ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2022, Vol. 58, No. 12, pp. 1610–1618. © Pleiades Publishing, Ltd., 2022.
Russian Text © The Author(s), 2022, published in Issledovanie Zemli iz Kosmosa, 2022, No. 4, pp. 3–11.

USE OF SPACE INFORMATION ABOUT THE EARTH
SPACE MONITORING OF CLIMATE-RELATED CHANGES

Correlation of Ground-Based and Satellite Measurements of Methane Concentration in the Surface Layer of the Atmosphere in the Tiksi Region

N. V. Rodionova*

Kotelnikov Institute of Radio Engineering and Electronics (Fryazino Branch), Russian Academy of Sciences,
Fryazino, Moscow oblast, 141190 Russia
**e-mail: rnv1948123@yandex.ru*

Received January 25, 2022

Abstract—In this work, the correlation of AIRS/Aqua satellite measurements of methane concentration in the surface layer of the atmosphere with ground-based measurements at the Voeikov Main Geophysical Observatory in Tiksi in 2011–2020 is determined. The correlation of satellite measurements with ground measurements depends on the season. In spring and summer, the correlation exceeds the autumn correlation, and it is lowest in winter. For the winter period (December, January, and February), the decrease in correlation is associated with possible inversions of air temperature (Yurganov et al., 2016; Anisimov and Kokorev, 2015). When the temperature contrast (TC) is less than 10°C (the difference between air temperatures at the surface and at a level of 4 km (600 hPa)), it is preferable to use satellite data averaged at the levels of 400–500 hPa. This gives an increase in the Spearman correlation coefficient (SCC) between ground and satellite measurements from 0.44 (1000 hPa) to 0.63 (400–500 hPa). However, the obtained regression relationship with a determination coefficient of 0.44 makes it problematic to use it for predicting ground-based data from satellite measurements in areas similar in climatic conditions to Tiksi.

Keywords: remote sensing, ground measurements, satellite measurements, methane concentration in the atmosphere, Spearman correlation coefficient

DOI: 10.1134/S0001433822120209

INTRODUCTION

Methane (CH_4) is one of the greenhouse gases. In comparison with other greenhouse gases, the content of methane in the atmosphere is lower; however, in the degree of greenhouse activity, methane exceeds carbon dioxide more than by 20 times (IPCC, 1995). There are natural (swamps and moist soil, freshwater bodies, wild animals, wildland fires, termites, geological sources, methane hydrates, and permafrost thaw) and anthropogenic (agriculture, hydrocarbon fuels, and biomass incineration) sources of methane. Along with the atmosphere, the soil contains methane in the form of a natural gas. Another source of methane in the Earth is gas hydrates, which can exist under conditions of high pressure (in the sea) or very cold climates (on land in permafrost regions). Gas hydrates on land can be decomposed with a release of CH_4 with climate warming; in the sea, it can be released as the sea level decreases (Eliseev, 2018). In the Arctic zone, the increase in air temperature is one-and-a-half to two times faster than the average over the Earth. This stimulates the activity of many natural methane sources, exerts an effect on the permafrost, and releases methane and other small gas components in huge quantities (Starodubtsev, 2018).

The most important sink of methane in the atmosphere, almost 90% of the full sink intensity, is methane decomposition in the reaction with the hydroxyl radical OH with the formation of carbon dioxide and water vapors (Cicerone and Oremland, 1988). In the winter months, with the termination of methane-sink processes, methane begins to accumulate in the atmosphere; in summer, processes of methane sink are triggered (Belan and Krekov, 2012).

There are few ground-based measurements of methane near the surface. In the Arctic, regular measurements of methane in Russia are carried out at two sites: Tiksi and Teriberka. Data of these observations are collected and systematized by the NOAA research group; the results are presented on the web portal http://www.esrl.noaa.gov/gmd/ccgg/. Data of remote sensing by the AIRS (Atmospheric Infrared Sounder) spectrometer onboard the American Aqua satellite are used in this work as satellite data.

This work is aimed at determining the correlation between ground-based measurements of methane

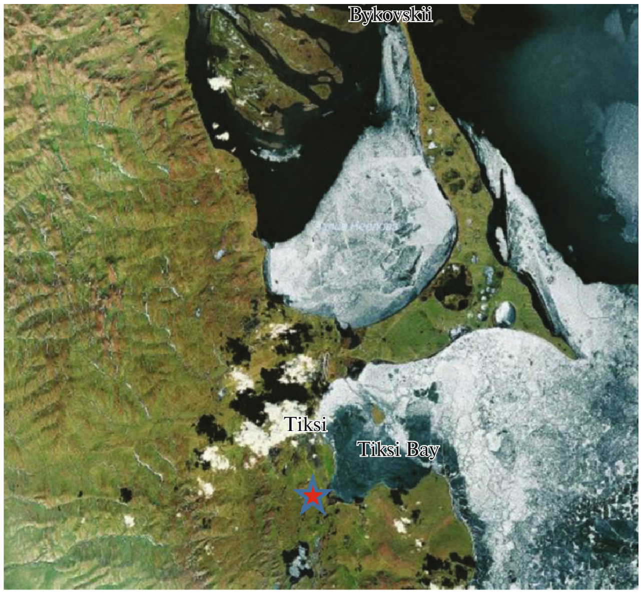

Fig. 1. Satellite image of the geographical area of the Tiksi settlement.

concentration in the surface layer of the atmosphere at the Tiksi station located in the Arctic zone and satellite measurements by the AIRS infrared spectrometer onboard the EOS Aqua satellite.

GROUND-BASED MEASUREMENTS

The Tiksi background monitoring station is located on the coast of the Laptev Sea; the coordinates of the station are 71.586166° N, 128.91882° E (Fig. 1, the red star). Works on observation of methane at the Tiksi station have been carried out since 2011. Samples of CH_4 at the station are taken all year round once a week by evacuated flasks. Concentrations of gaseous components at the Tiksi station are measured using a Picarro G2301 gas analyzer.

The data on ground-based measurements of methane concentration in the surface layer of the atmosphere for the out-station in Tiksi are available for free access at the World Data Centre for Greenhouse Gases (WDCGG) website https://gaw.kishou.go.jp/. In this work, measurements of methane concentration in the surface layer of the atmosphere at the out-station of the Voeikov Main Geophysical Observatory (MGO) in Tiksi are used (Ivakhov and Paramonova, 2021).

Figure 2a shows the plots of variations in the monthly average methane concentration according to ground-based measurements at the Tiksi out-station of the MGO for 2011–2020. Note the minimum of methane concentration in July (with the exception of 2020) and the maximum in September–October. Figure 2b presents the plot of interannual variations in the CH_4 concentration according to ground-based measurement at the Tiksi station with a stable rise and a trend line with a coefficient of determination $R^2 = 0.97$. Unfortunately, data for 2016 were insufficient (the data are available only for the first three months); for 2017, data for January and February were absent. As a result, measurements for these years were not included in the plot of interannual variations.

In winter, methane accumulation in the atmosphere takes place, whereas in summer, there is a methane sink; i.e., there is an inverse correlation with air temperature. Figure 3 presents the plot of variations in methane concentration according to regular (once per week) ground-based measurements at the Tiksi station for 2013 and the plot of air temperature by

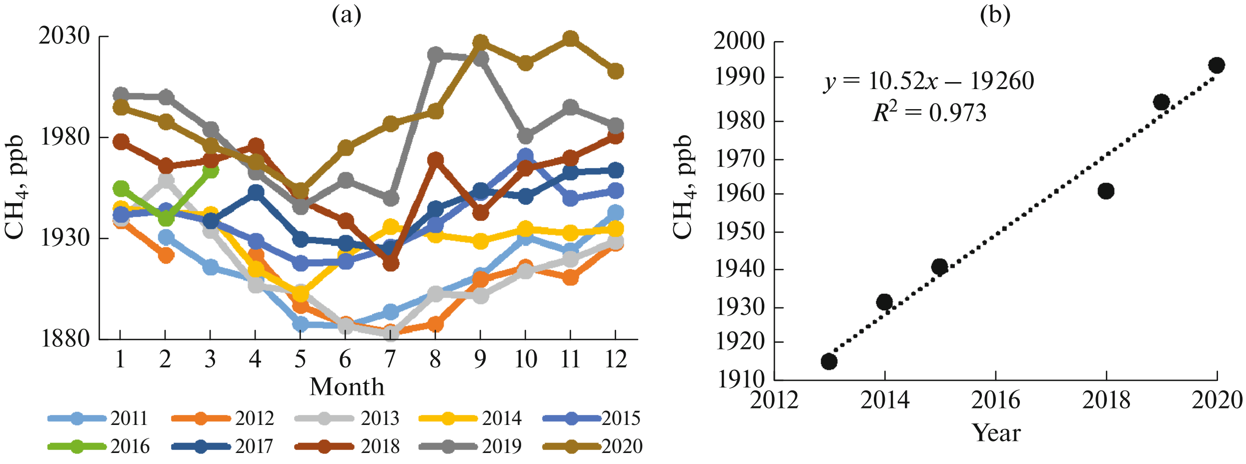

Fig. 2. Seasonal and interannual variations of methane concentration in the surface layer of the atmosphere according to ground-based measurements at the Tiksi MGO background monitoring station.

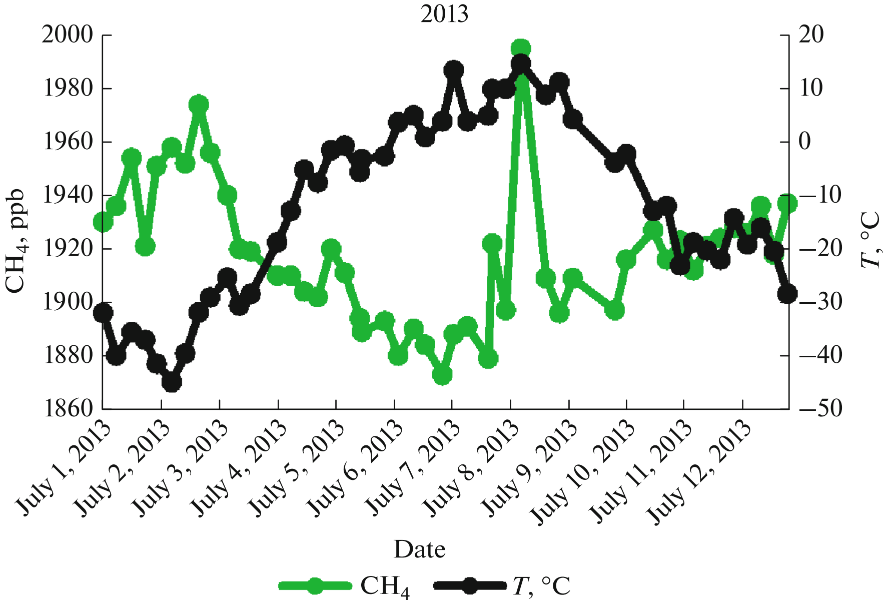

Fig. 3. Plots of variations in methane concentration according to regular ground-based measurements at the station in Tiksi for 2013 and values of air temperature.

archive data for the Tiksi airport (website rp5.ru) at the time of taking methane samples. The negative correlation of these data is evident. Table 1 presents values of the Spearman coefficient of correlation between air temperature and ground-based measurements of methane concentration in the surface layer of the atmosphere at the out-station in Tiksi for the period of 2011–2018, where ρ_s is the Spearman correlation coefficient, p is the value, and N is the number of measurements.

SATELLITE MEASUREMENTS OF METHANE CONCENTRATION

Spectra of infrared (thermal) radiation emitted by the Earth's surface have been measured since 2002 on the American Aqua satellite using the AIRS spectrometer. The methane content in the troposphere is estimated by radiation attenuation in the spectral ranges corresponding to the maximums of the absorption bands of this gas. The data on the methane content in the atmosphere are available for free access in the Giovanni system of data analysis and visualization; they are available through the link https://giovanni.gsfc.nasa.gov.

Table 1. Coefficient of the Spearman correlation between ground-based measurements of methane concentration in the surface layer of the atmosphere and air temperature

	2011	2012	2013	2014	2015	2017	2018
ρ_s	–0.52	–0.66	–0.69	–0.2	–0.21	–0.32	–0.26
P	1.5e-4	2e-6	0	0.07	0.06	0.02	0.04
N	44	39	47	51	51	37	46

Figure 4 presents the plots of (a) seasonal and (b) interannual variations in methane concentration in the surface atmosphere in the Tiksi region according to monthly average AIRS data. Averaging over the territory of 71°.5833–71°.6382 N, 128°.86–128°.9355 E (AIRS3STM v.7.0 product), barometric height of 1000 hPa, spatial resolution of 1° × 1°, for the period of 2011–2018. The figure also presents (Fig. 4b) standard deviations from average values according to daily AIRS data. Note that the rise of CH$_4$ values in autumn is accompanied by an increase in the standard deviation, especially noticeable for 2021. A significant difference between the seasonal variations in methane concentrations according to ground-based measurements (Fig. 2a) and satellite measurements (Fig. 4a) is the considerable decrease in methane concentrations in winter according to satellite data. A possible cause is discussed below.

Figure 5 shows monthly average maps of the methane distribution for the region of 71°–72° N, 128°–131° E, which includes Tiksi, according to AIRS data for 2021 (the green star in the map marks the location of Tiksi).

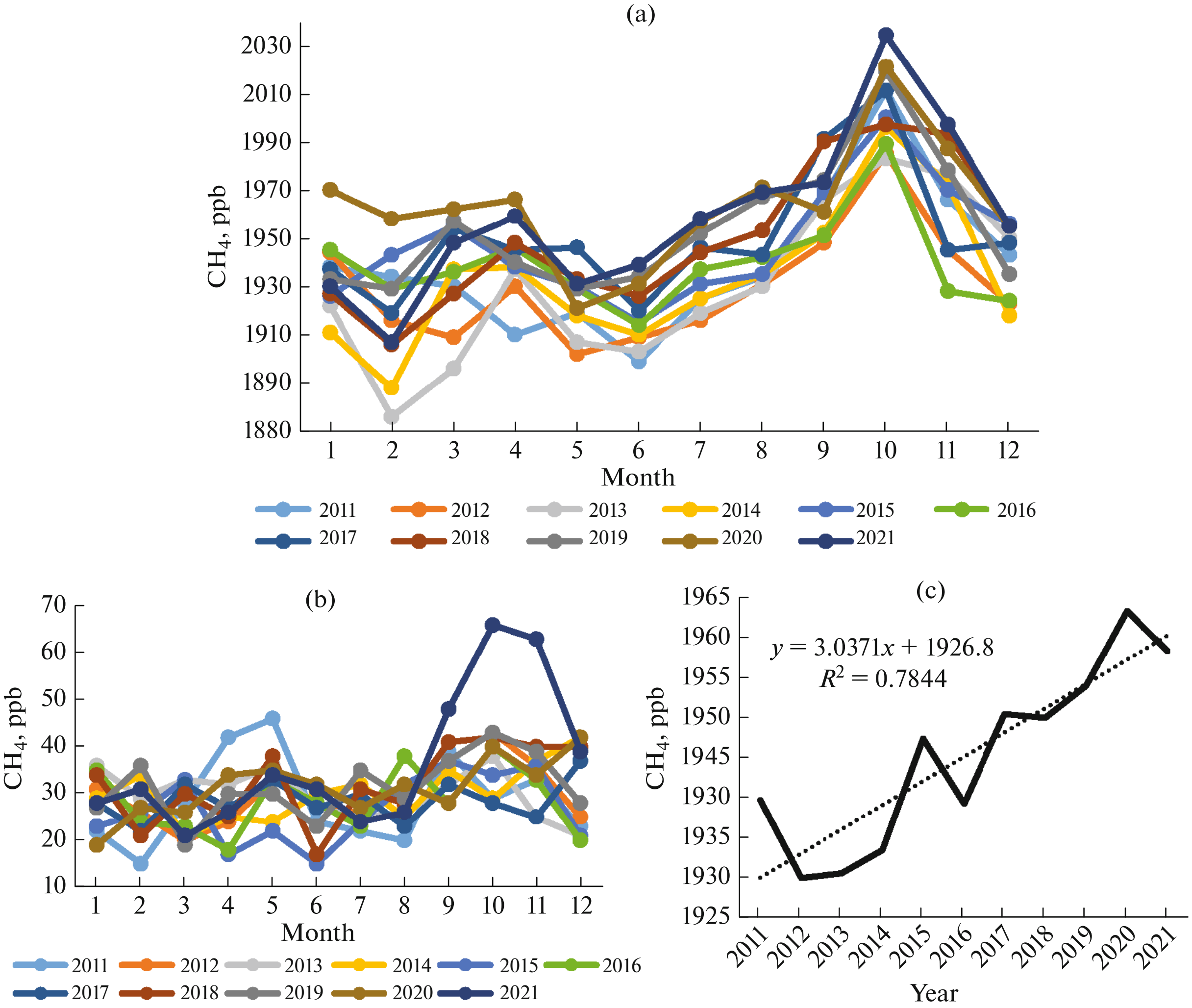

Fig. 4. (a) Seasonal variations, (b) standard deviations, and (c) interannual variations in methane concentration in the atmosphere at a level of 1000 hPa in the Tiksi region according to AIRS data.

CORRELATION BETWEEN SATELLITE AND GROUND-BASED MEASUREMENTS OF METHANE CONCENTRATION IN THE SURFACE ATMOSPHERE

Let us determine the correlation between the ground-based measurements of methane concentration in the surface layer of the atmosphere at the outstation in Tiksi and the satellite daily measurements by the AIRS (AIRS3STD v7.0 product), at the level of 1000 hPa, and with a spatial resolution of 1° in latitude and longitude. The correlation is determined by the freely available Attestat software used as an add-in in Excel. Table 2 presents values of the Spearman coefficient of correlation (SCC) between the values of methane concentration according to ground-based and satellite data. Note the presence of a positive correlation for 2011, 2012, 2015, and 2018, and the absence of correlation for 2013, 2014, and 2017. For 2014 (the absence of correlation) and 2015 (positive correlation), Fig. 6 shows plots of variations in CH_4 concentration for ground-based and satellite data.

The AIRS devices which use the outgoing radiation of the Earth in the middle IR region of about 7.8 μm are less sensitive to the lower troposphere. For a reliable determination of the concentration of atmospheric gases below 5 km, a sufficiently large positive

Table 2. Coefficient of the Spearman correlation between ground-based and satellite values of methane concentration in the surface layer of the atmosphere

	2011	2012	2013	2014	2015	2017	2018
ρ_s	0.48	0.33	–0.19	–0.03	0.42	0.12	0.27
P	2e-3	0.03	0.13	0.43	2e-3	0.25	0.05
N	33	33	36	47	43	32	37

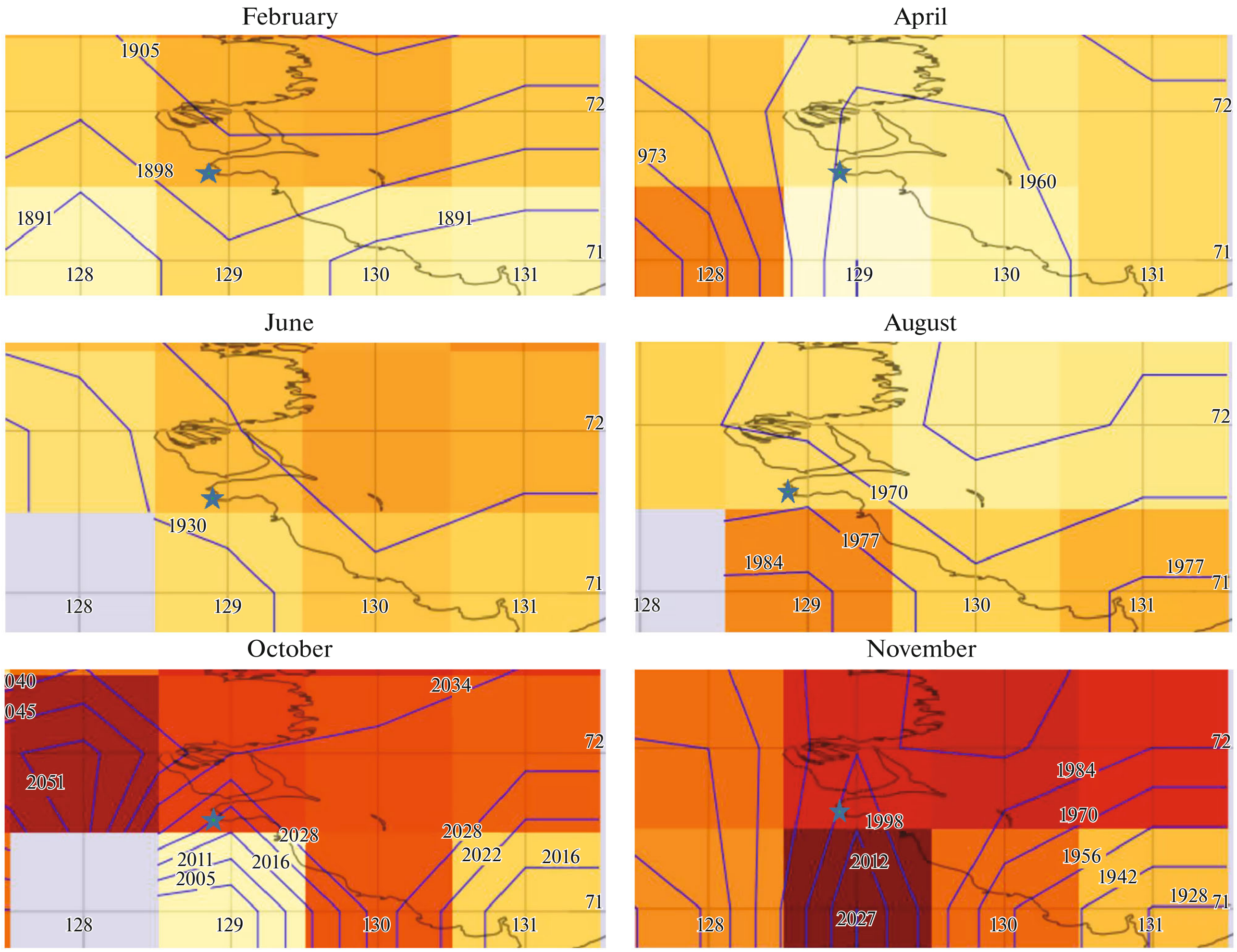

Fig. 5. Monthly average maps of the methane distribution according to AIRS data for 2021.

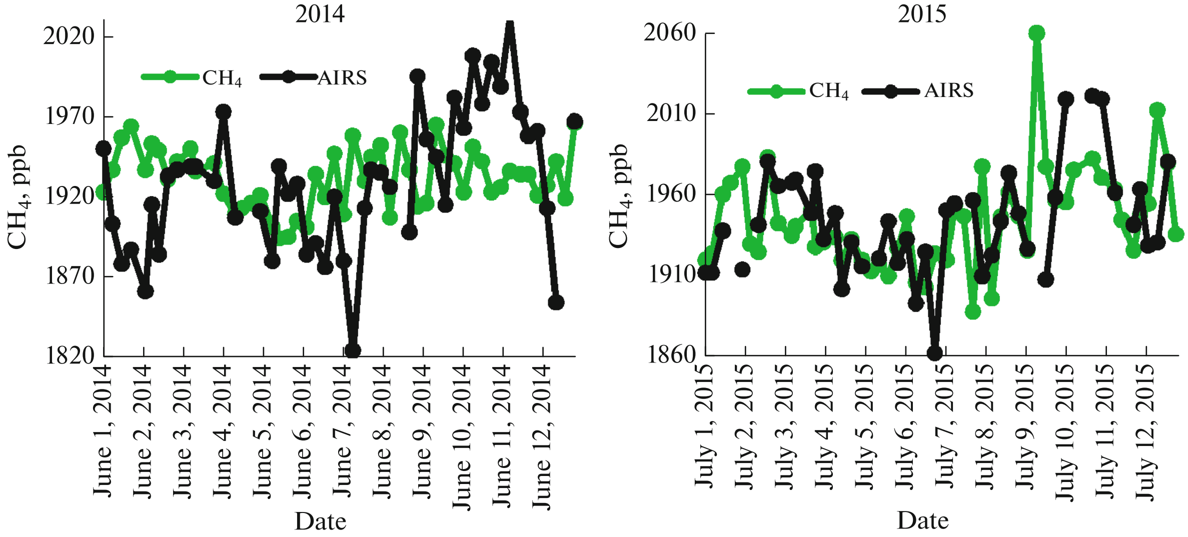

Fig. 6. Variations in CH_4 concentration in the surface atmosphere according to ground-based and satellite measurements for Tiksi in 2014 and 2015.

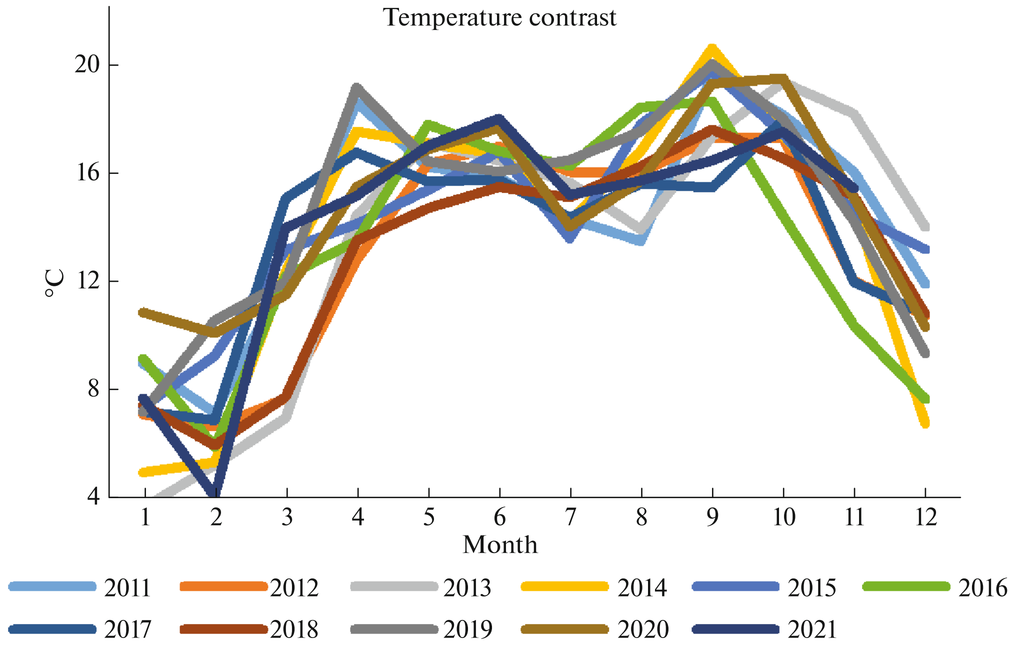

Fig. 7. Plots of the temperature contrast for Tiksi for the period of 2011–2021.

temperature contrast (TC) between the temperatures of the underlying surface and the boundary layer, on the one hand, and the temperatures of the upper-lying air layers, on the other hand, is necessary (Yurganov et al., 2016). It is conceivable that, for TC < 10°C, the methane concentration measured from a satellite is lower (Yurganov et al., 2016). The main cause of the decrease in the satellite values of methane concentration in winter is that the satellite does not see the surface and determines the methane concentration not near the surface, but in higher layers (Yurganov et al., 2016). This occurs if the difference between the temperatures at the surface (the level of 1000 hPa) and at a height of about 4 km (600 hPa) is less than 10°C, i.e., if the temperature contrast (TC) is less than 10°C. Figure 7 shows the TC value for Tiksi for the period of 2011–2021. The temperature values for different layers of the atmosphere were obtained by monthly data of the AIRS satellite with a spatial resolution of 1° × 1° (AIRS3STM v7.0 product). For January and February, the TC values are less than 10°C for almost all years.

Based on the fact that the largest deviations of the satellite values from ground ones due to the temperature inversion in the atmosphere occur in winter months, we find the correlation of ground and satellite data (1000 hPa) for four seasons: winter, the 1st, 2nd, and 12th months; spring, the 3rd, 4th, and 5th months; summer, the 6th, 7th, and 8th months; and autumn, the 9th, 10th, and 11th months. Figure 8 presents the plots of methane concentration in the surface layer of the atmosphere (1000 hPa) according to the ground and satellite data by season: winter, spring, summer, and autumn. Note that the satellite values for the winter season are underestimated relative to the ground values. In spring and summer, the ground and satellite values of methane concentration are almost at the same level. For autumn, the satellite values exceed the ground ones, with the exception of 2019 and 2020.

As was stated above, the problem with the choice of barometric levels for estimating methane concentrations in the near-surface layer of the atmosphere by satellite data is that the satellite does not see the atmosphere layers adjacent to the surface due to the presence of warmer layers above. For example, in (Anisimov and Kokorev, 2015), the authors used for the analysis satellite data averaged over the third and fourth barometric AIRS levels (850–700 hPa), which corresponds approximately to heights from 1.5 to 3 km. In (Starodubtsev, 2018), the barometric level of 400 hPa was used; this choice was caused by the recommendations presented in (Xiong et al., 2008), where the level of 400–500 hPa (~6–5 km) was proposed as the most effective one for estimating the methane concentration in the Arctic zone.

In order to clarify which barometric level is better for measuring the methane concentration, we found the correlation between the ground and satellite data for three barometric levels: level 1, 1000 hPa; level 2 is averaged over 700 and 850 hPa; and level 3 is averaged over 400 and 500 hPa. Table 3 presents the obtained value of the SCC for four seasons of 2011–2020. For the winter season, the values of the SCC are lowest as

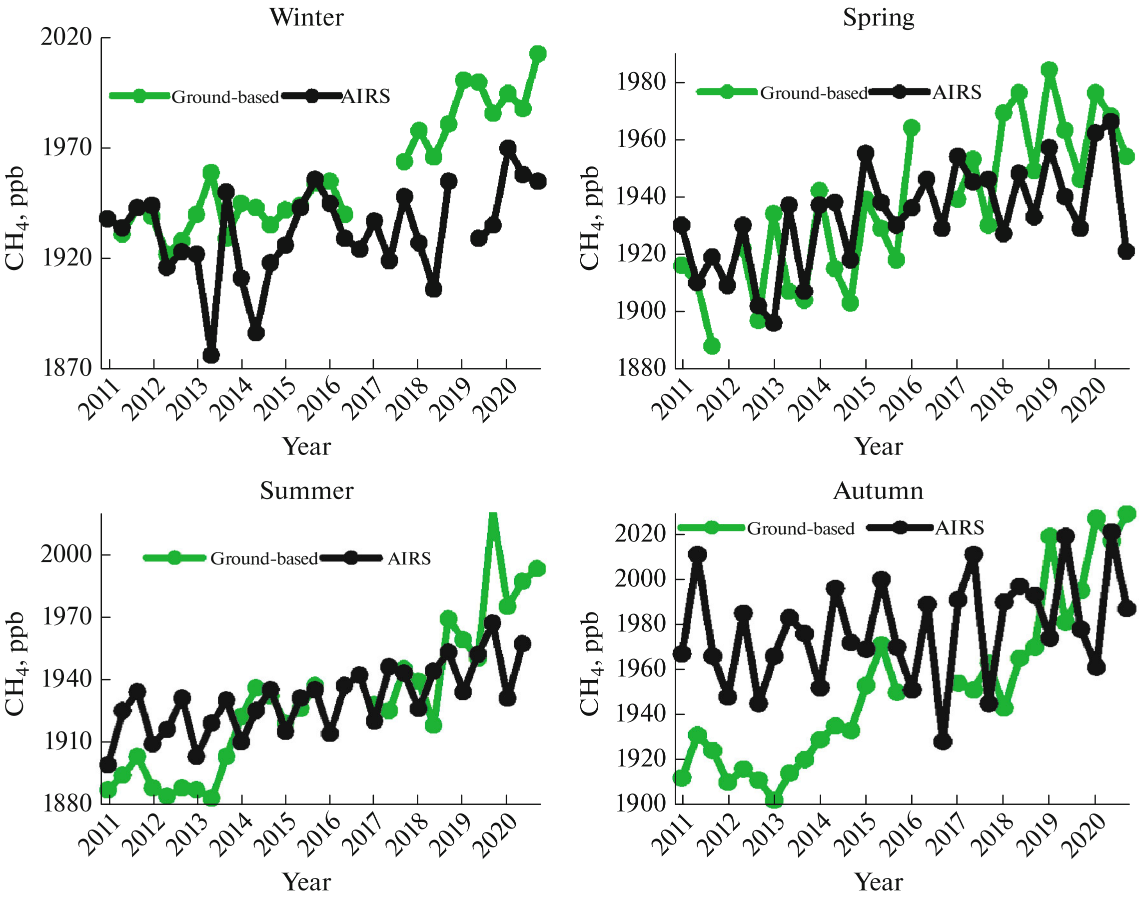

Fig. 8. Variations in CH_4 concentration in the surface layer of the atmosphere in the Tiksi region according to ground-based and satellite AIRS data at the barometric level of 1000 hPa for four seasons of 2011–2020.

Table 3. Correlation of ground-based and satellite measurements of methane concentration in the atmosphere in the Tiksi region at different barometric levels of AIRS measurements

	1000 hPa			
	Winter	Spring	Summer	Autumn
ρ_s	0.38	0.59	0.71	0.42
p	0.03	5e-4	2e-5	0.015
N	26	27	26	27
	700–850 hPa			
ρ_s	0.43	0.76	0.66	0.53
p	0.02	3e-6	2e-5	3e-3
N	26	26	27	26
	400–500 hPa			
ρ_s	0.49	0.74	0.62	0.74
p	5e-3	2e-5	2e-5	4e-6
N	26	24	26	27

compared to the other seasons: $\rho_s = 0.38$ (1000 hPa), 0.43 (700–850 hPa), and 0.49 (400–500 hPa). For the spring season, the SCC varies from 0.59 (1000 hPa) and 0.74 (400–500) to 0.76 (700–850 hPa). Here, the barometric level of 700–850 hPa is predominant for measurements. For the summer season, the SCC is the largest for measurements at the level of 1000 hPa and amounts to 0.71. For the autumn period, it is preferable to measure methane concentration at the barometric level of 400–500 hPa, for which the SCC is 0.74 as compared to 0.42 for the level of 1000 hPa. The conclusion over all four seasons is as follows: there is a significant advantage in the correlation between the values of ground-based and satellite measurements when the latter are measured at the barometric levels of 700–850 or 400–500 hPa instead of the barometric level of 1000 hPa.

Determination of the SCC between ground data and satellite measurements at different barometric heights for the sample of measurements for four seasons from 2011 to 2020 ($N \sim 105$) shows that the SCC for the level of 1000 hPa is $\rho_s = 0.44$ ($p = 1e{-}7$); for the level of 700–850 hPa, $\rho_s = 0.557$ ($p = 0$); and for the

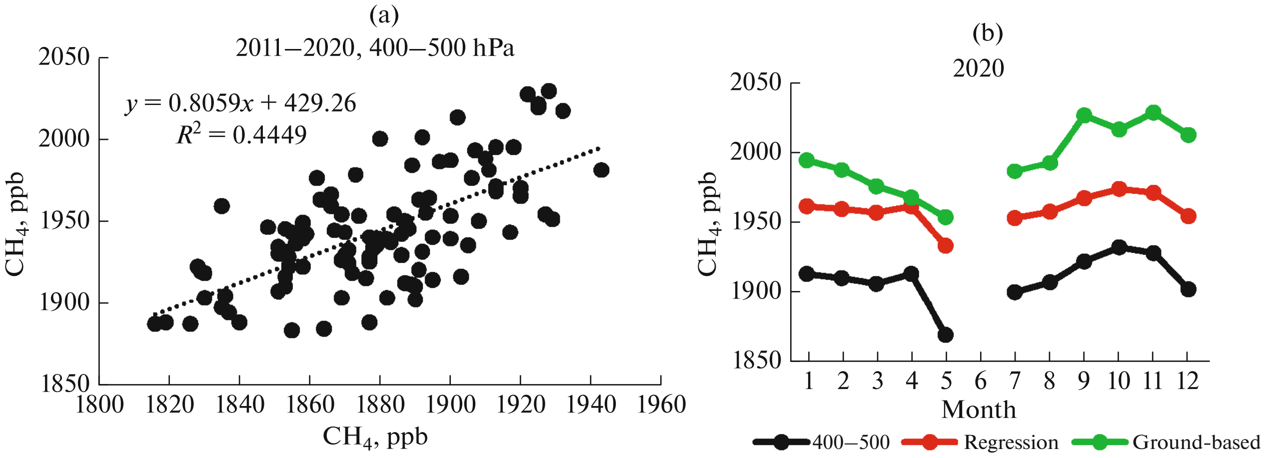

Fig. 9. Regression relationship between ground-based and satellite measurements at the barometric level of 400–500 hPa for Tiksi.

level of 400–500 hPa, $\rho_s = 0.63$ ($p = 0$). The advantage of using the barometric level of 400–500 hPa for satellite measurements was ascertained due to the higher correlation between ground-based and satellite measurements.

Figure 9a presents the plot of the regression relationship between the ground data at the Tiksi station and the satellite AIRS measurements of methane concentration at the barometric level of 400–500 hPa for 2011–2020 with the determination coefficient $R^2 = 0.44$. Comparison of the methane concentrations according to the obtained regression with ground data at the Tiksi station for 2020 revealed the residual values of 6–59 ppb (Fig. 9b); the values are lowest in the spring season.

It should be noted that the regression model was obtained for Tiksi and has a local application area bounded by territories with climatic conditions similar to Tiksi.

The correlation between the ground and satellite data is also influenced by the fact that the ground-based measurements are carried out locally in a small territory, while the spatial resolution of the AIRS/Aqua satellite measurements is 1° × 1°. In addition, Tiksi is situated on the coast of the Laptev Sea and the satellite at this spatial resolution sees not only the continental part, but also captures the sea surface, which also has an effect on the correlation between the ground and satellite data.

CONCLUSIONS

In this work, the correlation between AIRS/Aqua satellite measurements of methane concentration in the surface layer of the atmosphere and ground-based measurements at the out-station of the Voeikov MGO in Tiksi in 2011–2020 has been determined. A negative correlation between the ground data of methane concentration in the surface atmosphere and air temperature has been revealed; this is related to periods of methane emission and sink in the atmosphere. The correlation between the satellite AIRS measurements of methane concentration and ground-based ones varies depending on the season. In spring and summer, the correlation exceeds the autumn and especially the winter correlation. For the winter period (December, January, and February), the decrease in correlation is related to possible inversions of air temperature (Yurganov et al., 2016). If the temperature contrast TC is less than 10°C, it is recommended to compare satellite and ground data by considering satellite values not at the level of 1000 hPa, but at averaged value at the levels of 400–500 hPa. The determination of the SCC between ground data and satellite measurements at different barometric levels for the sample of measurements for four seasons from 2011 to 2020 ($N \sim 105$) shows that the SCC for the level of 1000 hPa is $\rho_s = 0.44$; for the level of 700–850 hPa, $\rho_s = 0.557$; and for the level of 400–500 hPa, $\rho_s = 0.63$. The determination coefficient of the regression relationship for the level of 400–500 hPa is $R^2 = 0.44$. Using the obtained regression for predicting is problematic. The residual value is 6–59 ppb when comparing ground methane concentrations expected according to the regression with the use of satellite measurements at the barometric levels of 400–500 hPa with those measured at the Tiksi station. The values of the residual are lowest for the spring season.

FUNDING

This work was carried out within the framework of the state contract for the Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, on the theme 0030-2019-0008 "Space."

REFERENCES

Anisimov, O.A. and Kokorev, V.A., Comparative analysis of land, marine, and satellite observations of methane in the lower atmosphere in the Russian Arctic under conditions of climate change, *Izv., Atmos. Ocean. Phys.*, 2015, vol. 51, no. 9, pp. 979–991.

Belan, B.D. and Krekov, G.M., The effect of anthropogenic factor on the content of greenhouse gases in the troposphere. 1. Methane, *Opt. Atmos. Okeana*, 2012, vol. 25, no. 4, pp. 361–373.

Cicerone, R.J. and Oremland, R.S., Biogeochemical aspects of atmospheric methane, *Global Biogeochem. Cycles*, 1988, vol. 2, no. 4, pp. 299–327.

Eliseev, A.V., Global methane cycle: A review, *Fundam. Prikl. Klimatol.*, 2018, vol. 1, pp. 52–70.

IPCC, Intergovernmental Panel on Climate Change, Second Assessment Report: Climate Change, Cambridge University Press, 1995, pp. 21–23.

Ivakhov, V. and Paramonova, N., Atmospheric CH_4 at Teriberka by Voeikov Main Geophysical Observatory, Dataset CH4_TER_surface-flask_MGO_-data1 at WDCGG, ver. 2021-10-17-2320. Accessed May 1, 2022. https://doi.org/10.50849/WDCGG_0046-6003-1002-01-02-9999

Starodubtsev, V.S., Investigation of variations in the concentration of methane and carbon dioxide in the Arctic zone, *Vestn. SVFU*, 2018, no. 3, pp. 80–88.

Xiong, X., Barnet, C., Maddy, E., Sweeney, C., Liu, X., Zhou, L., and Goldberg, M., Characterization and validation of methane products from the atmospheric infrared sounder (AIRS), *J. Geophys. Res.*, 2008, vol. 113.

Yurganov, L.N., Leifer, A., and Lund Mair, K., Seasonal and interannual variability of atmospheric methane over the seas of the arctic ocean according to satellite data, *Sovrem. Probl. Distantsionnogo Zondirovaniya Zemli Kosmosa*, 2016, vol. 13, no. 2, pp. 107–119.

Translated by A. Nikol'skii