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Determining the Total Ozone from Geostationary Earth Satellites

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Abstract—A method for determining the total ozone (TO) with high spatial (3×3 km^2) and temporal (15 min) resolutions by using measurements of the Earth's outgoing thermal radiation from Meteosat geostationary satellites is proposed. The method is based on measurements with a SEVIRI instrument (eight IR channels) and involves additional information on the three-dimensional field of the atmospheric temperature and on the surface temperature obtained from polar satellites (AIRS instrument). The inverse problem of TO determination is solved by the method of neural networks. TO measurements with the AIRS instrument are also used for training the neural networks. Ground-based TO measurements at the international ozonometric network are used for controlling the quality of AIRS data and detecting the errors of the proposed method of TO determination from SEVIRI data. The mean and rms differences between TO values obtained with the use of the proposed method and from the results of measurements at the international ozonometric network are shown to be 1.5 and 6.5%, respectively. Examples of TO distributions reconstructed with high spatial and temporal resolutions are presented. These examples show that the elaborated method for solving various scientific and applied problems and, in particular, for investigating stratospheric dynamics is promising.

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1. INTRODUCTION

The study of spatiotemporal variations in the ozone content in the Earth's atmosphere is an important problem connected with the substantial influence of ozone on the climate of the planet and the UV illuminance of the Earth's surface, as well as with the toxicity and high oxidizing abilities of ozone in the troposphere [1, 2]. Ozone investigations have long been carried out by ground-based and satellite methods. In recent decades, vast volumes of information about ozone content have been obtained with the use of various satellite methods [1–4]. Satellite sounding of the ozonosphere is based on measurements of transmittance spectra of the atmosphere on tangent paths from the radiation of the Sun, Moon, and stars in a wide region of the spectrum; measurements of the radiation of the atmosphere; as well as measurements of the reflected and scattered solar radiation at different geometry of satellite experiments. These observation methods are used mainly at polar satellites; however, attempts to determine the total ozone (TO) from geostationary satellites have been made recently [5–8]. A SEVIRI instrument measuring the outgoing radiation of the Earth in several channels in the visible and IR regions of the spectrum (including the band of ozone absorption near 9.6 μm) operates on a Meteosat geostationary satellite. This instrument makes it possible, in principle, to obtain unique information about a quasi-global TO distribution at a high rate (each 15 min) and a high spatial (up to 3×3 km^2) resolution. Such information is of considerable interest for studying mesoscale space–time TO variations, obtaining regional estimates of the UV illuminance of the Earth's surface in the operational regime, and constructing multiyear TO trends. A high rate of spatial TO-field observations can also be helpful in studying dynamic characteristics of the stratosphere.

As previous investigations have shown, the information content of TO measurements with the SEVIRI instrument is insufficiently high for obtaining data with an error smaller than 10% [5]. For this reason, an approach to TO determination from geostationary satellites on the basis of a combined use of measurements from polar and geostationary satellites is proposed, investigated, and illustrated in this study.

2. METHOD OF TO MEASUREMENTS FROM GEOSTATIONARY SATELLITES

The proposed method uses measurements of the outgoing radiation in IR channels of the SEVIRI instrument (Table 1).

Investigations have shown that the IR measurements alone do not contain a sufficient amount of information to determine TO with an admissible accuracy in all latitudinal zones where SEVIRI measurements are being performed [5]. The temperature profile T(z) and the surface temperature T_s are the most

Table 1. Infrared measuring channels of the SEVIRI instrument

Channel number	Channel center		Interfering and target atmospheric parameters
	cm^{-1}	μm	
4	2555.73	3.9	Surface temperature, low cloudiness, fogs
5	1588.79	6.3	Water vapor, wind, height of semitransparent cloudiness
6	1359.93	7.4	Semitransparent cloudiness
7	1148.28	8.7	″
8	1034.05	9.7	Ozone
9	927.76	10.8	Surface temperature, total content of water vapor
10	837.82	11.9	Surface temperature, total content of water vapor
11	749.7	13.3	Temperatures in the lower stratospheres clouds

Table 2. Information used in the method of TO retrieval

System of measurements	Instruments	Data	Purpose
Aura polar satellite	AIRS spectrometer	Stage 1. TO field; stages 1 and 2. Three-dimensional fields of atmospheric temperature and surface temperature	Stage 1. Construction of the solving operator of the inverse problem; stage 2. TO determination from SEVIRI data
Meteosat-8 geostationary satellite	SEVIRI	Radiation in eight IR spectral channels	Stage 1. Construction of the solving operator; stage 2. TO determination with the use of an independent sample
Ground-based ozonometric network	Dobson and Bruer spectrometers, M-124 photometer	TO	Control of the quality of TO measurements with AIRS and SEVIRI instruments

important additional parameters (apart from the vertical profile of ozone and TO) affecting the outgoing thermal radiation. The SEVIRI instrument cannot determine the atmospheric temperature profile; therefore, it is natural to invoke data on T(z) and T_s as additional information. Such information can be obtained from other satellites (in particular, polar satellites) equipped with more informative spectral instrumentation and from the results of weather analysis and forecasting. In implementing this method, we use the results of atmosphere sounding at 24 height levels and at the Earth's surface with an Aura satellite instrument (AIRS) [9, 10]. AIRS data are used for both constructing the solving operator of the inverse problem (first stage of the method) and TO determination from SEVIRI data for an independent set of measurements (second stage of the method). In the first case, apart from the fields of atmospheric and surface temperatures, TO data measured with the same instrument are employed. In the second case, only data on T(z) and T_s are used (Table 2). The sounding data with the AIRS instrument [9, 10] are freely accessible on the Internet at the address: http://disc.gsfc.nasa.gov/AIRS/data_products.shtml.

Additionally, we used data of ground-based TO measurements at the international ozonometric network (http://www.woudc.org) [11] both to control the accuracy of TO measurements with the AIRS instrument and to analyze the quality of the method proposed by us. The data of measurements with Dobson and Bruer spectrophotometers and with an M-124 filter ozonometer were used in this case. A brief summary of the main information used at different stages of implementation of the proposed method is given in Table 2.

The geostationary position of the SEVIRI instrument (Meteosat-8 satellite) makes it possible to perform observations in a circle with the center at the origin of geographical coordinates (the satellite is located precisely over this point) (Fig. 1). The size of this circle is controlled by the condition of visibility of the satellite from the observed point of the Earth's surface at a zenith angle less than 75°. For this reason we used only data of the stations located within the spec-

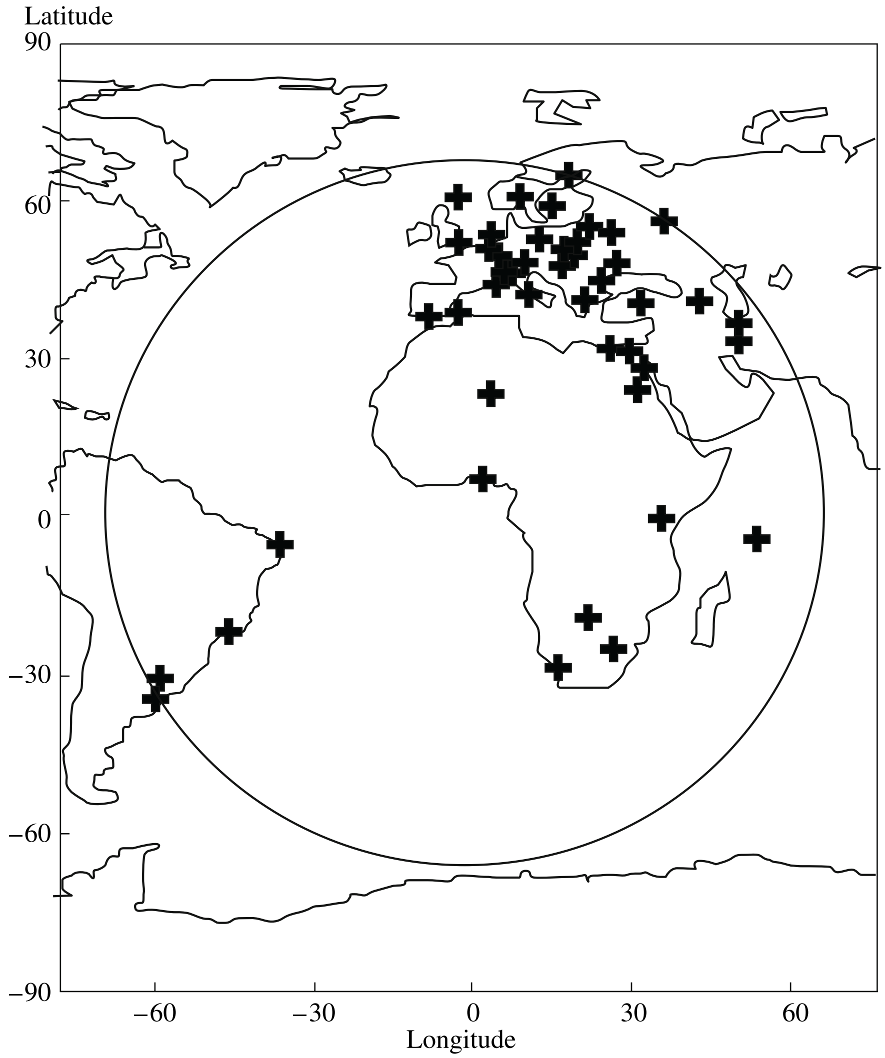

Fig. 1. Observation region of the SEVIRI instrument and positions of stations of the ozonometric network whose data are used in the study.

ified circle (41 stations). The positions of these stations and the region of observations from the Meteosat-8 geostationary satellite are shown in Fig. 1.

Although ground-based TO observations are undoubtedly more accurate and reliable and are used for validating satellite TO measurements, their limited number makes them unsuitable for direct use in the problems of constructing the solving operator in the regression approach to TO retrieval from satellite measurements with the SEVIRI instrument. For this reason we used data of TO measurements with the AIRS instrument for constructing the solving operator of the inverse problem [9, 10], which allowed us to almost completely cover the region of observations from the geostationary satellite by TO measurements. We used AIRS data of level 3, i.e., the data for each day of observations, collected together and averaged on the latitude–longitude grid with a step of one degree. Note that we selected the measurements on the ascending branches of trajectories of the AIRS satellite that corresponded to the daytime conditions of observations, which makes it possible to regard them as correlated in time (within several hours) with the ground-based TO observations from solar radiation.

Since we try to relate our algorithms of TO retrieval from SEVIRI measurements to the data of ground-based measurements, it is necessary to investigate the quality of the AIRS TO measurement results used by us. In order to do this, we selected pairs consisting of AIRS TO measurements and the measurements at ground-based stations in their 100-km vicinity that were performed on the same day. We used measurements conducted over 26 days which were approximately uniformly distributed over seasons; in all, 761 pairs of measurements were used. The statistical characteristics of TO values resulting from ground-based and satellite measurements and the TO differences (data of ground-based measurements are

Table 3. Statistical characteristics of comparison of data of ground-based and satellite TO measurements

Row	Type of measurements	Mean TO in DU	TO standard deviation in DU (%)	Mean difference in DU (%)	RMS difference in DU (%)	Correlation coefficient
1	Ground-based measurements	311.3	43.8 (14.0)	9.7 (3.1)	23.4 (7.5)	90.8
2	AIRS instrument	321.0	50.6 (16.3)			

Table 4. Statistical characteristics of a comparison between TO values obtained from SEVIRI measurements of the outgoing radiation with the use of the developed method and TO values obtained from ground-based measurements

Row	Number of neurons in the hidden layer and type of the activation function of the neural network	Deviations from data of ground-based measurements, %		
		Mean	rms	Correlation coefficient
1	1, logsig	–2.7	8.1	0.88
2	2, logsig	2.2	7.1	0.91
3	3, logsig	1.5	6.5	0.92
4	4, logsig	1.3	6.8	0.91
5	1, purelin	3.0	8.3	0.88
6	3, tansig	1.5	6.5	0.92
Without division into latitudinal belts				
7	3, tansig	2.7	7.1	0.91
8	3, logsig	2.8	7.0	0.92

subtracted from data of satellite measurements, and relative values of the differences are calculated with respect to data of ground-based measurements) are presented in Table 3 (rows 1, 2). The TO standard deviations for the two data sets are close to each other, although the variability of the data of TO satellite measurements is higher than that of ground-based data: 50.6 as opposed to 43.8 DU, which can be explained by their greater error. It follows from Table 3 that the rms discrepancy between satellite and ground-based TO data in relative units is 7.5%. The mean difference between these data is about 10 DU, i.e., 3.1%, and the correlation coefficient is 90.8%.

3. FORMATION OF THE SOLVING OPERATOR OF THE INVERSE PROBLEM (METHOD OF NEURAL NETWORKS)

In solving the inverse problem of TO retrieval from SEVIRI data with invoking additional information, we used a neural network (see, e.g., [12]). Networks with different numbers of layers, different amounts of neurons in a layer, and different functions of activation (designated as tansig, logsig, purelin) were considered. Since the amount of neurons in the output layer is controlled by the number of parameters calculated with the use of the neuron network, in our case it is a single neuron. Since the neural network, as opposed to multiple linear regression which was used by us previously [5], takes into account nonlinear dependences as well, the zenith angle at which the satellite is visible from the observed point of the Earth's surface was also included as one of the input parameters. Measurements in eight IR spectral channels of the SEVIRI instrument, the three-dimensional field of the atmospheric temperature, the surface temperature field, and the TO field (AIRS data) were used for training the neural network. Radiation intensities measured in eight SEVIRI channels, the height profile of the air temperature, and the underlying-surface temperature (AIRS data) served as the input parameters of the neural network when the inverse problem was solved. All of the results of investigations presented below are related to the case of a cloudless atmosphere.

In Table 4 the TO values reconstructed with the use of the SEVIRI instrument are compared to the data of ground-based measurements for neural networks with different structures. When analyzing Table 4, one can conclude that the networks with three neurons in the hidden layer and with the tansig or logsig functions of activation are optimal (rows 3, 6). The standard deviation of the reconstructed TO values from the TO values, resulting from ground-based measurements, is 6.5%, which is very close to the typical differences between the data of TO measurements with other instruments (for example, AIRS, TOMS, OMI, etc. [13]) from polar satellites.

It is interesting that the network with the linear activation function (Table 4, row 5) leads to a solution completely analogous to the solution of the problem by the method of linear regression, which allows us to compare the method of neural networks to the method of multiple linear regression and to find that the standard deviation decreases from 8.3 to 6.5%.

It should also be noted that the division of a sample into latitudinal belts (tropics and midlatitudes) with the use of the method of neural networks, as well as of the method of linear regression, also increases the accuracy of TO retrieval, although to a lesser degree (Table 4, rows 7, 8). These rows again demonstrate that the error in the solution of the inverse problem is almost completely independent of the choice of the activation function.

4. EXAMPLES OF TO FIELD RETRIEVAL FROM MEASUREMENTS OF THE OUTGOING IR RADIATION WITH THE SEVIRI INSTRUMENT

Recall that the main advantage of TO values obtained from SEVIRI measurements, when compared to data obtained from measurements with other instruments (e.g., AIRS), is a high spatiotemporal resolution and the coverage of a vast territory of the Earth's surface. A visual analysis of data in the entire area of measurements with a maximum spatial resolution presents difficulties, because the scale of the figure does not ensure the necessary spatial resolution (in such figures, about 3000 raster points should be shown along each coordinate). Two relatively small fragments of the successive TO distributions are presented in Figs 2a and 2b. These distributions were obtained on May 17, 2007, at the same site of European Russia, which includes St. Petersburg (59.9°N, 30.3°E) and Moscow (55.7°N, 37.6°E), and were separated by a time interval of 30 min. The areas where data are absent are cross-hatched.

Note the presence of areas with significant horizontal TO gradients and areas with rather low (less than 300 DU) TO values in Figs. 2a and 2b. The presented TO distributions are separated by a 30-min interval, which is negligibly small compared to the time of phoTOhemical relaxation of ozone in the lower and middle stratosphere (more than 24 h). Therefore, changes in the TO values obtained by us in different areas can be caused by horizontal motions in the stratosphere. Furthermore, we will investigate the problems associated with the use of such data for determining wind-field characteristics in the stratosphere.

The field of differences between the TO values presented in Figs. 2a and 2b (earlier data are subtracted from later ones) is shown in Fig. 2c. Considerable TO changes in some observation areas attaining 30–40 DU, i.e., the values noticeably exceeding the errors of TO measurements, are seen in these figures. The areas of TO increases and decreases are clearly recognizable; in particular, a band with alternating local areas of TO increases and decreases can be observed at 54–56°N. However, a uniform color that is close in intensity to the color characteristic of zero-TO changes prevails in the lower part of the field of TO differences in Fig. 2c, which points to the absence of any noticeable stratospheric air motions in this area, because the TO distribution in it is inhomogeneous (see Figs. 2a, 2b). The alternation of areas with TO increases and decreases (light and dark areas in Fig. 2c) can point to horizontal motions of air volumes with different ozone contents.

One more example of the TO distribution on February 16, 2006, at 11:45 in the region bounded by the equator, parallel 5°N, and meridians 41 and 47°E, is presented in Fig. 3a. Characteristic inhomogeneities of the TO distribution—maxima at the longitudes 43–44°E—are clearly seen in the figure.

Figure 3b demonstrates how the feature shown in Fig. 3a changes with time. Figure 3b shows the narrow light band (corresponding to the ozone decrease), which is extended from northeast to southwest and close to the southeastern edge of the maximum in Fig. 3a.

Note that sufficiently rigorous mathematical methods are currently available that can solve the problems of determining the velocities of the motion of clouds and inhomogeneities in the humidity field of the troposphere [14, 15]. These methods can be used to analyze the possibilities for estimating the wind in the stratosphere from SEVIRI measurements.

5. MAIN RESULTS AND CONCLUSIONS

The method of determining TO via the interpretation of measurements of the outgoing terrestrial radiation in eight IR channels of the SEVIRI instrument (Meteosat-8 geostationary satellite) while invoking the data of atmospheric sounding with the AIRS instrument from the Aura circumpolar satellite have been proposed, analyzed, and illustrated.

The neural networks used for solving the inverse problem of TO determination from the results of measurements of the outgoing thermal radiation with the SEVIRI instrument, while invoking information about the thermal state of the atmosphere and underlying

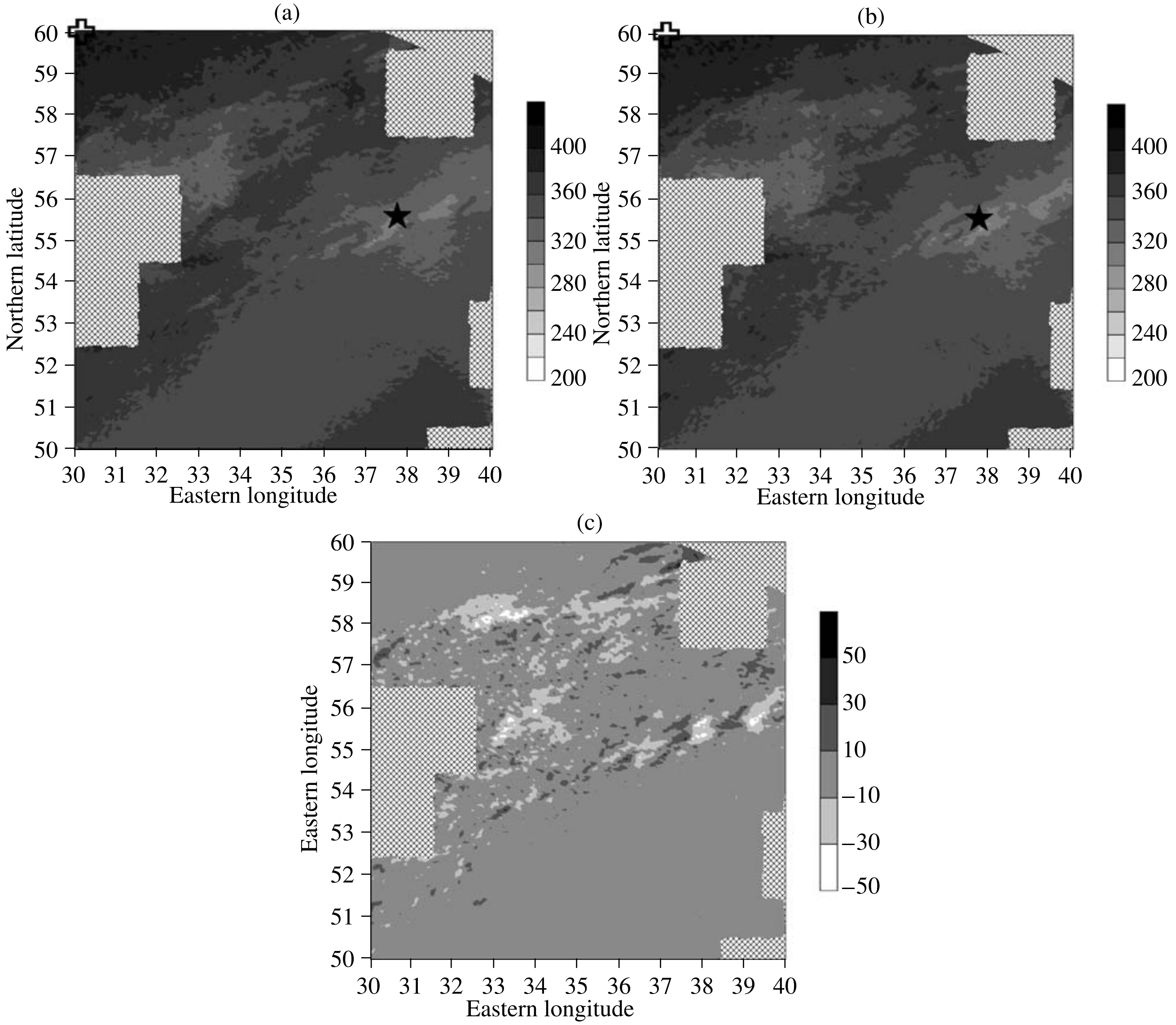

Fig. 2. TO distribution (DU) over a part of European Russia on May 17, 2007, (a) at 11:45, (b) 12:15, and (c) TO changes between these moments. The cross in the left-hand upper corner and the asterisk mark the positions of St. Petersburg and Moscow, respectively.

surface, have been constructed (i.e., their structures have been determined) and trained (i.e., their coefficients have been calculated).

The errors of TO retrieval with the proposed method have been obtained for different variants of the neural network, and an optimal variant of the network—the network with three neurons in the hidden layer and with a nonlinear activation function—have been chosen.

Examples of TO field retrieval for independent data sets have been presented, and the TO values have been compared to the data of ground-based measurements. The mean and rms differences of the results of TO retrieval with the developed method from the data of the international ozonometric network have been shown to be 1.5 and 6.5%, respectively.

It has been shown that the use of the method of neural networks for solving the inverse problem allows a more accurate TO retrieval than the use of the method of multiple linear regression.

Examples of TO field retrieval with a high spatiotemporal resolution (3×3 km^2, 30 min), particularly in European Russia, have been presented.

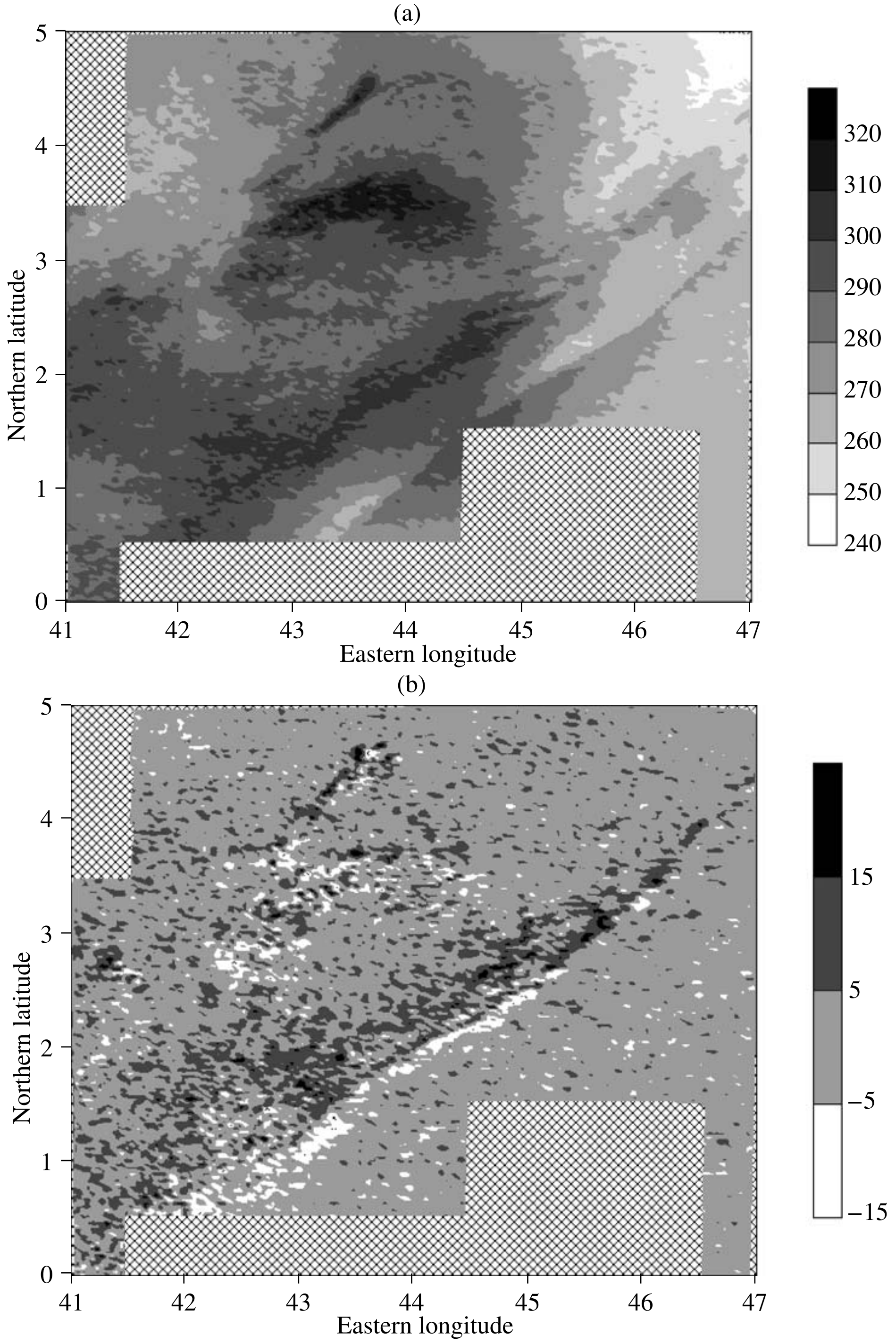

Fig. 3. (a) TO distribution (DU) on February 16, 2006, at 11:45 in the region bounded by the equator, parallel 5°N, and meridians 41 and 47°E, and (b) TO changes in this region during the time interval from 11:45 to 12:15.

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