Institution: University of Edinburgh (UoE)

Unit of Assessment: 7

Title of case study: Supporting UN Paris Agreement commitments by estimating global terrestrial carbon fluxes from satellite data

Period when the underpinning research was undertaken: 2012 – 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:
Professor Paul Palmer	Professor of Quantitative Earth Observation	10/2006 – present
Liang Feng	Postdoctoral Research Assistant	03/2004 – present

Period when the claimed impact occurred: 2014 - 31 December 2020

Is this case study continued from a case study submitted in 2014? Y/ N
N

1. Summary of the impact (indicative maximum 100 words)

UoE scientists led by **Palmer** have pioneered the interpretation of satellite measurements of atmospheric carbon dioxide (CO_2) and methane (CH_4) to infer the magnitude and distribution of their surface fluxes, underpinning the global response to the UN Paris Agreement to undertake global carbon stocktakes.

In recognition of his research and expertise, **Palmer** is the UK member of the European Commission CO_2 Monitoring Task Force that helps to define the upcoming CO_2 Copernicus Service, to which the UK Government committed EUR18,000,000,000 in 2019, and increased its annual European Space Agency (ESA) subscription to GBP73,000,000 in 2019.

The research also enabled the UK Space Agency to develop a business case to invest in the MicroCarb satellite mission, contributing directly to the measurement and monitoring of CO_2 from space.

2. Underpinning research (indicative maximum 500 words)

A group of University of Edinburgh (UoE) researchers, led by **Palmer**, are world leaders in techniques used to infer the surface fluxes of atmospheric carbon dioxide (CO_2) and methane (CH_4) using satellite measurement data.

For more than a decade, the group has played a key role in interpreting data from the Japanese Greenhouse gases Observing SATellite (GOSAT, launched in 2009) and the NASA Orbiting Carbon Observatory (OCO-2, launched in 2014). The critical step made by **Palmer's** group was to show the feasibility of space borne GHG observations, using data from the first dedicated GHG satellite GOSAT, achieving an agreement of better than 0.25% against reference measurements **[3.1]**. Their research has continued to support the fundamental scientific advances in retrieving accurate atmospheric CH_4 and CO_2 observations from space-borne sensors and demonstrating of the feasibility of robustly estimating surface fluxes from satellite data.

In his earliest work, **Palmer** was able to demonstrate the ability of space-based sun-glint data over the ocean to infer tropical land fluxes that are usually obscured by clouds (wet season) or aerosols (dry season) **[3.2]**. This influenced satellite teams to prioritise the processing of these data. He co-led a group of investigators to assess the robustness of

surface fluxes of CO_2 against assumptions embedded in atmospheric transport models and obtained by inverse methods **[3.3]**. Other groups built on this pioneering research to develop the co-retrieval of CH_4 and CO_2 in adjacent spectral fitting windows with the underlying assumption that taking the ratio reduced common errors. **Palmer** subsequently developed an approach that used this ratio directly by using in situ CO_2 and CH_4 anchor points to indirectly extract information from CO_2 and CH_4 fluxes **[3.4]**. In 2019, he produced the first multi-year regional CO_2 fluxes using GOSAT and OCO-2 data, highlighting the unprecedented consistency between fluxes inferred by different space-based data and by different atmospheric models. The work also highlighted gaps in knowledge of tropical land fluxes of CO_2 which had until then been inferred from sparse and distant in situ constraints **[3.5]**. The study attracted substantial interest from scientists and the media, for example **[3.5]** is in the 99th percentile of the tracked articles of a similar age in all journals (Altmetrics: https://www.nature.com/articles/s41467-019-11097-w/metrics). More recently, **Palmer** led the most comprehensive analysis of Chinese CO_2 fluxes using newly available ground measurement data across China and showed that Chinese Government policies focused on afforestation have resulted in large carbon sinks, corroborating those results using satellite observations of CO_2 **[3.6]**.

Collectively, these studies demonstrate that Palmer's research on satellite observations of GHG fluxes have reached a level of maturity and corroboration that they are trusted by policymakers to provide a powerful constraint on regional carbon fluxes, and therefore play a critical role in an emission monitoring and verification support capacity.

3. References to the research (indicative maximum of six references)

[3.1] Cogan, A. J., Boesch, H., Parker, R. Feng. L., **Palmer, P**. Blavier, J.P., Deutscher, N.M., Notholt, J. Roehl, C. Warneke, T. Wunch. D. (2012) 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 [104 Scopus citations]

[3.2] Feng L., **Palmer P. I.,** Boesch H., and Dance S. (2009). Estimating surface CO_2 fluxes from space-borne CO_2 dry air mole fraction observations using an ensemble Kalman Filter, ***Atmos. Chem. Phys***. *9*, 2619-2633., doi: 10.5194/acp-9-2619-2009 [87 citations]

[3.3] Chevallier, F., **Palmer, P.I.,** Feng, L., Boesch, H., O'Dell, C.W., and Bousquet, P. (2014) 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 [76 citations]

[3.4] Feng, L., **Palmer, P. I**., Bösch, H., Parker, R. J., Webb, A. J., Correia, C. S. C., Deutscher, N. M., Domingues, L. G., Feist, D. G., Gatti, L. V., Gloor, E., Hase, F., Kivi, R., Liu, Y., Miller, J. B., Morino, I., Sussmann, R., Strong, K., Uchino, O., Wang, J., and Zahn, A. (2017) Consistent regional fluxes of CH_4 and CO_2 inferred from GOSAT proxy XCH_4 : XCO_2 retrievals, 2010–2014, ***Atmos. Chem. Phys***., *17*, 4781–4797. doi: 10.5194/acp-17-4781-2017 [18 citations]

[3.5] Palmer, P.I., Feng, L., Baker, D. F. Chevallier, H. Boesch, P. Somkuti, (2019). Net carbon emissions from African biosphere dominate pan-tropical atmospheric CO_2 signal. ***Nature Communications,*** *10***,** 3344 doi: 10.1038/s41467-019-11097-w [13 citations]

[3.6] Wang, J., Feng, L., **Palmer, P.I.**, Liu, Y., Fang, S., Boesch, H., O'Dell, C.W., Tang, X., Yang, D., Liu, L. & Xia, C. (2020) Large Chinese terrestrial carbon sink estimated from atmospheric CO_2 data, ***Nature***, *586*, 720-723. doi: 10.1038/s41586-020-2849-9

The underpinning research listed was published in highly ranked academic journals (Scopus citations as of December 2020 shown above), and supported by peer-reviewed grants. Examples include:

PI, Palmer, P. (2008-2010). Preparing for CO_2 column datastreams from OCO and GOSAT satellite instruments. [Ne/F000014/1]. *NERC.* GBP145,530.

PI, Palmer, P. (2008-2018). National Centre For Earth Observation (NCEO) - Theme 3 Atmospheric Composition. [Uni of Reading/Nerc 08/03]. *NERC*. GBP677,692.

PI, Palmer, P. (2010-2011). Towards The UK Community Exploitation Of New Satellite Measurements Of CO_2 From The Greenhouse Gases Observing SATellite (GOSAT). [Ne/H003940/1]. *NERC*. GBP202,325.

PI, Palmer P. (2014-2021). National Centre for Earth Observation. [pr140015]. NERC/NCEO GBP1,460,812.

The research excellence of this group is also reflected by its membership of international science and mission teams. Palmer sits by invitation on the European Commission (EC) CO_2 Task Force for the CO_2 Copernicus Service that will soon launch a small constellation of CO_2 observing satellites (CO2M mission). This task force has produced a series of reports that encapsulate expert scientific advice about the measurement and infrastructure requirements for CO2M to address the Paris Agreement global stocktakes. These CO2M activities are directly linked with the recent increase in ESA subscriptions to fund satellites to enable the Copernicus CO_2 Monitoring Service.

4. Details of the impact (indicative maximum 750 words)

The far-reaching and global impact of the UoE group led by **Palmer** supported the commitment by UK, European and many international governments to the goals of the 2015 UN Paris Agreement to reduce carbon emissions and limit global warming to “well below 2 degrees”. Methods to measure carbon emissions and sinks are enshrined in international agreements, and countries are encouraged to develop independent sources of information (ie beyond simpler bookkeeping methods based on how much fuel was burned, coupled with a generic emission factor) to monitor the effectiveness of policy measures. For example, the UK includes such independent data as part of their United Nations Framework Convention on Climate Change submissions, supported by research described in sections 2 and 3, and the UK was the first major economy in the world to pass laws mandating verifiable net zero GHG emissions by 2050 **[5.1]**.

Impact on UK policy and investment

Based on an extensive study in collaboration with UK industry (funded by the UK Space Agency, UKSA), the team demonstrated that the UK has the technical and scientific capability to contribute to and exploit data from a CO_2 satellite mission **[5.1]**. This work led to the UKSA endorsing a business case for the development of a space based GHG monitoring capability as a high priority. As an immediate step the UK government invested GBP10,000,000 in 2019 to collaborate with the French Space Agency CNES on the development of the MicroCarb satellite mission. The decision to invest ‘*has been a direct result of research carried out by Professor Palmer and others as part of the ‘Bilateral Carbon Mission’ Study and the associated business case*’ **[5.1]**, paving the way to an operational space-based system monitoring UK net zero targets and supporting science and engineering communities and the UK space industry by securing and retaining science and engineering expertise **[5.1, 5.2]**.

Impact on European policy and investment

In 2019 the UK increased its contribution to the ESA’s Earth Observation programme by GBP73,000,000 **[5.5]**. In addition, ESA was given the go ahead by its Member States (including the UK), to develop an operational CO_2 mission (CO2M) and to launch the first satellite under the auspices of the European Copernicus programme, with the then President-elect of the European Commission directing the Commissioner for the Internal

market to "*explore ways in which we can make the most of our assets to deliver on climate objectives, including the use of Copernicus to monitor CO_2 emissions*" **[5.3, 5.4]**. CO2M is one of six high priority missions of the Copernicus programme funded under an envelope of EUR18,000,000,000 **[5.5]**. These decisions were driven by a strong commitment by the UKSA to monitor 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 the UoE group, including **[3.2]** and **[3.3]** **[5.1]**.

The cumulative scientific work led by the team has been influential in confirming the feasibility of CO2M and setting mission requirements **[5.6]**. The UoE **Palmer** group work has significantly advanced the use of satellite observations of CO_2 and CH_4 to develop knowledge of carbon cycles **([3.4]**, **[3.5]**, **[3.6]).** National and international recognition of the work led to **Palmer's** membership of the European Commission CO_2 Task Force in 2016 **[5.6]** to provide guidance and requirements in expert reports **[5.7, 5.8]**. The task Force have begun developing an operational European measurement and verification system, including the CO2M satellite data, to ensure the system meets the requirements to infer actionable information on fossil fuel CO_2 emissions to standards described in the 2015 Paris Agreement.

Impact on International policy and investment

The cumulative body of UoE research, including **[3.1]-[3.6]**, has directly contributed to long-term monitoring programmes of the global co-ordination Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Virtual Constellation group (AC-VC) in developing an international satellite constellation architecture to monitor global greenhouse gases from space, combining data from existing satellites into create a dedicated virtual satellite constellation **[5.5].** The UK GEO/CEOS Office supported **Palmer's** membership of the CEOS Carbon working group as UK representative.

Collaborative work between the UoE researchers and Chinese researchers has recently shown the benefit of a multi-decadal Chinese investment in afforestation using in situ and satellite measurements of CO_2 **[3.6]**. They showed using a variety of data that China's forests absorb approximately 1.11 billion tonnes of carbon annually, nearly 50% of Chinese anthropogenic emissions during the same period **[5.9]**, increasing confidence in the Chinese Government that the ongoing afforestation initiative will play a key role in achieving the net-zero emissions target by 2060, announced in 2020 by the Chinese President Xi Jinping.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1]: Head of Earth Observation and Climate, *UK Space Agency,* (testimonial letter, 10/12/2020)

[5.2]: Centre for EO Instrumentation. (09/2017). *The Bilateral Carbon Mission Project, Final Report* (figure 4, page 3; page 17)

[5.3] President-elect of the European Commission (Mission Letter to Thierry Breton, Commissioner for Internal Market, 07/11/2020)

[5.4] The European Space Agency. (09/11/2019). *The next phase of Copernicus* (Report from the European Space Agency Earth Observation programme Board).

[5.5] BBC News: Europe's new space budget to enable CO2 mapping, https://www.bbc.co.uk/news/science-environment-50594831

[5.6] Project Leader, Scientific and Technical Support to Copernicus European Commission, *Joint Research Centre European Commission* (testimonial letter, 13/11/2020)

[5.7] The European Commission. (11/2017). *An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support capacity - Baseline Requirements, Model Components and Functional Architecture*. Pinty B., G. Janssens-Maenhout, M. Dowell, H. Zunker, T. Brunhes, P. Ciais, D. Dee, H. Denier van der Gon, H. Dolman, M. Drinkwater, R. Engelen, M.

Heimann, K. Holmlund, R. Husband, A. Kentarchos, Y. Meijer, **P. Palmer** and M. Scholze https://www.copernicus.eu/sites/default/files/2019-09/CO2_Red_Report_2017.pdf

[5.8] The European Commission. (06/2019). *An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity – Needs and high level requirements for in situ measurements*. Pinty B., P. Ciais, D. Dee, H. Dolman, M. Dowell, R. Engelen, K. Holmlund, G. Janssens-Maenhout, Y. Meijer, **P. Palmer**, M. Scholze, H. Denier van der Gon, M. https://www.copernicus.eu/sites/default/files/2019-09/CO2_Green_Report_2019.pdf

[5.9] National Centre for Remote Sensing, *Chinese Ministry of Science and Technology,* (testimonial letter, 8/12/2020. Letter written in Mandarin)