ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2024, Vol. 60, No. 9, pp. 1122–1128. © Pleiades Publishing, Ltd., 2024.
Russian Text © The Author(s), 2024, published in Issledovanie Zemli iz Kosmosa, 2024, No. 2, pp. 3–10.

USING SPACE INFORMATION ABOUT THE EARTH EXPLORATION OF VEGETATION AND SOILS FROM SPACE

Dynamics of Changes in NDVI, Black Carbon, and Soil Moisture at the Burtinskaya Steppe Site of the Orenburg Nature Reserve According to Satellite and Ground Data in 2000–2022

N. V. Rodionova*

Kotelnikov Institute of Radio Engineering and Electronics (Fryazino Branch), Russian Academy of Sciences, Fryazino, Moscow oblast, 141190 Russia

**e-mail: rnv1948123@yandex.ru*

Received June 23, 2023

Abstract—In this work, the dynamics of changes and trends in climatic conditions, Normalized Difference Vegetation Index (NDVI), humidity of the upper soil layer, and content of black carbon in the atmosphere in conditions of steppe fires according to ground and satellite measurements for the period of 2000–2022 is traced for the Burtinskaya Steppe site of the Orenburg Nature Reserve. The negative trend in values of the Selyaninov hydrothermal coefficient (HTC) indicates a tendency to weaken the moisture supply of the territory, which favors the appearance of steppe fires. The consequence of climatic trends is a positive trend in values of black carbon in the atmosphere of the studied area, as well as a tendency to a decrease in humidity of the upper soil layer. Absolute interannual values are distinctive for 2010: the minimum value of NDVI and soil moisture, and the maximum value of black carbon.

Keywords: steppe, ground and satellite measurements, hydrothermal coefficient, NDVI, soil moisture, black carbon, correlation

DOI: 10.1134/S000143382470107X

INTRODUCTION

The steppe zone of Russia extends from the Black Sea to the Altai Mountains in the south of the country. The peculiarities of the steppe zone are formed, first of all, under the influence of climatic factors. The climate of the Russian steppe changes in the direction from south to east from moderately continental to sharply continental. The steppe zone is characterized by the warmest and driest climate. The moisture balance is sharply negative. These factors favor the occurrence of steppe fires. The impact of fires on the steppe is ambiguous. As a result of steppe fires arising mainly in spring and autumn, large amounts of gaseous and dispersed products of pyrolysis and combustion of steppe combustible materials are emitted into the atmosphere. The positive impact of fire on the vegetation cover consists of changes in the age composition of communities, loss of weedy plant species, and enrichment of soil horizons with ash elements. Negative factors of the impact of pyrogenic load on steppe vegetation consist in the fact that some species of annual plants fall out of the herbage, the temperature of the upper soil layers increases, which intensifies the process of desertification of the steppe; underground shoots and seeds freeze in winter. Under favorable meteorological conditions, the protected steppe recovers within 9–17 months, and fire does not cause catastrophic changes to the vegetation cover. One of the effects of fires on soils is that evaporation increases dramatically, the calcareous horizon rises, soils become depleted of organic matter, and other negative effects occur in a bare area in the next months after a fire on the soil surface (Buivolov et al., 2014).

In this work, by the example of the Burtinskaya Steppe site of the Orenburg Nature Reserve, the dynamics of changes for the period of 2000–2022 is traced in climatic conditions by the Selyaninov hydrothermal coefficient (HTC), in the content of black carbon in the atmosphere under conditions of steppe fires, and in changes in the biomass of the vegetation cover by NDVI values and values of surface soil moisture.

VARIATIONS IN THE HTC FOR BURTINSKAYA STEPPE FOR THE PERIOD OF 2005–2022

The Burtinskaya Steppe, a site in the Orenburg Nature Reserve, is located in Belyaevka raion, Orenburg oblast. The area of the site is 4500 ha. It has never been plowed, except for fallow areas of 1976 and 1982 with a total area of about 300 ha. Partially used for haying. Figure 1 shows the map of Belyaevka raion, Orenburg oblast (http://orensteppe.org/node/4966),

Fig. 1. Map of Belyaevka raion, Orenburg oblast.

in the southeast part of which the Burtinskaya Steppe is situated.

The climate of the Burtinskaya Steppe has obvious features of continentality with cold severe winter (in January, $-15.8°C$) and dry hot summer ($+22°C$). The average annual precipitation is 327 mm. The Burtinskaya Steppe is located in the subzone of southern chernozems (http://artlib.osu.ru/web/books/chibilev/book0114.pdf?ysclid=lh0g3obbty257593177).

The most commonly used quantitative measure of climate is the Selyaninov hydrothermal coefficient (Selyaninov, 1928, 1958). The HTC is determined as follows: $\mathrm{HTC} = 10\sum \mathrm{RR} \big/ \sum \mathrm{Ta}$, where $\sum \mathrm{RR}$ is the sum of precipitation for the vegetation period (the period with daily average air temperatures above 10°C) and $\sum \mathrm{Ta}$ is the sum of daily average temperatures for the same period. Figure 2 presents the plots of HTC values, as well as sums of temperatures and precipitation ×10 for May–September of 2005–2022 for the Orenburgskaya station (ID35121). The HTC plot repeats the precipitation plot with almost unchanged annual average variations in air temperature for May–September. The absolute minimum of the HTC and precipitation belongs to 2014 (HTC = 0.2165). The next HTC minimums in increasing order of values belong to 2010 (0.26) and 2021 (0.261). The negative trend of precipitation sums and weak positive trend of air temperature sums for the vegetation period became the basis for the negative trend of HTC values for 2005–2022, which indicates the tendency of increasing aridity of the territory.

BC VARIATIONS IN THE ATMOSPHERE OF BURTINSKAYA STEPPE UNDER CONDITIONS OF STEPPE FIRES

Steppe soils store a huge stock of carbon, including organic and inorganic carbon. One of the two fractions of inorganic carbon is black carbon, i.e. small and finest particles of coal formed as a result of natural fires. The source of black carbon (BC) emissions in the steppe is steppe fires. BC is the main component of soot. Its lifetime in the atmosphere is from several days to weeks. BC particles are easily washed away by precipitation. The moisture balance in the steppe zone is sharply negative, droughts are periodically repeated. The main part of steppe fires in the Reserve occurs at the end of the summer season from August to October, when field works on adjacent agricultural lands are carried out and the top of herbaceous plants dries up; less frequently they occur in April–May, when last year's dry grass burns. In 2009, 1900 ha burned in the Burtinskaya Steppe site. In 2010, 8100 ha of herbaceous vegetation burned as a result of fires in the Aituarskaya Steppe and Burtinskaya Steppe sites. In 2014, at the Burtinskaya Steppe site, a fire in the adjacent territory, 8 km from the site boundary, resulted in burning of grassy vegetation on a total area of 2000 ha. The fire was extinguished for almost two months until September 20, 2014 (Buivolov et al., 2014).

Figure 3 shows maps of fires in the territory of Burtinskaya steppe for 2002, 2009, 2010, and 2014 taken in the archive https://firms.modaps.eosdis.nasa.gov/map/#t:adv; d:2014-07-31.2014-08-30;@56.8,51.1,11z.

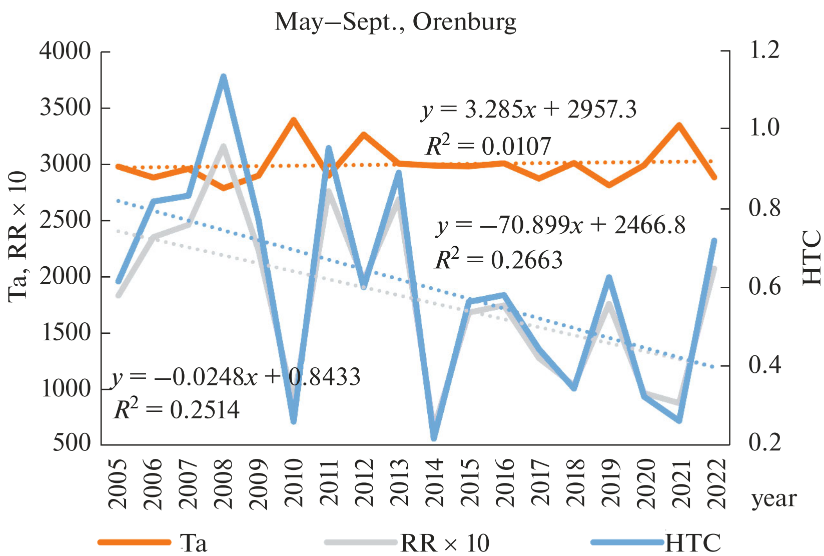

Fig. 2. Plots of the sum of temperatures and precipitation ×10 and HTC values for May–Sept. 2005–2022.

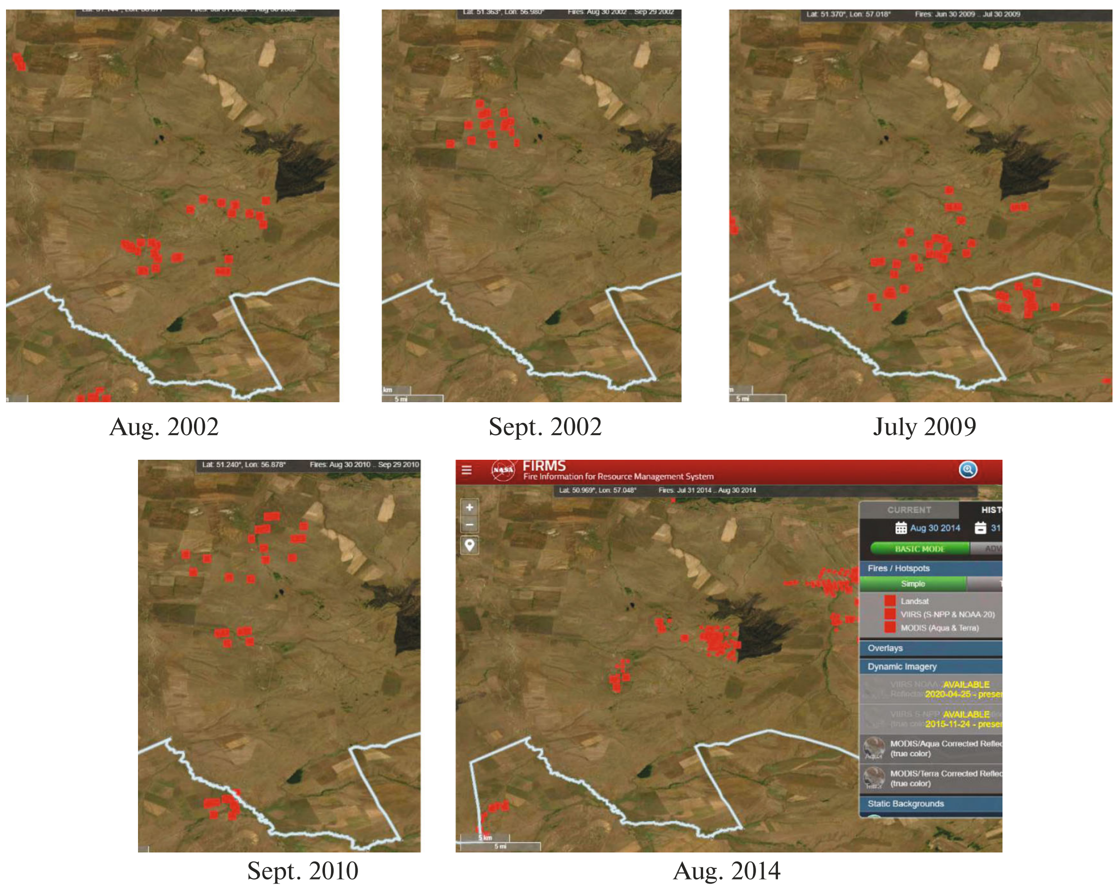

Fig. 3. Maps of fires in the territory of Burtinskaya steppe for 2002, 2009, 2010, and 2014.

The plots of edges of fires revealed in the period of 1991–2014 in the Burtinskaya Steppe site and the dynamics of burned areas from 1984 to 2014 were presented in (Bakiev et al., 2017; Pavleichik, 2016).

The main source of measurement of the BC content in the atmosphere is satellite monitoring based on data from the MERRA-2 satellite reanalysis data (http://giovanni.gsfc.nasa.gov) (Modern-Era Retro-

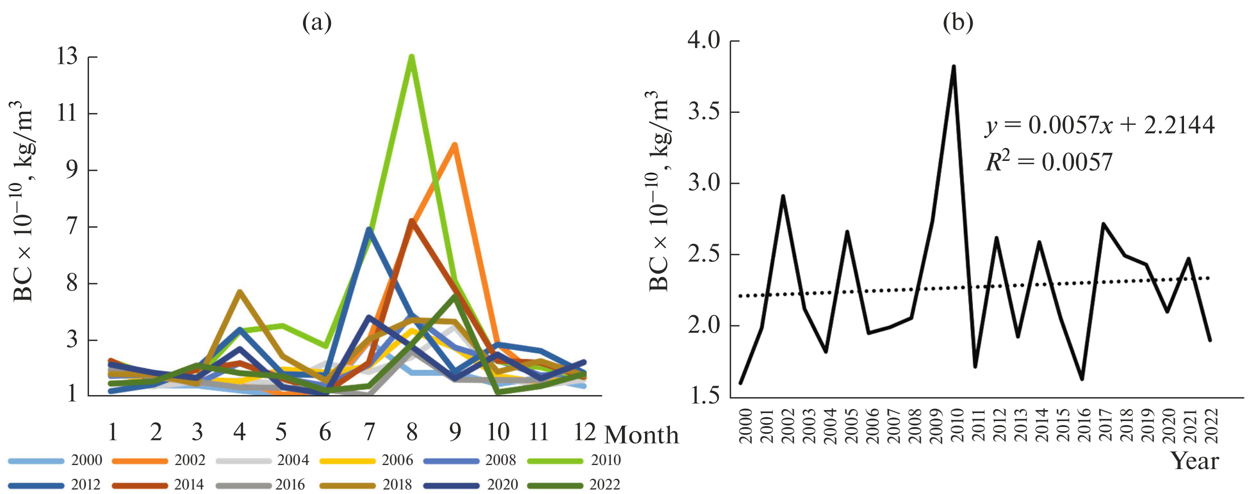

Fig. 4. (a) Seasonal and (b) interannual variations in black carbon values for 2000–2022.

spective analysis for Research and Application Version 2) (Gelaroet et al., 2017). The surface mass concentration of BC (SMC, kg/m^3) was estimated using monthly average data of the MERRA-2 reanalysis for 2000–2022 (the MERRA-2 product, model M2TMNXAER v5.12.4, the spatial resolution (SR) is 0.5° × 0.625° (latitude × longitude). The data are averaged over an area with the center at 51° N, 56.875° E (Burtinskaya steppe).

Figure 4 presents the plots of seasonal and interannual BC variations for the territory of Burtinskaya steppe for the period of 2000–2022. There are two peaks of BC values in the seasonal variations (Fig. 4a) (the plots are shown only for even-numbered years): in April and July–August–September. The absolute maximum of BC values belongs to August 2010 with the value of 13 × 10^{-10} kg/m^3; the next maximum in magnitude is September 2002 (9.9 × 10^{-10} kg/m^3) and April 2009 (7.6 × 10^{-10} kg/m^3). For 2014, the maximum belongs to September with the BC value of 4.8 × 10^{-10} kg/m^3.

For the interannual BC variations (Fig. 4b), the trend is positive both for the whole period under study (2000–2022) and for its individual cycles: 2000–2010 and 2011–2022 (the angle of the trend line decreased for the last cycle). The intensive fires in 2010 are associated with an outburst of interannual EC values of this year with the absolute maximum equal to 3.8 × 10^{-10} kg/m^3; the second maximum in the value belongs to 2002 (2.9 × 10^{-10} kg/m^3); the third one, to 2009 (2.7 × 10^{-10} kg/m^3). The BC values in 2005, 2011, 2012, 2014, and 2017 are close to the last one.

NDVI VARIATIONS IN THE TERRITORY OF BURTINSKAYA STEPPE IN 2000–2022

The dynamics of changes in the NDVI for 2000–2022 in the territory of Burtinskaya steppe is determined using the Giovanni system of data analysis and visualization (http://giovanni.gsfc.nasa.gov). We use monthly measurements of the MODIS (Terra) device with SR = 0.05° (the mean_MOD13C2_006_CMG_0_05_Deg_Monthly_NDVI product) averaged over an area (51.125°–51.175° N, 56.675°–56.725° E).

Figure 5a shows plots (for even-numbered years only) of seasonal variations in the NDVI for the period of 2000–2022. The maximum NDVI values belong to May–June. The absolute maximum is equal to 0.63 (June 2003). The absolute minimum of interannual NDVI values (Fig. 5b) belongs to 2010 (0.2745), which is obviously associated with fires in 2010. Then, the interannual NDVI values in ascending order are in 2019 (0.326), 2014 (0.336), 2009 (0.34), 2011 (0.342), and so on. The negative trend line of NDVI values for the cycle of 2000–2010 indicates a decreasing trend in biomass within the Burtinskaya steppe during this period, especially as a result of the fires in 2010. For the period of 2011–2022, there is a weakly positive trend associated with revegetation of the steppe. In particular, for 2016, the interannual NDVI value (0.45) almost reached the level of 2000.

VARIATIONS IN MOISTURE OF THE UPPER LAYER OF THE SOIL ACCORDING TO THE FLDAS MODEL

The Famine Land Data Assimilation System (FLDAS) (https://ldas.gsfc.nasa.gov/fldas) is usually used for obtaining information about many variables related to climate, including the moisture content in the soil, air humidity, evaporation, mean temperature of the soil, general norm of precipitation, etc. in semi-arid regions (McNally et al., 2017). The Noah 3.6 land surface model from FLDAS (Ek et al., 2003) is based on CHIRPS (Climate Hazards Center InfraRed Precipitation with Station data) ground and satellite data on precipitation (Funk et al., 2015) and present-day MERRA-2 retrospective analysis of the meteorologi-

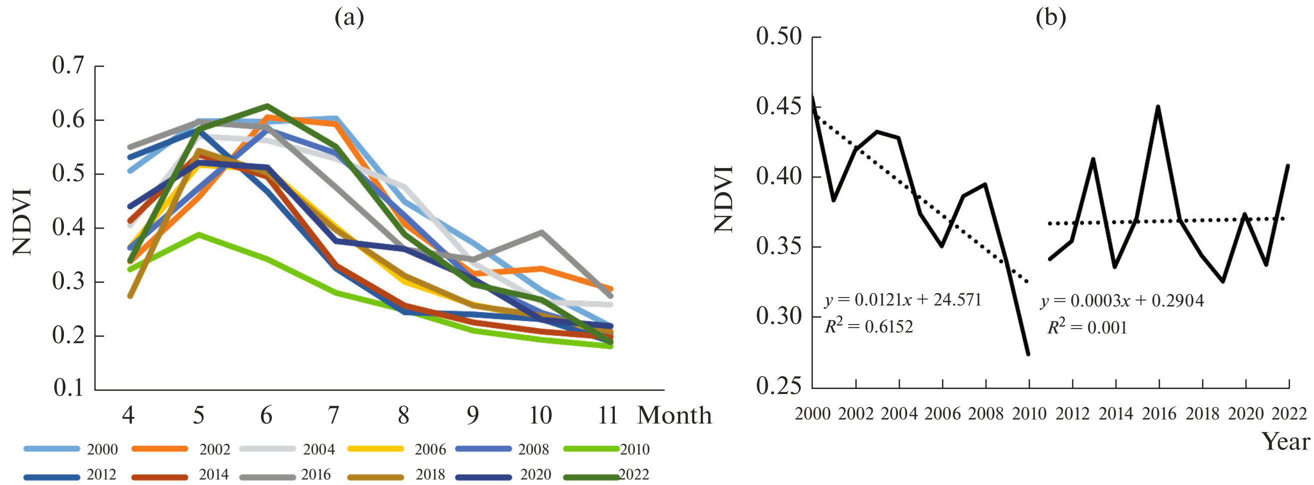

Fig. 5. (a) Seasonal and (b) interannual NDVI variations for Burtinskaya steppe for 2000–2022.

cal impact. Monthly FLDAS modeling results for more than 40 years from 1982 to the present are publicly available. An additional feature of FLDAS is that these data can be visualized using the Giovanni online tool.

First, let us determine whether there is a correlation between the soil moisture (SM) values calculated by the FLDAS model and ground measurements for the RUSWET-AGRO Orenburgskaya_#1 station in the Orenburg region the SM data of which are available on the International Soil Moisture Network (ISMN) website (https://ismn.geo.tuwien.ac.at/) from 1958 to 1998 (April–September).

The coordinates of the RUSWET-AGRO Orenburgskaya_#1 station are 52.17° N, 55.08° E. The location of the station is shown in Fig. 6 (indicated by the red arrow). The soil composition at depths of 0–

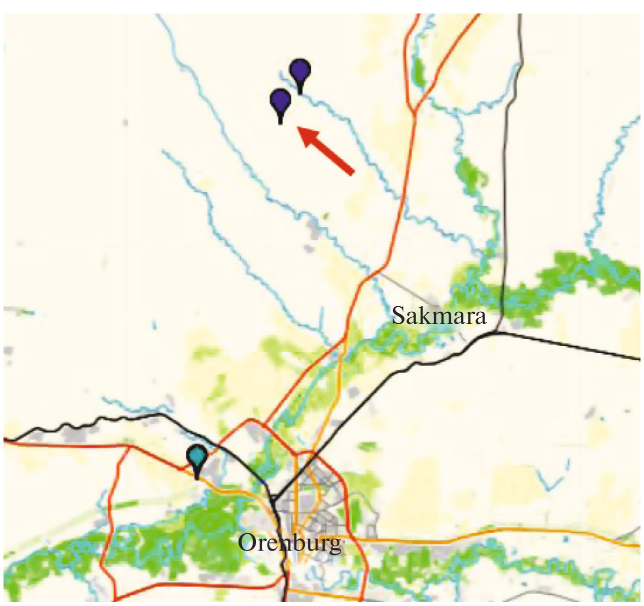

Fig. 6. Location of the RUSWET-AGRO Orenburgskaya_#1 station in the map of Orenburg oblast.

30 cm: saturation of 0.51 ($m^3 \times m^{-3}$), 23% of clay, 23% of sand, 54% of silt, 0.89% of organic carbon, and plowing lands soaked with rain. The ground measurements include the soil moisture at depths of 0–20 and 0–100 cm.

Figure 7a presents the plots of seasonal variations (three values per month) of ground measurements of soil moisture at depths of 0–20 cm at the Orenburgskaya_#1 station; Fig. 7b, the plots of monthly average SM values at depths of 0–10 cm according to the FLDAS model (the Model FLDAS_NOAH01_C_GL_M v001 product, SR = 0.1°, averaging over an area with the center at 52.15° N, 55.05° E) for 1994–1998.

The plot of monthly average variations in ground and FLDAS SM measurements for the Orenburgskaya_#1 station is presented in Fig. 8.

The Spearman coefficient of correlation (SCC) between monthly average values of ground SM measurements and those obtained based on the FLDAS model is equal to $\rho_s = 0.74$ ($p = 5 \times 10^{-6}$, $N = 26$).

The sufficiently high value of the SCC between ground and FLDAS SM values makes it possible to use the FLDAS model for estimating the SM in the region of the Burtinskaya steppe for the period 2000–2022. Figure 9a shows plots of seasonal variations in monthly average SM values at depths of 0–10 cm for the Burtinskaya steppe region using the FLDAS model (averaging over an area with the center at 51.15° N, 56.7° E). We note two maximums of SM values: in spring (March–April) and in autumn (November). The minimum of SM values belongs to summer months. Interannual variations of SM values by the FLDAS model (0–10 cm) for Burtinskaya steppe when averaging SM values for May–October are shown in Fig. 9b for the period 2000–2022 (only even-numbered years are shown). The absolute minimum of interannual SM values belongs to 2010 (0.18). The SM minimum in 2010 correlates with the minimum of the HTC (Fig. 2) and NDVI (Fig. 5), i.e., weak water

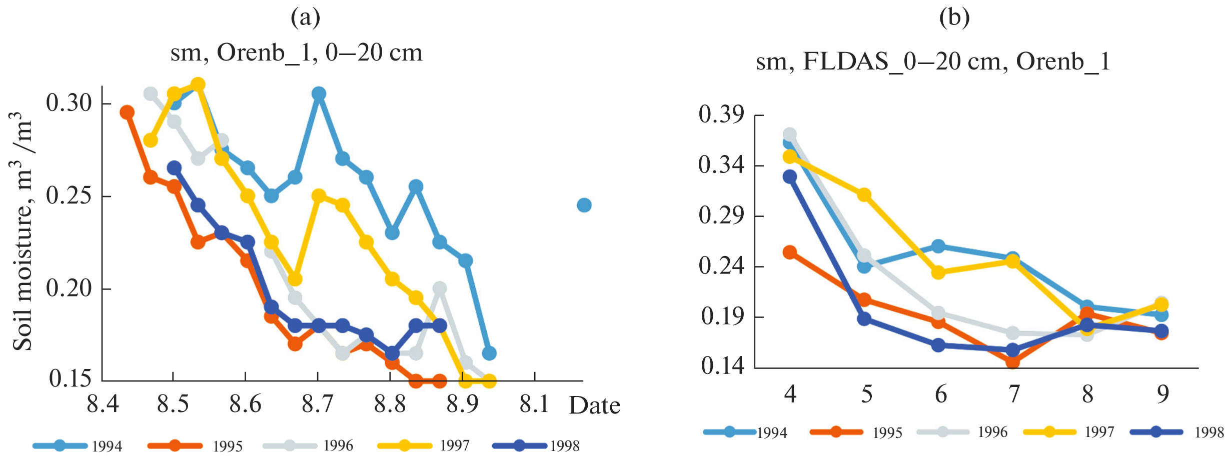

Fig. 7. (a) Seasonal variations in ground measurements of soil moisture at depths of 0–20 cm and (b) monthly average SM values at depths of 0–10 cm according to the FLDAS model for 1994–1998 at the Orenburgskaya_#1 station.

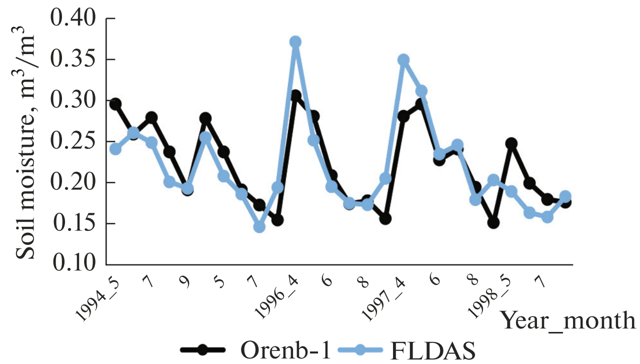

Fig. 8. Monthly average variations in SM values according to ground and FLDAS data for the Orenburgskaya_#1 station.

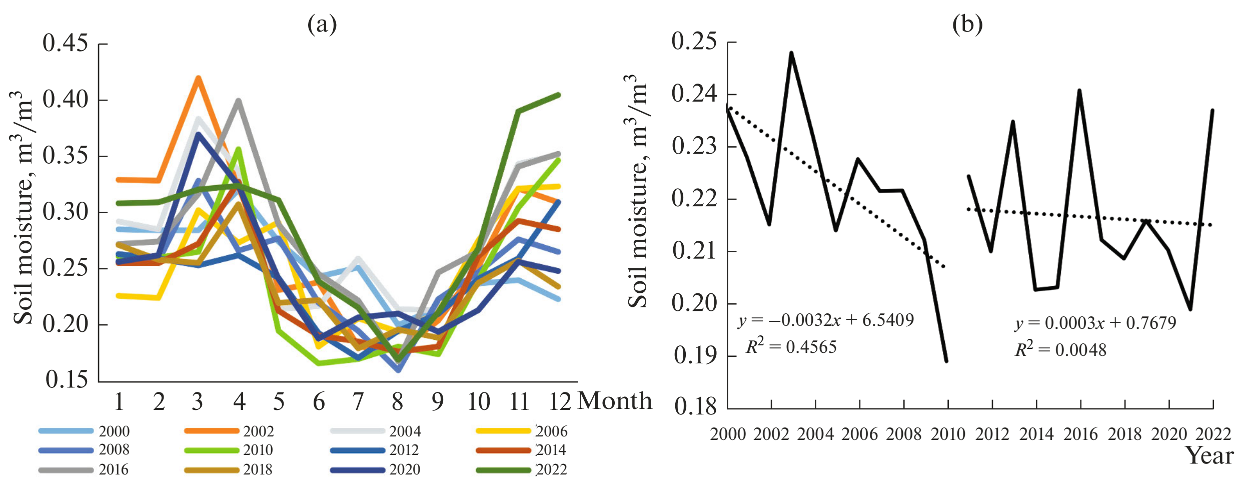

Fig. 9. Plots of (a) seasonal and (b) interannual variations in monthly average SM values at depths of 0–10 cm for the region of Burtinskaya steppe according to the FLDAS model.

availability of the territory favors the growth of steppe fires (the large steppe fire in 2010 (Buivolov et al., 2014)) with burning of herbaceous vegetation and reduction of topsoil moisture. As the values increase, the next SM minimums belong to 2021, 2014, and 2015. The trend line of interannual values of soil moisture is negative both for the period from 2000 to 2010 and for the period of 2011–2022; however, the slope of the trend line for the second cycle is insignificant.

Table 1 presents values of the SCC between the HTC, BC, NDVI, and SM (FLDAS) for Burtinskaya

Table 1. Value of SCC between HTC, BC, NDVI, and SM (FLDAS)

	HTC ↔ BC	HTC ↔ NDVI	HTC ↔ SM	NDVI ↔ BC	SM ↔ BC	NDVI ↔ SM
ρ_s	–0.51	0.43	0.75	–0.53	–0.41	0.77
p	0.01	0.04	0.0002	0.005	0.03	0.000007
N	18	18	18	23	23	23

steppe (ρ_s is the Spearman correlation coefficient, p is the statistical significance level of the SCC, and N is the number of years). As a result, under conditions of the variety of the data used (meteorological, satellite, and ground-based measurements and models), it has been found that these data correlate with values of the SCC from middle to moderate at a high level of statistical significance.

CONCLUSIONS

Summarizing the obtained results on seasonal and interannual variations in values of HTC, BC, NDVI, and SM for Burtinskaya steppe for the period of 2000–2022, one may distinguish the following aspects:

(1) The negative trend of HTC values for 2005–2022 indicates a tendency to weakening of water availability of the territory, which favors the occurrence of steppe fires. The consequence of climatic variations is the positive trend of the black carbon content in the atmosphere of the studied territory, as well as the tendency to some decrease in the moisture content of the upper soil layer. Interannual variations of the NDVI are characterized by two trends: negative for the period of 2000–2010 and weakly positive for the period of 2011–2022, which indicates the tendency to restore steppe vegetation after the steppe fires of 2010;

(2) The absolute interannual data highlighted the pyrogenic year 2010: the absolute minimum of the NDVI (0.27) and SM (0.188 m^3/m^3) and the absolute maximum of BC values (3.8×10^{-10} kg/m^3), as well as the second lowest minimum of the HTC (0.26) (after 2014 (0.21)) and precipitation 87.7 mm (measurements for May–September).

(3) Correlation between HTC, BC, NDVI, and SM values under conditions of the variety of data used to obtain them (meteorological, satellite, and ground-based measurements and models) takes place with values of the SCC from middle to moderate at a high level of statistical significance.

FUNDING

This work was carried out within the framework of the state task for the Kotelnikov Institute of Radioengineering and Electronics, Russian Academy of Sciences.

CONFLICT OF INTEREST

The author of this work declares that she has no conflicts of interest.

REFERENCES

Bakiev, A.G., Balkin, A.S., Barbazyuk, E.V., Galaktionova, L.V., Gorelov, R.A., Dusaeva, G.X., Kalmykova, O.G., et al., *Opyt organizatsii monitoringovykh issledovanii izmenenii stepnykh ekosistem posle pozhara: podkhody i metody* (History of Monitoring Studies of Post-Fire Changes in Steppe Ecosystems: Approaches and Methods), Orenburg: Tipografiya Yuzhnyi Ural, 2017.

Buivolov, Yu.A., Bykova, E.P., Gavrilenko, V.S., et al., Analysis of domestic and foreign experience in managing fires in the steppes and related ecosystems such as specially protected natural reserves. http://www.biodiversity.ru/programs/steppe/docs/pozhar/fires-in-steppe_review21012012.pdf.

Ek, M.B., Mitchell, K.E., Lin, Y., et al., Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J. Geophys. Res.: Atmos.*, 2003, vol. 108, p. 8851. https://doi.org/ 3296. https://doi.org/10.1029/2002JD00

Funk, C., Peterson, P., Landsfel, M., Pedreros, D., Verdin, J., Shukla, S., and Michaelsen, J., The climate hazards infrared precipitation with stations: A new environmental record for monitoring extremes, *Sci. Data*, 2015, vol. 2, p. 150066.

Gelaro, R., McCarty, W., Suarez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., and Wargan, K., The modern-era retrospective analysis for research and applications, version 2 (MERRA-2), *J. Clim.*, 2017, vol. 30, no. 14, pp. 5419–5454.

McNally, A., Arsenault, K., Kumar, S., et al., A land data assimilation system for sub-Saharan Africa food and water security applications, *Sci. Data*, 2017, vol. 4, p. 170012. https://doi.org/10.1038/sdata.2017.12

Pavleichik, V.M., Long-term dynamics of wildfires in steppe regions (using the Orenburg region as an example), *Vestn. Orenburg. Gos. Univ.*, 2016, no. 6, pp. 74–80.

Selyaninov, G.T., On agricultural assessment of climate, *Tr. Sel'skhokhoz. Meteorol.*, 1928, no. 20, pp. 165–177.

Selyaninov, G.T., Principles of agroclimatic zoning of the USSR, in *Voprosy agroklimaticheskogo raionirovaniya SSSR* (Problems in Agroclimatic Zoning of the USSR), Moscow: MSKh SSSR, 1958, pp. 7–14.

Translated by A. Nikol'skii