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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Spatial and Temporal Variability of CO_2 and CH_4 Concentrations in the Surface Atmospheric Layer over West Siberia

M. Yu. Arshinov[a], B. D. Belan[a, b], D. K. Davydov[a], G. Inouye[c], O. A. Krasnov[a], Sh. Maksyutov[c], T. Machida[c], A. V. Fofonov[a], and K. Shimoyama[c]

[a] *Zuev Institute of Atmospheric Optics, Siberian Division, Russian Academy of Sciences, Akademicheskii pr. 1, Tomsk, 634055 Russia*
[b] *Tomsk State University, Tomsk, 634050 Russia*
[c] *National Institute for Environmental Sciences, Tsukuba, Japan*

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Abstract—The diurnal and annual variation of the CO_2 and CH_4 concentrations and their spatial distribution over a network of sites developed over the territory of West Siberia are investigated. The CO_2 concentration gradient between the northern and southern regions of the territory is retained during the entire year. The diurnal behavior of the methane concentration remains neutral for much of the year, so that it is only at the end of the springtime and at the beginning of the summer that it exhibits a significant amplitude. The annual variation of CO_2 has a maximum in the month of December, the concentration starts to decrease in March, and reaches a minimum in July in August. In the central region of the territory, the annual variation of methane has two maxima (in July and in December and January); the greatest interyear methane concentration variability is recorded during the periods of the basic and secondary maxima.

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INTRODUCTION

The investigation of greenhouse gas behavior in the atmosphere plays a key role in predicting the global changes of Earth's climate. In this connection, of particular importance is the study of the distribution of sources/sinks of trace gases of the near-ground atmosphere over the regions of the planet [1]. Russia possesses vast areas of undisturbed or weakly disturbed ecological systems which occupy 65% of the territory of the country and represent a "white spot" in scientific research, since the greenhouse gas measurement data over its territory are almost lacking.

As is well known, apart from the interannual trend, the atmospheric CO_2 and CH_4 concentrations are subjected to seasonal cycles. Short temporal fluctuations, which reflect the presence of regional sources and sinks, are superimposed on their global content [2–5]. An analysis of the spatial distributions makes it possible to determine this component and to estimate the contribution made by individual territories to the carbon cycle. The numerous available models of atmospheric transfer, predicting the development of the situation with greenhouse gases in accordance with one or another scenario, are refined on the basis of the measured concentrations [6–8].

In order to fill a gap in the data on greenhouse gas concentrations in Russia, the Russian–Japanese project TOWERS was organized within the framework of the International Geosphere and Biosphere Program. In accordance with this project, a network of CO_2- and CH_4-measuring stations operating in an autonomous regime was developed over the territory of West Siberia. The description of this network can be found in [9], while the details of the measurements and the calibration are presented in [10].

Gas analyzers and meteorological sensors were mounted at radio relay towers located in different regions of West Siberia. The checking equipment was placed in containers at the tower base. In the containers, the climatic parameters optimal for gas analyzer operation were maintained.

The work on the network development started in 2001. The last of the planned sites in the village of Vaganovo in the Chelyabinsk region was put into exploitation in June 2008. Since at each of the sites the measurement duration could be different, varying from five–six years to one–two years and less, in this paper we present the data of the greenhouse gas monitoring for six sites which give the primary idea on the spatial distribution and temporal dynamics of CO_2 and CH_4 in the ground air layer in West Siberia.

DESCRIPTION OF MEASUREMENT SITES

The first measurement site was created near the village of Berezorechka in the Tomsk region. A tower equipped with measurement facilities is located within a vast woodland at 56°08′ North and 84°20′ East, at a distance of 60 km from Tomsk.

The second was the Parabel' site, created at the radio relay station Karasevoe in the Tomsk region. The measurement complex is located at the shore of the large marshy lake of Krugloe, 5 km in diameter. The site coordinates are 58°14′ North and 82°22′ East.

Three more sites were created almost simultaneously near the town of Noyabr'sk in the Yamalo–Nenets autonomous area (63°26′ North and 76°46′ East), near the village of Dem'yanskoe in the Tyumen region (59°47′ North and 70°52′ East), and in the small town of Igrim in the Khanty–Mansi autonomous area (63°11′ North and 64°25′ East). The measurement complex mounted at a tower, 30 km northeast of Noyabr'sk, is located within an woodland in the immediate vicinity of a gas pipeline. The Dem'yanskoe site is also located within an woodland. The complex in the town of Igrim (about 10000 inhabitants) is constantly subjected to man's impact. At 200 m from the site location, in a northeasterly direction, there is a gas boiler house with chimneys comparable in height with the tower at which the air intakes of the complex are mounted. For this reason, a part of the values should be discarded in data processing. Relatively pure air arrives at the measurement site from the west (from the Severnaya Sos'va river).

The next site was created at the village of Savvushka in the Altai territory. The measurement complex is located at the Kolyvan' hills, 1 km south of the village. The Pospelikha–Zmeinogorsk route passes 500 m westward from the village. The country (partially wooded steppe) is well blown through by winds. The site coordinates are 51°20′ North and 82°07′ East.

Each observation site represents a stationary tower equipped with a standard set of meteorological sensors and a container with the identical facilities for gas analysis, namely, a CO_2 analyzer LI-820 (LI-COR, Inc.) and methane sensor TGS-2611 (Figaro), as well as high-precision standard gas mixtures with CO_2 and CH_4 concentrations close to the observable background values. For studying vertical gradients, the samples are taken at two levels, the lower air intakes being always placed above the upper section of the surrounding vegetation in order to avoid an excess influence of the underlying surface.

Through a system of tubes and switch valves, the preliminarily dried air is continuously supplied to the gas analyzers which are under thermostabilized conditions. At each level the concentrations are measured hourly, while the calibration with respect to three gas standards is made twice a day. To economize the expensive "standards," an hourly additional calibration with respect to the gas mixture with relatively constant concentrations of the in situ-taken atmospheric components is made. All the processes of gathering, processing, and storing of the information is controlled by CR10X data loggers (Campbell Scientific Inc.). Apart from the measured concentrations, the main meteorological data are also recorded at each observation site.

On the basis of the information gathered by the measurement network and the data of the calibration with respect to standard gas mixtures, the actual carbon dioxide and methane concentrations are reconstructed; these indicate the variations of the parameters interesting for us not only in time but in space as well.

MEASUREMENT RESULTS AND THEIR DISCUSSION

Since, as noted above, the measurement series are different for the sites, we will restrict an analysis of the temporal dynamics of the CO_2 and CH_4 concentrations to the consideration of the diurnal and annual variations. The spatial distributions will be presented for average monthly values for the main year seasons.

Diurnal Behavior

We will first consider the data obtained at the Parabel' site averaged over four years of observations; they are presented in Fig. 1. Here, the vertical lines indicate root-mean-square deviations. Greenwich Time is given. The Parabel' site is chosen for the reason that the series of continuous measurements performed at this site were most prolonged and it is at the center of the territory under consideration. Moreover, any significant anthropogeneous sources are absent from this locality.

As can be seen in Fig. 1, in the month of January the CO_2 concentration variation is not higher than 1 ppm and is in the natural variability corridor. In April the daily amplitude amounts to 4 ppm, though it is still within the root-mean-square deviation corridor. The greatest and significant diurnal behavior was recorded in July, when the amplitude amounted to 25 ppm. In October, the diurnal behavior remained significant, though its amplitude decreased down to 5 ppm. These dynamics of the diurnal behavior are due to vital activity of the vegetation and are completely understandable.

The presence of two measurement levels makes it also possible to estimate the photosynthesis period of the plants absorbing carbon dioxide. At the Parabel' site, the lower and upper levels of the air intake are at heights of 40 and 75 m, respectively. Comparing the concentrations at these heights, as shown in Fig. 1, we can estimate the periods of the CO_2 sinkage and generation in the ground air layer. Thus, in January the CO_2 concentration is greater at the lower level than at the higher one from 9 a.m. to 7 p.m. This means that the plants breathe, thus giving off carbon dioxide. By night, the breathing process apparently weakens since the difference almost vanishes. Since photosynthesis depends on the vital activity rhythm of the vegetation and on the

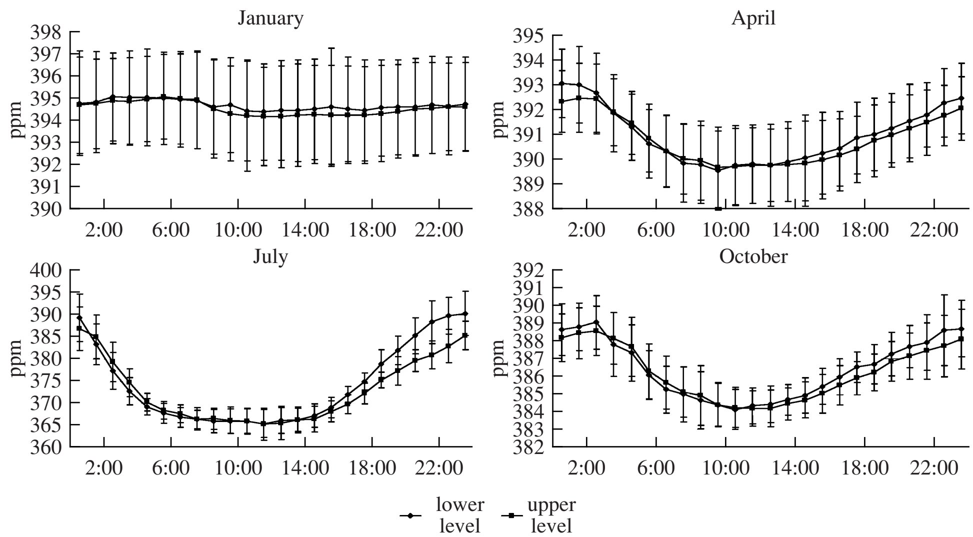

Fig. 1. Daily-average many-year dependence of the carbon dioxide concentration at the Parabel' site for the central months of seasons.

solar radiation flux, the transition from breathing to photosynthesis must also depend on the time of day. From Fig. 1 it follows that photosynthesis begins at 3 a.m. and ends at 1 p.m. in April, begins at 1 a.m. and ends at 3 p.m. in July, and begins at 3 a.m. and ends at 11 a.m. in October. Thus, the duration of the period when the CO_2 sinkage is more intense than its generation varies during the year.

Since the photosynthesis beginning and end depend on the solar radiance duration, which, in turn, is determined by the observation point latitude, we composed a table for the southern, central, and northern regions of the territory in which the moments of the CO_2 sinkage beginning and end are given for each month (table).

From table, it follows that from November to February the concentration difference between the levels is not observable, that is, there is no an appreciable CO_2 sinkage. However strange it may seem, the sinkage begins in the month of March over northern latitudes and only afterwards does it propagate throughout the entire territory. From April to October it is observable everywhere. True enough, its duration is different for various regions. Apparently, a certain role is played by not only the appearance of the solar radiation but also by the nature of the vegetation inherent in a given locality.

The diurnal behaviors for all the stations are compared in Fig. 2 for the central months of each season.

Periods of the photosynthesis beginning and end, and its duration (in hours) for the Savvushka, Parabel', and Noyabr'sk sites

Period	Savvushka			Parabel'			Noyabr'sk		
	Beginning	End	Duration	Beginning	End	Duration	Beginning	End	Duration
I	–	–	–	–	–	–	–	–	–
II	–	–	–	–	–	–	–	–	–
III	–	–	–	–	–	–	9	17	8
IV	6	10	4	4	15	11	4	16	12
V	2	13	11	2	15	13	2	16	14
VI	1	15	14	1	21	20	1	16	15
VII	3	13	10	3	13	10	2	15	13
VIII	4	12	8	4	13	9	5	15	10
IX	6	11	5	4	12	8	6	13	7
X	6	9	3	6	11	5	6	10	4
XI	–	–	–	–	–	–	–	–	–
XII	–	–	–	–	–	–	–	–	–

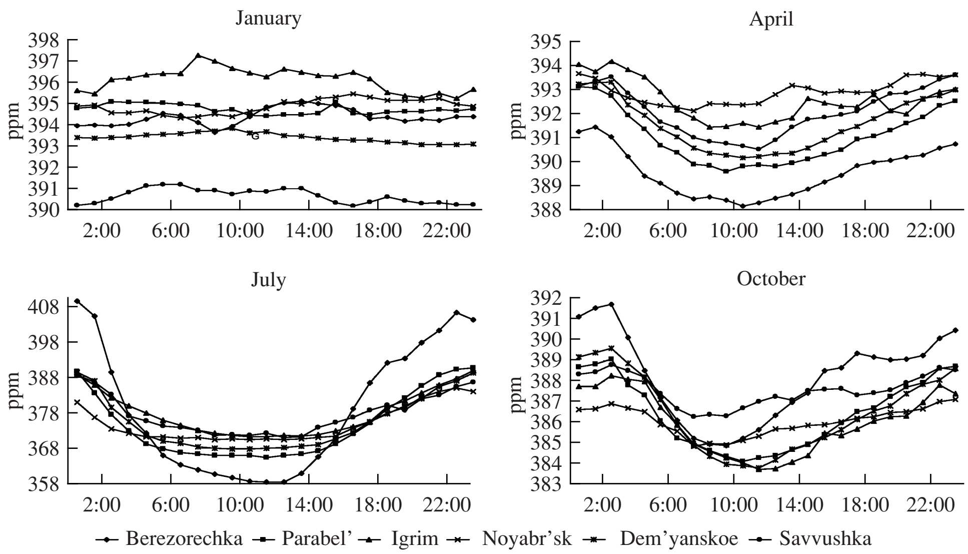

Fig. 2. Daily-average many-year dependence of the carbon dioxide concentration at all sites of West Siberia for the central months of various seasons.

As follows from Fig. 2, in January there is a fairly high gradient (5 to 6 ppm) between the southern (Savvushka) and northern (Igrim) regions, the diurnal behavior being neutral. In April, an appreciable diurnal behavior is observable; it is similar for all the sites except for that in Noyabr'sk. In this case, the gradient between the southern and northern regions decreases. The carbon dioxide concentrations are minimal at Berezorechka. In July, due to good air mixing, the differences in the diurnal behavior at most of the sites are smeared. Here, the diurnal behavior amplitude is 15 to 20 ppm. An exception from the general pattern is provided by the Berezorechka site, where the diurnal behavior amplitude amounts to 50 ppm. We note that during the intense photosynthesis period the CO_2 concentration here is 10 to 15 ppm lower than at the other sites, whereas at the vegetation breathing period it is 20 to 25 ppm higher. In October, the diurnal behavior is conserved at all the sites, though its amplitude decreases. The differences in the diurnal behaviors for different regions also become appreciable. This is particularly true for the sites located in Savvushka and Noyabr'sk. For the former site, it can be due to the influence of the forest steppe zone: there is little forest vegetation, while the vegetation period of the grass has already ended. At this period in the northern regions, the ground is already snow covered.

It seems interesting to consider the interyear variability of the carbon dioxide concentration at different seasons with account for the general trend of its increase on the planet [11, 12]. For this purpose, we will turn to the data of the Parabel' site presented in Fig. 3.

As follows from Fig. 3, minimum and near-minimum January concentrations were recorded in 2005 and 2007, while the maximum concentration was observed in 2006. In April, the CO_2 content increased from 2005 to 2007. In July and October, the distribution in years was more complicated. In these months, minimum concentrations were observed in 2005 and maximum ones in 2007, while the carbon dioxide content in 2004 was closer to that in 2007. For the present, it is difficult to interpret this behavior of CO_2. Before drawing the final conclusions, the state of the vegetation and the climate characteristics should be analyzed.

We will now turn to the consideration of the diurnal behavior of the methane concentration with reference to the example of the Parabel' site.

As can be seen from Fig. 4, a significant diurnal behavior of the methane concentration, outside the root-mean-square deviation corridor, is observable only in the months of April and June. In January, the dependence is more likely to be neutral. In October, it does not fall outside the natural variability corridor. Noteworthy is the fact that, as distinct from the carbon dioxide case, there is no concentration difference between the levels. This indicates that the methane source is located at the bottom and acts constantly.

For other regions of West Siberia, the methane behavior in the ground layer is presented in Fig. 5.

In January, the methane concentration dependence is neutral at all the sites of the region. The concentration gradient between the southern and northern territories varies from 100 to 140 ppb. In April, a weak diurnal behavior is observable over the northern regions (Igrim and Noyabr'sk) but it remains neutral over the central and southern regions. The difference in the concentrations between the north and the south is conserved. Characteristic of July is an increase in the diurnal behavior amplitude in individual northern and central regions. In Noyabr'sk and at the southern sites (Bere-

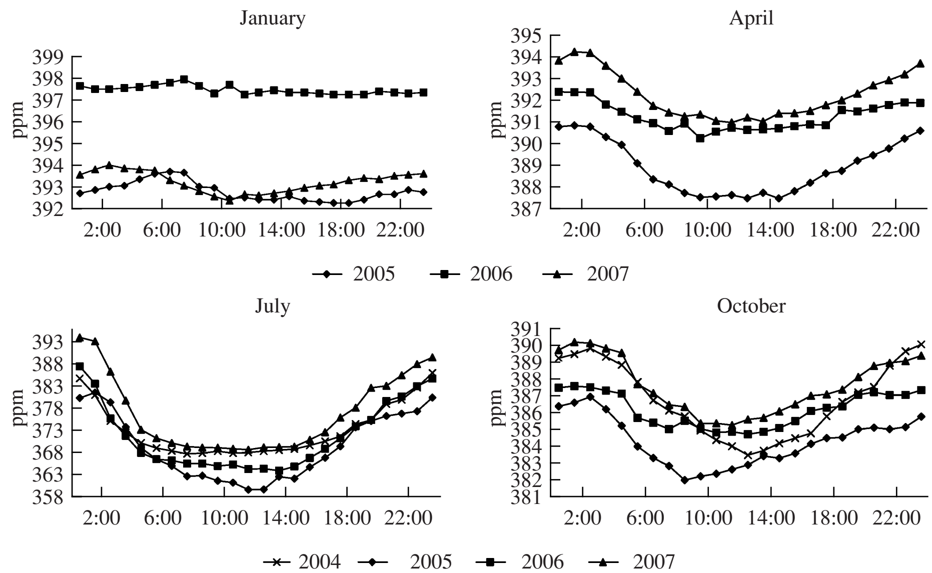

Fig. 3. Daily-average dependence of the carbon dioxide concentration at the Parabel' site for the central months of seasons in different years.

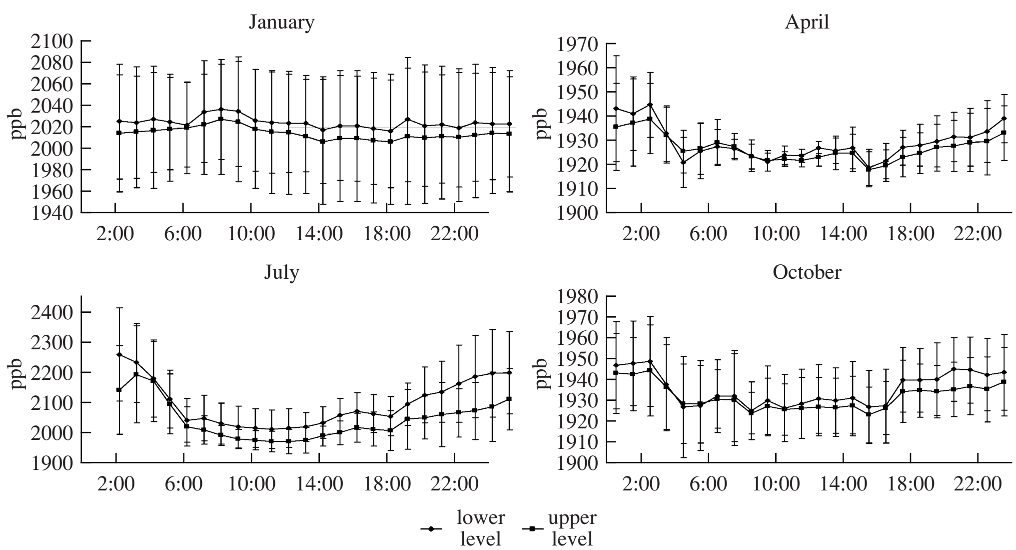

Fig. 4. Daily-average many-year dependence of the methane concentration at the Parabel' site for the central months of various seasons.

zorechka and Savvushka), the diurnal behavior remains neutral. The difference between the regions amounts to 340 ppb at night and decreases to 120 ppb during the daytime. In October, the diurnal behavior is neutral for most of the sites, the difference between them being slight (less than 100 ppb). An exception is the Noyabr'sk site, where the concentration is maximum, while the difference with the nearest site is greater than 100 ppb.

Thus, to summarize this section, we can note that at the territory of West Siberia the diurnal behavior of carbon dioxide and methane is different. This is apparently due to the different nature of the sources of these gases.

Annual Variation

We will begin an analysis of the annual variation with carbon dioxide, following the same pattern as that used in considering the diurnal behavior.

In Fig. 6, we have plotted the many-year-average annual variation obtained at the Parabel' site. The reason, for what precisely this site was chosen, was substantiated above. Here, the annual variation is obvi-

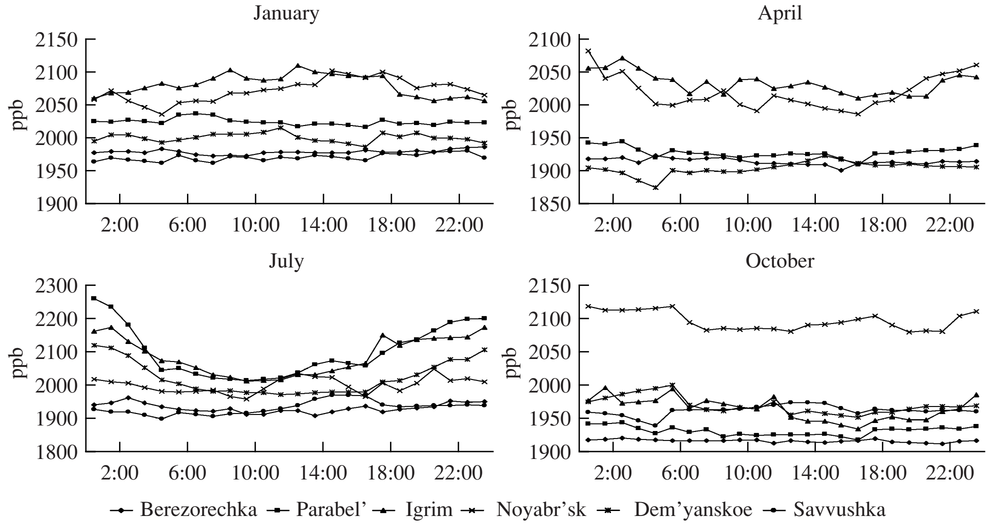

Fig. 5. Daily-average many-year dependence of the methane concentration at all sites of West Siberia for the central months of various seasons.

ously periodic, with a concentration maximum in December, when the vegetation activity is minimum, and a minimum in July and August, when it reaches its maximum. As can be seen from the figure, the carbon dioxide concentration starts to decrease already in March, with the decrease proceeding very intensely from May to July. Obviously, in July and August the CO_2 generation and sinkage rates are comparable. From September to December the sinkage rate is less than that of emission.

The data concerning the two heights presented in the same figure indicate that, as distinct from the diurnal behavior, the concentration differences between them are considerably lower and comparable with the measurement error. Therefore, during short time intervals, the CO_2 generation and sinkage processes are more dynamic than for long time intervals with large averaging. At this site, the year-average amplitude as a function of the level amounts to 22–24 ppm.

The laws established for this site are typical for all the other sites of West Siberia, which is inferred by the data in Fig. 7.

Obviously, at all the sites the annual variations of CO_2 are similar, the concentration difference being not greater than 5 ppm for a large share of a year. The differences are greater only near the maximum and minimum points. At our eyes, this indicates that for long time periods the intensities of the sources and sinks in different regions of West Siberia are comparable, which cannot be said of the carbon dioxide concentration variations for short time periods.

We are now coming to an analysis of the annual variation of methane at the Parabel' site, as shown in Fig. 8.

As distinct from carbon dioxide, the annual variation of methane has two maxima and two minima. The maxima are observed in July and in December and January, while the minima are observable in April and May and in October. Bearing in mind the distinctive features of methane generation and sinkage under natural conditions and the fact that it can be generated by anaerobic bacteria in the soil and liberated from marsh surfaces [13–15], it can be inferred that the winter maximum is due to the bacterium activity, while the summer one is of the marsh origin.

The pattern of the annual variation of methane over the territory of West Siberia is more diversified (Fig. 9).

In the northern regions, the main maximum is observable in winter and displaced to February with respect to the central regions. Over the southern regions, the summer maximum is not so intense and is

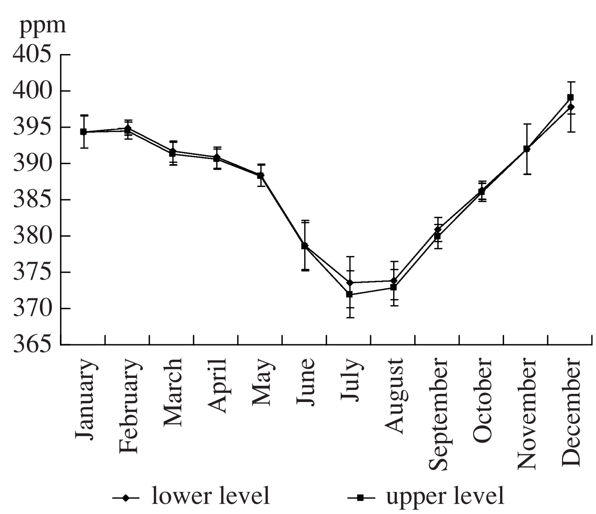

Fig. 6. Many-year-average annual variation of carbon dioxide concentration at the Parabel' site.

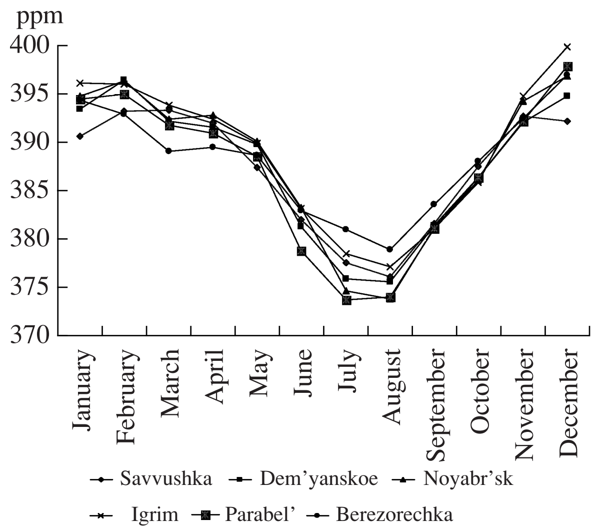

Fig. 7. Many-year-average annual variation of carbon dioxide concentration at all sites.

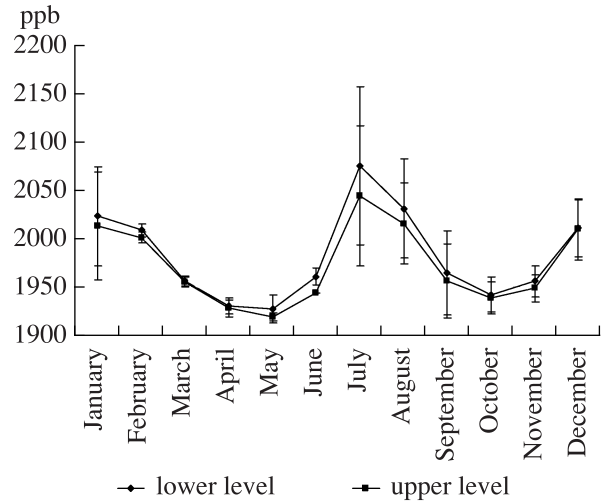

Fig. 8. Many-year-average annual variation of methane concentration at the Parabel' site.

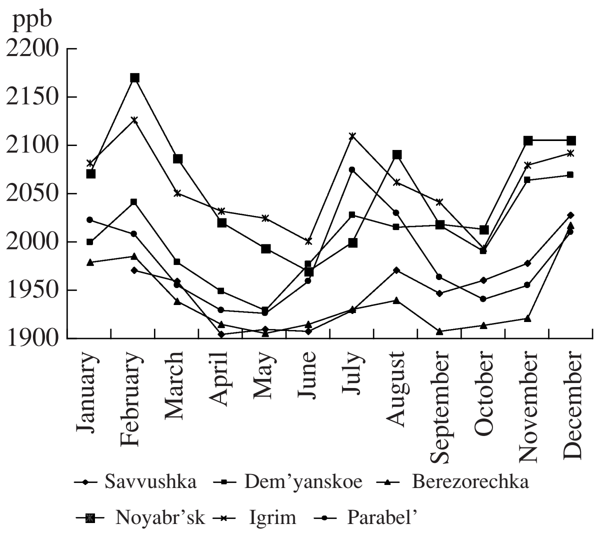

Fig. 9. Many-year-average annual variation of methane concentration at all sites.

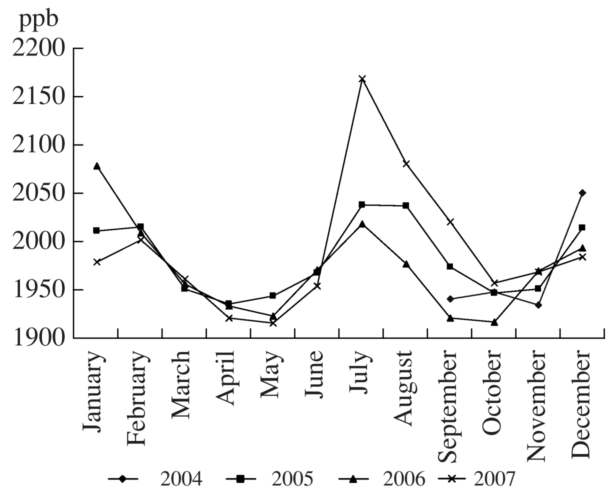

Fig. 10. Annual variation of methane at the Parabel' site in different years.

displaced to August. The annual variation amplitude is greater than 200 ppb in the northern regions and is on average 100 to 120 ppb in the southern regions. Apparently, this diversity reflects the presence of large marsh systems near the northern observation sites. During a year, the maximum differences between the sites vary from 100 to 250 ppb.

In conclusion of the section, we will consider the interyear methane variability at the Parabel' site.

As follows from Fig. 10, the methane concentration remains almost constant from one year to another in the transitional periods between the maximum and the minimum. The greatest interyear variability is recorded during the main and secondary maxima, amounting to 150 ppb. So far, it is difficult to identify the reason for this behavior. The data in Fig. 10 show that during the summer maximum the greatest values were recorded in 2007 and during the winter maximum in 2004 and 2006.

Spatial CO_2 and CH_4 Distributions Over the Territory of West Siberia

The presence of a distributed network of the sites operating in the monitoring regime makes it possible not only to investigate the temporal dynamics of CO_2 and CH_4 at each site and to determine the spatial differences between the concentrations by comparing the

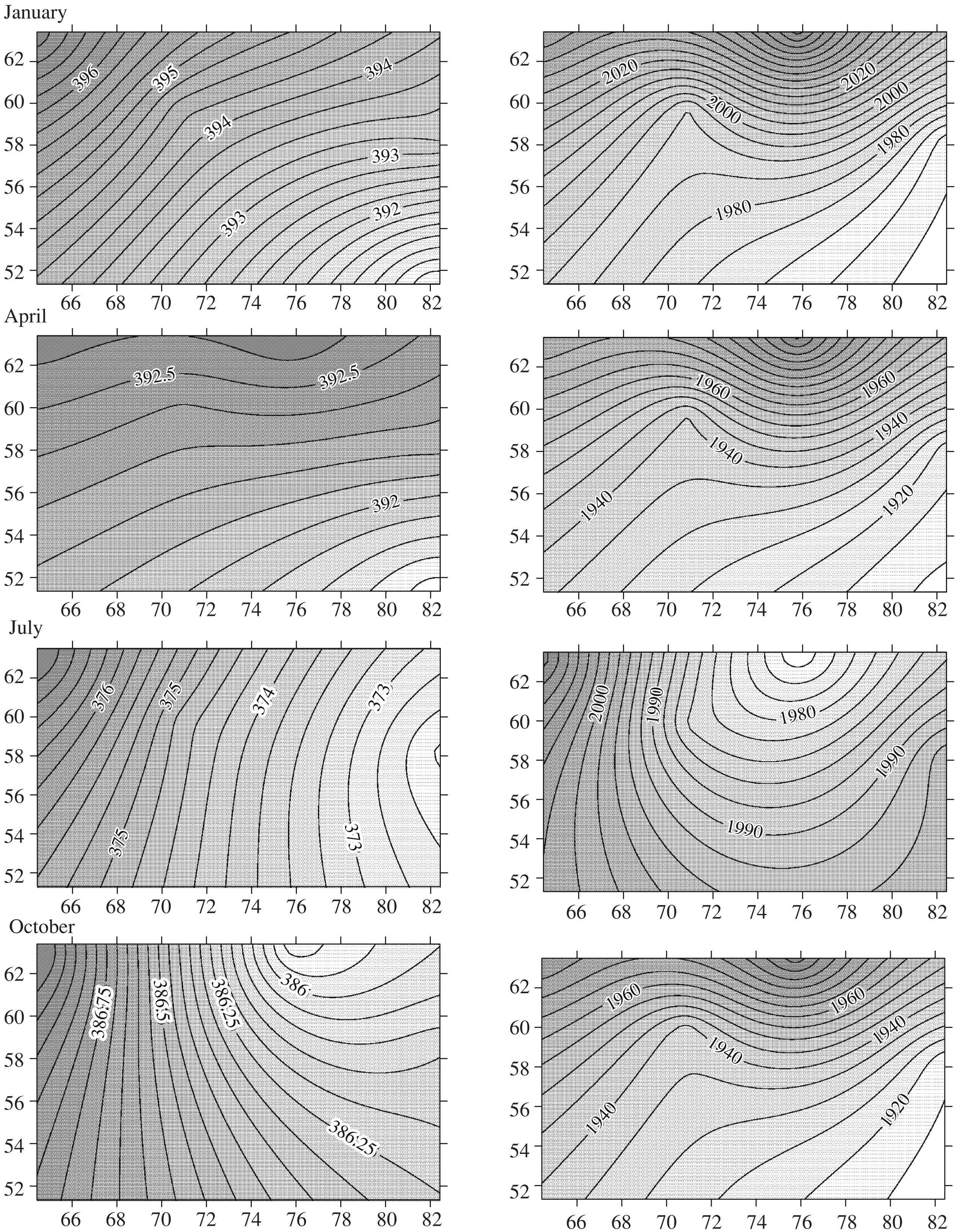

Fig. 11. CO_2 and CH_4 distributions over the territory of West Siberia for the central months of various seasons.

data, but also to plot the distribution charts for different moments of time. The examples of these charts are presented in Fig. 11.

For a while, we will not comment on this figure in detail. Clearly, the distributions of both CO_2 and CH_4 considerably vary from one month to another. The unambiguous information on the concentration gradients, at least, on its clear zonality, is still lacking. We will return to the construction of these charts after the information will have been gathered at the new sites developed in the village of Azovo in the Omsk region and the village of Vaganovo in the Chelyabinsk region, which will allow us to considerably refine the southwest sector of the chart.

CONCLUSION

An analysis of the diurnal behavior of the carbon dioxide concentration showed that over the territory of West Siberia its maximum amplitude is observable in the month of July, while in January the dependence is neutral. The period of CO_2 assimilation by vegetation begins in April and ends in October. The period of the greatest diurnal assimilation falls in May and June. The concentration gradient between the northern and southern regions of the territory is conserved during the entire year.

For a large share of time, the diurnal behavior of the methane concentration remains neutral and only at the end of spring and the beginning of summer a significant dependence appears. Over the territory of West Siberia, there is a northward methane concentration gradient. The mean difference between the southern and northern regions is 100 ppb, though at separate periods of a day it can amount to 340 ppb.

The annual variation of the carbon dioxide concentration is clearly expressed and significant, with a maximum in December, when the vital activity of vegetation is minimal, and a minimum in July and August when it reaches its maximum. The CO_2 concentration begins to decrease in March, the intensity of this process being very high from May to July. From September to December the sinkage rate is smaller than that of emission.

As distinct from carbon dioxide, in the central region of the territory the annual variation of methane has two maxima and two minima. The maxima are observable in July and in December and January, while the minima in April and May and in October. In the northern regions the main maximum is observable during winter and is displaced to February with respect to the central regions. Over the southern regions, the summer maximum is not so intense and is displaced to August. The amplitude of the annual variation of the concentration is greater than 200 ppb in the northern regions and is 100 to 120 ppb in the southern regions. Over the territory of West Siberia there is a northward methane concentration gradient. The mean difference between the southern and northern regions is 100 ppb, but at separate periods of a year it can amount to 240 ppb. The greatest interyear variability is recorded during the main and secondary maxima, amounting to 150 ppb.

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