
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

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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 CH₄ and CO₂ 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 CO₂ 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 O₃.

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 epi-

sodic 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 CH₄ 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

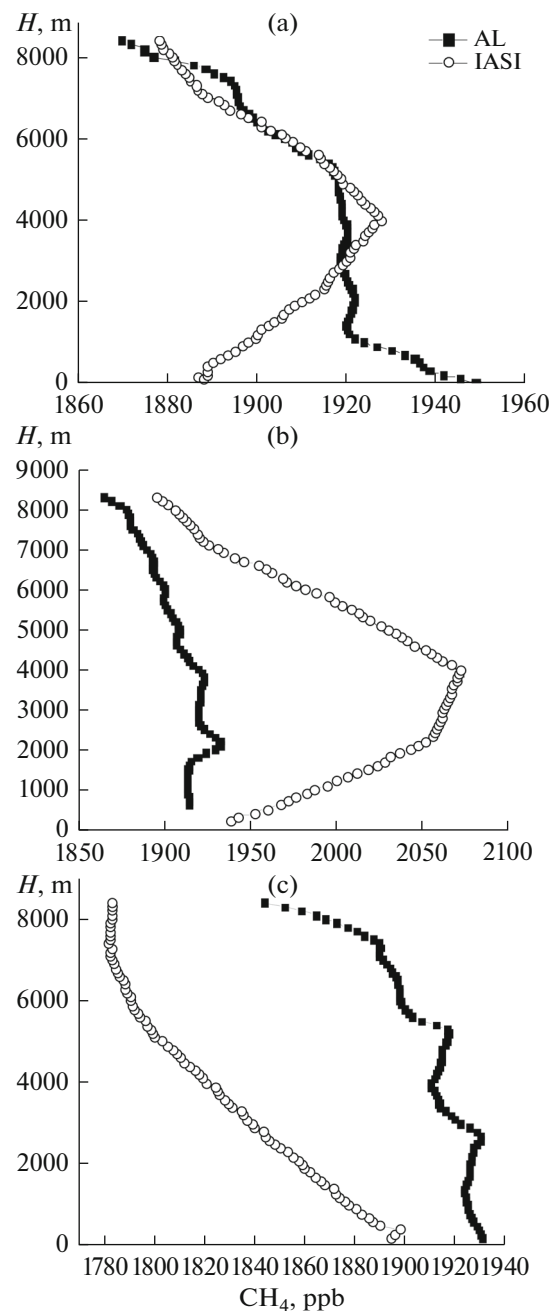


Fig. 1. Vertical distributions of AL- and IASI-measured CH₄ concentrations over (a, b) continent and (c) ocean.

Table 1. The distribution of CH₄ 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 CH₄ 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 CH₄ 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

Table 3. Distribution of CO₂ 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

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 $>10^\circ\text{C}$, versus $>25^\circ\text{C}$ in our experiments, suggesting that the instrument operated at temperatures exceeding the threshold.

The polar differences in the satellite measurements over continent and ocean are also recorded for CO₂ (Table 3).

Data in Table 3 indicate that AL- and IASI-measured vertical CO₂ distributions coincided in two cases over continent. For nine profiles, the satellite-based CO₂ concentration was larger than its AL counterpart. On the contrary, AL recorded higher concentrations in five cases over ocean. The IASI-derived CO₂ content was larger in just two cases.

Typical vertical CO₂ distributions, measured by both instruments over continent and ocean, are presented in Fig. 2.

Figure 2 shows that altitudinal variations in CO₂ 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 CO₂ 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

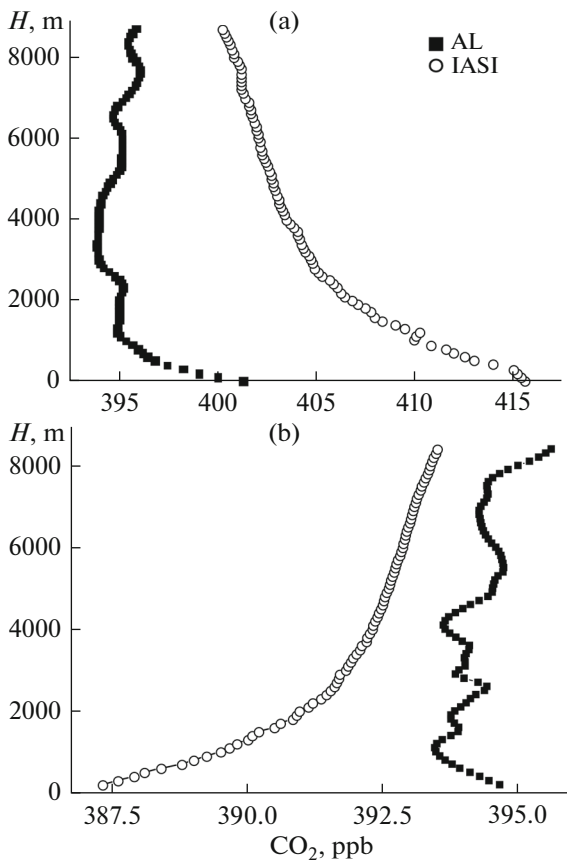


Fig. 2. Vertical distributions of AL- and IASI-measured CO₂ concentrations over (a) continent and (b) ocean.

and variability ranges. As for CH₄, 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].

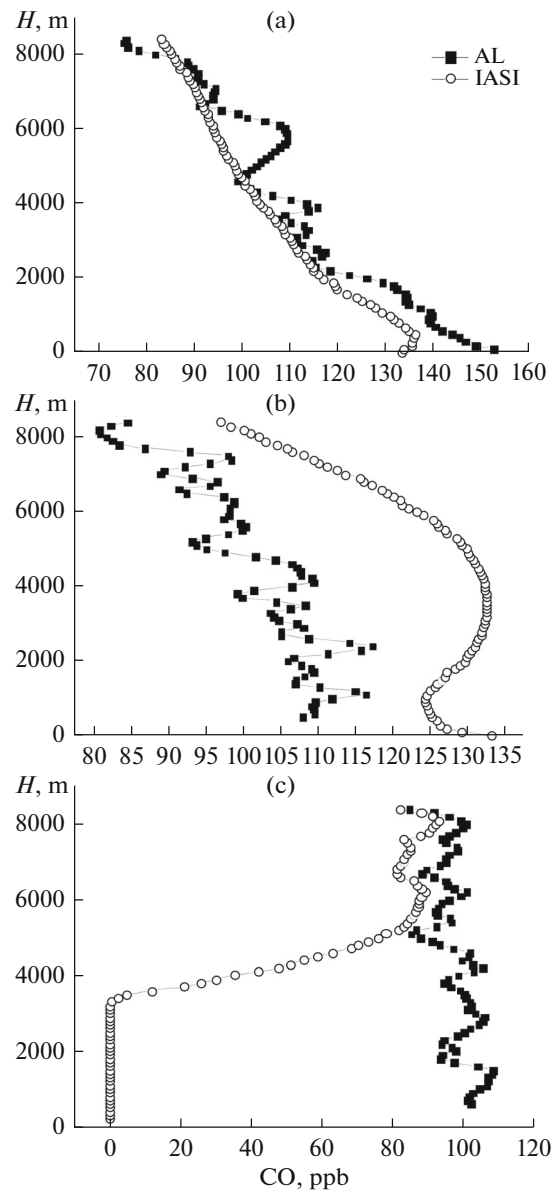


Fig. 3. Vertical distributions of CO concentrations over (a, b) continent and (c) ocean.

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 CO₂ 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 O₃ with IASI instrument, ozone-sondes, and other techniques were compared in many publications [40–45]; it was shown that O₃ 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 O₃ 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 O₃ 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 O₃ 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

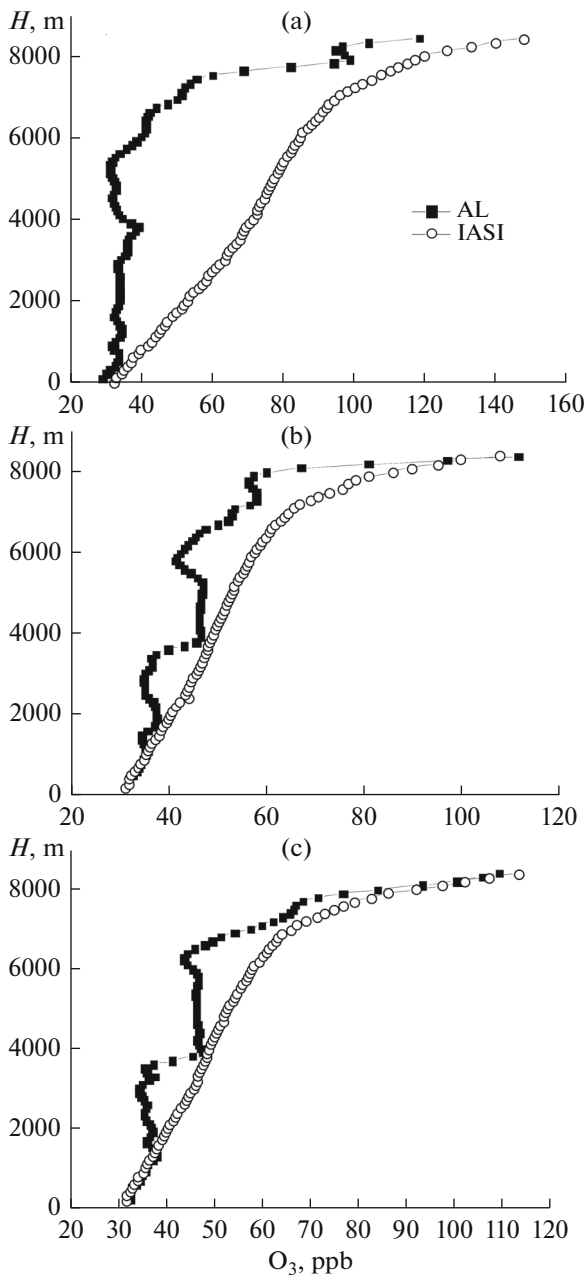


Fig. 4. Vertical distributions of O_3 concentrations over (a, b) continent and (c) ocean.

[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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