Injection height of smoke from biomass burning in Eastern Europe by the synergy of satellite active and passive remote sensing

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ABSTRACT

High frequency of agricultural fires is observed every year during the summer months (mainly in August) over Western Russia and Eastern Europe. This study investigates the initial injection height of aerosol generated by the fires over these regions during the biomass burning season, for the years between 2006 and 2008, as seen by CALIPSO. MODIS data are synergistically used for the detection of the fires and the characterization of their intensity. The vertical distributions of the smoke plumes generated by the active fires are analyzed to investigate the aerosol top height which is considered dependent on the heat generated by these fires. In most cases, the aerosol plumes are observed within the boundary layer, with no evidence for direct injection to the free troposphere. However, the range of top heights of the smoke layers found to range between 1.6 and 5.9 km indicating also cases when smoke penetrates in the free troposphere. Our results are finally compared with mixing layer heights taken by the European Centre for Medium-range Weather Forecast (ECMWF), indicating that ECMWF underestimates the mixing layer under strong fire activity, since the model does not take into account the strong updrafts generated by the fires.

1. INTRODUCTION

Biomass burning is a major source of air pollution and the second largest source of anthropogenic aerosols. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change [1] reports a contribution of roughly +0.04W/m2 of biomass burning aerosol to the global radiative forcing (RF) with a standard deviation of 0.07 W/m2. This estimate of the direct RF is more positive than that of the Third Assessment Report [1] and it is linked with improvements in the models in representing the absorption properties of biomass burning aerosol and the effects of their vertical distribution. Reference [2] showed that there are still significant uncertainties in the aerosol vertical distribution in global aerosol models, information that is critical in assessing the magnitude and even the sign of the direct RF of biomass burning aerosols.

The elevation at which wildfire smoke is injected into the atmosphere has a strong influence on how the smoke is dispersed, and is a key input to aerosol transport models. In addition to solid and gaseous material, fires release considerable amount of heat. The resulting plume possesses some buoyancy that generates strong updrafts above the fire. If the plume kept its initial buoyancy, it would rise to considerable heights in the atmosphere. However, strong turbulence mixes the plume with the surrounding air so that the plume temperature and the buoyancy are reduced. Eventually, the plume reaches a stable layer at which the updraft stops. Because of turbulence and mixing, the fire products are not entirely injected at this maximum height, but are rather distributed unevenly between the surface and the top height. Note that the updraft may lead to condensation within the plume, which releases some latent heat and increases the plume buoyancy [3]. After this initial injection phase, the smoke enters the general atmospheric circulation. The fraction that is within the boundary layer height is well mixed by diurnal convection. On the other hand, the fraction that reaches the free troposphere is then transported over very long distances. Indeed, the transport in the free troposphere is faster than in the boundary layer and, more importantly, there is less removal of material by scavenging and wet-removal processes. As a consequence, the injection height is a major parameter for a proper understanding and modeling of the atmospheric chemistry. It is also of considerable importance for the interpretation of observations.

Forest fires in Western Russia and Eastern Europe are a major source of pollution in the Northern Hemisphere [5]. For that reason, there has been increased interest in recent years to assess the impact of these fires on climate. According to an investigation of the spatial and temporal occurrence of fires in croplands based on the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire product [6], the Russian Federation was found to be the largest contributor to agricultural burning globally during the period 2001 to 2003, producing 31–36% of all agricultural fires. This globally highest concentration of agricultural fires, found to be extended across Russia in the latitudinal belt between 45^0 N – 55^0 N during the spring (April–May), as well as in Eastern Europe (Baltic countries, western Russia, Belarus, and the Ukraine) during the late summer (end of July and August).

This study investigates the initial injection height of aerosol generated by the fires over Western Russia and Eastern Europe during the biomass burning season, for the years between 2006 and 2008, using data from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the CALIPSO satellite. Aerosol layer top height is derived with great precision from CALIPSO space-borne lidar. The identification of the fire activity has been done using MODIS fire product data. Our results are finally compared with mixing layer heights taken by the European Centre for Medium-range Weather Forecast (ECMWF) for the investigation of the possibility that smoke penetrates in the free troposphere over the regions of strong fire activity.

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2. DATA

2.1 MODIS Active Fire

For the identification of the areas that are affected by biomass burning, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire product [6]. The MODIS sensor is a multi-spectral sensor with 36 spectral bands, ranging in wavelength from 0.4 to 14.2 µm, and fires are detected at 1-km spatial resolution (at nadir) using radiance measurements in the 4 µm and 11 µm channels. Measurements at several spectral bands are utilized for masking clouds, extremely bright surfaces, glint, and other potential sources of false alarms [6]. In the operational MODIS algorithm, only the 4 µm channel measurements are used to calculate the Fire Radiative Product (FRP), based on the measured brightness temperatures of the fire pixel and its neighboring surface background. There are two 4-µm channels on each MODIS sensor, one of which is a 'low-gain' channel that can record pixel-integrated brightness temperatures of up to ~ 500 K, thereby allowing unsaturated measurements to be made over even very large/most intensely burning wildfires. MODIS is a twin sensor flying on two NASA Earth Observing System (EOS) satellites: Terra (launched 19 December 1999) and Aqua (launched 4 May 2002). They are both polar orbiting, with Terra crossing the equator at approximately 10:30 AM and 10:30 PM local time, and Aqua at approximately 1:30 AM and 1:30 PM local time. Each MODIS sensor achieves near-global coverage once per day and once per night every 24 h, with higher latitude locations observed slightly more frequently because of increasingly large overlaps from successive satellite passes. Therefore, most fires detectable at a 1-km spatial resolution have the potential to have their FRP measured four times a day, except when covered by thick meteorological cloud. MODIS algorithms (including the fire algorithm) are updated periodically, leading to different versions, which are used to generate a series of Collections of the data products. The latest 'Collection 5' fire data were used for this study. Figure 1 shows the locations of the actives fires identified from MODIS observations during July and August of 2006, 2007 and 2008 over the area of our interest.

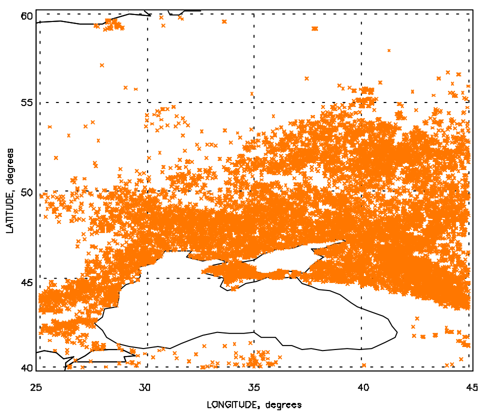

Figure 1. Active fires as seen by MODIS during July and August 2006, 2007, 2008 for the Western Russian and Eastern Europe area.

2.2 CALIPSO

The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission (http://www-calipso.larc.nasa.gov/) is a collaborative effort between the NASA Langley Research Center (LaRC), the Centre National D'Etudes Spatiales (CNES), Hampton University (HU), the Institut Pierre Simon Laplace (IPSL), and Ball Aerospace and Technologies Corporation (BATC) to study global radiative effects of aerosols and clouds on climate. CALIPSO is an Earth Science observation mission that launched on April 28, 2006 and flies in nominal orbital altitude of 705 km and an inclination of 98 degrees as part of a constellation of Earth-observing satellites including Aqua, PARASOL, and Aura – collectively known as the "A-train" [7]. The CALIPSO mission provides crucial lidar and passive sensors to obtain unique data on aerosol and cloud vertical structure and optical properties.

CALIPSO's lidar, CALIOP, is an elastically backscattered lidar operating at 532 and 1064 nm, equipped with a depolarization channel at 532 nm, that provides high-resolution vertical profiles of aerosols and clouds [7]. The lasers operate at 20.16 Hz and are Q-switched to provide a pulse length of about 20 ns. Each laser generates nominally 220 mJ per pulse at 1064 nm, which is frequency-doubled to produce about 110 mJ of pulse energy at each of the two wavelengths. Beam expanders reduce the angular divergence of the transmitted laser beam to produce a beam diameter of 70 meters at the Earth's surface (corresponding to a nominal laser beam divergence of 100 µrad) [7].

CALIPSO produces Level 1 and Level 2 science data products. The Level 1 data include: - lidar calibrated and geolocated profiles with associated browse imagery with horizontal resolutions of 1/3 km, 1 km and 5 km, an aerosol layer product at 5 km resolution (height, thickness, optical depth, and integrated attenuated backscatter) - an aerosol profile product with a horizontal resolution of 40 km and vertical resolution of 120 m (backscatter, extinction, and depolarization ratio). The Level 1 V2 (Version 2) attenuated backscatter profile product is used in this study along with Level 2 aerosol products relative to aerosol layering. For the period and area under study, the CALIPSO overpasses are presented in Figure 2:

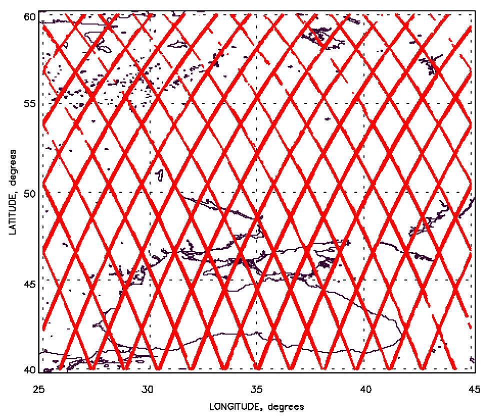

Figure 2. CALIPSO overpasses over Western Russian and Eastern Europe during July and August 2006, 2007, 2008.

2.3 ECMWF Mixing Layer Height

As explained above, one of the objectives of this paper is to analyze the height of the aerosol layer in relation to that of the mixing layer. We have therefore used the data from the European Centre for Medium-range Weather Forecast (ECMWF) that provides a diagnostic of the boundary layer height. This product is available with a 3-hourly and 25 km resolution.

The parameterization of the mixed layer (and entrainment) already uses a model level index as boundary layer height, but in order to get a continuous field, also in neutral and stable situations, the parcel lifting method (or bulk Richardson method) is used as a diagnostic, independent of the turbulence parameterization (see the model documentation at http://www.ecmwf.int/research/ifsdocs/CY28r1/Physics/Physics-04-09.html#wp972354). The three-hourly fields show a strong diurnal cycle (low values at night).

3. RESULTS AND DISCUSSION

For the detection of fires, we used the MODIS fire product over a grid extended to the latitudinal belt between 25^0 to 45^0 E, and the longitudinal belt between 40^0 to 60^0 N. The overall minimum and maximum values of the Fire Radiative Power (FPR) per (1 X 1-km) pixel detected by MODIS sensor for the period under study (2006-2008), ranged between 11.36 to 438.71 MW with a mean value of 50.23±57 MW. Additionally to the FPR, the “fire confidence” MODIS product has been used in this study, and only fires with fire confidence greater than 80% were used for aerosol top height calculations. MODIS dataset was then restricted to the geographical pixels crossed by CALIPSO laser beam.

The top of the aerosol layers for the pixels with fire confidence greater that 80% is then calculated by the CALIPSO Level-1 attenuated backscatter signal at 532 nm. This profile can be very noisy, especially during daytime acquisitions. To overcome the noise we applied a 5-km spatial averaging centered in the MODIS pixel and vertical smoothing of the profiles. Additionally, we have used the collocated CALIPSO Level-2 aerosol layer product. This product provides a description of the aerosol layers, including their top heights and bottoms, identified from the Level-1 data. However, the first and current release of this product shows many errors and one has to reject the erroneously identified aerosol layers. Following both of the products, three examples of attenuated backscatter profiles are presented in Figure 3 along with the aerosol layer CALIPSO product. In the first case (09 August 2008), the aerosol layer is well captured by CALIPSO algorithm, and the Level-2 automatic calculations are consistent with the profile giving an aerosol top height of the order of 1830m. In the second example presented in Figure 3 (17 August 2008), the CALIPSO’s aerosol product reports 3 aerosol layers. This is not consistent with the attenuated backscatter profile reported for the same day and time, since only one layer is visible. Another inconsistency between the products is presented in the third example of Figure 3 (15 July 2008). As a consequence, much caution is required in the use and analysis of the Level-2 aerosol product. As an attempt to overcome bad aerosol top height data, we analysed CALIPSO profiles separately, when the aerosol layer product showed a failure, by calculating the aerosol top height by the minimum of the first derivative of the signal.

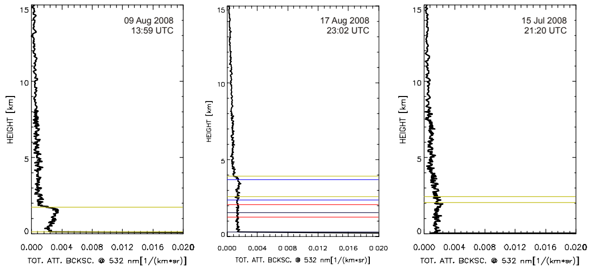

Figure 3. Examples of CALIPSO Level-1 attenuated backscatter profiles at 532 nm and the corresponding Level-2 aerosol layer product

After the calculation of the aerosol top height from CALIPSO for a total of 163 fire hot spots detected by MODIS (fire confidence greater than 80%), we found that these heights range from 1677m to 5940m, having a mean value of 3077±954m. The frequency distribution for our dataset, binned in 500m height intervals is presented in Figure 4.

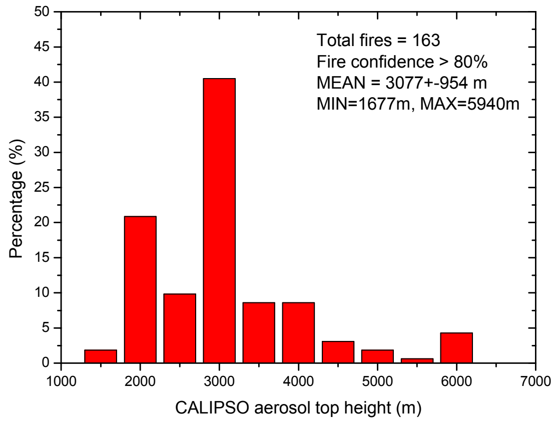

Figure 4. Frequency distribution of the aerosol top height binned in 500 m height intervals, as retrieved by CALIPSO over the Western Russian and Eastern Europe during July and August 2006, 2007, 2008.

An independent investigation of smoke aerosol height, performed using data from the CALIPSO satellite [8], found that wildfire smoke remains in the boundary layer. It did not observe smoke aloft in a sampling of the CALIPSO global record, except in rare cases far from sources, after other atmospheric processes have had time to lift the smoke to higher elevations.

To further investigate the conclusions of reference [8], we made an attempt to compare the aerosol top height CALIPSO retrievals with estimations of the mixing height provided by the ECMWF model. These comparisons are presented in Figure 5.

In Figure 5(a), all the collocated data of MODIS and CALIPSO for the period under study are presented and compared with ECMWF's mixing height estimations, showing, firstly, no agreement (correlation coefficient of 0.19). By keeping only 12:00 UTC ECMWF data, the correlation becomes better and of the order of 0.66 (Figure 5(b)). Restricting our dataset to cases where the fire confidence is greater than 80%, the correlation becomes worst (0.52, Figure 5(c)), while it gets better (0.79) for the remaining dataset where small or no fires were detected by MODIS (Figure 5(d)).

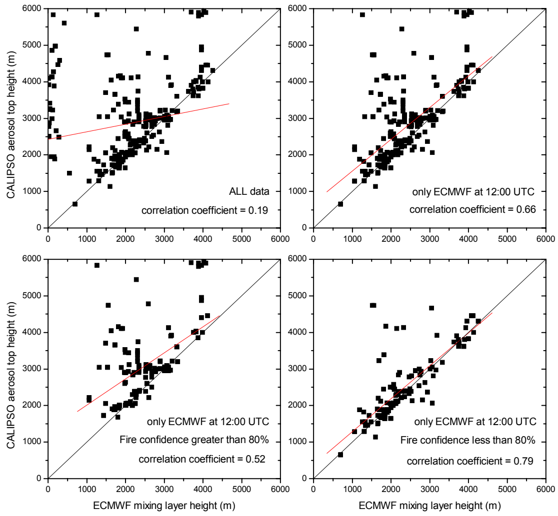

Figure 5.Comparison of aerosol top height derived by CALIPSO with mixing layer height from ECMWF model.

Our results presented in Figure 5(c) could be explained as follows: The ECMWF model seems to underestimate the mixing layer under strong fire activity, since the model does not take into account the strong updrafts generated by the fires. This is also supported by the better agreement of the model in Figure 5(d), where smaller or no fires are detected. However, in presence of strong fire activity, smoke particles can directly inject in the free troposphere, and this could also be a possible explanation of the greater values of CALIPSO's aerosol top heights compared with those of ECMWF's mixing heights. We additionally mention here that the possibility that the layers detected by CALIPSO in higher altitudes might be a result of atmospheric transport than direct injection is not considered strong, since the profiles analyzed showed a vertical homogeneity which is mainly attributed to strong convection and corresponding vertical mixing processes. No lofted layers have been observed in the total of 163 profiles examined.

4. CONCLUSIONS

The initial injection height of smoke aerosol generated by fires over Western Russia and Eastern Europe during the biomass burning season, for the years between 2006 and 2008, has been investigated using the synergy of CALIPSO and MODIS remote sensors. The range of top heights of the smoke layers found to range between 1.6 and 5.9 km indicating also cases when smoke penetrates in the free troposphere. This was investigated following a comparison of the retrievals with mixing layer heights from ECMWF model. However, this conclusion needs further future work, since the higher than ECMWF's mixing layer injection altitudes could be attributed also to the fact that the model does not take into account the strong updrafts generated by the fires.

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