Institution: University of Southampton

Unit of Assessment: 07 Earth Systems and Environmental Sciences

Title of case study: 07-12 Enhanced usability of satellite sea surface temperature data

1. Summary of the impact

Satellite measurements of sea surface temperature (SST) make a much greater impact on weather forecasting and climate change detection since University of Southampton (UoS) research revolutionised the way SST data are processed. Multiple satellite observations can now be combined into the more complete and detailed SST maps needed by fine resolution meteorological models and used for marine industry operations. Pioneering methodology using a new shipborne radiometer tests the quality of SST maps more rigorously than was previously possible. It provides the first traceable validation of data from the UK's AATSR sensor, confirming their fundamental reliability for observing climate change.

2. Underpinning research

During 1991-2012 a series of UK-designed Along-Track Scanning Radiometers (ATSR, ATSR-2 and AATSR) measured SST from European Space Agency (ESA) satellites. These observe the ocean skin, the top millimetre, whereas conventional thermometers on buoys measure temperature a few metres deep. The difference between these, ΔT, reaches 5K because of wind cooling and solar heating, and is difficult to characterise. This creates uncertainty >0.3K when comparing individual satellite and buoy data, hindering confirmation of ATSR's high accuracy for climate monitoring. Moreover, ATSR was overlooked for operational applications (e.g. weather forecasting) because of its poorer coverage. Thus despite the inherent high quality and low noise of the sensor, the ATSR datasets were largely ignored for 15 years.

This prompted Professor Ian Robinson's (UoS 1976 - present) research group to study sea surface thermal processes, seeking to improve the applicability of satellite SST data. Craig Donlon (UoS PhD 1990-94, UoS postdoc 1994-97, visiting fellow 2004-08) sought ways to measure skin SST from ships. In 1995, comparing observations from an early ship radiometer to conventional thermometry, he obtained evidence that the cool skin component of ΔT is quantifiable to accuracies better than 0.1K **[3.1]**, and attempted direct validations of satellite SST using ship radiometers. Subsequently Alice Stuart-Menteth (UoS PhD 2000-04) identified the diurnal warming factors contributing to ΔT **[3.2]**.

In 1996 Robinson and Donlon drew together other SST experts from space and meteorological agencies, including ESA, NASA, UK Met Office, Eumetsat, RAL and Météo-France, to participate in the EU-funded Concerted Action project for the Study of the Ocean's Thermal Skin (CASOTS). They developed strategies for better determination of ΔT and for reliable shipborne radiometry, discovering that the quality of each SST measurement from satellites must be evaluated in relation to the coincident ocean conditions, such as time of day, wind and sunshine. These insights led in 2002 to the formation of the Group for High Resolution Sea Surface Temperature (GHRSST) **[3.3]**. Donlon convened the first Science Team (ST) meeting, was elected ST Chair in 2002, and employed as Executive Director 2004-09. Robinson is a ST member (2003-13), joined by Southampton colleagues A.Stuart-Menteth, D.Poulter and W.Wimmer for periods.

In 2004 Donlon and Robinson helped to formulate the GHRSST protocols for producing usable SST datasets. These combine information from diverse satellite sensors to achieve SST maps with fine space-time resolution, full coverage and quantifiable accuracy. Robinson led the ESA-funded Medspiration project (2004-2008) which developed the prototype GHRSST data processing system, at last enabling AATSR data to underpin the evolution of new classes of global SST datasets **[3.4]**.

Concurrently Donlon designed the first infrared SST autonomous radiometer (ISAR) for unattended ship deployment, building the prototype at Southampton in 2001 **[3.5]**. ISAR measures *in situ* skin SST with uncertainty <0.1K, inter-calibrated against *Système International d'unités* (SI) standards. From 2004 to the present, funded by a £1 million+ contract from DECC, UoS researcher Werenfrid Wimmer developed ship radiometry as a tool for validating AATSR data with uncertainty <0.1K, using many thousands of match-up data from continuous monitoring by ISAR along UK-Spain ferry routes **[3.6]**.

3. References to the research (the best 3 illustrating quality of work are starred)

***[3.1]** Donlon, C.J., T.J. Nightingale, T. Sheasby, J. Turner, I.S. Robinson and W.J. Emery, Implications of the oceanic thermal skin temperature deviation at high wind speed, *Geophys. Res. Letters*, **26** (16), 2505-2508, 1999.

***[3.2]** Stuart-Menteth, A. C., Robinson, I. S. and Challenor, P., A global study of diurnal warming using satellite derived SST. *J. Geophys. Res*., **108** (C5), 3155 doi:10.1029/20025C001534, 2003.

***[3.3]** Donlon,C.J., Robinson, I.S., Casey, K. S. and 23 others. The Global Ocean Data Assimilation Experiment (GODAE) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP). *Bull. Am. Meteorol. Soc*., **88** (8), 1197-1213, 2007 (doi: 10.1175/BAMS-88-8-1197).

[3.4] Robinson, I.S., J.-F. Piollé, P. Le Borgne, D.J.S. Poulter, C. J. Donlon and O. Arino, Widening the application of AATSR SST data to operational tasks through the Medspiration Service. *Remote Sensing of Environment.* **116**, 126-139, 2012. doi:10.1016/j.rse.2010.12.019.

[3.5] Donlon C, Robinson I S, Reynolds M, Wimmer W, Fisher G, Edwards R, Nightingale T J An Infrared Sea Surface Temperature Autonomous Radiometer (ISAR) for Deployment aboard Volunteer Observing Ships (VOS). *Journal of Atmospheric and Oceanic Technology*, **25** (1): 93-113, 2008.

[3.6] Wimmer, W., Robinson, I.S and Donlon, C. J. Long-term Validation of AATSR SST data products using shipborne radiometry in the Bay of Biscay and English Channel. *Remote Sensing of Environment.* **11**6, 17-31, 2012. doi:10.1016/j.rse.2011.03.022.

Grants and Awards

Research Studentships: 1990-1993 C J Donlon (NERC); 1995-1998 S Keogh (NERC); 2000-2003 A Stuart-Menteth (Southampton funded).

1996-1997: ~ €80,000. from EU Environment Programme . *CASOTS - Concerted Action for Study of the Ocean's Thermal Skin*. PI: I S Robinson.

1999-2000: £18,000 from Southampton Instrument development fund. *Constructing a prototype autonomous shipborne radiometer (ISAR)*. PIs: C J Donlon and I S Robinson,

2004-2008: €1,100,000 (of which ~€300,000 to Southampton) contract from European Space Agency (Data Utilisation Envelope Programme). *Medspiration - European regional contribution to GHRSSST-PP*. Project manager: I S Robinson.

2004-2014: £1,317,254 Contract from Defra/DECC to UoS extended through five phases. *Validation of AATSR Sea Surface Temperature Products using the shipborne ISAR Radiometer*. Project Manager: I.S. Robinson, ISAR Scientist: W. Wimmer.

4. Details of the impact

Two major impacts can be traced from the Southampton SST research group:

A) The new capability to produce high-resolution blended SST datasets through the Group for High Resolution Sea Surface Temperature (GHRSST) **[5.1]**. Such datasets have rapidly become an essential link in the data chain by which ocean satellites improve the operational forecasting of environmental conditions on land and at sea. They are used by US, European, Japanese and Australian agencies to improve the reliability of daily SST maps and hence weather forecasts.

B) The new use of shipborne radiometry to establish the absolute accuracy of satellite SST measurements, traceable to international references, allows global time series to be used with enhanced confidence for monitoring the changes in spatial and temporal patterns of SST in response to climate change.

A) Southampton's SST research activities contributed directly to the creation of the GHRSST in 2002 through having trained its founding director, Craig Donlon, and by supplying several Science Team members. Their role in the successful evolution of GHRSST was to provide the scientific understanding of temperature structure near the ocean surface. This understanding was needed to underpin the procedures in the GHRSST Data Specification which is the "recipe" for successfully blending data from different satellites. Donlon et al. **[3.3]** describes the challenge of persuading several major agencies to agree to a common protocol for processing SST measurement from satellites. The newly specified GHRSST products were first prototyped by the Medspiration project **[3.4]** led from Southampton (2004-2008), that confirmed the effectiveness of the GHRSST approach. Until this point global SST data from individual satellite sensors had been inadequate for operational applications requiring daily SST at fine spatial resolution. By 2008, Medspiration data products, including AATSR data, were used routinely by agencies around the world as the primary source for creating their own SST analysis products. In 2009, the AATSR Exploitation Board acknowledged that,

"During the past two years, the operational use of (A)ATSR data has taken a major step forward as a result of the ESA-funded Medspiration project, the European backbone of GHRSST-PP". "A consensus view is emerging that (A)ATSR data, although offering less coverage than other sensors, are the most accurate available and can be used in multi-sensor analysis schemes as the benchmark against which data from other sensors can be bias-corrected" **[5.2]**.

Since 2008 the UK Met Office has been producing their own daily global SST analysis, OSTIA, that first grew from the availability of Medspiration products. The Met Office operational Numerical Weather Prediction system switched to use OSTIA after rapid melting of Arctic ice in 2007 had revealed problems in their previous SST analysis. This change has measurably reduced errors **[5.3]** and improved the quality of weather forecasts.

GHRSST is now a truly international collaboration with over US$18 million invested across all of the project activities **[5.4]**. It provides the framework within which all satellite SST data can be shared, indexed, processed, quality controlled, analysed and documented. Global and regional SST products are now produced by GHRSST regional data assembly centres in Australia, Japan, USA and Europe. SST products are passed in near real time to operational GHRSST global data assembly centres where they are integrated together into reliable, error-quantified, analysed SST maps, irrespective of cloud or weather.

High resolution SST maps based on GHRSST principles have become essential inputs to local weather forecasting models in many parts of the world making routine forecasts for many sectors of society. Meteorological agencies aim, for example, to issue flood warnings, predict the extent of ice on highways, or forecast rain probabilities in sufficient local detail that users as diverse as water companies, road gritters or farmers at harvest time can depend on them. The same SST maps are also needed by ocean forecasting systems for offshore industry and military operations, validation and forcing of ocean and atmospheric models, ecosystem assessment, tourism and fisheries research, amongst many others. **[5.5]**.

B) Southampton's development of the autonomous ship radiometer (ISAR) introduced a significant improvement to the quality assessment of satellite SST data. Comparison between satellite and ISAR measurements, which both observe the skin SST, completely eliminates the ~0.3K uncertainty from estimating ΔT when using buoy measurements in conventional validation. ISAR's calibration to better than 0.1K allows validation of AATSR data to an equivalent precision for each individual match-up between satellite and *in situ* observations. The high quality of AATSR data confirmed by ISAR **[3.6]** has encouraged widespread use of AATSR. It justifies the use of AATSR for bias adjustment of inferior SST datasets when producing analysed SST maps **[5.2]** with reliably estimated uncertainties. This is particularly valuable for operational forecasting applications where quantification of forecasting uncertainty is critical such as search and rescue or route-planning for sea transport of large structures **[5.5]**.

The Global Climate Observing System (GCOS) is the international body established to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. It has defined 50 Essential Climate Variables (ECV), of which SST is one, that are necessary to support the work of the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change (IPCC). Because ISAR is subjected to validation against an infrared radiation source before and after each autonomous deployment, every SST measurement is traceable to the S.I. reference standards against which the radiation source is tested. Thus accumulated ISAR observations can be treated as a SST "reference dataset", meeting the strict traceability requirements of the GCOS and are therefore useful for independent validation of other SST ECVs. The policy impact of this unique capability, contrasting with conventional SST measurements, is now acknowledged by Professor David Mackay, Department for Energy and Climate Change (DECC) Chief Scientific Advisor:

"*We recognise...in-situ measurement using radiometers traceable to international reference standards is highly desirable to ensure climate-quality datasets*" **[5.6]**.

The ESA Climate Change Initiative programme, overseen by Dr Craig Donlon **[5.7]**, has the task of producing a new SST dataset to the GCOS specification of an Essential Climate Variable, which requires that satellite SST validation must provide traceability to international reference standards. Using ISAR to validate AATSR SST data now provides the SI traceability needed to establish AATSR as the key input to the new global SST time series. ISAR-type sensors are specified by ESA as essential for validation of the AATSR successor instrument, SLSTR. This is further evidence of the impact of Southampton's ship radiometry work on ESA validation policy for climate quality satellite SST datasets **[5.8]**.

The published success of ISAR deployments created a demand from agencies around the world wishing to use shipborne radiometers. Since 2009, six ISARs have been sold by UoS to Institutes in USA (2), Japan, China, Denmark and UK, producing a turnover of £250,000, supporting a technician for two years and demonstrating a modest commercial and employment impact.

The Southampton group's major impact on operational applications of satellite oceanography has been recognized by the presentation of the prestigious 2011 Remote Sensing and Photogrammetry Society Award to Professor Robinson **[5.9]**.

5. Sources to corroborate the impact

[5.1] GHRSST web site home page : https://www.ghrsst.org/

[5.2] These excerpts are from section 4.2.1. (see pp. 49-50) of the (A)ATSR Exploitation Plan, Volume 1, (A)ATSR Project Overview.

Document reference ERSE-DTEX-EOPG-PL09-0003, Issue 1, 15 May 2009.
http://www.atsrsensors.org/pdf/(A)ATSR Exploitation Plan Volume 1 (Revised Issue 1).pdf

Can be accessed through http://www.atsrsensors.org/board.htm and selecting the link to:
ATSR Exploitation Plan (AEP)

[5.3] Figure 11 in section *5.3 Impact of OSTIA on ocean forecasting and NWP system,* in: Donlon, C. J., M. Martin, J. D. Stark, J. Roberts-Jones, E. Fiedler and W. Wimmer (2011). The Operational Sea Surface Temperature and Sea Ice analysis (OSTIA) system. *Remote Sensing of the Environment.* http://dx.doi.org/10.1016/j.rse.2010.10.017 2011.

[5.4] GHRSST information page https://www.ghrsst.org/ghrsst-science/what-is-ghrsst/

[5.5] GHRSST applications web page at https://www.ghrsst.org/users-partners/applications/ .

[5.6]. DECC Chief Scientific Advisor. The quotation comes from a letter outlining DECC's position on the importance of SST to climate policy and the role of satellite SST validation in the production of climate-quality datasets.

[5.7] Principal Scientist for Oceans and Ice at the European Space Agency/ESTEC. He can confirm the crucial importance of ship radiometry to ensure compliance with GCOS requirements and can also corroborate many of the other impacts being claimed.

[5.8]. The "Sentinel-3 Calibration and Validation Plan", produced jointly by ESA and Eumetsat in preparation for the 2014 launch of the *Sea and Land Surface Temperature (SLSTR)* sensor on the Sentinel-3 satellite for the EU Copernicus Programme, explicitly states the importance of shipborne radiometers for SST product validation:

"SSTskin measurements from in situ ship mounted radiometers in regional deployments shall complement the drifter data as they provide independent and SI standards-traceable measurements of SSTskin (i.e. exactly the same quantity measured by SLSTR). They also provide a method of "bridging the gap" between AATSR and SLSTR."

[ESA document reference: S3-PL-ESA-SY-0265, Issue 0, Revision 12, Date of Issue 21-9-2012] (Quotation is from bulleted list of Methodology on page 159/246, within section 6.2.4.1. "SST product validation"). The content of this document can be confirmed by Optical Sensors Performance, Products and Algorithm Manager at ESA.

[5.9] Remote Sensing and Photogrammetry Society Award to Professor Robinson: http://www.southampton.ac.uk/oes/news/2012/10/ian_robinson_remote_sensing_and_photogrammetry_society_award_2012.page