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## INVERSE PROBLEMS OF ATMOSPHERIC AND OCEAN OPTICS

# Comparison of Distributions of Atmospheric Gas Admixture Concentrations Measured by Remote and In Situ Instruments over the Russian Sector of the Arctic

**O. Yu. Antokhina[a], P. N. Antokhin[a], V. G. Arshinova[a], M. Yu. Arshinov[a], B. D. Belan[a, *], S. B. Belan[a], V. V. Belov[a], Yu. V. Gridnev[a], D. K. Davydov[a], G. A. Ivlev[a], A. V. Kozlov[a], K. S. Law[b], Ph. Nédélec[c], J.-D. Paris[d], T. M. Rasskazchikova[a], D. E. Savkin[a], D. V. Simonenkov[a], T. K. Sklyadneva[a], G. N. Tolmachev[a], and A. V. Fofonov[a]**

[a] *V. E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, Tomsk, 634055 Russia*
[b] *IPSL Laboratoire Atmosphères, Milieux, Observations Spatiales, UPMC Univ. Paris 06, Université Versailles St-Quentin, CNRS/INSU, UMR 8190, LATMOS-IPSL, Paris, France*
[c] *Laboratoire d'Aerologie, 14, Avenue E. Belin, 31400, Toulouse, France*
[d] *Laboratoire des Sciences du Climat et de l'Environnement, Unite mixte CEA-CNRS, Bat. 709, CE L'Orme des Merisiers, 91191 Gif sur Yvette, France*
**e-mail: bbd@iao.ru*

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**Abstract**—Data from aircraft and satellite sensing at the ocean–land boundary in the region of the Kara Sea in October 2014 are compared, using 11 and 7 profiles, which were synchronously measured over a continental part and ocean, respectively. It was found that the satellite usually overestimates the $CH_4$ and $CO_2$ concentrations in the 0–8-km layer over the continental part of the Arctic region and underestimates them over the ocean. Over continent, the satellite overestimates the methane concentrations by 28 ppb in the boundary layer and by much more in the middle (182 ppb) and upper (113 ppb) troposphere. Over ocean, the satellite measurements are, on average, lower by 37 ppb in the boundary layer, by 73 ppb in the middle troposphere, and by 71 ppb in the upper troposphere. Over continent, the discrepancy in $CO_2$ concentrations, measured with different instruments, is, on average, 18.2 ppm in the boundary layer and can vary from 3.2 to 26.5 ppm. In the middle troposphere (4 km), the average differences decrease to 10.8 ppm, with the range of differences even increasing somewhat, to 0.6–25.5 ppm. In the upper troposphere (8 km), the average difference in measurements between the instruments decreases to 2.8 ppm. The underestimation turns out to be greater in amplitude over the ocean. It is noteworthy that the comparison yielded acceptable results for CO and $O_3$.

*Keywords:* Arctic, atmosphere, air, vertical distribution, gases, remote sensing
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## INTRODUCTION

Air temperature rises faster in the Arctic region [1, 2] than in other areas on the globe, thus requiring our greater attention to the state of the Arctic environment. The temperature rise on this territory is attributed to changes in air composition [3, 4]. At the same time, observation network stations are lacking on a large part of the Arctic region, prohibiting the monitoring of atmospheric air composition in the classic sense. Measurements in the near-ground (near-water) air layer at drifting stations [5, 6] or onboard research vessels [7–9] partly fill this data gap. The vertical admixture distribution has been studied using airborne laboratories [10–13]. However, these measurements, though complex in character, are episodic and offer no way to estimate the long-term changes in air composition.

As at other remote sites on the globe, it is hoped that the problem of monitoring the air composition in the Arctic region may be solved through the development of satellite sensing systems. The overview in [14] suggests that in 2017 there were 15 types of operational spacecraft measuring the aerosol and gas composition of the atmosphere. However, so far the satellite measurements have not been sufficiently accurate [15], requiring perfection of both instrumental and methodological components of this sensing technique [16, 17].

Comparisons with data obtained by other methods are used to determine the errors of measuring any air admixture from satellites. For instance, comparisons are made against radiosondes for water vapor and

against ozonesondes for ozone. Satellite profiles for other gases and aerosol are compared most often with results from aircraft sensing [18–22]. These comparative data make it possible to identify the measurement errors and update the method for retrieving the profiles of gases and aerosol or formulate the conditions required to improve the technical characteristics of instruments themselves.

In the present paper, data from aircraft and satellite sensing are compared at the continent–ocean boundary in the region of the Kara Sea.

## DATA USED

Data were obtained in October 2014 onboard the OPTIK Tu-134 airborne laboratory (AL) in the region of Salekhard and over the Kara Sea water basin. The experiment, instrumentation, and synoptic situation were comprehensively described in [23].

The Infrared Atmospheric Sounding Interferometer (IASI) measurements on the MetOp satellite were used as satellite data. The profiles were retrieved using a standard method [24–26].

Comparisons were performed by selecting the satellite profiles collocated with AL measurements and time coincident within ±1 h of the moment of aircraft ascent or descent (a total of 11 profiles over continent and 7 profiles over ocean).

## DISCUSSION OF COMPARISONS

In contrast to similar comparisons of aircraft and satellite data, performed earlier [27, 28], analysis of comparisons for the Arctic region revealed a number of polar discrepancies. Therefore, the data were analyzed separately for the continent and ocean. All cases of spatiotemporal coincidence of aircraft and satellite profiles were subsequently divided into three groups. The data in the first group were those in which the profiles coincided in more than a half of the altitude range (Fig. 1a; under the heading "agree" in tables). Cases in the second group were those where the gas concentration, retrieved from satellite data, was larger than concentration measured onboard aircraft in the entire altitude range, considered here (Fig. 1b, under the heading "IASI is larger" in the tables). Cases in the third group were those when aircraft measurements gave larger gas concentration in the entire altitude range (Fig. 1c; under the heading "AL is larger" in the tables).

How the vertical profiles of $CH_4$ concentrations are distributed over the groups as functions of the character of the underlying surface is illustrated in Table 1.

From Table 1 it follows that, over the continent, with almost identical probabilities the satellite- and

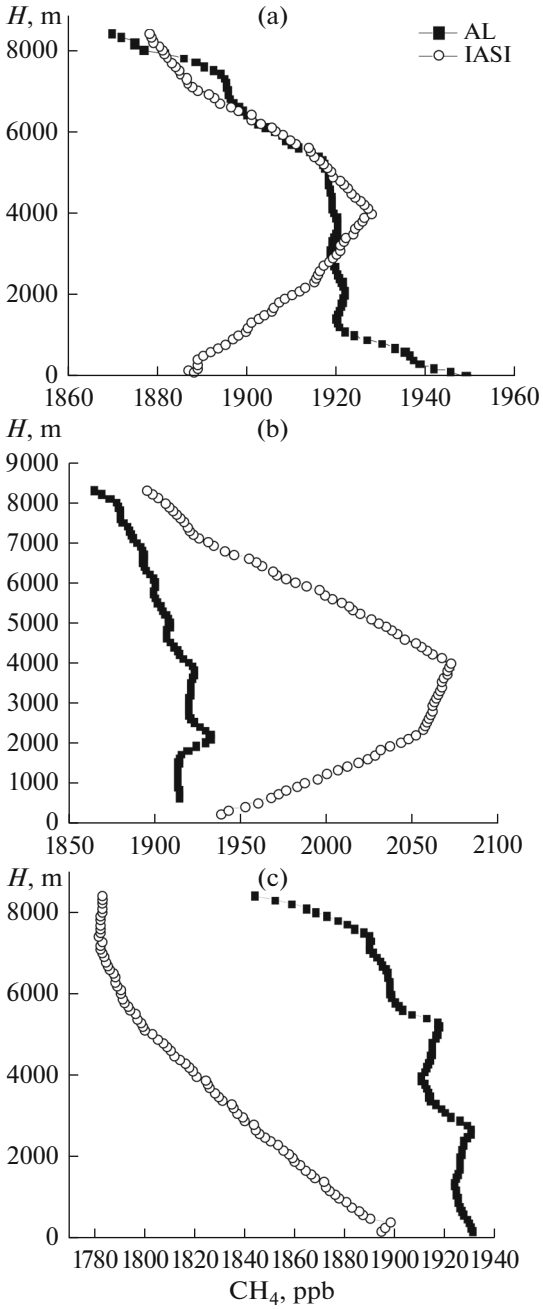


**Fig. 1.** Vertical distributions of AL- and IASI-measured $CH_4$ concentrations over (a, b) continent and (c) ocean.

**Table 1.** The distribution of $CH_4$ profiles, in which the AL- or IASI-measured concentrations were close in value or overestimated

| Surface | Agree | IASI is larger | AL is larger | Total |
|---|---|---|---|---|
| Continent | 4 | 4 | 3 | 11 |
| Ocean | 0 | 0 | 7 | 7 |

**Table 2.** Differences between AL- and IASI-measured $CH_4$ concentrations, ppb

| Surface | Altitude, km | Agree | | IASI is larger | | AL is larger | | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | | average | range | average | range | average | range | average | range |
| Continent | 0.2 | 55 | 0–113 | 28 | 24–58 | 26 | 24–27 | 36 | 0–113 |
| | 4.0 | 24 | 0–50 | 182 | 160–204 | 58 | 43–81 | 88 | 0–204 |
| | 8.0 | 25 | 20–31 | 113 | 61–142 | 45 | 20–74 | 61 | 20–142 |
| Ocean | 0.2 | | | | | 37 | 25–54 | 37 | 25–54 |
| | 4.0 | | | | | 73 | 57–102 | 73 | 57–102 |
| | 8.0 | | | | | 71 | 54–116 | 71 | 54–116 |

aircraft-based profiles are close in value (four cases), the satellite-derived concentrations exceed aircraft counterparts (four cases), and, conversely, aircraft-derived concentrations exceed those measured by satellite (three cases). How large can be the difference in concentration between different sensing techniques can be seen from Table 2. Figure 1 shows that the difference between the concentrations, obtained using different methods, markedly varied with altitude; therefore; the calculations and samples in Table 2 are for three altitudes: 0.2, 4.0, and 8.0 km.

Data in Table 2 indicate that over continent the concentration differences may reach 113 ppb in the atmospheric boundary layer, 204 ppb in the middle troposphere, and 142 ppb in the upper troposphere. The average deviations, estimated for different groups, exhibit asymmetry. The satellite overestimates concentration by 28 ppb in the boundary layer and by a much larger amount in the middle (182 ppb) and upper (113 ppb) troposphere. The underestimation is found to be much smaller: by 26, 58, and 45 ppb, respectively. The obtained discrepancies between IASI and AL data are larger than results in [29, 30] for extra-polar regions.

The satellite sensor underestimates the $CH_4$ concentrations in all 7 cases of comparing observations in all altitude ranges over ocean. On average, the concentration is underestimated by 37 ppb in the boundary layer, and by 73 ppb in the middle troposphere, and by 71 ppb in the upper troposphere. The maximal discrepancies reach 116 ppb. These estimates exceed those in [31, 32], which indicate that the random error of a single measurement should be ±20 ppb. The temperature contrast required for the IASI instrument to have sufficient sensitivity, was indicated in those works to be >10°C, versus >25°C in our experiments, suggesting that the instrument operated at temperatures exceeding the threshold.

**Table 3.** Distribution of $CO_2$ profiles, in which the AL- or IASI-measured concentrations were close in value or overestimated

| Surface | Agree | IASI is larger | AL is larger | Total |
|---|---|---|---|---|
| Continent | 2 | 9 | 0 | 11 |
| Ocean | 0 | 2 | 5 | 7 |

The polar differences in the satellite measurements over continent and ocean are also recorded for $CO_2$ (Table 3).

Data in Table 3 indicate that AL- and IASI-measured vertical $CO_2$ distributions coincided in two cases over continent. For nine profiles, the satellite-based $CO_2$ concentration was larger than its AL counterpart. On the contrary, AL recorded higher concentrations in five cases over ocean. The IASI-derived $CO_2$ content was larger in just two cases.

Typical vertical $CO_2$ distributions, measured by both instruments over continent and ocean, are presented in Fig. 2.

Figure 2 shows that altitudinal variations in $CO_2$ concentration, measured by AL and retrieved from IASI data, are similar in character. At the same time, substantial differences in concentrations can be seen, especially in the boundary layer and in the middle troposphere. The differences decrease with the increasing altitude. Inspection of Table 4 gives an idea of quantitative differences.

From Table 4 it follows that, over continent, the differences in $CO_2$ concentrations, measured with different instruments, are, on average 18.2 ppm in the boundary layer and can vary from 3.2 to 26.5 ppm. The average differences decrease to 10.8 ppm in the middle troposphere (4 km), with the range of the differences even increasing somewhat, to 0.6–25.5 ppm. The average difference between the satellite and aircraft data decreases to 2.8 ppm in the upper troposphere (8 km). The range of discrepancies also decreases to 0.8–15.4 ppm. Over ocean, the character of discrepancies with respect to altitude shows the same tendency, though with somewhat larger average values

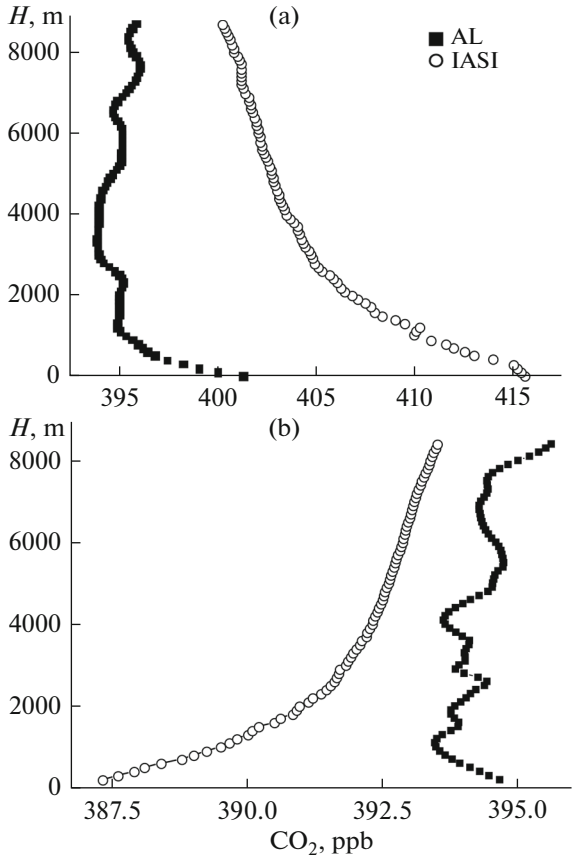


**Fig. 2.** Vertical distributions of AL- and IASI-measured $CO_2$ concentrations over (a) continent and (b) ocean.

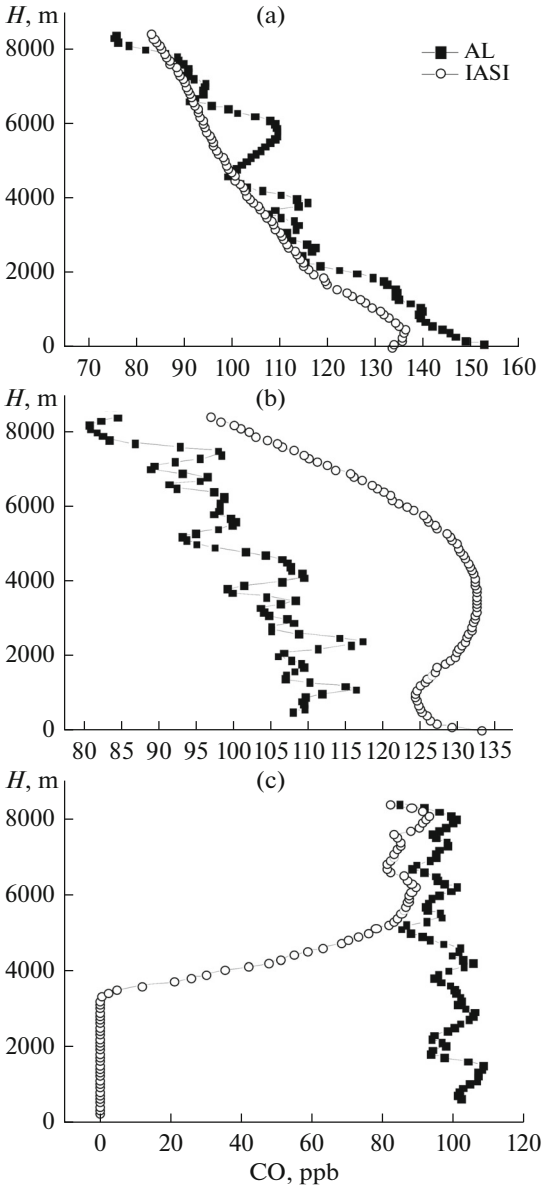


**Fig. 3.** Vertical distributions of CO concentrations over (a, b) continent and (c) ocean.

and variability ranges. As for $CH_4$, over ocean there is an asymmetry in discrepancies between the satellite and aircraft data.

The altitudinal dependence of the differences in AL and IASI measurements is most probably because the weighting functions for IASI, which determine the sensitivity of the instrument, peak in the 200–350-hPa layer [33–35]. The discrepancies in Table 4 between the satellite and aircraft data for the Arctic region turned out to be much larger than for other regions [25, 27, 28], with discrepancies being much larger than 1% accuracy, required for simulation [36].

Authors in a number of works [37–39] point out that the IASI sensor has weak sensitivity to CO in the troposphere; on the contrary, data in Fig. 3 and Table 5

**Table 4.** Differences between AL- and IASI-measured $CO_2$ concentrations, ppm

| Surface | Altitude, km | Agree | | IASI is larger | | AL is larger | | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | | average | range | average | range | average | range | average | range |
| Continent | 0.2 | 9.9 | 3.2–16.7 | 20.0 | 4.1–26.5 | 0 | 0 | 18.2 | 3.2–26.5 |
| | 4.0 | 4.7 | 0.6–8.8 | 12.1 | 6.6–25.5 | 0 | 0 | 10.8 | 0.6–25.5 |
| | 8.0 | 2.5 | 0.8–4.2 | 8.1 | 2.8–15.4 | 0 | 0 | 2.8 | 0.8–15.4 |
| Ocean | 0.2 | 0 | 0 | 14.6 | 3.9–25.3 | 21.9 | 7.5–30.6 | 19.8 | 3.9–30.6 |
| | 4.0 | 0 | 0 | 9.8 | 2.1–17.5 | 13.6 | 1.7–28.7 | 12.5 | 1.7–28.7 |
| | 8.0 | 0 | 0 | 5.8 | 1.4–10.2 | 10.7 | 2.2–19.8 | 9.3 | 1.4–19.8 |

**Table 5.** Distribution of CO profiles, in which AL- or IASI-measured concentrations were close in value or overestimated

| Surface | Agree | IASI is larger | AL is larger | Total |
|---|---|---|---|---|
| Continent | 7 | 2 | 2 | 11 |
| Ocean | 3 | 0 | 4 | 7 |

show that IASI sensitivity is sometimes sufficient in the Arctic region for a reliable retrieval of vertical distribution of the CO concentration.

From Table 5 it can be seen that, over continent, the satellite and aircraft data are close in value throughout this layer in seven cases out of 11. Figure 3a shows an example of this comparison, indicating that IASI-derived CO content was too high in two cases (Fig. 3b) and too low in two cases.

The compared measurements agree in three cases over ocean. The IASI instrument seemed to have insufficient sensitivity in four cases in the lower troposphere [37–39]. An example of these profiles is presented in Fig. 3c. It can be seen that IASI data are zero up to an altitude of 3.7 km. The compared concentrations tend to coincide above 4.5 km. The quantitative characteristics of the compared measurements are presented in Table 6.

Data in Table 6 show that, over the continent, the compared CO concentrations differ, on average, by 19.9 ppb in the atmospheric boundary layer, by 13.4 ppb in the middle troposphere, and by 13.9 ppb in the upper troposphere. Maximal discrepancies reach 44, 24, and 31 ppb, respectively. Over ocean, the differences are much larger because of insufficient sensitivity in the lower troposphere; on average, they are 68.5 ppb in the boundary layer, 30.4 ppb in the middle troposphere, and 6.9 ppb in the upper troposphere. No similar comparisons are found in the literature. Nonetheless, the IASI instrument can seemingly be used to control the vertical CO distribution in the Arctic region, at least over continental areas.

In contrast to the gases, considered above, the measurements of $O_3$ with IASI instrument, ozonesondes, and other techniques were compared in many publications [40–45]; it was shown that $O_3$ profiles are retrieved with accuracy comparable to other methods.

These same conclusions can also be drawn from comparison of IASI and AL measurements in the Arctic region (Fig. 4, Table 7).

From Fig. 4, it can be seen that the vertical $O_3$ profiles, measured by different methods, coincide in most cases, both over continent (Fig. 4b) and ocean (Fig. 4c). Out of 18 profiles, considered here, 16 profiles are found to agree (Table 7). In two cases there are discrepancies (Fig. 4a), mainly observed in the middle and upper troposphere.

Similar results for polar regions were also obtained in a number of foreign publications [46–48]. This agreement may be for two reasons. First, as our previous studies showed [23, 49–51], no photochemical $O_3$ production occurs in the Russian sector of the Arctic, especially in the fall period. Second, the surface of the continent was covered by snow in the period of experiment in the study region, thus screening the source of ozone-forming substances [52]. It is known that the water surface is not the source of their formation. The differences in the profiles stem from deviation of vertical distribution owing to tropopause sink, as was already indicated before [23].

We should also mention still another aspect. The type of model underlying the inversion scheme matters when the vertical distribution of $O_3$ concentration is retrieved from satellite measurements. As shown in

**Table 6.** Differences between AL- and IASI-measured CO concentrations, ppb

| Surface | Altitude, km | Agree | | IASI is larger | | AL is larger | | Total | |
|---|---|---|---|---|---|---|---|---|---|
| | | average | range | average | range | average | range | average | range |
| Continent | 0.2 | 18.0 | 3–44 | 21.5 | 13–30 | 25.0 | 18–32 | 19.9 | 3–44 |
| | 4.0 | 8.4 | 2–21 | 23.0 | 22–24 | 21.0 | 18–24 | 13.4 | 2–24 |
| | 8.0 | 13.6 | 0–31 | 20.0 | 18–22 | 9.0 | 6–12 | 13.9 | 0–31 |
| Ocean | 0.2 | 28.0 | 22–32 | 0 | 0 | 98.9 | 90–92 | 68.5 | 22–92 |
| | 4.0 | 3.7 | 0–6 | 0 | 0 | 50.5 | 15–68 | 30.4 | 0–68 |
| | 8.0 | 7.0 | 2–13 | 0 | 0 | 6.8 | 0–16 | 6.9 | 0–16 |

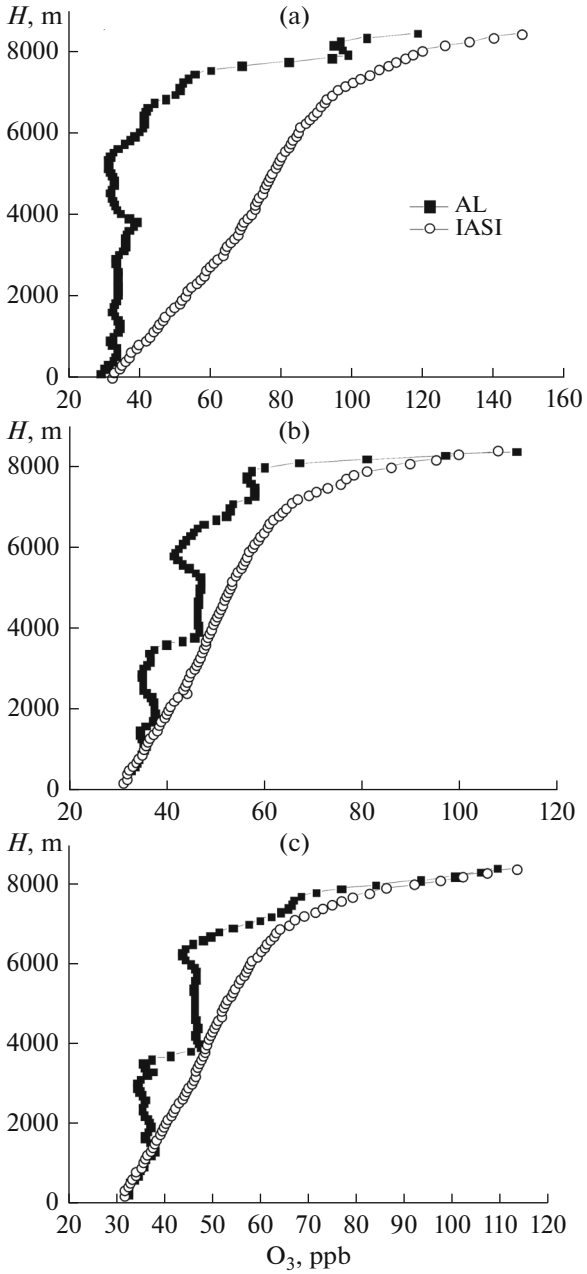


**Fig. 4.** Vertical distributions of $O_3$ concentrations over (a, b) continent and (c) ocean.

[27, 28], the underlying model for midlatitudes turned out to be far from the actual $O_3$ distribution. The model more adequately describes the average vertical $O_3$ distribution for Arctic regions, where no photochemical $O_3$ production takes place.

**Table 7.** Distribution of $O_3$ profiles, in which AL- or IASI-measured concentrations were close in value or overestimated

| Surface | Agree | IASI is larger | AL is larger | Total |
|---|---|---|---|---|
| Continent | 9 | 2 | 0 | 11 |
| Ocean | 7 | 0 | 0 | 7 |

## CONCLUSIONS

We compared the vertical profiles of $CO_2$ and $CH_4$ concentrations, measured onboard a satellite (IASI sensor) and the OPTIK Tu-134 airborne laboratory, and found few peculiarities. Specifically, for both gases, the satellite overestimates the concentrations in the layer of 0–8 km over the continental part of the Arctic region and underestimates them over the ocean. It is noteworthy that the satellite may overestimate $CO_2$ by as much as 26.5 ppm, and overestimate $CH_4$ by 204 ppb.

A number of authors point out that the IASI sensor has low sensitivity to CO in the troposphere; however, our measurements show that these instruments have much closer agreement over continent. Over ocean, the discrepancies are much larger in the lower troposphere owing to insufficient sensitivity. Nonetheless, the IASI instrument can seemingly be used to control the vertical CO distribution in the Arctic region, at least over continental areas.

In contrast to the above-mentioned gases, out of 18 $O_3$ profiles considered here, 16 are found to agree. Discrepancies exist in two cases. This agreement stems from more adequate (as applied to the region) use of the model in the absence of photochemical $O_3$ production in this region.

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## REFERENCES

1. T. G. Shepherd, “Effects of a warming Arctic,” Science **353** (6303), 989–990 (2016).
2. O. M. Johannessen, S. I. Kuzmina, L. P. Bobylev, and M. W. Miles, “Surface air temperature variability and trends in the Arctic: New amplification assessment and regionalisation,” Tellus A **68**, 28234 (2016).
3. S. R. Arnold, K. S. Law, C. A. Brock, J. L. Thomas, S. M. Starkweather, K. Salzen, A. Stohl, S. Sharma, M. T. Lund, M. G. Flanner, T. Petaja, H. Tanimoto, J. Gamble, J. E. Dibb, M. Melamed, N. Johnson, M. Fider, V.-P. Tynkkynen, A. Baklanov, S. Eckhardt, S. A. Monks, J. Browse, and H. Bozem, “Arctic air pollution: Challenges and opportunities for the next decade,” Elementa: Sci. Atmos., No. 4, 16 (2016).
4. N. Evangeliou, Y. Balkanski, W. M. Hao, A. Petkov, R. P. Silverstein, R. Corley, B. L. Nordgren, S. P. Urbanski, S. Eckhardt, A. Stohl, P. Tunved, S. Crepinsek, A. Jefferson, S. Sharma, J. K. Njgaard, and H. Skov, “Wildfires in northern Eurasia affect the budget of black carbon in the Arctic—a 12-year retrospective synopsis (2002–2013),” Atmos. Chem. Phys. **16** (12), 7587–7604 (2016).
5. A. P. Nagurnyi, “Analysis of measurement data on carbon dioxide concentration in the near-ice surface

atmosphere at North Pole-35 drifting ice station (2007–2008)," Rus. Meteorol. Hydrol. **35** (9), 619–623, 2010.

6. A. P. Nagurnyi and A. P. Makshtas, "Methane concentration in the atmospheric boundary layer from the measurements at North Pole-36 and North Pole-39 drifting ice stations," Rus. Meteorol. Hydrol. **41** (3), 199–204 (2016).
7. I. I. Pipko, S. P. Pugach, and I. P. Semiletov, "$CO_2$ dynamics on the shelf of the East Siberian Sea," Rus. Meteorol. Hydrol. **35** (9), 624–632 (2010).
8. I. P. Semiletov, N. E. Shakhova, I. I. Pipko, S. P. Pugach, A. N. Charkin, O. V. Dudarev, D. A. Kosmach, and S. Nishino, "Space-time dynamics of carbon and environmental parameters related to carbon dioxide emissions in the Buor-Khaya Bay and adjacebt part of Laptev Sea," Biogeosci. **10** (9), 5977–5996 (2013).
9. J. Yu, Z. Xie, L. Sun, H. Kang, P. He, and G. Xing, "$\delta^{13}C-CH_4$ reveals $CH_4$ variations over oceans from mid-latitudes to the Arctic," Sci. Rep. **5** (13760) (2015).
10. M. Giamarelou, K. Eleftheriadis, S. Nyeki, K. Torseth, and G. Biskos, "Indirect evidence of the composition of nucleation mode atmospheric particles in the high Arctic," J. Geophys. Res.: Atmos. **121** (2), 965–975 (2016).
11. C. L. Myhre, B. Ferre, M. Platt, A. Silyakova, O. Hermansen, G. Allen, I. Pisso, N. Schmidbauer, A. Stohl, J. Pitt, P. Jansson, J. Greinert, C. Percival, A. M. Fjaeraa, O'Shea, M. Gallagher, M. L. Breton, K. N. Bower, S. J. B. Bauguitte, S. Dalsoren, S. Vadakkepuliyambatta, R. E. Fisher, E. G. Nisbet, D. Lowry, G. Myhre, J. A. Pyle, M. Cain, and J. Mienert, "Extensive release of methane from Arctic seabed west of Svalbard during summer 2014," Geophys. Res. Lett. **43** (9), 4624–4631 (2016).
12. B. Quennehen, A. Schwarzenboeck, J. Schmale, J. Schneider, H. Sodemann, A. Stohl, G. Ancellet, S. Crumeyrolle, and K. S. Law, "Physical properties of pollution aerosol particles transported from North America to Greenland as measured during the POLARCAT summer campaign," Atmos. Chem. Phys. **11** (21), 10947–10963 (2011).
13. C. D. Zwaaftink, H. Grythe, H. Skov, and A. Stohl, "Substantial contribution of northern high-latitude sources to mineral dust in the Arctic," J. Geophys. Res.: Atmos. **121** (23), 13678–13697 (2016).
14. J. P. Burrows and R. Martin, "Satellite observations of tropospheric trace gases and aerosols. Introduction," IGAC Newslett., No. 35, 2–7 (2007).
15. J. Tollefson, "Carbon-sensing satellite system faces high hurdles," Nature (Gr. Brit.) **533** (7604), 446–447 (2016).
16. G. Popkin, "Commercial space sensors go high-tech," Nature (Gr. Brit.) **545** (7655), 397–398 (2017).
17. L. Costantino, J. Cuesta, E. Emili, A. Coman, G. Foret, G. Dufour, M. Eremenko, Y. Chailleux, M. Beekmann, and J.-M. Flaud, "Potential of multispectral synergism for observing ozone pollution by combining IASI-NG and UVNS measurements from the EPS-SG satellite," Atmos. Meas. Tech. **10** (4), 1281–1298 (2017).
18. R. Dupont, B. Pierce, J. Worden, J. Hair, M. Fenn, P. Hamer, M. Natarajan, T. Schaack, A. Lenzen, E. Apel, J. Dibb, G. Diskin, G. Huey, A. Weinheimer, Y. Kondo, and D. Knapp, "Attribution and evolution of ozone from Asian wild fires using satellite and aircraft measurements during the ARCTAS campaign," Atmos. Chem. Phys. **12** (1), 169–188 (2012).
19. T. Tanaka, Y. Miyamoto, I. Morino, T. Machida, T. Nagahama, Y. Sawa, H. Matsueda, D. Wunch, S. Kawakami, and O. Uchino, "Aircraft measurements of carbon dioxide and methane for the calibration of ground-based high-resolution Fourier Transform," Atmos. Meas. Tech. **5** (8), 2003–2012 (2012).
20. M. Inoue, I. Morino, O. Uchino, Y. Miyamoto, T. Saeki, Y. Yoshida, T. Yokota, C. Sweeney, P. P. Tans, S. C. Biraud, T. Machida, J. V. Pittman, E. A. Kort, T. Tanaka, S. Kawakami, Y. Sawa, K. Tsuboi, and H. Matsueda, "Validation of $XCH_4$ derived from SWIR spectra of GOSAT," Atmos. Meas. Tech. **7** (9), 2987–3005 (2014).
21. A. T. J. De Laat, I. Aben, M. Deeter, P. Nedelec, H. Eskes, J.-L. Attie, P. Ricaud, R. Abida, L. E. Amraoui, and J. Landgraf, "Validation of nine years of MOPITT V5 NIR using MOZAIC/IAGOS measurements: Biases and long-term stability," Atmos. Meas. Tech. **7** (11), 3783–3799 (2014).
22. H. S. Marey, Z. Hashisho, L. Fu, and J. Gille, "Spatial and temporal variation in CO over Alberta using measurements from satellites, aircraft, and ground stations," Atmos. Chem. Phys. **15** (7), 3893–3908 (2015).
23. O. Yu. Antokhina, P. N. Antokhin, V. G. Arshinova, M. Yu. Arshinov, B. D. Belan, S. B. Belan, D. K. Davydov, G. A. Ivlev, A. V. Kozlov, Ph. Nedelec, T. M. Rasskazchikova, D. E. Savkin, D. V. Simonenkov, T. K. Sklyadneva, G. N. Tolmachev, and A. V. Fofonov, "Vertical distributions of gaseous and aerosol admixtures in air over the Russian Arctic," Atmos. Ocean. Opt. **31** (3), 300–310 (2018).
24. T. August, D. Klaer, P. Schlussel, T. Hultberg, M. Crapeau, A. Arriga, A. O. Carroll, D. Coppens, R. Munro, and X. Calbet, "IASI on Metop-A: Operational Level 2 retrievals," . Quant. Spectrosc. Radiat. Transfer **113** (4), 1340–1371 (2012).
25. C. Crevoisier, A. Chedin, H. Matsueda, T. Machida, R. Armante, and N. A. Scott, "First year of upper tropospheric integrated content of $CO_2$ from IASI hyperspectral infrared observations," Atmos. Chem. Phys. **9** (14), 4797–4810 (2009).
26. C. Crevoisier, C. Clerbaux, V. Guidard, T. Phulpin, R. Armante, B. Barret, C. Camy-Peyret, J.-P. Chaboureau, P.-F. Coheur, L. Crepeau, G. Dufour, L. Labonnote, L. Lavanant, J. Hadji-Lazaro, and H. Herbin, "Towards IASI-New Generation (IASI-NG): Impact of improved spectral resolution and radiometric noise on the retrieval of thermodynamic,

chemistry and climate variables," Atmos. Meas. Tech. **7** (12), 4367–4385 (2014).

27. M. Yu. Arshinov, S. V. Afonin, B. D. Belan, V. V. Belov, Yu. V. Gridnev, D. K. Davydov, T. Machida, F. Nedelek, Zh.-D. Parizh, and A. V. Fofonov, "Comparison of satellite and aircraft measurements of gas composition in troposphere above the South of West Siberia," Opt. Atmos. Okeana. **26** (9) 773–782 (2013).
28. M. Yu. Arshinov, S. V. Afonin, B. D. Belan, V. V. Belov, Yu. V. Gridnev, D. K. Davydov, T. Machida, F. Nedelek, Zh.-D. Parizh, and A. V. Fofonov, "Comparison of satellite and aircraft measurements of gas composition in troposphere above Siberia in the period of wild fires of 2012," Issled. Zemli Kosmosa, No. **1**, 72–84 (2014).
29. C. Crevoisier, D. Nobileau, R. Armante, L. Crepeau, T. Machida, Y. Sawa, H. Matsueda, T. Schuck, T. Thonat, J. Pernin, N. A. Scott, and A. Chedin, "The 2007–2011 evolution of tropical methane in the mid-troposphere as seen from spase by MetOp-A/IASI," Atmos. Chem. Phys. **13** (8), 4279–4289 (2013).
30. X. Xiong, C. Barnet, E. S. Maddy, A. Cambacorta, T. S. King, and S. C. Wofsy, "Mid-upper tropospheric methane retrieval from IASI and its validation," Atmos. Meas. Tech. **6** (9), 2255–2265 (2013).
31. L. N. Yurganov and A. Leifer, "Estimates of methane emission rates from some Arctic and sub-Arctic areas based on orbital interferometer IASI data," Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli Kosmosa **13** (3), 173–183 (2016).
32. L. N. Yurganov, A. Leifer, and Mair K. Lund, "Seasonal and interannual variability of atmospheric methane over Arctic Ocean from satellite data," Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli Kosmosa **13** (2), 107–119 (2016).
33. A. V. Kukharskii and F. B. Uspenskii, "Monitoring of carbon dioxide mean tropospheric concentration over Siberian ecosystems from satellite-based high-resolution infrared sounders data," Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli Kosmosa **7** (4), 204–210 (2010).
34. A. V. Kukharskii and F. B. Uspenskii, "Determination of tropospheric mean carbon dioxide concentration from satellite high spectral resolution IR-sounder data," Rus. Meteor. Hydrol. **34** (4), 202–211 (2009).
35. A. B. Uspenskii, A. V. Kukharskii, S. V. Romanov, and A. N. Rublev, "Monitoring of $CO_2$ concentrations an the total methane in the troposphere above Siberia by IT sounding data from AIRS and IASI satellites," Issled. Zemli i kosmosa, No. 1, 14–21 (2011).
36. A. M. Michalak, L. M. P. Bruhwiler, and P. P. Tans, "A geostatistical approach to surface flux estimation of atmospheric trace gases," J. Geophys. Res. **109** (D14), D14109 (2004). doi 10.1029/2003JD004422
37. E. D. De Wachter, B. Barret, E. L. Flochmoen, E. Pavelin, M. Matricardi, C. Clerbaux, J. Hadji-Lazaro, M. George, D. Hurtmans, P. F. Coheur, P. Nedelec, and J. P. Cammas, "Retrieval of MetOp-A/IASI CO profiles and vilidation with MOZAIC," Atmos. Meas. Tech. **5** (11), 2843–2857 (2012).
38. A. Boynard, C. Clerbaux, L. Clarisse, S. Safieddine, M. Pommier, M. V. Damme, S. Bauduin, C. Oudot, and J. H. Lazaro, "First simultaneous space measurements of atmospheric pollutants in the boundary," Geophys. Res. Lett. **41** (2), 645–651 (2014).
39. O. E. Carcia, E. Sepulveda, M. Schneider, F. Hase, T. August, T. Blumenstock, R. Munro, A. J. Comez-Pelaez, T. Hultberg, A. Redondas, S. Barthlott, A. Wiegele, Y. Gonzalez, and E. Sanroma, "Consistency and quality assessment of the Metop-A/IASI and Metop- /IASI operational trace gas products ($O_3$, CO, $N_2O$, $CY_4$, and $CO_2$) in the subtropical North Atlantic," Atmos. Meas. Tech. **9** (5), 2315–2333 (2016).
40. J. Cuesta, M. Eremenko, X. Liu, G. Dufour, Z. Cai, M. Horfner, T. Clarmann, P. Sellito, G. Foret, B. Gaubert, M. Beekmann, J. Orphal, K. Chance, R. Spurr, and J.-M. Flaud, "Satellite observation of lowermost tropospheric ozone by multispectral synergism of IASI thermal infrared and GOME-2 ultraviolet measurements over Europe," Atmos. Chem. Phys. **13** (13), 9675–9693 (2013).
41. S. Safieddine, C. Clerbaux, M. George, J. Hadji-Lazaro, D. Hurtmans, P.-F. Coheur, C. Wespes, D. Loyola, P. Valks, and N. Hao, "Tropospheric ozone and nitrogen dioxide measurements in urban and rural regions as seen by IASI and GOME-2," J. Geophys. Res.: Atmos. 118 (18), 10555–10566 (2013).
42. H. Oetjen, V. H. Payne, S. S. Kulawik, A. Eldering, J. Worden, D. P. Edwards, G. L. Francis, H. M. Worden, C. Clerbaux, J. H. Lazaro, and D. Hurtmans, "Extending the satellite data record of tropospheric ozone profiles from Aura-TES to MetOp-IASI: Characterisation of optimal estimation retrievals," Atmos. Meas. Tech. **7** (12), 4223–4236 (2014).
43. N. Smith, Sr. W. L. Smith, E. Weisz, and H. E. Revercomb, "AIRS, IASI, and CrIS retrieval records at climate scales: An investigation into the propagation of systematic uncertainty," J. Appl. Meteorol. Climatol. **54** (7), 1465–1481 (2015).
44. A. Boynard, D. Hurtmans, M. E. Koukoli, F. Goutail, J. Bureau, S. Safieddine, C. Lerot, J. Hadji-Lazaro, C. Wespes, J. P. Pommereau, A. Pazmino, I. Zyrichidou, D. Balis, A. Barbe, S. N. Mikhailenko, D. Loyola, P. Valks, M. V. Roozendael, P. F. Coheur, and C. Clerbaux, "Seven years of IASI ozone retrievals from FORLI: Validation with independent total column and vertical profile measurements," Atmos. Meas. Tech. **9** (9), 4327–4353 (2016).
45. C. Wespes, D. Hurtmans, C. Clerbaux, and P.-F. Coheur, "$O_3$ variability in the troposphere as observed by IASI over 2008–2016: Contribution of atmospheric chemistry and dynamics," J. Geophys. Res.: Atmos. **122** (4), 2429–2451 (2017).
46. C. Wespes, L. Emmons, D. P. Edwards, J. Hannigan, D. Hurtmans, M. Saunois, P. -F. Coheur, C. Clerbaux, M. T. Coffey, R. L. Batchelor, R. Lindenmaier, K. Strong, A. J. Weinheimer, J. B. Nowak, T. B. Ryer-

son, J. D. Crounse, and P. O. Wennberg, "Analysis of ozone and nitric in spring and summer Arctic pollution using aircrat, ground-based, satellite observations and MOZART-4 model: Source attribution and partitioning," Atmos. Chem. Phys. **12** (1), 237–259 (2012).

47. M. Pommier, C. Clerbaux, K. S. Law, G. Ancellet, P. Bernath, P.-F. Coheur, J. Hadji-Lazaro, D. Hurtmans, P. Nedelec, F. Ravett, T. B. Ryerson, H. Schlager, and A. J. Weinheimer, "Analysis of IASI tropospheric $O_3$ data over the Arctic during POLARCAT campaigns in 2008," Atmos. Chem. Phys. **12** (16), 7371–7389 (2012).
48. J. Gazeaux, C. Clerbaux, M. George, J. Hadji-Lazaro, J. Kuttippurath, P. -F. Coheur, D. Hurtmans, T. Deshler, M. Kovilakam, P. Campbell, V. Guidard, F. Rabier, and J.-N. Thepaut, "Intercomparison of polar ozone profiles by IASI/MetOp sounder with 2010 Concordiasi ozonesonde observations," Atmos. Meas. Tech. **6** (3), 613–620 (2013).
49. V. G. Arshinova, B. D. Belan, G. A. Ivlev, T. M. Rasskazchikova, D. V. Simonenkov, G. N. Tolmachev, and A. V. Fofonov, "Complex assessment of the conditions of the air basin over Norilsk industrial region. Part 4. Vertical stratification of contaminants," Atmos. Ocean. Opt. **19** (10), 814–817 (2006).
50. B. D. Belan, G. N. Tolmachev, and A. V. Fofonov, "Ozone vertical distribution in the troposphere over south regions of Western Siberia," Atmos. Ocean. Opt. **24** (2), 181–187 (2011).
51. P. N. Antokhin, V. G. Arshinova, M. Yu. Arshinov, B. D. Belan, S. B. Belan, D. K. Davydov, G. A. Ivlev, A. V. Kozlov, F. Nedelek, J.-D. Paris, T. M. Rasskazchikova, D. E. Savkin, D. V. Simonenkov, T. K. Sklyadneva, G. N. Tolmachev, and A. V. Fofonov, "Large-scale studies of gaseous and aerosol composition of air over Siberia," Opt. Atmos. Okeana **27** (3), 232–239 (2014).
52. B.D. Belan, *Tropospheric Ozone* (Publishing House of IAO SB RAS, Tomsk, 2010) [in Russian].

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