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Summer mesosphere temperature distribution from wide-angle polarization measurements of the twilight sky

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ABSTRACT

The paper contains the results of wide-angle polarization camera (WAPC) measurements of the twilight sky background conducted in summer 2011 and 2012 at 55.2°N, 37.5°E, southwards from Moscow. The method of single scattering separation based on polarization data is suggested. The obtained components of scattering matrices show the domination of Rayleigh scattering in the mesosphere over the majority of observation time. It made possible to retrieve the altitude distribution of temperature in the mesosphere. The results are compared with the temperature data by TIMED/SABER and EOS Aura/MLS instruments averaged over the nearby dates and locations.

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1. Introduction

Thermal properties of upper atmosphere were the object of interest for a long time, but there was no possibility to study them before the start of rocketsonde epoch in the middle of the XX century. First attempts to measure the temperature at the mesospheric altitudes were made earlier basing on the meteors moderation observations. Lindemann and Dobson (1923) had found that the upper atmosphere (60 km) is warmer than the lower stratosphere, where temperature was already known. After the method modification by Fedynski and Stanukovich (1935) and Whipple (1943) it was shown that the temperature decreases at 80 km, but its values were still significantly overestimated.

However, the first observation of polar mesospheric clouds (in 1885), possibly invisible before and regularly observed after that revealed the probable relation with mesosphere thermal regime. This shows the global process of changing of physical conditions in mesosphere of the Earth during the last decades. These changes could be possibly related with increasing contribution of trace gases in all atmosphere layers. Radiative cooling by CO_2 was found to be one of the basic reasons of mesosphere temperature decrease in mid-latitudes (Kuhn and London, 1969).

The further study of such relations required the systematic temperature measurements in the mesosphere. The first long-time temperature data obtained by Kokin and Lysenko (1994) had shown sufficient negative trend: about -1 K per year. Further observations and analysis reviewed by Beig et al. (2003) had reduced this amount and shown its latitude dependency.

The basic problem of mesospheric investigations is the difficulty of direct measurements, especially *in situ* (Dyrland et al., 2010). The mesosphere is too high for balloons but too low for spacecrafts. During high-latitude summer period when the extremely low temperatures are observed, the mesosphere is continuously illuminated by the Sun, that restricts the time and location area for some types of measurements, such as nightglow emission and twilight observations. The experimental techniques currently in use are described in details by Lübken et al. (1994) and Beig et al. (2003). They can be separated in three groups: rocketsonde *in situ* measurements, ground-based and spacecraft remote sensing. Optical ground-based measurements are basically done by lidars. Rayleigh lidar techniques (Hauchecorne and Chanin, 1980) measure the backscattering coefficient altitude profile which can be the basis of the temperature calculation if the contribution of aerosol scattering is small. Sodium (She et al., 1992) and potassium (Von Zahn and Hoffner, 1996) Doppler lidars retrieve the temperature profiles inside the Na and K layers with better accuracy owing to higher S/N ratio. Lidar technique provides very good altitude resolution (better than 100 m now), but the number of mesosphere lidars on the Earth is still small, and there are no such devices near the observation point of this work (central Russia).

First continuous space-borne mesosphere temperature data were obtained by NASA Solar Mesosphere Explorer satellite (SME) in 1980s by measurements of Rayleigh scattering (Clancy

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and Rusch, 1989). The same method was used by Wind Imaging Interferometer (WINDII) onboard the NASA Upper Atmosphere Research Satellite (UARS, Reber et al., 1993) operated in 1991–2005. The wavelength of WINDII analysis (553 nm, Shepherd et al., 2001) is close to the one used in present paper. Mesosphere temperature values were also obtained by Halogen Occultation Experiment (HALOE, Remsberg et al., 2002) and High Resolution Doppler Imager (HRDI, Thulasiraman and Nee, 2002) onboard the same satellite. The vertical resolution of space limb measurements is about 1 km or more, they cover the entire globe, this is impossible for ground-based technique.

Recently, the mesosphere temperature is being measured by the Sounding of the Atmosphere using Broadband Emission Radiometry instrument (SABER, Russell et al., 1999) onboard the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) satellite launched in 2001, and Microwave Limb Sounder (MLS, Schwartz et al., 2008) onboard Earth Observing System (EOS) Aura satellite, launched in 2004, both by NASA. The experiments are based on the measurements of infrared emission of carbon dioxide (SABER) and microwave emission of oxygen (MLS). SABER data show rapid changes of summer mesosphere temperature at the latitudes above 40–50° (Xu et al., 2007) which makes all kinds of measurements especially important there. Polar mesopause summer temperatures by MLS and meteor radar data (Dyrland et al., 2010) are just 10–20 K less.

Twilight method of atmosphere sounding was under consideration for a long time since the pioneer work by Fesenkov (1923). But during the following decades the possibilities of the method were restricted by the contribution of multiple scattering, that was not known exactly even for the early twilight and significantly increased during the darker stage. Wide review of observational and theoretical works by Rozenberg (1966) reveals the underestimation of this contribution. Fast sky polarization decrease always observed at solar zenith angles from 95° to 99° (transitive twilight period by classification of Ugolnikov and Maslov, 2007) and caused by multiple scattering was interpreted in terms of upper atmospheric aerosol. This led to an assumed large concentration and unreal optical properties, giving no possibility to separate the single Rayleigh scattering and to measure the temperature.

Experimental method of single scattering separation basing on the study of polarization was suggested by Fesenkov (1966) and improved by Ugolnikov (1999), Ugolnikov and Maslov (2002). The results were in good agreement with the numerical simulations (Ugolnikov et al., 2004) during the early stages of twilight, but the dark stage remains hard for exact computer modeling (Postylyakov, 2004) even in a present time due to fast increase of effective scattering order. The basic experimental problem of mesospheric research by dark twilight analysis was the necessity of fast simultaneous measurements in different sky points during the short period. Using the scanning photometers (Zaginailo, 1993; Ugolnikov, 1999) or first generation CCDs (Ugolnikov and Maslov, 2002) provided just the small number of actual measurements corresponding to the mesosphere layer, making difficult to estimate the temperature or to build the dust profiles. However, the accuracy of polarization measurements had increased, and it helped to detect the depolarization effects caused by meteoric dust in the mesosphere (Ugolnikov and Maslov, 2007). In this paper we present the results of frequent all-sky polarization measurements.

2. Observations

Wide-angle polarization camera (WAPC) measurements had started in early summer of 2011 at the point 55.2°N, 37.5°E, about 60 km southwards from Moscow. From one side, this latitude is high enough to observe the summer mesosphere cooling. From another side, the twilight (even in June) is quite deep to run the procedure of single and multiple scattering separation described below and to study the mesosphere single scattering. The observation location is near the northern border of the area where it can be done. The mesopause shifts down to 85 km during the summer here (Xu et al., 2007), this altitude is in the work range of twilight sounding method.

The results of very first observation dates are presented by Ugolnikov and Maslov (2013), initial device properties are also described there. After some primary sessions in 2011 observations continued during the late spring and summer period of 2012 with improved measuring device. The camera photo and optical scheme are shown in Fig. 1. It consists of three consecutive lenses: Sigma AF 4.5 mm *f*/2.8 EX DC Circular Fisheye HSM (lens 1 in Fig. 1), MS Volna-3 80 mm *f*/2.8 (lens 2) and Mir-20 20 mm *f*/3.5 (lens 3). The lenses 1 and 2 have the common focal plane (focal plane 1 in Fig. 1). These two lenses build the infinitely remote diminished image of the sky with zenith angles up to 70°. This image is being fixed by CCD-camera with lens 3 and rotating polarization filter Vitacon P.L. The field radius of this camera is about 6°, and the light crosses the polarization filter by a small axis angle. This filter makes 120°-steps once in 40 s during the early twilight and once in a minute during the dark twilight and the night. Spectral filters fix the observational band, the same for 2011 and 2012, with effective wavelength equal to 540 nm. The sky images are created by CCD-matrix Meade DSI PRO II, the angular resolution (1 pixel) is about 0.3°. For better *S*/*N* ratio the sky background parameters are averaged inside the circles with radius 10 pixels (about 3°) placed in 5° one from another.

The observations start before the sunset or during the early twilight and continue through the night. The exposure times vary from 0.001 to 15 s. Stars astrometry and photometry data in the night sky frames are used to fix the camera orientation, field curvature and self polarization. Tycho 2 catalogue (Hog et al., 2000) is used as the star reference data with account of Earth's

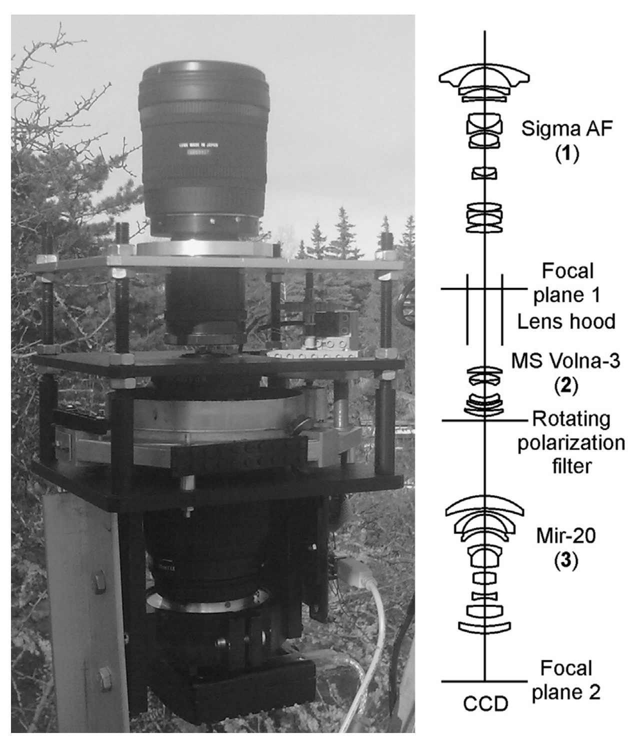

Fig. 1. The measuring device and its optical scheme.

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