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Comparison between Satellite and Ground-Based NO_2 Total Content Measurements

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Abstract—The results of measuring the total content of NO_2 by the *ERS-2* satellite (GOME instrumentation) in 1996 and in the first half of 1998 are compared to the data of simultaneous ground-based measurements carried out at Zvenigorod (Moscow region, Russia). In a number of cases, the satellite data are significantly greater in value than the ground-based data. For the first half of 1996, the mean difference between the GOME data and the half-sum of the sunset and sunrise ground-based data amounts to about 33%. The accuracy of the satellite measurements performed in 1998 is found to be significantly higher than that in 1996, which appears to be associated with the improvement of the GOME data processing technique.

INTRODUCTION

Monitoring nitrogen oxides in the atmosphere is of importance in connection with their role in the photochemical balance of ozone and other climatically and photochemically active gases [1, 2]. Information about the NO_2 content and horizontal distribution near the tropopause is of special interest. This information is necessary to estimate NO_x emissions due to increasing air traffic. These emissions affect the ozone content in the upper troposphere, creating, in particular, the maximum greenhouse effect.

A significant amount of information about spatial and temporal variations in the NO_2 content is obtained from satellite measurements. A slant geometry of observations is used in most such measurements. For example, in the SAGE II and POEM-2 experiments, NO_2 vertical profiles in the atmosphere were recovered from sunrise and sunset measurements of the absorption of solar radiation in the visible spectral region at slant paths [3, 4]. Similar measurements in the IR region of the spectrum were carried out in some satellite experiments by using IR instrumentation: a spectrometer [5] and the ATMOS interferometer [6, 7]. In the experiments described in [8–11], spatial and temporal variations in the NO_2 vertical structure were studied by measuring the thermal IR radiation of the earth's horizon. All those experiments studied the NO_2 distribution in the stratosphere.

Starting in 1995, nadir measurements of the NO_2 total content have been performed with the GOME spectrometer (*ERS-2* satellite). These measurements are based on an interpretation of the outgoing reflected and scattered solar radiation in the visible region [12]. A small absorption by NO_2 at nadir paths in the spectral region of interest (the optical thickness is 0.01–0.02, with variations of about 0.005) is responsible for a low accuracy of these measurements. According to the data of the European Space Agency (ESA), their errors can reach 100%. A comparison between satellite data and similar independently measured (ground-based, aircraft, sounding) data close to them in time and space makes it possible to estimate the actual accuracy of satellite measurements (see, for example, [13]), to reveal systematic errors in data obtained with different observation techniques, and to introduce corrections to data-processing algorithms.

The existing network of ground-based measurements of the NO_2 total content is sparse compared, for example, to the ground-based network of total ozone measurements. On the territory of Russia and other CIS states, the NO_2 total content is currently being measured at only five stations. This work compares the GOME data on the NO_2 total content and the ground-based data obtained at the Zvenigorod Research Station (ZNS) of the Institute of Atmospheric Physics (IFA), Russian Academy of Sciences. This station is incorporated into the International Network for Detection of Stratospheric Change (NDSC) as a station of high-quality NO_2 total content measurements.

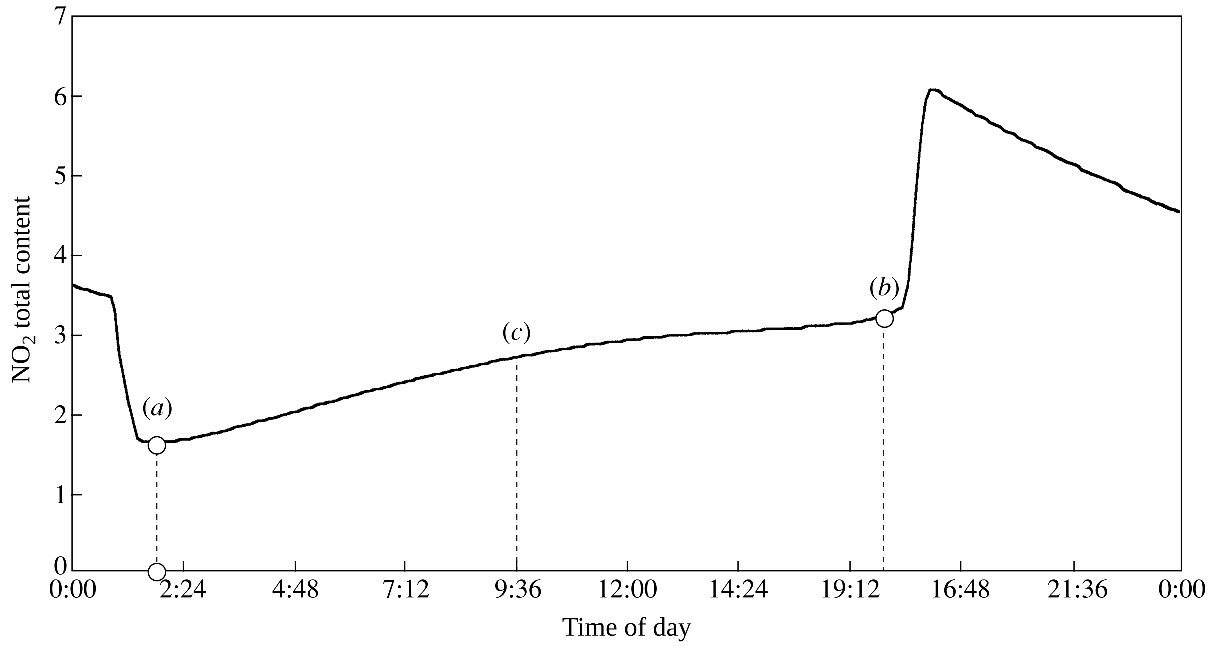

Fig. 1. Diurnal variation of the NO_2 total content near Zvenigorod in August calculated by a three-dimensional atmospheric model [20] (NO_2 unit is 10^{15} mol/cm^2, Greenwich time). Astronomical sunrise (*a*) and sunset (*b*) and also local noon (*c*) are marked in the figure.

GROUND-BASED MEASUREMENTS OF THE NO_2 TOTAL CONTENT AT THE IFA ZVENIGOROD RESEARCH STATION

The ZNS is situated at a distance of 60 km west of the center of Moscow and has the coordinates (55.42° N, 36° E). The station is placed in a rural area on the windward side of Moscow. The prevailing wind direction here is westward during most of the year. Major highways are far away from the station. Nevertheless, air pollution due to a distant transport of pollutants is observed occasionally in the troposphere. The pollutants are the most intense and frequent in winter. The procedure used to control the quality of data makes it possible to reject the data obtained under the conditions of a polluted troposphere. In addition, the interpretation technique used to determine the NO_2 total content and vertical profile enables the elimination of the NO_2 content in the polluted surface layer.

NO_2 observations at the ZNS have been carried out since March 1990. In studies [14, 15], the measurement method used at the ZNS is described and some results of NO_2 total content measurements at the ZNS are analyzed. In September 1997, comparisons with the NDSC benchmark instrument were made. The error in determining the NO_2 slant content amounts to about 10% [16].

The NO_2 content is determined from measurements of the intensity of solar radiation scattered at the zenith. The spectral range of the measured solar radiation is 435–450 nm, the resolution is 0.7 nm, and the scanning time is 40 s. Observations are performed during periods of sunrise and sunset twilight at solar zenith angles of 84° to 96°. The NO_2 total content at the path of radiation formation (slant content) is retrieved from spectral measurements taken by the differential-absorption method.

In order to determine the NO_2 total content in a vertical column of the atmosphere, it is necessary to know the corresponding air mass values. These values are calculated on the basis of the theory of solar radiation transfer in a spherical atmosphere in the single scattering approximation, with invoking a nonstationary one-dimensional photochemical model for O_x and NO_x. The model of radiative transfer in a spherical atmosphere takes into account ozone and NO_2 absorption, molecular and aerosol single scattering, refraction, and refraction divergence. The model's parameters—the vertical profiles of ozone, temperature, and air density—are extracted either from simultaneous measurements or, in their absence, from empirical models corresponding to the observation latitude and season [17–19].

The photochemical model makes it possible to calculate the daily variation of NO_2 vertical distribution, which is the input parameter of the model of radiative transfer. Considering photochemical processes is very important, because the NO and NO_2 contents undergo abrupt changes during periods of twilight.

The air mass values obtained are used in solving the inverse problem for the recovery of the NO_2 vertical distribution by a method similar to that employed by

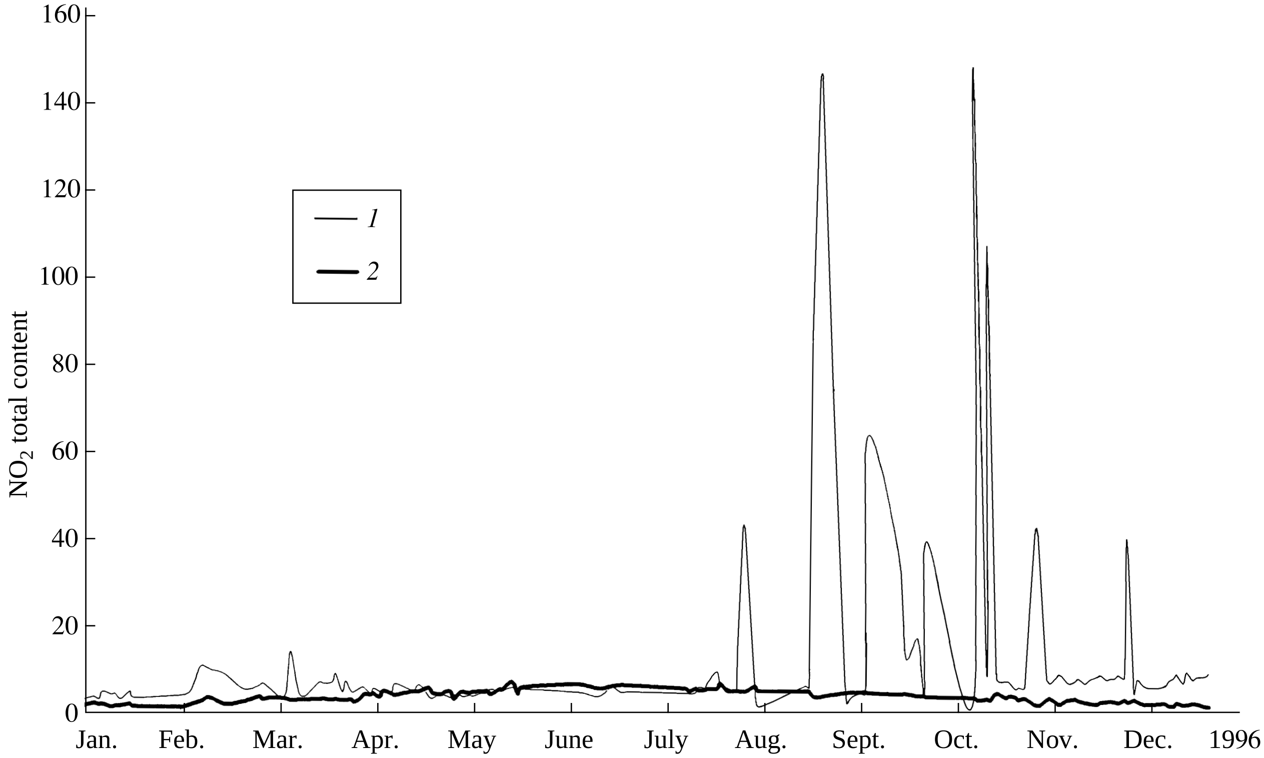

Fig. 2. Comparison of the data of daily GOME measurements of the NO_2 total content (*1*) with the arithmetic mean of the morning and evening NO_2 total contents inferred from ZNS observations (*2*) in 1996 (NO_2 unit is 10^{15} mol/cm^2).

McKenzie *et al.* [19]. The following quantities are determined: (1) the NO_2 content in 5-km layers in the stratosphere and troposphere (0–50 km), (2) the NO_2 content in a thin atmospheric surface layer, and (3) the NO_2 total contents in the troposphere (0–10 km) and stratosphere (10–50 km) as the sum of the NO_2 contents within the corresponding layers. The morning and evening NO_2 profiles and its total content are reduced to a solar zenith angle of 84°, which corresponds to the "daytime" portion of the NO_2 daily variation.

COMPARISON BETWEEN SATELLITE AND GROUND-BASED DATA OF NO_2 TOTAL CONTENT MEASUREMENTS

The NO_2 total content exhibits significant daily variations, especially at sunrise and sunset. An example of the calculated daily variation of the NO_2 content is presented in Fig. 1 (August, Zvenigorod). The calculation was made using a three-dimensional transport photochemical model of the atmosphere [20].

As follows from Fig. 1, the NO_2 content decreases abruptly at sunrise, then increases smoothly during daytime, and also increases abruptly at sunset. According to calculations, the NO_2 content varies rather slowly during daytime: the difference between evening and morning values ranges between 31% in winter and 57% in summer. The figure marks the times of astronomical sunrise (*a*) and sunset (*b*) and also the local noon point (*c*). The NO_2 content at this point is seen to be greater than its morning value but smaller than its evening value, being closer to the arithmetic mean of these two values. Since the *ERS-2* satellite equipped with the GOME instrument has a sun-synchronous orbit, its measurements occur at local noon points. Thus, the GOME data yield the NO_2 total content value closest to the arithmetic mean of the morning and evening values obtained from ground-based observations.

Figure 2 presents the results of pair comparisons between ground-based (ZNS) and satellite (GOME) data of NO_2 measurements. An ensemble of simultaneous measurements consisted of 331 GOME measurements taken during 1996 (processing version 2.0) and also 280 morning and 286 evening ground-based measurements. In order to take into account the NO_2 daily variation, we compared the GOME data to the arithmetic mean of the morning and evening values obtained from the corresponding ground-based data (in the absence of one of these two ground-based values, the available value was used in place of the arithmetic mean).

Comparing the satellite and ground-based data indicates that these data are generally inconsistent. The statistical characteristics obtained for the discrepancies observed between satellite (*s*) and ground-based (*g*) NO_2 measurements for the data ensembles under con-

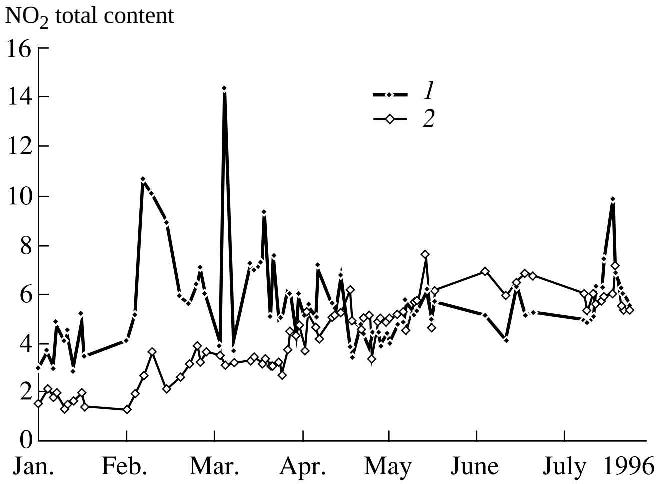

Fig. 3. Comparison of the data of daily GOME measurements of the NO_2 total content (*1*) with the arithmetic mean of the morning and evening NO_2 total contents inferred from ZNS observations (*2*) from January 1 to July 26, 1996 (NO_2 unit is 10^{15} mol/cm^2).

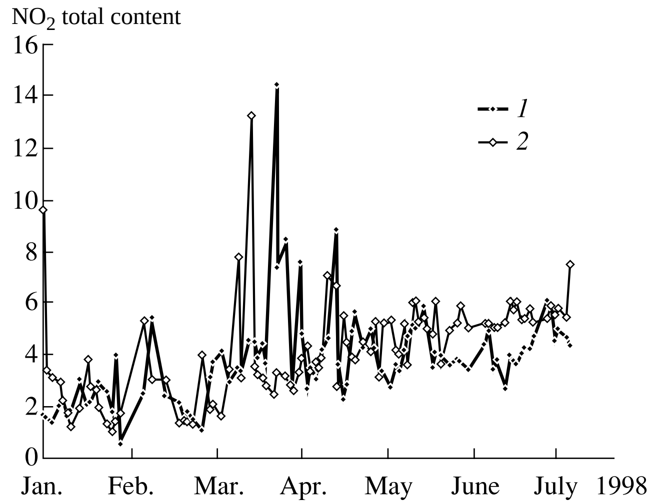

Fig. 4. Comparison of the data of daily GOME measurements of the NO_2 total content (*1*) with the arithmetic mean of the morning and evening NO_2 total contents inferred from ZNS observations (*2*) from January 1 to July 9, 1998 (NO_2 unit is 10^{15} mol/cm^2).

sideration also confirm this conclusion. The average discrepancy Δ_{s-g} amounts to 180%, the rms discrepancy σ_{s-g} reaches 550% (discrepancies are calculated about the average ground-based value), and the correlation coefficient R is equal to -0.04 ± 0.05. On the whole, the NO_2 total content obtained from the GOME data is significantly (several times) greater than that inferred from ground-based observations. Particularly strong discrepancies between satellite and ground-based data in the form of sharp significant increases in the NO_2 content inferred from GOME measurements were observed in the fall of 1996 (Fig. 2). Most likely, these discrepancies are associated with errors in the spectral calibration of GOME measurements in the period from July 29 to October 15, 1996. These errors were revealed by the ESA only after the data on the NO_2 total content had already been disseminated.

Figure 3 presents the results of a similar comparison made for an ensemble of data obtained from January to July 1996 (75 simultaneous measurements). This comparison demonstrates a better agreement between ground-based and satellite data. The average discrepancy Δ_{s-g} amounts to 33%, and $\sigma_{s-g} = 67\%$. As previously, the correlation between the data is insignificant: the correlation coefficient R is 0.00 ± 0.12. The figure clearly demonstrates substantial distinctions between the NO_2 seasonal variations inferred from satellite and ground-based (Zvenigorod) measurements. The results of NO_2 satellite measurements from January to April are substantially greater than the data of ground-based measurements and do not reveal any seasonal variation in NO_2. On the other hand, the ZNS data show an increase in the NO_2 total content from winter to summer, which is characteristic of NO_2.

A comparison between the data of ground-based evening measurements and the data of GOME measurements (processing version 2.3) made in the first half of 1998 is demonstrated in Fig. 4 (94 simultaneous measurements). The satellite NO_2 total content values are, on average, 8% less than the ground-based values, and the rms discrepancy comprises 57%. By comparing these results with the discrepancies obtained for the 1996 observational data, we can infer that the GOME data are in significantly better agreement with the ground-based data obtained in 1998. The correlation between the satellite and ground-based NO_2 data obtained in the first half of 1998 amounted to 0.22 ± 1.10. The statistical characteristics of the corresponding discrepancies are presented in the table.

ANALYSIS OF COMPARISON RESULTS

A significant discrepancy (up to 500% for the rms discrepancy) is revealed between the data of satellite and ground-based measurements of the NO_2 total content. The NO_2 content values inferred from GOME measurements are frequently greater than those obtained from ground-based measurements. In light of the fact that the ground-based instrumentation and method of measuring the NO_2 total content at the ZNS have been certified within the framework of the NDSC, we can address the low quality of the NO_2 content data inferred from the satellite GOME measurements carried out in the ZNS region in 1996 (processing version 2.0).

On the whole, the results of our comparisons between two systems of measuring the total NO_2 content are consistent with the data of other studies aimed at validating the GOME instrumentation. For example, the authors of work [21] compared the data of the GOME measurements taken from July to December 1995 with observational data of 19 ground-based stations located in different regions and showed that the GOME significantly overestimated the NO_2 content compared to ground-based observations: discrepancies were as high as 500%. In [22], NO_2 total content measurements were correlated with the simultaneous ground-based observations made in Bremen (Germany) and Ny-Alesund (Spitzbergen, Norway) in September 1995. The satellite data turned out to be, on average, 60% greater than the ground-based data. In [23], the GOME data were compared to the data of ground-based measurements of the NO_2 total content in Antarctica. It has been found that the GOME data are in good agreement with the data of ground-based observations and exceed them slightly.

Thus, the results of different studies demonstrate a systematic excess of the NO_2 total content values inferred from the GOME data over those obtained from ground-based measurements. Most authors [21–23] relate the observed discrepancy to some specific properties of NO_2 ground-based measurements. Under the conditions of the troposphere slightly polluted by nitrogen oxides, the method employed by most authors in ground-based measurements is more sensitive to the stratospheric part of the NO_2 layer. On the other hand, the data of GOME nadir measurements include the NO_2 total content throughout the entire atmosphere. In industrial and densely populated regions, the tropospheric NO_2 content can contribute significantly to the NO_2 total content. It is possible that this fact is responsible for the rather good agreement between the data of satellite and ground-based measurements in Antarctica, which represents the region with the background NO_2 content in the troposphere. However, this cause for discrepancies is unlikely in the case of NO_2 measurements at the ZNS, because these measurements are analyzed using an original interpretation method that makes it possible to determine the NO_2 total content from its tropospheric and stratospheric components.

It is believed that the main cause for discrepancies is a low information content (with respect to the NO_2 content) of nadir measurements of the outgoing reflected and scattered solar radiation. However, these discrepancies must be random rather than systematic in character.

The cloudiness frequently observed in the field of view of the GOME instrument must lead to the underestimation of the NO_2 content, because clouds partially shadow the troposphere.

There are also other possible causes for discrepancies.

(1) Spatial mismatch of measurements: the regions of formation of the solar radiation scattered at the zenith in ground-based measurements may be beyond the position of a frame of satellite measurements. In the presence of tropospheric air pollutants (for example, in the Moscow region) that do not cover Zvenigorod, an abrupt excess of the GOME data over the ground-based data is possible.

(2) Errors caused in satellite measurements by errors in determining the height and amount of clouds, the albedo of the underlying surface, and other parameters.

(3) Differences in the parameters of radiative models used for satellite and ground-based measuring systems: molecular absorption coefficients, prior information about the state of the atmosphere, etc.

Statistical characteristics of the discrepancies between satellite (s) and ground-based (g) NO_2 total content measurements in 1996 and 1998: average (Δ_{s-g}) and rms (σ_{s-g}) discrepancies and correlation coefficient R

	Jan.–Dec., 1996	Jan.–July, 1996	Jan.–July, 1998
Δ_{s-g}	176%	33%	–8%
σ_{s-g}	549%	67%	57%
R	–0.04 ± 0.05	0.00 ± 0.12	0.22 ± 0.10

CONCLUSIONS

A comparison between the GOME data on the NO_2 total content and the data of NO_2 content ground-based measurements at the Zvenigorod Research Station of the Institute of Atmospheric Physics, Russian Academy of Sciences, (56° N, 38° E), leads to the following inferences.

(1) A poor agreement is noted between the data of NO_2 total content measurements at the ZNS and the GOME data in 1996. On average, the GOME data significantly overestimate the NO_2 total content as compared to the data of ground-base measurements.

(2) A somewhat smaller discrepancy between satellite and ground-based data is obtained for an ensemble of data from January to July 1996. The correlation between the data of these two types of measurements remains very low. It is possible that a low quality of the GOME data obtained in the second half of 1996 is associated with gross errors in the on-line processing of measurement results.

(3) Satellite measurements taken in the first half of 1998 (processing version 2.3) yield significantly better results compared to the data of 1996 (processing version 2.0). This is possibly due to the improvement of the method used for processing GOME measurements. Satellite measurements from January to July 1998 yield NO_2 total content values that are, on average, 8% less than those obtained from ground-based measurements at the ZNS; the corresponding rms discrepancy σ_{s-g} = 57%.

On the whole, it is noteworthy that the GOME data on the NO_2 total content, which are disseminated by the ESA, should be used with care in solving scientific and applied problems. This is also confirmed by the fact that, in May–July 1999, the ESA performed additional tests and improvements of the processing algorithms used in the GOME measurements.

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