EVALUATION OF NERC CENTRES 2020: NATIONAL CENTRE FOR EARTH OBSERVATION EVIDENCE SUBMISSION

Submitted February 2020

1. List of research outputs

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	A new top-down approach for directly estimating biomass burning emissions and fuel consumption rates and totals from geostationary satellite fire radiative power (FRP)	2018	Remote Sensing of Environment	10.1016/j.rse.2017.12.016
D - Journal article	Acceleration of global N2O emissions seen from two decades of atmospheric inversion	2019	Nature Climate Change	10.1038/s41558-019-0613-7
D - Journal article	Accounting for model error in strong-constraint 4DVar data assimilation	2017	Quarterly Journal of the Royal Meteorological Society	10.1002/qj.2996
D - Journal article	Achieving Climate Change Absolute Accuracy in Orbit	2013	Bulletin of the American Meteorological Society	10.1175/BAMS-D-12-00149.1
D - Journal article	Amazon forests maintain consistent canopy structure and greenness during the dry season	2014	Nature	10.1038/nature13006
D - Journal article	Amplified surface temperature response of cold, deep lakes to inter-annual air temperature variability	2017	Scientific Reports	10.1038/s41598-017-04058-0
D - Journal article	An increase in methane emissions from tropical Africa between 2010 and 2016 inferred from satellite data	2019	Atmospheric Chemistry and Physics	10.5194/acp-2019-477
D - Journal article	Atmospheric CH4 and CO2 enhancements and biomass burning emission ratios derived from satellite observations of the 2015 Indonesian fire plumes	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-10111-2016
D - Journal article	Atmospheric observations show accurate reporting and little growth in India's methane emissions	2017	Nature Communications	10.1038/s41467-017-00994-7
D - Journal article	Changes in global net radiative imbalance 1985-2012	2014	Geophysical Research Letters	10.1002/2014GL060962
D - Journal article	Combining satellite observations and reanalysis energy transports to estimate global net surface energy fluxes 1985-2012.	2015	Journal of Geophysical Research	10.1002/2015JD023264
D - Journal article	Consistent regional fluxes of CH4 and CO2 inferred from GOSAT proxy XCH4 : XCO2retrievals, 2010–2014	2017	Atmospheric Chemistry and Physics	10.5194/acp-17-4781-2017
D - Journal article	Critical Southern Ocean climate model biases traced to atmospheric model cloud errors	2018	Nature Communications	10.1038/s41467-018-05634-2
D - Journal article	Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem.	2016	Journal of Geophysical Research	10.1002/2015JC011496
D - Journal article	Decoupled Freshwater Transport and Meridional Overturning in the South Atlantic	2019	Geophysical Research Letters	10.1029/2018GL081328
D - Journal article	Defining pyromes and global syndromes of fire regimes	2013	Proceedings of the National Academy of Sciences	10.1073/pnas.1211466110
D - Journal article	Delay in recovery of the Antarctic ozone hole from unexpected CFC-11 emissions	2016	Nature Communications	10.1038/s41467-019-13717-x

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	Development, Production and Evaluation of Aerosol Climate Data Records from European Satellite Observations (Aerosol_cci)	2016	Remote sensing of Environment	10.3390/rs8050421
D - Journal article	Direct retrieval of canopy gap probability using airborne waveform lidar	2013	Remote Sensing of Environment	10.1016/j.rse.2013.02.021
D - Journal article	Efficiency of short-lived halogens at influencing climate through depletion of stratospheric ozone	2015	Nature Geoscience	10.1038/ngeo2363
D - Journal article	Efficient emulation of radiative transfer codes using Gaussian processes and application to land surface parameter inferences	2016	Remote Sensing of Environment	10.3390/rs8020119
D - Journal article	Estimates of European uptake of CO2 inferred from GOSAT XCO2 retrievals: sensitivity to measurement bias inside and outside Europe	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-1289-2016
D - Journal article	Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data	2015	Atmospheric Chemistry and Physics	10.5194/acp-15-7049-2015
D - Journal article	Estimating urban Above Ground Biomass with multi-scale LiDAR	2018	Carbon Balance and Management	10.1186/s13021-018-0098-0
D - Journal article	Evaluating tropical phytoplankton phenology metrics using contemporary tools	2019	Scientific Reports	10.1038/s41598-018-37370-4
D - Journal article	Evaluating year-to-year anomalies in tropical wetland methane emissions using satellite CH4 observations	2018	Remote sensing of Environment	10.1016/j.rse.2018.02.011
D - Journal article	Evaluation of climate-related carbon turnover processes in global vegetation models for boreal and temperate forests	2017	Global Change Biology	10.1111/gcb.13660
D - Journal article	Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997	2016	Scientific Reports	10.1038/srep26886
D - Journal article	First observations of triple-frequency radar Doppler spectra in snowfall: Interpretation and applications	2016	Geophysical Research Letters	10.1002/2015GL067618
D - Journal article	Frequency of extreme Sahelian storms tripled since 1982 in satellite observations	2017	Nature	10.1038/NATURE22069
D - Journal article	Global height-resolved methane retrievals from the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp	2017	Atmospheric Measurement Techniques	10.5194/amt-10-4135-2017
D - Journal article	Global land surface temperature from the Along-Track Scanning Radiometers	2019	Remote sensing of Environment	10.1002/2017JD027161
D - Journal article	Growth in stratospheric chlorine from short-lived chemicals not controlled by the Montreal Protocol	2015	Geophysical Research Letters	10.1002/2015GL063783
D - Journal article	Hyperspectral remote sensing of foliar nitrogen content	2013	Proceedings of the National Academy of Science	10.1073/pnas.1210196109
D - Journal article	Impact of missing data on the estimation of ecological indicators from satellite ocean-colour time-series	2014	Remote Sensing of Environment	10.1016/j.rse.2014.05.016
D - Journal article	Intralake heterogeneity of thermal responses to climate change: a study of large northern hemisphere lakes	2018	Journal of Geophysical Research	10.1002/2017JD027661

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D - Journal article	Limited contribution of permafrost carbon to methane release from thawing peatlands	2017	Nature Climate Change	10.1038/nclimate3328
D - Journal article	Magnitude, spatial distribution and uncertainty of forest biomass stocks in Mexico	2016	Remote Sensing of Environment	10.1016/j.rse.2016.06.004
D - Journal article	Mapping local and global variability in plant trait distributions	2017	Proceedings of the National Academy of Science	10.1073/pnas.1708984114
D - Journal article	Mapping major land cover types and retrieving the age of secondary forests in the Brazilian Amazon by combining single-date optical and radar remote sensing data	2017	Remote Sensing of Environment	10.1016/j.rse.2017.03.016
D - Journal article	Modeling soil moisture-precipitation feedback in the Sahel: Importance of spatial scale versus convective parameterization	2013	Geophysical Research Letters	10.1002/2013GL058511
D - Journal article	Modeling stomatal conductance in the earth system: linking leaf water-use efficiency and water transport along the soil–plant–atmosphere continuum	2014	Geoscientific Model Development	10.5194/gmd-7-2193-2014
D - Journal article	Monsoon oscillations regulate fertility of the Red Sea	2015	Geophysical Research Letters	10.1002/2014GL062882
D - Journal article	Net carbon emissions from African land biosphere dominate pan-tropical atmospheric CO2 signal	2019	Nature Communications	10.1038/s41467-019-11097-w
D - Journal article	New Tropical Peatland Gas and Particulate Emissions Factors Indicate 2015 Indonesian Fires Released Far More Particulate Matter (but Less Methane) than Current Inventories Imply	2018	Remote Sensing of Environment	10.3390/rs10040495
D - Journal article	Non-destructive estimates of above-ground biomass using terrestrial laser scanning	2015	Methods in Ecology and Evolution	10.1111/2041-210X.12301
D - Journal article	Observational evidence for cloud cover enhancement over western European forests	2017	Nature Communications	10.1038/NCOMMS14065
D - Journal article	Observed and simulated precipitation responses in wet and dry regions 1850-2100.	2013	Environmental Research Letters	10.1088/1748-9326/8/3/034002
D - Journal article	Optical properties of Saharan dust aerosol and contribution from the coarse mode as measured during the Fennec 2011 aircraft campaign	2013	Atmospheric Chemistry and Physics	10.5194/acp-13-303-2013
D - Journal article	Persistent reduced ecosystem respiration after insect disturbance in high elevation forests	2013	Ecology Letters	10.1111/ele.12097
D - Journal article	Phytoplankton phenology indices in coral reef ecosystems: Application to ocean-color observations in the Red Sea	2015	Remote Sensing of Environment	10.1016/j.rse.2015.01.019
D - Journal article	Pre-rain green-up is ubiquitous across southern tropical Africa: implications for temporal niche separation and model representation	2017	New Phytologist	10.1111/nph.14262
D - Journal article	Previsual symptoms of Xylella fastidiosa infection revealed in spectral plant-trait alterations	2018	Nature Plants	10.1038/s41477-018-0189-7
D - Journal article	Quantifying the ozone and UV benefits already achieved by the Montreal Protocol	2015	Nature Communications	10.1038/ncomms8233

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	Recent northern hemisphere stratospheric HCl increase due to atmospheric circulation changes	2014	Nature	10.1038/nature13857
D - Journal article	Remote sensing of chlorophyll-a as a measure of cyanobacterial biomass in Lake Bogoria, a hypertrophic, saline-alkaline, flamingo lake, using Landsat ETM+	2013	Remote Sensing of Environment	10.1016/j.rse.2013.03.024
D - Journal article	Representation of model error in a convective-scale ensemble prediction system	2014	Non Linear Processes in Geophysics	10.5194/npg-21-19-2014
D - Journal article	Retrievals of the far infrared surface emissivity over the Greenland Plateau using the Tropospheric Fourier Transform Spectrometer (TAFTS)	2017	Journal of Geophysical Research	10.1002/2017JD027328
D - Journal article	Sampling uncertainty in gridded sea surface temperature products and Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage (GAC) data	2016	Remote Sensing of Environment	10.1016/j.rse.2016.02.021
D - Journal article	Satellite observations of stratospheric carbonyl fluoride	2014	Atmospheric Chemistry and Physics	10.5194/acp-14-11915-2014
D - Journal article	Satellite remote sensing of phytoplankton phenology in Lake Balaton using 10 years of MERIS observations	2015	Remote sensing of Environment	10.1016/j.rse.2014.11.021
D - Journal article	Satellite-based time-series of sea-surface temperature since 1981 for climate applications	2019	Scientific Data	10.1038/s41597-019-0236-x
D - Journal article	Sensing coral reef connectivity pathways from space	2017	Scientific Reports	10.1038/s41598-017-08729-w
D - Journal article	Size-partitioned phytoplankton carbon and carbon-to-chlorophyll ratio from ocean-colour by an absorption-based bio-optical algorithm.	2017	Remote Sensing of Environment	10.1016/j.rse.2017.02.015
D - Journal article	Strong constraint on modelled global carbon uptake using solar-induced chlorophyll fluorescence data	2018	Scientific Reports	10.1038/s41598-018-20024-w
D - Journal article	Strong constraints on aerosol-cloud interactions from volcanic eruptions	2017	Nature	10.1038/nature22974
D - Journal article	Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump	2016	Nature Geoscience	10.1038/ngeo2818
D - Journal article	The 30-year TAMSAT African Rainfall Climatology And Time-series (TARCAT) Dataset	2014	Journal of Geophysical Research	10.1002/2014JD021927
D - Journal article	The Community Cloud retrieval for CLimate (CC4CL). Part II: The optimal estimation approach	2018	Atmospheric Measurement Techniques	10.5194/amt-2017-333
D - Journal article	The decadal state of the terrestrial carbon cycle: global retrievals of terrestrial carbon allocation, pools and residence times	2016	Proceedings of the National Academy of Science	10.1073/pnas.1515160113
D - Journal article	The equivalent-weights particle filter in a high-dimensional system	2015	Royal Meteorological Society	10.1002/qj.2370
D - Journal article	The interaction between Faraday rotation and system effects in synthetic aperture radar measurements of backscatter and biomass	2015	Institute of Electrical and Electronics Engineers	10.1109/TGRS.2015.2395138

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	The open-ocean missing backscattering is in the structural complexity of particles	2018	Nature Communications	10.1038/s41467-018-07814-6
D - Journal article	The vertical distribution of volcanic SO2 plumes measured by IASI	2016	Atmospheric Chemistry and Physics	10.5194/acp-16-4343-2016
D - Journal article	Tropospheric ozone and ozone profiles retrieved from GOME-2 and their validation	2015	Atmospheric Measurement Techniques	10.5194/amt-8-385-2015
D - Journal article	Tropospheric Ozone Assessment Report: Present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation.	2018	Elementa	10.1525/elementa.291
D - Journal article	Underestimation of global photosynthesis in Earth System Models due to representation of vegetation structure	2019	Global Geochemical Cycles	10.1029/2018GB006135
D - Journal article	Understanding the effect of disturbance from selective felling on the carbon dynamics of a managed woodland by combining observations with model predictions	2017	Journal of Geopyhsical Research	10.1002/2017JG003760
D - Journal article	Unveiling aerosol-cloud interactions - Part 1: Cloud contamination in satellite products enhances the aerosol indirect forcing estimate	2017	Atmospheric Chemistry and Physics	10.5194/acp-17-13151-2017
D - Journal article	Variability of fire carbon emissions in equatorial Asia and its nonlinear sensitivity to El Nino	2016	Geophysical Research Letters	10.1002/2016GL070971
D - Journal article	Water-use efficiency and transpiration across European forests during the Anthropocene	2015	Nature Climate Change	10.1038/NCLIMATE2614
D - Journal article	Worldwide alteration of lake mixing regimes in response to climate change	2019	Nature Geoscience	10.1038/s41561-019-0322-x

2. Impact case studies

Centre: National Centre for Earth Observation

Title of case study: Observing forest carbon from space: UK economic and worldwide societal impacts

1. Summary of the impact

Forest carbon stocks and their changes, particularly in the tropics, are crucial in understanding and adapting to climate change. NCEO scientists at Sheffield and UCL have pioneered new forest observation techniques: P-band spaceborne radar and terrestrial laser scanning. This has led to a highly innovative satellite mission, BIOMASS, which will be built under a £192M contract awarded in 2016 to Airbus Defence and Space (UK) by the European Space Agency (ESA). Applications of NCEO forest research have further resulted in significant contributions to international guidelines and new protocols on tree mensuration. This progress has been mirrored by the success of a travelling exhibition illuminated by the beauty of tree scanning.

2. Underpinning Centre activities

Quantitative observation of forest above-ground biomass and its losses from deforestation or degradation and gains from forest growth has been a primary science driver for NCEO since its inception, continuing research in its precursor Centre for Terrestrial Carbon Dynamics (CTCD). Quegan (NCEO-Sheffield) has been a prime instigator of this research, providing leadership of multi-disciplinary observation and modelling teams in CTCD and then the Carbon Theme in NCEO from 2008 to 2014, together with key technical contributions. Both skill sets were crucial in the impact, as recognised in his NERC Award for Economic Impact in 2018.

A major element of Quegan's work has been leadership of the international research team that provided the scientific, technical, environmental and societal case for BIOMASS, whose primary objective is to radically improve our understanding of the worldwide distribution of forest carbon stocks and their changes, particularly in the tropics. A radical innovation of BIOMASS is its first spaceborne use of the P-band (70 cm) wavelength with its critical high sensitivity to biomass [1, 2]. Quegan was joint proposer of the mission in 2005 and has chaired the Mission Advisory Group since 2009.

NCEO national capability funding and discovery science grants supported Quegan's programme addressing crucial scientific issues for the mission. Particularly important was his demonstration with Rogers (NCEO-Sheffield) that ionospheric effects could be prevented from destroying the biomass information in the signal [3]; without this the mission would have failed at the first selection step. With Lomas (NCEO-Sheffield) he solved the longstanding problem of how to relate system errors to biomass errors, which allowed ESA to specify the instrument tolerances that industry has to work to [4]. His world-leading research on instrument calibration [5] and ionospheric correction produced methods that Airbus has embodied in the BIOMASS ground processor.

A fundamental contributor to the selection of BIOMASS by ESA in 2013 against extremely strong competition was Quegan's training in leading highly multi-disciplinary, multi-institutional teams gained in CTCD and NCEO. This allowed him to combine the diverse talents of the BIOMASS team (including NCEO colleagues Williams, Carreiras and Disney from Edinburgh, Sheffield and UCL respectively) to overcome the many scientific and technical challenges facing the mission. It also made him ideally placed to lead BIOMASS through the rigorous two-step 8-year selection procedure. This included his leading production of two comprehensive reports [6] that were reviewed by science panels and the EO community, and defence of the mission under intense, wide-ranging questioning in two three-day meetings.

Crucial in validating and calibrating BIOMASS products are precise measurements of biomass at field sites, which also give insight into structural factors affecting the satellite estimates. Disney (NCEO-UCL) pioneered the use of terrestrial laser scanning (TLS) to provide the necessary detailed 3D measurements of tree structure and biomass with accuracy essentially independent of tree size. A key step was then to show that TLS point cloud models can drastically improve estimates of biomass at site level [7, 8].

In its national public good (NERC NPG) work, NCEO operates, with Defra and UK Space Agency, a joint Office co-ordinating UK inputs to the Group on Earth Observations (GEO) and the Committee on Earth Observation Satellites (CEOS). Forests were identified as a key UK interest because of their relevance to government climate investments and the available UK expertise. The Office contracted Jim Penman (UCL) to bring our experts into the Global Forests Observation Initiative (GFOI) for forest carbon estimation (Quegan, Balzter) alongside other world-leading experts. The Office also supported involvement in CEOS WG Cal/Val to improve biomass validation worldwide: Disney was invited to co-chair the CEOS sub-panel on calibration and validation of satellite biomass.

References to the underpinning work (relevant NCEO staff highlighted)

1. **S. Quegan**, T. Le Toan, J. Chave, J. Dall, **J.-F. Exbrayat, M. Lomas,** M. Mariotti D'Alessandro, D. H. T. Minh, P. Paillou, K. Papathanassiou, F. Rocca, S. Saatchi, K. Scipal, H. Shugart, T. L. Smallman, M. J. Soja, S. Tebaldini, L. Ulander, L. Villard and **M. Williams** (2019). The European Space Agency BIOMASS mission: measuring forest above-ground biomass from space, *Remote Sensing of Environment*, **227**, 44-60, doi.org/10.1016/j.rse.2019.03.032
2. Le Toan T, **Quegan S,** Davidson MWJ, **Balzter H,** Paillou P, Papathanassiou K, Plummer S, Rocca F, Saatchi S, Shugart H, Ulander L (2011) The BIOMASS mission: Mapping global forest biomass to better understand the terrestrial carbon cycle. Remote Sensing of Environment, 115 (11), pp. 2850-2860 doi.org/10.1016/j.rse.2011.03.020
3. **Rogers, N.C., Quegan, S.,** Kim, J.S. & Papathanassiou, K.P. (2013). Impacts of ionospheric scintillation on the BIOMASS P-band satellite SAR. IEEE Trans. Geosci. Remote Sensing, 52, no. 1, doi.org/10.1109/TGRS.2013.2255880.
4. **Quegan, S**. and **Lomas, M. R.** (2015): The interaction between Faraday rotation and system effects in synthetic aperture radar measurements of backscatter and biomass, *IEEE Trans. Geosci. Remote Sensing*, **53**, no. 8, 4299-4312, doi.org/ 10.1109/TGRS.2015.2395138
5. Chen, J., **Quegan, S**. & Yin, X.J. (2011). Calibration of spaceborne linearly polarized low frequency SAR using polarimetric selective radar calibrators. Progress in Electromagnetic Research, 114, 89-111.
6. ESA (2012). *Report for Mission Selection: Biomass*. Science authors: **Quegan, S**., Le Toan T., Chave, J., Dall, J., Perrera, A. Papathanassiou, K., Rocca, F., Saatchi, S., Scipal, K., Shugart, H., Ulander, L. and **Williams, M.,** ESA SP 1324/1 (3 vol. series), European Space Agency, Noordwijk, the Netherlands.
7. Calders, K., Newnham, G., Burt, A., Murphy, S., Raumonen, P., Herold, M., Culvenor, D., Avitabile, V., **Disney, M. I.**, Armston, J. and Kaasalainen, M. (2014) Non-destructive estimates of above-ground biomass using terrestrial laser scanning, Methods in Ecol. and Evolution, doi.org/10.1111/2041-210X.12301.
8. **Disney, M. I.**, Boni Vicari, M., Calders, K., Burt, A., Lewis, S., Raumonen, P. and **Wilkes, P.** (2018) Weighing trees with lasers: advances, challenges and opportunities, Royal Society Interface Focus 8 (2), doi.org/10.1098/rsfs.2017.0048.

4. Details of the impact

NCEO research, leadership and international engagement, arising from its capability in physical forest observations, have had a range of significant impacts. A primary reason is the scientific and technological value of the work due to the truly global interest in observations of forest carbon and structure. This has led to economic impact to Airbus Defence and Space (UK), which is building the BIOMASS satellite, and societal/public impact through international export of knowledge.

The work of Quegan and colleagues produced a compelling scientific case for the BIOMASS mission and detailed technical requirements for the BIOMASS instrument (**Evidence Source A**), sharing knowledge of the science and technologies underpinning the mission through publications, presentations and working through ESA-enabled transfer of knowledge to industry. The successful exposition of the mission concept, led by Quegan, was fundamental in providing the opportunity for Airbus UK, with their strengths in radar missions, to win the €229m (£192m) ESA contract to build the satellite (**Evidence Source B**), which was signed in 2016.

A number of Quegan's contributions were particularly important for Airbus's successful bid and contract development. Crucial to mission selection was his demonstration that ionospheric effects could be corrected or reduced to a negligible level, which was fundamental in selecting the mission orbit (Research Reference [3]). Working with other scientists on the BIOMASS Mission Advisory Group, Quegan developed the methods to correct ionospheric Faraday rotation and scintillation in the ground processor for the Airbus contract, and provided error budgets for these corrections (**Evidence Source C, D**). Quegan's comprehensive resolution of how instrument errors translate into biomass errors specified the tolerances that Airbus must work to in building the instrument, with significant cost implications (Research Reference [3]). In addition, he developed the algorithms that Airbus will use in the ground processor to calibrate the BIOMASS instrument using a ground-based transponder, and demonstrated that Airbus's original plan to place the transponder near the magnetic equator to reduce ionospheric contamination was likely to lead to larger errors than a mid-latitude site (**Evidence Source E**). This led Airbus to use a site in Australia, with significant logistical and financial benefits. In recognition of his contribution to Airbus winning the prime contract for BIOMASS, NERC awarded Quegan its 2018 Economic Impact Award **(Evidence Source F).**

The work on forest carbon for the mission had additional impacts at international level. The most important element was the work of Penman (supported by NERC National Public Good), Quegan and Balzter (NCEO-Leicester) in the Global Forest Observations Initiative (GFOI). GFOI is a GEO flagship partnership of countries and institutions that collaboratively assist developing countries in estimating forest carbon for their national reporting, e.g., for REDD+ financial support or to meet reporting obligations to the United Nations Framework Convention on Climate Change (UNFCCC). Penman chaired and was a lead author of the Advisory Group for the development of the methods and guidance document (MGD version 2 or MGD2) for estimation of emissions and removals of greenhouse gases. Quegan and Balzter (NCEO-Leicester) were co-authors. **(Evidence Source G).**

The impact of MGD2 has been significant **(Evidence Source H)**. It has been downloaded over 9000 times, which indicates comprehensive global coverage, given the highly specific nature of the content and its audience. The MGD content has been made more accessible and user-friendly through the online platform REDDcompass developed under Australian funding. REDDcompass has over 300 users per month from over 50 different countries who all utilize the MGD content; 60% are return visitors. It has been endorsed by the World Bank administered Forest Carbon Partnership Facility (FCPF) which includes 47 developing countries across Africa, Latin America and the Asia Pacific, including 4 countries who have now signed to enter the FCPF Carbon Fund. "The FCPF has benefited significantly from the work of GFOI, including through the use of GFOI's Methods and Guidance Documentation (MGD)" **(Evidence Source I)**.

The impact has also reached into international guidelines for nationally determined contributions (NDCs) to UNFCCC for both the MGD2 and ground-based terrestrial laser scanning (TLS). The MGD was directly referenced 14 times in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories **(Evidence Source J)**.The TLS approach is also recommended in the Guidelines as a significant new technology providing non-destructive and highly detailed tree measurements independent of the tree size and shape that are otherwise only available from destructive methods (Research Reference [8]). Aboveground biomass calculated from TLS data is independent of allometry and has quantifiable accuracy; many trees can be efficiently sampled and measured. This provides fundamental data to test existing allometric models or develop new ones for national greenhouse gas inventories.

TLS has had significant impact because of its adoption within the new international CEOS calibration/validation protocol for best practice in situ biomass measurements to calibrate forest height and biomass estimates from satellite and aircraft missions (**Evidence source K**). These include the NASA GEDI and the NASA/India NISAR forest structure missions, as well as BIOMASS. Disney has already been engaged by ESA and NASA to make TLS measurements in tropical forests in Gabon and Californian redwoods in support of these three missions.

TLS has much wider application, e.g., in the context of urban green space, which has large positive health, wellbeing and economic benefits, but is currently undervalued. NCEO-UCL began to use TLS for measuring carbon in 'urban forests'. This led to work with the UK charity Trees For Cities (TfC) to support their aim of increasing trees in underserved urban areas in the UK and internationally (they recently planted their millionth tree in UK cities). The NCEO-UCL work has provided new open tools to allow TfC to track the development of their tree planting projects, helping to demonstrate the effectiveness of donor funding **(Evidence Source L).**

Finally, this pattern of UK benefit leading to international export of knowledge has proved just as valid in public engagement where the focus has been to communicate the importance of forest carbon and EO in addressing current knowledge gaps and influencing public perceptions of tropical forests. Disney was invited to include his TLS 3D measurement of Amazon rainforests in a major exhibition initially at the V & A museum in London. The curator commented that Disney's work changed their approach to the exhibition, shifting their focus to show how a deeper understanding of the natural environment can have vast consequences. "We wanted to show our visitors that by changing the way forests are measured, we can change their value, and may ultimately contribute to their preservation. In short, how a laser scan of a tree could help save the world." The exhibition, entitled "The Future Starts Here" received approximately 140,000 paying visitors in its month run in 2018. Its success in London led to international export, showing in Stockholm in 2019 and it is booked to appear in Hamburg in 2020 (**Evidence Source M**).

3. **Sources to corroborate the impact**

Evidence Source A: Biomass and SMOS Mission Manager, Directorate of Earth Observation Programmes

Evidence Source B: Letter from BIOMASS Project Manager at Airbus UK

Evidence Source C: Rogers, N. C. and Quegan, S. (2014). The accuracy of Faraday Rotation estimation in satellite Synthetic Aperture Radar images, *IEEE Trans. Geosci. Remote Sensing,* **52**, no. 8, 4799 – 4807, doi.org/10.1109/TGRS.2013.2284635. This paper defines the Faraday correction algorithm in the Airbus ground processor.

Evidence Source D: J.-S. Kim, K. Papathanassiou, R. Scheiber, S. Quegan (2015). Correction of ionospheric scintillation induced distortions on polarimetric SAR data, *IEEE Trans. Geosci. Remote Sensing*, doi.org/10.1109/TGRS.2015.2431856. This paper defines the ionospheric scintillation correction in the Airbus ground processor.

Evidence Source E: S. Quegan, M.Lomas, K.P. Papathanassiou, J-S Kim, S. Tebaldini, D. Giudici, M. Scagliola, P. Guccione, J. Dall, P. Dubois-Fernandez & P. Paillou, Report to ESA/ESTEC on Contract No. 4000116784/15/NL/CT: Consolidation of external Biomass calibration methodology, Supplement: S. Quegan and M. Lomas: Numerical Solutions of Sensor Errors for a PARCS system.

Evidence Source F: NERC Impact Awards 2018 Application Form. Weighing the world's forests from space: the ESA BIOMASS mission

Evidence Source G: GFOI 2016, Integration of remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests: Methods and Guidance from the Global Forest Observations Initiative, Edition 2.0, Food and Agriculture Organization, Rome. http://www.fao.org/gfoi/components/methods-and-guidance-documentation/en/

Evidence Source was H: Letter from GFOI Manager, FAO

Evidence Source was I: Letter of endorsement for GFOI from World Bank Forest Carbon Partnership Facility.

Evidence Source was J: Good Practice Guidelines to national Greenhouse Gas reporting IPCC GPG GHG reporting 2019 https://www.ipcc-nggip.iges.or.jp. For TLS, see vol 4, chapter 2 https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf

Evidence Source was K: Committee on Earth Observation Satellites (CEOS) sub-panel on calibration and validation of satellite biomass, https://lpvs.gsfc.nasa.gov/Biomass/AGB_home.html)

Evidence Source was L: Letter from TfC Impact Coordinator, Trees for Cities

Evidence Source was M: Letter from Curator of Contemporary Architecture and Urbanism, Curator of the Future Starts Here Exhibition, Victoria & Albert Museum, London.

Centre: National Centre for Earth Observation

Title of case study: Carbon Monitoring with EO data

1. Summary of the impact

NCEO's work in measuring and monitoring atmospheric carbon dioxide (CO_2) and methane (CH_4) using satellites, and inferring the responsible surface fluxes, has made a significant contribution towards underpinning the global response to the Paris Agreement to reduce carbon emissions and actively undertake a global carbon stocktake. NCEO groups at Leicester and Edinburgh have used satellite measurements of CO_2 and CH_4 to make substantial contributions to basic science in the context of understanding the global carbon cycle. As a consequence, NCEO studies have defined requirements for satellite mission concepts to quantify national greenhouse gas fluxes. The work has enabled the UK Space Agency (UKSA) to develop a business case to invest in the MicroCarb satellite mission and for the European Commission, working with the European Space Agency (ESA), to develop the CO_2 Copernicus Service and to launch the first satellite. The work has also had an influence at a global level by working with international colleagues in the Committee on Earth Observation Satellites (CEOS) to design a virtual constellation of satellites drawing together the resources of the world's space agencies to observe greenhouse gases.

2. Underpinning Centre activities

Scientists at NCEO-Leicester and NCEO-Edinburgh, led by Boesch and Palmer, respectively, are world leaders in studying space-borne measurements of atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) and relating those to surface fluxes. Both groups have, for more than a decade, played a key role in interpreting data from the Japanese Greenhouse gases Observing SATellite (GOSAT, launched in 2009) and NASA Orbiting Carbon Observatory (OCO-2, launched in 2014). This joint research by observational and modelling groups has been a consistent element of the NCEO research programme since its inception, supporting the fundamental scientific development of retrieving CO_2 and CH_4 from space-based observations and the subsequent scientific analysis methods of these data, used by today's satellite greenhouse gas (GHG) missions. The key steps in the research were the demonstration of accurate retrievals of CH_4 and CO_2 from spaceborne sensors and of the feasibility of robustly estimating surface fluxes from space-borne data using atmospheric inverse methods.

Boesch's NCEO team, with collaborators from NASA JPL, have developed and demonstrated the application of optimal estimation techniques to CO_2 retrievals from satellites [e.g. 1]. 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 [2]. 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 greenhouse gases [3].

Palmer and his team have played a key role in assessing the ability of these satellite data, working initially with GOSAT data but more recently with OCO-2 data, to infer robust regional fluxes of CO_2 and CH_4. In his earliest work, he 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) [4]. 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 inverse methods [5]. Retrieval groups (including NCEO) later pioneered the co-retrieval of CH_4 and CO_2 in nearby spectral fitting windows with the underlying assumption that taking the ratio reduced common errors. Palmer pioneered 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 [6]. In 2019, he led the analysis of CO_2 fluxes from GOSAT and OCO-2. He produced the first multi-year regional CO_2 fluxes, highlighting the unprecedented consistency between fluxes inferred by different space-based data and by different atmospheric models. The work also highlighted gaps in our knowledge of tropical land fluxes of CO_2 which had until then been inferred from sparse and distant in situ constraints [7]. The study attracted substantial interest from scientists and the media. Broadly speaking, this work provides confidence in our ability to use these data to help support global stocktakes. Leadership in the NERC GAUGE project has helped to deliver the first measurement-led estimates of the UK carbon budget, and to propose a blueprint for a nationwide integrated measurement programme.

The research excellence of the NCEO groups is reflected by their membership of international science and mission teams. As an example, Boesch is a member by invitation of the Copernicus Anthropogenic CO2 Monitoring mission (CO2M) in which he directly provides scientific advice to ESA for the development of CO2M. Palmer sits by invitation on the companion European Commission (EC) CO2 Task Force for CO2M that 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.

The cumulative body of work from these two groups has directly contributed to long-term monitoring programmes such as the ESA's Climate Change Initiative, ESA CCI, (http://www.esa-ghg-cci.org/) and the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/#!/home). Boesch and Palmer have contributed, together with other world-leading experts, to the efforts of the CEOS Atmospheric Composition Virtual Constellation group (AC-VC) in providing guidance towards an international constellation architecture for monitoring greenhouse gases from space [8]. The UK GEO/CEOS Office support the membership of Palmer in the CEOS Carbon WG.

3. References to the underpinning work (NCEO investigators are in bold)

[1] **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

[2] **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. 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

[3] 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.

[4] **Feng L., Palmer P. I., Boesch H**., and Dance S., Estimating surface CO_2 fluxes from space-borne CO_2dry air mole fraction observations using an ensemble Kalman Filter, *Atmos. Chem. Phys*., 2009

[5] 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

[6] **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.: 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, https://doi.org/10.5194/acp-17-4781-2017, 2017.

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

[8] A Constellation Architecture for monitoring Carbon Dioxide and Methane from Space, White paper by the CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team, 2018, available from
http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf

4. Details of the impact

NCEO researchers have helped to demonstrate, working within the international community, that satellite observations of GHGs have now reached a sufficiently high level of maturity to provide a powerful constraint on regional carbon fluxes, and therefore can now play a critical role in an emission monitoring and verification support capacity.

This far-reaching and global impact of NCEO research is a consequence of the commitment by UK, European and many international governments to support the goals of the 2015 Paris Agreement to reduce carbon emissions to limit global warming "to well below 2 degrees". Methodologies to measure carbon emissions and sinks are enshrined in international agreements and countries are encouraged to develop independent sources of information to monitor the effectiveness of policy measures. The UK is the first major economy in the world to pass laws to reach net zero GHG emissions by 2050.

Based on an extensive NCEO-led study in collaboration with UK industry (funded by UKSA), NCEO demonstrated to the UKSA that the UK has the technical and scientific capability to contribute to and exploit a CO_2 mission. This work led to the UKSA endorsing a business case committing to the development of a space based GHG monitoring capability as a high priority for the UK. As an immediate step the UK government invested £10M to collaborate with the French Space Agency CNES on the development of the MicroCarb satellite mission. MicroCarb, due to be launched in 2021, will be the first dedicated European CO_2 satellite, paving the way towards an operational space-based system and demonstrating the UK's commitment to tackling climate change by integrating UK science and engineering communities. The UKSA financial investment is supporting the UK space industry by helping to secure jobs and know-how. [**Evidence Source A, B, C**].

The work of NCEO has resulted in decisions far beyond the immediate collaboration on MicroCarb. The European Space Agency, at its November 2019 Space 19+ Ministerial Council, was given the go ahead by its Member States, including the UK, to develop an operational CO_2 mission and to launch the first satellite under the auspices of the European Copernicus programme [**Evidence Source D, E**]. This CO_2 mission is one of six high priority missions of the Copernicus programme funded under an envelope of €1.8bn [**Evidence Source F**]. The UK increased its contribution by 15% to the European Space Agency's Earth Observation programme. 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 [**Evidence Source A**].

The CO2M mission will carry a near-infrared and shortwave-infrared spectrometer to measure atmospheric carbon dioxide produced by human activity. These measurements will help reduce current uncertainties in estimates of emissions of CO_2 from the combustion of fossil fuel at national and regional scales. This will provide a unique and independent source of information to assess the effectiveness of policy measures, and to track their impact towards decarbonising Europe and meeting national emission reduction targets.

The cumulative scientific work of NCEO led by Boesch and Palmer has been influential in confirming the feasibility of CO2M and setting requirements [**Evidence Source G, H**]. Building on extensive work by Boesch on earlier missions [**Evidence Source I, J]**, Boesch has helped to advance the fundamental methods on CO_2 and CH_4 remote sensing to the level required for CO2M. Through NCEO support and NCEO-lead ESA projects, Boesch's NCEO team has provided key insights into instrumental and retrieval uncertainties and how they impact the mission performance. This information described by the ESA Mission Requirements Document (MRD) formulates and justifies the specific mission requirements for CO2M, and directly influences the designs proposed by industry. Boesch, as a member of the international CO2M Mission Advisory Group, drafted, reviewed and endorsed the MRD [**Evidence Source K, G**]. The work of Palmer's NCEO group has significantly advanced our ability to use satellite observations of CO_2 and CH_4 to develop carbon cycle knowledge, by combining cutting-edge models and data within a Bayesian framework. These advancements led to his invited involvement in the European Commission CO2 Task Force [**Evidence Source H**] to provide guidance and requirements in expert reports [**Evidence Source L, M**] for the development operational European measurement and verification system, including the CO2M satellite data, and to ensure the system meets the requirements to infer actionable information on fossil fuel CO_2 emissions.

The work carried out by NCEO has given UK and European funders the confidence to invest in this system which will provide a unique and independent source of information for policy makers to assess the effectiveness of policy measures and to track their impact towards the goals of the Paris Agreement, including the quinquennial global carbon stocktakes and the intervening national emission reduction targets.

5. Sources to corroborate the impact

Evidence Source A: Letter from Head of Earth Observation and Climate, UK Space Agency

Evidence Source B: REDACTED

Evidence Source C: Final Report, UKSA Bilateral Carbon Mission Project

Evidence Source D: Mission Letter, President-elect of the European Commission to Commissioner for Internal Market: 'You should 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'

Evidence Source E: *Report from the European Space Agency Earth Observation programme Board: The next Generation Copernicus, ESA/PB-EO(2019)10, rev.2*

EVIDENCE F: BBC NEWS: EUROPE'S NEW SPACE BUDGET TO ENABLE CO2 MAPPING, HTTPS://WWW.BBC.CO.UK/NEWS/SCIENCE-ENVIRONMENT-50594831

Evidence Source G: Letter from CO2M Mission Scientist, Head of Atmospheric Section, European Space Agency

Evidence Source H: Letter from Project Leader, Scientific and Technical Support to Copernicus European Commission, Joint Research Centre European Commission

Evidence Source I: CarbonSat Mission Selection Report, available from https://esamultimedia.esa.int/docs/EarthObservation/SP1330-1_CarbonSat.pdf

Evidence Source J: Algorithm Theoretical Basis Documents ATBD for the NASA OCO-2 mission, available from https://docserver.gesdisc.eosdis.nasa.gov/public/project/OCO/OCO2_L2_ATBD.V6.pdf

Evidence Source K: Copernicus CO2 Monitoring Mission Requirements Document https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v2.0_Issued20190927.pdf

Evidence Source L: 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 (2017) An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support capacity - Baseline Requirements, Model Components and Functional Architecture, doi: 10.2760/39384, European Commission Joint Research Centre, EUR 28736 EN, available from https://www.copernicus.eu/sites/default/files/2019-09/CO2_Red_Report_2017.pdf

Evidence Source M: 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. Heimann, O. Juvyns, A. Kentarchos and H. Zunker (2019) An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity – Needs and high level requirements for in situ measurements, doi: 10.2760/182790, European Commission Joint Research Centre, EUR 29817 EN, available from https://www.copernicus.eu/sites/default/files/2019-09/CO2_Green_Report_2019.pdf

National Centre for Earth Observation – Environment Statement

1. Context, mission and strategy

The National Centre for Earth Observation (NCEO) carries out internationally acknowledged and peer-reviewed strategic research focussing on environmental science for Earth system challenges and its global impact as inspired and served by Earth Observation (EO) principally from instruments in space. Our 147 multi-disciplinary research staff and students produced 21 papers in the highest impact journals (Nature-group and PNAS; 27 including Scientific Data and Scientific Report). More than 15 of our staff participate in 17 international Mission/Science Advisory groups and Science teams that elaborate the science gain from individual satellite missions. In the evaluation period, we have provided the lead scientists for two ESA Earth Explorer missions (Biomass, Forum) as well as the Principal Investigators of two national instruments on international platforms ((A) ATSR, GERB). Our NERC research income was £34.33 million over the last five years with a total of £56.8 million in that time. Over 80% of NCEO papers are collaborative and more than 60% include collaboration with an international co-author.

1.1 Context

NCEO is just over ten years old, having been formed in 2008 from seven pre-existing small centres of excellence[1]; this is the first cross-centre NERC Evaluation in which it has participated. The current NCEO operation has a remit agreed by NERC Council in 2012/3 and re-affirmed in 2017. NERC Council advocated NCEO focus on holistic Earth system challenges in the areas of observation and interpretation of change; evaluation of models; exploring predictability and new observing methods. Underlying capabilities of NCEO are intended to be expertise in Earth system data sets and tools; data assimilation systems; data analytics.

NCEO is a distributed NERC research centre with primary capabilities shared between five scientific units and identified expert scientists elsewhere. The core groupings are based at the Universities of Leicester, Reading and Edinburgh, in Oxfordshire (Rutherford Appleton Laboratory and University of Oxford) and in London (Imperial College London, King's College London, University College London). The NCEO Director, Professor Remedios, is at the University of Leicester. NCEO senior scientists are at: the Universities of Leeds, Sheffield, Surrey and Swansea, Plymouth Marine Laboratory (PML) and UK Centre for Ecology and Hydrology. NCEO operates EO data facilities through CEDA (CEDA archive and JASMIN) and governs facilities: Field Spectroscopy Facility (FSF) at Edinburgh and NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) at PML. Each NCEO unit has its own significant specialisations, e.g., data assimilation for carbon cycle in Edinburgh or vegetation sensing in London. NCEO is multi-disciplinary, the chief traditional disciplines being physics, meteorology, geography and environmental sciences, marine sciences and maths.

NCEO is organised in divisions, each led by Divisional Directors, covering three broad scientific and infrastructure areas of capability: Data Assimilation; EO Data-Model Evaluation; and EO Instrumentation and Facilities. Within and across each area, there are particular foci, e.g. data assimilation into key models, climate data sets, evaluation of models, radiative transfer tools, aircraft instrumentation and data facilities.

1 Centre for observation of Air-Sea Interactions & Fluxes; Climate and Land Surface Systems Interaction Centre (CLASSIC); Centre for Observation and Modelling of Earthquakes and Tectonics (COMET); Centre for Polar Observation and Modelling (CPOM); Centre for Terrestrial Carbon Dynamics (CTCD); Data Assimilation Research Centre (DARC); Environmental Systems Science Centre (ESSC).

Environmental science challenges are integrated across divisions, allowing agility in response to a range of fascinating questions, for example our work on carbon includes data assimilation expertise for terrestrial, atmospheric (inversion) and oceanic carbon working with expert staff producing climate-quality greenhouse gas, ocean colour and above-ground biomass datasets.

Nationally, NCEO's long-term research provides long-term strategic delivery within its remit of EO and Earth system science. An important context is the major international EO dimension to national work. NERC science benefits hugely from being able to access and exploit international EO missions, particularly through the European Space Agency (ESA) and EUMETSAT which currently receive UK investments. Most recently in 2019, the UK agreed a €250 million contribution to EO on top of its C-MIN 2016 contribution of €50 million per annum, including a contribution to launch the next wave of innovative Copernicus satellites. We have an extensive compendium of approved missions in our science areas over the next 10 years.

1.2 Mission and Strategy

Our vision is "to be a globally outstanding UK scientific institution dedicated to leading EO research for Earth system science and its applications, encouraging, collaborating with, and building the EO community to serve science and society." Our research delivers transformational EO for key challenge areas such as global carbon, water cycles and climate monitoring.

Our centre encompasses a broad range of interests and systems for interrogating the Earth system globally and regionally, based on our science techniques and EO data. The essence of our strategy is to ensure that 1) NCEO focusses its research on science challenges which are recognised to be at the forefront of Earth system challenges and which have impact in the wider world. 2) NCEO science is at the cutting edge of real-world observations producing high-quality data, methods for fusing data with leading models and initiating new missions with novel outcomes; 3) NCEO staff work closely with public and private organisations wishing to take advantage of their capability and knowledge.

Given our vocation as a NERC research centre operating on decadal timescales, we meet the broad aims above by: a) collaborating in leading and informative publications (approx.150 per year); b) producing long-term, high quality data sets particularly for climate (> 10 ECV datasets); c) proposing and delivering, in collaboration, novel EO satellite missions (17+ missions); d) providing coherent and structured support to data-informed models capable of diagnosis, parameter estimation and prediction (> 5 models); e) growing new computing and sensor infrastructure (section 3); f) developing skilled practitioners of EO data assimilation (> 70 PGR students; section 3.2); g) growing strategic partnerships with government and industry in our sector (section 4).

1.3 Research Objectives and progress during the evaluation period

NCEO did not take part in the 2013 evaluation and subsequently CPOM and COMET exited from NCEO; we have not used their information in this submission. As objectives for the evaluation period, we choose to use the documented 2014 NCEO strategic Business Plan (Remedios on appointment as Director) as our foundation for the period. The NCEO objectives for 2014-2019 in research and impact were: a) Innovative data assimilation for Earth state representation, its model-mediated assessment and interrogation, with NWP-related impact; b) historical and new observations of Earth System evolution and impact in operational and business services using critical long-term data sets; c) model-data evaluation and policy impact for global ESM and component models; d) provision of instrument, data facilities and key tools for use by the wider NERC community with impact from NERC technologies. Many of the activities carried out in support of these objectives are long-term and will continue into the next assessment period, not least because the nature of EO systems.

In data assimilation (DA), we have concentrated resource on improving the techniques for environmental science models whilst also ensuring we maintain a team in theoretical DA looking at next generation systems. Work on terrestrial carbon models, ocean biological modelling and inverse modelling of greenhouse gases has yielded productive results with possibilities going forwards for incorporation into more operational systems. We have been developing schemes that support national community models such as JULES and ERSEM/MEDUSA. Benefits include closer association with the corresponding Met Office/Hadley Centre models. Recent activities have begun to support complex assimilation into the sea ice model CICE and hydrological flow (HydroJules). We also support DA for CARDAMOM, Tomcat and GEOS-Chem. NCEO staff have prioritised particle filters because of the need for non-linear assimilation methods in next generation models. Van Leeuwen won an ERC grant (£2.4 million). Progress has also been made in characterising observational uncertainties, which are crucial to assimilation systems, and this work has led to improvements in the numerical weather prediction systems at the Met Office and DWD.

Considerable progress has been made in EO datasets and in the underpinning algorithms where NCEO research and development has benefitted from a long-term plan to deliver the required research including demonstrating the rigour of EO methodologies, deriving meaningful uncertainties with traceability and data quality. Leveraging funding from the ESA CCI programme intensified the science work for critical Essential Climate Variables (ECVs) from sea surface temperature to greenhouse gases and tropospheric ozone to ocean colour. These data sets have also been supporting the development of the Copernicus Climate Change Service. We have shown increasing strength in climate-related datasets such as top-of-atmosphere radiative forcing and fire radiative power. There were big wins for new ESA explorer missions in the form of the final selection of the BIOMASS mission [Quegan, Williams, Carreiras] and FORUM [Brindley]. Microcarb [Boesch, Palmer] was also selected for funding by the UK with France. The period also saw the selection for the first builds for the Copernicus high priority candidate missions in the shape of the CO2 Monitoring mission (CO2M) [Boesch, Palmer] and that for land surface temperatures (LSTM) [Ghent].

Alongside these innovations, we have steadily improved techniques and capabilities for model evaluation. Through core team involvement in the multi-centre UK Earth System Modelling (UKESM) model with the Met Office, we have increased efforts and have a role in co-ordinating its evaluation [Brindley, Parker]. We have also worked on model evaluation (e.g. in examining the results of CMIP5 and CMIP6) in all of our areas: terrestrial carbon and vegetation; climate-composition interactions; energy, flux and water cycle; integrated climate data-model systems.

In the Infrastructure division, we have invested in the science of radiative transfer tools, and laboratory and atmospheric spectroscopy (facilities are covered separately). We have increasingly experimented with airborne remote sensing, both to provide unique science measurements and to generate data to support future EO satellite mission development. This has included deploying our own GHOST instrument for shortwave infrared sensing based greenhouse gas assessment and co-operating with NASA-JPL in deploying for the first time outside of the USA their state-of-the-art Hyperspectral Thermal Emission Spectrometer (HyTES) alongside our own optical and thermal infrared payloads. Operations have steadily improved in ability to archive data and service the UK community with EO-related infrastructure; this element has included a close co-operation with NCAS.

During this time, our research income has remained broadly steady (see section 3) and diverse. Our publications have reached approximately 150 per year. There has been an increasing connectivity and interest from government departments. We received a contract to examine the use of EO data for air quality, to run international offices (GEO/CEOS Office) and to support academic-industry partnerships which can exploit the datasets produced by the research community (Space4Climate, see later). Our GEO/CEOS Office co-ordinates policy inputs from Defra, UK Space Agency and NERC to the inter-governmental Group on Earth Observations (GEO) and the inter-agency Committee on Earth Observation Satellites (CEOS); Defra is the policy lead for GEO and UK Space Agency is the lead for CEOS.

1.4 Research Strategy for the next five years

Essential elements of our strategy for the next five years have been built around responses to NERC commissioning in conjunction with directions of travel in international science, EO mission selections and support from UK government. The principal aims are firstly to affirm our leading role as innovative and rigorous researchers using state-of-the-art techniques to progress environmental science for the global and resilient environment. Secondly, we wish to be developing new scientific systems, from new satellite missions to virtual laboratories that can contribute more effectively to the information required to address the leading challenges of today at the national and international level, for example, carbon trajectories for the Paris Agreement. Finally, we recognise our research matters but also our data matter so the digital environment in which we operate is essential to connecting to our stakeholders.

Scientifically, we have crystallised our detailed science into five future objectives:

- To be a focal point for state-of-the-art EO methods, tools and high-quality datasets which enable NERC and international scientists to undertake world-leading science,
- To maintain an internationally well-recognised and leading data assimilation centre for theory development and innovation in domain-specific and coupled models for the Earth system,
- To be a world leading diagnostic centre for the global and regional carbon cycle variability and change, including oceans, terrestrial and atmosphere, deriving and integrating cutting edge EO datasets into models using data assimilation
- To progressively extend EO-driven, data-model frameworks to study large-scale coupling of the biosphere-atmosphere during the Anthropocene,
- To deliver an observation driven centre focused on diagnosing energy and water exchange in the Earth system, capable of elucidating key processes and emerging climate events.

These drivers focus our efforts over the next years on environmental science challenges of carbon emissions, large-scale air quality, disruptive injections to the atmosphere such as from fires, control of land surface moisture and ocean-atmosphere exchange. We intend to strengthen work with other NERC centres in ocean and polar science; ice-land-ocean-atmosphere interactions could be crucial for Earth system sensitivity. Our observation systems aim to extend towards increased use of sensor networks and flexible airborne platforms from drones to aircraft for hire. We are already expanding our research to include analysis-ready data techniques, data cubes and commercial satellite instrument performance (calibration and sensitivity) with potential utility for new science. We will strengthen our efforts to make our science systems accessible and quick to respond to events.

1.5 Interdisciplinarity

Interdisciplinarity is part of the culture in NCEO and reflected by the staff being located in a range of departments and Schools at their host institutions including (in order) physics; meteorology; geography; geosciences and environment; marine science; maths and statistics. We have expertise across terrestrial, atmospheric and oceanic environmental science, chemistry, computational techniques and space technology. Examples of cross-fertilisation include work on solar energy at NCEO Imperial and institution of a cross-faculty Earth Observation group [Brindley], the Edinburgh Centre for Sustainable Forests and Landscapes [Williams], projects to demonstrate air quality at health at King's [Wooster] and land cover as a service for policy related to development, poverty and urbanisation at UCL [Disney].

For NCEO as a whole, the main drivers are:1) the necessity to work on the latest space technologies with physicists and engineers in order to develop innovative and fit-for-purpose instrumentation; 2) the incentives to work with mathematicians and computational scientists on the theories and successful implementations of advances in data assimilation methods, optimisation techniques and the new frontiers of hybrid machine learning and data assimilation approaches; 3) the challenge to increase the success of environmental science in changing behaviours, supporting wider use of new technologies and policy change.

Notable successes in funded interdisciplinary projects include the £10 million Leverhulme Centre for Wildfires, Environment and Society [Wooster, Brindley] and the £13.75 million Research England-funded Manufacturing, Engineering and Earth Observation Research Centre (METEOR) project in Space Technologies [Remedios, Boesch, Balzter, Battaglia]. Postgraduate training provides us with particularly useful links in the mathematical sciences. Through the EPSRC CDT in the Mathematics of Planet Earth, based at Imperial College London and the University of Reading, mathematical expertise has been brought into EO related problems, especially in the area of data assimilation.

1.6 Research environment and integrity

NCEO aim to be 100% compliant with a research environment where publications and data are freely accessible. Our datasets are released on open data portals, unless restricted by funder agreements. Much of our work is climate-related for which open access, reproducibility, traceability and metadata are essential. NCEO staff are gradually publishing their data in data journals with associated doi. Regarding publications, most NCEO staff work at Universities where there are processes to ensure open access as early as possible. The same principles apply to our non-University staff. We estimate that fewer than 10% of our publications may be restricted due to journal charges, a lack of allocated resource or the ability of a non-NCEO lead author on a paper to pay. We continuously look for mechanisms to alleviate these residual problems.

As for publications, Universities are signatories to the relevant research integrity principles and concordats. We expect all our staff to follow these principles and to conduct their research with honesty, with care and with organisation of software and data.

2. <u>People</u>

NCEO's structure of three science divisions (DA, EODM and EOIF) and a Directorate of support staff provides our route to manage and encourage people in tandem with their line managers at host institutions. The Divisional Directors foster the staff in their areas and critically the profiles of skills therein; the NCEO Centre Manager has responsibility for the Directorate working with the NCEO Director. They liaise with line managers to discuss performance in respect of NCEO workplans, more formal appraisal and most importantly career support and training. The NCEO Senior Programme and Innovation manager (Stott) provides a high level link to NERC, government and industry. Across-Centre initiatives and focussed fora, for example the NCEO Researchers Forum, are initiated and agreed by the NCEO Executive Team leading to action by the Directors and support staff. The Director provides further feedback and engagement with high-level objectives through visits to each host institution in turn, accompanied by relevant Divisional Directors, the objective being engagement with all staff through talks and discussion.

2.1 Staffing Strategy and Staff Development

The NCEO staffing strategy with respect to science staff has the following overarching principles: 1) to encourage researchers to achieve high quality discoveries, datasets and data-model schemes; 2) to assure a core of long-term staff who can achieve continuity of long-term research and build fit-for-purpose systems requiring decadal efforts; 3) to maintain a healthy profile of research leaders, PDRAs, and students; 4) to train staff to be agile and flexible in their research so they can respond quickly to the demands of new priorities; 5) to encourage staff in open, sustainable and EDI-compatible practices alongside the policies of their host institutions; 6) to encourage staff to gain experience working with stakeholders and deepen their relationships with them.

2.2 Relationship between Research Strategy and Staffing Strategy

Our research strategy informs our staffing strategy and provides it with a long-term view. The staffing strategy also needs to respond to short-term demands, for example the need to deliver projects in a timely and productive manner. Overall, however, we find that high level research directions are reflected very clearly in the staff profile that we need for critical mass as segmented by skill (EO data inversion algorithms, data assimilation, modelling, field experience, EO mission design) and science interest (carbon, water cycle, biosphere-atmosphere, ocean-atmosphere, urban studies). In each of our key areas, we have one, ideally more, senior scientist(s) working with a group of staff. We adopt the same approach in pulling together cross-division teams which are needed more and more, particularly as we respond to NERC national capability (NC) provision.

To drive our staffing strategy, we test each area and programme team for the core skills needed for research delivery, the correct balance of senior and junior staff and the strength of the area going forward. In 2014, we appointed Divisional Directors for the first time (Boesch, Brindley, Van Leeuwen, Wooster) and a Science Director (Palmer). We also appointed staff in new areas or where we identified the need to strengthen a research base: spectroscopy and its exploitation (Harrison), cloud-precipitation (Battaglia, Mroz) and top-of-the atmosphere radiation (Brindley). The commissioning of NC led to further needs for appointment (e.g., Swaminathan to support UKESM, Pinnington to support JULES DA). To support us in this process for the next five years, we have generated roadmaps for the next 5+ years, illustrating the opportunities afforded by new and continuing satellite missions and expected science of significance and impact. All staff have seen and discussed these; the roadmaps will guide future staff appointments and staff development going forward.

NCEO does not operate large physical infrastructures. We have good staff retention in our computational and CEDA/JASMIN support. We are experimenting with increasing the number of staff with software engineering skills. Likewise, we have taken on two new staff members with experience of field instrumentation alongside the Field Spectroscopy Facility to ensure we can maximise use of ground-based or aircraft instruments.

2.3 Research Staff Development

Research staff development is an important consideration for NCEO, both for the careers of individuals and for NCEO itself in agreement with the Concordat for Researchers. At the beginning of the evaluation period, there was a gap in middle level staff in NCEO and we have tackled this in ways we intend to sustain over the next five years. Firstly, we encourage staff to take on positions of responsibilities with support of line managers and mentors, e.g. NCEO Evaluation Scientist for UKESM (Parker) and GHRSST Project Scientist (Veal). Secondly, we introduce appropriate staff gradually into national and international satellite missions, networks and committees, providing them career-building opportunities where they are exposed to strategic thinking and processes, international co-ordination and world-leading scientists. In addition, we encourage appropriate courses for leadership and skills with fellowship applications and project leadership positions for scientific development. Six staff attended the NERC Future Leaders course

We support fair staff promotions articulating what staff need to achieve in higher level job roles and how they achieve this. Eight staff have obtained research fellowships over the period and one obtained a Defra Policy Fellowship (Poulsen). Throughout the year, we hold a range of scientific meetings, whether programme-related, NCEO and National EO conferences, the NCEO researchers' forum or topic-specific meetings where staff can support each other. Alongside these measures, we encourage staff to take advantage of their host institution scientific culture, staff development and appraisal systems.

Overall, at the less experienced level, nine staff were promoted to the equivalent of NERC band 5 and six obtained personal fellowships during the evaluation period; all but one of the promotions and fellowships were obtained in the last three years.

NCEO has also encouraged leadership at senior level, particularly in scientific terms, ranging from scientific leadership of satellite missions and international protocols to assimilation for national models. As noted in section 4.6, we have significant roles leading satellite missions. We have 3 Lead Authors in IPCC AR6 compared to none in AR5. Significant achievements during the period have led to promotions to Professor (Boesch, Disney) and Associate Professor/Reader (Brindley, Lawless, Quaife). Within institutions with NERC-type grades, three staff at RAL and CEH have received individual merit awards (Kerridge, Kershaw, Taylor). Bennett was promoted to CEDA Division Head and Poulsen to Section Leader equivalent to lecturer.

2.4 PGR Training and support

All NCEO students are joint between the University where the student is registered and NCEO. NCEO staff have acted as primary supervisor to 71 students over the evaluation period. NCEO is a joint supervisor for 4 students. The majority are directly NERC-funded (60) with fourteen partially funded through NERC NCEO NC. Four are co-funded through NERC NCEO NC funding and EPSRC funding (CDT; see below). Others have been funded by EPSRC, the European Space Agency, the Bill and Melinda Gates Foundation, NPL and University-sourced funds.

Over the evaluation period, NERC and EPSRC funding has shifted from algorithm and direct support to DTPs and CDTs. NCEO is a partner with the NERC DTPs Scenario (Reading and Surrey); CENTA-2 led by Birmingham; the Edinburgh E3-4; the Oxford DTP in Environmental Research; the Grantham Science and Solutions for a Changing Planet DTP at Imperial College and the London DTP. In addition, NCEO is a partner in the EPSRC Maths for Planet Earth CDT (Imperial College and Reading University). NCEO staff at Edinburgh and Leeds are part of the new NERC-funded Centre for Satellite Data in Environmental Science (SENSE).

NCEO employs a Training Manager to oversee NCEO provision, co-ordinate our DTP/CDT inputs and report on students' progress to completion. PGR students are recruited formally by the University of the primary NCEO staff supervisor. The NCEO Executive Team reviews the recruitment of students who are partially funded through NC. In addition to benefitting from the research expertise of NCEO supervisors, our students gain experience working alongside staff on major long-term projects and have training in specialist EO techniques and career skills. They attend annual two-day researcher forums, staff meetings and NCEO-organised conferences. Training includes data assimilation, publishing datasets, processing data on JASMIN, use of the Earth System Model evaluation tool, producing digital visualisations. Career skills include preparing a project proposal, communicating science to different audiences, writing blogs, working with the media and producing podcasts. Student progress is monitored by their host institution. There are regular meetings with their NCEO primary supervisor. Students feedback to NCEO through the researchers' forum, staff meeting, staff conference and during NCEO Director visits to institutions.

During the evaluation period, 96% (45 out of 46) of students submitted on time. One resigned due to ill health. Currently, 29 students remain in full-time study. After completion 63% joined academia; 13% industry; 12% public sector; 12% other/unknown.

A number of NCEO students have won prizes including Rodriguez-Veiga (RSPSoc 2017 PhD thesis award), Cafaro (EGU 2018 Outstanding Student Poster award), Somkuti (U. Leicester Doctoral Inaugural lecture award 2019), Tabeart (MPE CDT best MRes award 2016).

2.5 Equality and Diversity

NCEO promotes and supports equality and diversity at all partner institutions (93% holding at least an Athena-Swan bronze award) where mandatory EDI training is provided. In addition, NCEO Principles for EDI are circulated to all NCEO staff and students

NCEO treats young researchers as equals with established academic staff. NCEO events are structured to enable staff at all levels to contribute in a friendly but academically vibrant environment.

In a staff survey (December 2019 – 69% return) NCEO compares well to similar STEM subjects (Source: Equality + higher education – staff statistical report 2019). 61% of NCEO

staff are under 45 (as compared to 53% Earth, Environment Sciences and 59% in Physics. NCEO has a male/female split of 66% to 31% (non-disclosure also an option). Earth, Environment Sciences returned 64%/36% and Physics at 81%/19% respectively. With respect to BAME/White identity the NCEO survey returned 15%/83% respectively. This compares to Earth and Environmental Sciences (96% white) and Physics (92% white).

NCEO staff work 85%/15% full time/part-time. Our procedures for part-time and flexible working must accord with host institution's requirements as legal employers. We work with HR departments to agree working patterns that both meet staff circumstances and a productive work life.

In selecting staff for submission for the NERC Evaluation exercise the NCEO Code of Practice was fully implemented. All staff who met the criteria were submitted. All staff were consulted regarding output reductions. NCEO followed the process set out in the Code of Practice and no reductions were requested from NERC.

3. Income, infrastructure and facilities

3.1 Income

NCEO maintains a healthy income level (average £11.6 million per annum; last four years), giving a five-year total income of £56.8 million. This corresponds to £1.2 million per submitted staff researcher. Income from UKRI research councils remains the majority and is typically around 60% of the total incoming finance, with NERC being the majority source. The NERC national capability money has remained broadly steady during the period at £4.72 million per annum in 2018/19 (£2.65 million already allocated to 2024) whilst unsurprisingly NERC competitively won income varies from year-to-year an average of 45% of NERC NC. Other external monies have remained very steady. We have a large range of funders in addition to NERC particularly UK space Agency and Defra in the UK and internationally from the European Space Agency, EC H2020 and FP7 and Eumetsat.

NCEO has been successful in proposals for larger grants, particularly highlight topics working as part of a broader community, for example GAUGE and Greenhouse (£5.8m). NCEO is active in agenda setting through UK town hall meetings and programme workshops, particularly around the science challenges of climate, carbon, water cycle and large-scale land-atmosphere interactions. The nature of EO missions requires detailed scientific justification and therefore we work across the community to encourage debate, to share new science ideas and promote new techniques (both for EO data but also data-model interfaces) that could transform our science. Our national conference also acts as a gathering point for ideas as do our joint meetings with other NERC centres.

Our collaborations in large European programmes have been very important to our scientific success in addition to the funding from NERC. We have been very successful with ESA with whom we collaborate very well. A highlight has been the ESA Climate Change Initiative (CCI) projects which has provided an impetus to EO climate data research. NCEO scientists have led consortium projects on sea surface temperature (Merchant) and ocean colour (Sathyendranath) with leadership in new projects on land surface temperature (Ghent); each project values between £1.5 and £2 million. NCEO also has substantial roles in projects such as greenhouse gases, biomass and atmospheric composition variables. With the political situation, we will focus even further on UK-ESA strategic relationships, working to make the most of the substantial UK subscriptions to ESA, as well as UK national programmes.

We have connected our work to impact in a number of ways as discussed in the section 4 but in terms of income, the most productive has been in mission design and technology. Working with the UK Space Agency Centre for Earth Observation Instrumentation, we have worked over the time to support design and build of new instruments, most recently a G band radar. The usage of NCEO data is steadily increasing but as important in income terms is our ability to work with SMEs such as Assimila, institutes such as STFC-RAL and NPL and large companies such as CGI to generate joint projects. The advent of Space Park Leicester, for example, will increase joint working with industry across NCEO and build the size of the joint activities.

Part of our strategy going forward therefore is to increase the ability of our up and coming research scientists to apply for grants and contracts. NCEO does not have an investment fund although joint appointments are an effective means of stretching our resources in one or two cases. The ability of our staff to contribute to income generation is vital and to which they are keen to respond. In this, we positively approach staff seeking to identify opportunities for new projects; we regularly ask staff to identify any EDI barriers due to sex, age or position and we support them in positive actions. The number of fellowships is one example of success in this area.

A second element is to work with our data dissemination platforms, such as CEDA and NEODAAS to make it easier for the community to access high quality EO data sets. These exercises should benefit the wider community as modern technology is providing very different ways to access information, to share data and most importantly to integrate it. Our staff view current developments in NERC's Digital Environment as a future opportunity. The upcoming COP-26 and year following could well generate some excellent climate activities.

A third element is to provide the community with EO data in more accessible forms, as well as mathematical techniques such as AI and data assimilation. We have recently appointed a new Divisional Director for DA who has expertise in AI (Carrassi). Finally, working with industry and government, we are building cases for underpinning exciting science programmes with key investments that will provide evidence for policy and economic growth. The UK investment in the TRUTHS mission at the ESA Ministerial 2019 is an example of that policy.

3.2 Infrastructure and Facilities

Our facilities play a central role in supporting the community, in introducing experts and non-experts to environmental science with EO and providing networks for collaborations. Our NERC facilities have all been recently reviewed and renewed in 2019, being commended for excellence in publication and in user engagement.

3.2.1 Computing and Data Infrastructures

NCEO has a heavy reliance on data processing, data archival and data dissemination. All of these systems, except for University-specific computing, are open to the wider NERC community and indeed are open to the international community in the case of data dissemination.

Centre for Environmental Data Analysis
The CEDA Archive operates the atmospheric and earth observation data centre functions on behalf of NERC for the UK atmospheric science and earth observation communities. It covers climate, composition, observations and numerical weather prediction (NWP) data as well as various earth observation datasets, including airborne and satellite data and imagery. Prior to November 2016 these functions were operated by CEDA under the titles of the British Atmospheric Data Centre (BADC) and the NERC Earth Observation Data Centre (NEODC). Subsequently, CEDA has operated as a unified organisation under the joint governance of NCAS and NCEO through a CEDA Board. It is also part of NERC's new Environmental Data Service. Six CEDA staff are specifically identified as NCEO and are experts in EO data archival and computing.

The CEDA Archive as a whole hosts 625 dataset collections with 6214 datasets, with over 80,000 users accessing data between 2013 and today, fulfilling both an archival and data dissemination function. Year-on-year user numbers increased from ~12000 in 2013 to ~19000 in 2019. The overall data volume on CEDA has also grown substantially from ~2Petabytes (~2Pb) in 2013 to over 13 Pb in 2019. A large proportion of the growth in usage is the storage of EO data sets (7 Pb in 2019) of which there are 90 dataset collections, 1202 datasets; 593 of those are NCEO datasets fully or partially funded by NERC. Data from NCEO include atmospheric profiles, cloud data (type and height), sea-level height, plankton products, biomass maps, ozone profiles land- and sea-surface temperature, vegetation height and terrestrial lidar data for forests.

Since CEDA stores data on the JASMIN compute facility, the NCEO data are available to users within that processing framework alongside data from CMIP5 and 6. The UK space Agency has co-invested in storage of Copernicus Sentinel data of value to the UK research community. CEDA also hosts the ESA CCI data portal disseminating high quality data sets, many of which are from the UK and NCEO. The ESA CCI portal has resulted in over 1000 users per year of CCI data. Finally CEDA and the Satellite Applications Catapult, funded by the UK Space Agency, have provided a UK Collaborative Ground Segment for Sentinel data to support the UK community (research, government and commercial).

JASMIN

The JASMIN facility is a "super-data-cluster" located within and delivered by the STFC Rutherford Appleton Laboratory, supported by NERC through NCAS, NCEO and HPC support. JASMIN is a cluster of over 400 hosts and 7976 CPU cores, which have processed over 60 million jobs in 2019 (mid-range HPCs typically see ~100000). After a recent upgrade, its “QuoByte” storage was the world’s largest storage capacity at 45 Pb useable.

JASMIN has 1428 users (Jan. 2019) in total with the LOTUS batch cluster growing from less than 20 users in July 2013 to over 175 active users by the end of 2018. NCEO is a keen user of the compute capabilities at JASMIN, particularly for data analysis of surface temperature, atmospheric composition and water cycle. Increasingly, we use it as an accessible platform for climate-model data evaluation including CMIP5/6 and UKESM data.

The UK space Agency has co-invested with NCEO in a Climate Data from Space Zone for processing EO climate data operationally for UK data supply to the Copernicus Climate Change Service. Through JASMIN facilities, CEDA is providing a data and processing environment for pilot activities within Defra to produce Analysis Ready Data from Copernicus Sentinel satellites.

NCEO and other computing facilities

NCEO scientists have access to a range of other facilities in which it is not involved in the governance including host Universities. Researchers within NCEO have used the EPSRC/NERC supported ARCHER at Edinburgh (national facility) to produce atmospheric and oceanic model simulations alongside data assimilation applications. NCEO scientists at Leicester use the ALICE HPC cluster of 170 compute nodes (4760 processing cores) extensively to determine atmospheric composition, surface temperature and rainfall from EO instrumentation. Aerosol and atmosphere composition data processing at Oxford is undertaken on the ARC system (7520 cores). Terrestrial carbon analyses at Edinburgh are performed on the Edinburgh Eddie (7000 cores) and Cirrus Tier-2 national HPC service (280 compute nodes). These facilities enable NCEO staff additional opportunities to deliver high quality EO-based information to the community.

NCEO also makes extensive use of cloud-computing services such as Google Earth Engine and Amazon Web Services to produce land cover maps and change detection as well as using them as platforms for workshops and training events.

NEODAAS

NCEO is responsible for the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS), based at the Plymouth Marine Laboratory and for most of the period at the University of Dundee; the Dundee node has recently closed due to improvements in other routes for fast data transmission. NEODAAS is a service unique in the UK that provides bespoke EO data products to support and inform a wide range of scientific sectors, as well as providing real-time monitoring for key applications such as NERC cruise support and UK aquaculture. NEODAAS receives, processes, archives and serves to users local to global data and products from multiple polar-orbiting and geostationary satellites, including in near-real time. NEODAAS PML were recently awarded £1M of 'transformational capital' that will enable their processing to extend to GPU-enabled deep learning applications which are becoming a topic of great interest in the EO community and beyond. NEODAAS data have been used in impact studies, for example to identify two proposed Marine Protected Areas (MPAs) for breeding kittiwakes.

3.2.2 Field instrumentation and laboratories

NCEO offers the community access and support to remote sensing instrumentation. It also has laboratory facilities it uses to support its science.

The Field Spectroscopy Facility

NCEO's primary responsibility in instrumentation is the NERC-supported Field Spectroscopy Facility (FSF). FSF is based around the provision of state-of-the-art spectroscopy instruments and other light measurement devices to the UK research community, with a focus on high levels of radiometric accuracy and precision and excellent user support and training. FSF work with national bodies such as NPL in support of calibration/validation. An award of close to £1 million will enable them to increase their support to atmospheric and terrestrial science.

The new money will commission ground-based remote sensing of column amounts of major air pollutants and greenhouse gases. It will deliver an extension of their ground- and point-based field spectroscopy capability to UAV-based combined hyperspectral imaging and lidar.

Instrumentation for field and airborne spectroscopy

NCEO is building a ground-based and airborne instrument capability for accurate remote sensing. Working with the STFC Rutherford Appleton Laboratory, NCEO have setup a UK site contributing to the international Total Column Carbon Observing Network (TCCON) at Harwell campus. TCCON is a primary ground-based reference network for satellite greenhouse gas measurements. NCEO also supports the use of novel, portable ground-based spectrometers for near-surface level atmospheric trace gas analysis and greenhouse gas column observations, and radiometers for land surface temperature; one greenhouse gas instrument is currently deployed to Uganda in conjunction with the NERC MOYA project. NCEO have created a hub in Kenya for satellite product validation in the region, focused on Land Surface Temperature, Soil Moisture and Evapotranspiration.

We have quite recently instituted a user-accessible NCEO Airborne instrumentation capability, with an instrument operator and engineer expert in integrating new systems into various aircraft including the NERC/BAS twin otters. "Guest sensors" can operate alongside NCEO's baseline imaging spectrometers and very high resolution optical/thermal imager payloads, which are on long-term loan through NERC. Work so far has primarily been in support of NCEO Science and in collaboration with NASA and ESA, from whom substantial external funding has been obtained.

Laboratory facilities

NCEO staff working with instrumentation typically use laboratory facilities at their host institutions but NCEO has additional labs at Leicester and King's. In 2021, NCEO Leicester will be moving to Space Park Leicester, creating a first headquarters for NCEO and providing new laboratory facilities including new radiometer and optical calibration space, a rooftop laboratory for environmental measurements, and a spectroscopy laboratory to underpin atmospheric remote sensing. Currently, laboratory spectroscopy for the remote sensing of the atmosphere is carried out in the STFC RAL High Resolution Spectroscopy Facility and at PTB laboratories in Germany. Spectroscopic data are freely available through the international reference HITRAN and GEISA databases (Harrison). These activities will complement a terrestrial spectroscopy laboratory at NCEO-King's where a mix of indoor and field spectrometers and IR imagers are housed alongside an environmental chamber for thermal infrared calibration. NCEO-King's have also developed a combustion chamber facility able to support their work on landscape fire and fire emissions, both in terms of providing a controllable environment in which to perform combustion experiments (fire radiative power and chemical composition) and also providing an arena where instruments can be tested under conditions similar to those that they will encounter during field campaigns related to biomass burning measurements.

4. Collaboration and contribution to the research base, economy and society

4.1 Research Collaborations and Partnerships

NCEO has extensive research collaborations and partnerships through its role as a national centre, through integrative studies in key NERC grants, as part of programmes initiated through host institutions, through EO satellite mission projects and in EU H2020 projects for example Fiduceo (Merchant) for accurate climate data. We strive to reach the best science and we expect staff to form productive collaborations with other very good scientists.

Nationally, NCEO works closely with all the other main NERC centres, e.g. through the NC multi-centre programmes UKESM and ACSIS, but also in smaller, more focussed areas, e.g. NCEO and CEH joint work on methane and hydroJULES, and studentships e.g. joint NCEO-CPOM studentship at Reading. We have many working relationships with the Met. Office both formally through JWCRP but also generally in data assimilation, atmospheric chemistry and EO data sets (e.g. projects such as the NERC-funded Swelter-21 and EU H2020 Eustace). In our activities in EO satellite missions, we have excellent collaboration and technology links with institutes such as RAL, ATC and NPL.

In pure research, we do not have preferential partnerships outside of PGR training, rather aiming to have good collaborations according to science area. For example, there is a strong greenhouse gas community in the UK in which NCEO plays a full role and we have both led large, multi-partner projects (e.g. GAUGE) and collaborated in other projects (Bristol, DARE-UK; Royal Holloway, MOYA). In fire research, Imperial, King's and NCEO have partnered in the Leverhulme Centre for Wildfire, Environment and Security. We have productive collaborative partnerships with colleagues at the University of Leeds in (land-atmosphere interactions and atmospheric chemistry) and Aberystwyth (terrestrial EO data and biomass).

Internationally, NCEO is hugely collaborative through European and wider satellite missions, the associated projects and teams. Again our collaborations are particular to scientific objectives but include NASA JPL (USA), IFAC and CNRS (Italy), KNMI (Netherlands), FZJ (Germany), Max-Plank Jena (Germany) and the Universities of Bremen, Beihang and Bologna, Colorado and Maryland (to name a few). We have hosted visiting scientists from a wide variety of organisations, for example, Korea (Yonsei), China (Qingdao, IAP/CASP), Brazil (Inpe) and Kenya (KFRI).

4.2 Collaboration with research users, research environment and impact connectivity

The NCEO strategy for engaging the community is "Support, Make Accessible, Communicate and Collaborate, Create focal points and Train". We support the community by discussion fora, surveys and representation which then creates opportunities. NCEO organises the NERC Centres EO forum which is expanding to provide an EO academic working group as part of the Space Academic Network (SPAN). Support to government investment agreements such as the ESA Ministerial 2015 and 2019 (Space 19+) and to Copernicus arrangements has involved surveying the community on key UK research; we are a central government point-of-contact for the EO community. We were able to agree UK science membership of the NASA/CNES/UK SWOT mission following UK investment and a call for the community to apply.

We further support and communicate with the community through conferences, an NCEO community mailing list and social media (e.g. twitter). Conferences have been increasingly successful. Working with RSPSoc and CEOI (Centre for Earth Observation Instrumentation), we have organised the first national EO conferences (2015 260 attendees; 2018 360 attendees) and we now have more than 170 attending our smaller NCEO/CEOI conferences in the intervening years. We have also run workshops on agriculture, forestry and carbon, and analysis-ready data.

Aside from conference and website, our key focal points for research users combine communication, sharing of research knowledge and impact. We work mainly across government-sponsored community engagement offices and programmes: GEO/CEOS office (Defra, UK Space Agency), Space4Climate (UK Space Agency and industry), Satellite Applications Catapult; CEOI.

4.3 Impact, economy and society

NCEO works with three broad communities to produce impact in addition to public benefit: a) government departments and space agencies; b) the operational meteorological and Copernicus service community; c) industry. We have supported the Defra EO Centre of Excellence, formed in 2015, scientifically and hosted trials of analysis-ready data to support Defra agency monitoring. We work with Ofcom to extend government understanding of frequency usage by the EO community (including commercial companies) supporting them to devise their space spectrum strategy. We also work extensively with the UK Space Agency UKSA) and space industry to look at development of national strategies for growth. Remedios sits on the Space Sector Council (advises at Ministerial level) and Space Growth Partnership Board advising on trends in EO and user uptake, including new space providers of satellites. Increasingly, NCEO is collaborating with the EO downstream industry to grow applications, for example, Ecometrica's Forests 2020 project (NCEO Edinburgh, Leicester) under the UKSA IPP programme.

In the operational meteorological community, as well as strategic arrangements we have many individual staff relationships with the Met Office and ECMWF that support data assimilation, expert use of EO data and collaboration to improve the design of new instruments. The advent of Copernicus has increased our delivery of data and knowledge to external communities of users (thousands), through the Atmosphere (Wooster), pre-operational Climate (Merchant, Kerridge, Boesch), Marine (Ciavatta) and Land Services (Merchant, Balzter) including UK Corine (Balzter).

NCEO collaborates with a range of environmental data and space technology companies who are keen to work with UK science expertise in order to refine data techniques or space mission design and sensor technologies. In its activities across government-sponsored programmes (section 4.2), University-based R&D accelerators, and ESA projects, NCEO works to share knowledge and improve the reach of UK research inspiration. Two particular University projects, heavily influenced by Space Park Leicester worth £100 million (includes University, Leicester Enterprise Partnership, Research England and NERC) and the Institute for Environmental Analytics (HEFCE Catalyst; £5.6 million) at Reading.

Budgets for space projects extend from hundreds of millions of pounds to billions of pounds for programmes such as Copernicus. Hence this is big business, requiring government approval and space technology companies stand to gain large sums from science success. NCEO works strategically and one-to-one with a range of companies (Airbus, SSTL, Thales Alenia Space, CGI, Telespazio Vega and SMEs). Approved missions, e,g., Sentinel-3, Sentinel-5P, Microcarbs, BIOMASS, FORUM, LSTM, have given industry benefit from NCEO expertise.

4.4 Engagement with the public

The outreach programme of NCEO has been very active throughout 2013 to 2019, although only lightly resourced. We have undertaken three major streams of activities with the enthusiastic participation of staff: 1) Our "Tim Peake" inspired EO Detective project competitions classroom resources; 2) Support of MOOCs developed by a company, Imperative Space, on behalf of ESA and Eumetsat; 3) special events for a variety of audiences. The EO Detective project was initiated to celebrate Tim Peake's flight on the International Space Station (ISS) and NERC's 50th anniversary celebrations. By summer 2019, usage of our resources at Stem Learning UK had reached over 100,000 children; this includes our work for the NERC/BEIS-funded Polar Explorer programme (BAS/STEM Learning). EO Detective has also provided supporting materials for the Scouting Association Scouts Astronautics Activity badge. MOOCs provide an online learning environment through which we have supported an SME Imperative Space, particularly in ESA's "Climate from Space" (over 20,000 participants) and "EO from Space (13,000 participants): the Optical View"

(Wooster, Remedios, Disney and NCEO teams). In events, we have contributed to the NERC Showcases, Big Bang Fairs and Farnborough Air Shows. We have contributed to the Royal Society Summer Science Exhibition (UKESM) and will be leading a stand on EO measurements of carbon at the 2020 event. Several of our staff are STEM ambassadors. We supported exhibits in the Science museum, Victoria & Albert museum and NERC events at the Natural History museum. We also work closely with the National Space Academy in Leicester, enabling interactions with very different communities.

4.5 Sustainability of discipline and responsiveness to national/international priorities

The value of EO, particularly that from space, continues to grow with many scientific challenges underpinned by a need for accurate observations of the real world, improved use of data assimilation and artificial intelligence type techniques, and dual-use of observations and models to diagnose and constrain future environmental development. NCEO scientists will be working on new missions with launches in the early to mid-2020s: greenhouse gases (Microcarb), aerosol-cloud and radiation (Earthcare), forest biomass (BIOMASS), atmospheric composition and air quality (Sentinels 4 and 5), solar-induced fluorescence (FLEX) and the first far-infrared radiation explorer mission (FORUM).

NERC science benefits hugely from being able to access and exploit these international EO missions, particularly through the European Space Agency (ESA), EUMETSAT and Copernicus which all receive UK investments. NCEO plays the major technical and advisory role for NERC in respect of supporting the community to be able to access and make use of this NERC-related space infrastructure. Most recently, the UK agreed an uplift of 15% (€250 million contribution) to ESA's EO programme. Increasingly, NERC science makes use of the direct data or derived products from the operational, UK-funded, European Eumetsat and Copernicus satellite systems. Copernicus data remains free and open. In addition the UK subscribed at Space 19+ to the build of the next 6 innovative Copernicus satellites which are closest to expanding operations of the system.

The coming years will see significant, urgent science drivers and planned, major EO missions in timely fashion. These will continue to set our anticipated science goals which we will test through international mechanisms such as GEO, CEOS, IPCC, GCOS and WMO's WCRP. We further test those science drivers with government scientists, including Chief Scientific Advisors and Heads of Policy and Evidence teams. We also receive valuable advice from our International Science Advisory Board which includes leaders from, for example, the NSF Decadal Survey conducted for NASA.

Overall NCEO and its staff are very well placed to undertake the necessary research to underpin these developments, our strengths lending themselves to digital, global and resilient environments. Through our NC programmes, we are able to support collaborative and community work from climate and carbon resilience to global impacts of changing landscapes.

4.6 Evidence of wider influence

NCEO is highly esteemed within the National and International Earth observation community. Evidence of this is notable from the number of research consortia that we lead and are invited to join, the large number of satellite missions that NCEO are invited to take an advisory role in and the number of international committees and boards on which NCEO staff are included.

NCEO plays a major role in shaping current and future EO missions through its involvement in **international Mission and Science Advisory Groups and EO working groups.** This includes: ATSR PI and Chair of ATSR Science Advisory Group (Remedios), GERB Science Team (Allan Remedios, Brindley is GERB PI), CERES Science Team (Allan), Copernicus Expansion Mission LTSM MAG (Ghent), MAG for S4, S5P and 3MI (Siddans), GPM MAG (Battaglia), Earthcare MAG (Battaglia), SKIM MAG (Battaglia), Science Team NASA GPM (Battaglia), ESA and EUMETSAT CIMR (Merchant), ESA FLEX MAG (North), ESA Carbonsat MAG (Boesch), NASA OCO-2 Science Team (Boesch, Palmer), ACE Science Team (Harrison), ESA BIOMASS MAG (Quegan, Williams), GHRSST Science Team (Embury), EUMETSAT METimage SAG (Embury, Merchant), Swedish Space Agency SAG (Sathyendranath), ESA CO2M MAG (Boesch), Science Team CNES MicroCarb

(Boesch, Palmer), EU CO2 Monitoring Task Force (Palmer), ESA Sentinel3 Mission Performance Centre (Ghent, North, Nenciolli, Bulgin, Embury, Corlett), MIPAS Data Quality WG (Moore, Dudhia), S3 OLCI/SYN WG of ESA/EUMETSAT (Sathyendranath), IOCCG WG in phytoplankton functional types (Sathyendranath; Chair).

NCEO has a strong representation in **National and International advisory board and working groups** related to EO including: Steering Committee of WMO UNEP Ozone Assessment (Chipperfield), GEO Programme Board Member (Balzter), CEOS WG (Climate- Merchant; WGISS - Conway, Cal/Val – Disney), CEOS Strategic Implementation Team (Remedios), GCOS Terrestrial Observation for Climate Panel (Ghent, Quegan), ESA Earth Science Advisory Committee (Merchant), AMS Atmospheric Radiation Committee (Allan), CMSAF Review/Advisory Board (Allan), Co-chair of GOFC-GOLD Fire Team (Wooster), UK CMIP6 Analysis Committee (Swaminathan), GEISA Science Committee (Harrison), ESA BiDS Programme Committee (Feng), Science Advisory Board CLIVAR-CONCEPT (Haines), CLIVAR Global Synthesis and Observations Panel and co-chair (Haines); Co-chair of the International Land Surface Temperature and Emissivity Working Group (Remedios).

Within the assessment period NCEO staff have been part of the following **National and NERC groups**: NERC Science Board (Williams), NERC Joint Capital Advisory Group (Wooster), UK Space Agency EO Advisory Committee (Remedios - chair until 2014, Sathyendranath, Merchant), National Measurement System programme Expert group: Energy and Environment (Remedios), Space Sector Council (Remedios), Space Growth Partnership Board (Remedios). Battaglia is the Co-Director of the UK Centre for Earth Observation Instrumentation (UK Space Agency).

NCEO Staff have served on the following **grant awarding panels**: NERC Peer Review College (Allan, Boesch, Roulestone, Chipperfield, Quegan, Battaglia, Dall'Olmo, Balzter, van Leeuwen, Lewis, Palmer, Taylor), NERC Pool of Chairs for grant panels (Remedios, 2013-2014), EPSRC Fellowship Committee (Roulestone), Royal Society Newton Advanced Fellows panel (Palmer), Academy of Finland Flagship Programme Panel (Remedios).

NCEO Staff serve on several **International Advisory Boards:** MPI Biogeochemistry (Williams), Alfred Wegner Institute Germany (Sathyendranath), SRON (Kerridge), International Biogeochemical Argo Steering Team (Dall'Olmo), Member of Conseil Scientifique, Institu Oceanographique, Monaco (Sathyendranath).

NCEO staff contributed to or were lead authors of the following **international reports**: IPCC 6th Assessment Report (Lead authors: Sathyendranath (Ch.8) and Allen (Ch. 2), contributing authors: Swaminathan (Ch.4), Racault (WG-II, Ch. 3)), SPARC Report on Mystery of Carbon Tetrachloride (Harrison, Chipperfield), CEOS Strategy for carbon observations from Space (Sathyendranath; Lead Author Ocean domain), CEOS WGISS Reports (Conway), Tropospheric Ozone Assessment Report (Kerridge Latter, Siddans), WCPP Final Report CONCEPT Heat 2019 (Haines), ESA report for mission selection, Carbonsat (Boesch), GCOS Implementation Plan (Brindley), An Operational Anthropogenic CO_2 emissions Monitoring & Verification Support Capacity, Report from the CO_2 Monitoring Task Force (Palmer), CEOS White Paper on A Constellation Architecture for monitoring Carbon Dioxide and Methane from Space (Boesch, Palmer).

NCEO staff have won a number of **notable prizes** during the assessment period including: four Royal Society Wolfson Merit Award (Balzter, Chipperfield, Palmer, Williams), Royal Society of Chemistry Award 2018 (Chipperfield), 2018 NERC Economic Impact Award (Quegan), 2019 Remote Sensing and Photogrammetry Society (RSPSoc) Award for long standing and highly acclaimed services to Remote Sensing and Earth Observation Science (Wooster), 2018 Royal Geographical Society's Cuthbert Peek Award (Balzter), Panikkar Memorial Lecture and Medal, UNESCO 2013 (Sathyendranath), La Grande Médaille, Albert Premier 2013 (Sathyendranath), American Meteorological Society's Louis Batten Author's Award 2015 (Roulstone), 2015 Buchan Prize, Royal Meteorological Society (R. Allen), Winner Copernicus Masters - Sustainable Living Challenge 2017 and Finalist Planet Daily Change Challenge 2018 (Balzter, Rodriguez Veiga), 2014 NASA Goddard Space Flight Center Robert H. Goddard Award for Exceptional Achievement in Science (A.

Battaglia), NASA Group Achievement Award for GPM (A. Battaglia), NASA's "Henry J. E. Reid" Award for an outstanding paper (Bantges), MDPI Remote Sensing award (Best Paper in for 2015 – Boesch; 2018 Young Investigator - Brewin).

NCEO Staff hold a number of **honorary positions** at other institutions, Taylor is a Visiting Professor at Leeds University, Kerridge is a Visiting Research Fellow at Oxford University, Palmer is a Visiting Scientist, Laboratoire des sciences du climat et de l'environnement, Palmer is a Distinguished Visiting Scientist of Jet Propulsion Laboratory, USA, Harrison is a visiting scientist at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany.

NCEO has successfully supported its staff to apply for **fellowships** with six ESA Living Planet Fellowships (Anand, Brewin, Knappett, Parker, Povey and Racault), one Industrial Strategy Fellowship (Proud) and one Japan Society for the Promotion of Science (JSPS) Fellowship (Rodriguez Veiga).

NCEO has significant involvement in **conference committees** with 33 staff regularly being asked to convene conference sessions and many examples of memberships in conference organising committees. Examples include ESA Living Planet Symposium (Conway, Fillingham, Boesch, Palmer), European Radar Conference EuRAD (Battaglia), ERAD 2016 conference committee (Battaglia), Big Data from Space Conference Series (Conway), International Workshop on Greenhouse Gas Measurements from Space (Boesch), ESA Carbon from Space Workshop (Boesch), International Symposium on Data Assimilation (Nichols). NCEO staff have been session chairs at AGU, EGU, EUMETSAT Meteorological satellite conference and many others.

NCEO staff have given 55 **keynote or invited talks** during the assessment period including at NASA JPL, AGU, EGU, IGARSS 2019, Climate Symposium 2014 or ESA Living Planet Symposium.

NCEO staff are **members of editorial board** for 13 journals: Remote Sensing for Ecology and Conservation (Disney), Biogeoscience (Williams, 2014-2015), Nature Scientific Reports (Sathyendranath), ICES Journal of Marine Science (Sathyendranath), Frontiers in Earth Science/Climatology and Meteorology (A. Battaglia), Elementa (Palmer), Atmospheric Environment (Palmer), Environmental Research Communications (Palmer), MWR (Carrassi), *Nonlinear* Processes in Geophysics (Carrassi), Frontiers (Carrassi), Atmospheric Chemistry and Physics (Chipperfield), Remote Sensing (Balzter, Carreiras), and **associate editors** for: Journal of Climate (Allen), Monthly weather review (Fowler and Lawless), AMS Journal of atmospheric and oceanic technologies (Battaglia), Biogeoscience (Ciavatta). All submitted staff regularly review articles for peer review journals, including Nature, Science, JGR, Atmospheric Chemistry and Physics or Remote Sensing of the Environment and Quarterly Journal of the Royal Meterological Society.

ENVIRONMENT COMPONENT DATA

Total income (funding and capital): £m

2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
12.89	11.14	11.51	12.92	11.93	11.28