger stages of the integrated foreign economic cooperation between Russia and the leading countries are as follows: cooperation at the level of fuel and raw materials; transition to the stage of material- and labor-intensive products; then, to the stage of capital-intensive goods; further, to the technology-intensive stage. The last two stages are related to the area of high technologies and research and development. Consistency and appropriateness of the scheme is supported by practice of the use of the factor of the international division of labor by Japan, and later, by the newly industrialized countries. ■

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WORKSHOPS OF THE INTERNATIONAL CARTOGRAPHIC ASSOCIATION

The International Workshop “GIS Support for Modernization. Organizational, Technological, and Human Resources Potential” (September 25–October 9, 2011) was conducted with financial support from the Russian Foundation for Basic Research. The workshop was attended by 78 students and experts in the field of GIS and remote sensing data to discuss challenges of sustainable development, integrated management, environmental management, and ecology. There were 16 reports, 8 workshops and role-playing games, as well as a conference of young scientists. Among lecturers and students attending the workshop, there were 11 doctors and 18 candidates of sciences with more than half of the participants under 35 years of age.

The International Workshop on geoinformatics and sustainable development,

as part of the activity of the International Cartographic Association’s Commission “GI for Sustainability” has been held for seven years (since 2005, in Ukraine, Turkey, and China [four times]). As a rule, visits to places of interest from the standpoint of geoinformatics are arranged during the workshops. The workshop conducted in Russia was structured under this scheme also; it was held, similar to the first workshop in 2005, on board a ship (Fig. 1), en route Perm–Astrakhan–Perm (covering a distance of 5,130 km) with reports delivered in the cities-stops: Kazan, Saratov, Astrakhan, Volgograd, and Samara. Each day, while the ship was sailing, invited instructors delivered lectures and workshops and role-playing games were conducted. During the day, students visited universities of the cities-stops, where they got familiar with the activities in the field of geoinformatics, listened to reports by local



experts, and made presentations to local teachers and students on the current topics of geoinformatics.

The Workshop's activities started in Perm (September 25) where several presentations were made, including a report on "Geoinformation support for sustainable development in Russia and the CIS" by Prof. V.S. Tikunov (Moscow State University). The report had a focus on the use of modern technologies in models of sustainable development. The need to integrate the efforts of Russian and foreign scientists in joint international projects, particularly in the Arctic, was specifically stressed. R. Stampach, Czech Republic, made a report on "Digital Earth – vision, progress and future" where he presented the idea of establishment and functioning of the International Society for Digital Earth and its development prospects. Issues of formation of spatial databases based on international experience were also addressed.

At Kazan (Volga) Federal University (September 28), issues of creating spatial data infrastructures in Russia (A.V. Koshkarev, Ph. D., geology; Institute of Geography RAS) and the use of GIS in ecology and environmental management (A.A. Saveliev, doctor of biological sciences; Kazan State University) were examined.

In Saratov, Professor A.N. Chumachenko, Provost for Innovation (Saratov State National Research University) made a presentation on "Integrated Regional GIS: the goal, objectives, and content". There he reviewed issues of analysis and synthesis of spatially distributed geo-environmental, geo-demographic, and socio-economic information of various territorial and sectoral levels of hierarchy necessary for implementation of measures to ensure sustainable economic growth in a stable economic environment with positive social and demographic processes. A report on "Sustainable Development and Education" (D.S. Ermakov, doctor of pedagogical sciences, University of the Russian Academy of Education [Novomoskovsk Branch], a

private educational institution for higher professional education) outlined problems facing modern society in the implementation of the concept of sustainable development.

At Astrakhan State University (October 2), V.E. Gershenzon (Ph. D., technical sciences), director general of the Engineering Technical Center "ScanEx", spoke on modern technology and technical solutions in operational space monitoring and pointed to the geo-portal solutions and possible thematic application of remote sensing data of the Earth for the regional economy of Russia. A follow-up seminar on board confirmed the interest to the stated theme.

Scientists of Volgograd State University (October 4) shared their achievements in the introduction of GIS methods in practical and theoretical activities (Fig. 2). In particular, a report by S.S. Khrapov (Ph. D.) "A specialized geographic information system for management of computer modeling in monitoring and forecasting of the atmosphere and hydrosphere", was devoted to issues of development of mathematical modeling of the dynamics of surface water to describe flooding of the territories. It also discussed the development of computer models based on GIS methods to model the dynamics of surface water and particulate matter transport in air and water. A. Plyakin (Ph. D., economics), in his speech "A GIS-based approach to managing socio-economic development of the region (a case study for the Southern Federal District)", dealt with issues of improving the stability of the region. T.Yu. Gribtsova, a representative of the Government Information Technology Center of Volgograd region, described the experience of using GIS in the design of spatial data infrastructure, with emphasis on creating a system to monitor the use of agricultural land.

Representatives of Samara State Aerospace University spoke about mathematical methods used in the automated interpretation of remotely sensed data (Prof. V.V. Sergeev, doctor of physical-



mathematical sciences). A. Chernov, head of JSC "SamaralInformsputnik" (Ph.D, physical-mathematical sciences) emphasized the problems of spatial data infrastructures at the regional level. D. Mayer, a representative of company ProGIS (Austria), spoke about a practical implementation of GIS in agricultural management in the country. A tour to the Volga Center for Receiving and Processing Remote Sensing Data was organized and conducted.

In the cities-stops, the participants met with a number of organizations' leaders. Thus, they met with different deans in Perm (Prof. A.I. Zyryanov), in Kazan (Prof. O.P. Ermolayev), in Saratov (Prof. V.Z. Makarov), and in Astrakhan (Prof. A.N. Barmyn) and with the university president in Samara (V.A. Soifer, corresponding academician, RAS).

On board the ship, a role-playing game was conducted based on the results of the presentations (Fig. 3). The game focused on features of designing spatial data infrastructure, using an international

project in the basin of the river Amur as a case study. A discussion of the usage of modern technology in practical activities has led to a conclusion that it is necessary to develop national standards for spatial data infrastructure.

A class "Visual and aesthetic representation of a base map for online mapping services" was held by the staff of the Engineering Technical Center "ScanEx"; the class demonstrated features of presentation of web-maps and the structuring of their content and symbolic space. A subsequent seminar has reinforced the students' skills in creating digital cartographic symbols.

Among other seminars there was a seminar on a forecast of the world's population with an emphasis on Russian reality, where students, divided into six groups, had the opportunity to develop a computer system with demographic scenarios (optimistic, pessimistic, and average) for Russia, as well as to consider possible scenarios of changes in Latvia and Tajikistan.



S. Pyankov (Ph. D., technical sciences), head of the GIS Center of Perm State University, spoke on development of geoinformatics in the Perm region; its relationship with the development of the GIS-technologies' market in Russia was demonstrated. The resulting discussion was devoted to the geoinformatics' place in the Earth Sciences and characteristics of the object of research. Then, the main on-going projects and the nearest future of the GIS Center were presented.

On board the ship, there was also a two-day conference of young scientists "The use of GIS and remote sensing data in solution of spatial problems". Young scientists from Russia, Belarus, and Czech Republic actively participated. There were 11 reports by eight organizations that use modern technical and software solutions in their work. Active discussion of the results of scientific studies has shown wide interest of the participants to the topics covered at the workshop. The most interesting to the participants were the reports by the Belarus team on the

use of remote sensing data for the internal land management and by S.A. Timonin (graduate student, Moscow State University) "Geovisualization and spatial-statistical analyses of the population forecast».

The workshop participants recognized excellent organization and the success of the first experience of conducting the Workshop in Russia and stated that it is necessary:

1. to support organizational-management efforts to create new teaching units (departments) in "Cartography and Geoinformatics" and to increase a number of students in this specialty in the higher educational institutions in the Russian Federation, considering that, currently, the demand for specialists is two to three times greater than the number of graduates in this field in the universities of Russia;
2. to intensify the implementation of inter-institutional and inter-regional scientific and educational projects, as well as to promote more active participation of students,

teachers, and professionals in international educational projects (e.g., UNIGIS, etc.);

3. recognizing the importance of participation in international conferences, to use the "InterCarto-InterGIS" conferences more widely as the platform for scientific, practical, and educational exchange;

4. to recommend to the future workshops addressing issues of interdisciplinary studies with geographic information technologies; of creation of distributed databases; of the use of mobile GIS, of unmanned aerial vehicles, of high-precision positioning systems, of cloud technologies, and of GIS in urban planning and design activities (territorial planning schemes);

5. to recognize the need for publishing in journals on geoinformatics of high rating;

e.g., "Geoinformatica. An International Journal on Advances of Computer Science for Geographic Information Systems», "International Journal of Digital Earth», "ISPRS International Journal of Geo-Information», "Geographical Systems. The International Journal of Geographical Information, Analysis, Theory and Decision», etc.;

6. to consider new forms of participation of experts in the workshop including the use of Internet technologies;

7. to support the promotion of this form of training in the future and to propose the next workshop in Abrau-Dyurso, Krasnodar kray (September 2–7, 2012).

Sergey V. Pyankov, Vladimir S. Tikunov

INSTRUCTIONS FOR AUTHORS CONTRIBUTING TO “GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY”

AIMS AND SCOPE OF THE JOURNAL

The scientific English language journal ‘GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY’ aims at informing and covering the results of research and global achievements in the sphere of geography, environmental conservation and sustainable development in the changing world. Publications of the journal are aimed at foreign and Russian scientists – geographers, ecologists, specialists in environmental conservation, natural resource use, education for sustainable development, GIS technology, cartography, social and political geography etc. Publications that are interdisciplinary, theoretical and methodological are particularly welcome, as well as those dealing with field studies in the sphere of environmental science.

Among the main thematic sections of the journal there are basics of geography and environmental science; fundamentals of sustainable development; environmental management; environment and natural resources; human (economic and social) geography; global and regional environmental and climate change; environmental regional planning; sustainable regional development; applied geographical and environmental studies; geo-informatics and environmental mapping; oil and gas exploration and environmental problems; nature conservation and biodiversity; environment and health; education for sustainable development.

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2. Papers are accepted in English. Either British or American English spelling and punctuation may be used. Papers in French are accepted under the decision of the Editorial Board.
3. All authors of an article are asked to indicate their **names** (with one forename in full for each author, other forenames being given as initials followed by the surname) and the name and full postal address (including postal code) of the **establishment(s)** where the work was done. If there is more than one institution involved in the work, authors’ names should be linked to the appropriate institutions by the use of 1, 2, 3 etc superscript. **Telephone and fax numbers and e-mail addresses** of the authors could be published as well. One author should be identified as a **Corresponding Author**. The e-mail address of the corresponding author will be published, unless requested otherwise.
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2. The **title** should be concise but informative to the general reader. The **abstract** should briefly summarize, in one paragraph (up to 1,500 characters), the general problem and objectives, the results obtained, and the implications. Up to six **keywords**, of which at least three do not appear in the title, should be provided.

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4. All **figures** (including photos of the authors) are required to be submitted as separate files in original formats (CorelDraw, Adobe Photoshop, Adobe Illustrator). Resolution of raster images should be not less than 300 dpi. Please number all figures (graphs, charts, photographs, and illustrations) in the order of their citation in the text. **Composite figures** should be labeled A, B, C, etc. Figure captions should be submitted as a separate file.

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ISSN 2071-9388

SOCIALLY SCIENTIFIC MAGAZINE "GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY"

No. 01(v. 05) 2012

FOUNDERS OF THE MAGAZINE: Faculty of Geography, M.V. Lomonosov Moscow State University and Institute of Geography of the Russian Academy of Sciences

The magazine is published with financial support of the Russian Geographical Society.

The magazine is registered in Federal service on supervision of observance of the legislation in sphere of mass communications and protection of a cultural heritage. The certificate of registration: ПИ МФС77-29285, 2007, August 30.

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Moscow 105120 Russia
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Phone 7-495-9167574
Fax 7-495-9167673
E-mail: om@aov.ru

Sent into print 06.03.2012
Order N gi112

Format 32 × 46 cm/2
55 p. sh.
Digital print
Circulation 500 ex.