3-D Fire Radiative Power Modelling Approach

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Report by

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EXECUTIVE SUMMARY

Biomass burning is a key Earth system process, a major element of the terrestrial carbon cycle and a globally highly significant source of certain atmospheric trace gases and (primarily fine mode) aerosols. Natural and anthropogenic biomass burning occurs on all continents except Antarctica, with an estimated average of 3.5 - 4.5 million km² of vegetation burnt in global wildfires each year (though this does not include the very large numbers of "small" agricultural fires that are difficult to map using current coarse spatial resolution remote sensing datasets). As such, landscape fires are arguably the most important and widespread ecosystem disturbance agent worldwide and their pyrogenic gaseous and particulate emissions are recognized to be highly significant at the global scale, where Earth's atmospheric chemistry, cloud and rainfall characteristics, and radiative budget are all influenced. Understanding these impacts of fire is seen as critical to improved understanding of these issues, and because of the spatial scales and high temporal variability's involved satellite Earth Observation (EO) has much to contribute, including thermal infrared methods. The use of thermal remote sensing in the study of vegetation fires is therefore the focus of this study.

Vegetation combustion is a multifaceted process that involves simultaneous coupled heat and mass transfer, with the chemical reactions and fluid flows made more complex by the nature and non-uniformity of 'natural' fuels. Nevertheless, the thermal remote sensing of vegetation fires uses techniques common to the majority of thermal remote sensing applications, based around the measurements of EM radiation at middle infrared (MWIR) and longwave infraed (LWIR) wavelengths, and most recently around the derivation of a fires radiative power output (FRP), which in a number of experiments and studies has been shown to be well related to its rate of fuel consumption and thus trace gas and aerosol emission. This FRP approach is now used within the Copernicus Atmosphere Service (CAMS) to derive fire emissions for atmospheric modelling and forecasting, and will be applied to the new data to be gathered by the SLSTR instrument onboard Sentinel-3 that will be launched late in 2015.

Now that Fire Radiative Power (FRP) has become an established technique for wildfire emissions assessment, there is perceived to be an increased need to study the sensitivity of FRP retrievals to fire and observation parameters. In this context, this project has linked simulated representations of wildfire (or wildfire measurements) to 3D radiative transfer models that allow for the modelling of two dimensional views of a wildfire scene, based on the 3D radiation fields emitted and/or reflected from the fire and the surrounding surfaces and then transmitted through the atmosphere. This provides:

(i) an approach potentially capable of allowing examination of a much wider range of fire and observations conditions than can empirical data alone, and with greater realism than can be gained using current simulation approaches,

(ii) the ability to have access to information on the underlying 'fire behaviour' (e.g. fire intensity, and rates of spread and fuel consumption) and fire characteristics (e.g. temperatures and FRP output) represented by the fire model or fire observations, for comparison to the same values estimated from the simulated imagery

(iii) a tool that can be used to study a more complex and/or wide ranging set of cases in order to enable sensitivity analyses to be conducted, including potentially in fire situations where 'ground-truth' data for evaluating the measurements made using real satellite or airborne imagery is extremely challenging to obtain.

In the context of the above, this project has specifically developed, demonstrated and applied an approach to simulating the thermal imagery of spreading vegetation fires moving within landscapes. Our primary radiative transfer model is DART (Gascon, 2001), a widely used European 3D radiative transfer model operating in the VIS to LWIR spectral region. However, DART does not normally include the capacity to include fire as a scene component, and thus as part of this project major adaptations and extensions have been made to DART to enable the 3D radiance fields from fires embedded in wider 3D scenes to be simulated at thermal infrared wavelengths. Further adaptations have focused on enabling DART to efficiently simulate larger landscapes, and using new sensor geometries such as a pinhole camera and an imaging scanner. This latter development moves beyond most, if not all, remote sensing 3D scene simulation models that simulate remote sensing acquisition of landscapes assuming the whole landscape is observed along the same viewing direction This assumption maybe acceptable when a relatively small landscape is observed from an altitude ensuring that the divergence of the FOV over the landscape can be neglected, but it disqualifies direct comparison of modelled images with actual observations that do not meet this assumption - as is conducted in the context of this project. To be allied with the enhanced version of DART that is now very capable of fire scence simulations, and which is already now publically available, we have developed a standalone separate radiative transfer model for comparison purposes and for rapid simulation testing (SRTE3.9), along with two approaches to set up the 3D voxel-based 'fire scene' used by the radiative transfer models: (i) 3DFireScene that represents a set of procedures necessary transform the type of 2D fire information output from fire spread models or from fire observations into to the type of 3D structure which contains flames (i.e. hot soot), hot combusting vegetation fuel, and cooling ground and their associated parameters at each time-step, and (ii) a method to exploit of the Wildland Fire Dynamics Simulator (WFDS; Mell et al., 2007), an existing computational fluid dynamics vegetation fire model based upon the widely-used FDS model of NIST that was originally developed to study the spread and intensity of structural (building) fires and which has a dedicated fuel model to support vegetation fire simulation built in.

We have applied our developed toolkit and methods to the simulation of three types of fire: (i) A set of rather small-scale experimental fires for which detailed observation are available, conducted within a ~ 10 m × 10 m domain but whose behavior is similar to much larger scale fire events; (ii) a savannah fire within a domain of ~ 400 m× 400 m observed by airborne MWIR imagery from which the necessary parameters for the simulation have been extracted (e.g. fire front rate of spread), and (iv) larger landscape-scale fires of the type able to be simulated by typical fire spread models operating at this scale, for example the Canadian model 'Prometheus' that can operate within domains of many km or tens of km.

We demonstrate the use of the completed system by conducting a sensitivity study to simultaneously model many different views of certain of these fires, and compare these simulations to understand the effect on the FRP computation from remotely sensed imagery of intrinsic observation parameters such as the view zenith angle, the view azimuth angle, and the measurement spatial resolution. We find the impact of the camera orientation to be weak, which suggests the assumption of lambertian-type emission from these fires is reasonable. However, flames are generally small in these fires (< 5 m length) and a stronger effect could be present in e.g. torching forest fires. We also note that the cooler smoke plume is not simulated in our system, which may yet have an important effect when aligned with the line of sight of the imager. Simulation of the impact of such smoke plumes could be the focus of further work in this area.