Institution: University of Leicester		
Unit of Assessment: 9		
Title of case study: Global Food Security and City Living in a Changing Climate: Enabling the Copernicus Agricultural and Urban Monitoring Mission.		
Period when the underpinning research was undertaken: 2010–Present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): 1) Darren Ghent 2) David Llewellyn-Jones 3) John Remedios 4) Gary Corlett 5) Michael Perry	**Role(s) (e.g. job title):** 1) Senior Research Fellow in Physics 2) Fellow & Emeritus Professor in Physics 3) Director of National Centre for Earth Obs 4) Senior Researcher in Physics 5) Researcher in Physics	**Period(s) employed by submitting HEI:** 1) 2010–Present 2) 2003–Present 3) 2000–Present 4) 1998–2018 5) 2016–Present
Period when the claimed impact occurred: 2014–Present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

In the past decade world population has grown by almost 1 billion to 7.8 billion in 2020 and continues to increase. Pressures on agriculture, which already accounts for 70% of freshwater usage, and on urban living will intensify due to climate change. Research at the University of Leicester has been pivotal in deriving high quality, land surface temperature data from thermal infra-red satellite instruments through new algorithms and datasets to support research on crop production and urban heat/health. The Leicester team has provided the critical scientific evidence base to the European Space Agency (ESA), industry and governments, leading directly to a decision by European governments to invest EUR380,000,000 to build the first European operational thermal infra-red satellites: the Copernicus Land Surface Temperature Monitoring mission for agriculture and urban services.

2. Underpinning research

The Land Surface Temperature Group (LSTG) at the University of Leicester (UoL) is a world leader in thermal remote sensing research with an extensive track record in mapping the Earth's surface temperature from space. Consistent land surface temperature (LST) data is integral to food security assessments, is increasingly relevant to crop productivity systems and is essential for forecasting drought.

The foundations of LSTG success were laid by Llewellyn-Jones and Remedios through their innovative exploitation of Along Track Scanning Radiometers (ATSRs) to investigate accurate sea and land surface temperatures. Since 2010, Ghent, Remedios and the LSTG have developed the first high quality LST algorithms and related cloud detection techniques for the ATSR series **[R1]**. These were subsequently applied to the follow-on Sea on Land Surface Temperature Radiometer on the Copernicus Sentinel-3 mission with Ghent as the LST Algorithm Manager.

The ATSR and Sentinel-3 instruments, with 1 x 1 km resolution, are aimed at reporting accurate global and regional temperatures. The LSTG's physically based algorithms and datasets were instrumental in achieving this, through the LSTG-led international ESA DUE GlobTemperature and Climate Change Initiative projects on LST.

A key step forward **[R1]** was the demonstration that LST data from the ATSRs were of sufficient quality (1 K uncertainty) to meet the Global Climate Observing Systems requirements for an LST Essential Climate Variable dataset. The study also rigorously showed that the underlying, physical radiative transfer modelling was fully representative of real-world situations with traceability to the algorithm coefficients for producing the LST.

Based on this assessment, further study of the long-term, climate-quality dataset, in co-operation with the Met Office, crucially established that satellite-observed LST could be used as a variable to understand global temperature change, with anomaly departures over time that match those of the *in situ* air temperature record **[R2]**.

A robust data set for climate change assessment should include well characterised and verified uncertainties. Ghent expanded the uncertainty analysis from **[R1]** to develop a comprehensive uncertainty model for LST sensors, accounting fully for known random and systematic components **[R3]**. The uncertainty process included, for the first time for LST, approaches to treating complex correlation length scales and verification of uncertainty estimates.

Interdisciplinary research with colleagues in the National Centre for Earth Observation has exploited these accurate LST data to instigate new tests of the sensitivities of crops to changes in evapotranspiration and drought, both for yield and stress. Agricultural drought is a particularly disastrous regime wherein water content cannot sustain crops, hence threatening food security. **[R4]** developed new methods of estimating natural drought sensitivity globally, identifying regions that are sensitive to soil water control on vegetation. Research in West Africa, India and China has improved measures of yield and early warning signals of agricultural drought **[R5]**. This approach has also proven successful at the scale of individual cities, but in-depth studies require sensors with much higher spatial resolution (typically sub-50 m) and more consistent, sophisticated algorithms that can cope with the heterogeneity of LST and surface emissivity at these scales. The LSTG have developed the first optimal estimation based LST algorithm **[R6]** for both lower and high spatial resolution datasets, providing a very different capability and approach to urban LST. This new algorithm is also very robust at agricultural field scales and transforms our capability for deriving relevant LST data through new high-resolution satellites.

3. References to the research

R1. Ghent D, Corlett GK, Goettsche F, **Remedios J**, 'Global land surface temperature from the Along-Track Scanning Radiometers', *Journal of Geophysical Research-Atmospheres*, 2017.

R2. Good EJ, **Ghent D**, Bulgin C, **Remedios J**, 'A spatiotemporal analysis of the relationship between near-surface air temperature and satellite land surface temperatures using 17 years of data from the ATSR series', *Journal of Geophysical Research-Atmospheres*, 2017.

R3. Ghent D, Veal K, Trent T, Dodd E, Sembhi H, **Remedios J***,* 'A New Approach to Defining Uncertainties for MODIS Land Surface Temperature', *Remote Sensing*, 2019.

R4. Gallego-Elvira B, Taylor C, Harris P, **Ghent D**, Veal K, Folwell S, 'Global observational diagnosis of soil moisture control on the land surface energy balance' *Geophysical Research Letters*, 2016.

R5. Tagesson, T., Horion, S., Nieto, H., Zaldo Fornies, V., Mendiguren Gonzales, G., Bulgin, C. E., **Ghent, D.**, and Fensholt, R. (2018), Disaggregation of SMOS soil moisture over West Africa using the Temperature and Vegetation Dryness Index based on SEVIRI land surface parameters. *Remote Sensing of Environment*, 206, 424-441.

R6. Perry, M., **Ghent, D.**, Jimenez, C., Dodd, E., Ermida, S., Trigo, I. F., and Veal, K. (2020). Multi-Sensor thermal infrared and microwave land surface temperature algorithm intercomparison. *Remote Sensing*, 12(24), 4164.

4. Details of the impact

Earth Observation satellites have become significant information sources for commercial services, government policy and citizen information but they require well-justified missions in order for governments to make policy decisions to invest. The European Copernicus flagship programme is the largest operational provider of publicly accessible Earth Observation data in the world, delivering services for citizens across Europe including the UK.

The cumulative research work of the LSTG over a decade, and the pivotal role of Ghent, has been central to the European Space Agency (ESA) being able to define and implement Europe's first high spatial resolution, thermal infrared mission. This mission, Copernicus Land Surface Temperature Monitoring (LSTM), is built primarily to deliver operational agricultural and urban services. The translation of LSTG research has resulted in precise specifications and mission concepts giving industry the required knowledge to construct the mission and enabling them to receive contracts of hundreds of millions of euros.

The first critical role for Ghent and Remedios was to support ESA in understanding the key needs and benefits for the mission. Studies led by Remedios with Surrey Satellite Technologies Ltd in 2016 **[E1]** and then by Ghent in 2017 **[E2]** identified the service applications that had become possible through progress in LST science. Significant needs in agricultural management and food security were highlighted, supported by publications demonstrating drought forecasting advances and evapotranspiration sensitivity **[R4, R5]**. LSTG and their international teams **[E2]** also articulated a wider range of information needs for water rights management, water quality monitoring, soil composition and mineralogy, volcano monitoring and fire detection**.**

In the study by Ghent, together with Corlett and Remedios, precursor work established the essential concept of LSTM, undertaking a precise trade-off analysis between service requirements and LSTM sensor capability. The main objectives of a new LST mission could be achieved with an LST accuracy of 1K at 50 m resolution. This requires the instrument to have three or more spectral bands, demonstrated using the unique optical estimation approach **[E2]**.

The economic benefits of the identified applications to agriculture and plant health, urban temperature information and active fire mapping at the 1K accuracy of LSTM have since been formally assessed as EUR1,200,000,000 over 10 years (medium case scenario) **[E3]**.

The second crucial role for LSTG, particularly for Ghent, was in leading further instrument specification activities for LSTM, the results of which are captured in the key ESA Mission Requirements Document (MRD). As a procuring agency, ESA needs verifiable design performance which enables it to define, design, achieve funding and implement the building of industrially built systems with the required performances. In turn, the industrial construction teams need precise, robust specifications allowing design, cost and delivery of instruments and platforms to targets with minimised risk. The MRD documents the science inputs used to specify mission characteristics, instrument design and specifications for production by industry **[E4, E5]**.

In order to support the MRD, the next steps were to formalise the LSTG inputs further alongside two industrial contracts (phase A/B1) led by Airbus UK and Thales Alenia Space, France.
First, in 2018, Ghent was appointed by ESA as a member of their international LSTM Mission Advisory Group (MAG) which is responsible for reviewing and extending scientific information that ESA needs in order to define and build the mission, including MRD inputs **[E5]**.
Second, Ghent became book captain for the MRD algorithms chapter to define the methods to be put into operational production in the mission ground segment **[E4]**.
Third, Ghent and LSTG were asked by ESA to lead the LSTM science study A/B1 in parallel to the industrial studies; the international science study team also included University of Valencia, INRAE(Avignon), CESBIO, and University of Toulouse.

This science study provided the key scientific inputs for the mission, through detailed calculations of the specifications and trade-offs using the research techniques and algorithms developed and published by the LSTG **[R6]**. Examples include optimisation of the spectral bands for the instrument, centre wavelengths and limits on their tolerance; radiometric noise and absolute accuracy thresholds for the mission; orbit swath and spatial resolutions **[E6].**

Ultimately, all recommendations, thresholds and requirements provided by Ghent and the team were approved by ESA, in consultation with the MAG and written formally into the MRD **[E4, E5].**

The study also specifically addressed questions from the industrial teams, via ESA, and this has been particularly important to refine performances to meet targets, achieve stability and satisfy cost constraints. Examples include spectral band configurations and sensitivity to out-of-band responses, channel signal-to-noise ratios and impacts of pseudo-noise on ultimate LST uncertainties **[E6]**.

The Ghent and LSTG activities were therefore critical in ESA's selection of LSTM as a Copernicus High Priority Candidate Mission. As a result of the definition of mission objectives from LSTG research (and validated by the economic assessment), the clear MRD and the industry design to that MRD, ESA was able to put forward LSTM as a credible operational mission to its member state governments **[E7]**.

In November 2019, the ESA Council of Ministers including the UK government (represented by the UK Space Agency) agreed a budget to build six high priority satellites including LSTM **[E8]**, increasing the subscription by 29% to EUR1,800,000,000 **[E9]**. Subsequently, ESA were able to procure LSTM from industry and in November 2020 Airbus were awarded the contract to build two LSTM satellites at a price of 380 million euros **[E10]**, delivering this first European operational land temperature system to the specification advised by the LSTG working with the MAG.

5. Sources to corroborate the impact

E1. Surrey Satellite Technologies and U. Leicester. Final Report 2016, Sentinel Convoy for Land, ESA Contract 4000103356/11/NL/FC.

E2. Ghent D, 'Thermal InfraRed Imager Scientific sIMulation ESA Study – Final Report' 2017. ESA Contract 4000120368/17/NL/AF/hh.

E3. Copernicus ex-ante benefits assessment, Final Report, December 2017, Price Waterhouse Cooper, France: https://www.copernicus.eu/en/news/news/study-estimates-copernicus-benefits-be-10-times-its-costs

E4. Copernicus High Spatio-Temporal Resolution Land Surface Temperature Mission: Mission Requirements Document, ESA-EOPSM-HSTR-MRD-3276, Rev.2, 8/3/2019: http://esamultimedia.esa.int/docs/EarthObservation/Copernicus_LSTM_MRD_v2.0_Issued20190308.pdf

E5. Testimonials: ESA technical officers.

E6. Ghent D, et al. 'Assessment of the potential use of the high resolution Thermal Infra-Red (TIR) band – Final Report' 2020. ESA Contract 4000117242/16/NL/FF/mc.

E7. ESA Copernicus Long-Term Scenario Proposal for ESA Council of Ministers, ESA_PB-EO_2019_11,REV.1_EN, May 2019.

E8. Press release on ESA's Council at Ministerial Level, Space19+: http://www.esa.int/Newsroom/Press_Releases/ESA_ministers_commit_to_biggest_ever_budget

E9. Earth observation, deep space exploration big winners in new ESA budget https://spaceflightnow.com/2019/11/29/earth-observation-deep-space-exploration-big-winners-in-new-esa-budget/

E10. (a) Airbus press release on LSTM contract: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Contracts_signed_for_three_high-priority_environmental_missions
(b) ESA 'Monitoring Earth's skin heat for crops and climate': http://www.esa.int/Applications/Observing_the_Earth/Monitoring_Earth_s_skin_heat_for_crops_and_climate; and Future Earth Article, 2019: https://futureearth.org/2019/12/03/ministers-boost-esas-budgets-for-new-satellite-missions/
(c) EU Earth Observation for Agriculture 'Guidelines on the Improvement of Future Missions Support for Thematic Applications', 2019: http://eo4agri.eu/sites/eo4agri.eu/files/public/content-files/deliverables/EO4AGRI_D3.7-Guidelines-on-the-improvement-of-future-missions-support-for-thematic-applications-v1_v1.0.pdf