On integration of a Fire Assimilation System and a chemical transport model for near-real-time monitoring of the impact of wild-land fires on atmospheric composition and air quality

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Abstract

The paper presents two versions of the Fire Assimilation System (FAS) jointly developed by the Finnish Meteorological Institute and Russian State Hydrometeorological University. The system versions are based on (partly) independent satellite products from the MODIS instrument: Temperature Anomalies (TA) of the Rapid Response systems (hot-spot counts) and the Fire Radiative Power (FRP). The observed quantities – the pixel absolute temperature and radiative emissivity – are converted to emission fluxes via empirical emission factors. The products are available in near-real time and thus are utilized for the operational evaluation and forecasting of the atmospheric composition over Europe. Both versions of FAS are integrated with the Air Quality and Emergency Modelling System SILAM, which uses the estimated emissions for the atmospheric composition simulations merging them with the anthropogenic and natural emission fluxes. Using the SILAM simulations of selected episodes and MODIS aerosol optical density observations for comparison, the recalibration of the literature-available emission factors has been done. The results of the operational air quality forecasts with the integrated system are available from http://silam.fmi.fi. Comparison of the TA- and FRP-based emission estimates and the corresponding patterns of the fire-induced pollution showed both similarities and differences originating from the physical background of these products. Namely, the TA-based emission stresses the large agglomeration of (possibly, small) fires, while the FRP system tends to highlight powerful individual fires.

Keywords: Fire Assimilation System, wild-land fires, dispersion modelling, air quality.

WIT Transactions on Ecology and the Environment, Vol 119,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/FIVA080341

1 Introduction

In average, about 5000 km^2 of wooded land in Europe is burnt annually by more than 50,000 fires. Burning areas spread over all countries, being particularly strong in the southern arid regions and eastern part of Europe. At a global scale, forests of Russia and Brasilia, as well as savannas in central Africa are among the mostly affected areas. Total estimates of the consumed biomass vary widely, estimated between 5 and 10 Gtons annually (Scholes and Andreae [1]; Chin *et al.* [2]).

The impact of fires onto climate processes, atmospheric composition and air quality also vary widely, so as its estimates made within different studies (e.g. Barbosa *et al.* [3]; Wotawa *et al.* [4]; Schultz [5]; Generoso *et al.* [6]; Duncan *et al.* [7]; Soja *et al.* [8]; van der Werf *et al.* [9,10] Schultz *et al.* [11]). Regional specific of the fires adds-on to the complexity of the phenomenon. Thus, in forests the main impact and amount of consumed biomass can be attributed to comparatively small number of major episodes, while e.g. in Africa and in arid regions a typical intensity of individual fires is usually smaller but their number is much higher (Schultz *et al.* [11]).

At present, most of the fires are ignited by humans, either deliberately or not. It is, therefore, difficult to make any quantitative predictions about individual fire events. The forecasting capability of various fire indices also appears quite limited. Therefore, at present a widely used methodology for obtaining the fire information for real-time applications is based on operational remote sensing of active fires – by means of aircrafts or satellites.

There are two main types of remote-sensing information suitable for assessing the features and impacts of fires. Most of the above works are based on analysis of burnt areas, which are performed on a monthly or, rarely, half-monthly basis. The other type of input data is based on surface temperature observations and their derivatives, which are available both in near-real-time and from archives.

One of early operational Fire Alarm Systems based on satellite information has been developed in Finland in mid-1990s and is still running operationally at Finnish Meteorological Institute. The system utilizes the AVHRR and AATSR hot-spot information and generates alarm messages if an overheated pixel (compare to neighbouring) appears anywhere in Finland. The system, however, provides only qualitative information (appearance of the fire) and does not contain any variable describing its strength or composition of the emitted species.

The current paper describes the new-generation Fire Assimilation System jointly developed by Finnish Meteorological Institute and Russian State Hydrometeorological University. The methodological part of the paper presents the system basics and main elements of the information flow. The main output of the system consists of global emission fluxes from wild-land fires provided with daily resolution. The emissions in Europe are utilized by the SILAM chemical transport model (http://silam.fmi.fi), which includes the fire-induced emission into the operational forecasts of atmospheric composition. This application also

www.witpress.com, ISSN 1743-3541 (on-line)

enables indirect verification of the FAS itself via comparison of modelled concentrations with in-situ and remote-sensing observations.

2 Outline of the Fire Assimilation System algorithm

Current FAS contains two semi-independent lines utilising different satellite products. The first one is based on Rapid-Response System Temperature Anomaly data (FAS-TA). The system receives the input from ASCII telegrams containing location, temperature and detection confidence of the detected thermal anomalies (T4 brightness temperature). This brightness temperature is then scaled with an empirical coefficient to an emission flux of PM 2.5. Advantages of the scheme are its simplicity and NRT availability of the data, which allow its fast implementation. However, the information obtained from TA value alone is quite limited. Additionally, this algorithm neglects the background temperature of the fire pixels (i.e. the temperature of the same pixel in case of no fire). Since the complicated methods of restoration of the actual fire intensity from the vegetation map and its state before the fire are very uncertain, their application could bring only moderate improvements at a price of dramatic rise of complexity. Therefore, we keep this simple system as a base-case of FAS processing. Implications of its simplicity are discussed further.

A more theoretically rigorous approach is based on using the FRP retrievals with empirical scaling to emission rates. In the current FAS it is done with the approach following that of Ichoku and Kaufman [12].

The key parameter for FAS-FRP is the emission rate of total PM per unit FRP: smoke emission coefficient *Ce* [kg J^{-1}]. According to Ichoku and Kaufman [12], C_e varies from 0.02-0.06 kg/MJ for boreal regions, 0.04-0.08 kg/MJ for Africa (mainly savannas and grassland), and 0.08-0.1 kg/MJ for Western Russian regions. Since for *Ce* determination a very crude estimate of atmospheric transport was employed (based on a fixed-level wind and without any real dispersion model involved), the authors suggested that the coefficients are probably overestimated by about a factor of 2. Using these estimates as the starting point, we developed the emission coefficients based on actual land-cover information rather than on geographical region.

The procedure included three steps.

Firstly, from 250m-resolution maps of LANDSAT for Europe (used as a test domain) we created a 10-km integrated pattern of prevailing types of vegetation, which, for the sake of simplicity, extendibility and robustness of the final estimates, included just three types: grassland and agriculture land, forests, and a mixture of these.

Secondly, for these three types, we assumed three gradations of the total-PM emission coefficients: 0.1 kg MJ^{-1} for forest and 0.05 kg MJ^{-1} grass/agriculture lands while for mixed areas an average of 0.08 kg MJ^{-1} was used. These values were deduced from the prevailing land cover in the above domains processed by Ichoku and Kaufman [12].

Thirdly, a limited number of well-determined fire episodes in April-May and August of 2006 in Europe was selected, for which the actual location of most of the fire pixels was attributed to one of the land cover types for each day (Figure 1). For these episodes, the generated emission files were submitted to the chemical transport model SILAM, which simulated atmospheric dispersion of the plumes. The results were compared with in-situ (Finnish PM 2.5 Helsinki-Kumpula, Uto, Virolahti, Oulu, Vaasa) and satellite (MODIS AOD) observations and the systematic deviations in both column-integrated and near-surface PM concentrations were attributed to the emission scaling.

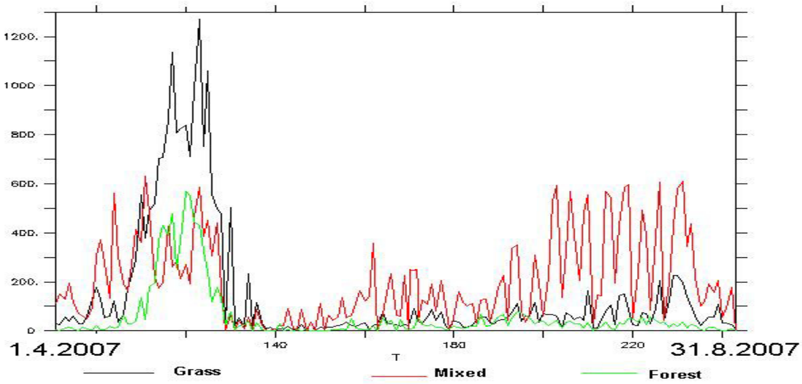

Figure 1: Temporal evolution of fire FRP distributed between the land use types for the fire season of 2006. Periods selected for the system calibration are end-April and mid-August.

As seen from Figure 1, the fire season of year 2006 has several well-pronounced episodes with clear dominance of one of the land-use types in the total count of burning areas. The episodes were also sufficiently long (up to a week for some sites) to average out the random fluctuations in the model simulations. Importantly, the plumes from these fires were easily distinguishable from the anthropogenic pollution in the AOD maps, which also increased the accuracy of the calibration.

The main reference dataset was the aerosol optical depth from MODIS converted (as extension to the product) to mass of aerosol m^{-2}. This dataset was utilised for setting-up the emission coefficients. The in-situ observations were mainly involved as an independent data for checking the obtained parameterizations. The main reason for that was that near-surface values appeared very sensitive to injection height and boundary layer description in the SILAM model. Also, ground-based observations are essentially point-wise and comparatively scarce. In view of these uncertainties and necessity to have an independent control dataset for verification of the emission calibration, we based the main calibration procedure on the above MODIS datasets and used the surface observations only as indicators of characteristic PM levels.

Under the assumption that inside the fire plumes the AOD was entirely dominated by the biomass-burning products (supported by e.g. Saarikoski *et al.*, [15] where it is shown that over 80% of PM 2.5 during some specific episode of May 2006 originates from fires), we attributed all systematic discrepancy between the observed and calculated column AOD to errors in the emission rates – and corrected the emission factors accordingly.

3 Integration with the atmospheric composition system SILAM

The above algorithm generates the PM fire emission. To obtain the other species, we scaled the fluxes using the mean ratios between the emission factors for total PM and other substances suggested by Andreae and Merlet [13]. Then both particulate and gaseous emission fluxes are merged with anthropogenic inventories from European Monitoring and Evaluation Programme EMEP (http://www.emep.int) and introduced into the modelling system SILAM.

SILAM is an air quality and emergency system that has been created to provide an environment capable of supporting various types of dispersion models and suitable for approaching a wide range of tasks (http://silam.fmi.fi, Sofiev *et al.* [14]). The dispersion tools allow choosing between the Eulerian and Lagrangian dynamic kernels and eight different chemico-physical cocktails of species. For most of the simulations, we currently use Eulerian dynamics and a combination of basic acid and ozone chemistry with inert particles for fire and anthropogenic primary PM emission, as well as the sea salt production terms to account for the background marine aerosol contribution.

The specific simulations presented below and a more detailed consideration by Sofiev *et al.* (this issue) have been made over the whole of Europe with spatial resolution of about 30 km and hourly averaging of the output fields.

Evaluation of the output concentration fields has been done against several independent datasets. In-situ data were obtained from national and international observational networks, and information from the AIRBASE database of European Environment Agency (for the periods and regions where the information was available). Remote-sensing information about the tropospheric composition obtained from several independent sources was the complementary set of data. The primary source was MODIS, which provides the vertically-integrated aerosol optical depth (AOD) but we also utilised the OMI satellite retrievals for NO2.

4 Results and discussion

One of the main outcomes of the study is the time series of the European emission from fires shown in Sofiev *et al.* (this issue), where both the quantitative estimations of the European biomass burning emissions and their contribution compared to that of anthropogenic and natural sources are presented. Here we concentrate on comparison of the two approaches – the FAS-TA and FAS-FRP.

First of all, the comparison of the fire-induced emissions with anthropogenic primary PM release to the atmosphere shows that at annual level they are practically the same: mean over 2.5 years (2006-2008) leads to ~7.5 kton of PM 2.5 day^{-1}. Data submitted by European countries in 2005 within the scope of EMEP programme lead to ~9 kton of PM 2.5 day^{-1}, so that the difference between these estimates is well within the uncertainty of both values (Boschetti *et al*. [16]).

Secondly, the spatial distribution of the emission locations strongly depends on the type of satellite product used. An example in Figure 2 shows that the main stress of FAS-TA (left-hand panel of Figure 2) is put on the number of fires, which are all reported as having the similar strength (in Figure 2 the size of a marker is proportional to the integrated PM emission by a particular fire). To the opposite, FAS-FRP highlights the variation of strengths of the individual fires but tends to miss the smallest ones altogether.

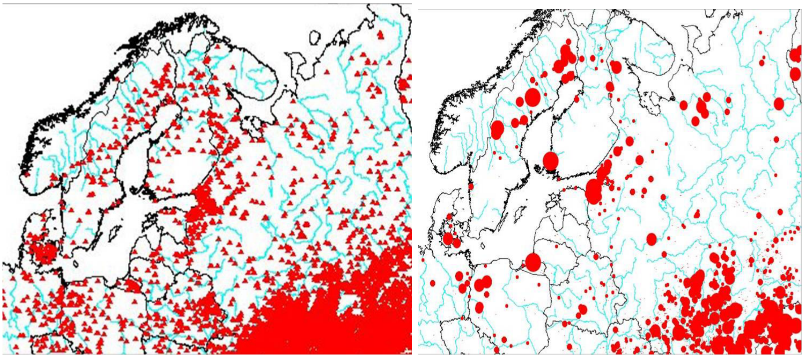

Figure 2: TA- (left-hand panel) and FRP- (right-hand panel) based total emission estimates for May-August 2006 (relative units). The size of marker is proportional to emission value.

Such behaviour of the two algorithms evidently follows from the methodology behind each of them. The TA system is based on just an absolute temperature, which does not vary too strongly, while FRP uses the difference of 8-th power of actual and background temperatures, thus being much more sensitive to both values. This apparent advantage also shows a weak point: the FRP algorithm is more sensitive to even small errors in temperature retrievals, while all what is needed for TA is robust determination of burning pixels. For the latter parameter the Rapid Response System has a separate variable characterising the probability of the pixel to be burning. The current FAS does not use its value but it can be included as an additional factor affecting the emission fluxes (actually, reducing them if the probability of correct diagnostic of a pixel to be burning is substantially less than 1).

This crucial difference between the approaches has significant outcome to the subsequently estimated pollution concentrations. As seen from example in

Figure 3 for the 4.3.2008, large number of small-scale fires in the south-east of Europe was interpreted by TA-algorithm as substantially stronger emitter than that claimed by FRP. Also, FRP system lost several small-scale burnings in Spain and elsewhere while TA has reported them as significant sources.

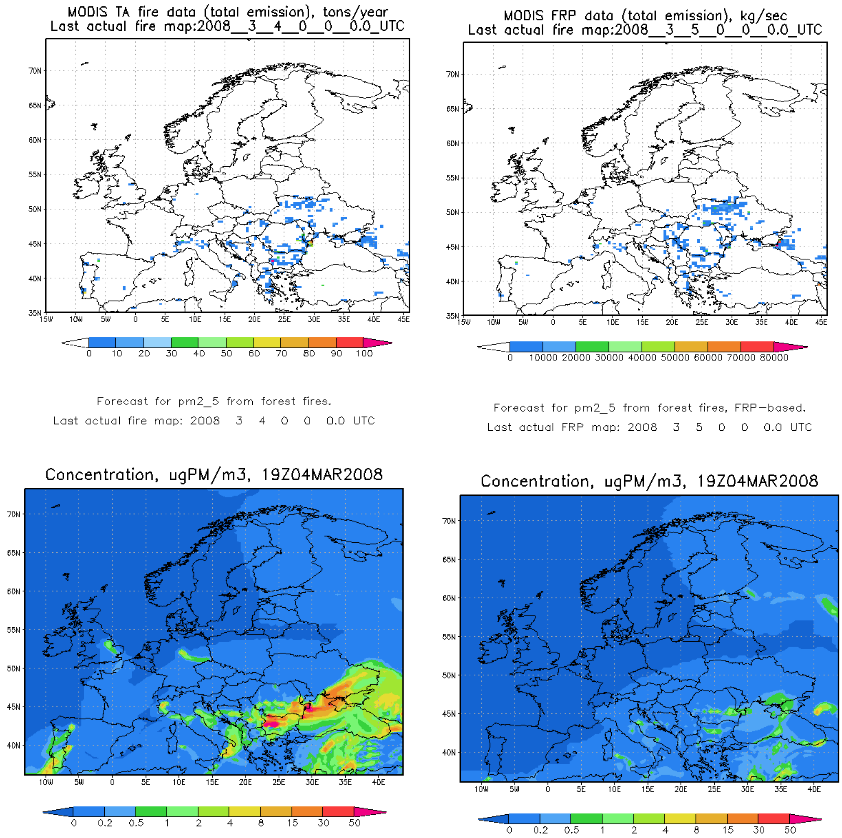

Figure 3: An example of PM 2.5 emission (integrated over 27.2.2008-4.3.2008) and vertically-integrated concentrations originated from fires, as estimated by FAS-TA (left-hand panel) and FAS-FRP (right-hand panel).

It is premature now to conclude on what algorithm is more accurate. In evaluation, the signal from fires has to be differentiated from that of anthropogenic and natural sources, which is possible only for major events where both algorithms provide quite similar estimates. From physical point of view, FRP algorithm is better grounded but still the selection of 8-th power is pretty arbitrary and the scaling coefficient is based on fitting to quite noisy data.

Therefore, we tend to consider the difference between these two systems as uncertainty in estimates of the fire emissions.

5 Conclusions

The biomass-burning sources of atmospheric pollution are important contributors to the atmospheric composition over Europe. Development and operational implementation of the dual-line Fire Assimilation System in Finnish Meteorological Institute helped to improve the air quality forecasts, especially for spring and summer seasons when the emission from fires is comparable with that of other sources.

The fire emissions are derived from hot-spot counts (temperature anomaly) and fire radiative power products of MODIS instrument onboard of NASA Aqua and Terra satellites and provided, together with anthropogenic and biogenic emission fluxes, to SILAM dispersion modelling system.

Comparison of TA- and FRP- based systems showed that the algorithms tend to report the major fire events pretty similarly while the difference between the emission estimates for small-scale burnings can be substantially different. Current level of the system evaluation does not allow firm conclusions on what algorithm is better: strong and weak points exist in both sub-systems.

Acknowledgements

The Fire Assimilation System of FMI has been developed within the scope of the EU-GEMS project and is currently being updated within the IS4FIRES project of Academy of Finland. The operational forecasts have been supported by the EU-GEMS and ESA-PROMOTE projects. Networking support of the COST-ES0602 Action is also appreciated.

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