Institution: Swansea University

Unit of Assessment: 17 - Geography, Environmental Studies and Archaeology

Title of case study: Using land-surface satellite data to improve weather forecasts and climate predictions

1. Summary of the impact

Researchers in the Global Environmental Modelling and Earth Observation (GEMEO) group at Swansea University have used satellite data to improve weather forecasts and climate predictions. Using observations of the Earth's land surface from NASA's orbiting Moderate Resolution Imaging Spectrometer (MODIS) flying on board the Terra and Aqua satellites, Swansea University has worked directly with two leading meteorological agencies — the UK Met Office and the European Centre for Medium-Range Weather Forecasts (ECMWF) — to refine the way in which land is represented in their numerical weather prediction models. Improved weather forecasting is of clear benefit to society, facilitating day-to-day planning by the public, agriculture, commerce, utility suppliers and transport sectors, as well as preparation for extreme weather events such as floods, heat waves and droughts. The Met Office provides daily weather forecasts for the UK, while the ECMWF model is routinely used by over 30 countries for weather, aviation planning and extreme event warning. The Met Office states that the research presented here has resulted in significantly improved weather forecasts, in particular of rainfall and temperature, and more realistic climate simulations to inform the Intergovernmental Panel on Climate Change (IPCC). The ECMWF reports improvement of precipitation forecast, increasing predicted summer rainfall by 7%, and its variability, which is relevant to flood and drought forecast, increased by 30%.

2. Underpinning research

Context: GEMEO researchers use satellite observations to study the role of the land surface in the climate system. Past and present members of the GEMEO group include permanent staff Professor M. Barnsley (1995-2007), Professor P. North (2000-present, Dr S. Los (2001-present), and post-doctoral researchers Dr P. Hobson (1996-2000), Dr C. Houldcroft (2004-2007) and Dr W. Grey (2003-2008). The group has worked closely with the numerical weather prediction (NWP) and climate modelling communities and led the Climate and Land Surface Systems Interaction Centre (CLASSIC) funded by the Natural Environment Research Council (NERC) from 2003 to 2008 [G1-G2]. It has also been supported by research funding from the National Aeronautics and Space Administration (NASA) [G3] and the European Space Agency (ESA) [G4]. Research in close collaboration with these space agencies, the UK Met Office and ECMWF has aimed to improve operational weather forecasts and predictions of climate change. This has been achieved by research on global land albedo and vegetation cover. Albedo is a measure of the Earth's reflectivity, and is defined as the proportion of the Sun's radiation reflected by the surface. Albedo affects the energy budget of the planet, and is therefore a key driver of global weather patterns and long-term climate. For example, a change in surface albedo of just 4% has roughly the same impact on the Earth's energy balance as all of the heat-trapping carbon dioxide that has been emitted by humans to date. Specifically, we have constrained spatial and temporal changes in the albedo, and used satellite measurements to compile global albedo datasets that have been applied for the first time to Met Office predictive computer models of weather and climate. Similarly the seasonal cycle of vegetation has been observed and modelled, which strongly affects evaporation, rainfall and photosynthesis, and applied to improve the ECMWF model.

Extracting information from global satellite data: Research (led by Barnsley) has focused on estimating albedo from satellite observations. Barnsley pioneered methods to extract information from satellite data by observing the land surface at any one location from different viewing angles [R1]. These methods were used to demonstrate that valuable information can be obtained by exploiting multiple views, and formed the basis of subsequent MODIS satellite albedo products. Barnsley was a member of the NASA MODIS albedo team (1996-2007), and contributed to the release by NASA of these global albedo datasets to the general public from 2002, with subsequent updates over the following decade [R2]. Los, in collaboration with North, derived long-term vegetation datasets from satellite observations and developed methods to detect changes in the land surface while eliminating artefacts introduced by the satellite itself, the solar angle and changes in the atmosphere [R3]. The datasets were funded and distributed by NASA's

International Satellite Land Surface Climatology Initiative (ISLSCP) II, and provide validated datasets of vegetation properties, giving detailed information on seasonal and annual variations in vegetation across the globe [R4].

Improvement of operational weather forecasts: Using funding from NERC CLASSIC, Swansea led a collaboration with the UK Met Office to assemble improved global albedo datasets that could be directly used in the Met Office's operational weather forecasting model [R5]. Houldcroft and collaborators analysed satellite time-series data in order to separate albedo contributions from vegetation and soil and accurately model how albedo changes in space and time across the world. The research identified and corrected large errors in the existing Met Office model albedos, resulting in improved weather forecasts. Vegetation is represented in Met Office and ECMWF models primarily by Leaf Area Index (LAI) at each location globally, giving a measure of absorption of light, rainfall interception and evaporation. Los used datasets developed at Swansea in collaboration with ECMWF to implement and evaluate the first seasonal vegetation cycle in the ECMWF model [R6], giving explicit variation of LAI with season and location globally. The previous model had only a constant vegetation leaf area throughout the year, with a single value for each land cover class. The change resulted in improved operational weather forecasting, in particular in its predictions regarding the water cycle (rainfall, evapotranspiration and variability).

3. References to the research

Journal impact factor (JIF) and article citations from Web of Science as of July 2013 are given as indicators of quality of the research.

[R1] M. Barnsley *et al.* On the information content of multiple view angle (MVA) images. *Int. J. Remote Sens.* 18 (9), 1937-1960 (1997); DOI: 10.1080/014311697217963. [JIF: 1.1; citations: 48].

[R2] C.B. Schaaf *et al*. First operational BRDF, albedo nadir reflectance products from MODIS. *Remote Sens. Environ*. 83 (1-2), 135-148 (2002). DOI: 10.1016/S0034-4257(02)00091-3. [JIF: 5.3; citations: 618; main output of NASA MODIS albedo team collaboration].

[R3] S. O. Los *et al.* A method to convert AVHRR Normalized Difference Vegetation Index time series to a standard viewing and illumination geometry. *Remote Sens. Environ.* 99, 400-411 (2005). DOI: 10.1016/j.rse.2005.08.017 [JIF: 5.3; citations 41].

[R4] S. O. Los. ISLSCP II FASIR-adjusted NDVI Biophysical Parameter Fields, 1982-1998. (2010), in ISLSCP Initiative II collection dataset (http://daac.ornl.gov/). DOI: 10.3334/ORNLDAAC/970. [Reviewed by NASA ISLSCP Committee]

[R5] C. J. Houldcroft *et al.* New vegetation parameters and global fields of background albedo derived from MODIS for use in a climate model. *J. Hydrometeorol.* 10(1): 183-198 (2009). DOI: 10.1175/2008JHM1021. [JIF: 3.3; citations: 22].

[R6] B. J. J. M. Van den Hurk *et al.* Impact of leaf area index seasonality on the annual land surface evaporation in a global circulation model. *J. Geophys. Res.*, 108, 4191 (2003). DOI: 10.1029/2002JD002846. [JIF: 3.1; citations: 28].

Funding for the work was provided by [G1] NERC CLASSIC, a Swansea-led collaboration with the NERC Centre for Ecology and Hydrology, the UK Met Office, Durham, Leicester and Exeter Universities (P.I., Barnsley; £2.1M, NERC 2002-2008); [G2] NERC National Centre for Earth Observation (NCEO) (P.I., Los; 2008-2014, £960k); [G3] NASA (P.I., Los; £25k, 2001-2005); [G4] ESA GlobAlbedo (P.I., North; 2009-2014, £185k).

4. Details of the impact

Our research and datasets were used to improve the two leading weather forecasting models for Europe, which are run by the UK Met Office and the ECMWF. The involvement of these agencies as research collaborators has undoubtedly enhanced the effectiveness and speed of uptake of this research. Advances in weather forecasting allow improved planning by the public, agriculture, commerce, utility suppliers and transport sectors, as well as preparation for extreme weather events such as floods, heat waves and droughts. The UK Met Office model is also used to provide projected future climate information to the UK government and the IPCC, to inform policy on climate change and energy, and to plan mitigation strategies for likely future climate scenarios.

Improved land albedo in the UK Met Office weather and climate models: The UK Met Office provides daily weather forecasts for the UK. The forecasts are published on the Met Office website, broadcast on most TV channels, including the BBC, and folded into many derived (internet) weather predictions and apps. The forecasts are used directly for maritime and aviation safety and routing, agricultural planning, and flood forecasting (in collaboration with the UK Environment Agency). The estimated benefit to the UK economy of Met Office forecasts is more than £300m.

Swansea has worked with the Met Office to directly improve the surface albedo component of its forecast models, and their improvements have been implemented in all versions of the Met Office models since changes made during 2008-9. Swansea researchers have also collaborated with NASA to develop satellite mapping of albedo with the MODIS instrument [C1], resulting in one of the most widely used datasets by weather forecast agencies worldwide, including the USA. Following a multi-year analysis of the MODIS dataset, Swansea, in conjunction with the UK Met Office, led development of a new, seasonally varying climatology of soil background and vegetation albedo (referred to as 'CLASSIC' albedo [R5]). This permitted accurate temporally and spatially varying albedo to be incorporated within the UK Met Office Unified Model. The UK Met Office uses a single set of models, referred to as the Unified Model, to calculate their day-to-day weather forecasts, and to build scenarios of future climate change.

The CLASSIC albedo data were initially tested in the Met Office experimental model High-Resolution Global Environment Model (HiGEM), and officially became part of this model from 2008 onwards. The impact of the CLASSIC albedo in HiGEM is documented [C2], which notes (pp 1866, and1871-1872): "…*the new albedo [data] significantly improved forecast temperatures, especially over desert regions, with additional improvements in wider circulation*." Following this, the CLASSIC albedo was included in the main Unified Model in November 2008. The implementation of the CLASSIC albedo is documented and its impact evaluated by the Met Office [C3] *"This change … uses MODIS data to derive a much more accurate specification of the albedo of the Met Office Surface Exchange Scheme (MOSES)… It is likely that the CLASSIC albedos are the best albedos that can be produced. Tests in the NAE [North Atlantic European] showed [that] the CLASSIC albedo improved forecasts of near surface temperature, cloud and visibility" (pp.13-14). "Overall, the package of changes [including albedo] provided a significant improvement to the Met Office capability for Numerical Weather Prediction"* (p35).

The Swansea albedo was also included by the Met Office for climate simulations within the model HadGEM2, which is a coarse resolution version of the Unified Model suitable for decadal to century predictions. This model was used by the UK Met Office Hadley Centre from 2009 to 2013 to advise the UK government regarding climate policy and for contributions to the Fifth Assessment Report of the IPCC, which informs governments worldwide of the current status of climate change and summarises the latest knowledge. The impact of the Swansea albedo improvements for climate change discussed in the IPCC report is documented in [C4], which reports: "*the more realistic surface albedo leads to significant improvements over HadGEM1 (used for the Fourth Assessment Report of the IPCC) in predictions of surface temperature, moisture, vegetation distribution, and global carbon cycle."*

Swansea's collaboration with the Met Office is ongoing under the ESA-funded GlobAlbedo project [G4], which aims to further refine global estimates of surface albedo, using a longer time series and more accurate correction for atmospheric effects in the measurements.

Improved vegetation modelling in the ECMWF Integrated Forecasting System: The ECMWF provides global weather forecasts for up to 15 days to most national weather services in Europe. The model used for this is referred to as the Integrated Forecasting System. As a result of analysis of the satellite datasets of vegetation cover and seasonal change developed by Los [R3, R6, C5], Swansea research has led to improvements in the model's treatment of the global land surface. In 2011, ECMWF implemented a new land-surface model into their forecasting system. An important component of this new model is the introduction of a seasonal cycle of leaf area index that was pioneered [R6] in collaboration with Los. In this study, Los used satellite data developed at Swansea to implement a more realistic dynamic, seasonal cycle of vegetation; the previous ECMWF model had only a static vegetation cover that did not reflect seasonal changes. The implementation of the new land-surface model has improved the representation of weather, in particular placing better constraints on the evaporation of water from soil and transpiration of water by plants. Transpiration estimates correspond to water use by vegetation, are so also directly useful to agriculture and hydrological planning. The changes have resulted in significantly better precipitation forecasts. Discussion of the implementation is given in the written submission by ECMWF [C6]: *"The study found that incorporation of an improved seasonal vegetation cycle in the model led to a systematic and relevant alteration of the hydrological cycle and energy budget, and had the potential to improve the overall forecasting skill of the model… The success of this study eventually led to the incorporation of a much advanced land surface model in the Integrated Forecasting System."*

The implementation of seasonal changes in vegetation has resulted in significant improvements in the Integrated Forecasting System. For example, the previous model, which employed constant vegetation, displayed unrealistically low seasonal variation in evapotranspiration. In the updated model, the variation in evapotranspiration has approximately doubled in the tropics and mid latitudes during the boreal summer. This provided justification for further improvements, such as the implementation of a new photosynthesis model, allowing better prediction of long-term trends in heat-trapping atmospheric carbon dioxide concentrations and associated global warming. The set of improvements in the Integrated Forecasting System are documented in [C7]. Implementation in the ECMWF model of the seasonal leaf area index cycle improved rainfall forecast, which was too low, increasing forecast rainfall on average by 7% in the Northern Hemisphere during summer, and increased precipitation variability (needed for flood and drought forecasting) by up to 30%.

5. Sources to corroborate the impact

C1. MODIS albedo / BRDF team Algorithm Theoretical Basis Document (ATBD), available at http://modis.gsfc.nasa.gov/data/atbd/atbd_mod09.pdf.

C2. L. C. Shaffrey *et al.*, "U.K. HiGEM: The New U.K. High-Resolution Global Environment Model—Model Description and Basic Evaluation", *J. Climate*, 22, 1861–1896 (2011). DOI: 10.1175/2008JCLI2508.

C3. M.E. Brooks *et al.*, "Changes to the Met Office NWP System for Parallel Suite 20: Operational November 2008", Met Office Forecasting Research Technical Report No. 553 11/4/2011 (2011).

C4. G. M. Martin *et al.*, "The HadGEM2 family of Met Office Unified Model climate configurations", *Geosci. Model Dev.*, 4, 723–757 (2011). DOI:10.5194/gmd-4-723-2011.

C5. ISLSCP: http://daac.ornl.gov

C6. Submission on file from leader of the original ECMWF study on seasonal cycle impacts implementation, with confirmation from a current ECMWF Senior Scientist.

C7. Bousetta *et al.,* "Natural land carbon dioxide exchanges in the ECMWF integrated forecasting system: Implementation and offline validation", *J. Geophys. Res.*, 118, 1-24 (2011). DOI:10.1002/jgrd.50488.

Individuals who can corroborate the impact:

C8. Senior Global Model Development Scientist, UK Met Office, for verification of claims of UK Met Office improvements.

C9. Senior scientist, Physical Aspect Section/Model Division, Research Department, European Centre for Medium-Range Weather Forecasts, for verification of claims for ECMWF forecast improvements.