

O.O. Kavats, D.A. Khramov, K.L. Sergieieva, V.V. Vasyliiev

OPEN ACCESS SATELLITE DATA FOR GLOBAL GREENHOUSE GAS MONITORING

Abstract. Open satellite concentration data for the main greenhouse gases (CO_2 , CH_4 , N_2O) are considered in terms of their possible use for local, regional, and global monitoring. The main data characteristics are provided. The satellite products most suitable for global monitoring of greenhouse gas concentrations are specified. The disadvantages of existing satellite data are analyzed.

Keywords: greenhouse gas, CO_2 , CH_4 , N_2O , concentration, satellite monitoring, TROPOMI, GOSAT, OCO-2.

Problem statement. Global warming or the enhanced greenhouse effect is the planet warming due to increased concentrations of greenhouse gases because of human activities [1]. The environmental, economic, and social consequences of global warming may affect all humankind in the future, and some of them (retreat of glaciers, earlier flowering of plants, changes in agricultural productivity) are already observed. Control over this phenomenon is possible only with comprehensive monitoring of greenhouse gas emissions at the local, regional, and global levels. An important role in enforcing such controls is played by satellite instruments for measuring the greenhouse gases concentration.

The main greenhouse gases with increasing concentrations are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons, hydrofluorocarbons, and ozone (O_3) in the lower atmosphere. In the Paris Agreement under the United Nations Framework Convention on Climate Change, three gases as critical drivers of climate change are listed: CO_2 , CH_4 , and N_2O [2]. Let's consider satellite products containing data on these major greenhouse gases concentration.

The **objective** of the research is to describe the capabilities of satellite instruments for solving the problems of greenhouse gases concentration monitoring at the local, regional, and global levels. For this, operational satellite instruments providing open and free data, are considered. Information on greenhouse gases

concentration for earlier periods, including from no longer operational satellites, can be found in [3, 4]. For each instrument, the data main characteristics and the data accessing method are specified. In addition, multicomponent data are considered, combining the results of satellite and in-situ measurements.

Operational **satellite instruments** for measuring the greenhouse gases concentration, with publicly available data, are given in Table 1. Data application level: spot, national, and global. At a spot level, satellite data allows monitoring of a specific greenhouse gas emissions source, such as a thermal power station. National and global levels — emission monitoring at the country (region) and global levels. Detailed information about satellites and instruments can be obtained from online databases CEOS Database (<http://database.eohandbook.com>) and WMO OSCAR (<https://space.oscar.wmo.int/satellites>).

Table 1

Satellite instruments for measuring greenhouse gas concentration

Satellite	Instrument	Greenhouse Gas	Level
SciSat-1*	ACE	CO ₂ , CH ₄ , N ₂ O	global
Sentinel-5P	TROPOMI	CH ₄	spot, national, global
Metop-A/B/C	IASI	CO ₂ , CH ₄ , N ₂ O	national, global
GOSAT	TANSO-FTS	CO ₂ , CH ₄	national, global
GOSAT-2	TANSO-FTS-2	CO ₂ , CH ₄	national, global
Aqua	AIRS	CH ₄	national, global
Suomi NPP/JPSS	CrIS	CH ₄	national, global
OCO-2	OCO-2	CO ₂	spot, national, global
OCO-3-on-ISS	OCO-3	CO ₂	spot, national, global

* SciSat-1 data are publicly available till August 2020 [5, 6]. Only the ACE project scientific team can get access to up-to-date data.

Satellite data. Open data characteristics of operating satellites for measuring greenhouse gas concentrations are presented in Table. 2.

Table 2

Open satellite data characteristics

Satellite, Instrument	Temporal Resolution	Available since	Spatial Resolution, km	File Format
Sentinel-5P, TROPOMI	daily	May 2018	5.5×7	netCDF-4
Metop-A/B/C, IASI	14-15 images per day per one satellite	May 2009	12	Native, netCDF-4
GOSAT, TANSO-FTS	daily, monthly	April 2009	10.5	HDF, TAR
GOSAT-2, TANSO-FTS-2	daily	March 2009	9.7	HDF
Aqua, AIRS	daily, monthly	September 2002	1° (about 111 km)	HDF
Suomi NPP/JPSS, CrIS	daily	April 2021	14	netCDF
OCO-2, OCO-2	16 days	September 2014	2.25×1.29	netCDF
OCO-3-on-ISS, OCO-3	16 days	August 2019	2.25×1.29	netCDF

Sentinel-5P TROPOMI. Among the main greenhouse gases, TROPOMI measures the concentration of methane (Sentinel-5 Precursor Level 2 Methane (L2_CH4_) <https://s5phub.copernicus.eu/dhus/#/home>).

Methane concentration data are disseminated as OFFL (offline) products. The time delay is 5 days after a sensing date.

The methane concentration map on January 17, 2022, is represented in Fig.1. HDF/netCDF files were visualized with Panoply (<https://www.giss.nasa.gov/tools/panoply/>).

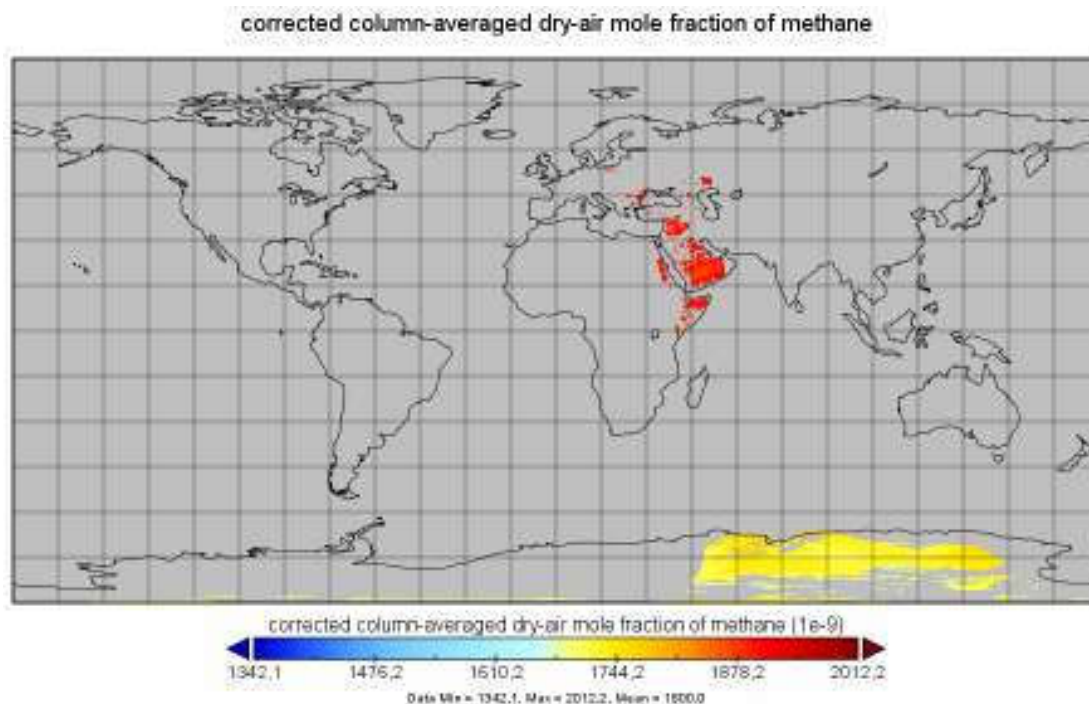


Figure 1 — Concentration of CH₄ retrieved from image

S5P_OFFL_L2_CH4__20220117T091456_20220117T105626_22090_02_020301_20220119T012159

Methane concentration (ppb):

CH4___/PRODUCT/methane_mixing_ratio_bias_-corrected.

Concentration measurement accuracy assessment (standard error):

CH4___/PRODUCT/methane_mixing_ratio_precision. It is recommended to multiply all values by 2 [7].

Data quality: CH4___/PRODUCT/qa_value. It is recommended to use qa_value > 0.5 [7].

Here and below, the corrected values of the gas concentration are used. TROPOMI data bias was corrected based on comparison with in-situ observations [8]. GOSAT/GOSAT-2 CO₂ and CH₄, as well as OCO-2/OCO-3 CO₂ data, were corrected in the same way.

Google Earth Engine converts Sentinel-5P Level-2 to Level-3 products (Sentinel-5P OFFL CH4 [9]), converting netCDF files to the lat-lon fixed grid using the HARP toolset (<https://github.com/stcorp/harp>).

According to de Gouw et al. [10], TROPOMI data can be used to monitor methane emissions caused by oil and natural gas production.

Metop IASI (<https://iasi.aeris-data.fr/catalog/>). IASI Trace Gases product contains atmospheric N₂O, CH₄, and CO₂ column concentrations combining measurements from Metop-A/B/C satellites (Metop-A was decommissioned on October 15, 50

2021). Gas concentrations are evaluated using artificial neural networks trained on synthesized RTTOV model data and a set of trace gas profiles from the MOZART model. The data are provided in demo mode [11].

The total content of greenhouse gases in the atmospheric column (kg/m^2):

- `integrated_ch4`;
- `integrated_co2`;
- `integrated_n2o`.

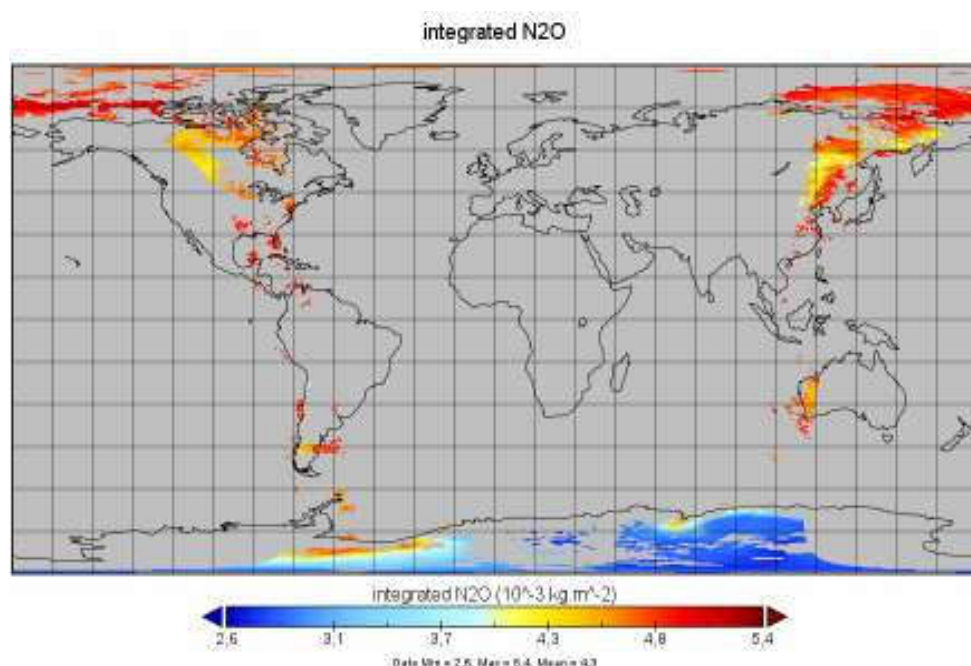


Figure 2 — Concentration of N_2O retrieved from Metop IASI Trace Gases (January 19, 2022, 18:17:55 UTC)

GOSAT TANSO-FTS measures carbon dioxide and methane concentration. Data are provided in HDF format at the end of the month. In L2 products, one month's daily data are archived in TAR (https://data2.gosat.nies.go.jp/index_en.html)

GOSAT Level-2 daily products:

- L2 CO_2 column amount (SWIR)
- L2 CH_4 column amount (SWIR)

Level 2 data:

CO_2 concentration (ppmv): `Data/mixingRatio/XCO2BiasCorrected` (CH_4 : `CH4BiasCorrected`);

Standard error: `Data/mixingRatio/XCO2StandardError` (CH_4 : `XCP4StandardError`).

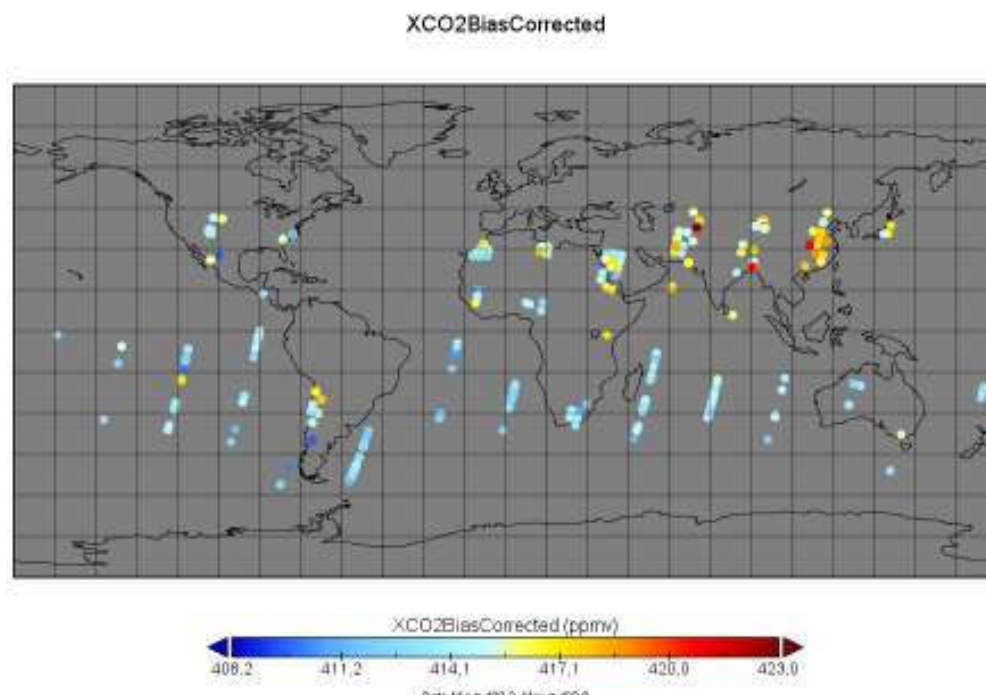


Figure 3 — Atmospheric CO₂ column concentrations on December 1, 2021
(GOSATTFTS20211201_02C01SV0298R211201GU000.h5)

Level-3 monthly products are suitable for global monitoring:

- L3 global CO₂ distribution (SWIR);
- L3 global CH₄ distribution (SWIR).

(the structure is similar to Level-2 products).

GOSAT-2 TANSO-FTS-2 is an improved version of GOSAT Fourier Transform Spectrometer: five bands instead of four (two TIR bands), bands (except TIR) are split in two polarization components (P and S), band 3 has been extended to observe carbon monoxide [12].

Data on carbon dioxide and methane concentration are provided in daily product GOSAT-2 TANSO-FTS-2 SWIR L2 Column-averaged Dry-air Mole Fraction Product in HDF. File description: NIES GOSAT-2 Product File Format Descriptions (<https://prdct.gosat-2.nies.go.jp/index.html>).

Gas concentration (ppm):

- RetrievalResult/xco2
- RetrievalResult/xch4

Standard error: RetrievalResult/*_uncert

Quality flags: RetrievalResult/*_quality flag (values: 0 – Good, 1 – Fair, 2 – Poor, 3 – NotGenerated).

GOSAT-2 does not provide monthly products like GOSAT L3.

AIRS Aqua. Atmospheric Infrared Sounder (AIRS) on Aqua satellite currently measures methane concentrations in the middle and upper troposphere, at altitudes of 5–15 km (measurement of carbon dioxide concentration was stopped due to the failure of some instruments). These measurements are much less dependent on cloud cover since they are performed above the lower cloud layer.

Aqua/AIRS L2 Near Real Time (NRT) Standard Physical Retrieval (AIRS-only) V7.0 (AIRS2RET_NRT) can be used for operational monitoring.

Level-3 data are generated from Level-2 products with quality indicators: best (0) or good (1):

- Aqua/AIRS L3 Daily Standard Physical Retrieval (AIRS-only)
1° × 1° V7.0 (AIRS3STD)
- Aqua/AIRS L3 Monthly Standard Physical Retrieval (AIRS-only)
1° × 1° V7.0 (AIRS3STM)

AIRS-only means that the measurements are performed only by the AIRS instrument.

AIRS L3 products include ascending и descending indicators corresponding to observations on the day and night sides of the orbit. Ascending has a suffix "_A", descending — "_D". There are also ascending_TqJoint and descending_TqJoint data with improved quality control.

Ascending data fields (similarly for descending):

- Concentration (ppm · 10⁻⁶):
ascending_TqJoint/Data_Fields/CH4_VMR_TqJ_A
- Standard error:
ascending_TqJoint/Data_Fields/CH4_VMR_TqJ_A_sdev

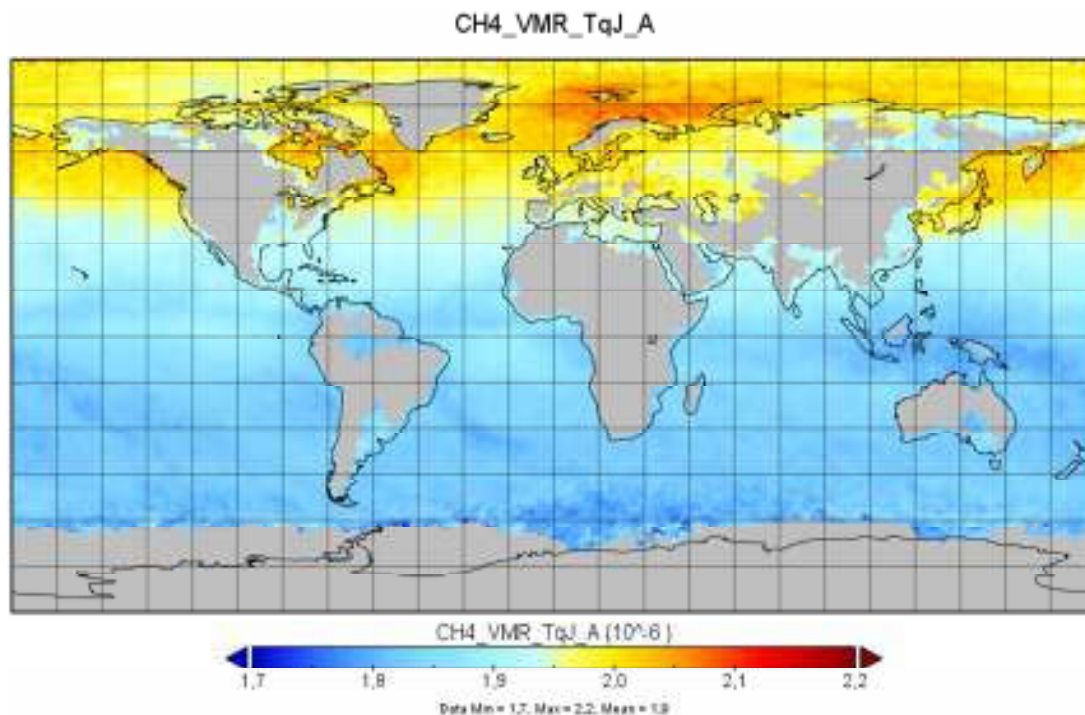


Figure 4 — Methane concentration (ascending_TqJoint) on January 12, 2021
(AIRS.2021.12.01.L3.RetStd_IR031.v7.0.4.0.G22011212218)

AIRS L3 Monthly composites are also of interest.

TROPESS AIRS-Aqua L2 Methane for Forward Stream, Standard Product V1 (TRPSDL2CH4AIRSFS) contains the vertical distribution of the retrieved atmospheric state of methane

(https://disc.gsfc.nasa.gov/datasets/TRPSDL2CH4AIRSFS_1/summary).

- Temporal Extent: February 2021 — present
- Spatial Resolution: 45 km × 45 km
- Vertical Resolution: 2 km
- Temporal Resolution: daily
- File Format: netCDF

Suomi NPP/JPSS1 CrIS. Methane concentration is presented in the TROPESS CrIS-JPSS1 L2 Methane for Forward Stream, Standard Product V1 (TRPSDL2CH4CRS1FS).

Data access: https://disc.gsfc.nasa.gov/datasets/TRPSDL2CH4CRS1FS_1/summary

OCO-2/OCO-3 measures carbon dioxide concentration once every sixteen days. Data peculiarities are the relatively high spatial resolution (2.25 km × 1.29 km) and narrow swath. Given a cloud cover, data for global monitoring must be collected during a month or more. There are no such ready products.

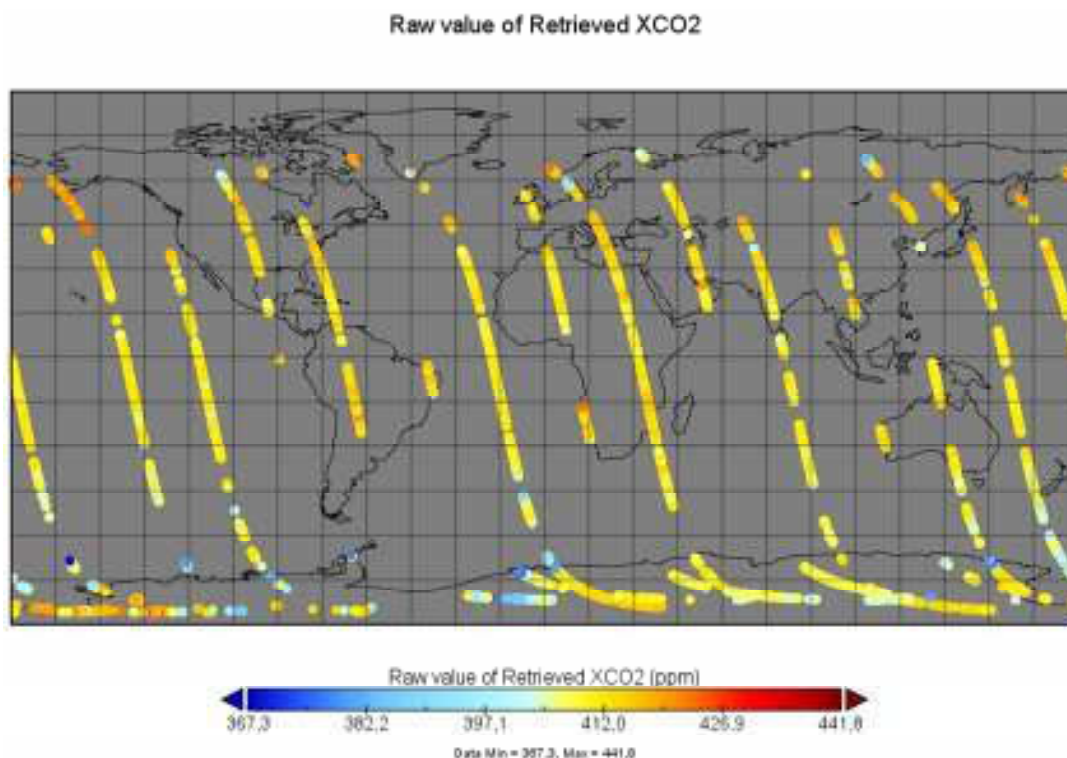


Figure 5 — Concentration of CO₂ on October 31, 2021
(oco2_LtCO2_211031_B10206Ar_220103202233s)

Daily products:

- OCO-2 Level 2 bias-corrected XCO₂ and other select fields from the full-physics retrieval aggregated as daily files, Retrospective processing V10r (OCO2_L2_Lite_FP).

Data access:

https://disc.gsfc.nasa.gov/datasets/OCO2_L2_Lite_FP_10r/summary

- OCO-3 Level 2 bias-corrected XCO₂ and other select fields from the full-physics retrieval aggregated as daily files, Retrospective processing V10r (OCO3_L2_Lite_FP)

Data access:

https://disc.gsfc.nasa.gov/datasets/OCO3_L2_Lite_FP_10r/summary

Data fields:

- Concentration: xco2
- Quality flag: xco2_quality_flag
- Standard error: xco2_uncertainty

Multicomponent data. Copernicus Atmosphere Monitoring Service (CAMS) provides observation-based data (satellite and in-situ) and modeling results. CAMS supports many products, in particular, CAMS global emission inventories [14].

Typically, these products are at a spatial resolution from 0.1° to 0.5° and are updated twice a year. They are much less operational but more detailed than satellite data (for example, describe greenhouse gas emissions from various industries).

Conclusions. Up-to-date open-access satellite data on main greenhouse gases concentration are reviewed. Among them, the most data are on the methane concentration measured both in the atmospheric column and in the middle troposphere. Of greatest interest is the Sentinel-5P Level 2 Methane Product, which can be successfully used for spot, national, and global monitoring.

Data on carbon dioxide concentrations are almost as widely available. Among them are unique measurements of the vertical concentration distribution of TROPES AIRS-Aqua L2 Methane for Forward Stream. OCO-2/OCO-3 data are best suited for spot measurements but have a comparatively longer repeat cycle (16 days). The use of GOSAT L3 global CO₂ distribution products is promising for global monitoring. At the same time, there is a lack of data at a sufficiently high spatial resolution and with a high acquisition frequency, like the Sentinel-5P methane data. The situation should significantly improve after the launch of a pair of TANGO satellites (CH₄, CO₂, and NO₂ concentration measurement at a spatial resolution of 300 m) and the CO2M satellite (CO₂ concentration at a spatial resolution of 2 km), scheduled for 2024 and 2025, respectively [15, 16].

There is a lack of data on nitrous oxide concentration. Currently, the only choice is the Metop IASI Trace Gases (integrated_n2o) product. However, these data are experimental ([17], see Section 8.3).

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Відкриті супутникові дані для глобального моніторингу парникових газів

Розглянуто відкриті супутникові дані про концентрацію основних парникових газів (CO_2 , CH_4 , N_2O). Дані надаються супутниковими інструментами Sentinel-5P TROPOMI, Metop-A/B/C IASI, GOSAT TANSO-FTS, GOSAT-2 TANSO-FTS-2, Aqua AIRS, Suomi NPP/JPSS CrIS, OCO-2 та OCO-3. Мета досліджень полягає в описі можливостей супутникових інструментів для вирішення задач моніторингу концентрації парникових газів на місцевому, регіональному та глобальному рівнях. Розглянуті комбіновані дані, що поєднують результати супутникових та наземних вимірювань.

Більшість даних по визначенню концентрації метану вимірюється у стовпній атмосфері і в середній тропосфері. Найбільший інтерес представляє продукт Sentinel-5P Level 2 Methane, який може успішно застосовуватися для вирішення завдань точкового, національного та глобального моніторингу. Широко представлені дані по визначенню концентрації вуглекислого газу. Серед них є унікальні виміри вертикального розподілу концентрації TROPES AIRS-Aqua L2 Methane for Forward Stream з періодичністю зйомки в 1 добу. Дані OCO-2/OCO-3 найкраще підходять для точкових вимірювань з періодичністю зйомки в 16 діб. Для глобального моніторингу є перспективним використання продуктів GOSAT L3 global CO_2 distribution. Разом з тим, відчувається дефіцит даних, що поєднують досить високу просторову роздільну здатність з високою частотою зйомки, подібних до даних Sentinel-5P для метану. Ситуація має суттєво покращитися після запусків пари супутників TANGO (вимірювання концентрації CH_4 , CO_2 та NO_2 з просторовою роздільною здатністю 300 м) та супутника CO2M (концентрація CO_2 з просторовою роздільною здатністю 2 км), запланованих на 2024 та 2025 р. відповідно. Продукт Metop IASI Trace Gases (integrated_n2o) є єдиними експериментальними даними по концентрації закису азоту.

Кавац Олена Олександрівна — к.т.н., доцент кафедри інформаційних технологій і систем Українського державного університету науки і технологій.

Храмов Дмитро Олександрович — к.т.н., старший науковий співробітник, Інститут технічної механіки НАН України і ДКА України.

Сергєєва Катерина Леонідівна — к.т.н., доцент кафедри інформаційних технологій та комп'ютерної інженерії Національного технічного університету "Дніпровська політехніка".

Васильєв Володимир Володимирович — к.т.н., доцент кафедри комп'ютерних наук та прикладної математики, Національного університету водного господарства та природокористування.

Kavats Olena Oleksandrivna — Ph.D., Associate Professor of the Department of Information Technology and Systems of Ukrainian State University of Science and Technology.

Khramov Dmitriy Alexandrovich — Ph.D., Senior Researcher, Institute of Technical Mechanics NASU and SSAU, Ukraine.

Sergieeva Kateryna Leonidivna — Ph.D., Associate Professor of the Information Technologies and Computer Engineering Department of Dnipro University of Technology.

Vasyliiev Volodymyr Volodymyrovych — Ph.D., Associate Professor of the Department of Computer Science and Applied Mathematics of National University of Water and Environmental Engineering.