Institution: University of Leicester

Unit of Assessment: UoA9: Physics

Title of case study: Evidencing, informing and applying satellite-based information on sea surface temperature change for climate

1. Summary of the impact

Climate change is one of the most critical challenges facing modern society and there is a paramount requirement for government policy informed by science, and scientifically credible public information. Observations of sea surface temperatures, and their corroboration, are a focus for governments -- climate change mitigation is economically important in a warming world. This UoA has provided the science leadership for a major satellite programme, the ATSRs, specifically designed to provide high-quality sea temperature data. Results from our research reduce uncertainties on global temperature change with unexpectedly wide benefits also to operational oceanography and weather forecasting. Public visibility through the Science Museum is also high.

2. Underpinning research

Earth Observation Science (EOS) began at Leicester in 1993 with the appointment to an externally-funded Chair of David Llewellyn-Jones and has now expanded into a research group ~30 strong led by Professor John Remedios, based in the Space Research Centre of the Department of Physics and Astronomy.

From the beginning, a flagship of the EOS research has been the scientific leadership from Leicester of the Along-Track Scanning Radiometers (ATSRs), a series of satellite instruments flying on European platforms (ERS-1; ERS-2 and Envisat). These UK-funded, thermal infra-red sensors of novel design were instigated explicitly to achieve the accuracy in sea surface temperatures (SSTs) necessary to investigate climate change in recent decades; Leicester research has been central to the effort to demonstrate performance and evidence the ATSR observations of SSTs.

Llewellyn-Jones has been the Principal Investigator of the ATSRs throughout their lifetimes and led this multi-institutional project from the development and use of novel research instruments to climate policy relevant operational systems. The instruments and science programmes for the first two instruments (ATSR-1; ATSR-2) were funded by SERC and NERC, and later instruments by impact-orientated agencies (see impact section). Remedios has been the Science Manager for the ATSRs since 2003 and Dr. Gary Corlett has been the Leicester ATSR Validation Scientist since 2004.

Detailed scientific research at Leicester has focussed on sea surface temperature data with its accuracy, trends and time series as a prime driver of our work [**1-6**]. A major key step forward came in 2004 when Sean Lawrence together with Llewellyn-Jones published a paper [**1**] showing that time tendencies (or trends) in sea surface temperature data could be observed very well in the ATSR data, even over short timescales, and also in other satellite data sets [**2**].

The next steps were to establish the true quality of the ATSR sea surface temperature data and to improve the data retrieval skill to maximise the data quality. Within the Unit, extensive research (see [3] and references therein; [4, 5]) was required involving leadership of international, collaborative teams of scientists analysing standard ocean sensor systems and dedicated ship cruise data to validate the data. The state-of-the-art Leicester results of this investigation are detailed in papers showing that current ATSR data are accurate to better than 0.3 K per pixel with low bias of less than 0.05 K [**4, 5** and references in **3**] and 0.015 K on a monthly global mean [**3**].

The culmination of the Leicester ATSR research has been to produce climate records demonstrating that ATSR data are highly suitable for climate research, which independently

corroborate (for the first time) the in situ record which has been historically used to document surface temperature change, and which confirm the low uncertainty and low bias in climate temperature records [**3, 6**]. These findings are evidenced in Chapter 2 and Figure 2.17 of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report see impact below) in which three co-authored Leicester papers on SSTs are referenced, including [**5**] and [**6**]).

3. References to the research

Leicester authors are shown in bold.

1. **Lawrence, S. P., D. T. Llewellyn-Jones**, and S. J. Smith (2004), The measurement of climate change using data from the Advanced Very High Resolution and Along Track Scanning Radiometers, J. Geophys. Res., 109, C8, C08017, doi: 10.1029/2003JC002104.

2. **Good, S.A., G.K. Corlett, J.J. Remedios, E.J. Noyes,** and **D.T. Llewellyn-Jones** (2007), The global trend in sea surface temperature from 20 years of Advanced Very High Resolution Radiometer data, Journal of Climate, 20, no. 7, 1255-1264, doi: http://dx.doi.org/10.1175/JCLI4049.1

3. **Veal, K., G.K. Corlett, D.J. Ghent. D. Llewellyn-Jones** and **J.J. Remedios** (2013**)**, A time series of mean global skin SST anomaly using data from ATSR-2 and AATSR, Remote Sensing of Environment, 135, 64–76, 2013; doi: 10.1016/j.rse.2013.03.028.

4. **Noyes, E. J**., P. Minnett, **J. J. Remedios, G. K. Corlett, S. A. Good, and D. T. Llewellyn-Jones** (2006), The Accuracy of the AATSR Sea Surface Temperatures in the Caribbean, Remote Sensing of Environment, 101, 38-51, 10.1016/j.rse.2005.11.011.

5. Embury, O, C.J. Merchant and **G.K. Corlett** (2012), A reprocessing for climate of sea surface temperature from the along-track scanning radiometers: Initial validation, accounting for skin and diurnal variability effects, Remote Sensing of Environment, 116, 62-78, doi:, 10.1016/j.rse.2011.02.028.

6. Merchant, C.J., O. Embury, N.A. Rayner, D.I. Berry, **G. Corlett**, K. Lean, **K. Veal**, E.C. Kent, **D. Llewellyn-Jones**, **J.J. Remedios** and R. Saunders (2012), A twenty year independent record of sea surface temperature for climate from Along Track Scanning Radiometers, J. Geophys. Res., 117, C12013, doi: 10.1029/2012JC008161, [Editor's highlight]

4. Details of the impact

The impact agenda has been a part of the ATSR story since the inception of the programme as its objective was to deliver climate science relevant to policy. However a major step occurred in the 1990s when Llewellyn-Jones was able to use evidence from ATSR-1 to show that the ATSR sea surface temperature (SST) data were capable of forming a climate SST data set and hence an important public utility for government. As a result, the predecessor departments to the Department of Energy and Climate Change (DECC) agreed to fund the third AATSR instrument for climate science and policy support, bringing a series of research instruments together to form a system for obtaining surface temperature data with climate quality as advocated by Leicester [**a**].

DECC is now the lead Department for Government policies on both international and domestic climate change mitigation, and a strong science evidence base is crucial for developing these policies. DECC fully recognises the importance of sea surface temperature as one of the essential climate variables (ECVs), and that the most accurate climate time series for SSTs are those that have been derived from the ATSR instrument series as described in the Leicester research section. Results from Leicester on the quality validation, interpretation and subsequent application of these high quality ATSR SST records, on their interpretation and on corroboration of the historical in situ record have made an important contribution to the scientific evidence that informs the development of government policy with respect to reductions of greenhouse gas emissions and the UK's own requirements to reduce greenhouse gas emissions by 80% by 2050 [**a,b**].The ATSR

data have also contributed to the UK government's commitment to climate monitoring obligations under the United Nations Framework Convention on Climate Change's (UNFCCC) treaty [**c**].

Internationally, in terms of climate impact, the datasets and their comparisons to in situ time series of global mean SST are cited for the first time in the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report [**a,d**]. Hence the ATSR observations of temperature change are part of the evidence chain open to international government scrutiny and important at a time of apparent hiatus in surface temperature warming.

The AATSR has also had an increasing and unexpected impact on operational oceanography both during its lifetime [**e**] and on successor sensors [**f**] respectively, due particularly to the work carried out by Corlett in assessing the accuracy of ATSR data and implementing operational functionalities for data quality. Reference [**e**] describes how the Group for High Resolution SST (GHRSST), by providing access to AATSR data, has enabled operational services using AATSR data. These successes have been used to define the requirements for operational ocean services as part of the European Commission GMES/Copernicus service (the Earth Observation equivalent of Galileo for navigation) resulting in an EC-funded Sea and Land Surface Temperature instrument (SLSTR or ATSR-4) on the Sentinel-3 satellite. This instrument is deliberately ATSR-like in technique, accuracy and precision [**f**]. Llewellyn-Jones and Remedios have vigorously used Leicester results, and those of the international ATSR community, to support the views of operational users as to the importance and utility of ATSR-type data for the future.

The impact on operational oceanography was so strong that an unexpected benefit of AATSR has been its use within a sea surface temperature analysis system which is used to drive the forecast models for weather forecasting at the Met Office and the European Centre for Medium Range Weather Forecasting [**g**]. This is because of the AATSR data's great utility for correcting the biases of other sea surface temperature observations which feed into the analysis and then the weather forecasts [**h**], as demonstrated by Corlett's work at Leicester

Finally, Leicester ATSR science has specifically contributed to public information on climate science. Llewellyn-Jones at Leicester worked very closely with exhibition staff, on behalf of DECC, to arrange the AATSR engineering model as one of the centrepieces of the "Atmosphere – exploring climate science" gallery in the Science Museum in South Kensington, opened in December 2010 by HRH The Prince of Wales. The model hangs from the roof of this special exhibit and is thus visible to the huge numbers of visitors per year (>1.5 million; 737,000 in the first year compared to 400,000 target). Accompanying interactive display material is based on interviews with Llewellyn-Jones, because of his PI role, and includes a video presentation by Llewellyn-Jones explaining the science and the provision of credible observational evidence on surface temperature change. [**i**]

5. Sources to corroborate the impact

a) Letter from the Dept. for Energy and Climate Change evidencing the contribution of AATSR and Leicester research to government policy.

b) Policy statement on "Taking international action to mitigate climate change; Responsible ministers The Rt Hon Gregory Barker MP and The Rt Hon Edward Davey MP". Located on gov.uk Inside Government. https://www.gov.uk/government/policies/taking-international-action-to-mitigate-climate-change/supporting-pages/scientific-evidence-to-help-us-understand-climate-change

c) UNFCC reports from UK government (The UK's Fifth National Communication under the United Nations Framework Convention On Climate Change; UK Report on national activities with respect to the GCOS Implementation Plan) http://unfccc.int/files/national_reports/annex_i_natcom/submitted_natcom/application/pdf/gbr_nc5.pdf; http://unfccc.int/methods_and_science/research_and_systematic_observation/items/4499.php

d) Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report: Report of Working

Group I, September 2013. The report is available at http://www.ipcc.ch/report/ar5/wg1/. Chapter 2 is the appropriate chapter.

e) Robinson, I, J-F. Piolle, P. LeBorgne, D. Poulter, C. Donlon, and O. Arino (2012), Widening the application of AATSR SST data to Operational Tasks through the Medspiration Service, Remote Sensing of Environment, 116. 126-139, doi: 10.1016/j.rse.2010.12.019.

f) The Copernicus/GMES operational programme of the European Commission: Strategic Implementation Plan for the GMES Fast Track Marine Core Service; 24/04/2007. http://www.copernicus.eu/pages-principales/library/implementation-groups/marine-core-service-mcs/

g) Donlon, C.J., M. Martin, J. Stark, J. Roberts-Jones, E. Fiedler and W. Wimmer, The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) (2012), Remote Sensing of Environment, 116, 140-158, doi:10.1016/j.rse.2010.10.017).

h) Letter from Met Office Weather Services plus ATSR is referenced in the following report http://www.metoffice.gov.uk/media/pdf/h/e/FRTR561.pdf

i) Letter from the Science Museum and linked web-site stories. http://www.bis.gov.uk/ukspaceagency/news-and-events/2010/Dec/atsr-at-science-museum; http://webarchive.nationalarchives.gov.uk/20101213191958/http://ukspaceagency.bis.gov.uk/20411.aspx; exhibition at http://www.sciencemuseum.org.uk/climatechanging/atmospheregallery.aspx.