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REMOTE SENSING OF ATMOSPHERE,  
HYDROSPHERE, AND UNDERLYING SURFACE

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## Comparison between Greenhouse Gas Fluxes Measured with the Equipment of Yakovlev-40 Aircraft Laboratory and ZOTTO Observatory

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**Abstract**—The ongoing global warming leads to the need in continuous monitoring of greenhouse gas concentrations and the magnitude of their fluxes. Gas exchange between terrestrial ecosystems and the atmosphere is mainly measured using eddy covariance, gradient, and chamber methods. This work compares greenhouse gas fluxes measured using the eddy covariance technique onboard an aircraft laboratory and with the gas analysis system and meteorological sensors at ZOTTO observatory. Instrument suites of the aircraft laboratory and the observatory are described. The comparison results showed that CO<sub>2</sub> and CH<sub>4</sub> fluxes measured by two different methods at the same altitudes coincide in sign, are close to each other in the value for carbon dioxide, and differ by up to 2 times for methane. The results are of interest to specialists who study greenhouse gas fluxes using the eddy covariance method.

**Keywords:** atmosphere, vertical distribution, eddy covariance, carbon dioxide, methane, flux

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### INTRODUCTION

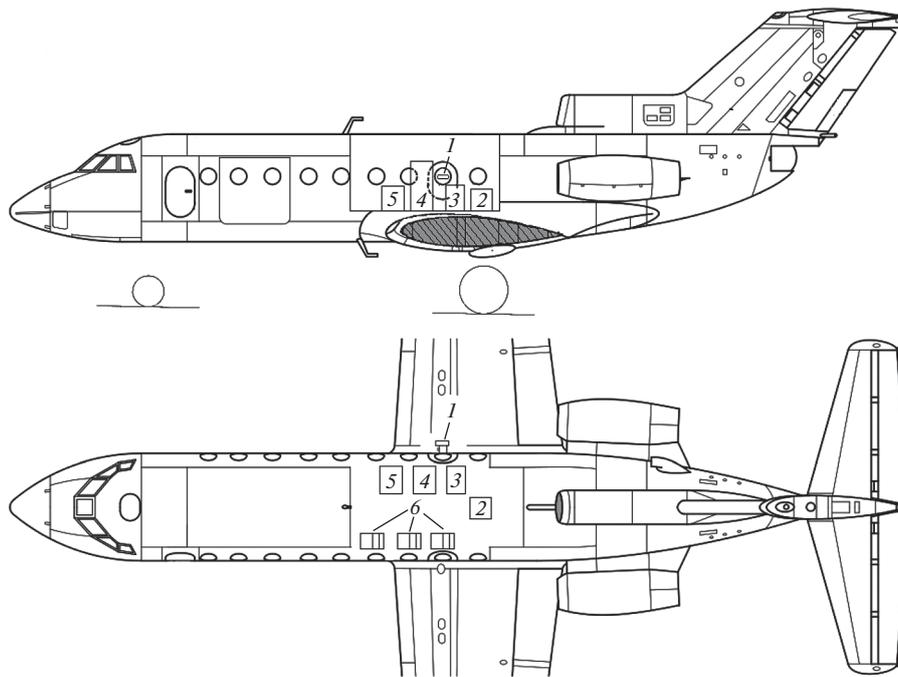
The ongoing global warming requires monitoring of the growth of greenhouse gas concentrations as the main cause of changes in the radiative heat flux into the Earth's atmosphere. The increase in the atmospheric content of these gases is a consequence of the imbalance between their emission and removal from the atmosphere. In order to assess this imbalance, it is necessary to monitor greenhouse gas fluxes. To determine the carbon emission or absorption (sink) by vegetation under natural conditions, measurements are carried out in remote (background) regions, where the anthropogenic effect is minimal, usually with the use of eddy covariance, gradient, or chamber methods [1].

It is generally accepted that the eddy covariance method is the most accurate; it is considered as reference when comparing measurement data [2]. Studies using this method can explain temporal and daily variations in local fluxes, which expands our understanding of the mechanism of carbon absorption in the environment [3]. However, the coverage of a territory by data from one such measuring complex is small. The realistic assessment of the atmospheric carbon balance is required, which would link local (ecosys-

tem) fluxes and their integral magnitudes over the Earth's surface on a regional (continental) scale.

The idea of using aircraft to measure gas exchange between the Earth's surface and the atmosphere was suggested more than 40 years ago [4, 5]. Observations with up-to-date instruments mounted on board an aircraft can provide results no less accurate than those from high masts (towers), and the main difference is in data interpretation [6]. Aircraft provide a near “instantaneous” pattern of the turbulence field over area territory, and their data are not subject to time trends and non-stationary effects like tower measurements. The main advantage of airborne measurements of turbulent fluxes with the use of the eddy covariance method is greater spatial representativeness than that of stationary ground-based measurements and higher temporal resolution and accuracy than those of model calculations [4].

The onboard eddy covariance method for measuring turbulent fluxes of greenhouse gases has been implemented in monitoring mode only in the USA. A network of 33 aircraft sounding stations equipped with small machines of different types has been created here [7]. Periodic measurements are carried out in the



**Fig. 1.** Arrangement of scientific equipment onboard OPTIC Yakovlev-40 aircraft laboratory: air intake, temperature and humidity sensor, and GLONASS/GPS receivers (1); rack of KOMPANAV-5.2 IOA integrated inertial system, DAS speed sensor, PPD-1 total pressure receiver, and DVbP-13 barometric altitude sensor (2); rack for onboard equipment power supply unit (3); rack for Picarro G2301-m CO<sub>2</sub>/CH<sub>4</sub>/H<sub>2</sub>O gas analyzer uninterruptible power supply (Delta RT-2K) (4); central onboard computer (5); flight attendant seats (6).

Great Britain, France, and Germany [5, 6, 8]. As far as can be judged from publications, no similar studies have been conducted in Russia. To fill this gap, we have assembled a set of equipment onboard Yakovlev-40 aircraft to measure greenhouse gas fluxes using the eddy covariance method [9].

When using a new method and introduction a set of equipment for its implementation, the question of measurement reliability and accuracy always arises. This problem is solved during sounding by means of intercalibration with other laboratory aircraft or by comparing with data received at high-altitude facilities [10–12].

Since there are no instruments which perform measurements with the use of the eddy covariance method in the Russian Federation, we compare our results with data from the equipment located at ZOTTO observatory in the region of Zotino village of Turukhansky district of Krasnoyarsk region.

The aim of the work is to compare greenhouse gas fluxes measured by the eddy covariance method from Yakovlev-40 aircraft and with a gas analysis system and meteorological sensors of ZOTTO observatory.

## MATERIALS AND METHODS

### *Scientific Equipment of the Aircraft Laboratory and ZOTTO Observatory*

To measure greenhouse gas fluxes by the eddy covariance method, a set of necessary equipment was assembled and mounted onboard a Yakovlev-40 aircraft (Fig. 1).

Concentrations of CO<sub>2</sub> and CH<sub>4</sub> were measured with a G2301-m gas analyzer (Picarro Inc., USA). Its operation is based the cavity ring-down spectroscopy (CRDS). This device was specially developed by the manufacturer for aircraft research. The gas analyzer ensures measurements of CO<sub>2</sub> concentrations in the range 0–1000 ppm with uncertainty < ±0.04 ppm, and of CH<sub>4</sub>, in the range 0–20 ppm with uncertainty < ±0.0006 ppm (the uncertainties were estimated in calibration with WMO standard gas mixtures).

To measure the vertical wind speed, a strapdown inertial navigation system (SINS) “KompaNav-5.2 IOA” was used, which was designed for determining the location coordinates, motion parameters, and orientation angles of an aircraft. The system is based on Russian fiber-optic gyroscopes and accelerometers based on microelectromechanical systems. As an additional source of navigation information, the SINS includes a GPS/GLONASS satellite navigation sys-

**Table 1.** SINS specification

Parameter	Value
<i>Main parameters</i>	
Angular velocity, deg/s	300
Linear acceleration	$\pm 10g$
Speed, m/s	up to 300
Pitch, deg	$\pm 90$
Roll, deg	$\pm 180$
Yaw, deg	0–360
Altitude, m	20000
<i>Accuracy parameters</i>	
Horizontal coordinates, m	6
Limits of permissible instrumental error	No more than $\pm 2.5$ m
Ground speed, m/s	0.1
Vertical speed, m/s	0.15
Orientation angles (roll and pitch), deg	0.07
Azimuth, deg.	0.2
Altitude, m	4
Air speed, m/s	1.5

**Table 2.** Technical characteristics of ZOTTO observatory instruments

Instrument	Model	Measured parameter	Range	Uncertainty, % [10]
Gas analyzer CO <sub>2</sub> /CH <sub>4</sub> /H <sub>2</sub> O	EnviroSense 3000i (CRDS); Picarro Inc., USA	SO <sub>2</sub> , ppm	0–1000	$< \pm 0.04$
		CH <sub>4</sub> , ppm	0–10	$< \pm 0.0003$
		H <sub>2</sub> O, ppm	0–7000	$< \pm 10$
Ultrasonic anemometer- thermometer	Solent-R3; GILL Instruments, United Kingdom	Wind speed, m/s	0–45 (resolution 0.01)	$\pm 1$
		Wind direction, deg	0–359 (resolution 1)	$\pm 1$
Temperature and humidity sensors	KPK 1/6-ME-H38, Germany	Temperature, °C	–40–+80	$\pm 0.2$
	MELA Sensortechnik, Germany	Relative humidity, %	0–100	$\pm 2$

tem receiver Ublox NEO-8M, which determines the vertical component of the aircraft speed relative to the air in the range from –50 to +50 m/s with uncertainty  $\pm 0.15$  m/s. Specification the SINS integrated with GPS/GLONASS receiver (KompaNav-5.2 IOA model) are given in Table 1.

Air pressure and temperature were measured using previously manufactured meteorological system [13]. A Honeywell HIH-3602-C temperature sensor measures in the range from –40 to +85°C with uncertainty  $\pm 0.5$  °C; a Young Model 61302 pressure sensor measures in the range 150–1150 hPa with uncertainty  $< \pm 1.5\%$ .

The measuring complex of ZOTTO observatory is described in detail in [14]. It is equipped with a high mast (301 m), where sampling devices and pipelines

supplying air to the gas analyzers are mounted at altitudes of 4, 52, 93, 159, 227, and 301 m. Greenhouse gas concentrations were measured with a gas analyzer, the characteristics of which are given in Table 2.

#### *Experimental Geometry*

Greenhouse gas fluxes were measured at ZOTTO observatory between 10:00 and 12:00 local time on November 1, 2023. The flight diagram is shown in Fig. 2.

The aircraft flew at altitudes of 100, 200, 300, 400, 500, 1000, and 1500 m above the ground level along a square centered at the point of the tall mast. The location of the square was chosen based on actual data from the Yeniseisk weather station received before

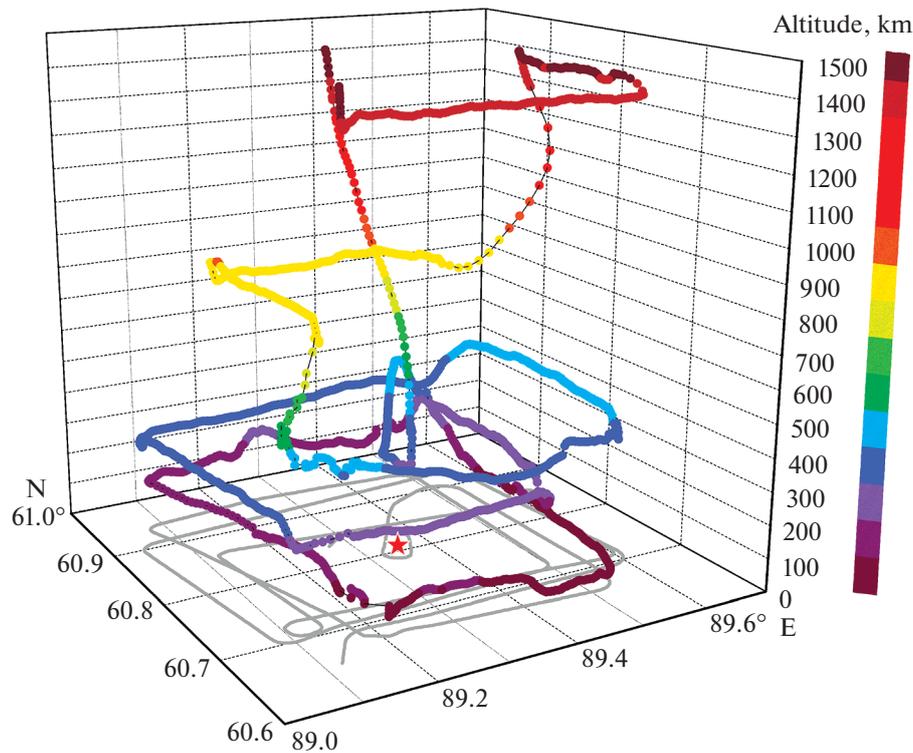


Fig. 2. Scheme of atmospheric sounding in the region of ZOTTO observatory; the mast is marked with the asterisk.

departure so as two sides coincided with the wind direction or were opposite to it, and the other two sides were perpendicular to it. The flight lasted 10 min at each altitude level and covered two sides of the square (hereinafter referred to as sections 1, 2, 3, and 4). It should be noted that such an ideal pattern is not always observed in a real experiment. This is confirmed by the data presented below.

#### *Synoptic Conditions During the Experiment*

Figure 3 shows the surface weather map for 13:00 local time on November 1, 2023, which characterizes the synoptic conditions during the period of atmospheric sounding. The measurement area was evidently located on the southwestern periphery of a large anticyclone centered near Khatanga village. This weather provided clear conditions, which allowed flights below 600 m.

According to [15], anticyclonic weather is accompanied by descending vertical air currents, which produce temperature inversions preventing air exchange between layers. Small pressure gradients indicate low wind speeds and possible variations in wind direction.

## RESULTS AND DISCUSSION

### *Vertical Distribution of Air Temperature and Greenhouse Gas Concentrations*

Since the measuring methods at the mast and the laboratory aircraft differ in terms of recording rates, altitude resolution, etc., the analysis below is carried out with combined data. Aircraft profiles are constructed with a vertical resolution of 20 m, and mast profiles are constructed at the above-mentioned levels.

Figure 4 shows a multi-layer inversion in the experimental region near 250, 500, 900, and 1500 m above the earth's surface from 10:00 to 12:00 local time. It is possible to distinguish an additional ground inversion in Fig. 4a. This corresponds to the already mentioned anticyclonic conditions and does not help to the study of the vertical distribution of greenhouse gas fluxes. However, it is quite problematic to select situations with ideal conditions in the airports of departure and intermediate refueling and sounding region, given distances between them of more than 1000 km. In addition, this stratification of the atmosphere should lead to special vertical profiles of the concentrations of the gases under study.

Due to the fact that the experiment was carried out under conditions where the physiological activity of the vegetation cover was minimal and the gas emission prevailed over the photosynthetic carbon assimilation by terrestrial ecosystems in the region under study, the

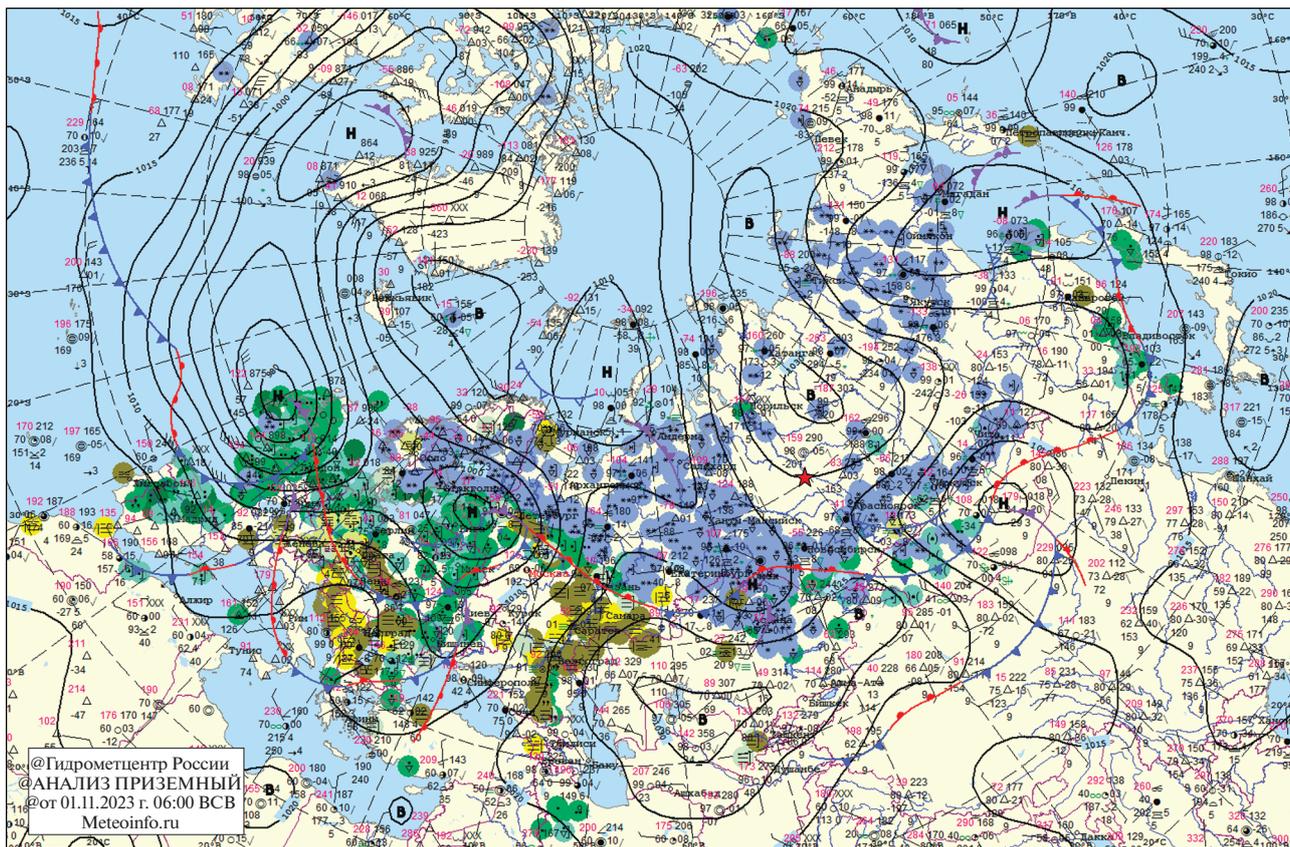


Fig. 3. Surface weather map for 06 UTC (13:00 local time) on November 1, 2023; the mast is marked with the asterisk.

vertical distribution of CO<sub>2</sub> indicates the presence of a source near the underlying surface (Fig. 4b). The dynamics of CO<sub>2</sub> concentration is insignificant in the surface air layer. Figure 4b shows the small peaks of the curves of CO<sub>2</sub> concentrations to generally coincide with the inversions seen on the temperature profile (Fig. 4a).

The vertically variations in the methane concentration are completely different (Fig. 4c). Its behavior is near neutral from the surface layer to an altitude of 700 m, with small variations reflecting the presence of temperature inversions. The main peak is recorded at an altitude of 850–900 m. This CH<sub>4</sub> distribution is possible under a combination of two factors: air advection from areas with its high concentrations and the presence of a local source.

It should be noted here that the measurements of ZOTTO high-altitude mast cover a significant domain, which, due to the western transfer, is shifted to Western Siberia [14], which causes a significant effect of the surrounding wetlands, including the complexes of the Great Vasyugan Swamp, on the mast measurements of methane concentration. This is also confirmed by the data in Fig. 4c, which shows a sharp increase in methane concentration after 11:00 local

time, when the internal mixing layer disappears [16, 17].

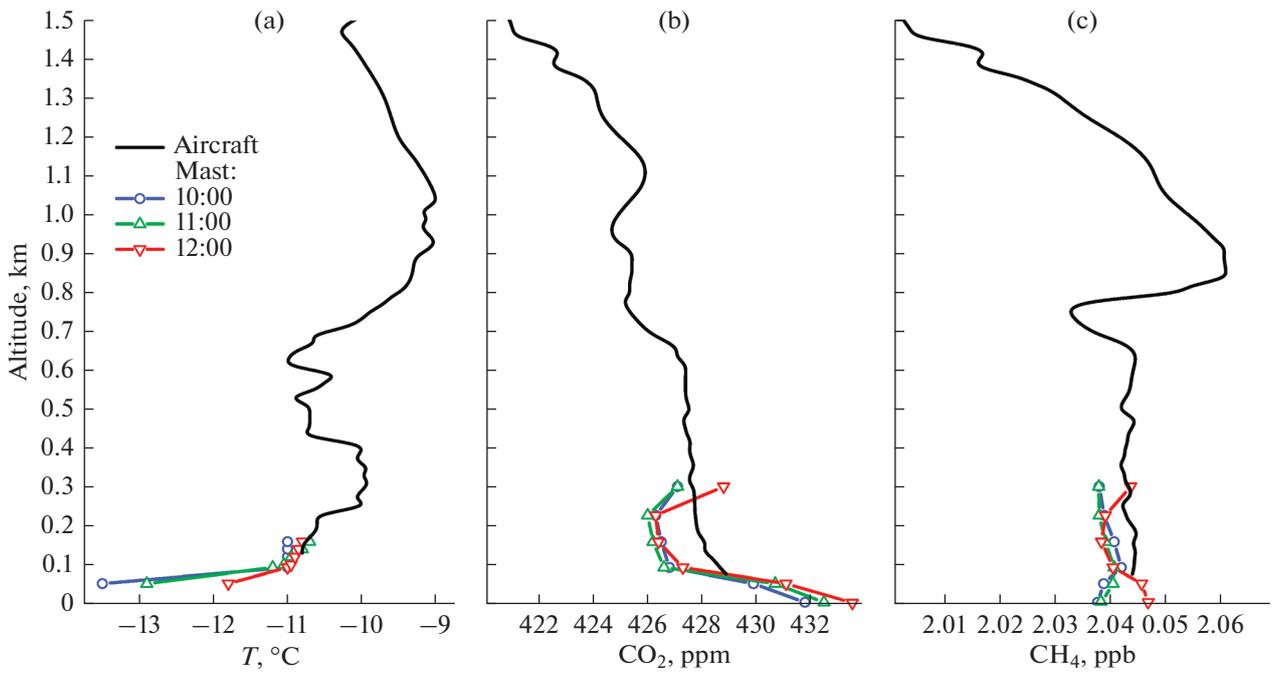
*Greenhouse Gas Fluxes*

According to [18, 19], a gas flux measured by the eddy covariance method from an aircraft is calculated by the formula

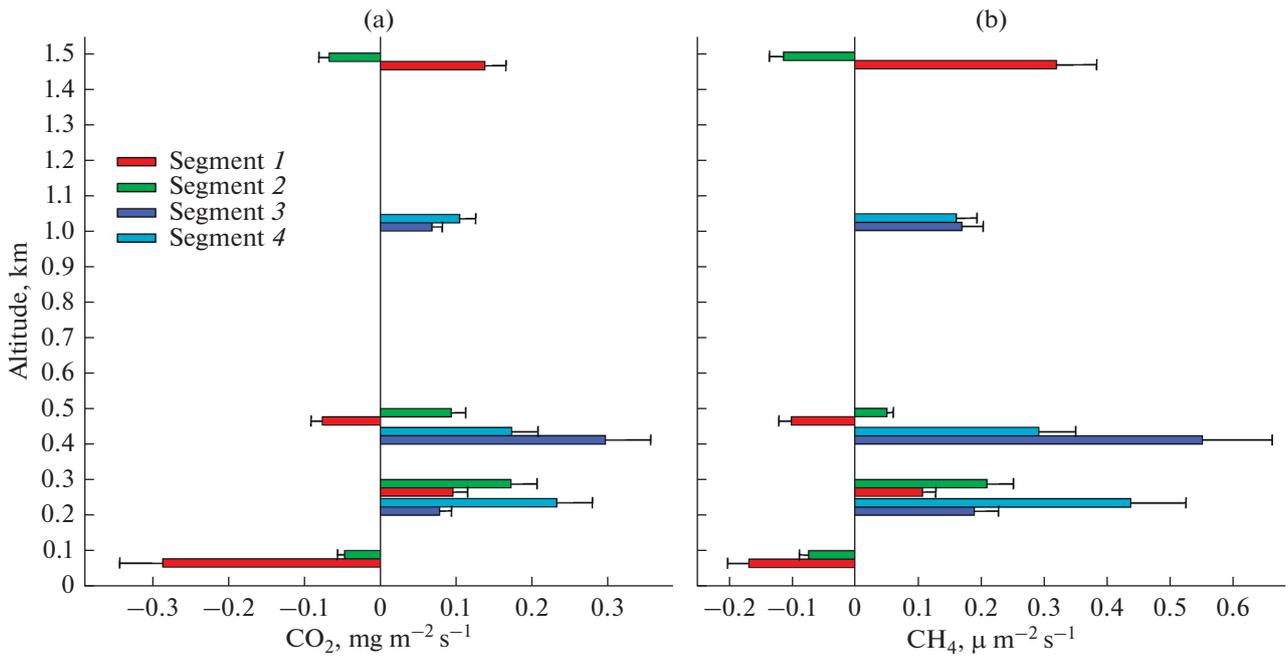
$$F = \frac{1}{N} \sum (C' - C)(w' - w),$$

where  $C'$  and  $C$  are the fluctuations and average mass concentrations of a gas under study in a region;  $w'$  and  $w$  are the fluctuations and average vertical air velocity in the region;  $N$  is the number of samples included in the processing.

The number  $N$  is estimated from the following considerations. The flux  $F$  should correctly reflect the heterogeneity of the underlying surface, which is the source or sink of a gas under study. Study [20] has shown a distance of 3 km to be sufficient for this. The second circumstance is the frequency of counts for recording  $C'$  and  $w'$ . For ground-based measurements, it should be at least 10 Hz [2, 3]. The analysis of methodological issues in [21, 22] has shown frequency of 1 Hz to be sufficient for aircraft measurements of gas



**Fig. 4.** Vertical distribution of (a) air temperature, (b) CO<sub>2</sub> and (c) CH<sub>4</sub> concentrations in the region of ZOTTO observatory.

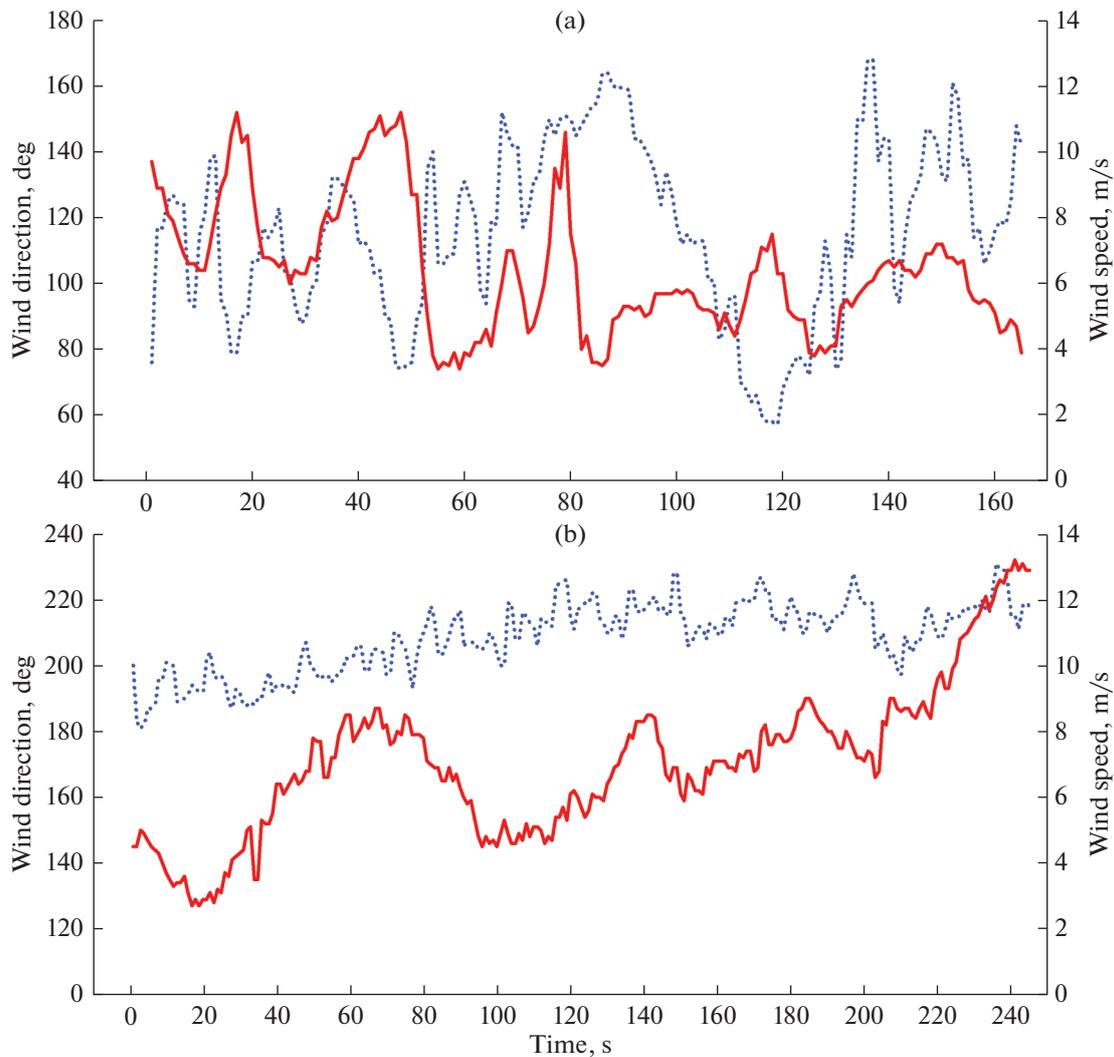


**Fig. 5.** Fluxes of (a) CO<sub>2</sub> and (b) CH<sub>4</sub> measured at different altitudes in the region of ZOTTO observatory with the onboard equipment of Yakovlev-40 aircraft laboratory.

concentrations and vertical wind speed. Therefore, at an aircraft speed of 100 m/s, the averaging period should be equal to 300 s or 5 min. Based on this, the length of our sections was determined during sounding

in the region of ZOTTO observatory. The found greenhouse gas fluxes are shown in Fig. 5.

One can see the CO<sub>2</sub> and CH<sub>4</sub> fluxes to vary from  $-0.3$  to  $+0.3 \text{ mg m}^{-2} \text{ s}^{-1}$  and from  $-0.2$  to  $+0.55 \text{ μg m}^{-2} \text{ s}^{-1}$ ,



**Fig. 6.** Distribution of wind speed (solid curve) and direction (dashed line) at an altitude of 100 m: (a) segment 1; (b) segment 2.

respectively, throughout the experimental period. These values are close to those recorded in other regions [23–25]. They are predictably significantly lower than over industrial regions, such as London [26, 27]. The difference between  $\text{CO}_2$  and  $\text{CH}_4$  fluxes at the same altitude, but in different regions is also noteworthy. Works [21, 22] suggest measuring the fluxes under wind stable in both direction and speed.

Let us analyze Fig. 6, which shows the distribution of wind speed and direction at an altitude of 100 m in sections 1 and 2. The wind speed and direction stronger varied in section 1. The ranges of variations in the wind direction was wider than  $100^\circ$ , and of the wind speed, 8 m/s, whereas there were  $40^\circ$  and the same 8 m/s in section 2. The influence of synoptic conditions and coastal orography of Yenisei river, located 30 km from the mast, is obvious. However, it is impossible to predict a similar meteorological situation for the experiment region yet.

During the experiment at ZOTTO observatory, measurements by the eddy covariance method were not carried out. However,  $\text{CO}_2$  and  $\text{CH}_4$  concentrations and meteorological parameters at the above-mentioned altitudes were recorded. Based on these data, greenhouse gas fluxes were estimated by the gradient method. It is based on the Monin–Obukhov similarity theory and is described in detail in [28].

Flux magnitudes were calculated for each layer between the two measurement levels. The results were reduced to the middle of a layer. The comparison between the gradient and eddy covariance methods [29–33] showed their similar results and coincidence within 18–25%.

Figure 7a shows  $\text{CO}_2$  fluxes measured by different methods at intersecting levels (100 and 200 m) to coincide in sign and be close in magnitude. The estimates for methane show the coincidence in sign and near two-fold difference in magnitude (Fig. 7b). This dif-

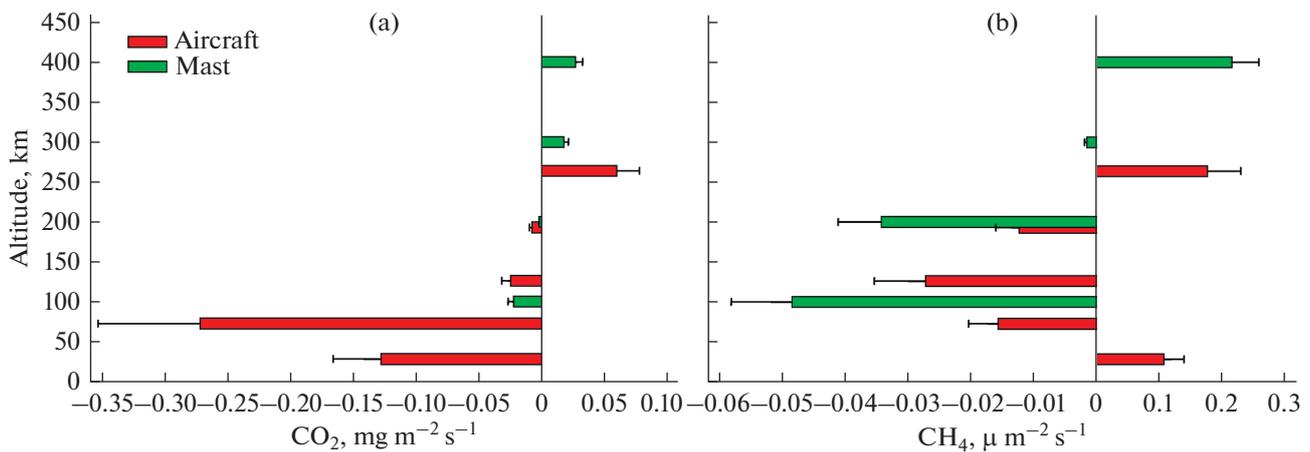


Fig. 7. Average fluxes of (a) CO<sub>2</sub> and (b) CH<sub>4</sub> in the region of ZOTTO observatory.

ference can be explained if we take into account the stratification of the atmosphere on the day of the experiment, the features of the vertical distribution of CO<sub>2</sub> and CH<sub>4</sub>, and wind regime instability.

It should be noted that the differences between aircraft measurements and estimates from mast monitoring data can be considered natural and they have been previously noted, for example, in [34, 35]. They are due to not only fundamental difference in the methods, but also to the fact that the aircraft collects information from a larger territory. Each method has proper spatial and temporal scales of averaging.

## CONCLUSIONS

An experiment on atmospheric sounding in the region of the high mast of ZOTTO observatory was conducted. The comparison between greenhouse gas fluxes measured from an aircraft and calculated based on observatory monitoring data shows their coincidence in sign and a sufficient degree of proximity of magnitude for CO<sub>2</sub> fluxes at the same altitudes. As for methane fluxes, they coincide in sign, but differ in magnitude by up to two times. A final conclusion requires the comparison to be made for other weather conditions. Therefore, we plan to perform a similar experiment in summer.

## FUNDING

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## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

## REFERENCES

1. M. V. Glagolev, "Inverse modelling method for the determination of the gas flux from the soil," *Dinamika Okruzhayushchei Sredy Global'nye Izmeneniya Klimata* **1** (1), 17–36 (2010).
2. M. Riederer, A. Serafimovich, and T. Foken, "Net ecosystem CO<sub>2</sub> exchange measurements by the closed chamber method and the eddy covariance technique and their dependence on atmospheric conditions," *Atmos. Meas. Tech.* **7** (4), 1057–1064 (2014). <https://doi.org/10.5194/amtd-6-8783-2013>
3. E. Falge, D. Baldocchi, J. Tenhunen, M. Aubinet, P. Bakwin, P. Berbigier, C. Bernhofer, G. Burba, R. Clement, K. J. Davis, J. A. Elbers, A. H. Goldstein, A. Grelle, A. Granier, J. Guomundsson, D. Hollinger, A. S. Kowalski, G. Katul, B. E. Law, Y. Malhi, T. Meyers, R. K. Monson, J. W. Munger, W. Oechel, K. T. Paw, K. Pilegaard, U. Rannik, C. Rebmann, A. Suyker, R. Valentini, K. Wilson, and S. Wofsy, "Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements," *Agric. For. Meteorol.* **113** (1–4), 53–74 (2002).
4. R. L. Desjardins, E. J. Brach, P. Alno, and P. H. Schuepp, "Aircraft monitoring of surface carbon dioxide exchange," *Science* **216** (4547), 733–735 (1982).
5. D. H. Lenschow, R. Pearson, Jr., and B. B. Stankov, "Estimating the ozone budget in the boundary layer by use of aircraft measurements of ozone eddy flux and mean concentration," *J. Geophys. Res.* **86**, 7291–7297 (1981).

6. Y. Sun, J. Ma, B. Sude, X. Lin, H. Shang, B. Geng, Z. Diao, J. Du, and Z. Quan, "A UAV-based eddy covariance system for measurement of mass and energy exchange of the ecosystem: Preliminary results," *Sensors* **21**, 403 (2021).  
<https://doi.org/10.3390/s21020403>
7. <https://gml.noaa.gov/ccgg/aircraft/index.html>. Cited April 20, 2024.
8. B. M. Erland, C. Adams, A. Darlington, M. L. Smith, A. K. Thorpe, G. R. Wentworth, S. Conley, J. Liggio, S.-M. Li, C. E. Miller, and J. A. Gamon, "Comparing airborne algorithms for greenhouse gas flux measurements over the Alberta oil sands," *Atmos. Meas. Tech.* **15** (19), 5841–5859 (2022).  
<https://doi.org/10.5194/amt-2022-120>
9. B. D. Belan, P. N. Antokhin, M. Yu. Arshinov, S. B. Belan, D. K. Davydov, G. A. Ivlev, A. V. Kozlov, D. A. Pestunov, D. E. Savkin, D. V. Simonenkov, G. N. Tolmachev, and A. V. Fofonov, RF Patent for Utility Model No. 228158 (August 16, 2024).
10. *Airborne Measurements for Environmental Research*, Ed. by M. Wendisch and J.-L. Brenguier (Wiley-VCH, Weinheim, 2013).
11. L. Mahrt, "Flux sampling errors for aircraft and towers," *J. Atmos. Ocean. Technol.* **15**, 416–429 (1998).  
[https://doi.org/10.1175/1520-0426\(1998\)015<0416:FSEFAA>2.0.CO;2](https://doi.org/10.1175/1520-0426(1998)015<0416:FSEFAA>2.0.CO;2)
12. J. H. Prueger, J. L. Hatfield, W. P. Kustas, L. E. Hipps, J. I. Macpherson, C. M. U. Neale, W. E. Eichinger, D. I. Cooper, and T. B. Parkin, "Tower and aircraft eddy covariance measurements of water vapor, energy, and carbon dioxide fluxes during SMACEX," *J. Hydrometeorol.* **6** (12), 954–960 (2005).  
<https://doi.org/10.1175/JHM457.1>
13. B. D. Belan, G. Ancellet, I. S. Andreeva, P. N. Antokhin, V. G. Arshinova, M. Y. Arshinov, Y. S. Balin, V. E. Barsuk, S. B. Belan, D. G. Chernov, D. K. Davydov, A. V. Fofonov, G. A. Ivlev, S. N. Kotel'nikov, A. S. Kozlov, A. V. Kozlov, K. Law, A. V. Mikhal'chishin, I. A. Moseikin, S. V. Nasonov, P. Nedelec, O. V. Okhlopkova, S. E. Ol'kin, M. V. Panchenko, J.-D. Paris, I. E. Penner, I. V. Ptashnik, T. M. Rasskazchikova, I. K. Reznikova, O. A. Romanovskii, A. S. Safatov, D. E. Savkin, D. V. Simonenkov, T. K. Sklyadneva, G. N. Tolmachev, S. V. Yakovlev, and P. N. Zenkova, "Integrated airborne investigation of the air composition over the Russian sector of the Arctic," *Atmos. Meas. Tech.* **15** (13), 3941–3967 (2022).  
<https://doi.org/10.5194/amt-15-3941-2022>
14. J. Winderlich, H. Chen, C. Gerbig, T. Seifert, O. Kolle, J. V. Lavric, C. Kaiser, A. Hofer, and M. Heimann, "Continuous low-maintenance CO<sub>2</sub>/CH<sub>4</sub>/H<sub>2</sub>O measurements at the Zotino Tall Tower Observatory (ZOTTO) in Central Siberia," *Atmos. Meas. Tech.* **3** (4), 1113–1128 (2010).  
<https://doi.org/10.5194/amt-3-1113-2010>
15. V. I. Vorob'ev, *Synoptic Meteorology* (Gidrometeoizdat, Leningrad, 1991) [in Russian].
16. B. D. Belan, "Dynamics of the atmospheric mixing layer as it follows from data on aerosol," *Atmos. Ocean. Opt.* **7** (8), 558–562 (1994).
17. Yu. S. Balin and A. D. Ershov, "Vertical structure of aerosol fields in the atmospheric boundary layer reconstructed from laser sensing data," *Atmos. Ocean. Opt.* **12** (7), 592–599 (1999).
18. A. Tremblay, C. Roehm, L. Varfalvy, and M. Garneau, *Greenhouse Gas Emissions—Fluxes and Processes* (Springer, Berlin, 2005).
19. G. Burba, *Eddy Covariance Method for Scientific, Industrial, Agricultural and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates* (USA, 2013).
20. D. S. Sayres, R. Dobosy, C. Healy, E. Dumas, J. Kochendorfer, J. Munster, J. Wilkerson, B. Baker, and J. G. Anderson, "Arctic regional methane fluxes by ecotope as derived using eddy covariance from a low-flying aircraft," *Atmos. Chem. Phys.* **17** (13), 8619–8633 (2017).  
<https://doi.org/10.5194/acp-17-8619-2017>
21. B. Yuan, L. Kaser, T. Karl, M. Graus, J. Peischl, T. L. Campos, S. Shertz, E. C. Apel, R. S. Hornbrook, A. Hills, J. B. Gilman, B. M. Lerner, C. Warneke, F. M. Flocke, T. B. Ryerson, A. B. Guenther, and J. A. de Gouw, "Airborne flux measurements of methane and volatile organic compounds over the Haynesville and Marcellus shale gas production regions," *J. Geophys. Res.: Atmos.* **120** (12), 6271–6289 (2015).  
<https://doi.org/10.1002/2015JD023242>
22. J. T. Shaw, G. Allen, P. Barker, J. R. Pitt, D. Pasternak, S. J.-B. Bauguutte, J. Lee, K. N. Bower, M. C. Daly, M. F. Lunt, A. L. Ganesan, A. R. Vaughan, F. Chibesakunda, M. Lambakasa, R. E. Fisher, J. L. France, D. Lowry, P. I. Palmer, S. Metzger, R. J. Parker, N. Gedney, P. Bateson, M. Cain, A. Lorente, T. Borsdorff, and E. G. Nisbet, "Large methane emission fluxes observed from tropical wetlands in Zambia," *Global Biogeochem. Cycl.* **36** (6) (2022).  
<https://doi.org/10.1029/2021GB007261>
23. R. C. Zulueta, W. C. Oechel, J. G. Verfaillie, S. J. Hastings, B. Gioli, and W. T. Lawrence, "Aircraft regional-scale flux measurements over complex landscapes of mangroves, desert, and marine ecosystems of Magdalena Bay, Mexico," *J. Atmos. Ocean. Technol.* **30** (7), 1266–1294 (2013).  
<https://doi.org/10.1175/JTECH-D-12-00022.1>
24. M. Loechli, B. B. Stephens, R. Commane, F. Chevallier, K. McKain, R. F. Keeling, E. J. Morgan, P. K. Patra, M. R. Sargent, C. Sweeney, and G. Keppel-Aleks, "Evaluating Northern Hemisphere growing season net carbon flux in climate models using aircraft observations," *Global Biogeochem. Cycl.* **37** (2), GB007520 (2023).  
<https://doi.org/10.1029/2022GB007520>
25. R. L. Desjardins, D. E. Worth, J. I. MacPherson, M. Bastian, and R. Srinivasan, "Flux measurements by the NRC Twin Otter atmospheric research aircraft: 1987–2011," *J. Adv. Sci. Res.* **13**, 43–49 (2016).  
<https://doi.org/10.5194/asr-13-43-2016>
26. A. Font, C. S. B. Grimmond, S. Kotthaus, J.-A. Morgui, C. Stockdale, E. O'Connor, M. Priestman, and B. Barratt, "Daytime CO<sub>2</sub> urban surface fluxes from airborne measurements, eddy-covariance observations and emissions inventory in Greater London," *Environ. Pollut.* **196**, 98–106 (2015).  
<https://doi.org/10.1016/j.envpol.2014.10.001>

27. S. J. O' Shea, G. Allen, Z. L. Fleming, S. J.-B. Bauguitte, C. J. Percival, M. W. Gallagher, J. Lee, C. Helfter, and E. Nemitz, "Area fluxes of carbon dioxide, methane, and carbon monoxide derived from airborne measurements around Greater London: A case study during summer 2012," *J. Geophys. Res.: Atmos.* **119** (8), 4940–4952 (2014).  
<https://doi.org/10.1002/2013JD021269>
28. T. Foken, *Micrometeorology* (Springer, Berlin; Heidelberg, 2006).
29. P. Viterbo, A. Beljaars, J.-F. Mahfouf, and J. Teixeira, "The representation of soil moisture freezing and its impact on the stable boundary layer," *Q. J. R. Meteorol. Soc.* **125** (559), 2401–2426 (1999).
30. X. Wang, C. Wang, and B. Bond-Lamberty, "Quantifying and reducing the differences in forest CO<sub>2</sub>-fluxes estimated by eddy covariance, biometric and chamber methods: A global synthesis," *Agric. Forest Meteorol.* **247**, 93–103 (2017).  
<https://doi.org/10.1016/j.agrformet.2017.07.023>
31. K. Wang, C. Liu, X. Zheng, M. Pihlatie, B. Li, S. Haapanala, T. Vesala, H. Liu, Y. Wang, G. Liu, and F. Hu, "Comparison between eddy covariance and automatic chamber techniques for measuring net ecosystem exchange of carbon dioxide in cotton and wheat fields," *Biogeosci.* **10** (11), 6865–6877 (2013).  
<https://doi.org/10.5194/bgd-10-8467-2013>
32. B. B. Almand-Hunter, J. T. Walker, N. P. Masson, L. Hafford, and M. P. Hannigan, "Development and validation of inexpensive, automated, dynamic flux chambers," *Atmos. Meas. Tech.* **8** (1), 267–280 (2015).  
<https://doi.org/10.5194/amt-8-267-2015>
33. Y. You, R. M. Staebler, S. G. Moussa, J. Beck, and R. L. Mittermeier, "Methane emissions from an oil sands tailings pond: A quantitative comparison of fluxes derived by different methods," *Atmos. Meas. Tech.* **14** (3), 1879–1892 (2021).  
<https://doi.org/10.5194/amt-14-1879-2021>
34. B. Gioli, F. Miglietta, B. De Martino, R. W. A. Hutjes, H. A. J. Dolman, A. Lindroth, M. Schumacher, M. J. Sanz, G. Manca, A. Peressotti, and E. J. Dumas, "Comparison between tower and aircraft-based eddy covariance fluxes in five European regions," *Agric. Forest Meteorol.* **127** (1), 1–16 (2004).  
<https://doi.org/10.1016/j.agrformet.2004.08.004>
35. R. A. Hannun, G. M. Wolfe, S. R. Kawa, T. F. Hanisco, P. A. Newman, J. G. Alfieri, J. Barrick, K. L. Clark, J. P. DiGangi, G. S. Diskin, J. King, W. P. Kustas, B. Mitra, A. Noormets, J. B. Nowak, K. L. Thornhill, and R. Vargas, "Spatial heterogeneity in CO<sub>2</sub>, CH<sub>4</sub>, and energy fluxes: Insights from airborne eddy covariance measurements over the mid-Atlantic region," *Environ. Res. Lett.* **15** (3), 035008 (2020).  
<https://doi.org/10.1088/1748-9326/ab7391>

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