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Soil–Atmosphere Greenhouse Gas Fluxes in a Background Area in the Tomsk Region (Western Siberia)

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Abstract—The dynamics of greenhouse gas fluxes, measured from 2017 to 2021 at the Fonovaya Observatory of V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, is studied. It is shown that the annual average fluxes of CO_2 at the Observatory varied from −283 (sink) to +31 mg m^{-2} h^{-1} (emission). A minimal emission of 1351 mg m^{-2} h^{-1} was recorded in 2019, and a maximum of 1789 mg m^{-2} h^{-1}, in 2021. The lowest sink was observed in 2017 (2099 mg m^{-2} h^{-1}); the largest, equal to 2304 mg m^{-2} h^{-1}, was in 2018. The annual average methane fluxes ranged from −0.032 in 2018 to −0.047 mg m^{-2} h^{-1} in 2020. The daily maximal methane emission was recorded in 2018 and was equal to 0.915 mg m^{-2} h^{-1}, and the daily minimal emission, in 2021 (0.095 mg m^{-2} h^{-1}). The maximal sink varied from year to year in a narrower range from −0.241 to −0.361 mg m^{-2} h^{-1}. The soil of the measurement area turned out to be a strong source of SO_2 and CH_4 and a weak source of N_2O. The annual average fluxes of NO_2 were in the 0.00–0.011 mg m^{-2} h^{-1} range. The interannual emission maxima weakly changed from 0.237 to 0.301 mg m^{-2} h^{-1}, and sink maxima, from −0.206 to −0.245 mg m^{-2} h^{-1}.

Keywords: atmosphere, air, nitrogen dioxide, sulfur dioxide, carbon dioxide, methane, ozone, nitrogen oxide, carbon monoxide, flux

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INTRODUCTION

The global climate change continues despite the measures taken by the international community to reduce the factors which cause it [1, 2]. The main factor is still an increase in the concentration of greenhouse gases due to anthropogenic activities [3]. Therefore, for more reliable climate forecasting, the most accurate data on the distribution of the concentrations of these gases and the trends in their changes both on the global and local scales are required. To monitor the content of greenhouse gases, the World Meteorological Organization started the Global Atmosphere Watch Programme [4]. A number of countries created national monitoring systems [5–7]. In addition, regional monitoring networks are being developed in international collaborations [8–11].

Foreign greenhouse gas monitoring networks include hundreds of automatic posts and several dozen stations that perform complex measurements. They provide a wealth of information which allow monitoring the distribution of greenhouse gases and their trend across the globe. The territory of Russia is a "blank spot" in the numerical simulation of the climate changes, since the related measurements, if any, are carried out at a few sites by a few enthusiasts, which is clearly not enough for such a vast territory. A fairly complete list of works devoted to this problem is given in [12]. This allows us not to dwell on this issue in detail. The only monograph [13] on this topic can also be noted. It is expected that the Decree of the Government of the Russian Federation on the Creation of a Single Unified Greenhouse Gas Monitoring System in Russia, issued in 2022, is to essentially change the situation.

An important peculiarity of greenhouse gas monitoring is the distinguishing between natural and anthropogenic sources, which makes it possible to estimate the contribution of each of them to the total content of climatically important atmospheric gases [14]. To estimate the emission or sink power under natural conditions, measurements are carried out in remote (background) areas free of anthropogenic effect [15]. Most measurements are carried out by eddy covariance, gradient, or chamber techniques [16, 17]. The eddy covariance technique is considered the most accurate and reference when comparing measurements [18, 19], although it cannot be classified as absolute. It overestimates the net primary production of a forest ecosystem by 25% and underestimates its respiration by 10% [20]. In this work, we used data on greenhouse gas fluxes obtained by the plenum chamber technique. The comparison [21] between these data and the eddy covariance results revealed a flux ratio of 0.94 in a cotton field and of 1.00 in a wheat field. The similar study [22] of the deposition of ozone, carbon dioxide, and nitrogen oxides has shown the differences in the fluxes to be 4–10%.

This work is devoted to the study of fluxes of greenhouse gases CO_2, CH_4, and N_2O in a background region of the Tomsk region.

1. MEASUREMENT SITE AND TECHNIQUES

Greenhouse gas fluxes were measured on a meadow ecosystem territory at the Fonovaya Observatory of V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS), located on the eastern bank of the Ob river 60 km west of Tomsk (56°25′07″ N, 84°04′27″ E; 80 m above sea level). The Observatory is surrounded by southern taiga forests typical for Western Siberia. There are no large industrial facilities nearby. The measuring complex of the Observatory is described in [23].

To measure greenhouse gas fluxes between the soil and the atmosphere during the growing season, we used a complex consisting of a Picarro G2508 $N_2O/CH_4/CO_2/NH_3/H_2O$ gas analyzer and an automatic system of plenum chambers developed at IAO SB RAS [24]. The G2508 analyzer operates in recirculation mode with a Picarro A0702 vacuum pump. An opaque chamber measures the respiration of the ecosystem, while a transparent chamber measures the net ecosystem exchange, which allows determining the net primary production. Chambers of 0.324 m^3 in volume are opened and closed by an automatic pneumatic control system according to the following schedule: (1) one chamber is closed (5 min), the other is open (5 min); (2) vice versa (5 min); (3) both chambers are open (10 min) for ventilation in order to normalize the natural ecosystem conditions (three such cycles per hour).

Greenhouse gas monitoring has been carried out since 2016. The measurements of the CO_2, CH_4, and N_2O fluxes begin after the snow melts (April) and end in October, when frosts set in. Here, we present the results for 2017–2021, which are provided with data for the entire growing cycle.

2. MEASUREMENT RESULTS

2.1. Daily Variations

Daily cycle is one of the key natural cycles; it is determined by the solar radiation. During the day, the nature of the "underlying surface–atmosphere" interaction changes and, hence, the direction of gas fluxes may also change. The location of a gas source is also important. For example, the source of water vapor is evaporation from the underlying surface, while ozone is generated in the upper tropospheric layers or is transported from the stratosphere.

Figure 1 shows the daily average variations in CO_2, CH_4, and N_2O fluxes, as well as their five year (2017–2021) average variations. Since the main way of atmospheric CO_2 sink to the land is its absorption by vegetation during photosynthesis [25, 26], the daily variation in the solar radiation is also shown (Fig. 1d).

Figure 1a shows the CO_2 flux variation during the day at the measurement site. From 07:00 to 19:00, CO_2 sinks from the atmosphere due to the photosynthesis. At night, the sink stops and CO_2 returns to the atmosphere due to the respiration of meadow vegetation. The interannual difference in daytime and nighttime fluxes is of interest in Fig. 1a. Nighttime flux values are in the range 450–550 mg m^{-2} h^{-1} and weakly change from year to year. Midday CO_2 fluxes can vary from −600 (2021) to −1200 mg m^{-2} h^{-1} (2019). The change from positive to negative values occurs around 07:00 local time on average, and from negative to positive values, at 19:00. As seen in Fig. 1e, the CO_2 emission starts exceeding the sink and vice versa when the total solar radiation intensity passes through a point of about 100 W m^{-2}. A relative change in CO_2 fluxes at noon (up to two times) and the solar energy dynamics, which varies by no more than 20%from year to year, are also of interest. This apparently confirms the conclusion about the features of photosynthesis at the measurement site, even other conditions being equal [27].

Methane fluxes are directed from the atmosphere to the soil within 24 hours (Fig. 1b). The change in their intensity weakly depends on the time of day or night. However, a slight decrease in the intensity can be noted during the transitional periods: in the morning and in the evening. In 2018, 2019, and 2021, the methane sink from the atmosphere was stronger during the daytime, and in 2017 and 2020, at night. The value of daytime fluxes varied from −0.028 to −0.048 mg m^{-2} h^{-1}.

Nitrous oxide fluxes were positive for almost 24 hours at the Fonovaya Observatory, unlike CO_2 and CH_4, though not very significant (Fig. 1c). This suggests that the meadow ecosystem in this area is rather a source of N_2O. The value of fluxes varied from −0.005 (at night) to +0.024 mg m^{-2} h^{-1}. Their daily fluctuating variations are quite pronounced. The flux is maximal in the afternoon and minimal at the middle of night. There is even a weak flux of N_2O from the atmosphere to the soil in the afternoon. The small interannual variability of nitrous oxide fluxes should also be noted.

2.2. Seasonal Variations

Seasonal and annual variations are pronounced in natural processes, in addition to the above discussed

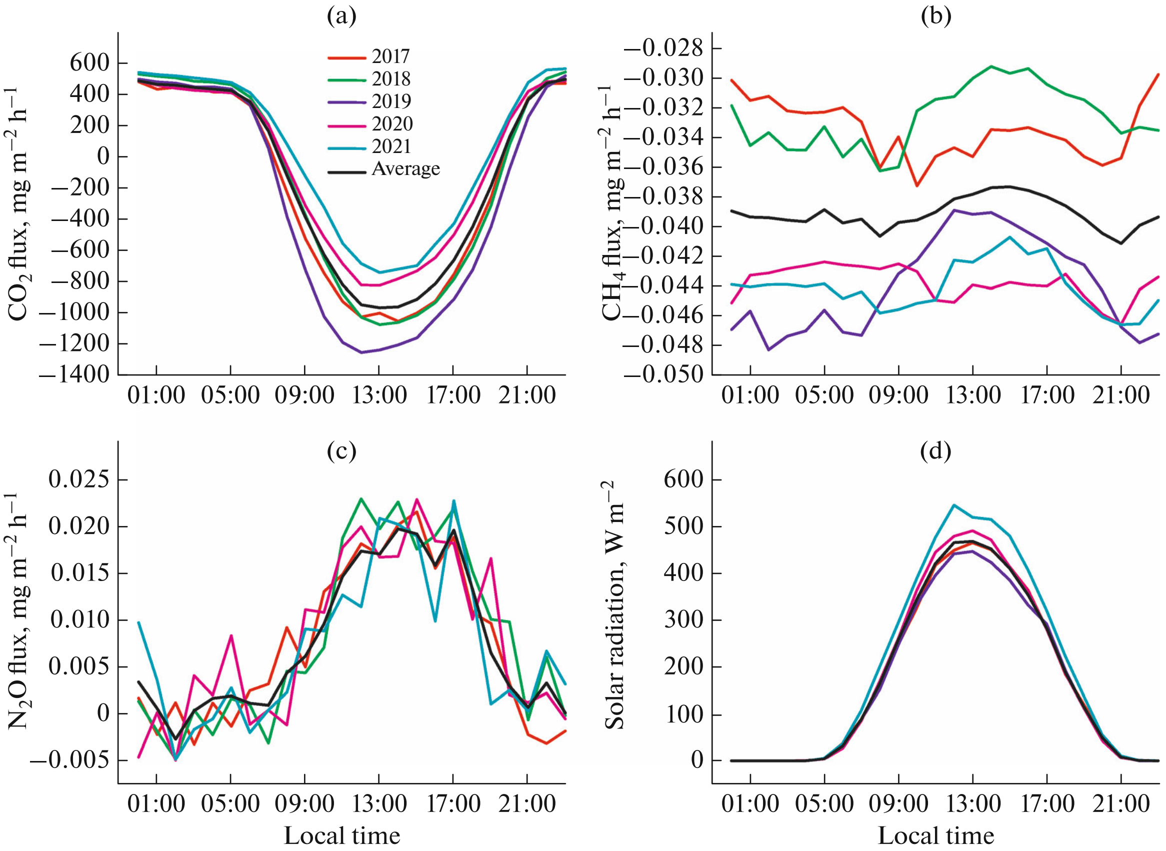

Fig. 1. Growing-season average daily variations in (a–c) greenhouse gas fluxes and (d) solar radiation at the Fonovaya Observatory in 2017–2021.

daily cycle. They also appear in the atmosphere-to-the-surface fluxes of gaseous impurities (Fig. 2).

Inconsistent behavior of CO$_2$ fluxes in 2017–2021 is seen from Fig. 2a. In 2017–2019, the carbon dioxide absorption began in May and in June-July. Then the vegetative activity weakened and respiration increased against the background of biomass accumulation. The CO$_2$ sink continued, but was much weaker. A surge in the absorption in July 2017 was associated with grass cutting in the chamber of the measuring complex, which confirmed the above said. In 2020 and 2021, the seasonal variations in CO$_2$ fluxes drastically changed. The CO$_2$ sink was recorded during the first phase of the growing cycle, and the daily average fluxes became positive starting from July and remained so until the end of the season. If we consider the data on the solar radiation and air temperature (Figs. 2d and 2f), no cardinal changes in their values were observed from July to October as compared to previous years. We discuss possible reasons for this behavior of CO$_2$ fluxes below.

Methane fluxes are negative throughout the warm season, which indicates the sink of this gas from the atmosphere at the Fonovaya Observatory. The flux is minimal May and maximal in July–August. This seasonal behavior might well be associated with the activity of microorganisms in the soil, which react to the temperature of its upper layer. The similarity of the seasonal variations in methane fluxes and air pressure is also seen (Figs. 2b and 2e).

Nitrous oxide fluxes remain positive almost throughout the growing season (Fig. 2c), except for September-October in certain years. The rate of change in N$_2$O fluxes was proportional to the air temperature (Fig. 2f). As shown in [28], N$_2$O is produced in soil in significant quantities in the cycle of nitrogen-containing organic compound transformations.

The emission rate is affected by climate factors, such as air and soil temperature and humidity [29–31]; therefore, the similarity of variations in N$_2$O fluxes and air temperature is not accidental.

During the warm season, the daily behavior in the greenhouse gas fluxes also noticeably changes (Fig. 3). For CO$_2$, this is shown in the amplitude of its fluctuations (Fig. 3a), which is maximal in June and minimal in October. Seasonal variations in CH$_4$ flux values are pronounced under almost neutral daily behavior (Fig. 3b). The CH$_4$ sink is minimal in May and maximal in July–August. The behavior of N$_2$O fluxes varies from month to month; the amplitude is maximal In July-August and the behavior is almost neutral in September–October.

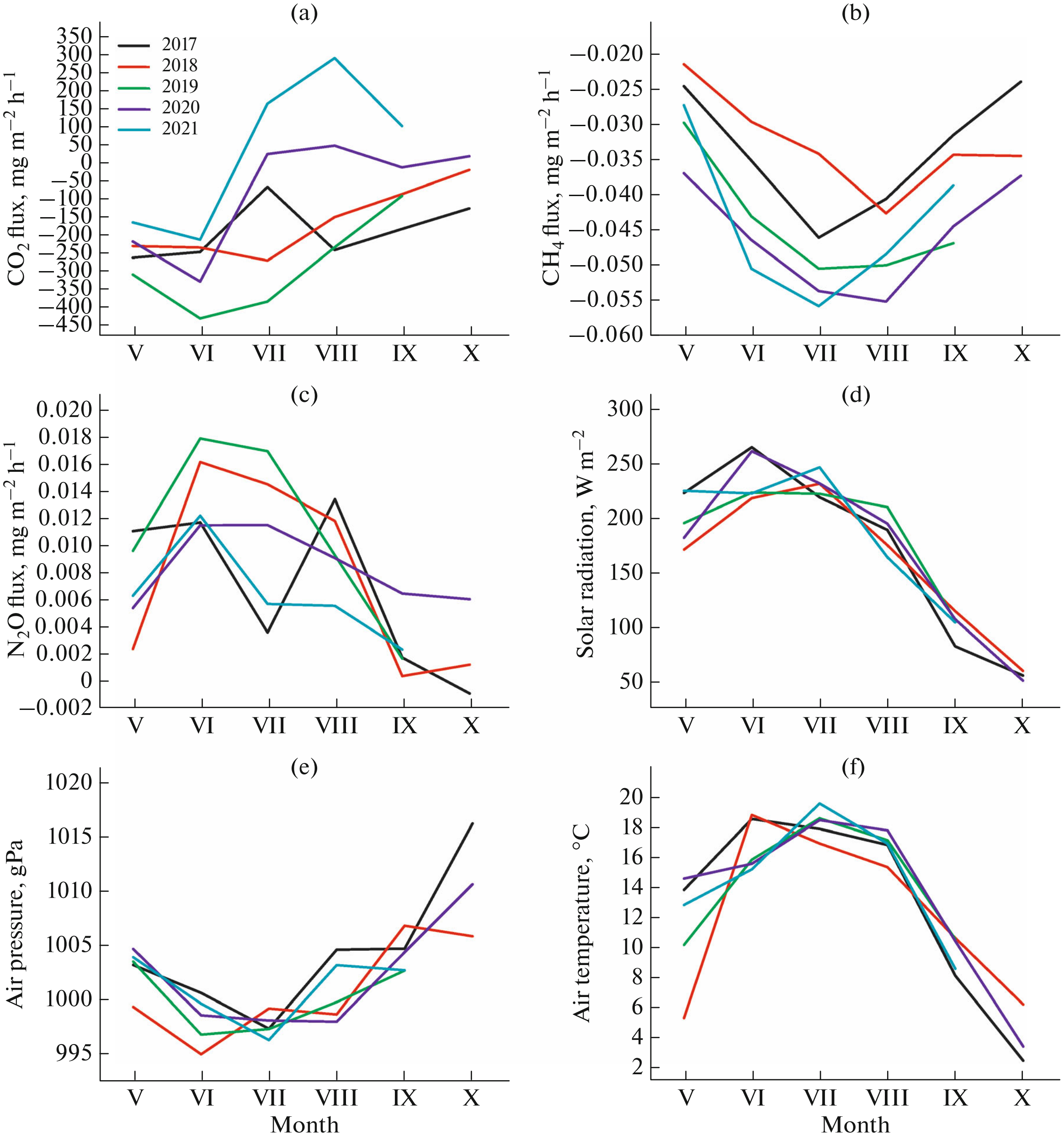

Fig. 2. Seasonal variations in (a) CO_2, (b) CH_4, and (c) N_2O fluxes; (d) solar radiation, (e) air pressure, and (f) air temperature at the Fonovaya Observatory.

2.3. Interannual Variability

Let us consider the change in greenhouse gas fluxes over five years on the basis of the growing season average data (Fig. 4). It can be seen that none of the three gases under study has an unambiguous trend in the soil–atmosphere fluxes. Thus, the CO_2 absorption first increased to -283 mg m^{-2} h^{-1} in 2019, then began to decrease, and the resulting flux became positive in 2021 (Fig. 4a), i.e., the CO_2 sink changed to emission. The methane flux is directed to the soil (Fig. 4b). It was minimal in 2018 and maximal in 2020. The variations in methane fluxes are directly opposite to the trend in the air temperature variations (Fig. 4d). Fluxes of N_2O behave in a completely different way. The N_2O emission was minimal in 2021 and maximal in 2019 (Fig. 4c). This does not correlate with other environmental parameters. Since the gas exchange between the underlying surface and the atmosphere is a multiparametric process, it is difficult to expect unambiguous results in a short period of time.

The main parameters of greenhouse gas fluxes at the Fonovaya Observatory for 2017–2021 are tabulated.

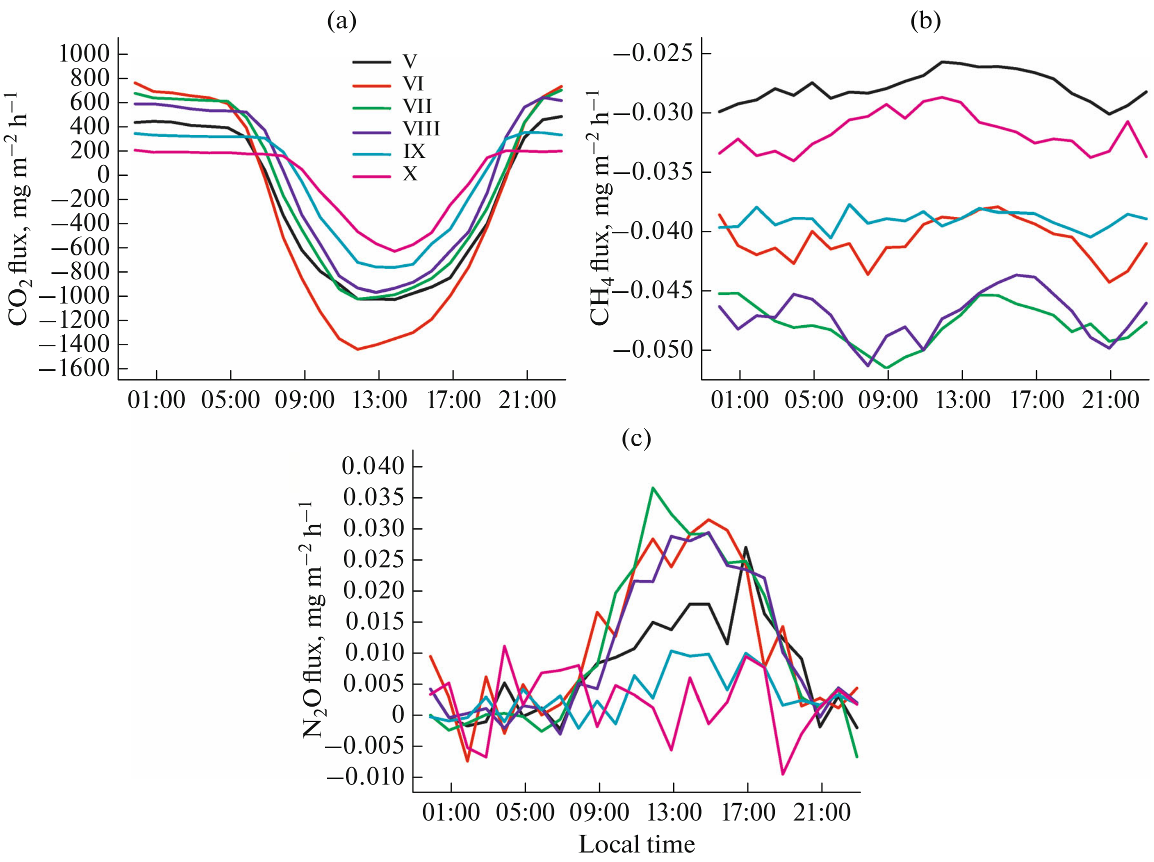

Fig. 3. Daily variations in fluxes of (a) CO_2, (b) CH_4, and (c) N_2O in different months of the growing season.

The data in Table 1 show that the growing season average CO_2 fluxes changed from −283 (sink) in 2019 to +31 mg m^{-2} h^{-1} (emission) in 2021 at the Observatory site. An emission minimum of 1351 mg m^{-2} h^{-1} was recorded in 2019, and a maximum of 1789 mg m^{-2} h^{-1}, in 2021. The sink was minimal in 2017 (2099 mg m^{-2} h^{-1}) and maximal (2304 mg m^{-2} h^{-1}) in 2018. Thus, the seasonal average fluxes have changed by almost an order of magnitude, the maximal fluxes (emission) by 30%, and sink by 10% for five years.

Seasonal average methane fluxes turned out to be less variable. They ranged from −0.032 in 2018 to −0.047 mg m^{-2} h^{-1} in 2020. The emission changed by almost an order of magnitude in some years: the maximum was recorded in 2018 (0.915 mg m^{-2} h^{-1}), and the minimum, in 2021 (0.095 mg m^{-2} h^{-1}). The max-

Table 1. Average, maximal (emission), and minimal (sink) fluxes (mg m^{-2} h^{-1}) of greenhouse gases on the territory of the Fonovaya Observatory with the meadow ecosystem in 2017–2021

Greenhouse gas	Flux	2017	2018	2019	2020	2021
CO_2	average	−191 ± 238	−195 ± 227	−283 ± 194	−93 ± 191	31 ± 265
	max.	1965	1964	1351	1445	1789
	min.	−2099	−2304	−2294	−2124	−2192
CH_4	average	−0.036 ± 0.01	−0.032 ± 0.008	−0.045 ± 0.008	−0.047 ± 0.008	−0.044 ± 0.011
	max.	0.158	0.915	0.307	0.218	0.095
	min.	−0.327	−0.284	−0.361	−0.241	−0.246
N_2O	average	0.008 ± 0.058	0.008 ± 0.060	0.011 ± 0.063	0.009 ± 0.062	0.007 ± 0.063
	max.	0.261	0.261	0.270	0.301	0.237
	min.	−0.206	−0.214	−0.238	−0.245	−0.245

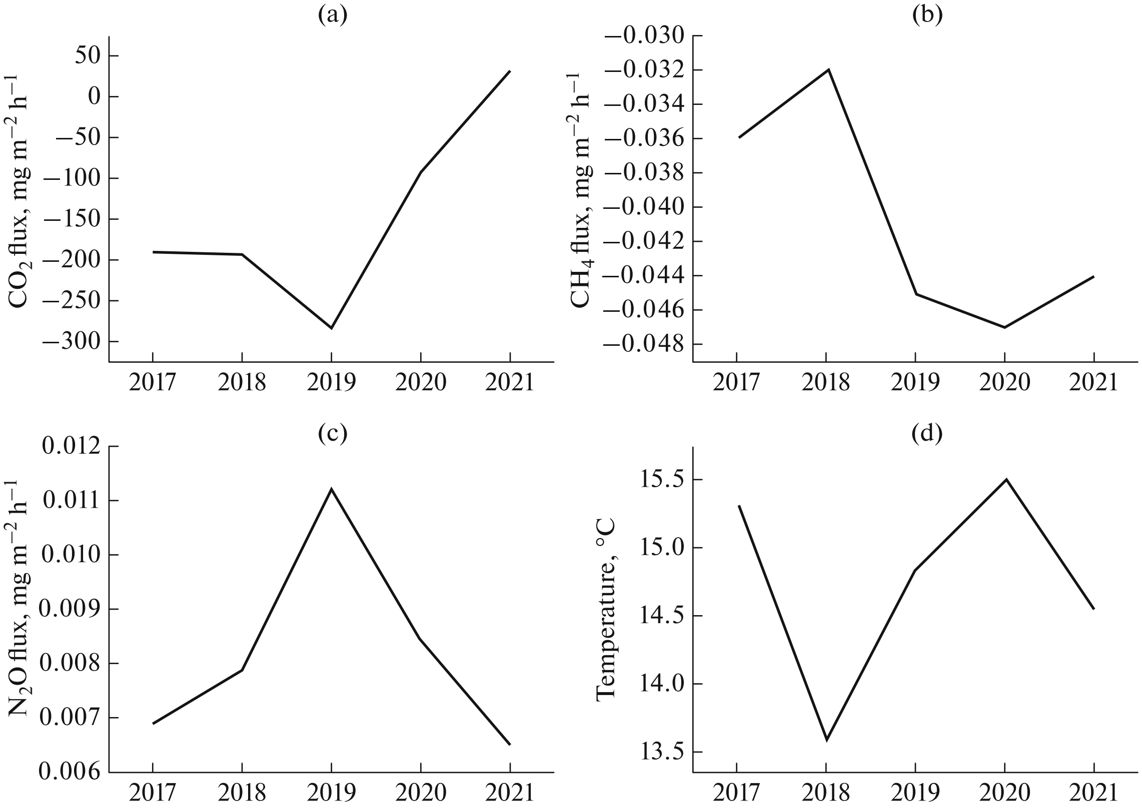

Fig. 4. Seasonal average (a–c) greenhouse gas fluxes and (d) air temperature on the territory of the Fonovaya Observatory with meadow vegetation.

imal sink varied in a narrower range, from −0.241 to −0.361 mg m^{-2} h^{-1}, in the annual cycle. The methane emission was apparently caused by certain intra-annual natural processes. This will be the subject of a separate study.

Unlike SO_2 and CH_4, the soil of the measurement site turned out to be a weak source of N_2O, the average annual fluxes of which varied from 0.007 to 0.011 mg m^{-2} h^{-1}. The maximal emissions and sinks also weakly changed (from 0.237 to 0.301 mg m^{-2} h^{-1} and −0.206 to −0.245 mg m^{-2} h^{-1}) in the period under study. In this regard, the Fonovaya Observatory justifies its name.

3. RESULTS AND DISCUSSION

Carbon dioxide fluxes are actively monitored all over the world [5–8, 12–16]. On the territory of Siberia and adjacent regions, the experiments were carried out mainly in swamp areas [32–34]. The results obtained in the Finnish boreal forest in [35] are the closest to our estimates. The coincidence is very good in terms of both flux values and their seasonal variations.

A situation for methane is similar. A lot of results of studies of swamps or lakes have been published [36–38], but there are almost no works on the forest regions of Siberia. We previously compared CO_2 and CH_4 fluxes measured at the Fonovaya Observatory [39] and at one of the sites at the Vasyugan swamp [36–38]. The analysis showed a CO_2 sink at both sites; it was an order of magnitude more intense at the Fonovaya Observatory: −4377.2 and −429.0 mg m^{-2} h^{-1}, respectively. The swamp was a source of methane throughout the season, while a sink was observed on average at the Fonovaya Observatory.

The study of nitrous oxide fluxes showed that measurements made in areas where fertilizers are used give very high fluxes [40–42]. In the background regions, on the contrary, weak emissions or sink of this gas are observed [43, 44]. The flux values in [43, 44] are very close to the values we obtained; the daily and seasonal variations also coincide. Small N_2O fluxes in background regions led the authors of [45] to the conclusion that it is necessary to increase the number of chambers for measuring greenhouse gas fluxes in order to ensure the representativity of regional estimates.

Let us dwell on one more fact which follows from the analysis of Fig. 2a, that is, a large interannual difference in the seasonal variation in the CO_2 concentration. Since the final CO_2 flux is the difference between the sink due to photosynthesis and emissions

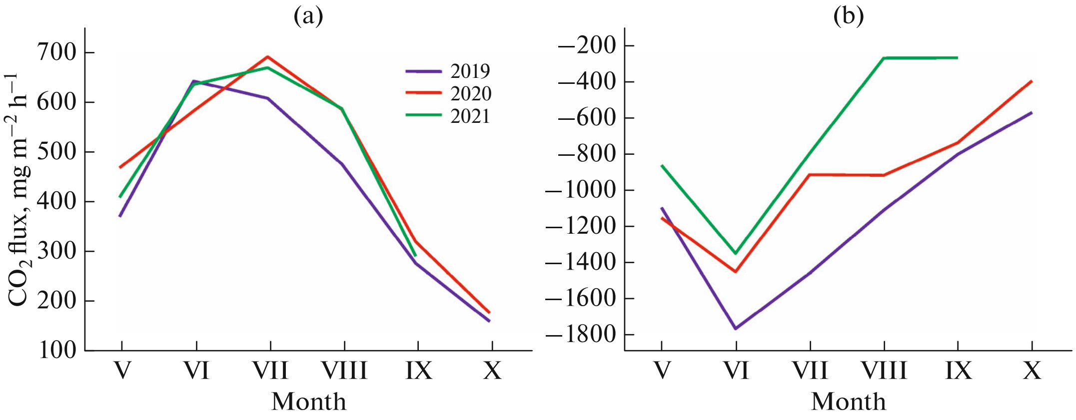

Fig. 5. CO_2 fluxes (a) at night and (b) in daytime.

due to vegetation respiration, CO_2 could change as a result of one or the other process. We compare only the nighttime fluxes (clean breathing of ecosystems) and daytime fluxes, when photosynthesis dominates (Fig. 5).

Figure 5 shows that the CO_2 sink decreased due to both these factors. From June to August, the intensity of respiration markedly increased at night and the excess, as compared to the previous year, remained until October. During the same period, the photosynthetic sink of carbon dioxide became less intense (Fig. 5b). These differences persisted until the end of the growing season. No pronounced interannual differences in the air temperature and solar radiation (see Figs. 2e and 2f) have been recorded; therefore, this fact is difficult to explain. It is similar to the summer increase in the CO_2 concentration in the atmospheric boundary layer [46], which has not yet been explained. Probably, accumulation of CO_2 in the atmosphere has led to incapability of Siberian meadow ecosystems of coping with the absorption of such an amount. But this can only be verified by the monitoring in next years.

CONCLUSIONS

The analysis of “soil–atmosphere” exchange with CO_2, CH_4, and N_2O in the background region near Tomsk have shown features in the daily and seasonal variations in all these gases and differences in their interannual variability. On average, a growing season is characterized by CO_2 and CH_4 sink from the atmosphere and weak N_2O emission.

The fluxes are characterized by a sign change from positive at night to negative during the day. The absolute value of the daytime sink is mainly higher than the nighttime emission. Methane fluxes are directed from the atmosphere to the soil throughout the day. In contrast to SO_2 and CH_4, N_2O is transported from the soil to the atmosphere for almost 24 h at the Fonovaya Observatory.

As for the seasonal variations, the CO_2 absorption begins in May and attains a peak in June-July. Then the vegetation activity weakens, and the nighttime respiration begins predominating. The CO_2 sink continues, but much weaker. This pattern was observed in 2017–2019. In 2020 and 2021, the seasonal behavior of CO_2 fluxes drastically changed. The CO_2 was observed during the first phase of the vegetation cycle; the fluxes became positive in July and remained so until the end of the season. This could be due to the fact that the nighttime respiration intensity significantly increased in the period from June to August, and its predominance, as compared to the previous year, persisted until October. The sink of CO_2 due to photosynthesis greatly decreased in that period. Such differences persisted until the end of the growing season in 2020 and 2021. The CH_4 fluxes were negative throughout the warm season, and the N_2O fluxes remained positive almost throughout the growing season. The methane sink was minimal in May and the maximal in July–August.

During the warm season, the daily variations in the greenhouse gas fluxes also markedly change. For CO_2, this is shown in the amplitude of oscillations; for CH_4, in a change in their value under almost neutral daily behavior; and variations in the fluxes from month to month are characteristic for N_2O.

In the long-term context, the growing-season average sink of CO_2 had been increased since 2017 to -283 mg m^{-2} h^{-1} in 2019, then began to decrease, and became positive in 2021. The absorption of methane by the meadow ecosystem of the Fonovaya Observatory prevailed over its emission throughout the period under study. Emission of N_2O was minimal in 2021 and maximal in 2019.

Since the values of greenhouse gas fluxes do not correlate at all with other environmental parameters, and the exchange between the underlying surface and the atmosphere is a multiparameter process, additional study of its individual factors is required.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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