Evaluation of large-scale smoke aerosol fluxes on the example of Siberian boreal forest fires in July 2016

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Abstract. A technique is proposed for determining of the large-scale smoke aerosol fluxes using a wind field reanalysis data and the satellite monitoring data of the aerosol optical depths and the vertical profile of the attenuation coefficient. The directions of the long-range transport of the Siberian smoke haze fragments were determined in July 2016. The maximum large-scale mass fluxes and the total mass of the smoke aerosol during the transfer of air masses through the Ural meridian to the west (0.38*10⁶ ton/day and 1.38*10⁶ tons) and through the 115ºE meridian to the east (0.26*10⁶ ton/day and 0.72*10⁶ tons) were estimated.

1. Introduction

Large-scale smoke hazes strongly affects the radiation regime of the atmosphere [1-6]. Due to a long-range transport fragments of the smoke haze are propagated to large areas. In particular, in July 2016, the Siberian smoke haze (SSH) spread to the area of more than 16 mln km² [7-9]. Estimates of the total mass and radiation effects of the smoke aerosol are obtained [7-11]. Analysis of the evolution of SSH showed the long-range smoke aerosol transport occurred not only in the West direction, but also in the East, as well as in the North and South-East directions. In this paper, we estimated large-scale aerosol mass fluxes during the long-range transport of the SSH fragments.

2. Large-scale forest fires in Siberia in July 2016

Abnormally high temperatures with a lack of precipitation contributed to the spread of forest fires in Siberia in July 2016. Massive forest fires occurred in the Tyumen oblast, in Krasnoyarsk kray and in Irkutsk oblast. The number and maximum total radiation power of fires (RPF) was observed in Evenkia in the period from 16 to 24 July. The total burning area exceeded 4500 km², and the total RPF reached approximately 500 GWt.

3. Some features of atmospheric circulation over Northern Eurasia in July 2016

In July 2016, an anomalous Eastern transport was observed over Northern Eurasia in the troposphere, which ensured the transfer of the smoke air masses to Europe first through the Ural meridian [11], and then on the territory of many European countries [12, 13]. An intensive smoke transport through the Ural Meridian was observed in the period from 07.19 to 07.27.2016. The nature of atmospheric circulation in this period is evidenced by Fig. 1a which shows the wind field built according to the
ERA-Interim reanalysis at the level of 850 mb. Figure 1a shows the frontal line (1), located on the
Ural meridian, selected for the calculation of the corresponding large-scale aerosol flux.

From 25 to 31 July, there was an intense eastward flux of smoke aerosol at latitudes from about 65°
to 70°N. as an example in Fig. 1b shows the wind field on 07.23. 2016 at the level of 850 mb (1-the
frontal line of the transfer of smoke air masses on the meridian 115°E).

Figure 1. Wind velocity field: (a) 07.19.16 at the level 850 mb (1 – smoke transfer front line through
Ural meridian and (b) 07.23.2016 at the level 800 mb (1 – smoke transfer line towards the east through
meridian 115°E).

4. Spatial distribution of the aerosol optical depth and estimation of the smoke aerosol fluxes

The transport of smoke aerosol in the atmosphere can be judged by the observed evolution of
the spatial distribution of aerosol optical thickness (AOT) [10]. According to the known distribution of
AOT, it is possible to reconstruct the spatial distribution of the smoke aerosol in the atmosphere,
including the distribution of AOT along a given frontal line and, in particular, to determine for a given
time the average value $\tau_{ex}$ on the frontal line, the length of which is equal to $L$ (km).

In the case of a thin smoke layer, where the perpendicular to the frontal line of the component of
the average wind speed is $V_f$, the mass flux of the smoke aerosol $F_i = mV_f$, where $m=0.24\tau_{ex}$
(ton/km$^2$) [3,14] and the total mass transferred through the frontal line of the smoke aerosol
$M= \int F(t)dt$. (tons).

As an example in Fig. 2a shows the distribution of AOT at the wavelength of 550 nm 07.19.2016
obtained from the data of the MODIS spectrometer installed on the Terra satellite [15-16]. 07.22.
2016, which indicates the large-scale transfer of smoke aerosol through the Ural Meridian (60°E).

The transfer of smoke aerosol to the East through meridian 115°E 07.23.2016 is shown at Fig. 2b.
5. Wind speed profiles in the troposphere

To estimate the smoke aerosol fluxes, it is necessary to know the vertical profiles of wind speed and aerosol mass concentration. Wind speed profiles were received according to ERA-Interim reanalysis.

Fig. 3a shows the average wind speed profile during the transfer of air masses 19.07.2016 through the Ural meridian. It is easy to see that in this case, the wind speed at altitudes greater than 1 km varies by about 20-25%.

Fig. 3b shows the determination results of wind speed profiles 23.07 (1), 26.07 (2) and 29.07.2016 (3) when transferring the smoke aerosol to the East (meridian 115°E). In this case, there is a strong temporal variability of profiles and large vertical gradients of the wind speed.

Figure 2. Aerosol optical depth spatial distribution for wavelength 550 nm: (a) 07.19 – 07.22.2016 (50° – 65°N, 50° – 85°E) and (b) 07.25 – 07.30.2016 (55° – 80° N, 90° – 125°E).

Figure 3. Average wind velocity profile: (a) 07.19.16 (meridian 60°E), (b) 07.26 (1) and 07.29.2016 (2) at the meridian 115°E.
6. Vertical profiles of aerosol attenuation coefficient

In [14] is offered a one-parameter model of the atmospheric haze, which allows to determine the volume and mass concentration of the aerosol according to the measurements of the scattering coefficient. For the large-scale smoke hazes in Russia, the scattering coefficient and the attenuation coefficient were close ("white smoke"), which allows to determine the mass concentration of the smoke aerosol by the known value of the attenuation coefficient at the wavelength of 550 nm. For the smoke aerosol whose properties do not depend on height, it is not difficult to obtain the relation between the aerosol optical thickness and the aerosol content in the atmosphere.

Satellite aerosol monitoring using the CALIPSO lidar CALIOP as one of the products gives vertical profiles of the attenuation coefficient at wavelengths of 532 and 1064 nm [17-19]. By selecting CALIPSO satellite trajectories close to the frontal lines, it is possible to obtain averaged vertical coefficient profiles for given time periods.

On fig. 4a is presented the average vertical profiles of the attenuation coefficients at wavelengths 532 nm (1) and 1064 nm (2) according to monitoring data 07.20.2016, obtained during the passage of the satellite CALIPSO through the Ural meridian. The observed the relation between the profiles at wavelengths of 532 and 1064 nm indicates the dominance of the fine fraction of the smoke aerosol, which is typical for the large-scale smoke hazes in Russia [3]. In this case, the observed smoke aerosol in the middle troposphere at heights of 1.5-3.5 km and the smoke aerosol in the boundary transfer to the East (Fig. 4b) the smoke aerosol was observed mainly in the layer of about 2.5 to 4.5 km, where the wind speed generally exceeded 10 m / s.

![Figure 4. The average extinction coefficient profiles](image)

In the presence of information about the profiles of the attenuation coefficient $\varepsilon(z)$ at a wavelength of 532 nm, which is close to the attenuation coefficient at a wavelength of 550 nm, and the wind speed $V_f(z)$, large-scale fluxes are determined from $F = 20.7L \int \varepsilon(z)V_f(z)dz$.

Taking into account the known errors of laser remote sensing it is necessary to control the results of determination of the recovered optical thickness $\tau_{ex} = \int \varepsilon(z)dz$.

7. Large-scale fluxes of the smoke aerosol

According to satellite monitoring of the attenuation coefficient and the aerosol optical thickness, the large-scale fluxes of the smoke aerosol were determined using the data of reanalysis of the wind
velocity profiles during the transfer through the Ural Meridian to the West and Meridian 115°E to the East, and the total masses of smoke transferred through these meridians in the second half of July 2016 were estimated.

The smoke aerosol flux through Ural meridian 07.20.2016 reached 0.38*10^6 ton/day and through meridian 115°E 0.26*10^6 ton/day (07.26.2016). The smoke aerosol mass transferred through Ural meridian in the period from 07.18 to 07.26.2016 is equal 1.38*10^6 tons. As to the smoke aerosol transfer through meridian 115°E (07.24-07.31.2016) the total mass of the smoke aerosol was equal 0.72*10^6 tons.

8. Conclusion
The method of evaluating large-scale smoke aerosol fluxes has been developed. Mass forest fires and atmospheric circulation features in Siberia in July 2016, which led to the spreading of the smoke haze over a significant part of Northern Eurasia, are briefly characterized. Variations of the vertical wind velocity profiles are analyzed according to the ERA-Interim reanalysis data. Using the satellite lidar monitoring data on the vertical profiles of the attenuation coefficient, estimates of the large-scale fluxes were obtained for the long-distance transport of the Siberian smoke haze fragments in July 2016 through the Ural meridian to the west (0.38*10^6 ton/day) and through the 115°E meridian to the east (0.26*10^6 ton/day). The total mass of the smoke aerosol transported through the Ural meridian (1.38*10^6 tons) and through 115°E meridian (0.72*10^6 tons) was determined.

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