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Impact of climate change on natural fire danger in Ukraine

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Abstract—This research focuses on the objective assessment of the pyrological regime in climate change conditions. The present state (1981–2010) of climatic characteristics determining the natural fire danger in Ukraine is investigated. For all physicogeographical zones, the change in the pyrological regime, its significance throughout the current climatic period were estimated. Since the beginning of the 21st century, there has been an increasing tendency in fire danger. It resulted in increasing number of forest fires and theirs areas. In most regions of Ukraine, authenticity of such changes is 90–99%.

The impact of climate change on the number and area of forest fires in the country (e.g., in the Kherson region) is discussed. The article presents the quantitative relationships of the level of fire danger in the region with the thermal regime, humidity and wind regimes. The decisive influence of air temperature on the degree of natural fire danger is proved. The effect is most marked by the area of fires and much less by their numbers.

Possible changes of climatic characteristics and extreme weather conditions in Ukraine in 2021–2050 relative to the current climatic period for the scenario SRES A1B and their impact on forest fires were found.

Key-words: climate change, climatic projection, forest fire, fire danger

1. Introduction

Meteorological conditions are major factors in determining fire safety and fire regulations of forestry services. Air temperature and soil humidity, rainfall, and wind speed affect the conditions of fire, speed and features of its development, strategy and tactics of suppression. Averaged over long time, these characteristics describe the pyrological vulnerability of climate, which defines the propensity of the territory for forest fires. In Ukraine, for the assessment of fire danger, a composite index is used that takes into account air temperature, dew point, and daily amount of precipitation. It is a basis for determining the class of fire danger in terms of weather. Temporal changes in meteorological conditions caused by climate change strongly affect pyrological regime and fire safety of the regions.

It is apparent that the weather conditions in Ukraine, like on the planet in general, are changing (UNFCCC, 2009, 2012; *Balabukh et al.,* 2013, 2014). Many of the registered changes of the climate system, according to reports of the Intergovernmental Panel on Climate Change (IPCC), are unusual or unprecedented in recent decades or even millennia (IPCC, 2013). They have mostly negative consequences and will be strengthened in the future. It is expected that by the end of the 21st century, in Eastern Europe, the risk of fire danger will increase, particularly in the southern regions, increasing the risk of forest and peat fires. In Ukraine, we observe a significant increase in the number of forest fires and their area, which is likely due to climate change. For the past 30 years (1981–2010), the annual number of forest fires has increased by 2.6 times. The North Black Sea region suffers the most from wildfires in Ukraine. In 2007, 95% of forests in the Kherson oblast and Crimea were affected by forest fires of varying intensity (*Zibtsev*, 2010).

Taking into account this all-round facts, the main task is to study of pyrological characteristics of the climate in Ukraine, their regional features, and changes throughout 1981–2010, and to examine the projections of fire danger change in the 21st century. This information allows us to define regions most suffer from nature forest fire danger, predict the changes of areas distribution, and develop the reduction of adaptation measures concerning negative effects.

2. Data and methods

The main climate characteristics, which affect the fire danger, are those that determine the processes of drying-wetting wood-burning materials. The air temperature (average, minimum, and maximum values), relative humidity (daily average and minimum values), annual precipitation, number of days without rain, wind regime, number of days with thunderstorms, duration of the warm season, vegetative period belong to them.

The estimation of pyroclimatic regime includes the calculation of fire indexes – the special mathematical formulas that formalize the influence of basic meteorological parameters on the wildfire. Such indexes and systems for the assessment, monitoring, and prediction of fire hazard have been developed to solve the natural firefighting challenges in different countries around the world. The most known of them are the Canadian Wildland Fire Information System – CWFIS the Fire Monitoring, Mapping, and Modeling – Fire M3

(Canada), the National Fire-Danger Rating System – NFDRS (USA), and the European Forest Fire Information System – EFFIS.

In Ukraine, the nature forest fire danger is calculated using the Nesterov composite index (*Nesterov*, 1949). Its main advantage is the easy calculation which based on observation data. According to *Gubenko* and *Rubinstein* (2012), this index has fairly gross correction for precipitation and does not take into account the duration of period without rain. The equation for Nesterov composite index is:

$$КПО = КПО_{n-1} * K_{on} + \left[t \left(t - t_d \right) \right]_n , \quad (1)$$

where $КПО_n$ is the value of Nesterov composite index that is calculated for the current day, *n* (°C); $КПО_{n-1}$ is the value of Nesterov composite index, which is calculated for the previous day, *n-1* (°C); K_{on} is the adjustment precipitation coefficient (it is equal to 1 if the rainfall is less than 3 mm, or to 0 if it is greater than or equal to 3 mm); t is the air temperature (°C); t_d is the dew-point (°C); $t - t_d$ is the dew-point deficit (°C).

According to the $КПО_n$ value, the fire danger is classified into five categories:

$КПО_n < 400$ °C – fire security (I category);

$400 \leq КПО_n < 1000$ °C – low fire danger (II category);

$1000 \leq КПО_n < 3000$ °C – moderate fire danger (III category);

$3000 \leq КПО_n < 5000$ °C – high fire danger (IV category),

$КПО_n \geq 5000$ °C – very high fire danger (V category).

If $КПО_n$ is more than 10000 °C, it is an extreme fire danger.

The research of pyrological characteristics of climate and its temporal fluctuation was conducted for the period 1981–2010 using daily temperature, wind speed, precipitation and relative humidity data from the 187 meteorological stations across of Ukraine. Calculation of the characteristics of climate change that affect the frequencies of forest fires was conducted for the period 2021–2050 relatively to the recent climatic period (1981–2010) according to the regional climate model REMO with resolution of 25 km derived from global model simulation ECHAM5 (ECAP, 2009). Based on these data the average values of the selected indicators for the two specified periods were determined. The next step was calculation of their changes and theirs significance. Since these two periods are independent and climatic indicators are subject to normal distribution, the estimation of the significance of the expected change was carried out according to the Student's t-criterion, and the probability (*p-value*) of this change was determined *(Sachs,* 1976).The zero hypothesis is that both samples have the same mean values: $H_0 : \overline{x_1} = \overline{x_2}$. If the calculated value of the t-criterion is greater than its critical value, the hypothesis of the equality of means is rejected. That is, with the probability *p,* the difference is significant.

The calculations were made for the scenario A1B, which belongs to the first group and involves the growth of the population by the middle of the 21st century with the subsequent reduction of emissions. It is the average between scenarios B1 and A2 and the balanced use of fossil and renewable energy sources. According to its characteristics, the SRES A1B scenario corresponds to the scenario RCP6.0 proposed in the IPCC Fifth Assessment Report (IPCC, 2013).

The main tendencies of climate change were defined for the whole area of Ukraine. The analysis of the climate change impact on the nature forest fire was conducted by the example of the Kherson region, which is the most vulnerable area to natural fire danger in Ukraine. This is the hottest and driest region of Ukraine, where man-made pine forests dominate, which are the most vulnerable to forest fire (*Hodakov* and *Zharikova*, 2011*; Zibtsev,* 2010).

For spatial distribution (mapping) we used the Information and Reference System “"Natural Elemental Meteorological Events in Ukraine”, which was developed at Ukrainian Hydrometeorological Institute, Department of Synoptic Meteorology (*Balabukh et al.,* 2010).

All terms and definitions that have been used in this article are presented in *Table 1*:

Table 1. Definition of terms applied in Ukraine

Term/designation	**Definition**
warm days	Annual count of days when daily minimum temperature is equal to or greater than 0 °C.
summer days	Annual count of days when daily mean temperature is equal to or greater than 15 °C.
hot days	Annual count of days when daily maximum temperature is equal to or greater than 25 °C.
warm period	Time period from April to October.
number of days with atmospheric drought	Annual count of days when average daily relative humidity is less 50% and maximum daily air temperature is more than 25 °C.
number of days without rain	Count of days when daily precipitation (R) is less than 0.01 mm.
vegetation days	Count of days when daily mean temperature is equal or greater than 5 °C, when vegetation of agricultural plants is beginning.
active vegetation days	Count of days when daily mean temperature is equal or greater than 10 °C, when vegetation of agricultural plants is intensive.

Their using is regulated by the relevant government documents: standards, guidelines, manuals. Some of them do not match with the definitions of indicators used in several international projects, but they are mandatory to be defined this way in Ukraine.

For estimation of the observed climate change, we used linear trend coefficient calculated using the least squares method. The significance of the change was evaluated according to the Student's criterion (t-test): the probability of that the value of the t-criterion is equal to or exceeds the value calculated by the actual data was determined (*Sachs,* 1976). All statistical analyses were performed using StatSoft, Inc, STATISTICA 6.0.

For indication of the assessed likelihood of an outcome or a result, we used the next terms: “virtually certain” 99–100% probability ($p > 0.01$), “very likely” 90–100% ($0.1 \geq p > 0.01$), “likely” 66–100% ($0.34 \geq p > 0.1$), “about as likely as not” 33–66% ($0.67 \geq p > 0.34$), “unlikely” 0–33% ($0.90 \geq p > 0.67$), “very unlikely” 0–10% ($0.99 \geq p > 0.9$), “exceptionally unlikely” 0–1% ($p > 0.99$) (IPCC*,* 2013).

3. Results

3.1. The state of natural fire danger in Ukraine throughout the current climatic period

Air temperature is one of the most important factors influencing the possibility of wood-burning materials flaming. The spatial-temporal analysis of pyrological indicators of the thermal regime has shown that the south areas of Ukraine have the thermal conditions most favorable for the occurrence of forest fires (*Figs. 1 and 2*). The highest average and mean of maximum values of air temperature per year are observed in this region. These values can be 9 °C and 14 °C, or more. In summer, these values exceed 21 °C and 28 °C. On the southern part of Ukraine, the warm days count more than 300, and the vegetation period is more than 235 days. In this area, there can be 130 summer days and more than 80 hot days. The sum of positive average daily air temperatures ranges from 2300 °C in the northeast of the country to 4000 °C – in the south. The sum of negative average daily air temperatures rises from north-east to south-west from –550 °C in the Sumy and Kharkiv regions to –200 °C and more in the Crimea. Moreover, for all territory of Ukraine, the sum of positive daily average temperatures prevails. In the south part of the country, the difference between the sum of positive and negative daily average temperatures reaches 3500 °C. The sum of maximum daily air temperatures that exceed 25 °C in south is 200% greater than in the northeastern and northwestern regions of the country, and it equals to 2500 °C and more.

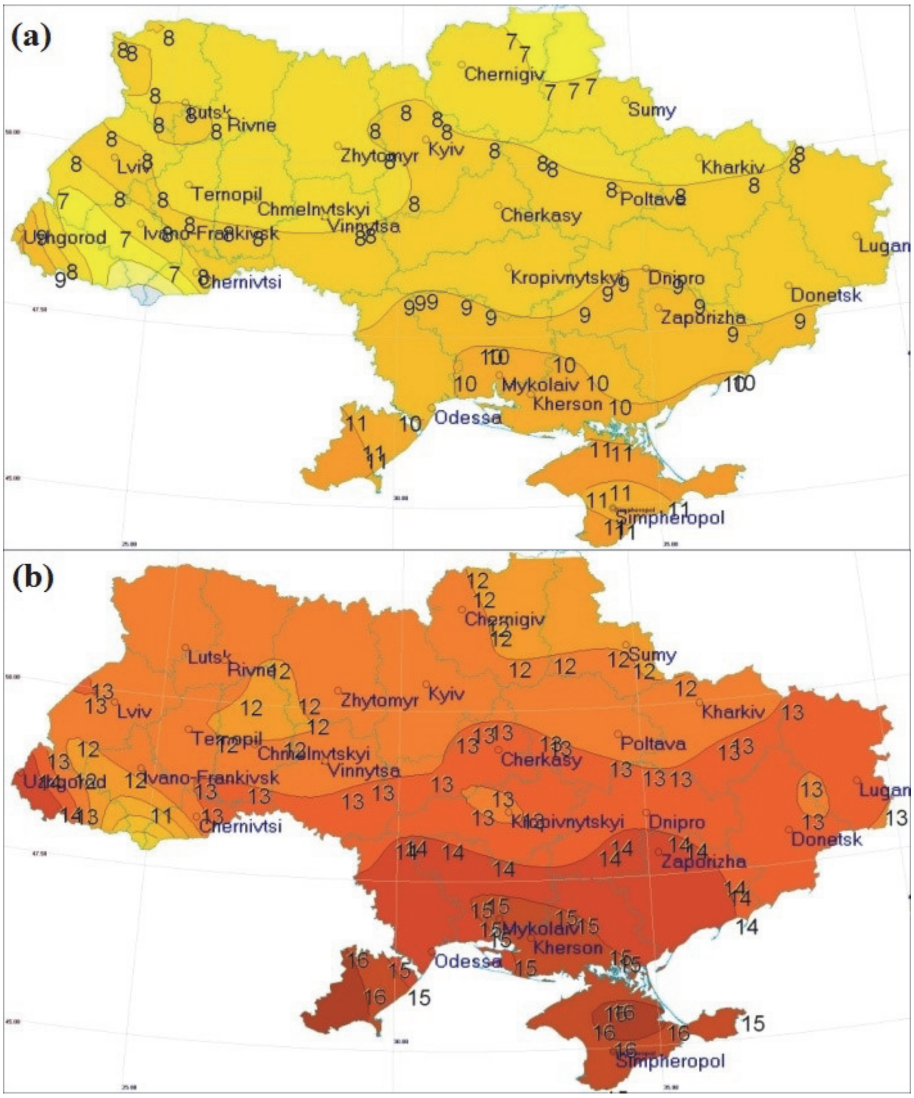

Fig.1. Average (a) and mean maximum (b) values of air temperature per year in 1981–2010.

Besides thermal regime, precipitation is also an important factor that affects nature forest fires. The presence of sufficient moisture in the atmosphere, especially in summer, reduces the frequency of forest fires. In the current climatic period (1981–2010), the field of average annual precipitation in Ukraine maintains a zonal distribution of isolines, influenced by the Crimea and the Carpathian Mountains. The values gradually increase from south to north in the range of 400 to 650, respectively. In mountainous areas, there is a natural increase in precipitation caused by physical and geographical conditions. It is the wettest zone, where the annual precipitation is above 1100 mm. The most arid zone is the southern area (steppe zone). The annual precipitation varies between 380–550 mm per year. Thus, it is the main risk zone for this component of pyroclimatic regime. The rest of territory has a sufficient, but unstable wetting, which ensures partial opportunities for reducing the frequency of forest fires (*Fig. 2*).

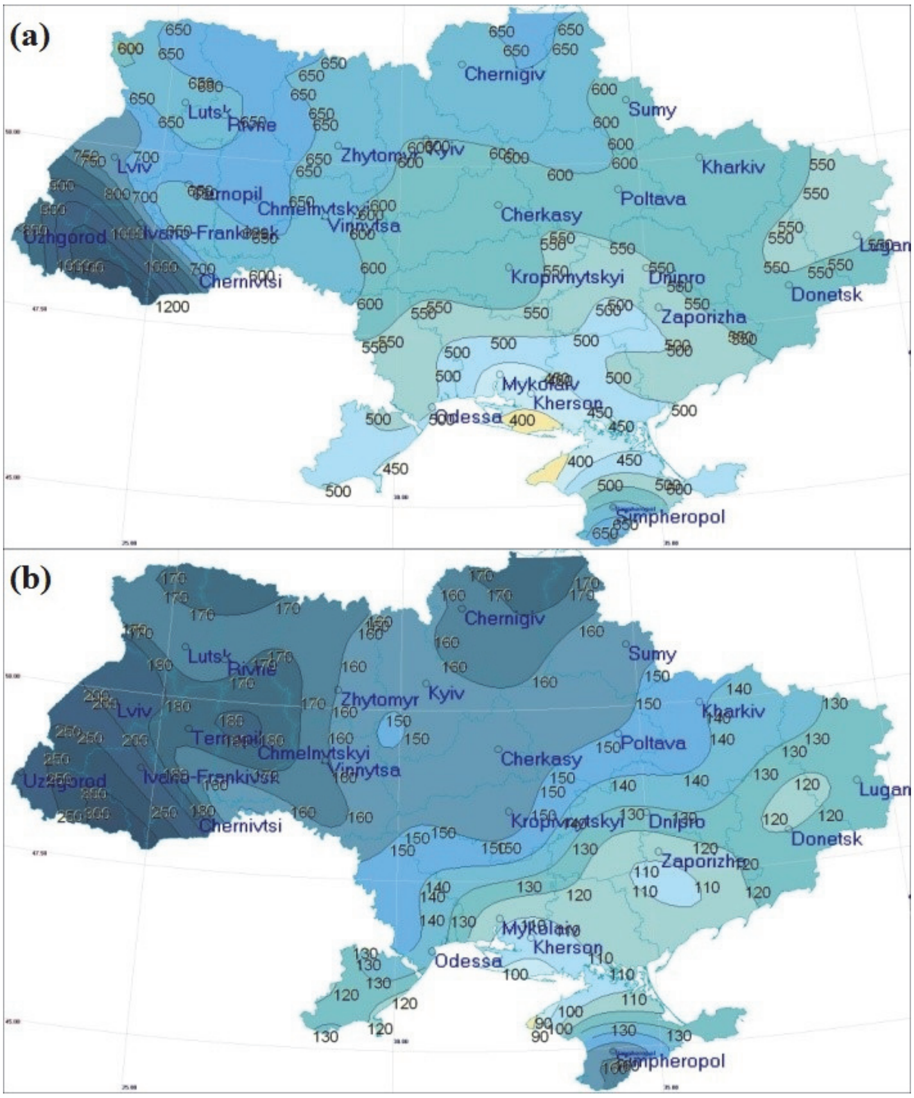

Fig. 2. Average annual precipitation (a) and amount of precipitation in summer (b) in 1981–2010.

In summer, in the steppe zone less than 200 mm precipitation fall, and in spring and autumn – less than 125 mm. At the same time, in some areas of the Kherson and Mykolaiv regions, precipitation may be less than 100 mm in summer. Deficiency of precipitation contributes to a significant increase in fire danger in this region.

Relative humidity also affects the nature fire danger, in particular, the intensity and the type (lowland ore overhead) of the fire. In the presence of sufficient moisture in the atmosphere, the combustion temperature is reduced due to heat losses by evaporation. If relative humidity is 40–50% or more the lowland fire is dominant. When it is lowered to 30%, the fire danger substantially increases and if it is 20%, the lowland fire may become the overhead fire (*Ozhogin,* 1939). The average humidity of air throughout the fire danger season in Ukraine is in the range of 40–65%, which contributes to the formation of mainly lowland fires. The number of days with average daily relative humidity less than 30% grows from 10 days on northwest to 35 days on southeast during the warm period, while on the coast areas it is decreasing again (*Fig. 3*). The same trends are typical for humidity less than 50%. That is, the southern and southeastern regions of the country are the most arid and favorable for the emergence of lowland fires that can become overhead fires.

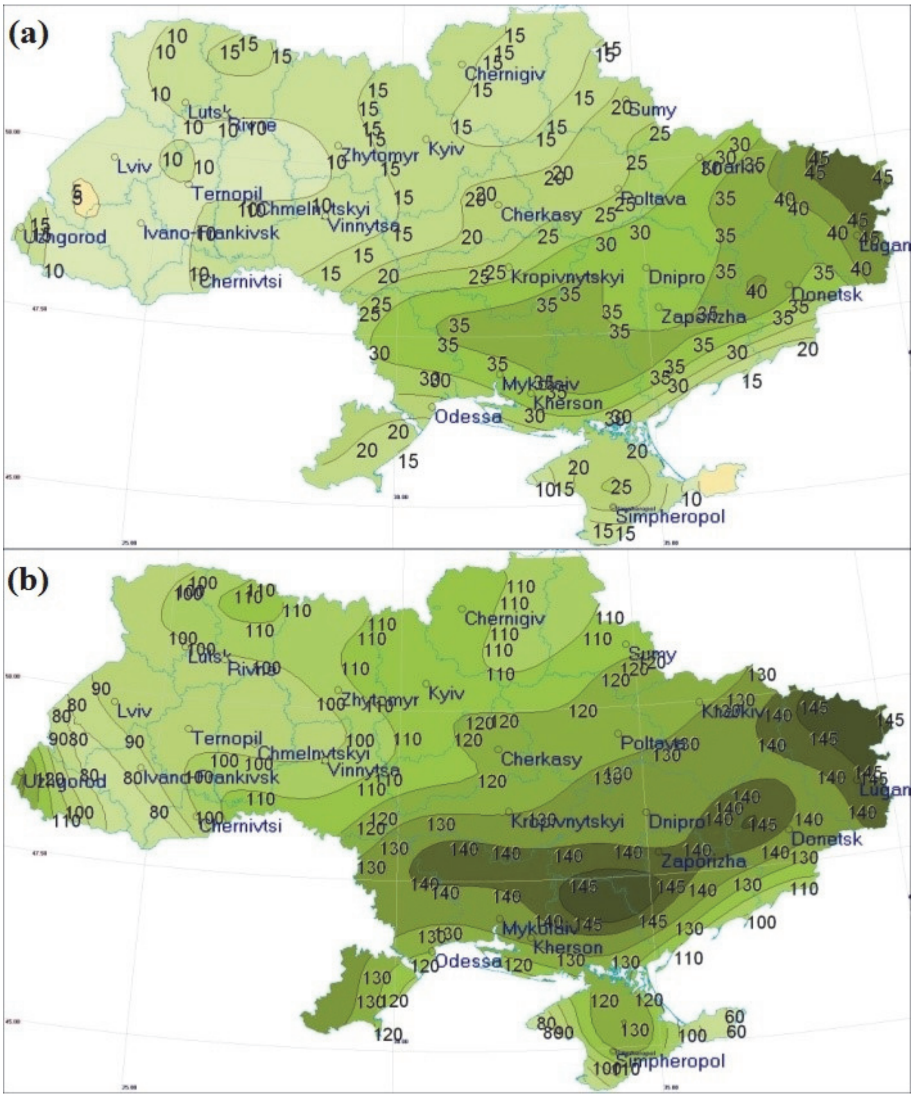

Fig. 3. Average number of days with average daily relative humidity less than 30% (a) and 50% (b) throughout the warm periods in 1981–2010.

Over the long absence of precipitation, when the daily amount of precipitation is less than 0.01 mm, the average daily relative humidity is less than 50%, and the maximum daily air temperature is more than 25 °C, there are favorable conditions for the formation of atmospheric drought. The largest number of days with atmospheric drought (15–20 days per year) was observed in the steppe and eastern forest steppe zones (10–15 days per year). In the central forest steppe it is 3–4 days per year, in the Polissya region it is 1–2 days, and in the rest territories it is even less. The probability of forest fire formation significantly increases in the absence of precipitation.

The largest number of days (about 5 months – 150 days or more) without rain ($R < 0.01$mm/day) throughout warm period was observed in the eastern areas of country (*Fig. 4*). To the north and northwest, this number is decreasing, and in the Carpathians it is the smallest (about 3 months – 110 days or less).

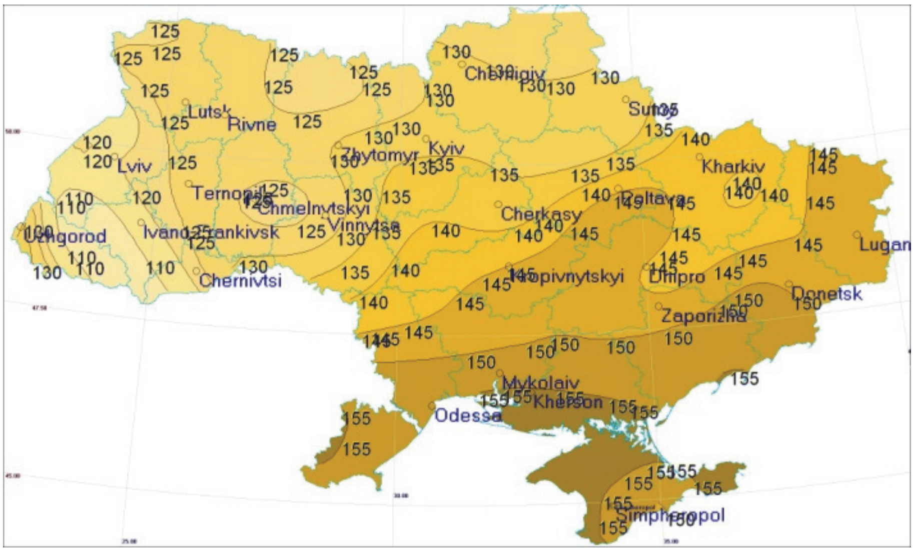

Fig. 4. Number of days without rain throughout the warm periods in 1981–2010.

In Ukraine, precipitation amount of 3 mm/day plays an important role in causing fires. It is a parameter that has to be taken into account when assessing the degree of fire risk in the country. It is believed that if the daily precipitation amount is 3 mm, the natural fire danger decreases and the comprehensive indicator of fire danger Nesterov is zeroed. In south region, the number of days with daily precipitation more than 3 mm may be 70 throughout the warm period. The maximum duration of the period with daily precipitation less than 3 mm (the period when $КПО_n$ increases) reaches 55 days or more, while in the western part of the country it is twice less (*Fig. 5*).

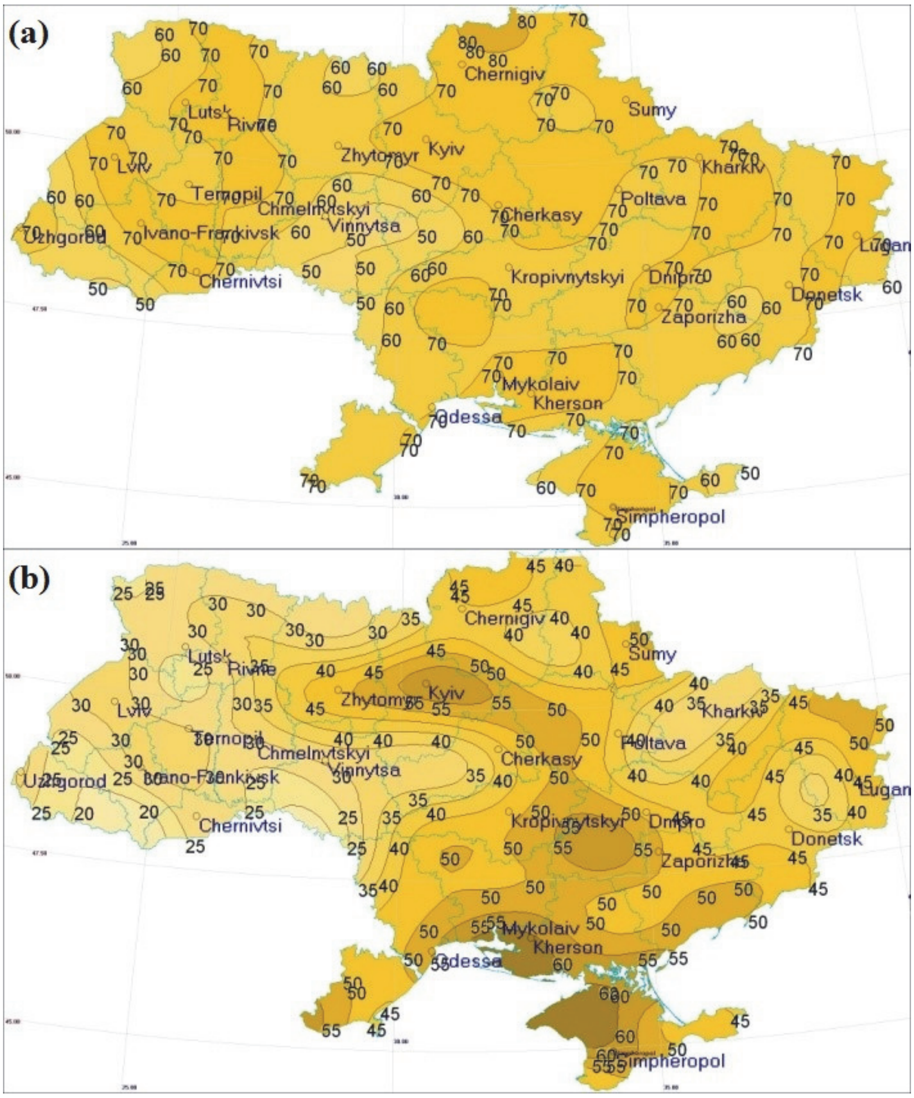

Fig. 5. Number of days with precipitation less than 3 mm (a) and maximum duration of period with that condition throughout the warm periods in 1981–2010 (b).

Since the forest fires depend on several factors and their interactions, climatic conditions favorable for the occurrence of natural forest fires are often described using different indices. In Ukraine and the post-Soviet territory, the Nesterov composite index (*КПО*) is the most known index that is used to analyze the impact of meteorological conditions on the forest fires, as well as on the monitoring and forecasting of forest fires. Application of the Nesterov index is regulated by the relevant government documents: standards, guidelines, and manuals.

The analysis of the spatial distribution of *КПО* index has shown that in Ukraine, the natural fire danger is rising from northwest to southeast gaining the highest values in August, especially in the Kherson and Mykolaiv regions, where *КПО* daily mean values exceed 250 °C or more, and *КПО* maximum values reach 50000 °C, which is 10 times higher than limit for the very high fire danger (V category) (*Fig. 6*).

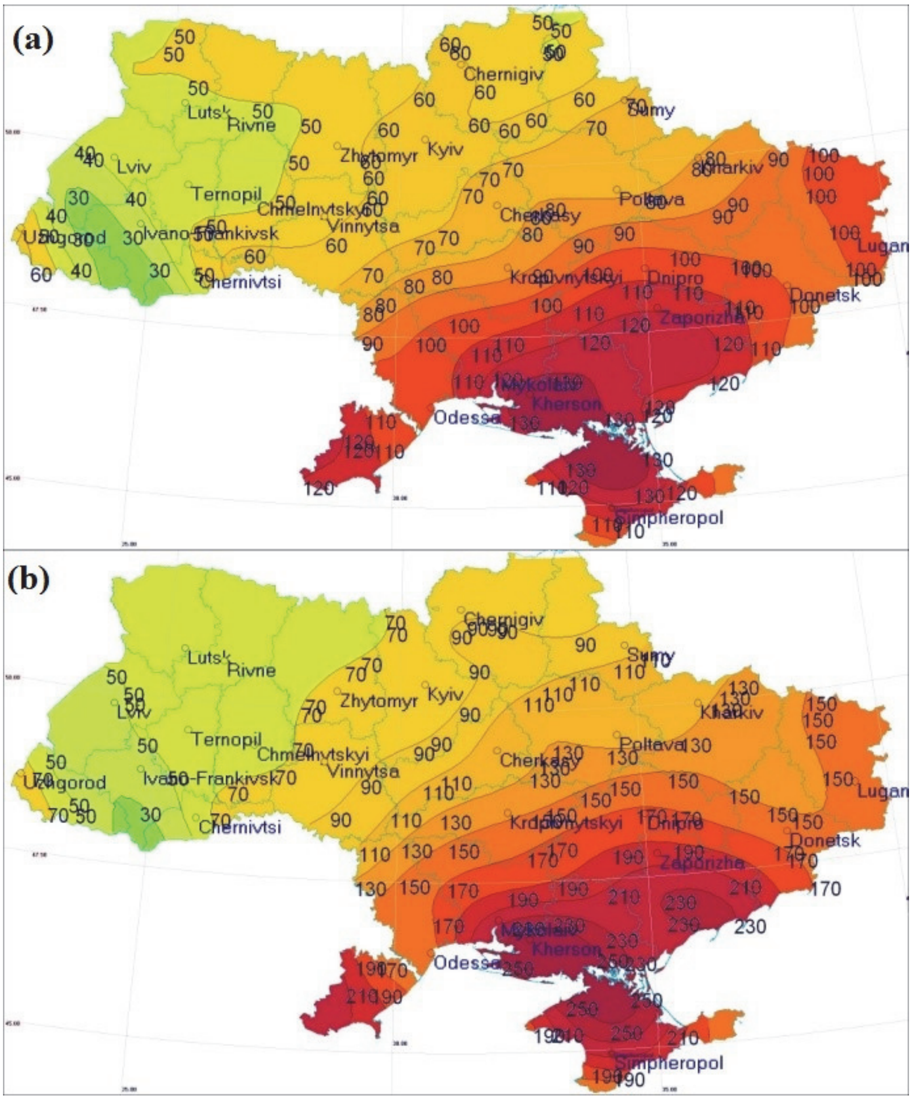

Fig. 6. *КПО* daily mean values for the warm periods (a) and the August (b) in 1981–2010.

Maximum days with very high fire danger (≥5000 °C) in warm period have increased by 30 days or less in the west and northwest areas to 80–90 days or more in the southeast. At the same time, in the southern part of the country there can be one or two months (35–50 days) with extreme fire danger (≥10000 °C), while in the northwest this value is 2–3 times lower (*Fig. 7*).

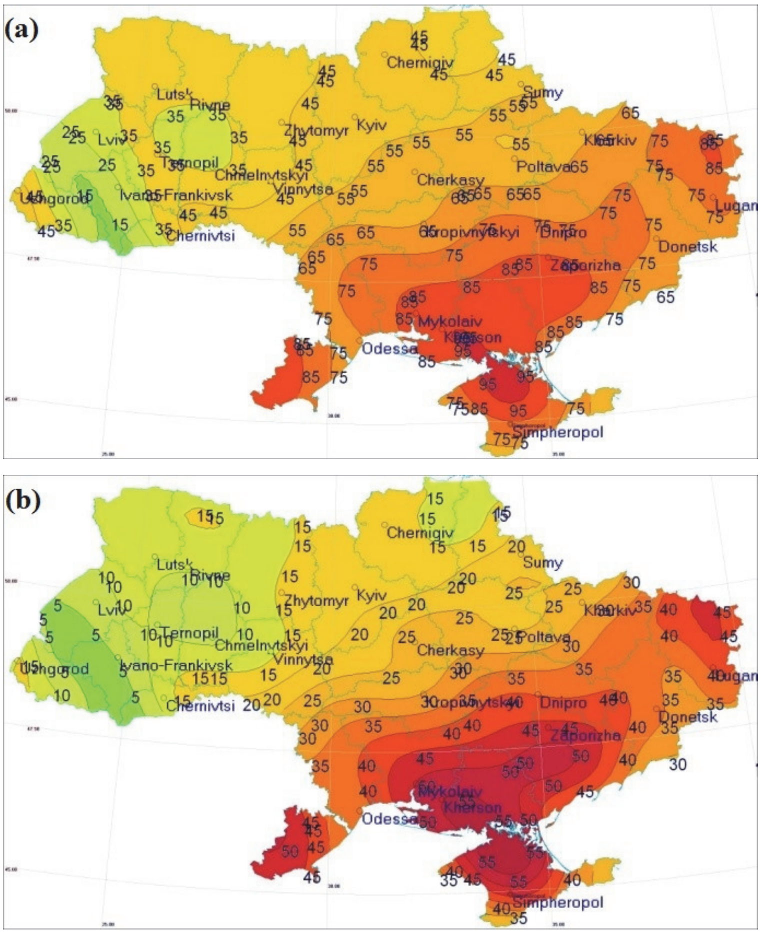

Fig. 7. Maximum number of days marked with V category: very high fire danger (≥5000 °C) (a); extreme fire danger (≥10000 °C) (b) in the warm periods in 1981–2010.

It follows from the results, that in the current climatic period, the most favorable climatic conditions for the emergence of natural fires in Ukraine are observed in the south and southeast of the country, especially in the Kherson and Mykolayiv regions. Since the Kherson region is characterized by man-made pine forests, which are the most dangerous for ignition, this region is the most fire-hazardous in Ukraine.

3.2. The main characteristics of trends of natural forest fires in Ukraine

A steady growth of the number of forest fires and their area has been observed for the past decades in Ukraine. Over the past 30 years (1981–2010), the annual number of forest fires in the country has increased by 2.6 times. Areas affected fire slightly increased since 1987, but after 1991, they have risen by 3–5 times (*Zibtsev,* 2010). It is largely due to climate change. Since the mid 70's, the steady transition of the anomaly of the average annual global air temperature is above 0 °C relatively to the basic climatic period of 1961–1990 (IPCC, 2013). However, in Ukraine, such transition is observed only in the late 90's due to an increase in the minimum, maximum, and average daily air temperatures (*Balabukh et al.,* 2013).

The rate of air temperature change (average, minimum, and maximum values) approximately equals to 0.3 °C per 10 years in 1961–2013 is. The average annual air temperature has risen by 0.8 ºC relatively to the climate normal (1961–1990) for the last twenty years (1991–2013). This is due to increasing of maximum and minimum temperatures in Ukraine (*Fig. 8*).

The changes were more intense in the current climatic period. According to the results of t-test analysis, it is “virtually certain” that the average annual temperature has increased in most of the country, and it is “very likely” for the rest of its territory. These changes are about 0.57 °C / 10 years, which is more intense than in 1961–2013 (0.3 °C / 10 years) and significantly exceeds the rate of change of global surface temperature (0.13 °C / 10 years in 1995–2012) (*Balabukh et al.,* 2014; IPCC, 2013). However, the rates of temperature change are uneven across the country. The highest rate of change was in the steppe and the eastern forest steppe region it was 0.6–0.7 °C / 10 years with a maximum in the Sumy region. In the central forest steppe region the process of rising was slightly slower, just 0.5–0.6 °C / 10 years. In Polissya and the western forest steppe, the rate was 0.3–0.4 °C / 10 years.

The rate of change also varies during the year. In summer, the average air temperature increased more intensely than in other seasons. It has grown from 0.7 °C / 10 years in the northwest of the country to 0.9 °C / 10 years in the south. Over Ukraine it was 0.83 °C / 10 years. The largest air temperature increase was in January (1.7 °C / 10 years), August (1.6 °C / 10 years), and July (1.5 °C / 10 years). The average temperature in spring has risen by 0.5 °C. This is due to an increase in May (0.7 °C / 10 years). Temperature in autumn changed by 0.4 C / 10 years. Growth of the minimum temperature prevailed in the winter season, the same for maximum prevailed in the summer.

Annual average maximum temperature also increased. The rate was 0.6 °C /10years. But, it rose from northwest to south and southeast. Thus, in the western forest steppe, the values were 0.4–0.5 °C / 10 years, while in the steppe and eastern forest steppe they were 0.6–0.7 °C / 10 years, reaching 0.72 C / 10 years in the Lugansk region. The analysis of annual variation of rate has shown that maximum values were in summer. In summer the average rate was 1.0 °C / 10 years, with a maximum value of 1.0–0.1 °C / 10 years in the steppe and eastern forest steppe regions.

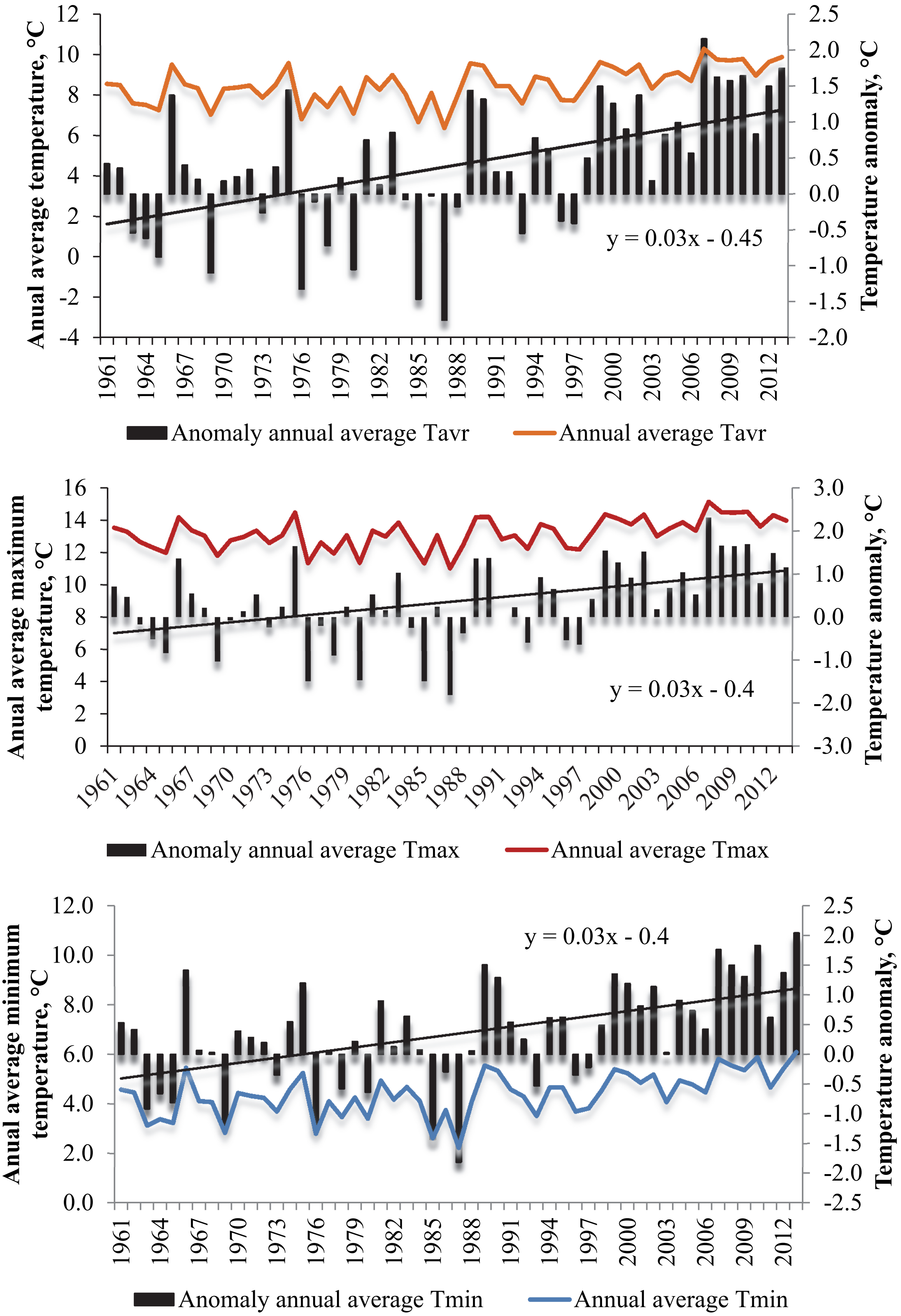

Fig. 8. Annual average (a), mean maximum (b), and mean minimum (c) land-surface air temperatures and theirs anomalies (°C), relatively to the climatic norm in 1961–2013, in Ukraine.

Significant increasing of the air temperature in the whole year resulted in the increasing number of warm days in Ukraine on average by 8 days per 10 years (*Fig. 9*). Throughout the 1981–2010 period, it is “very likely” that its duration has grown to 7–11 and 6–9 days in forest steppe and steppe regions, respectively. Such changes are “likely” to be occurring in the Polissya region too.

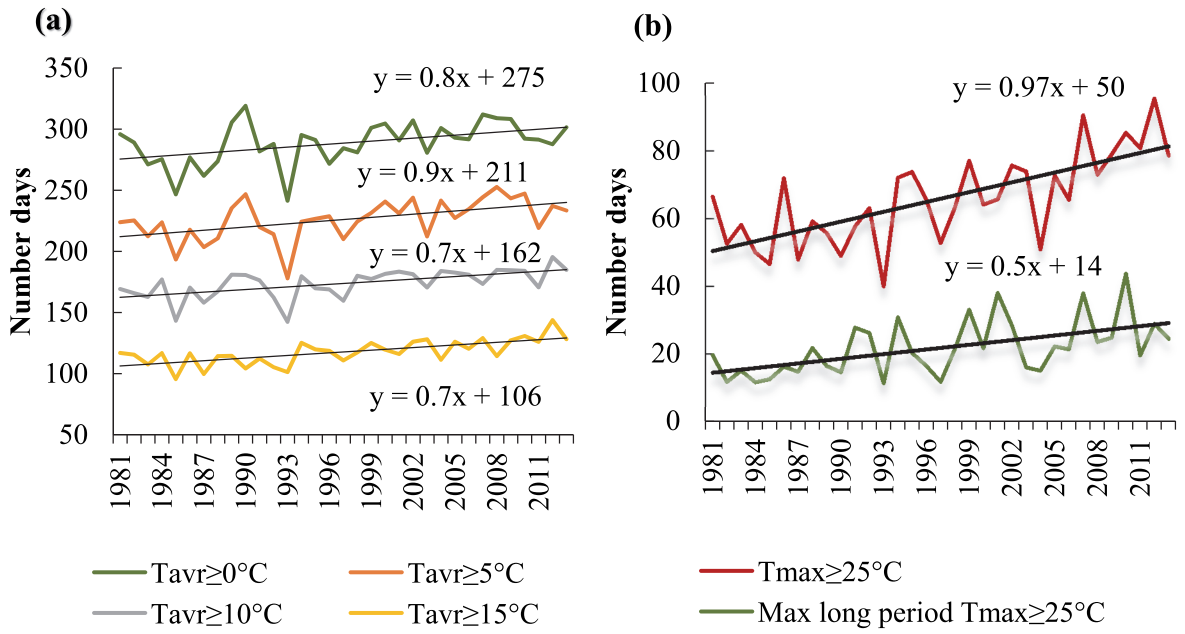

Fig. 9. Trends of annual number of warm days (daily mean temperature ≥0 °C), summer days (daily mean temperature ≥15 °C), vegetation days (daily mean temperature ≥5 °C) and active vegetation days (daily mean temperature ≥10 °C) (a), hot days (daily maximum temperature ≥25 °C) and maximum duration of periods with daily maximum temperature ≥25 °C (b) in Ukraine in the period 1981–2013.

For Ukraine it is “very likely” and “likely” that the number of vegetation and active vegetation days increases for 9 and 7 days, respectively. The intensity of these changes decreases from west to east. Due to the rise of temperature, the number of summer days, when the average daily temperature is above 15 °C increases. The rate of change is 7 days / 10 years and it is “virtually certain” (*Fig. 9*). In the west of the country, these changes are greatest (7–10 days / 10 years). In the northern and southern regions, the number of summer days “very likely” increases by 3–5 days / 10 years, and in the central and eastern regions – “likely” by 2–3 days / 10 years.

It is “virtually certain” that the number of hot days, when the daily maximum temperature is above 25 °C, is also rising. Generally for Ukraine, the rate of change is 9–10 days / 10 years. The maximum duration of the period with this temperature also increases by 5–6 days / 10 years.

3.2.1. Regime of humidity

Since the beginning of the 21st century, the precipitation, unlike air temperature, has not changed significantly, although in the current climatic period, it likely increased by 2–3% per 10 years. There was a redistribution of rainfall between seasons. In autumn, total precipitation, “very likely” increased by 13% / 10 years; in the spring this growth was 200% lower, only 5–6%/ 10 years, and for the winter and summer seasons, in Ukraine there were not significant changes. However, these changes were very heterogeneous throughout the country, especially in summer.

The greatest fire danger is characterized for summer. In this period, the total precipitation has reduced on a considerable territory of the country. The most intense changes are observed for the Polissya and eastern forest steppe region, where the precipitation deficit “very likely” has increased to 23% / 10 years. In return, in the western forest steppe, especially in the Ivano-Frankivsk region and Volhyn, their sum significantly increased and reached 37 and 29% / 10 years.

Although the average amount of precipitation per year in the current climatic period in Ukraine grew a little bit, it is “very likely” that a number of days with precipitation significantly decreased almost throughout the country. The intensity of the change rose from the west (6–9 days / 10 years) to the south and south-east (10–11 days / 10 years). The maximum duration of period with rain (R > 0.01 mm/day) was also reduced by 1–2 days / 10 years almost throughout the country.

Significant increasing of duration of period without rain that was accompanied by a significant increase in air temperature, especially its maximum values, led to an increase in the number of days with atmospheric drought. “Likely”, its number has grown by 2–3 days / 10 years general, for Ukraine. The aridity increased the most intensively in the steppe (3–7 days / 10 years) and eastern forest steppe (3–5 days / 10 years). The increase of the repeatability of arid conditions in the zone of sufficient atmospheric humidification, covering Polissya and the northern forest steppe areas is a dangerous tendency. It is “likely”, that in this region the number of arid days increased by 1–2 days / 10 years.

It is “very likely”, that throughout the current climatic period in Ukraine, the average annual, spring and summer relative humidity decreased by 0.7, 1.6, and 1.5% per 10 years, respectively. “Likely”, it increased in winter (0.4% / 10 years) and did not have significant changes in autumn (0.4% / 10 years). This process was observed almost throughout the country, and it was the most intense in the eastern forest steppe (1.4% / 10 years in Sumy region) and in the northern Steppe (0.6–1.2 / 10 years). A very intense reduction of moisture in the atmosphere was observed also in the Chernihiv region (1.5% / 10 years).

In spring, the atmospheric circulation changed and the essential increase in temperature led to notable decrease in average-for-season relative humidity (*Lipins'kyy*, 2003). The intensity of process is intensifying from west, northwest to south southeast. In the west forest steppe the rate is 0.9–1.3% / 10 years in contrary to the south steppe, where it equals to 2.3% / 10 years. The maximum rate of the change was 2.5% / 10 years in the Cherkasy region. The same trends were typical for the summer. In autumn, the average-for-spring relative humidity "unlikely" changed, except for the south steppe, where it probably increased.

An estimation of inter-year variability of the degree of fire danger for all regions of Ukraine in 1981–2010 was conducted. Based on results of analysis during this period in the country, there is a growth in the maximum number of days with an extreme fire danger. The most significant changes (1–2 days/ 10 years) are observed in the north and northeast areas of the country. These changes are not typical for the whole fire season. October, May, and September are exceptions. During these months, fire safety did not change almost throughout the country, and in some areas it even decreased. But in April, June, and August, a number of days with V category of fire danger is getting bigger in Ukraine.

Since the natural fire danger strongly depends on a combination of various meteorological factors, its temporal and spatial changes have a different scale, and sometimes even the direction of the trend is changing. That is, they are characterized by distinct regional features due to the climatic and microclimatic features of the territory that needs further research.

Thus, regional climate changes in Ukraine that affect fire danger are consistent with global changes in the thermal regime: the average for the year and seasons, and the minimum, maximum, and average temperatures increase; the number of warm and summer days increases; the number of days with active vegetation increases; the number of hot days and the duration of the hot period increase, the aridity during the warm period and the number of days with extreme fire danger increase.

3.3. Impact of climate change on the natural forest fires in Ukraine

A comprehensive analysis of the climatic parameters of the thermal regime, the regime of humidification, and the number and areas of forest fires, conducted by the example of Kherson region, where the greatest natural fire danger has been identified in Ukraine, showed that climate change significantly influences the fire danger.

The research showed that the risk of fire in the Kherson region largely depends on the thermal, moisture, and wind regimes. 10 weather stations across the region were used to characterize the territory. The influence of temperature is crucial. It is established that the temperature more affects the area of fires and much less affects their number (*Table 2*).

Table 2. Relationships between the number of forest fires per year (y) and the climatological conditions (x) in the Kherson region of Ukraine

Meteorological parameters	**Pearson's correlation**			**Regression**
	r(x,y)	**t**	**(1-p)value**	
average temperature in October	0.60	3.0	0.008	y =42.1x–257
maximum temperature in October	0.59	2.9	0.010	y =36.9x–367
minimum temperature in October	0.55	2.7	0.017	y =39.1x–67
minimum temperature in September	0.58	2.8	0.012	y =45.5x–354
the average temperature in September	0.53	2.5	0.022	y =37.4x–438
maximum temperature in September	0.45	2.0	0.061	y =24.9x–355
number of days without rain	0.44	1.9	0.079	y =4.1x–104.3
maximum duration of hot days periods	0.40	1.8	0.096	y = 2.5x + 187
number of days with thunderstorm	0.40	1.8	0.096	y = 2.5x +100
maximum daily wind speed	0.39	1.7	0.113	y = 5.1x+142
average annual temperature	0.25	1.0	0.312	y =34.3x–167
average summer temperature	0.23	0.9	0.367	y=21.9x–293
amount of precipitation in July	–0.40	–1.7	0.104	y = –1.4x+270
annual precipitation	–0.40	–1.8	0.098	y = –0.4x+397
annual average relative humidity	–0.41	–1.8	0.092	y = –7.9x+709
amount of precipitation during the summer	–0.47	–2.1	0.051	y = –0.9x+328

It is established that in the northwest Black Sea region (south of Ukraine), the number of fires per year depend on the air temperature mainly in October and September: the higher the average, minimum, and maximum temperatures during this period, the greater the number of fires that may occur in the region (*Table. 2*) Generally, in South-Eastern Europe, the greatest number of forest fires is observed in the summer-autumn period. The increase in air temperature and aridity in recent years leads to an increase in the risk of forest fires in the autumn, not only in Ukraine, but also in some EU countries, in particular, Hungary, Slovakia, and Czech Republic (European Commission, 2006). The same tendencies are typical for many regions of Russia (*Roshydromet*, 2008).

Analysis of the regression model calculations presented in *Table 2* shows, that the increase in the average monthly temperature by 1 °C can cause the growth of annual forest fires by almost 20%. The increase in the frequency of forest fires substantially depends (r = 0.4) on the maximum duration of hot periods, the number of days without rain, the wind speed, and the average number of days with thunderstorm. The greater the importance of these factors, the more likely they strengthening wildfires.

Analysis showed that increasing of annual precipitation by 20%, particularly throughout the fire danger period, can lead to a decrease in the number of forest fires in the region by 18%, and an increase in the average annual relative humidity by 10% may cause a decrease in the number of fires almost by 40%. It is established that in increase in the number of days without rain can lead to an increase of annual number of fires almost by 20%. It also can grow by 13% with a 5 m / s increase in the maximum daily wind speed.

The area of fires in the northern Black Sea region mostly depend on the maximum duration of hot periods, the number of hot days and the atmospheric drought (r = 0.76–0.60). During the 1996–2013 period, the annual average area of forest fires, in the Kherson region, amounted to 3.1 hectares. It is established, that the increase of the drought duration periods and increase of the duration of the period of hot days leads to an increase in the average area of fires by 130% and 65%, respectively. Growth of the number of hot days, when the maximum daily temperature exceeds 25 °C and 30 °C during 10 days, can lead to an increase of the area fires by 60% and 80%, respectively (*Table 3*).

Table 3. Relationships between the average annual area of forest fires (y) and the climatological conditions (x) in the Kherson region of Ukraine

Meteorological parameters	**Pearson's Correlation**			**Regression**
	r(x,y)	**t**	**(1-p)value**	
maximum duration with of periods with maximum daily temperature ≥ 25 °C	0.76	4.7	0.000	y =0.2x–7.3
number of days with maximum daily temperature ≥ 30 °C	0.68	3.7	0.002	y =0.25x–6.0
number of days with maximum daily temperature ≥ 25 °C	0.60	3.0	0.008	y =0.18x–13.2
average summer maximum temperature	0.61	3.1	0.007	y =2.5x–67
average summer temperature	0.59	2.9	0.011	y =2.9x–62
average summer minimum temperature	0.52	2.5	0.026	y =3.1x–51
average temperature in October	0.58	2.8	0.012	y =2.0x–19
minimum temperature in October	0.55	2.7	0.017	y =2.0x–10.7
maximum temperature in October	0.55	2.6	0.018	y =1.7x–23.7
number of days with atmospheric drought (maximum daily temperature ≥25 °C and maximum daily relative humidity ≤ 50%)	0.60	3.0	0.008	y =0.4x–2.9
average annual maximum temperature	0.55	2.6	0.019	y =3.4x–50
average annual temperature	0.51	2.4	0.030	y =3.5x–35
average annual minimum temperature	0.44	1.9	0.070	y =3.0x–17
average spring maximum temperature	0.50	2.3	0.034	y =2.6x–37
average spring temperature	0.45	2.0	0.062	y =2.8x–29
number of days with fog	–0.39	–1.7	0.109	y =–0.24x+12
amount of precipitation during summer	–0.41	–1.8	0.094	y =–0.04x+8.4
amount of precipitation in July	–0.41	–1.8	0.088	y =–0.07x+6.4
annual average relative humidity	–0.58	–2.9	0.011	y =–0.6x+39

The area of forest fires also significantly depend on the average, minimum, and maximum temperatures in summer, spring, and the whole year (r = 0.61–0.45). Thus, the growth of annual average temperature and temperature during the summer by 1 °C can lead to an increase in the average area of fires almost by 110 and 90%, respectively. Like the number of fires, their area in the Kherson region also depends on the air temperature in October, but this affect is somewhat less.

The presence of sufficient moisture in the atmosphere contributes to the reduction of forest fire frequency. *Table 3* shows that in the Black Sea region of Ukraine, the number of forest fire decreases when total precipitation in summer, especially in July, is growing and atmosphere has the less moisture content. The precipitation has large heterogeneity and variability in time. According to the World Meteorological Organization recommendations, their change is considered significant if it equals to 20% or more.

Unlike the number of fires, their area in the north part of the northern part of the Black Sea region mostly depends on the maximum duration of the hot period, the number of days with heat, and the atmospheric drought (r = 0.76–0.60) (*Table 2*). In 1996–2013 the annual average area of forest fires in the Kherson region was 3.1 ha. It is proven that increase in duration of drought and maximum duration of hot periods by 10 days lead to an increase in the average area of fire by 130 and 65%, respectively. Growth of hot days, when the maximum daily air temperature exceeds 25 and 30 °C, by 10 days may lead to an increase in the fire area by 60% and 80%, respectively.

Based on *Table 2*, the fire area greatly depends on minimum, maximum, and average air temperatures in summer, spring, and the whole year (r = 0.61–0.45). So, increase in annual average temperature and temperature in summer by 1 °C may cause an increase in the average fire area almost by 110 and 90%. Like a number of fires, the fire area also depends on air temperature in October; however, this effect is somewhat less.

Availability of sufficient moisture in the atmosphere also contributes to reducing the average area of the fire, which greatly depends on the relative humidity, rainfall during summer (especially in July), and the number of days with fog. It is established that the increase in the annual amount of precipitation by 20% could reduce the average area of the fire by 32% (*Table 2*).

3.4. Projections of changing in natural fire danger

According to the results of the regional model REMO-ECHAM5 presented in the framework of the European project Ensemble-based Predictions of Climate Changes and their Impacts (ECAP, 2009), the projections of changes in the average long-term indicators of the thermal and humidification regimes in Ukraine were simulated by the middle of the 21st century (2021–2050), relatively to the current climatic period (1981–2010) for the scenario SRES

A1B. Analysis of the results shows that by the middle of the 21st century, in Ukraine, a further increase in the temperature is expected according to the SRES A1B scenario. It is “virtually certain” that the annual average, mean maximum and mean minimum temperatures in Ukraine show an increasing tendency compared to the period of 1981–2010. However, these changes will be uneven and strengthened from west to east, peaking in the east (*Fig. 10*).

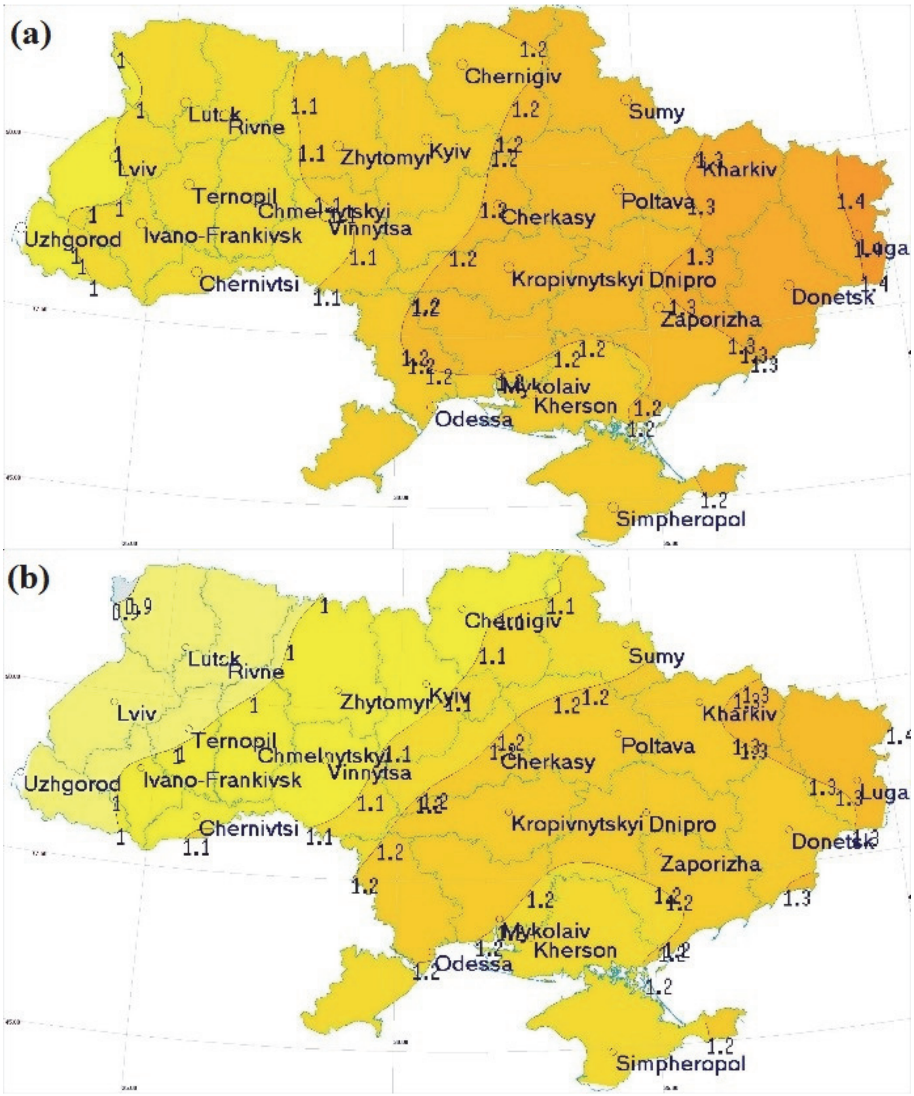

Fig. 10. Projected change in the annual mean (a) and mean annual maximum (b) air temperatures in 2021–2050, relatively to the period 1981–2010. Changes calculated by the RCM REMO-ERCHAM5 model for SRES A1B scenario.

The greatest growth is most expected in autumn and winter *(Fig. 11)*. This increase in the minimum temperature in winter is greater than the maximum (1.4 and 1.1 °C, respectively). The most significant change may be the increased extreme temperatures in February (a minimum of 2.1 °C and a maximum of 1.7 °C). Extreme monthly average temperature in autumn could grow by 1.3 °C in summer – by 0.9–1.0 °C, and in spring – by 0.6–0.7 °C. The greatest changes (1.9 and 1.7 °C) can be expected in October. By the middle of the 21st century, minimum temperature likely increases in December (1.1 °C), although in the last two decades it has not changed, and in some regions decreasing was observed.

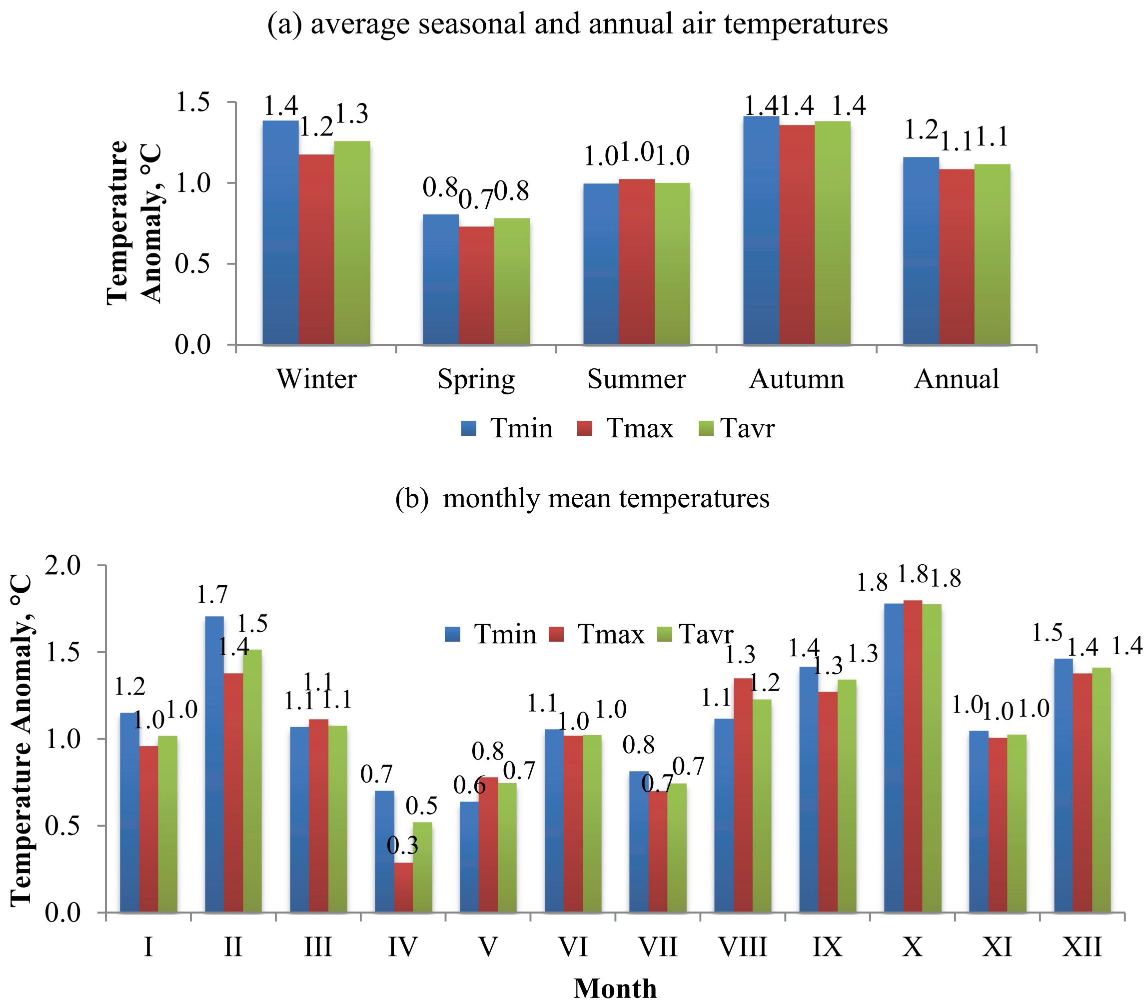

Fig.11. Projected change in the average seasonal and annual air temperatures (a) and monthly mean air temperature in 2021–2050, relatively to 1981–2010 period. Changes were calculated on the RCM REMO-ERCHAM5 model for SRES A1B scenario.

It is “virtually certain” that according to scenario A1B, annual average air temperature could grow by 1.1 °C (*Fig. 11)* and could be 9.8 °C in 2021–2050, against the value of 8.7 °C in 1981–2010, what will lead to an increase in the average area of fire almost by 10%, while its number will increase by 5%. In the west and central forest steppe regions this change may be 1.1 °C or less, and in the north steppe, particularly in Luhansk, this change may be 1.3 °C or more (*Fig. 10*). Accordingly, fires can be more extensive. Major changes are expected in winter and autumn, and it can be more than 1.6 °C in this region. In summer, the growth of the average season temperature can be from 0.7 to 1.3 °C, and in spring it can be 0.6–0.9 °C and more. By the middle of the 21st century it will lead to an increase in the number of forest fire by 13% and in their areas by 20% in Ukraine.

With a probability of 99%, it is expected that the average maximum temperature per year in 2021–2050 will increase in Ukraine by 1.2 °C, and will contribute to an increase in the average area of fires by 15% (*Fig. 11*). This growth will intensify from the northwest (0.9 °C) to the southeast and will reach a maximum (1.3 °C) in the Lugansk region. The biggest changes are expected in autumn and winter: generally for Ukraine they are 1.4 and 1.2 °C. In summer, average-for-season maximum temperature will grow by 0.7–1.3 °C. Herewith its values will be 28.5 °C or more across the steppe zone and Lugansk region, and it will be 25°C in Polissya. It will result in a significant increase in the fire danger. Those tendencies are the same for autumn. Changes above 1.5 °C will be observed almost throughout the country, and will reach a top in the east.

By the middle of the 21st century, with a probability of 99%, it is expected that the duration of hot periods will increase by 2–3 weeks compared to the current climatic period of 1981–2010 (from 12–15 days in the western forest steppe to 18–20 days in the eastern forest steppe). Across Ukraine the warm period could be 10–10.5 month (or even 11 month in the Crimea) by the middle of the 21st century. At the same time in Polissya, the number of warm days will reach 300 days per year, which was typical for the southern steppe on the beginning of the century. The duration of vegetation and active vegetation periods will significantly increase by 7 and 11 days, which will help to accumulate more biomass and, accordingly, to cause more intense fires.

Generally for Ukraine it is "very likely" that a number of hot days will increase by 10 days. In the northern and western regions its change will be 5–7 days, but in the southern region it will be 12–15 days. The number of hot days per year will exceed 100 days in the south steppe. It has the most significant influence on the growth of fire danger and may result in an increase in the average area of fires 1.3–1.4 times. It is expected that period with extreme fire danger will grow.

By the middle of the 21st century in Ukraine, the humidification regime may change, although the change of the annual precipitation is "unlikely". It is expected that the precipitation will be redistribution between seasons: during the warm season, its amount will decrease almost all over the country, except

Polissya, and the winter season, when it will "very likely" grow almost by 13% or more.

The number of days with precipitation and days without rain will not have significant change until the middle of the 21st century compared with the current climatic period. Exceptions are certain districts in the southern steppes and Crimea where it is "likely", the number of days with precipitation will decrease by 1.2%, and the number of days without rain will increase by 3–4%. It is "likely" that the maximum duration of the period with precipitation will increase, and the period without rain will decrease by 4–5%. An increase in the number of arid days is "virtually certain", it could be by 40–60% more. The biggest changes are possible in the Polissia, forest steppe, and Transcarpathia regions, what will increase the fire risk in these regions.

Based on analysis of the projections of the change in relative humidity, the moisture content in the atmosphere by the middle of the century may also change, although these changes will be ambiguous across the country and throughout the year. The annual average relative humidity will increase across territory of Ukraine. In the Polissya, Lviv, Vinnitsa, and Sumy regions, the probability of these changes will be above 70%.

In summer the relative humidity will decrease rather than grow. Such changes are likely to reach 2–3% in the steppe, especially in the southern part. In the autumn, the moisture content in the atmosphere will increase throughout the country. The biggest change (up to 2%) will be in the western, central forest steppe, Polissia, and Transcarpathia regions.

4. Conclusions

As a result of the climate change analysis in Ukraine, it was found that over the past decade the thermal mode, moisture, and wind frequency have changed significantly, affecting the number and area of forest fires. These changes led to an increase in the fire risk in the region. Evaluation of possible changes in these characteristics to the middle of the 21st century showed that under the SRES A1B scenarios, it could be expected further increase in the temperature throughout the year, growth in the number of hot days and in the sultry duration period. Since these processes are accompanied by an increase duration of the drought period, these changes significantly affect an increase of the fire risk: the number of forest fires and their area can significantly increase by the middle of the 21st century in Ukraine.

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