Institution: University of Leicester		
Unit of Assessment: 7		
Title of case study: Supporting the Global Fight Against Climate Change From Space		
Period when the underpinning research was undertaken: 2006–Present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): 1) Professor Hartmut Boesch 2) Professor John Remedios 3) Professor Paul Monks 4) Dr Robert Parker	**Role(s) (e.g. job title):** 1) Professor in Earth Observation Science 2) Director of the National Centre for Earth Observation 3) Professor of Atmospheric Chemistry and Earth Observation Science 4) Senior Research Fellow	**Period(s) employed by submitting HEI:** 1) 2007- Present 2) 2000 - Present 3) 1996 - Present 4) 2009 - Present
Period when the claimed impact occurred: 2013–Present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Climate change is one of the most significant global threats in the 21st Century. The Kyoto Protocol and subsequent Paris Agreement have sought to reduce greenhouse gas (GHG) emissions across the world to limit global warming. Scrutiny of global progress and political response is dependent on independent and accurate monitoring of these emissions.
The Leicester Greenhouse Gas Remote Sensing Group (GGRSG) has redefined monitoring methods, protocols and processes providing significantly improved accuracy and reliability of satellite-derived GHG data. Their research has enabled international environmental and space programmes to provide governments and space agencies with resources and recommendations to facilitate monitoring and verification. GGRSG researchers are now playing a leading role in the first-ever purpose-built European CO_2 Monitoring satellite mission and were instrumental in devising the European operational system, which meets the political and delivery needs for monitoring and verification of carbon emissions.

2. Underpinning research

The University of Leicester is a world leader in remote sensing of greenhouse gases (GHGs) from space with over a decade of successful intensive research across three broad areas: development of fundamental methods for reliable CO_2 and CH_4 measurement from space, specification of new space-based concepts for GHG sensing and linking space-based data to surface GHG fluxes (both emissions and uptake). For more than a decade, the team has played a key role in interpreting data from the ENVISAT SCIAMACHY instrument (launched 2002), the Japanese Greenhouse gases Observing SATellite (GOSAT, launched in 2009) and NASA Orbiting Carbon Observatory (OCO-2, launched in 2014). This research has been supporting the fundamental scientific development of retrieving CO_2 and CH_4 concentrations (or columns) from space-based observations and the subsequent scientific analysis methods of these data, as used by today's satellite GHG missions. The key steps in the research were the demonstration of accurate retrievals of CH_4 and CO_2 from space-borne sensors and to demonstrate the feasibility of robustly estimating surface fluxes from space-borne data using atmospheric inverse methods. As one of the first groups in Europe to conduct research into GHG retrievals from satellites, they discovered the need to include suitable *a priori* information within existing retrieval methods (Weighting Function Modified Differential Optical Absorption Spectroscopy WFM-DOAS) in order to minimize the errors on the retrieved CO_2 columns from the SCIAMACHY instrument. This led to the development of Full Spectral Initiation (FSI) WFM-

DOAS which generates a reference spectrum for each individual observation using the estimated properties of the atmosphere and surface at the time of the measurement **[R1]**.

Boesch and GGRSG, with collaborators from NASA Jet Propulsion Laboratory, have developed and demonstrated the application of further advanced retrieval methods adopting optimal estimation techniques to GHG retrievals from satellites **[**e.g. **R2]**. A critical step was the application to the first dedicated GHG satellite GOSAT and to show the feasibility of space-borne GHG observations with an agreement of better than 0.25% against reference measurements **[R3]**. Implicitly, this research has been crucial in overcoming the technical and scientific challenges and in characterising and understanding the retrieval uncertainties in remote sensing of GHGs which led to the development of new techniques for GHG data analysis from satellites with improved accuracy and significantly reduced errors **[R3, R4]**. These datasets are now underpinning major initiatives such as the European Space Agency's Climate Change Initiative (http://www.esa-ghg-cci.org/) and the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/#!/home) **[R5]** and national programmes such as the NERC GAUGE (Greenhouse gAs Uk and Global Emissions) and NERC MOYA (Methane Observations and Yearly Assessments) projects. Collaborative research within the National Centre for Earth Observation (with Uni. Edinburgh) and with Uni. Bristol and LSCE, France, has shown the robustness and consistency of the techniques for surface fluxes which have been significant research challenges in evaluating carbon budgets **[R6]**. The success of these research techniques has facilitated the first country-scale (India) verification of methane emissions from space **[R7]** and also means that GHG satellite instruments are now being designed with much more confidence than a decade ago.

The group's expertise is recognised internationally and their input valued highly. For example, since 2011, Boesch has been a member of the European Space Agency (ESA) Mission Advisory Group (MAG), providing scientific advice for the ESA Earth Explorer 8, CarbonSat and in 2018 for the Copernicus Anthropogenic CO_2 Monitoring CO2M missions. In these roles, he directly provides scientific advice to ESA for the development of missionsThe CO2M activities are directly linked with the recent increase in ESA subscriptions to fund satellites to enable the Copernicus CO_2 Monitoring Service. GGRSG expertise is also crucial in the development of the first-ever European CO_2 Monitoring satellite mission, the joint CNES/UKSA satellite, MicroCarb: Boesch is a member of the Microcarb Science team.

3. References to the research

R1. **Barkley, M. P**., Frieß, U., and **Monks, P. S**. 'Measuring atmospheric CO_2 from space using Full Spectral Initiation (FSI)' WFM-DOAS, *Atmos. Chem. Phys*., 6, 3517-3534, https://doi.org/10.5194/acp-6-3517-2006, 2006.

R2. Boesch, H.; Baker, D.; Connor, B.; Crisp, D.; Miller, C. Global Characterization of CO_2 Column Retrievals from Shortwave-Infrared Satellite Observations of the Orbiting Carbon Observatory-2 Mission. *Remote Sens*., 3, 270-304, 2011.

R3. Cogan, A. J., **H. Boesch, R. J. Parker**, L. Feng, P. I. Palmer, J.-F. L. Blavier, N. M. Deutscher R. Macatangay, J. Notholt, C. Roehl, T. W arneke, D. Wunch, 'Atmospheric carbon dioxide retrieved from the Greenhouse gases Observing SATellite (GOSAT): Comparison with ground-based TCCON observations and GEOS-Chem model calculations', *J. Geophys. Res.*, 117, D21301, doi:10.1029/2012JD018087, 2012.

R4. Connor, B., **Bösch, H**., McDuffie, J., Taylor, T., Fu, D., Frankenberg, C., O'Dell, C., Payne, V. H., Gunson, M., Pollock, R., Hobbs, J., Oyafuso, F., and Jiang, Y.: Quantification of uncertainties in OCO-2 measurements of XCO_2: simulations and linear error analysis, *Atmos. Meas. Tech.,* 9, 5227–5238, https://doi.org/10.5194/amt-9-5227-2016, 2016.

R5. Buchwitz M, Reuter M, Schneising O, **Boesch H**, Guerlet S, Dils B, Aben I, Armante R, Bergamaschi P, Blumenstock T, et al., The Greenhouse Gas Climate Change Initiative (GHG-CCI): Comparison and quality assessment of near-surface-sensitive satellite-derived global CO2 and CH4 data sets. *Remote Sensing of Environment* **162**:344-362 01 Jun 2015.

R6. Chevallier, F., P. I. Palmer, L. Feng**, H. Boesch**, C. W. O'Dell, and P. Bousquet, Towards robust and consistent regional CO_2 flux estimates from in situ and spaceborne measurements of atmospheric CO_2, *Geophys. Res. Lett*., 41, 1065–1070, doi:10.1002/2013GL058772, 2014.

R7. Ganesan, A.L., Rigby, M., Lunt, M.F. **R. J. Parker, H. Boesch**, N. Goulding, T. Umezawa, A. Zahn, A. Chatterjee, R. G. Prinn, Y. K. Tiwari, M. van der Schoot, Paul B. Krummel 'Atmospheric observations show accurate reporting and little growth in India's methane emissions'. *Nat Commun* **8,** 836, doi:10.1038/s41467-017-00994-7, 2017.

4. Details of the impact

On June 27th 2019 the UK became the first major economy in the world to make a legislative commitment to achieving net zero GHG emissions by 2050. This builds on the global objectives outlined in the 2015 Paris Agreement to limit global warming to well below 2°C compared to pre-industrial levels. Success in demonstrating these commitments is dependent upon the ability of governments to measure and monitor GHG emissions.

The first dedicated European GHG Mission: MicroCarb

GGRSG research directly affected the UK Space Agency's decision to invest into the MicroCarb mission. MicroCarb will be the first dedicated European CO_2 satellite, due to launch in 2022. The mission will allow scientists to track the exchange of carbon between the surface and atmosphere, necessary to understand the response of natural carbon pools to climate change and quantify human CO_2 emissions. MicroCarb will also have capability for a 'City Mapping Mode' with higher resolution **[E1]**. MicroCarb represents an important step towards a longer-term operational European monitoring system coordinated by the Copernicus program, and it is demonstrating the UK's commitment to tackling climate change by integrating UK science and engineering communities **[E2]**.

The results of GGRSGC research have demonstrated the importance of rigorous, scientifically-based algorithms, quality calibration, and capable data processing for successful CO_2 measurements with the accuracy needed for operational monitoring. As stated by the UK Space Agency's Head of Earth Observation and Climate: "*the scientific work by NCEO [at UoL and Edinburgh] researchers has shown to the UK Space Agency that satellite observations of CO_2 and CH_4 have now reached a sufficiently high level of maturity'* and that *'based on the scientific work carried out by NCEO, UKSA is now convinced that space based GHG monitoring capability is a high priority for the UK"* **[E3]**. As an immediate step, the UK government (BEIS via the UK Space Agency), made the strategic decision to invest GBP10,000,000 into the MicroCarb mission to ensure the UK was fully involved in CO_2 measuring missions. The long term need for climate security meant it was vital that industry undertook key roles and that investment built on the UK space sector commitment to climate data from space for climate services as a growth area for industry **[E3, E4]**. As stated in **[E3]**, this *"decision to invest in the MicroCarb mission has*

been a direct result of research carried out by NCEO [at UoL and Edinburgh] as part of the 'Bilateral Carbon Mission' Study and the associated business case". The study has been led by Boesch who also developed substantial parts of the business case submitted by UK Space Agency to the Treasury **[E4, E5]**.

The investment into MicroCarb has directly contributed to the growth of the space sector in the UK in key priority areas including ground segment, information services and ground calibration. UK companies involved in MicroCarb include world leaders in space systems design Thales Alenia, aerospace technology solutions company GMV UK, global leaders in measurement solutions the National Physical Laboratory and Research and Development company RAL Space **[E1]**. Thales Alenia, a key partner in project delivery, emphasised the importance of the project, saying that MicroCarb will be *"Ultimately helping decision makers to develop the best policies to make the world a better place"* **[E6]**.

Driving European climate change commitments

The work of GRSG has resulted in decisions far beyond the immediate collaboration on MicroCarb. ESA was given the go ahead in 2019 by the ESA Council of Ministers, including the UK, to build two operational CO_2 monitoring missions (CO2M) to be launched under the Copernicus Programme **[E7].** The UK increased its contribution by an additional £200 million to the ESA Earth Observation programme **[E3]**. As stated in **[E3]**, *'this decision was driven by a strong commitment to monitoring climate from space including the future space-based CO_2 monitoring system of the Copernicus program (CO2M) informed by knowledge from the research carried out by NCEO [at UoL and Edinburgh]'.*

CO2M provides a unique and independent source of information for policy makers to assess the effectiveness of policy measures aimed at climate change mitigation and to track their impact towards the goals of the Paris Agreement. According to the Head of the Copernicus Unit at the European Commission, CO2M "*is the largest environmental space programme ever designed in Europe to monitor our dynamic Earth. This CO_2 initiative constitutes a significant positive step towards climate change mitigation and will further consolidate Europe's leading position on the global stage in this policy field of utmost and critical importance for mankind"* **[E8]**.

The work carried out by GGRSG and international collaborators has given UK and European governments the confidence to invest in an operational monitoring system **[R2, R3, R4]**. The cumulative scientific work of GGRSG led by Boesch, has *"demonstrated to ESA that satellite observations of CO_2 and CH_4 have reached a sufficiently high level of maturity to be implemented as satellite instrument, as evidenced in many peer-reviewed publications"* **[E9]**.

Building on extensive work by Boesch on earlier missions [**E10, E11]**, Boesch has helped to advance the fundamental methods on CO_2 remote sensing to the level required for CO2M. Through ESA projects, Boesch's GGRSG team has provided key insights into instrumental and retrieval uncertainties and how they impact the mission performance. As stated by ESA: "*Boesch's outstanding contributions significantly supported the identification and formulation of specific mission requirements for observing greenhouse gases and the science studies provided ESA with the required detailed justification"* **[E9]**.

The decision for CO2M has also had a significant economic impact. The contract for the build of the first two satellites has been signed between ESA and the consortium lead OHB, Germany, with a total contract value of EUR445,000,000 **[E12]**. UK space industry (Thales Alenia Space) has been contracted to develop payload components worth EUR42,000,000. The design of the spacecraft build by industry is directly dictated by the ESA Mission Requirements Document (MRD) which formulates and justifies the specific mission requirements for CO2M **[E13]**. The

work of GGRSG has significantly contributed to the formulation of the MRD and Boesch, as a member of the international CO2M Mission Advisory Group, drafted, reviewed and endorsed the MRD **[E11]**.

Through direct collaboration with EUMETSAT, the European operational satellite agency for monitoring weather, climate and the environment from space, Boesch's research has also influenced the design and architecture of the operational CO2M processing ground-segment **[E14]** that will generate the primary operational data stream of the CO_2 monitoring service.

5. Sources to corroborate the impact

E1. Space4climate Webpage: http://www.space4climate.com/microcarb-satellite/
E2. UK Space Agency, Press Release, 2017. https://www.gov.uk/government/news/uk-space-agency-and-cnes-join-forces-to-curb-climate-change
E3. Testimony: Head of Earth Observation and Climate, UKSA.
E4. MicroCarb Business Case "The Bilateral Carbon Mission, Supporting the Business Case, Version 5.2" CONFIDENTIAL.
E5. Final Report, UKSA Bilateral Carbon Mission Project.
E6. UK Space Agency, Press Release, 2017. https://www.gov.uk/government/news/thales-alenia-space-signs-contract-with-the-uk-space-agency-to-work-on-climate-change-mission
E7. BBC news article: https://www.bbc.co.uk/news/science-environment-50594831
E8. Copernicus, Press Release, 2018 'Helping countries verify their CO2 emission reductions'. Article covering CO2M Mission
E9. Testimony:CO2M Mission Scientist, Head of Atmospheric Section, ESA.
E10. CarbonSat Mission Selection Report, available from: https://esamultimedia.esa.int/docs/EarthObservation/SP1330-1_CarbonSat.pdf
E11. Algorithm Theoretical Basis Documents ATBD for the NASA OCO-2 mission, available from: https://disc.gsfc.nasa.gov/information/documents?title=OCO-2%20Documents
E12. OHB Press Release, 2020. https://www.ohb.de/en/news/2020/ohb-and-esa-sign-contract-for-copernicus-atmospheric-co2-monitoring-mission
E13. Copernicus CO2M Mission Requirements Document
E14. Testimony from Greenhouse Gas and CO2M project scientist and Head of Remote Sensing and Products Division, EUMETSAT.