
USING SPACE-BASED INFORMATION ABOUT THE EARTH
SPACE MONITORING OF WILDFIRES,
THEIR CONSEQUENCES, AND FOREST ECOSYSTEMS

Spatiotemporal Analysis of Multi-Year Wildfires and Emissions of Trace Gases and Aerosols in Russia Based on Satellite Data

V. G. Bondur^{a, *}, O. S. Voronova^a, E. V. Cherepanova^a, M. N. Tsidilina^a, and A. L. Zima^a

^a*AEROCOSMOS Research Institute for Aerospace Monitoring, Moscow, 105064 Russia*

**e-mail: office@aerocosmos.info*

Received June 11, 2020; revised June 12, 2020; accepted June 15, 2020

Abstract—An analysis is performed of the annual and intraseasonal dynamics of wildfire areas and volumes of trace gas components (CO, CO₂, CH₄, NO, and NO₂) and fine aerosols (PM_{2.5}) caused by wildfires in Russia and its large regions over 19 years. The analysis is based on results from satellite monitoring, allowing for the effect anomalies in weather and climate have on the intensity of fires. It is shown that the average size of areas burned monthly in the European part of Russia fell by half in April, May, and September, and by a factor of four in July and August over the period 2011 to 2019, compared to the respective months in 2001–2010. A negative trend is observed for spring and autumn from 2010 to 2019 in the Siberian and Ural federal districts, along with a summer increase in fire areas. It is found that over 19 years, the dynamics of the burned areas is weakly defined for most months of the fire season in the Far Eastern Federal District. Extremely high volumes of emissions of different trace gases (including CO and CO₂) and aerosols caused by wildfires were detected in the Siberian Federal District in 2003 and 2012.

Keywords: wildfires, remote sensing, satellite data, satellite monitoring, emissions, trace gases, aerosols

DOI: 10.1134/S0001433820120348

INTRODUCTION

Wildfires in the Russian Federation are an annual phenomenon that threatens the human population, forest resources, and infrastructure (Isaev et al., 1995; Vorob'ev et al., 2004; Bondur, 2011; Bondur et al., 2017). They are one of the main sources of emissions of harmful trace gases and aerosols into the atmosphere, affecting the ecology of the environment and changes in climate (Bondur, 2016; Bondur and Ginzburg, 2016; Bondur et al., 2020; Vinogradova, 2016; Shvidenko et al., 2011).

The vast areas and inaccessibility of many sites in the Russian Federation make it difficult to detect and analyze the consequences of wildfires in a timely manner. The most effective way of monitoring wildfires and assessing their consequences promptly is to use space-based techniques and technologies (Bondur, 2011, 2016; Bondur et al., 2017, 2019a, 2019b; Bondur and Gordo, 2018; Bartalev et al., 2012; Shchetinskii et al., 2008; Sochilova and Ershov, 2007; Xu and Zhong, 2017; Lin et al., 2019).

The main sources of operational data for detecting wildfire sources are low-resolution spatial data from the Terra, Aqua, NOAA, Suomi NPP, FengYun-3, Meteor-M 2, and other satellites. They provide data with high periodicity and allow us to detect sources of fire promptly in vast areas, including ones that are hard to reach. The use of data from these satellites pro-

vides the best and most complete operational information, which is especially important when monitoring forest, steppe, and peat fires and estimating the volumes of wildfire-induced emissions of harmful trace gases (trace gas components and fine aerosols) into the atmosphere. This is done to ensure the safety of inhabited areas and prevent negative effects on the environment, forest resources, and human health (Bondur, 2011, 2016; Bondur et al., 2017, 2019a, 2019b; Bondur and Gordo, 2018; Bondur and Ginzburg, 2016, 2015; Pu et al., 2004; Giglio et al., 2016).

More detailed analyses of fire areas and the consequences of wildfires, including estimates of burned areas and losses of forest resources, use medium-resolution satellite data from such satellites as Landsat, SPOT, Sentinel-2, Canopus, etc. (Bondur, 2016; Bondur et al., 2017; Bondur and Gordo, 2018; Sochilova and Ershov, 2007). We can also detect and continuously monitor large-scale fires in a timely manner using low spatial resolution data from such geostationary satellites as Himawari, FengYun-2, etc. (Xu and Zhong, 2017; Lin et al., 2019).

This work presents the results from a spatiotemporal analysis of wildfire areas and emissions of trace gas components and fine aerosols caused by wildfires throughout the Russian Federation and in its individual large regions over the period 2001 to 2019, based on satellite monitoring data.

RESEARCH TECHNIQUE

To analyze the dynamics of wildfire areas in Russia and calculate the volumes of emissions of trace gas components and aerosols caused by wildfires over the period 2001 to 2019, we processed satellite monitoring data using an approach described in detail in previous works (Bondur, 2011, 2016; Bondur et al., 2017).

The research technique had several steps. At the first step, the areas burned were calculated on the basis of spatial analysis of daily MOD14 data with a spatial resolution of 1 km (Giglio et al., 2016) for the fire period (April to October). The calculations considered the area actually burned over one year, ignoring the recurrence of fires in the same zone during the fire season.

All detected areas were then identified with respect to the predominant type of soil–vegetation cover according to data in the MCD12Q1 v6 product (MODIS Land Cover Type 500 m), based on the classification of the International Geosphere–Biosphere Program (IGBP) (Friedl et al., 2010). A total of 13 types of soil–vegetation cover (including four classes of forest cover; four classes of shrub, steppe, and meadow vegetation; two classes of agricultural land, and three classes of vegetation-free areas) were identified throughout the Russian Federation. In this work, we updated values of the coefficients of emission that correspond to different types of burned vegetation in the formula for determining the total weight of matter (Seiler and Crutzen, 1980; Bondur, 2016; Bondur et al., 2017; Bondur and Gordo, 2018) emitted into the atmosphere, according to the data from (Wiedinmyer et al., 2011; Akagi et al., 2011).

At the final stage, the monthly and annual total values of wildfire areas and the volumes of trace gas emissions (CO_2 , CO, CH_4 , NO, and NO_2) and fine aerosols (PM_{2.5}) caused by wildfires over the period 2001 to 2019 were calculated for the entire area of the Russian Federation and its individual regions using satellite monitoring data on the types of soil–vegetation cover and burned areas. It should be emphasized that burned biomass emissions caused by wildfires are formed mainly of such carbon-containing trace gas components as CO and CO_2 , which have a long-term impact on the regional and global climate (Bondur, 2016; Bondur and Ginzburg, 2016).

The data were processed statistically to obtain a clear picture of the situation and subsequently interpret the results. The spatial distribution of the areas burned (allowing for the predominant burning season) was determined by calculating an area's frequency of burning for each month during the period 2001 to 2019.

Our study covered four large Russian regions: the European part of Russia (EPR), which includes the Central, Northwestern, Southern, North Caucasian, and Volga federal districts; the Ural Federal District (UrFD); the Siberian Federal District (SFD); and the Far Eastern Federal District (FEFD). The selection of

the four large regions was based on most executive measures (for, e.g., firefighting, reducing fire areas, and reforestation) being taken at the federal level. This division also reflects natural and climatic features, particularly the strong effect the Atlantic Ocean has on the climatic conditions of the EPR, the influence of the Ural Ridge on the movement of the air mass in the UrFD, and the effect Asian maximum and the Arctic and Pacific air masses have on the climatic conditions of the FEFD and SFD.

The annual and seasonal dynamics throughout the country and in the selected regions was studied by calculating normalized values for the burned areas.

RESULTS AND DISCUSSION

Figure 1 shows the values of the total areas burned throughout the Russian Federation during the fire season (April–October) from 2001 to 2019.

Analysis of the results presented in Fig. 1 allowed us to determine the years with the greatest areas burned, along with general trends of their changes. Figure 1 shows that the total area of wildfires throughout Russia was 365.5 thousand km^2 in 2003, considerably exceeding the values for other years of the given period. Extremely large areas burned were also characteristic of 2008 (295.2 thousand km^2), 2002 (272.4 thousand km^2), 2006 (261.2 thousand km^2), and 2012 (258.4 thousand km^2).

The number of wildfire areas generally tended to fall throughout the country from 2001 to 2013 (see Fig. 1). This was followed by a slight increase from 2013 to 2019. An exception was 2017, when the minimum number of wildfires was recorded (122.5 km^2).

The spatial distribution of wildfire areas throughout Russia during the fire season (April–October) from 2001 to 2019 is shown in Fig. 2a. Different colors indicate the fire areas characteristic of different seasons (spring, summer, and autumn). In Fig. 2a, the largest areas burned in Russia are seen for the spring (April and May) and summer (June–August) months.

In spring (April–May), fires generally cover fields, meadows, and steppes in the forest–steppe and steppe zones of the EPR, UrFD, and SFD. In the FEFD, fires occur mainly in the mixed forest zone in the southeast of the area, which is currently occupied by farmlands (see Fig. 2a). In summer months, fires most strongly affect taiga forests in the UrFD, SFD, and FEFD, while the main areas exposed to fire in the EPR are located in the southern part of the region, mainly on agricultural lands (see Fig. 2a). In autumn, wildfire sources are detected in the intensive farming zone in all districts along the southern borders of the Russian Federation. In the forest zone, fragmentary fires are observed mainly in the taiga zone of the SFD and FEFD (see Fig. 2a) (Bondur et al., 2019b).

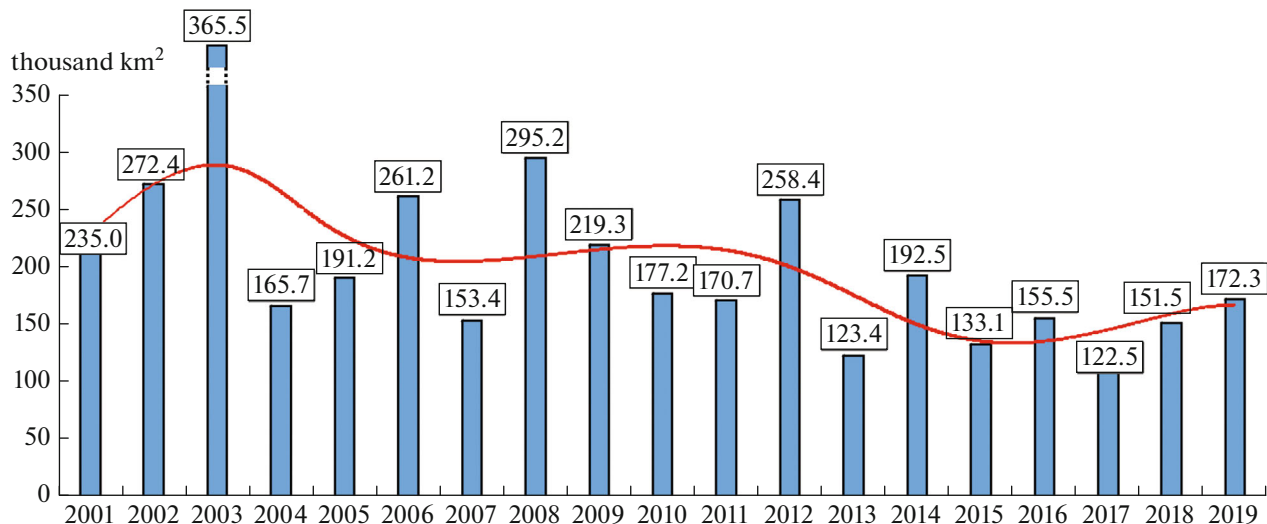


Fig. 1. Total sizes of areas burned in the Russian Federation from 2001 to 2019.

Figure 2b shows the graphs of the monthly distribution of wildfire areas throughout the Russian Federation. According to the figure, these values were greatest in May 2003 (133.79 thousand km²) and 2006 (103.19 thousand km²), April 2008 (118.46 thousand km²), and 2009 (90.68 thousand km²) over the studied 19-year period. The largest areas burned in July and August were recorded in 2012 (76.19 thousand km²) and 2002 (68.99 thousand km²), respectively.

The annual dynamics of wildfire areas according to satellite monitoring data for the considered large regions of the Russian Federation (EPR, UrFD, SFD, and FEFD) from 2001 to 2019 is shown in Fig. 2c. We can see from the figure that the total area burned by wildfires tended to shrink during this period, and has not exceeded 200 thousand km² per year since 2012. According to the figure, the trend towards a reduction of fire areas was observed for the EPR and UrFD, while the dynamics of fluctuations in areas burned in the SFD and FEFD have been cyclical over the last 19 years, rising at one time and falling at another.

To determine the contribution from individual large regions to the statistics of burned areas throughout the country, we analyzed intraseasonal fluctuations in the values of these areas for all months of the fire season in each region. Figure 3 shows graphs of the distribution of areas burned for each month of this period from 2001 to 2019 for the SFD (Fig. 3a), FEFD (Fig. 3b), EPR (Fig. 3c), and UrFD (Fig. 3d). Since the fire areas have tended to shrink throughout Russia since 2010 (see Fig. 1), most likely due to the introduction of effective fire prevention measures, the analysis presented below describes the pattern of variation in the dynamics of fire areas in different regions in periods before and after 2010.

The effectiveness of such measures is most clearly demonstrated by the example of the EPR (Fig. 3c). The average monthly burned area from 2011 to 2019 was halved for April, May, and September, and reduced by a factor of four for July and August, compared to 2001–2010. It changed slightly for July and October during this period, but we can see a trend toward a gradual reduction in the size of burned areas for October in these years: from 7.38 thousand km² in 2014 to 1.9 thousand km² in 2019 (Fig. 3c). After 2010, the largest fire areas in the EPR were recorded in April: from 7.25 thousand km² in 2011 to 21.59 thousand km² in 2019, with unstable interannual fluctuations being observed (Fig. 3c).

In the UrFD, the size of burned areas also fell more than by a factor of 2.5 in April–May and September–October (i.e., during the season of mainly agricultural burns) from 2011 to 2019, compared to the previous decade. The areas of forest fires grew for June–August between 2010 and 2019. The total area of fires in July was thus 23.63 thousand km² over 10 years (2001–2010), and it rose 1.5 times from 2011 to 2019 to exceed 37 thousand km² (see Fig. 3d).

A similar situation with negative dynamics of the growth in burned areas during the spring–autumn season and positive dynamics during summer has been observed in the SFD over the last decade (see Fig. 3a). The greatest reduction in fire areas for this region is characteristic of May (by more than half from 2011 to 2019, compared to the period of 2001–2010). In contrast, a trend towards an increase in burned areas in the summer months from 2012 to 2019 has been recorded in the SFD in the last decade compared to the previous period from 2001 to 2010 (see Fig. 3a). The total value of fire areas in June was this no more than

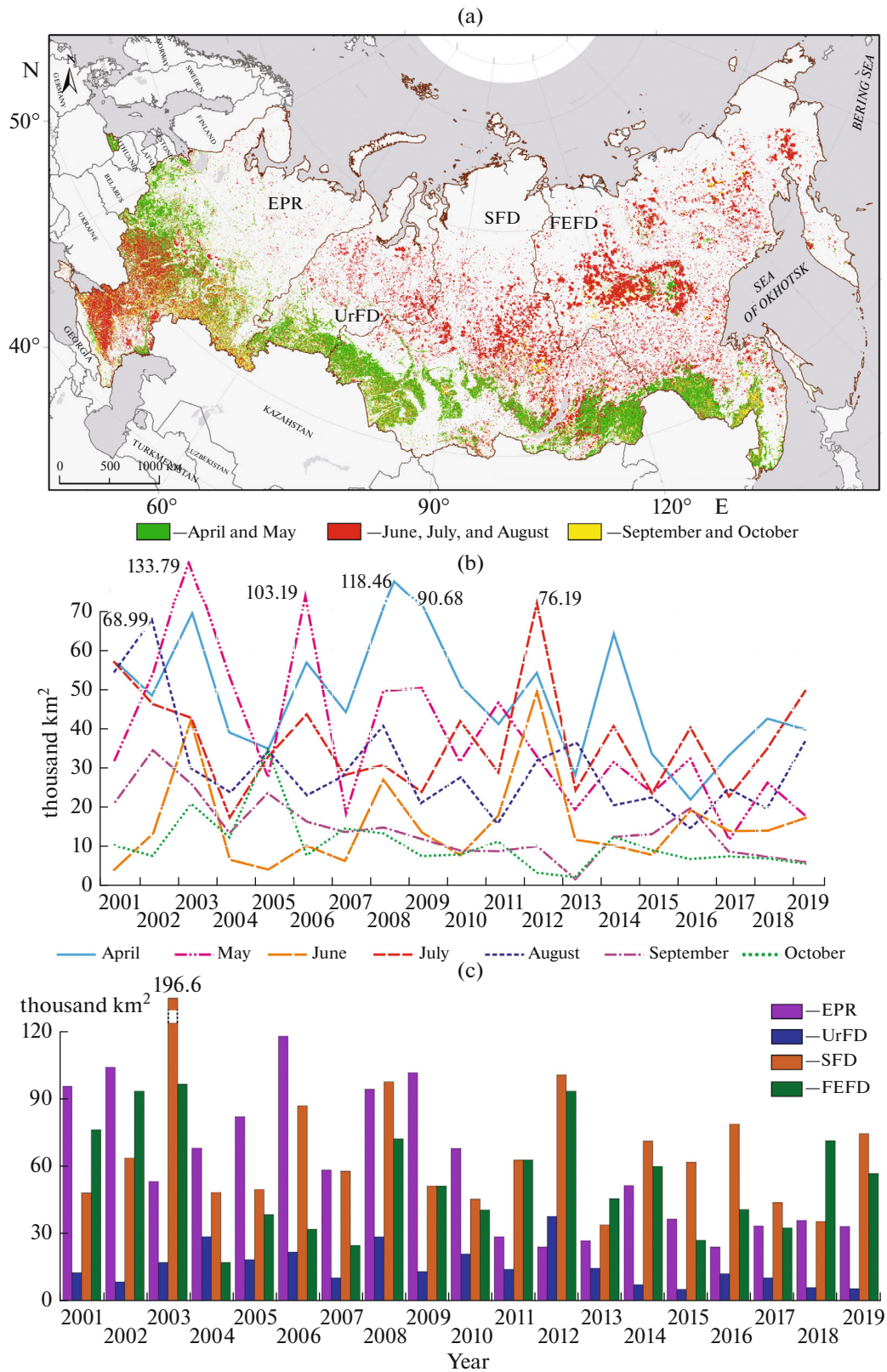


Fig. 2. Spatiotemporal dynamics of wildfire areas from April to October 2001–2019: (a) spatial distribution of areas burned in different seasons for all areas of the Russian Federation; (b) graphs of the distributions of wildfire areas according to month for all Russian areas; and (c) wildfire areas in different regions of Russia (EPR, UrFD, SFD, and FEFD).

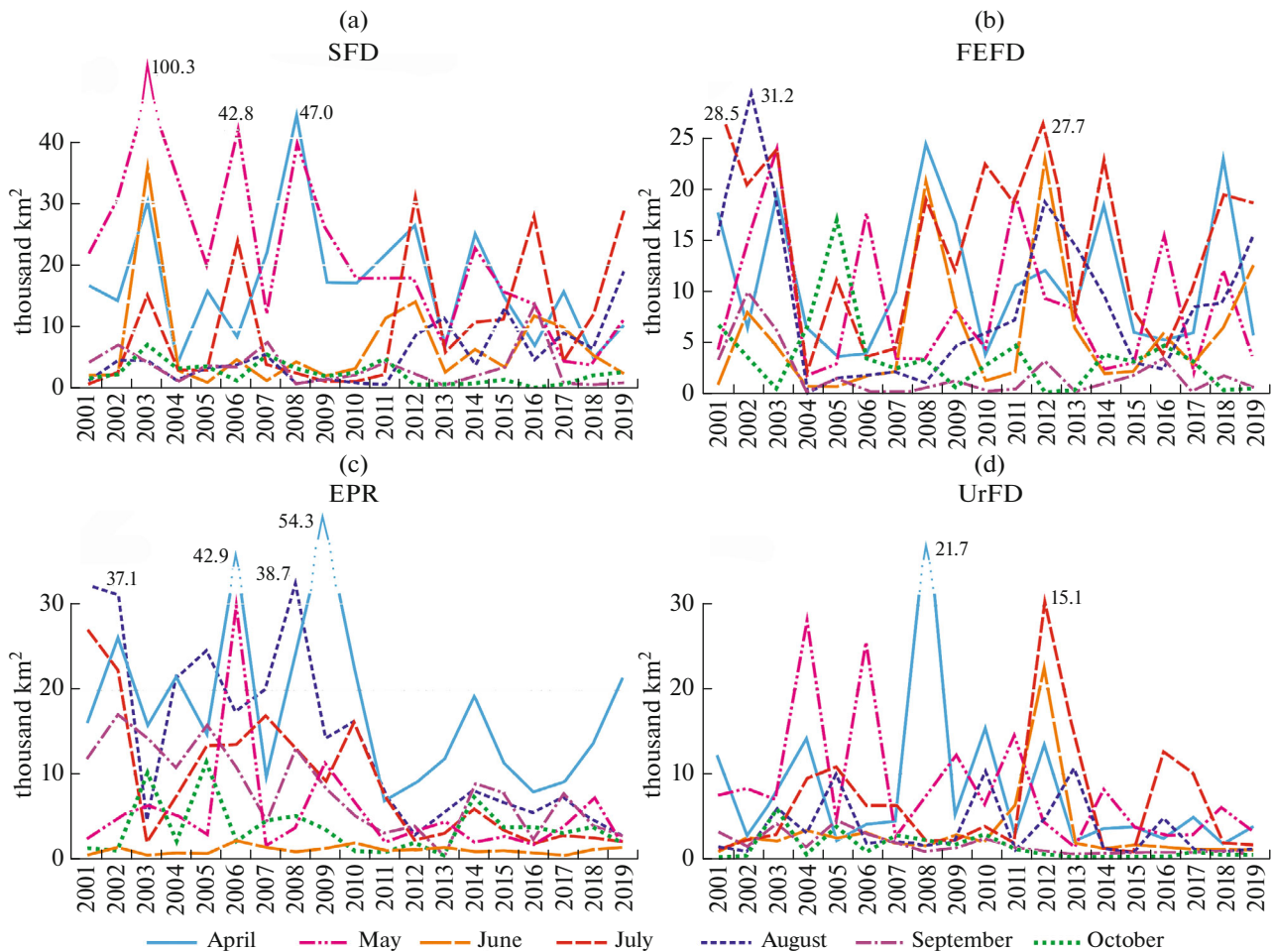


Fig. 3. Distribution of wildfires according to month in different regions of the Russian Federation in the period 2001 to 2019: (a) SFD, (b) FEFD, (c) EPR, and (d) UrFD.

5000 km²/year from 2001 to 2010, except for catastrophic fires in 2003 (35.64 thousand km²) (see Fig. 3a). In the next period (from 2011 to 2019), it did not exceed this level only in June 2013, 2015, and 2019. Fire areas of less than 5000 km²/year were recorded in this region during these years, but were higher for other years: they exceeded 10000 km² in 2011, 2012, and 2016 (see Fig. 3a). Since the early 2000s, a total of 57 thousand km² burned out in the SFD in July over 10 years, and this index has grown to 133.81 thousand km² over the last 9 years. It should be noted that while there were only two years with catastrophic fires in July between 2001 to 2010 (2003 (15.27 thousand km²) and 2006 (23.55 thousand km²)), the frequency of large fires and the areas burned in the SFD rose in the following years: 30.89 thousand km² in 2012, 27.86 thousand km² in 2016, and 28.13 thousand km² in 2019 (see Fig. 3a).

In the FEFD, the general dynamics of burned areas is weak for most of the months of the fire season over the 19 monitoring years (see Fig. 3b). We can see a reduction in burned areas in September–October, but

the size of burned areas are almost the same for the two periods of observation (2001–2010 and 2011–2019) in the other months (see Fig. 3b). The largest areas burned areas in July were recorded in the FEFD, compared to other regions (SFD, EPR, and UrFD) (see Fig. 3). The total values of this parameter in the FEFD were 147.18 thousand km² for the period 2001 to 2010 and 138.33 thousand km² for the period 2011 to 2019. The sizes of burned areas were lower for the SFD, EPR, and UrFD during these periods: 57.67 and 133.81 thousand km² for the SFD, 135.52 and 31.33 thousand km² for the EPR, and 23.63 and 24.05 thousand km² for the UrFD, respectively.

The results from this and other recent studies based on satellite monitoring data (Bondur et al., 2019a,b; Bondur et al., 2020) indicate that the general frequency of wildfires tended to fall throughout the country over the long term. Although the areas burned were 4.9 times larger during the wildfires in 2019 than the average values for the period 2001 to 2019 and 1.15 times larger in 2018 than the average values for the

period from 2001 to 2018, the total number of fire sources fell with respect to the average long-term values. This was due primarily to antifire measures that were taken after the catastrophic fires in 2010 in the European part of Russia (Bondur, 2011; Vinogradova et al., 2016). It is also explained by the uncontrolled burning of dry grass on all categories of land in the Russian Federation having been prohibited since the end of 2015 (Decree of the Government of the Russian Federation of November 10, 2015, no. 1213), while earlier bans were selective.

Despite all the measures taken, however, the fire seasons in Siberia and the Far East in 2018–2019 were among the most catastrophic fire periods ever (Bondur et al., 2019, 2020; Voronova et al., 2020; Kononov et al., 2018). The main causes of forest fires in 2019 were careless handling of fire and dry thunderstorms under the conditions of long-term drought and abnormally hot and windy weather that were observed in the zone of the effect of a blocking anticyclone with positive geopotential anomalies (Forecast..., 2019; Bondur et al., 2020).

Studies of the weather–climatic features in the regions of Northern Eurasia have revealed the effect of blocking anticyclones in areas with high temperatures that contribute to the development of intensive wildfires. Enhanced blocking of anticyclonic activity in the atmosphere, particularly over continental regions (Bondur, 2011; Bondur et al., 2020; Sitnov et al., 2017), combined with drying summer trends in the intracontinental mid-latitude regions (Yuanhuizi He et al., 2020) contributes to an increased likelihood of wildfires and their negative consequences.

Figure 4 presents the total volumes of emissions of trace gas components (CO_2 , CO, CH_4 , NO, and NO_2) and fine aerosols (PM2.5) into the atmosphere due to wildfires that occurred in the Russian Federation from 2001 to 2019. The volumes of emissions into the atmosphere depend on the weight of the burned organic matter, its chemical composition, the conditions of fire initiation and propagation, and the type and intensity of the fire. Biomass burning is the source of many gases, but studies usually deal with emissions of solid substances and greenhouse gases: CO_2 , CO, CH_4 , and nitrogen oxides (NO) (Bondur, 2016; Bondur and Ginzburg, 2016; Vivchar et al., 2010).

Analysis of the volumes of emissions of different components into the air in the Russian Federation according to the satellite data for 2001 to 2019 (Fig. 4) revealed extremely high volumes of emissions due to wildfires in 2003: CO_2 (731 million tons), CO (39.7 million tons), CH_4 (1.68 million tons), NO (0.37 million tons), NO_2 (1.31 million tons), and PM2.5 (4.8 million tons). In 2012, the second largest maximum volume of emissions due to wildfires was recorded during the given period: CO_2 (490.3 million tons), CO (27.4 million tons), CH_4 (1.16 million tons),

NO (0.27 million tons), NO_2 (0.89 million tons), and PM2.5 (3.3 million tons).

Figure 5 shows the results from estimating the volumes of emissions of trace gases caused by wildfires in different regions of Russia (SFD, FEFD, EPR, and UrFD), based on examples of (a) CO_2 , (b) CO, (c) CH_4 , (d) NO, (e) NO_2 , and (f) PM2.5 calculated with allowance for annually burned areas, according to the satellite monitoring data for the fire periods (April to October) from 2001 to 2019.

Analysis of the results presented in Fig. 5 shows that such compounds as CO_2 and CO, make the largest contributions to emissions from wildfires. At the same time, the volumes of CH_4 , NO, NO_2 , and PM2.5 emissions are relatively low. Subsequent research therefore focused on determining the volumes of carbon monoxide and dioxide emissions.

Figure 6 presents results from estimating the volumes of trace gas emissions due to wildfires in the SFD (Fig. 6a), FEFD (Fig. 6b), EPR (Fig. 6c), and UrFD (Fig. 6d), based on the example of CO and CO_2 emissions calculated with allowance for annually burned areas, determined according to the satellite monitoring data for the period 2001 to 2019. Since the distributions of the volumes of CO and CO_2 emissions are similar for the given period, an axis of values was additionally introduced to represent the volumes of CO_2 emissions on the box-and-whisker plots of CO.

Analysis of the results presented in Fig. 6a shows that fires in the SFD make a substantial contribution to CO and CO_2 emissions. The maximum average annual emissions of harmful pollutants into the atmosphere in this region of Russia are typical of May and July, with peak values recorded in May 2003 (11.2 million tons of CO and 188 million tons of CO_2) and in July 2012 (8.1 million tons of CO and 116.8 million tons of CO_2) and 2019 (5.9 million tons of CO and 89.2 million tons of CO_2). Emissions of carbon monoxide and carbon dioxide in summer months are characterized by considerable interannual fluctuations with generally higher values over the 19 years. The yearly distribution of emissions is symmetric for September–October (their average values are 0.18–0.23 million tons/year for CO), except in certain cases (e.g., September 2016, when the volumes of CO_2 and CO emissions exceeded 55 and 3.5 million tons, respectively).

Figure 6b presents the volumes of CO and CO_2 emissions due to wildfires in the FEFD. Analysis of this figure shows that the maximum values of emissions in this region were recorded in July 2003. The range of the values of CO and CO_2 emissions due to wildfires in the FEFD varied from 0.2 to 3.6 and 3.2 to 77.4 million tons in July from 2001 to 2019, respectively; the median value was 1.2 million tons for CO and 35 million tons for CO_2 . The distribution and values of CO emissions in April were similar in the SFD and FEFD (the median was around 1 million tons),

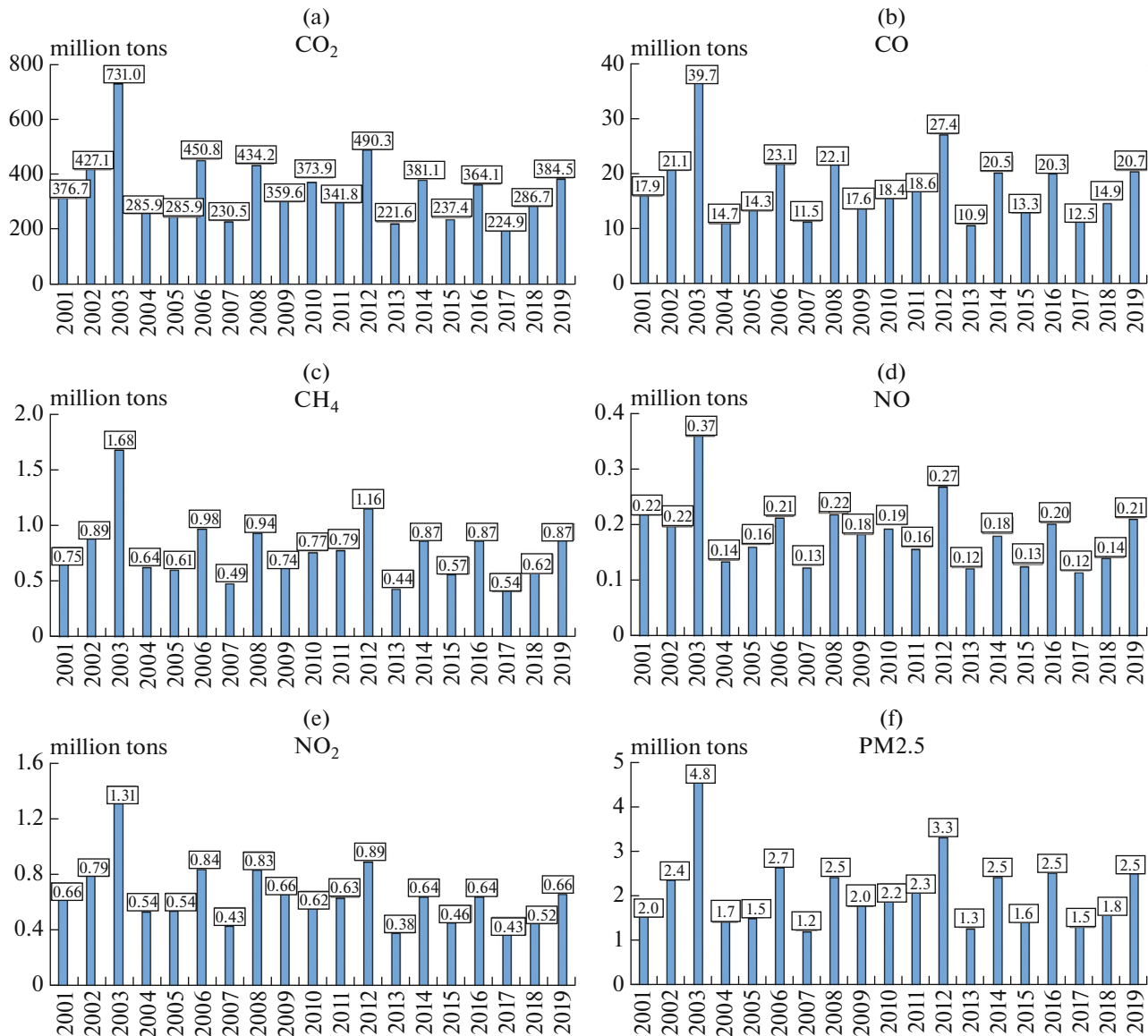


Fig. 4. Total annual volumes of emissions of different trace gases caused by wildfires in the Russian Federation from April to October 2001–2019: (a) CO₂, (b) CO, (c) CH₄, (d) NO, (e) NO₂, and (f) PM_{2.5}.

but the volumes of CO emissions in May fell in the FEFD (the median was 0.4 million tons) and steadily increased in the SFD during this month (the median was 1.7 million tons) throughout the 19-year period of observation (see Figs. 6a, 6b). A similar pattern is also seen for the distribution of the volumes of CO₂ emissions in the SFD and FEFD in April and May from 2001 to 2019 (see Figs. 6a and 6b).

In the EPR (see Fig. 6c) and UrFD (see Fig. 6d), the median values of the average annual CO volumes for the given period do not exceed 0.5 million tons for most of the months except April in the EPR. The maximum emissions of the average annual CO volumes were recorded in April–May, but it should be noted that all of these data were obtained before 2010.

Based on our analysis of the annual average monthly estimates of the volumes of emissions of carbon-containing trace gases according to the satellite monitoring data, we studied the contributions from all regions and followed their changes over the 19 years. Figure 7 shows the contributions from the SFD, FEFD, EPR, and UrFD regions to the volumes of CO and CO₂ emissions due to wildfires from 2001 to 2019. According to the figure, the contribution from the EPR to the CO and CO₂ emissions in April was greatest from 2001 to 2010. In some years, the volume of emissions reached 60–80% of the total volumes of emissions throughout the Russian Federation. From 2012 to 2017, the distributions of CO and CO₂ emissions were similar between the EPR, SFD, and FEFD (within 20–40%).

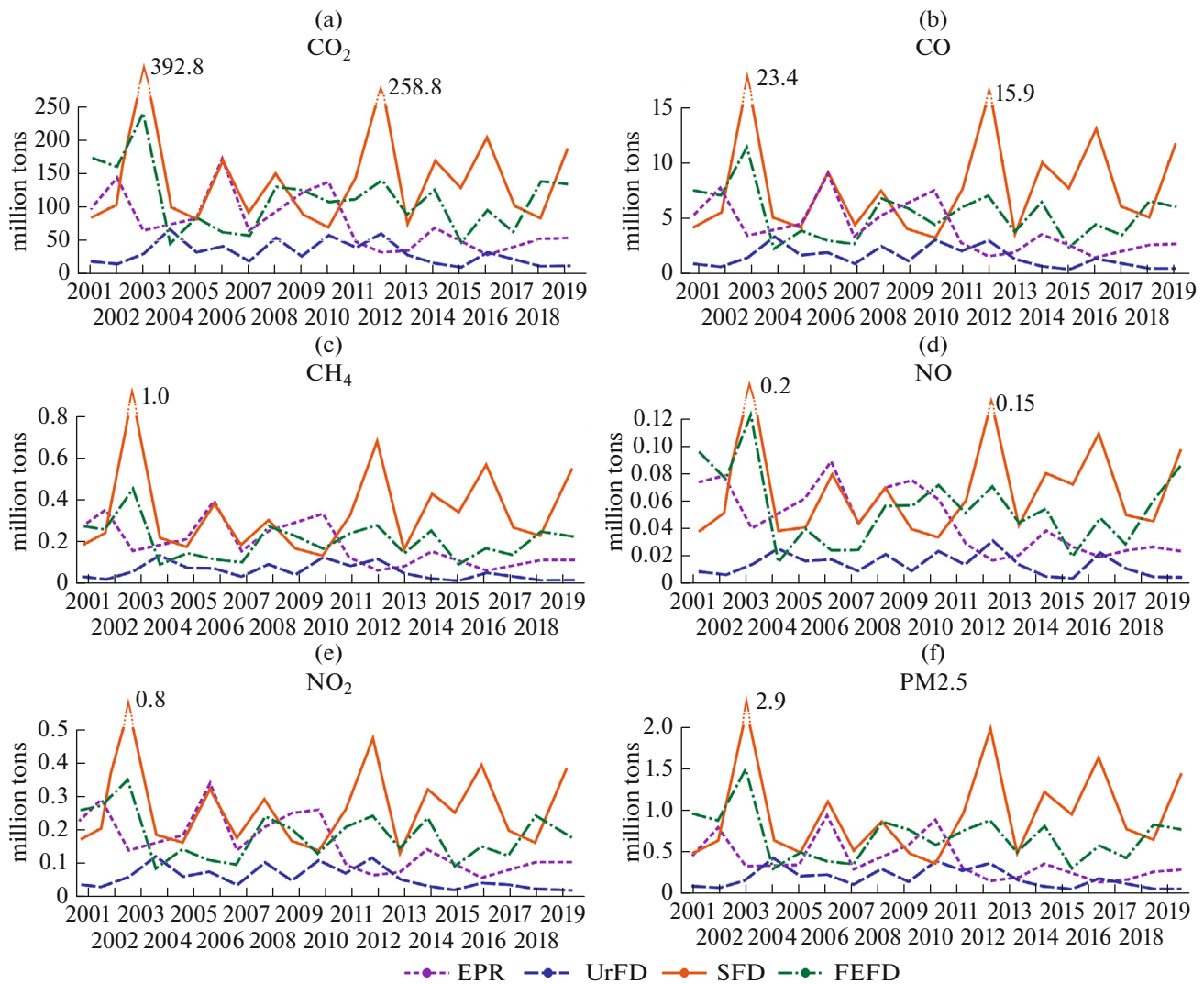


Fig. 5. Volumes of emissions caused by wildfires that occurred in the SFD, FEFD, EPR, and UrFD from April to October 2001–2019: (a) CO₂, (b) CO, (c) CH₄, (d) NO, (e) NO₂, and (e) PM_{2.5}.

In the last two years, the volumes of CO and CO₂ emissions have increased in the EPR, reaching 60% of the emissions throughout Russia.

In May, the greatest CO and CO₂ emissions from 2001 to 2017 were observed in the SFD (from 40 to 80% of total volumes throughout Russia), but the effect of the FEFD has been growing gradually since 2012, with a clearly defined 1–2 year cyclicity of high and low volumes of emissions (see Fig. 7).

In the EPR and UrFD, the total contribution to CO and CO₂ emissions in June did not exceed 20%, while the SFD and FEFD cyclically contributed 60–80% of the CO and CO₂ emissions. It should be noted that this is the only month when the greatest annual emissions in the SFD corresponded to the minimum volumes in the FEFD and *vice versa* (i.e., they were actually in antiphase) (see Fig. 7). The contribution

from the EPR to CO and CO₂ emissions was 40% in July from 2001 to 2010 and fell from 10 to almost 0% in 2011–2019. The contribution from the UrFD to CO and CO₂ emissions was 2 to 26% in July. The maximum values were recorded in 2005 (17%), 2007 (16%), 2013 (26%), and 2017 (22%). The greatest contribution of the FEFD was over 70% in 2008. Every 3–4 years, the greatest annual emissions in the SFD in July reached 80% of the volumes of CO and CO₂ emissions throughout the country (see Fig. 7).

In August, the EPR's contribution to CO and CO₂ emissions predominated until 2010, being more than 80% of all emissions throughout Russia in some years (2004 and 2008). In the UrFD, the interannual variations in the CO and CO₂ contribution generally had the same trend in August as in July and rose only slightly. The role of the SFD and FEFD has constantly

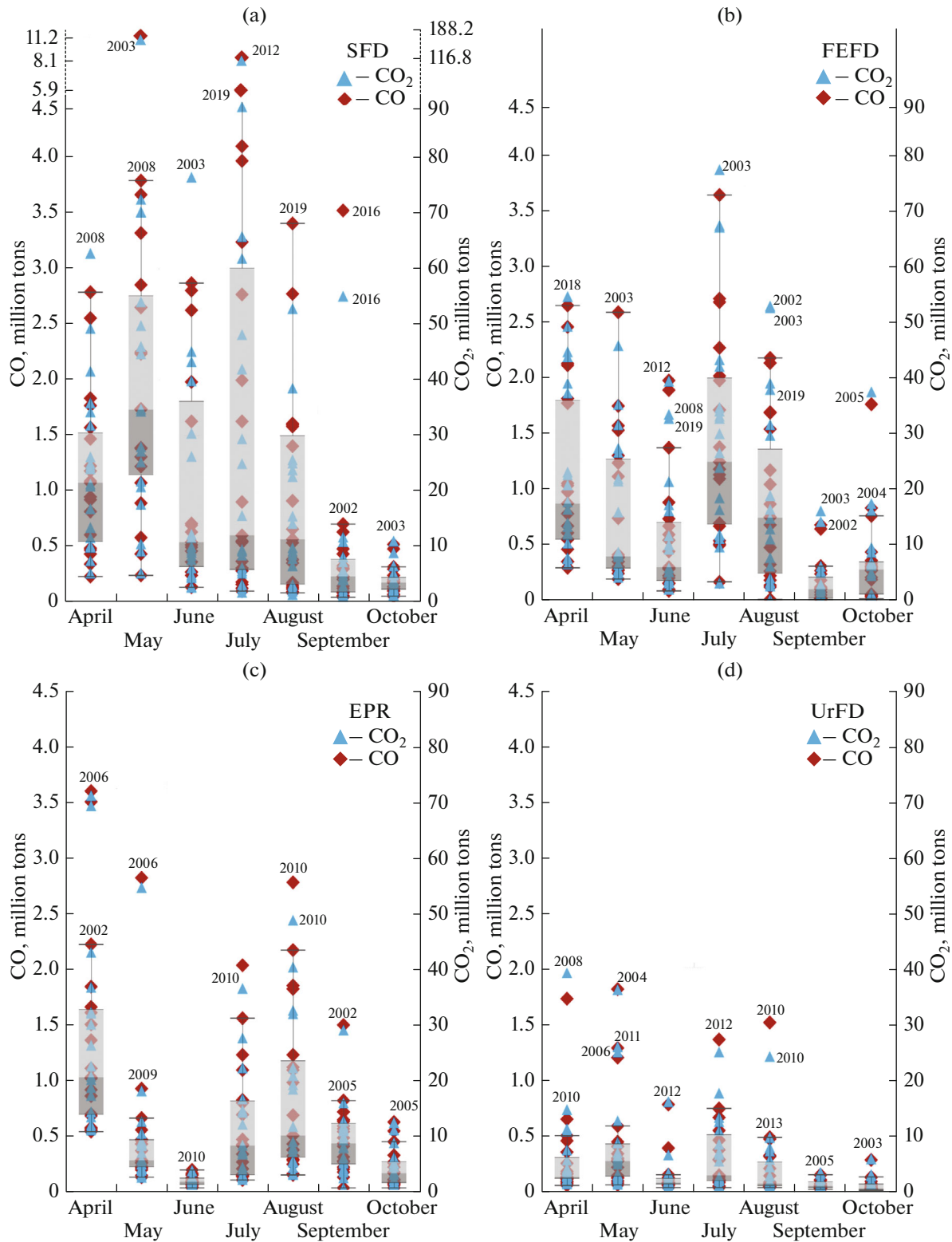


Fig. 6. Distribution of annual CO and CO₂ emissions with indication of quartiles in the fire season from 2001 to 2019 for selected regions of the Russian Federation: (a) SFD; (b) FEFD; (c) EPR; and (d) UrFD.

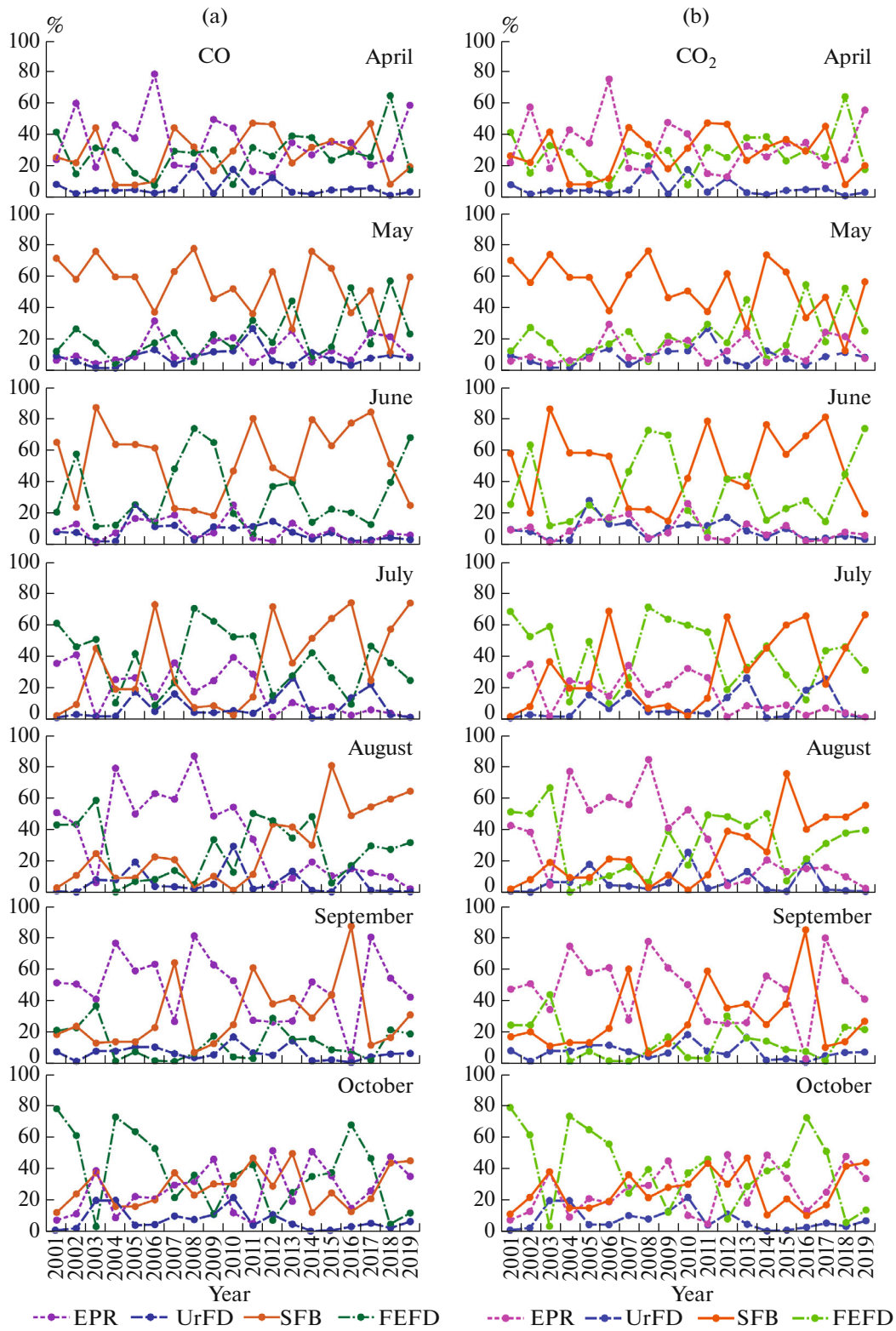


Fig. 7. Distribution of the contributions from the SFD, FEFD, EPR, and UrFD regions to (a) CO and (b) CO₂ emissions due to wildfires from 2001 to 2019.

grown since 2008, reaching 80% (in 2015) for the SFD and 50% (in 2011 and 2014) for the FEFD. It is interesting to note that the volumes of CO and CO₂ emissions grew almost simultaneously in this month, in contrast to June and July (see Fig. 7).

In September, the EPR and SFD made the largest contribution to CO and CO₂ emissions due to wildfires throughout the period of observation from 2001 to 2019. The graphs of the dynamics of the volumes of CO and CO₂ emissions are asynchronous for these regions; i.e., the SFD was characterized by the minimum values of CO and CO₂ emissions in those years when their values were greatest for the EPR (Fig. 7).

The contribution from the UrFD to CO and CO₂ emissions has fallen in October since 2010. The dynamics of emission volumes is smooth in the SFD and EPR, as there were only small fluctuations that did not exceed 50% of the contribution from the regions to the general situation. These fluctuations were rarely less than 20%, while the contribution from the FEFD to CO and CO₂ emissions in October exceeded 60% in 2001, 2002, 2006, and 2016 (see Fig. 7).

Our analysis based on the satellite monitoring data thus allowed us to identify some patterns in the spatio-temporal dynamics of changes in areas burned in the Russian Federation from 2001 to 2019 and assess the contribution from large regions of the Russian Federation to emissions of the main trace gas components (including carbon-containing gases and fine aerosols) caused by wildfires over the 19-year period.

CONCLUSIONS

Our research shows there was a general trend toward a reduction in wildfire areas in the Russian Federation from 2001 to 2019, despite the catastrophic fires in Siberia and the Far East in 2019. The main contribution to the reduction of areas burned came from the EPR and UrFD, due mainly to administrative and legal measures taken after 2010.

According to the results from our analysis of satellite data, the dynamics of fluctuations in the areas burned in the SFD and FEFD was cyclical from 2001 to 2019, falling at one time and rising at another, due most likely to the effect of such natural factors as blocking anticyclones and precipitation, temperature, and wind anomalies. In the spring–autumn period, the size of burned areas clearly tended to shrink in the zones of intensive farming in all regions of the country in April, May, September, and October from 2010. The period from June to August (when forest fires predominate) was characterized by cyclical fluctuations (one-year fluctuations for July and two- to three-year fluctuations for June and August) from 2001 to 2019 (with maxima in 2002, 2003, and 2012, and with no clearly defined minima).

Estimates of the volumes of emissions of different trace gases and fine aerosols due to wildfires through-

out the Russian Federation revealed extremely high values in 2003: CO₂ (731 million tons), CO (39.7 million tons), CH₄ (1.68 million tons), NO (0.37 million tons), NO₂ (1.31 million tons), and PM_{2.5} (4.8 million tons). In 2012, a second maximum was recorded for the considered period: the volumes of emissions due to wildfires were 490.3 million tons of CO₂, 27.4 million tons of CO, 1.16 million tons of CH₄, 0.27 million tons of NO, 0.89 million tons of NO₂, and 3.3 million tons of PM_{2.5}.

According to the results from satellite monitoring, the EPR made a substantial contribution to carbon oxide emissions in April and September–October throughout the period of observation. Although the volume of emissions during the fire season has clearly tended to fall in the EPR since 2010, the values of emissions have grown in the spring–autumn period over the last three years (e.g., in September 2017, when the volume of emissions in the region reached 80% of the emissions throughout Russia). It was found that the pattern of CO and CO₂ emissions was asynchronous in the SFD and EPR (i.e., the SFD was characterized by minimum emissions in those years when peak values were observed for the EPR). The SFD and FEFD make the greatest contributions to CO and CO₂ emissions in the Russian Federation (due mainly to forest fires that occurred from May to August). These regions are characterized by interannual fluctuations of maximum and minimum values. In June, the contributions from the SFD and FEFD are as much as 60–80% of all CO and CO₂ emissions caused by fires in the country (i.e., the greatest annual emissions in the SFD correspond to the minimum ones in the FEFD and *vice versa*). Since 2012, the contribution from the SFD became predominant in July, reaching almost 80% of total emissions throughout Russia every 3–4 years. The EPR made the greatest contribution to CO and CO₂ emissions in August until 2010, being more than 80% of total emissions throughout Russia in 2004 and 2008. Since 2008, the effect the Siberian and Far Eastern regions have on CO and CO₂ emissions due to fires throughout Russia has grown steadily, reaching 80% for the SFD in 2015 and 50% for the FEFD in 2011 and 2014. At the same time, in contrast to June and July, the volumes of CO and CO₂ emissions grew almost simultaneously.

It was found that the UrFD with its relatively small annual size of burned areas makes a lesser contribution to CO and CO₂ emissions caused by wildfires throughout Russia. However, it should be noted that the region's contribution in July–August has been more than 20% in some years since 2010, in contrast to the period before 2010, when the average contribution of this region did not exceed 5%.

Our analysis of the results from satellite monitoring thus revealed the patterns of the spatial and seasonal distributions of wildfire areas at the regional and

national levels. Despite the general trend toward a reduction in areas burned by wildfires throughout Russia over the given period (from 2001 to 2019), regional analysis showed that the fire areas in the Siberian and Far Eastern regions grew and shrank cyclically in summer in different years, thereby displaying a trend towards an increase in the frequency of occurrence of strong fires.

Our results testify to the high efficiency of using satellite monitoring data for quantitative assessment of the spatiotemporal dynamics of burned areas, along with the volumes of trace gas emissions (particularly carbon oxides) and fine aerosols caused by wildfires throughout the Russian Federation and in its large regions.

FUNDING

The reported study was funded by RFBR, MOST (China) and DST (India) according to the research project no. 19-55-80021.

REFERENCES

- Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crouse, J.D., and Wennberg, P.O., Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos. Chem. Phys.*, 2011, vol. 11, pp. 4039–4072. <https://doi.org/10.5194/acp-11-4039-2011>
- Bartalev, S.A., Egorov, V.A., Efremov, V.Yu., Loupyan, E.A., Stytsenko, F.V., and Flitman, E.V., Burnt area assessment based on the combined use of MODIS and LANDSAT-TM satellite data of various spatial resolution, *Sovrem. Probl. Distantionnogo Zondirovaniya Zemli Kosmosa*, 2012, vol. 9, no. 2, pp. 9–26.
- Bondur, V.G., Satellite monitoring of wildfires during the anomalous heat wave of 2010 in Russia, *Izv., Atmos. Ocean. Phys.*, 2011, vol. 47, no. 9, pp. 1039–1048.
- Bondur, V.G., Satellite monitoring of trace gas and aerosol emissions during wildfires in Russia, *Izv., Atmos. Ocean. Phys.*, 2016, vol. 52, no. 9, pp. 1078–1091. <https://doi.org/10.1134/S0001433816090103>
- Bondur, V.G. and Ginzburg, A.S., Emission of carbon-bearing gases and aerosols from natural fires on the territory of Russia based on space monitoring, *Dokl. Earth Sci.*, 2016, vol. 466, no. 2, pp. 148–152. <https://doi.org/10.1134/S1028334X16020045>
- Bondur, V.G. and Gordo, K.A., Satellite monitoring of burnt-out areas and emissions of harmful contaminants due to forest and other wildfires in Russia, *Izv., Atmos. Ocean. Phys.*, 2018, vol. 54, no. 9, pp. 955–965. <https://doi.org/10.1134/S0001433818090104>
- Bondur, V.G., Gordo, K.A., and Kladov, V.L., Spacetime distributions of wildfire areas and emissions of carbon-containing gases and aerosols in northern Eurasia according to satellite-monitoring data, *Izv., Atmos. Ocean. Phys.*, 2017, vol. 53, no. 9, pp. 859–874. <https://doi.org/10.1134/S0001433817090055>
- Bondur, V.G., Tsidilina, M.N., Kladov, V.L., and Gordo, K.A., Irregular variability of spatiotemporal distributions of wildfires and emissions of harmful trace gases in Europe based on satellite monitoring data, *Dokl. Earth Sci.*, 2019a, vol. 485, no. 2, pp. 461–464. <https://doi.org/10.1134/S1028334X19040202>
- Bondur, V.G., Tsidilina, M.N., and Cherepanova, E.V., Satellite monitoring of wildfire impacts on the conditions of various types of vegetation cover in the federal districts of the Russian Federation, *Izv., Atmos. Ocean. Phys.*, 2019b, vol. 55, no. 9, pp. 1238–1253. <https://doi.org/10.1134/S000143381909010X>
- Bondur, V.G., Mokhov, I.I., Voronova, O.S., and Sitnov, S.A., Satellite monitoring of Siberian wildfires and their effects: Features of 2019 anomalies and trends of 20-year changes, *Dokl. Earth Sci.*, 2020, vol. 492, no. 1, pp. 370–375. <https://doi.org/10.1134/S1028334X20050049>
- Decree of the Government of the Russian Federation of November 10, 2015, no. 1213.
- Forecast of the emergency situation in the Russian Federation for 2020, Vserossiyskiy nauchno-issledovatel'skiy institut po problemam grazhdanskoy oborony i chrezvychaynyh situatsiy MCHS Rossii, December 12, 2019, no. 6276-19-3-2.
- Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., and Huang, X., MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets, *Remote Sens. Environ.*, 2010, vol. 114, pp. 168–182.
- Giglio, L., Schroeder, W., and Justice, C.O., The collection 6 MODIS active fire detection algorithm and fire products, *Remote Sens. Environ.*, 2016, vol. 178, pp. 31–41.
- He, Y., Chen, F., Jia, H., and Bondur, V.G., Different drought legacies between rain-fed and irrigated croplands in a typical Russian agricultural region, *Remote Sens.*, 2020, vol. 12, no. 11, id 1700. <https://doi.org/10.3390/rs12111700>
- Isaev, A.S., Korovin, G.N., et al., *Ekologicheskie problemy pogloshcheniya uglekislogo gaza posredstvom lesovosstanovleniya i lesorazvedeniya v Rossii: Analiticheskiy obzor* (Environmental Issues of Carbon Dioxide Absorption through Reforestation and Afforestation in Russia: An Analytical Review), Moscow: Tsentr ekologicheskoi politiki Rossii, 1995.
- Konovalov, I.B., Lvova, D.A., Beekmann, M., Jethva, H., Mikhailov, E.F., Paris, J.-D., Belan, B.D., Kozlov, V.S., Ciais, P., and Andreae, M.O., Estimation of black carbon emissions from Siberian fires using satellite observations of absorption and extinction optical depths, *Atmos. Chem. Phys.*, 2018, vol. 18, pp. 14889–14924. <https://doi.org/10.5194/acp-18-14889-2018>
- Lin, Z., Chen, F., Li, B., Yu, B., Jia, H., Zhang, M., and Liang, D., A contextual and multitemporal active-fire detection algorithm based on FengYun-2G S-VISSR data, *IEEE Trans. Geosci. Remote Sens.*, 2019, vol. 57, no. 11. <https://doi.org/10.1109/TGRS.2019.2923248>
- Pu, R., Gong, P., Li, Z., and Scarborough, J., A dynamic algorithm for wildfire mapping with NOAA/AVHRR data, *Int. J. Wildland Fire*, 2004, vol. 13, no. 3, pp. 275–285. <https://doi.org/10.1071/WF03054>
- Seiler, W. and Crutzen, P.J., Estimates of gross and net fluxes of carbon between the biosphere and atmosphere

- from biomass burning, *Clim. Change*, 1980, vol. 2, no. 3, pp. 207–247.
- Shchetinskii, V.E., Kotelnikov, R.V., Sementin, V.L., Lupyan, E.A., Flitman, E.V., Shcherbenko, E.V., Gal-leev, A.A., Efremov, V.Yu., Tolpin, V.A., Mazarov, A.A., Krashennnikova, Yu.S., and Ershov, D.V., *Primenenie informatsionnoi sistemy distantsionnogo monitoringa "ISDM Rosleskhoz" dlya opredeleniya pozharnoi opasnosti v lesakh Rossiiskoi Federatsii (Izдание vtoroe)* (The Use of the "ISDM Rosleskhoz" Information System of Remote Monitoring in Assessing the Fire Hazard in Forests of the Russian Federation (Second Edition)), Pushkino: Avialesookhrana, 2008.
- Shvidenko, A.Z., Shchepashchenko, D.G., Vaganov, E.A., Sukhinin, A.I., Maksyutov, Sh.Sh., McCallum, I., and Lakyda, I.P., Impact of wildfire in Russia between 1998–2010 on ecosystems and the global carbon budget, *Dokl. Earth Sci.*, 2011, vol. 441, no. 4, pp. 1678–1682.
- Sitnov, S.A., Mokhov, I.I., and Dzhola, A.V., Impact of Siberian wildfires on the content of carbon monoxide in the atmosphere over European Russia in summer 2016, *Opt. Atmos. Okeana*, 2017, vol. 30, no. 2. <https://doi.org/10.15372/AOO20170207>
- Sochilova, E.N. and Ershov, D.V., Mapping and assessment of forest-damaged fires and fire carbon emissions from satellite images of high spatial resolution, *Sovrem. Probl. Distantionnogo Zondirovaniya Zemli Kosmosa*, 2007, vol. 2, no. 4, pp. 322–331.
- Vinogradova, A.A., Smirnov, N.S., and Korotkov, V.N., Anomalous wildfires in 2010 and 2012 on the territory of Russia and supply of black carbon to the Arctic, *Atmos. Oceanic Opt.*, 2016, vol. 29, no. 6, pp. 545–550. <https://doi.org/10.1134/S1024856016060166>
- Vivchar, A.V., Moiseenko, K.B., and Pankratova, N.V., Estimates of carbon monoxide emissions from wildfires in northern Eurasia for air quality assessment and climate modeling, *Izv., Atmos. Ocean. Phys.*, 2010, vol. 46, no. 3, pp. 281–293.
- Vorob'ev, Yu.L., Akimov, V.A., and Sokolov, Yu.N., *Lesnye pozhary na territorii Rossii: sostoyanie i problemy* (Forest Fires in Russia: Conditions and Problems), Moscow: Deks-Press. 2004.
- Voronova, O.S., Zima, A.L., Kladov, V.L., and Cherepanova, E.V., Anomalous wildfires in Siberia in summer 2019, *Issled. Zemli Kosmosa*, 2020, no. 1, pp. 70–82.
- Wiedinmyer, C., Akagi, S.K., Yokelson, R.J., Emmons, L.K., Al-Saadi, J.A., Orlando, J.J., and Soja, A.J., The Fire INventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning, *Geosci. Model Dev.*, 2011, vol. 4, pp. 625–641. <https://doi.org/10.5194/gmd-4-625-2011>
- Xu, G. and Zhong, X., Real-time wildfire detection and tracking in Australia using geostationary satellite: Himawari-8, *Remote Sens. Lett.*, 2017, vol. 8, no. 11, pp. 1052–1061. <https://doi.org/10.1080/2150704X.2017.1350303>

Translated by D. Zabolotny