Institution: University College London

Unit of Assessment: 17B – Geography, Environmental Studies & Archaeology: Geography

Title of case study: Development of models permitting the use of Earth Observation data to monitor global climate change and land management

1. Summary of the impact (indicative maximum 100 words)

Albedo and fire impacts have been identified as Essential Climate Variables, i.e. key to climate monitoring systems and for informing land-use management. UCL research underpinned development of global, long-term satellite albedo and burned area products, which have become de facto standards distributed freely by NASA and the European Space Agency (ESA). The albedo data are used by meteorological agencies such as the UK Met Office, and for climate monitoring by organisations such as the UN Food and Agriculture Organisation (FAO). The burned area data are used for fire management by government agencies including the US Department of Agriculture and South African National Parks Agency.

2. Underpinning research (indicative maximum 500 words)

Albedo defines the reflectivity of the Earth's surface and determines how solar energy is partitioned between the surface and atmosphere. It varies as a result of natural processes (e.g. snowfall, vegetation growth) and human activities (e.g. forestry, agriculture) and is a sensitive indicator of environmental vulnerability. Thus consistent long-term satellite observations of the land surface are key requirements for global climate monitoring and for addressing the needs of the United Nations Framework Convention on Climate Change (UNFCCC), which came into effect in 1994. If satellite products are based on fundamental physical principles, rather than locally calibrated empirical relationships, their utility is increased hugely: they are comparable with field measurements, are consistent across space and time and with models of weather and climate.

Turning satellite observations of reflected sunlight into albedo requires models of how surface reflectance changes over time. Since 1996, a number of breakthroughs by the Environmental Monitoring and Modelling (EMM) Research Group at UCL has made this modelling approach feasible for global coverage in real-time. This has resulted in physically based albedo (http://modis-land.gsfc.nasa.gov/brdf.html) and fire impact (http://modis-land.gsfc.nasa.gov/brdf.html) products from satellite observations. Previously, such applications had been limited in both space and time, making them unsuitable for global climate and monitoring applications. EMM work was critical in proving that physically realistic models could be used to produce albedo rapidly and accurately on global scales and, crucially, to provide uncertainty in resulting outputs [a].

This research by UCL's Professor Philip Lewis between 1999 and 2005, in collaboration with NASA colleagues, led to the development of an algorithm to use data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on two NASA satellites to provide a global 1km albedo product [b]. Prof Lewis and UCL lecturer Dr Mathias Disney then worked with the NASA MODIS team at Boston University to develop the implementation and testing of this algorithm [c] in 1998–2004. Lewis's key contribution was to demonstrate that albedo models could be made linear, drastically increasing efficiency and providing uncertainty estimates as a by-product (critical in the adoption of the product in climate forecasting). Disney and Lewis then led European testing of the MODIS albedo product in 1997–2005. In 2009–2012 Lewis led development of Globalbedo for the European Space Agency (ESA), which builds on the MODIS albedo product, updating it with observations from other ESA satellites (http://www.globalbedo.org/index.php).

Fire has significant impacts on forestry, agriculture and health (witness recent large fires in the US) and is a major source of natural and anthropogenic change to the land surface. Approximately 464 million ha of land are burned each year, releasing 2.5 Pg of carbon into the atmosphere. Fires are hard to monitor due to their dynamic, unpredictable nature. The methods developed by EMM for estimating albedo turned out to have more general application in modelling surface change including that caused by fire [d], and led to the development of the MODIS Burned Area product by UCL researchers (2000 to present), provided by NASA through the MODIS FIRE centre at the University of Maryland (http://modis-fire.umd.edu/Burned_Area_Products.html). Algorithm development was led by Lewis and developed in [e]. Current work is funded by NERC and ESA to develop new fire monitoring and impact applications.

Lewis joined UCL Geography as a lecturer in 1992 and made key developments in the modelling approach during 1997-2005. Disney joined the department as a lecturer in 2006 and extended the development and testing of the approach during 2002–2007. Further developments for improved fire mapping (Lewis, Disney), and optimal albedo estimation (Lewis) are ongoing.

3. References to the research (indicative maximum of six references)
(UCL authors [at time of research] in **bold**)

[a] Wanner, W, Strahler, A. H., Hu, B., **Lewis, P., Muller, J.-P.**, Li, X., Barker-Schaaf, C. L. & **Barnsley, M. J.** (1997) Global retrieval of bidirectional reflectance and albedo over land from EOS MODIS and MISR data: theory and algorithm. *Journal of Geophysical Research* 102, 17143-17162. doi: 10.1029/96JD03295. (ISI Journal Impact Factor [JFI]: 3.1; SCOPUS Citations: 140)

- Paper describes key theoretical developments required for global albedo, and outlines how the NASA product will approach this.

[b] Strahler, A., Lucht, W., Barker-Schaaf, C., **Muller, J.-P.**, Tsang, T., Gao, F., Li, X., **Lewis, P.**, **Barnsley, M.J.**, Hobson, P. H., Disney, M. I., Roberts, G., Dunderdale, M., Doll, C., D'Entremont, R. P., Hu, B. & Liang, S., Privette, J.L. and Roy, D. (1999) MODIS BRDF/albedo algorithm theoretical basis document (ATBD), version 5.0, NASA (2013 above) http://modis.gsfc.nasa.gov/data/atbd/atbd_mod09.pdf (NASA report, not indexed by SCOPUS, 156 citations via Google Scholar)

- Publicly-available report describing the NASA MODIS albedo algorithm in full, making clear all assumptions and limitations and providing users with a complete product description.

[c] Schaaf, C.B., Gao, F., Strahler, A.H., Lucht, W., Li, X., Tsang, T., Strugnell, N., Xiaoyang, Z., Jin, Y., **Muller, J.-P.**, **Lewis, P.**, Barnsley, M.J., Hobson, P. H., **Disney, M.I.**, **Roberts, G.**, **Dunderdale, M.**, **Doll, C.**, D'Entremont, R.P., Hu, B., Liang, S., Privette, J.L. & Roy, D. (2002) First operational BBRDF, albedo nadir reflectance products from MODIS, *Remote Sensing of Environment* 83(1-2), 135-148. doi: 10.1016/S0034-4257(02)00091-3 (JIF: 5.1 [top in field]; Citations: 631)

- Paper outlines the developments in method since the original mission conception, shows the first examples of the product and describes the first validation and testing work.

[d] Roy, D. P., **Lewis, P**. & Justice, C. (2002) Burned Area Mapping Using Multi-Temporal Moderate Spatial Resolution Data – a Bi-Directional Reflectance Model-Based Expectation Approach. *Remote Sensing of Environment* 83, 263-286. doi: 10.1016/S0034-4257(02)00077-9 (JIF: 5.1 [top in field]; Citations: 151)

- Paper is first description of how the principle underpinning the MODIS albedo product could be used more generally for change monitoring, specifically for measuring burned area.

[e] Roy, D. P., Jin, Y., **Lewis, P. E**. & Justice, C.O. (2005) Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment* 97(2), 137-162. doi: 10.1016/j.rse.2005.04.007. (JIF: 5.1 [top in field]; Citations: 158)

- Paper describes the prototyping and testing of the burned area mapping approach outlined in [d], and this was subsequently used as evidence to successfully convince NASA to adopt burned area as part of the MODIS suite of products.

Key peer-reviewed grants

PI: Prof Phillip Lewis, Co-I Dr Mat Disney. 'NERC National Centre for Earth Observation (NCEO) – Carbon Theme'; Sponsor: NERC; Period: 2008-2013; Amount : £440k

PI: Prof Phillip Lewis. 'Fire Modelling & Forecasting System (FireMAFS)'. Sponsor: NERC; Period: 2008-2010, Total amount: £400K, UCL component £17k.

PI: Prof Phillip Lewis. 'ESA Globalbedo'. Sponsor: ESA ESRIN; Period: 2009-2013; Amount: €1M.

4. Details of the impact (indicative maximum 750 words)
The research described in section 2 made a vital contribution to the development of the MODIS Bidirectional Reflectance Distribution Function and Albedo Product MOD43B, and to the subsequent development of the MODIS Burned Area product. The availability of routine,

automated, near-real-time data is a vital part of global monitoring by the Global Climate Observing System, the Committee on Earth Observation Satellites and the UNFCCC. This research has led to the development of the de facto standard albedo and fire Essential Climate Variables (ECVs) distributed by NASA and the European Space Agency (ESA), and used to model climate change and provide data for planning and climate change agreements. Albedo is a primary ECV, and the MODIS product has been used globally for environment, security, management and climate-related applications since 2001. The Burned Area product, conceived by UCL researchers as an outgrowth of the albedo product, enables officials in the United States, Australia and South Africa (among other places) to accurately monitor fire impacts and develop fire management plans.

Albedo: The Earth's surface temperature is partly controlled by its albedo: lower albedo means more radiation is absorbed rather than reflected, and thus the higher the temperature (and vice versa). The albedo depends on the nature of the surface; thus forests, cultivated fields and bare soil will all have different albedos and affect the weather, and more broadly, the climate, differently. For this reason, in 2007, the International Panel on Climate Change Fourth Assessment Report (IPCC AR4) [1] identified globally consistent albedo measurement as essential for monitoring climate change. In 2009 the UN Food and Agriculture Organisation (FAO) identified MODIS albedo as a key component of the Global Terrestrial Observing System (GTOS) [2], a programme to support sustainable development by establishing global observation and modelling networks to provide the evidence required to detect and manage environmental change. GTOS, as directed by the UN Framework Convention on Climate Change (UNFCCC), defines protocols and standards for monitoring and measurement to facilitate agreement on managing environmental change. Thus research has contributed directly to the capacity for global climate change monitoring broadly, and to the attainment of GTOS' objectives more specifically. A specific example of this use is by CICERO, an agency which advises the Norwegian government on climate change. This uses Globalbedo, the refinement to MODIS albedo described in section 2, to analyse the effects of anthropogenic vegetation change. [5]

MODIS albedo has been widely adopted to improve numerical weather prediction (NWP), which is vital to policy and commercial decisions relating to weather events. MODIS albedo is used to parameterise and test leading global NWP schemes, e.g. the European Centre for Medium-Range Weather Forecasting (ECMWF) model [3]. In 2007, the ECMWF incorporated the MODIS albedo product into its operational Integrated Forecasting System, which improved its forecasting capability demonstrably [4]. ECMWF forecasts using MODIS albedo, developed through UCL research, are provided to a range of agencies, such as the UK's Met Office, who use the products to develop short- to medium-range forecasts, e.g. to give early warning of potentially severe weather [6]. In November 2008 the UK Met Office integrated MODIS albedo into its NWP suite as part of a 'significant upgrade', thus improving forecasting of near-surface temperature, cloud and visibility [7]. In 2013, the Met Office began upgrading to use Globalbedo to eliminate the MODIS bias towards higher temperatures in summer, saying "Tests show that they (Globalbedo data) help to give more accurate temperature forecasts over the United States and Asia, especially in summer" [5].

Burned area (BA): The MODIS Burned Area product developed by UCL researchers and distributed by NASA is also a key component of GTOS [8]. In 2010, the Burned Area product was incorporated as a core part of the UN FAO Global Fire Information Management System (GFIMS) [9], an international monitoring system which delivers data to monitoring and emergency response projects conducted by national mapping agencies and other stakeholders. The product is widely used by park and natural resource managers to monitor fire, particularly in remote areas where fires may go unwitnessed and regrowth swiftly covers the extent of fire damage. These data are then used to plan management and rehabilitation, and for preserving and enhancing biodiversity.

The US National Interagency Fire Center (http://www.nifc.gov) relies on the MODIS BA product via the FAO's GFIMS [9] to develop aggregate records of fire extents, complementing data on active fires. It provides these data to its constituent agencies (e.g. the National Park Service, US Forest Service) to use in developing land and fire management plans. The USDA Forest Service, for instance, provides burn scar maps using a modified version of the MODIS Burned Area algorithm [9] Similar organisations in Australia (Landgate FireWatch) and Brazil (INPE) also generate burned area maps for use by emergency services, using MODIS data from GFIMS [9].

The BA product has also had direct impacts on conservation and biodiversity management in sub-Saharan Africa. At the Kruger National Park, a 1.9 million hectare game reserve in South Africa, the National Parks Service (SANPARKS) has used MODIS data since 2006 to map burned areas, monitor fires and analyse fire intensity and heterogeneity. Where unreported fires are detected, rangers are sent to assess the fire impacts on the ground and feed these data back into the park fire information system. The park's fire ecology manager describes how the mapping system, which remained in use through the impact period, improved mapping accuracy and captured the patchiness in burned areas, thus preventing over-estimation of burned areas and mapping their heterogeneity. By assessing the impact of fire over time on the park's flora and fauna, SANPARKS can make informed decisions about fire management to maintain the park's fragile ecosystem [10].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[1] Importance of consistent albedo measurement to monitoring climate change: Forster, P. et al. (2007) Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S. et al (eds.)]. Cambridge University Press, Cambridge, UK & New York, USA: http://bit.ly/18R6Yek [UN report; PDF], pp. 182–184.

[2] MODIS albedo as component of GTOS: GTOS (2009) Global Terrestrial Observing System: assessment of the status of the development of the standards for the essential climate variables, T8: Albedo and reflectance anisotropy, Barker-Schaaf et al. http://bit.ly/1b0AeQF [PDF], e.g. p. 3.

[3] MODIS albedo as component of NWP: Viterbo, P. (2009) Land Surface observations: Requirements for operational NWP in data assimilation and verification, ECMWF/GLASS Workshop on Land Surface Modelling and Data Assimilation and the implications for predictability, Reading, 9-12 November 2009: http://bit.ly/15zWizv [PDF], p. 14.

[4] Improvement to ECMWF forecasting due to incorporation of MODIS albedo: Morcrette, J.-J. et al. (2008). Impact of a New Radiation Package, McRad, in the ECMWF Integrated Forecasting System. Monthly Weather Review 136. DOI 10.1175/2008MWR2363.1.

[5] Use of Globalbedo data by Met Office and CICERO: Presentation for Globalbedo Phase II review, 3 July 2013 (available on request), ESA press release 6/9/2013: http://bit.ly/17DnWNR.

[6] Users of ECMWF data: http://www.ecmwf.int/about/overview/; http://www.ecmwf.int/about/cooperation/.
Use of ECMWF data by Met Office: http://bit.ly/1bRt84Q [PDF], e.g. pp. 2–4.

[7] Changes to the Met Office NWP System for Parallel Suite 20: Operational November 2008 Forecasting Research Technical Report No. 553, 11/4/2011. Met Office 2011. http://bit.ly/15zWizu [PDF], e.g. p. 13.

[8] GTOS (2009) Global Terrestrial Observing System: assessment of the status of the development of the standards for the essential climate variables, T13: Fire and fire disturbance, Csiszar et al. http://www.fao.org/gtos/doc/ECVs/T13/T13.pdf.

[9] GFIMS (2011) http://www.fao.org/nr/gfims/burned-area/en/; List of international agencies relying on GFIMS: http://www.fao.org/nr/gfims/activities/global/jp/; FireWatch (Western Australia): http://firewatch.dli.wa.gov.au/; INPE, Brazil: http://sigma.cptec.inpe.br/queimadas/faq.php; USDA Active Fire Map: http://activefiremaps.fs.fed.us/burnscar.php .

[10] Improved mapping in Kruger National Park: Govender, N. Mutanga, O., Ntsala, D. Veld fire reporting and mapping techniques in the Kruger National Park, South Africa, from 1941 to 2011. *African Journal of Range & Forage Science* 2012, 29(2): 63–73. (see p. 69–71) DOI 10.2989/10220119.2012.697918. Description of how maps are used provided by the Programme Manager for Fire Ecology & Biogeochemistry, Kruger National Park.