Institution: Swansea University

Unit of Assessment: 14

Title of case study: Global satellite data for improved climate and weather predictions

Period when the underpinning research was undertaken: January 2000 - December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Peter North	Professor	2000-Present
Mike Barnsley	Professor	1995-2007
Sietse Los	Reader	2001-Present
Caroline Houldcroft	PDRA	2004-2007
William Grey	PDRA	2003-2008
Will Davies	PDRA	2010-2012
Andreas Heckel	PDRA	2008-2019
Kevin Pearson	PDRA	2019-2020

Period when the claimed impact occurred: 1st August 2013 – 31st December 2020.

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

The Global Environmental Modelling and Earth Observation (GEMEO) group at Swansea University has led research working directly with leading meteorological agencies and operational providers of satellite data, including the European Space Agency (ESA) and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), resulting in improved weather prediction models and publicly available satellite datasets. The UK Met Office states that the research has resulted in significantly improved weather forecasts. The forecast model improved by GEMEO research is routinely used by 6 major national agencies in addition to the UK. The European Centre for Medium Range Weather Forecast (ECMWF) report an improved air quality product due to their assimilation of the Swansea atmospheric datasets. These datasets have enabled more realistic climate simulations in the UK to inform the Intergovernmental Panel on Climate Change (IPCC), and the datasets have been used by 7 other national meteorological agencies to benchmark their climate models. Improved weather forecasting is of benefit across society, facilitating day-to-day planning for the public, agriculture, commerce, utility suppliers, aviation, and transport sectors.

2. Underpinning research

***Context*:** Researchers from the Global Environmental Modelling and Earth Observation (GEMEO) group at Swansea University have focussed on improving global measurement and modelling of two key quantities for climate, surface albedo and atmospheric aerosol. Albedo – the proportion of the sun's radiation that is reflected by the surface – affects the energy budget of the planet and is therefore a key driver of global weather patterns and long-term climate. For example, an increase in surface albedo of only 4% would have roughly the same effect on the Earth's energy balance as the removal of all the carbon dioxide that has been emitted by humans to date. Atmospheric aerosols originate from sources such as wildfires, emissions from pollution, and desert dust. They have a net cooling effect on climate, but with high uncertainty, and additionally are a major factor in air quality, where it is estimated that 3,700,000 premature deaths annually can be attributed to high concentrations of atmospheric particulate matter, with a need to improve global monitoring and forecast.

The GEMEO group have worked closely with the UK Met Office, the European Centre for Medium-Range Weather Forecasts (ECMWF) and other climate modelling communities, under funding from NERC [**G1**], ESA [**G2-G5**] and the EU Copernicus programme [**G6,G7**]. Research has focused on new techniques for satellite observations of atmospheric aerosols, the use of this

information to correct images and provide precise albedo measurements, and to allow improved operational weather forecasts, air quality models and predictions of climate change.

Atmospheric aerosol algorithm and dataset development

While both surface albedo and atmospheric aerosol are needed independently from satellite observations of reflected sunlight, any such measurements include a mixture of contributions from both aerosol and albedo. Fundamental research by Swansea University developed new methods that accurately separate atmospheric signals from surface signals in satellite images [**R1**] using physical model inversion techniques. The innovation was by modelling how the land surface reflectance changes at multiple angles of view, coupled with precise modelling of atmospheric scattering and absorption, the surface reflectance and atmospheric aerosol components of the satellite signal could be accurately and independently retrieved. The work was originally developed for individual images from the (A)ATSR satellite instrument series [**R1**], and developed under funding from ESA and NERC, to apply this globally, over both land and ocean [**R2**], and to extend the retrieval to further satellite instruments [**R3-R5**].

Evaluation by independent experts over a series of tests conducted by the ESA Climate Change Initiative indicated that the algorithms and datasets developed by Swansea University had the highest quality among the available methods for European satellites [**R4**]. In particular the Swansea retrieval was found to provide lowest bias compared to global ground-based networks of aerosol optical depth, and provided rigorous propagation of uncertainty required for climate models [**R4**]. Consequently, with further ESA and Copernicus funding [**G4, G5**], Swansea developed the datasets to meet the needs of climate quality for international distribution, including conforming to international standards in product format, naming and documentation, and producing consistent aerosol for the full 1995-2012 time period of the ATSR mission, with the aim to provide quality assured global datasets for verification of climate models to be submitted to the IPCC [**R4**].

The success of the aerosol product has resulted in scientific leadership by Swansea University in developing new operational products for the recently launched Sentinel-3 satellite (2016-present) intended for use by global weather forecast, air quality, and climate prediction agencies, such as ECMWF [**R5, G3, G6, G7**].

New datasets of surface albedo datasets and climate model integration

The ESA GlobAlbedo project aimed to produce a new surface albedo dataset for climate modelling, with improvements in accuracy, timespan and propagation of uncertainty compared to existing MODIS albedo. Under funding from the GlobAlbedo Project [**G5**], Swansea University extended their aerosol and surface reflectance method to retrieve surface reflectance from images from SPOT-VGT and MERIS satellite sensors, and propagation of all errors. Further challenges were to integrate measurements over time and to provide albedo averaged over all view angles, and to develop a rapid computational processing chain. The project resulted in the release of a 15-year dataset of global land surface albedo [**R6**].

A second challenge addressed by Swansea was to enable use of satellite albedo datasets within numerical weather prediction and climate models, to replace pre-existing approximations based on land cover type only. Research led by Houldcroft and collaborators [**G1, R7**], working with the UK Met Office, resulted in a new method to analyse satellite time series data. The key scientific advance was to separate differing albedo contributions from vegetation and soil background, and further partition into albedo values for vegetation types; this allowed accurate modelling of spatial distribution of albedo, as well as seasonal change, and the provision of the first global dataset of soil albedo based on satellite observations.

3. References to the research

All research papers have been peer-reviewed (published in Q1/Q2 journals (JCR 2019)). **R5** summarises GlobAlbedo research and dataset, with further detailed theoretical basis and dataset availability linked within this. **R6** is a technical report commissioned by ECMWF. Papers were supported with funding from NERC and ESA. SU authors in **bold**.

[R1] **North, P.** (2002) Estimation of aerosol opacity and land surface bidirectional reflectance from ATSR-2 dual-angle imagery: Operational method and validation. Journal of Geophysical Research: 107(D12). https://doi.org/10.1029/2000JD000207
[R2] **Bevan, S., North, P., Los, S., Grey, W.** (2012) A global dataset of atmospheric aerosol optical depth and surface reflectance from AATSR. Remote Sensing of Environment 116:199-210. https://doi.org/10.1016/j.rse.2011.05.024
[R3] **Davies, W., North, P.** (2015) Synergistic angular and spectral estimation of aerosol properties using CHRIS/PROBA-1 and simulated Sentinel-3 data. Atmospheric Measurement Techniques 84:1719-1731. https://doi.org/10.5194/amt-8-1719-2015
[R4] Popp, T., … **Heckel, A., …North, P.,** et al (2016). Development, Production and Evaluation of Aerosol Climate Data Records from European Satellite Observations (Aerosol_cci). Remote Sensing 8: 421. https://doi.org/10.3390/rs8050421
[R5] **North, P., Heckel, A**. (2019) SLSTR Global Aerosol, Algorithm Theoretical Basis Document (ATBD) v1.1, ECMWF Copernicus Climate Change Service Report, C3S_D312b_Lot2.1.2.2_v1.1_201902_ATBD_AER_Annex_C_SU_v1.1a, available https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-aerosol-properties?tab=doc (last access: 21 December 2020)
[R6] Muller, J.-P., …**North, P., Heckel, A.** …et al (2012) The ESA GlobAlbedo Project for mapping the Earth's land surface albedo for 15 years from European Sensors. IEEE Geoscience and Remote Sensing Symposium (IGARSS) 22-27 July 2012, Munich, Germany, IEEE. http://www.globalbedo.org/docs/Muller-GlobAlbedo-abstractV4.pdf
[R7] **Houldcroft, C.J., Grey, W.F., Barnsley, M.,** Taylor, C.M., **Los, S.O., North, P.** (2009) New vegetation parameters and global fields of background albedo derived from MODIS for use in a climate model. Journal of Hydrometeorology 10:183-198. https://doi.org/10.1175/2008JHM1021.1

Grants

[G1] Los, S. (PI) North, P. (PI) (2008-2017) NERC National Centre for Earth Observation (NCEO), NERC, [R8/H12/82], GBP844,990.
[G2] North, P. (PI) (2007-2010) MERIS/AATSR synergy algorithms for cloud screening, aerosol retrieval and atmospheric correction, and BEAM implementation. ESA, [ESRIN Contract No. 21090/07/I-LG], leadership of GBP273,522 project, SU share GBP82,005.
[G3] North, P. (PI) (2015-2020) Sentinel-3 Mission Performance Centre (S3-MPC). ESA, [GGR809] GBP169,686.
[G4] North, P. (PI) (2010-2020) ESA Aerosol Climate Change Initiative (CCI). ESA [GGR0761], GBP373,838.
[G5] North, P. (PI) (2009-2014) Global land surface albedo (GlobAlbedo). ESA, [ESRIN contract 22390/09/I-OL], GBP127,209.
[G6] North, P. (PI) (2017-2018) ECMWF Copernicus Climate Change Service Lot 5. Deutsches Zentrum fiir Luft- und Raumfahrt e.V. [GGR1030], GBP25,487.
[G7] North, P. (PI) (2018-2020) ECMWF Copernicus Climate Change Service ITT 312B. Deutsches Zentrum fiir Luft- und Raumfahrt e.V. [GGR1045], GBP53,094.

4. Details of the impact

Improvements in weather forecasting benefit society, both in economic and other terms, facilitating day-to-day planning for the public, agriculture, commerce, utility suppliers, aviation, and transport sectors, and improved preparation and response to extreme events such as storm damage, flooding and drought. Long term climate projections are required for formulation of cost-effective mitigation strategies and climate adaptation. SU research resulted in new global datasets of atmospheric aerosol and surface albedo, and these have been used by prominent meteorological agencies in Europe, Australia, the US and India, leading to improved modelling and forecasts. SU datasets have also been used as benchmarks for the ongoing IPCC 6th Assessment.

Improvement in weather, climate, and air quality modelling

The Swansea ATSR (SU-ATSR) aerosol dataset (1995-2012) [**R2, R4**] has been used by ECMWF to produce the high-resolution atmospheric composition product (CAMS Reanalysis, CAMSRA).

The product combines satellite aerosol data with the ECMWF Integrated Forecast Model to produce a continuous spatial and temporal map of aerosol, and to derive the related quantity of atmospheric particulate matter (PM2.5, PM10) needed for air quality. Working with SU under the ESA Climate Change Initiative [**G4**], experiments by ECMWF found inclusion of the SU_AATSR data in a version of the IFS model over a 3-month period showed an improved fit with independent observations over Africa, North and South America and Europe compared with the previous use of NASA MODIS data alone, leading to a global error reduction of approximately 30% [**C1**]. ECMWF included the full 10-year dataset in the CASMRA reanalysis in 2018 [**C2**]. The CAMSRA product serves a wide variety of users, providing expected conditions for regional air quality models, long-range transport of air pollution, radiative forcing for climate and downwelling radiation used to find sites suitable for solar energy generation. For example, in 2020 CAMSRA was used for improved modelling of global air quality and health analysis by the UK Met Office and World Health organisation [**C3**].

SU research has led to improvements in the UK Met Office Unified Model (UM). The UM is a numerical model of the land, ocean and atmosphere that is used for weather forecasts across a range of timescales, used for daily forecasting for the UK, as well as the national meteorological agencies of India, Korea, the Philippines, Australia, Republic of South Africa and New Zealand. The same model is also configured to provide climate change projections to inform UK climate planning and contribution to the IPCC AR6. The Swansea background albedo and vegetation albedos [**R7**] and the GlobAlbedo dataset [**R6**] were included in the UM (GA6.1) in 2014 [**C4**] and continued in the current model version (GA7.0) [**C5**]. This resulted in consistent improvements in five-day temperature forecasting, with a bias reduction of 20% at the centre of continental land masses in Summer [**C4**]**.** Evaluation by the Met Office shows the radiation changes were responsible for the vast majority of improvements in this field from this upgrade. Out of the radiation changes, the albedo change was responsible for roughly half of the improvement in temperature errors over North America (where biases were particularly large). Specifically, the evaluation by the UK Met office notes: *"The impact of this change is to improve the surface energy budget of the model, which specifically improves near-surface temperature errors over continental land in the summer hemisphere*" [**C4, p1503**]. The albedo changes [**R6, R7**] have also been implemented in model configurations publicly available for offline analysis (JULES *Global Land GL 7.0/7.1*) and for climate modelling by the UK, (HadGEM3-GC3) and have been used for their current submissions of climate forecasts to the IPCC [**C5, C6**]**.**

Impact on satellite dataset providers and use in model verification.

The aerosol dataset has improved the global climate record available to develop and test climate models for IPCC. In 2016, the SU-ATSR aerosol dataset was accepted by the World Climate Research Programme (WCRP), under the Obs4MIPS initiative, to provide quality-assured global datasets for the verification of climate models to be submitted to the IPCC under the Coupled Model Intercomparison Project (CMIP) protocol [**C7, p12**]. This dataset forms one of only three global benchmark aerosol datasets, and the only one from European instruments. The SU-ATSR and the new SU Sentinel-3 dataset (2017-2020) were additionally accepted in 2019 by the ECMWF Copernicus Climate Change Service (C3S) intended as a European contribution to climate model verification [**C8**]. Under [**G3**] SU worked closely with EUMETSAT to develop a satellite aerosol product from Sentinel-3, based on the SU-ATSR algorithm, to be delivered continuously in under 3 hours to meet the needs of operational users in weather and air quality forecast agencies. This resulted in August 2020 in the release of the first Sentinel-3 aerosol product routinely produced in near real time by EUMETSAT allowing access to global users both by internet and direct satellite downlink under the EUMETCAST system [**C9**].

The SU-ATSR dataset has been directly used during the period 2016-2020 by national agencies, to provide verification and testing for 14 global models of aerosol optical properties to be submitted to the IPCC 6th Assessment. The model benchmarking is necessary to provide credibility and bias estimates of climate models. The following national agencies have used the SU-ATSR dataset in this process: Norwegian Meteorological Institute; LSCE/IPSL, CEA-CNRS-UVS (France); NASA Goddard Space Flight Centre (USA); NOAA, Geophysical Fluid Dynamics Laboratory (USA);

European Centre for Medium-Range Weather Forecasts (UK); Finnish Meteorological Institute; Royal Netherlands Meteorological Institute; UK Met Office and NASA Goddard Institute for Space Studies (USA). Comparisons are summarised in [**C10, C11**]. In these model evaluations [**C11**] noted the ATSR series provided the longer record length to 2000, while [**C10**] highlighted the unique ability of the SU-ATSR dataset to provide reliable information not only on total aerosol amount but also on aerosol particle size, and how aerosol optical depth varies with wavelength, needed for full evaluation of radiation balance, while other datasets could only provide total aerosol amount at accuracy needed for benchmarking.

Finally, Swansea has enabled wider impact of research by facilitating use of methods, datasets and software tools by other practitioners in remote sensing. The surface reflectance algorithm and software developed by SU [**R4-R6**] for the satellite instruments MERIS, (A)ATSR, SPOT-VGT, Sentinel-2, and Sentinel-3 have been made available through the open-source BEAM/SNAP software in collaboration with the companies of Brockmann Consult, ARGANS Ltd, and ACRI-ST [**G2**, **G6**]. For example, this tool forms a fundamental part of the processing for ESA CCI Land Cover projects, allowing accurate atmospheric correction to improve land cover accuracy [**C12, p324**], with benefit to a wide range of users of these global land cover products.

5. Sources to corroborate the impact.

[C1]. Presentation by ECMWF to ESA Aerosol CCI, 18 March 2018, available on file.
[C2]. Inness, A. et al. (2019) The CAMS reanalysis of atmospheric composition. Atmospheric Chemistry and Physics 19:3515-3556. https://doi.org/10.5194/acp-19-3515-2019.
[C3]. Shaddick, G., Salter, J.M., Peuch, V.-H., Ruggeri, G., Thomas, M.L., Mudu, P., Tarasova, O., Baklanov, A., Gumy, S. (2021) Global Air Quality: An Inter-Disciplinary Approach to Exposure Assessment for Burden of Disease Analyses. Atmosphere 12:48. https://doi.org/10.3390/ (published Dec 31, 2020)
[C4]. Walters. D. et al. (2017). The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. Geoscientific Model Development 10:1487-1520. https://doi.org/10.5194/gmd-10-1487-2017
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[C8]. Copernicus Climate Change Service (C3S): Global aerosol datasets and documentation available on https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-aerosol-properties?tab=overview (Accessed 21 Dec 2020).
[C9]. EUMETSAT Copernicus Sentinel-3 NRT Aerosol Optical Depth Product: https://www.eumetsat.int/S3-AOD
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[C11]. Mulcahy, J. P. et al. (2020). Description and evaluation of aerosol in UKESM1 and HadGEM3-GC3.1 CMIP6 historical simulations. Geoscientific Model Development 13:6383–6423. https://doi.org/10.5194/gmd-13-6383-2020
[C12]. Bontemps, S., et al. (2015) Multi-year global land cover mapping at 300 m and characterization for climate modelling: achievements of the Land Cover component of the ESA Climate Change Initiative. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-7/W3, 323–328, https://doi.org/10.5194/isprsarchives-XL-7-W3-323-2015