Institution: King's College London

Unit of Assessment: UoA 17

Title of case study: Fire Radiative Power for Real-Time Satellite Observation of Wildfires and Quantification of their Smoke Emissions

1. Summary of the impact

Research by Kings' Department of Geography on the remote sensing of fire radiative power (FRP) has had a transformative impact on assessments of global wildfires and their smoke emissions. The research has been supported by the EU Framework programme and NERC's "Knowledge Exchange" and "National Centre for Earth Observation" Programmes (see list in Section 3.), and has provided new methods for estimating wildfire fuel consumption and smoke emissions to support many applications ('smoke' being a mixture of soot, greenhouse gases, and reactive gases that greatly affects Earth's atmosphere). The impact includes: (1) The delivery of real-time daily maps of global wildfire smoke emissions as part of the EU's *Copernicus* (formally 'GMES') Global Monitoring programme that supports real-time atmospheric modelling, forecasting and air quality early warning efforts. (2) Development of a series of new and publically available "FRP" products derived from satellite Earth Observation data and delivered direct to users worldwide. (3) Substantial changes to the design of two key 'next generation' European Earth Observation satellites. (4) FRP being included in the 50 'Essential Climate Variables' stated by the Global Climate Observing System (GCOS) as being required to support the UN Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). In recognition of these impacts, Wooster's Research Team and collaborators (Met Office/ECMWF) were awarded the London Development Agency's Knowledge Transfer Award for Environmental Science in 2008 (NERC sponsored), and in 2011 Wooster received the Royal Geographical Society's Cuthbert Peek Award for 'innovation in applying earth observation science to monitor fires in the landscape'.

2. Underpinning research

From his PhD research on the satellite Earth Observation of active volcanoes, Wooster developed approaches to link remotely-sensed infrared measurements of the radiative energy emitted by a warming or cooling body to the mass (and temperature) of that body. Initially used to quantify lava flow energy budgets using data from Earth Observation satellites, the method showed the potential to be inverted to estimate the mass of lava produced in an eruption via measurements of the infrared radiative energy emitted (Ref a). Now at King's from Jan 1998 with an RCUK Earth Observation Science Lectureship 50% funded by NERC for the first 5 years, Wooster adapted this prior research to interrelate measurements of the infrared energy emitted by burning vegetation fires to the mass of fuel being burned, applying this to the types of large wildfire observable from orbiting satellites. Wooster (Ref b) developed a new sensor-independent algorithm to quantify the rate of infrared energy released by a burning wildfire (the so-called 'fire radiative power'; or FRP) using data from Earth orbiting satellites. Demonstrating the advantages of the new FRP algorithm, Wooster (Ref b) also made the first intercomparisons between FRP measurements made near simultaneously by two different satellite instruments, in order to demonstrate how the FRP estimates are relatively independent of the specific satellite sensor used. Building on this work, Wooster (Ref c, d and e) then conducted the first laboratory- and field-based experiments that proved that FRP directly relates firstly to fuel consumption rate, and also to the rate of emission of smoke. In Ref e Wooster also developed and tested the first ever algorithm for mapping FRP from wildfires using data from a geostationary satellite. Previous work on FRP had been conducted with low Earth orbit satellites only, which observe any particular location on Earth at best only a few times per day, week or month. Geostationary satellites are designed to provide real-time, uninterrupted data for weather forecasting purposes, and since they orbit Earth at much greater distances they can view one complete side of the Earth almost constantly, thus allowing near continuous real-time coverage of the observed fires and their FRP. Finally, with NERC National Centre for Earth Observation and European Space Agency (ESA) support, in Ref (f) Wooster commenced development of new fire detection and FRP algorithms for the 'next generation' European satellite missions, which by now were being influenced by this research and were being physically re-designed by ESA and EUMETSAT specifically with FRP observations in mind.

3. References to the research

Supporting Grants

2011-14 Monitoring Atmospheric Chemistry and Climate II (€266,000 to KCL; EU FP7)

2010-13 Pre-Launch Sentinel-3 SLSTR Fire Product (£168k, NERC NCEO Mission Support,)
2011-12 Improving Representation of Fire Smoke Transport in a Key Operational Atmospheric Monitoring & Forecasting Scheme (£125k, NERC Knowledge Exchange)
2009-11 Monitoring Atmospheric Chemistry and Climate (€135k to KCL; EU FP7)
2008-10 Development of a Geostationary Forest Fire Monitoring and Characterising System for China and the Wider Asian Region (£62k, ICUK)
2009-10 Validation of a Geostationary Fire Product (€96k, EUMETSAT)
2008-13 NERC National Centre for Earth Observation - Carbon Theme (£200k, NERC)
2008-09 SENTINEL-3 SLSTR Prototype EO Products - FRP (€25k, ESA)
2007-08 GEOFIRE - A Global Geostationary Biomass Burning Emissions Estimation System for Use in Forecasting of Atmospheric State. (£191k, NERC Knowledge Exchange)
2005-06 A Geostationary Fire Product for Africa (£51k, NERC Knowledge Exchange)
2002-03 Retrieval of Fire Radiative Energy to Support Biomass Burning Emission Inventories: Derivation via New Spaceborne Mid-IR Radiometry (£133k, NERC)

Key peer reviewed outputs and publications (**King's Personnel are in Bold**)

(a) Wooster, M.J., Wright, R., Blake, S. and Rothery, D.A. (1997) Cooling mechanisms and an approximate thermal budget for the 1991-1993 Mount Etna lava flow, *Geophysical Research Letters*, 24, 3277-3280. doi: 10.1029/97GL03166

(b) Wooster, M.J, Zhukov, B. and Oertel, D. (2003) Fire radiative energy for quantitative study of biomass burning: Derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment,* 86: 83-107. doi: 10.1016/S0034-4257(03)00070-1

(c) Wooster, M.J., Roberts, G., **Perry, G.** and Kaufman, Y.J. (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: calibration relationships between biomass consumption and fire radiative energy release. *Journal of Geophysical Research* 110, D21111: doi: 10.1029/2005JD006318.

(d) Freeborn, P.H., Wooster, M.J., Hao, W.M., Ryan, C.A.,Nordgren, B.L. Baker, S.P. and Ichoku, C.(2008) Relationships between energy release, fuel mass loss, and trace gas and aerosol emissions during laboratory biomass fires, *Journal of Geophysical Research*, 113, D01102, doi: 10.1029/2007JD008489

(e) Roberts, G., Wooster, M.J., **Perry, G.L.W**., **Drake, N.,** Rebelo, L-M., Dipotso, F. (2005) Retrieval of biomass combustion rates and totals from fire radiative power observations: application to southern Africa using geostationary SEVIRI Imagery. *Journal of Geophysical Research* 110, D21111: doi: 10.1029/2005JD006018.

(f) Wooster, M.J., Xu, W. and Nightingale, T. (2012) The Sentinel-3 SLSTR active fire detection and FRP Dataset: Pre-launch algorithm development and performance evaluation using MODIS and ASTER data, *Remote Sensing of Environment, 120,236-254.* doi: 10.1016/j.rse.2011.09.033

4. Details of the impact

Wooster's research on fire radiative power (FRP), and the algorithms and data products resulting from it, have had, and continue to have, major instrumental impacts on the European capacity to map, quantify and monitor global wildfires and their effects, including through (1) the near-real time mapping of fire location, FRP and fuel consumption rates; (2) quantification of wildfire smoke emissions to the atmosphere; on abilities to map global atmospheric concentrations of greenhouse gases, reactive gases, and aerosols in real-time, and (3) on public-early warning capabilities in relation to reduced air quality episodes. This research gained this impact in particular through its application in Stages 1 and 2 of the European Commission's operational global Earth system monitoring scheme *Copernicus* (formally known as GMES: Global Monitoring for Environment and Security), generating four discrete instrumental impacts.

1. Under *Copernicus* Stages 1 and 2, the GEMS project (Global and Regional Earth-system Monitoring using Satellite and *in-situ* data) and its successors MACC (Monitoring Atmospheric Composition and Climate) and MACC-II, a Global Fire Assimilation System (GFAS) "based on satellite-based fire radiative power products (FRP)" (Ref i: 528) was developed for the operational *Copernicus* Atmosphere Service that will provide users real-time atmospheric monitoring and forecasting data. Wooster's FRP was used because, "FRP has been quantitatively linked to the combustion rate (Wooster *et al.,* 2005)…" (Ref i: 528). Describing GFAS' development at the European Centre for Medium-Range Weather Forecasts (ECMWF), Ref i (p.528) state that: "In order to provide accurate estimates of aerosol, reactive gas and greenhouse gas emission fluxes to the atmospheric systems, a global fire assimilation system (GFAS) based on satellite-based fire radiative power (FRP) products is being developed". The GEMS 'Copernicus Atmosphere Service

Phase 1' final report (Ref ii:15) confirms that GFAS is based on the FRP approach of Wooster *et al.* (2003) and Roberts *et al.* (2005) (Refs b and e, see Section 3).

2. As a result of the application of Wooster's FRP concept to existing satellite technologies, and via his instrumental role within Europe's Meteorological Satellite Agency (EUMETSAT), EUMETSAT now offers two publically accessible services for which Wooster is named author of both the algorithm descriptions (ATBDs - e.g. Ref iii) and user manuals (FRP_PIXEL; http://landsaf.meteo.pt/algorithms.jsp?seltab=12&starttab=12 and FRP_GRID; http://landsaf.meteo.pt/algorithms.jsp?seltab=13&starttab=13). Together these form the "FRP products from [the current Meteosat 2nd Generation] SEVIRI" (Ref iv: 2), that offer "the potential to significantly reduce the uncertainly of fire emissions estimates" (Ref iv:.2). Further, Space Agency EUMETSAT commissioned Wooster to review the next [3rd] generation Meteosat satellites Mission Requirements Regarding Fire Applications (Ref v), leading to the introduction of an "extended dynamic range for fire monitoring applications" (Ref vi: 6). The impact involved EUMETSAT confirming the presence of dedicated fire observation channels for the planned 3rd generation satellite, and in accordance with Wooster's (Ref v) suggestions physically re-designing the 3.8 µm channel of the new Meteosat's Full Disk High Spectral Resolution Imagery Mission [FDHSI] to deliver a maximum 450 K brightness temperature measurement, rather than the previously planned 400 K. Wooster's work therefore had a significant, direct and instrumental impact on the design of next generation of European geostationary weather satellite technology.

3. There is a clear, and increasingly documented, public benefit (e.g. to asthma sufferers) from information systems supported by the *Copernicus* Atmosphere Service. To help plan the GMES development, in 2006 PricewaterhouseCoopers (PwC) undertook a socio-economic analysis into the benefits expected from GMES, including that of the *Copernicus* Atmosphere Service (Ref vii: 112). The analysis states that "GMES services could potentially help to measure and predict air quality, and as a consequence the prospective benefits could be two-fold. First, through prediction, the information gathered from short and medium term forecasting of air pollution levels could provide a 'poor air quality' alert system directly to people susceptible to poor air quality, such as those with asthma. Second, they will then be able to make decisions to reduce the impact of the air quality on their health, resulting in reduced detrimental health impacts. Trials of such a system, using cell phone messages to alert vulnerable users, are already being undertaken within GMES". The expected benefits identified by PwC are now being realised. Impact is being projected by a number of public health information services, such as MyAir (www.myair.eu/) and AirText (www.airtext.info/), powered by the outputs of the *Copernicus* Atmosphere Service. These services supply air quality forecasts and warnings direct to the public via web, email and SMS-text messages. Many European citizens have signed up to these services, including for example over 7000 asthma suffers in London alone, with "80 per cent of users saying it has helped them manage their symptoms better and reduce their exposure to air pollution" (Ref viii: 1). Outside Europe, the Beijing Environmental Monitoring Centre (http://zx.bjmemc.com.cn/) has also made use of *Copernicus* Atmospheric Service products to support similar initiatives. Furthermore, Ref vii (page 110) outlines the use of the *Copernicus* [GMES] Atmosphere Service within a series of 'European Environmental Protection Policy Domains', including the Convention on Long-Range Transport of Air Pollutants, the Gothenburg Protocol (that set emission ceilings for 2010 for four pollutants, three of which are substantially emitted by biomass burning), and the new Air Quality Directive implemented in 2008 (ec.europa.eu/environment/air/quality/legislation/existing_leg.htm). Taking into account its use in health applications, and in treaty verification and international negotiations, for the period 2006-30, PwC (Ref ix: 16) assessed the benefits of air quality information delivered by the *Copernicus* Atmosphere Service, supported by the Global Fire Assimilation System, to be €4.1 billion.

4. In addition to air quality and health applications, of further relevance to treaty verification and international negotiations is the designation of FRP as part of the 50 'Essential Climate Variables' (ECVs) identified by the Global Climate Observing System (GCOS) as required to support the UN Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change [www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables]. The Fire Disturbance ECV explicitly embraces FRP (Ref x: 10), and the new Sentinel satellite programme of the European Space Agency (ESA) has the aim of supporting both ECV production and the EU's *Copernicus*/GMES programme

(www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/ESA_s_Living_Planet_Programme) and www.esa.int/Our_Activities/Observing_the_Earth/GMES/Sentinel-3. The specifications and physical design of the Sentinel-3 satellites SLSTR instrument, currently being readied for a 2014 launch, were significantly altered on advice from Wooster (Ref xi), changing the middle infrared (3.7 µm; F1) "fire channel" maximum signal and removing a 27 Kelvin gap in radiometric coverage that would otherwise have prevented the detection of many fires. These contributions demonstrate that, as well as the existing use of Wooster's FRP algorithms and products highlighted above, Wooster's work continues to have an ongoing instrumental impact on satellite instrument design, in this case with regard to Europe's next generation operational polar-orbiting system. After launch of Sentinel-3, the European Space Agency will generate an FRP data record by processing data from the SLSTR though a new algorithm (Ref f) developed by Wooster under contract to the Space Agency.

5. Sources to corroborate the impact Reports and other published evidence of impact

(i) Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.-J., Razinger, M., Schultz, M. G., Suttie, M., and van der Werf, G. R. (2011) Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeochemistry,* 9, 527-554. http://www.biogeosciences.net/9/527/2012/bg-9-527-2012.html [accessed 11/6/2013]**,** doi 10.5194/bg-9-527-2012 (Wooster's research linking FRP & combustion rate in the Global Fire Assimilation System (GFAS) of the Copernicus Atmospheric Service)
(ii) ECMWF (2010) *A Monitoring and Forecasting System for Atmospheric Composition*, Final report of GEMS project, 184pp. *cordis.europa.eu/documents/documentlibrary/114724421EN6.pdf* [accessed 11/6/2013] (GFAS " most accurate fire observation product for emissions estimation").
(iii) Govaerts, Y., Wooster, M., Freeborn, P. Lattanzio, P. and Roberts, G. (2010) Algorithm Theoretical Basis Document for MSG SEVIRI Fire Radiative Power (FRP) Characterisation, Products LSA-31 (FRP Pixel) and LSA-32 (FRP Grid) *http://landsaf.meteo.pt/GetDocument.do?id=278* [accessed 11/6/2013] (King's authorship of the algorithms used to produce the real-time FRP_Pixel and FRP_GRID data products at the EUMETSAT Land Surface Analysis Satellite Applications Facility [LSA SAF]).
(iv) Textor, C., Schultz, M., Kaiser, J., Flemming, J., Granier, C. and Hollingsworth, T. (2006) *Expression of Interest for Listing of a European Project on a Global Fire Assimilation System*, www.ecmwf.int/research/EU_projects/HALO/pdf/GFAS_ExpressInterest5.pdf [accessed 24/5/2013] (indicates that when planning the GFAS the FRP method "has the potential to significantly reduce the uncertainty of fire emission estimates" - including via use of the LSA SAF FRP Products).
(v) Wooster, M.J. and Roberts, G.J. (2004) Review of MTG FDHSI Mission Requirements Regarding Fire Applications, Report for EUMETSAT contract EUM/PPS/SOW/04/0055, 22pp. http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=pdf_mtg_rep13&RevisionSelectionMethod=LatestReleased&Rendition=Web [accessed 16/10/13] (King's input into design of Meteosat Third Generation satellite imaging system with respect to fire observations)
(**vi**) EUMETSAT (2005) Studies initiated through MMT actions to consolidate MTG Observation Missions before start of pre-Phase A at Industry level, 2nd MTG Mission Team Meeting, 11pp, http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=pdf_mtg_mmt2_04&RevisionSelectionMethod=LatestReleased&Rendition=Web [accessed 16/10/13] (as for (v))
(vii) PWC (2006a) Main Report Socio-Economic Benefits Analysis of GMES, ESA Contract 18868/05, 204pp. esamultimedia.esa.int/docs/GMES/261006_GMES_D10_final.pdf [accessed 11/6/2013] (states policy uses of the Copernicus Atmospheric Service)
(viii) ESA (2007) London Asthma Sufferers Get Space-Based Help www.esa.int/Our_Activities/Observing_the_Earth/GMES/London_asthma_sufferers_get_space-based_help [accessed 11/6/2013] (use of early warning for asthma sufferers)
(ix) PWC (2006b) Executive Summary Socio-Economic Benefits Analysis of GMES, ESA Contract 18868/05, 27pp. esamultimedia.esa.int/docs/GMES/261906_Executive_Summary_final.pdf [accessed 11/6/2013] (states financial and public benefits of the Copernicus Atmospheric Service)
(x) GCOS (2009) Essential Climate Variables: T13 - Fire, 39pp. [accessed 11/6/2013] http://www.fao.org/gtos/doc/ecvs/t13/t13.pdf FRP part of fire disturbance Essential Climate Variable
(xi) Wooster (1998) SLSTR Fire Channels - A note on some fire-related design issues presented at (A)ATSR Science Advisory Group 27 Nov 2008 (Prof. Martin Wooster) [wildfire.geog.kcl.ac.uk/wp-content/uploads/2012/07/SLSTR-Advisory-Report-Wooster.pdf] [accessed 24/6/2013] (input into the design of the SLSTR "fire channels" for ESA's Sentinel-3 satellite).