EVALUATION OF NERC CENTRES 2020: NATIONAL CENTRE FOR ATMOSPHERIC SCIENCE EVIDENCE SUBMISSION

Submitted February 2020

1. List of research outputs

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	A growing threat to the ozone layer from short-lived anthropogenic chlorocarbons	2017	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-17-11929-2017
D - Journal article	A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns	2013	Journal of Geophysical Research: Atmospheres.	https://doi.org/10.1002/2013jd020062
D - Journal article	A large ozone-circulation feedback and its implications for global warming assessments.	2015	Nature Climate Change	https://doi.org/10.1038/nclimate2451
D - Journal article	A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models.	2013	Journal of Climate	https://doi.org/10.1175/jcli-d-12-00573.1
D - Journal article	A multi-model intercomparison of halogenated very short-lived substances (TransCom-VSLS): linking oceanic emissions and tropospheric transport for a reconciled estimate of the stratospheric source gas injection of bromine	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-9163-2016
D - Journal article	A pervasive role for biomass burning in tropical high ozone/low water structures	2016	Nature Communications	https://doi.org/10.1038/ncomms10267
D - Journal article	A projected decrease in lightning under climate change	2018	Nature Climate Change	https://doi.org/10.1038/s41558-018-0072-6
D - Journal article	A reversal of climatic trends in the North Atlantic since 2005	2016	Nature Geoscience	https://doi.org/10.1038/ngeo2727
D - Journal article	Active and widespread halogen chemistry in the tropical and subtropical free troposphere	2015	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1505142112
D - Journal article	Addressing model error through atmospheric stochastic physical parameterisations: Impact on the coupled ECMWF seasonal forecasting system.	2014	Philosophical Transactions of the Royal Society, A	https://doi.org/10.1098/rsta.2013.0290
D - Journal article	Advances in understanding mineral dust and boundary layer processes over the Sahara from Fennec aircraft observations	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-8479-2015
D - Journal article	Alpine ice evidence of a three-fold increase in atmospheric iodine deposition since 1950 in Europe due to increasing oceanic emissions	2018	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1809867115
D - Journal article	An unexpected disruption of the atmospheric quasi-biennial oscillation	2016	Science	https://doi.org/10.1126/science.aah4156
D - Journal article	Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years	2018	Nature	https://doi.org/10.1038/s41586-018-0007-4
D - Journal article	Arctic sea ice melt leads to atmospheric new particle formation	2017	Scientific Reports	https://doi.org/10.1038/s41598-017-03328-1

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D - Journal article	Atmospheric Conditions during the Arctic Clouds in Summer Experiment (ACSE): Contrasting Open Water and Sea Ice Surfaces during Melt and Freeze-Up Seasons.	2016	Journal of Climate	https://doi.org/10.1175/JCLI-D-16-0211.1
D - Journal article	Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine	2013	Nature Geoscience	https://doi.org/10.1038/ngeo1687
D - Journal article	Atmospheric isoprene ozonolysis	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-9521-2015
D - Journal article	Atmospheric seasonal forecasts of the 20th Century: multi-decadal variability in predictive skill of the winter North Atlantic Oscillation and their potential value for extreme event attribution	2017	Quarterly Journal of the Royal Meteorological Society	https://doi.org/10.1002/qj.2976
D - Journal article	Black carbon absorption enhancement in the atmosphere determined by particle mixing state	2017	Nature Geoscience	https://doi.org/10.1038/ngeo2901
D - Journal article	Characterization of a real-time tracer for isoprene epoxydiols-derived secondary organic aerosol (IEPOX-SOA) from aerosol mass spectrometer measurements	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-11807-2015
D - Journal article	Chlorine as a primary radical:evaluation of methods to understand its role in initiation of oxidative cycles	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-14-3427-2014
D - Journal article	Climate Impacts From a Removal of Anthropogenic Aerosol Emissions	2018	Geophysical Research Letters	https://doi.org/10.1002/2017gl076079
D - Journal article	Cloud Banding and Winds in Intense European Cyclones: Results from the DIAMET Project	2015	Bulletin of the American Meteorological Society	https://doi.org/10.1175/bams-d-13-00238.1
D - Journal article	Coarse mode mineral dust size distributions, composition and optical properties from AER-D aircraft measurements over the Tropical Eastern Atlantic	2018	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-18-17225-2018
D - Journal article	Composition and physical properties of the Asian Tropopause Aerosol Layer and the North American Tropospheric Aerosol Layer	2015	Geophysical Research Letters	https://doi.org/10.1002/2015gl063181
D - Journal article	Contrasting interannual and multidecadal NAO variability	2015	Climate Dynamics	https://doi.org/10.1007/s00382-014-2237-y
D - Journal article	CPMIP: measurements of real computational performance of Earth system models in CMIP6	2017	Geoscientific Model Development	https://doi.org/10.5194/gmd-10-19-2017
D - Journal article	Decadal predictions of the cooling and freshening of the North Atlantic in the 1960s and the role of ocean circulation.	2014	Climate Dynamics	https://doi.org/10.1007/s00382-014-2115-7
D - Journal article	Deconstructing the climate change response of the Northern Hemisphere wintertime storm tracks	2015	Climate Dynamics	https://doi.org/10.1007/s00382-015-2510-8
D - Journal article	Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols	2014	Geophysical Research Letters	https://doi.org/10.1002/2014gl060811
D - Journal article	Diesel-related hydrocarbons can dominate gas phase reactive carbon in megacities	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-9983-2015

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D - Journal article	Direct evidence for a substantive reaction between the Criegee intermediate, CH2OO, and the water vapour dimer	2017	Physical Chemistry Chemical Physics	https://doi.org/10.1039/c4cp04750h
D - Journal article	Discrepancy between simulated and observed ethane and propane levels explained by underestimated fossil emissions	2018	Nature Geoscience	https://doi.org/10.1038/s41561-018-0073-0
D - Journal article	Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall	2015	Nature Climate Change	https://doi.org/10.1038/nclimate2664
D - Journal article	Effects of halogens on European air-quality	2017	Faraday Disscusions	https://doi.org/10.1039/c7fd00026j
D - Journal article	Efficiency of short-lived halogens at influencing climate through depletion of stratospheric ozone	2015	Nature Geoscience	https://doi.org/10.1038/ngeo2363
D - Journal article	Emergence of healing in the Antarctic ozone layer	2016	Science	https://doi.org/10.1126/science.aae0061
D - Journal article	Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale	2019	Nature Communications	https://doi.org/10.1038/s41467-019-09776-9
D - Journal article	Enhanced global primary production by biogenic aerosol via diffuse radiation fertilisation	2018	Nature Geoscience	https://doi.org/10.1038/s41561-018-0208-3
D - Journal article	Enhanced light absorption by mixed source black and brown carbon particles in UK winter	2015	Nature Communications	https://doi.org/10.1038/ncomms9435
D - Journal article	ENSO representation in climate models: from CMIP3 to CMIP5	2014	Climate Dynamics	https://doi.org/10.1007/s00382-013-1783-z
D - Journal article	Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models	2014	Climate Dynamics	https://doi.org/10.1007/s00382-013-1883-9
D - Journal article	Estimating changes in global temperature since the preindustrial period.	2017	Bulletin of the American Met eorological Society	https://doi.org/10.1175/bams-d-16-0007.1
D - Journal article	Evaluating the performance of low cost chemical sensors for air pollution research	2016	Faraday Discussions	https://doi.org/10.1039/c5fd00201j
D - Journal article	Evaluation of Weather Noise and Its Role in Climate Model Simulations	2013	Journal of Climate	https://doi.org/10.1175/jcli-d-12-00292.1
D - Journal article	Evidence for renoxification in the tropical marine boundary layer	2017	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-17-4081-2017
D - Journal article	Evidence of strong, widespread chlorine radical chemistry associated with pollution outflow from continental Asia	2016	Nature Scientific Reports	https://doi.org/10.1038/srep36821
D - Journal article	Exploring the impact of CMIP5 model biases on the simulation of North Atlantic decadal variability	2015	Geophysical Research Letters	https://doi.org/10.1002/2015gl064360
D - Journal article	Exposure to nitrosamines in thirdhand tobacco smoke increases cancer risk in non-smokers	2014	Environment International	https://doi.org/10.1016/j.envint.2014.06.012
D - Journal article	Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models.	2015	Climate Dynamics	https://doi.org/10.1007/s00382-014-2426-8

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D - Journal article	Future Arctic ozone recovery: The importance of chemistry and dynamics.	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-12159-2016
D - Journal article	Global impacts of tropospheric halogens (Cl, Br, I) on oxidants and composition in GEOS-Chem	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-12239-2016
D - Journal article	Global reconstruction of historical ocean heat storage and transport	2019	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1808838115
D - Journal article	Global risk of deadly heat.	2017	Nature Climate Change	https://doi.org/10.1038/nclimate3322
D - Journal article	Globally significant CO2 emissions from Katla, a subglacial volcano in Iceland	2018	Geophysical Research Letters	https://doi.org/10.1029/2018gl079096
D - Journal article	Have aerosols caused the observed Atlantic multidecadal variability?	2013	Journal of Atmospheric Sciences	https://doi.org/10.1175/jas-d-12-0331.1
D - Journal article	High winter ozone pollution from carbonyl photolysis in an oil and gas basin	2014	Nature	https://doi.org/10.1038/nature13767
D - Journal article	How Do Atmospheric Rivers Form?	2014	Bulletin of the American Meteorological Society	https://doi.org/10.1175/bams-d-14-00031.1
D - Journal article	How well are tropical cyclones represented in reanalysis datasets?	2017	Journal of Climate	https://doi.org/10.1175/jcli-d-16-0557.1
D - Journal article	Impact of variable atmospheric and oceanic form drag on simulations of arctic sea ice	2015	Journal of Physical Oceanography	https://doi.org/10.1175/jpo-d-13-0215.1
D - Journal article	Impacts of bromine and iodine chemistry on tropospheric OH and HO_2: Comparing observations with box and global model perspectives	2018	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-18-3541-2018
D - Journal article	In situ measurements of cloud microphysical and aerosol properties during the break-up of stratocumulus cloud layers in cold air outbreaks over the north atlantic	2018	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-18-17191-2018
D - Journal article	In situ measurements of cloud microphysics and aerosol over coastal Antarctica during the MAC campaign	2017	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-17-13049-2017
D - Journal article	Increased frequency of extreme La Nina events under greenhouse warming	2015	Nature Climate Change	https://doi.org/10.1038/nclimate2492
D - Journal article	Increased water-use efficiency and reduced CO 2 uptake by plants during droughts at a continental scale	2018	Nature GeoScience	https://doi.org/10.1038/s41561-018-0212-7
D - Journal article	Increased wind risk from sting-jet windstorms with climate change	2018	Environmental Research Letters	https://doi.org/10.1088/1748-9326/aaae3a
D - Journal article	Increasing Autumn Drought over Southern China associated with ENSO Regime Shift	2014	Geophysical Research Letters	https://doi.org/10.1002/2014gl060130

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D - Journal article	Increasing frequency of extreme El Niño events due to greenhouse warming	2014	Nature Climate Change	https://doi.org/10.1038/nclimate2100
D - Journal article	Interactions between the night-time valley-wind system and a developing cold-air pool	2016	Boundary-Layer Meteorology	https://doi.org/10.1007/s10546-016-0155-8
D - Journal article	Iodine observed in new particle formation events in the Arctic atmosphere during ACCACIA	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-5599-2015
D - Journal article	Iodine's impact on tropospheric oxidants	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-1161-2016
D - Journal article	Irreducible uncertainty in near-term climate projections	2016	Climate Dynamics	https://doi.org/10.1007/s00382-015-2806-8
D - Journal article	Kinetics of stabilised Criegee intermediates derived from alkene ozonolysis	2015	Physical Chemistry Chemical Physics	https://doi.org/10.1039/c4cp04186k
D - Journal article	Lightning NOx , a key chemistry-climate interaction: Impacts of future climate change and consequences for tropospheric oxidising capacity	2014	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-14-9871-2014
D - Journal article	Linking African Easterly Wave activity with equatorial waves and the influence of Rossby waves from the Southern Hemisphere	2018	Journal of the Atmospheric Sciences	https://doi.org/10.1175/jas-d-17-0184.1
D - Journal article	Lower vehicular primary emissions of NO2 in Europe than assumed in policy projections	2017	Nature Geoscience	https://doi.org/10.1038/s41561-017-0009-0
D - Journal article	Multi-model analysis of Northern Hemisphere winter blocking: Model biases and the role of resolution	2013	Journal of Geophysical Research: Atmospheres.	https://doi.org/10.1002/jgrd.50231
D - Journal article	Multi-model evaluation of the sensitivity of the global energy budget and hydrological cycle to resolution	2018	Climate Dynamics	https://doi.org/10.1007/s00382-018-4547-y
D - Journal article	Newly detected ozone-depleting substances in the atmosphere	2014	Nature Geoscience	https://doi.org/10.1038/ngeo2109
D - Journal article	Novel insights on new particle formation derived from a pan-european observing system	2018	Scientific Reports	https://doi.org/10.1038/s41598-017-17343-9
D - Journal article	Observational evidence of European summer weather patterns predictable from spring	2018	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1713146114
D - Journal article	Observations of cloud microphysics and ice formation during COPE	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-799-2016
D - Journal article	Observations of ozone-poor air in the tropical tropopause layer	2018	Atmospheric Chemistry And Physics	https://doi.org/10.5194/acp-18-5157-2018
D - Journal article	Observed microphysical changes in Arctic mixed-phase clouds when transitioning from sea ice to open ocean	2016	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-16-13945-2016
D - Journal article	Ocean Heat Uptake Processes: A Model Intercomparison	2015	Journal of Climate	https://doi.org/10.1175/jcli-d-14-00235.1

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D - Journal article	OH reactivity in a South East Asian tropical rainforest during the Oxidant and Particle Photochemical Processes (OP3) project	2013	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-13-9497-2013
D - Journal article	On the Reliability of Seasonal Climate Forecasts.	2014	Journal of the Royal Society Interface	https://doi.org/10.1098/rsif.2013.1162
D - Journal article	On the Structure and Dynamics of Indian Monsoon Depressions.	2016	Monthly Weather Review	https://doi.org/10.1175/mwr-d-15-0138.1
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	https://doi.org/10.5194/acp-13-303-2013
D - Journal article	Organic aerosol components derived from 25 AMS data sets across Europe using a consistent ME-2 based source apportionment approach	2014	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-14-6159-2014
D - Journal article	Photo-tautomerization of acetaldehyde as a photochemical source of formic acid in the troposphere	2018	Nature Communications	https://doi.org/10.1038/s41467-018-04824-2
D - Journal article	Potential controls of isoprene in the surface ocean	2016	Global Biogeochemical Cycles	https://doi.org/10.1002/2016gb005531
D - Journal article	Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)	2013	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-13-2063-2013
D - Journal article	Processes controlling atmospheric dispersion through city centres	2015	Journal of Fluid Mechanics	https://doi.org/10.1017/jfm.2014.661
D - Journal article	Protein sequences bound to mineral surfaces persist into deep time	2016	eLife	https://doi.org/10.7554/elife.17092
D - Journal article	Quantifying the ozone and ultraviolet benefits already achieved by the Montreal Protocol	2015	Nature Communications	https://doi.org/10.1038/ncomms8233
D - Journal article	Recent Northern Hemisphere stratospheric HCl increase due to atmospheric circulation changes	2014	Nature	https://doi.org/10.1038/nature13857
D - Journal article	Reconciled climate response estimates from climate models and the energy budget of Earth	2016	Nature Climate Change	https://doi.org/10.1038/nclimate3066
D - Journal article	Redox Couple Involving NOx in Aerobic Pd-Catalyzed Oxidation of sp3-C−H Bonds: Direct Evidence for Pd−NO3−/NO2− Interactions Involved in Oxidation and Reductive Elimination	2017	Journal of the American Chemical Society	https://doi.org/10.1021/jacs.6b10853
D - Journal article	Regional climate impacts of a possible future grand solar minimum	2015	Nature Communications	https://doi.org/10.1038/ncomms8535
D - Journal article	Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget.	2017	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1714308114

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D - Journal article	Representing ozone extremes in European megacities: the importance of resolution in a global chemistry climate model.	2014	Atmospheric Chemistry And Physics	https://doi.org/10.5194/acp-14-3899-2014
D - Journal article	Response of El Nino sea surface temperature variability to greenhouse warming	2014	Nature Climate Change	https://doi.org/10.1038/nclimate2326
D - Journal article	Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production	2016	Nature Geoscience	https://doi.org/10.1038/ngeo2721
D - Journal article	Rising atmospheric methane: 2007-2014 growth and isotopic shift	2016	Global Biogeochemical Cycles	https://doi.org/10.1002/2016gb005406
D - Journal article	Sahel decadal rainfall variability and the role of model horizontal resolution	2016	Geophys. Res. Lett.	https://doi.org/10.1002/2015gl066690
D - Journal article	Sea ice decline and 21st century trans-Arctic shipping routes.	2016	Geophysical Research Letters	https://doi.org/10.1002/2016gl069315
D - Journal article	Secondary Organic Aerosol Formation and Organic Nitrate Yield from NO3 Oxidation of Biogenic Hydrocarbons	2014	Environmental Science and Technology	https://doi.org/10.1021/es502204x
D - Journal article	Secondary organic aerosol reduced by mixture of atmospheric vapours	2019	Nature	https://doi.org/10.1038/s41586-018-0871-y
D - Journal article	September Arctic sea-ice minimum predicted by spring melt-pond fraction	2014	Nature Climate Change	https://doi.org/10.1038/nclimate2203
D - Journal article	Slowdown of the Walker circulation at solar cycle maximum	2019	Proceedings of the National Academy of Science	https://doi.org/10.1073/pnas.1815060116
D - Journal article	Sources and contributions of wood smoke during winter in London: assessing local and regional influences	2015	Atmospheric Chemistry And Physics	https://doi.org/10.5194/acp-15-3149-2015
D - Journal article	Submicron particle mass concentrations and sources in the Amazonian wet season (AMAZE-08)	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-3687-2015
D - Journal article	Systemic swings in end-Permian climate from Siberian Traps carbon and sulfur outgassing	2018	Nature Geoscience	https://doi.org/10.1038/s41561-018-0261-y
D - Journal article	The 30-year TAMSAT African rainfall climatology and time-series (TARCAT) dataset.	2014	Journal of Geophysical Research: Atmospheres.	https://doi.org/10.1002/2014jd021927
D - Journal article	The Climatology, Meteorology, and Boundary Layer Structure of Marine Cold Air Outbreaks in Both Hemispheres	2018	Journal of Climate	https://doi.org/10.1175/JCLI-D-15-0268.1
D - Journal article	The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models	2015	Journal of Climate	https://doi.org/10.1175/jcli-d-14-00545.1
D - Journal article	The effect of complex black carbon microphysics on the determination of the optical properties of brown carbon	2015	Geophysical Research Letters	https://doi.org/10.1002/2014GL062443
D - Journal article	The effect of secondary ice production parameterization on the simulation of a cold frontal rainband	2018	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-18-16461-2018

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D - Journal article	The Holocene temperature conundrum	2014	Proceedings of the National Academy of Sciences	https://doi.org/10.1073/pnas.1407229111
D - Journal article	The inconstancy of the transient climate response parameter under increasing CO_2	2015	Philosophical Transactions of the Royal Society, London	https://doi.org/10.1098/rsta.2014.0417
D - Journal article	The increasing threat to stratospheric ozone from dichloromethane.	2017	Nature Communications	https://doi.org/10.1038/ncomms15962
D - Journal article	The influence of anthropogenic aerosol on multi-decadal variations of historical global climate	2013	Environmental Research Letters	https://doi.org/10.1088/1748-9326/8/2/024033
D - Journal article	The influence of biomass burning on the global distribution of selected non-methane organic compounds.	2013	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-13-851-2013
D - Journal article	The Influence of Entrainment and Mixing on the Initial Formation of Rain in a Warm Cumulus Cloud	2013	Journal of the Atmospheric Sciences	https://doi.org/10.1175/jas-d-12-0128.1
D - Journal article	The Influence of Stratospheric Vortex Displacements and Splits on Surface Climate	2013	Journal of Climate	https://doi.org/10.1175/jcli-d-12-00030.1
D - Journal article	The interaction of moist convection and mid-level dry air in the advance of the onset of the Indian monsoon	2016	Quarterly Journal of the Royal Meteorological Society	https://doi.org/10.1002/qj.2815
D - Journal article	The MCM v3.3.1 degradation scheme for isoprene	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-11433-2015
D - Journal article	The origins of ice crystals measured in mixed-phase clouds at the high-alpine site Jungfraujoch	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-12953-2015
D - Journal article	The role of air-sea coupling in the simulation of the Madden-Julian oscillation in the Hadley Centre model	2014	Quarterly Journal of the Royal Meteorological Society	https://doi.org/10.1002/qj.2295
D - Journal article	The role of horizontal resolution in simulating drivers of the global hydrological cycle	2014	Climate Dynamics	https://doi.org/10.1007/s00382-013-1924-4
D - Journal article	The role of human influence on climate in recent UK winter floods and their impacts.	2016	Nature Climate Change	https://doi.org/10.1038/nclimate2927
D - Journal article	The role of moist convection in the West African monsoon system: Insights from continental-scale convection-permitting simulations	2013	Geophysical Research Letters	https://doi.org/10.1002/grl.50347
D - Journal article	The role of northern Arabian Sea surface temperature biases in CMIP5 model simulations and future projections of Indian summer monsoon rainfall	2013	Climate Dynamics	https://doi.org/10.1007/s00382-012-1656-x
D - Journal article	The role of orography in the regeneration of convection: A case study from the convective and orographically-induced precipitation study	2015	Meteorologische Zeitschrift	https://doi.org/10.1127/metz/2014/0418

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D - Journal article	The upper end of climate model temperature projections is inconsistent with past warming	2013	Environmental Research Letters	https://doi.org/10.1088/1748-9326/8/1/014024
D - Journal article	Total volcanic stratospheric aerosol optical depths and implications for global climate change	2014	Geophysical Research Letters	https://doi.org/10.1002/2014gl061541
D - Journal article	Traffic and nucleation events as main sources of ultrafine particles in high-insolation developed world cities	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-5929-2015
D - Journal article	Transition from high- to low-NOx control of night-time oxidation in the southeastern US	2017	Nature Geoscience	https://doi.org/10.1038/ngeo2976
D - Journal article	Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models	2015	Journal of Climate	https://doi.org/10.1175/jcli-d-14-00131.1
D - Journal article	Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP)	2013	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-13-3063-2013
D - Journal article	UKESM1: Description and evaluation of the UK Earth System Model	2019	Journal of Advances in Modeling Earth Systems	https://doi.org/10.1029/2019MS001739
D - Journal article	Understanding high wintertime ozone pollution events in an oil- and natural gas-producing region of the western US	2015	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-15-411-2015
D - Journal article	Unexpected vertical structure of the Saharan Air Layer and giant dust particles during AER-D	2018	Atmospheric Chemistry and Physics	https://doi.org/10.5194/acp-18-17655-2018
D - Journal article	Upstream cyclone influence on the predictability of block onsets over the Euro-Atlantic region	2019	Monthly Weather Review	https://doi.org/10.1175/mwr-d-18-0226.1
D - Journal article	Using a case-study approach to improve the Madden-Julian oscillation in the Hadley Centre model	2013	Quarterly Journal of the Royal Meteorological Society	https://doi.org/10.1002/qj.2314
D - Journal article	Validation of the summertime surface energy budget of Larsen C Ice Shelf (Antarctica) as represented in three high-resolution atmospheric models	2015	Journal of Geophysical Research: Atmospheres.	https://doi.org/10.1002/2014jd022604
D - Journal article	Variability of the North Atlantic summer storm track: mechanisms and impacts on European climate	2013	Environmental Research Letters	http://dx.doi.org/10.1088/1748-9326/8/3/034037
D - Journal article	Variation in climate sensitivity and feedback parameters during the historical period	2016	Geophysical Research Letters	https://doi.org/10.1002/2016gl068406
D - Journal article	Very Strong Methane Growth in the 4 Years 2014-2017: Implications for the Paris Agreement	2019	Global Biogeochemical Cycles	https://doi.org/10.1029/2018gb006009
D - Journal article	Warm-air advection, air mass transformation and fog causes rapid ice melt	2015	Geophysical Research Letters	https://doi.org/10.1002/2015GL064373
D - Journal article	Wind-Tunnel Simulation of Weakly and Moderately Stable Atmospheric Boundary Layers	2018	Boundary-Layer Meteorology	https://doi.org/10.1007/s10546-018-0337-7

2. Impact case studies

Centre: National Centre for Atmospheric Science
Title of case study: International Measures to Control Ozone-Depleting Substances

1. Summary of the impact

NCAS has played a leading role in demonstrating the depletion of the stratospheric ozone layer following anthropogenic emissions of halogenated compounds and other Ozone Depleting Substances (ODS). This has been a key input into the assessment reports that have made the case to policy-makers for strengthening the phase-out schedules for ODS under the Montreal Protocol. Our research has made a direct contribution to recent new changes to the Montreal Protocol that have ensured a more rapid phase-out of a wider range of ODS and their replacements, leading to significant global health and climate benefits during this evaluation period.

2. Underpinning Centre activities

NCAS undertakes research in stratospheric ozone and related processes through its LTSS programmes in Long-term Global Change and Climate and High-Impact Weather. The underpinning activities are supported through multi-centre working, for example through the LTSM project ACSIS, which are then leveraged by many individual grant awards and researchers. Work by Professor *John Pyle* on ozone depletion models stretches back more than 30 years and has been central to the development of international treaties. Professor Pyle's work has been recognised previously with numerous research impact awards, including from NERC. NCAS' underpinning activities over this evaluation period have been focused on new primary research to support updated assessments of the impacts of ozone loss (e.g. the 2018 WMO/UNEP assessment), the impacts on climate, and new estimates of the effects on human health. Such activities have included developing and implementing an improved model of stratospheric ozone, enabled through the UKCA model chemistry and physics scheme, which has been implemented in several different meteorological and climate model configurations. NCAS skills and expertise supports UKCA code, which has a global user community, and has enabled the UK to participate in model inter-comparison exercises associated with stratospheric ozone predictions.

In addition to modelling and numerical simulations, we have an observation programme for ozone depleting substances (ODS), led by Dr *David Oram*. NCAS makes long-term measurements of atmospheric trace gas halocarbons, through a record collected in the Southern Ocean (the Cape Grim Archive) and throughout the troposphere and lower stratosphere using aircraft. NCAS provides unique measurements as part of IAGOS (In-service Aircraft for a Global Observing System) by collecting samples from Lufthansa passenger aircraft flights on global long-haul routes, with subsequent laboratory analysis for a range of different chemicals of relevance to ozone depletion. We have supported the development of new laboratory methods for ODS, using trace analytical mass spectrometry to discover new halocarbon compounds in air (often unintended by-products of chemical manufacturing). We have also determined high precision trends and identified source regions, through model inversions. The sensitivity of these analysis methods allows

ODS to be quantified at mole fractions as dilute as a few parts per quadrillion. NCAS' long-term global change research has enabled the UK to play an authoritative and leading role within the UNEP / WMO stratospheric ozone assessments, and dedicated time and resources for engagement in this impact activity are central to our research strategy.

3(a) Underpinning research

John Pyle has made world-leading contributions to stratospheric science. His major contribution has been the development of integrated chemistry-climate models for the stratosphere. The physical and chemical processes in his numerical models have been evaluated successfully against atmospheric observations, and the UM_UKCA model developed in collaboration with the Met Office is now established as a gold standard in climate prediction. This model is used internationally and is a key component of the UK Earth System Model (UKESM1).[1] UM_UKCA has been used to explain the role of ozone depleting substances (ODS) in past changes in atmospheric composition and to make projections about future changes. Since the creation of NCAS in 2000, Pyle and his NCAS colleagues (including *David Oram*) have published over 60 scientific papers that have greatly increased our understanding of the extent and causes of ozone depletion in the stratosphere, the factors that determine the rate of recovery of the ozone layer, the relationship between climate and chemical reactions of ODS with ozone, and the threat of anthropogenic, short-lived ODS that are currently outside the remit of the Montreal Protocol. Oram has led an extensive programme measuring ozone depleting substances (ODS) that are included as evidence emissions in the 2018 ozone assessment. These measurements of uncontrolled very-short-lived ODS have highlighted the potential importance of species such as dichloromethane for future ozone depletion [2].

Understanding ozone depletion in the stratosphere. UM_UKCA calculations performed by NCAS demonstrate that chlorofluorocarbons (CFC) and other halogenated compounds have depleted ozone in the Arctic. The model shows that the severe Arctic ozone loss that occurs in some winters follows the same chemical mechanism as found in Antarctica.[3] NCAS has pioneered studies on the relationship between stratospheric ozone levels and climate, which is now a major concern of the Montreal Protocol. Many global warming projection models use simplified estimates of atmospheric composition changes, often setting stratospheric ozone at constant pre-industrial levels. NCAS-led calculations on the complex feedback effects between atmosphere, land surface, ocean and sea ice have demonstrated that chemistry-climate feedbacks exert a significantly more important influence on global warming projections than previously realized [1]

Impact of the Montreal Protocol. Our calculations project the future evolution of ozone, and explain how atmospheric ozone concentrations are slowly recovering and responding to regulation. These chemistry-climate model projections show that, had the Montreal Protocol not been enacted, ozone depletion would have been even more severe - an Arctic ozone hole would have developed, leading to large changes in surface temperature and UV radiation [4]. In collaboration with epidemiologists, Pyle has extended these studies to demonstrate the very significant human health benefit of the Montreal Protocol by reducing future increases in skin cancer [5].

Short-lived ozone depleting substances. Modelling and observations by NCAS have shown that the scientific framework for regulation of short-lived ODS is different to that of the longer-lived gases like CFCs. For short-lived gases, the ozone depletion potential (a concept enshrined in legislation) varies with region and season of emission, whereas for long-lived gases it is constant. We have also demonstrated the threat posed to the environment by the very short-lived substance dichloromethane, an ODS that is not controlled by the Montreal Protocol. Very short-lived ODS were previously thought to play a minor role in ozone depletion due to their short atmospheric lifetimes. Pyle and collaborators showed that atmospheric concentrations of dichloromethane have risen recently and are continuing to increase rapidly, which will delay the recovery of the Earth's ozone layer. Our observations have also shown that the growing atmospheric abundance of another short-lived substance, dichloroethane. The impact of these short-lived ODS is now at the forefront of discussions of future regulation by the Montreal Protocol [6].

3(b) References to the underpinning work

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[2] Hossaini, R.; Chipperfield, M. P.; Montzka, S. A.; Leeson, A. A.; Dhomse, S. S.; Pyle, J. A. The Increasing Threat to Stratospheric Ozone from Dichloromethane. *Nat. Commun.* **2017**, *8*, 186–190. 10.1038/ncomms15962

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[6] Oram, D.E., Ashfold, M.J., Laube, J.C., Gooch, L.J, Humphrey, S., Sturges, W.T., Leedham-Elvidge, E., Forster, G.L., Harris, N.R.P., Mohammed Iqbal Mead, Azizan Abu Samah, Siew Moi Phang, Chang-Feng Ou-Yang, Neng-Huei Lin, Jia-Lin Wang, Baker, A.K., Brenninkmeijer, C.A.M., and Sherry, D., A growing threat to the ozone layer from short-lived anthropogenic chlorocarbons, Atmos. Chem. Phys., 17, 11929–11941, 2017 10.5194/acp-17-11929-2017

4. Details of the impact

To quote Kofi Annan's address to the United Nations, "*It is impossible to devise effective environmental policy unless it is based on sound scientific information*". Annan went on to point out "*Perhaps the single most successful international environmental agreement to date has been the Montreal Protocol, in which states accepted the need to phase-out the use of ozone-depleting substances.*" Over the last 7 years, NCAS research has continued to have a major impact on measures to further strengthen the Montreal Protocol, and have

contributed directly to international agreements on the phase-out of ODS and, most recently in this NERC evaluation period the *additional* international agreement for phase-out or phase-down of some of their chemical replacements [7].
The **Montreal Protocol on Substances that Deplete the Ozone Layer** came into force in response to the scientific evidence that human-induced depletion of the ozone layer was occurring. Every country in the world has signed the Protocol. Initially, the Protocol regulated only a handful of CFCs and set a schedule to phase-down their use. However, it is an agreement which is continually evolving as new scientific evidence comes to light, so changes to the Protocol have led to more rapid phase-out of CFCs and the addition of new controls for many more ODS (e.g. HCFCs). The 2016 amendment to the Protocol added hydrofluorocarbons (HFCs), which are potent climate gases, to the list of controlled substances with an agreement to phase-down their use over the next 30 years.[8,9]

The Protocol mandates that the measures it introduces must be assessed every 4 years on the basis of available scientific, environmental, technical, and economic information. It specifies a scientific assessment process by which international panels of experts are required to prepare reports to guide policymakers in their decisions regarding the Protocol. The **Scientific Assessment of Ozone Depletion Assessments** written by Scientific Assessment Panel (SAP) are published by the WMO. Pyle has contributed evidence to all the WMO Assessments to date, and for the three most recent Assessments, including in 2014 and 2018, was one of four international co-chairs of the SAP[10,11]. The 2018 Assessment contains 50 citations to original research by Pyle and Oram, including the publications above. The WMO Assessments feed into the on-going Montreal Protocol regulation process and hence have continuing and wide-reaching impact.

At least twice a year, there are meetings of the representatives of the governments of all 197 signatories of the Protocol, which are called the **Conference of the Parties, Meetings of the Parties, and Open Ended Working Groups**. The WMO Assessments produced by the SAP feed directly into these meetings, advising and supporting decision makers in modifying the Protocol. Pyle attends these meetings to present the scientific evidence on which the decisions taken are based. NCAS' work on short-lived ODS led to a specific plenary discussion of this problem at the Meetings of the Parties at MOP29 in 2017, and this is discussed in the Executive Summary of the 2018 Assessment.[12-15]

A World Avoided. The controls put in place by the Montreal Protocol have had a significant impact on the sustainability of the planet and have averted long-term threats to future health. In 2018, definitive evidence was obtained to show that the hole in the ozone layer over Antarctica has begun to shrink.[13] The models that originally identified problems with CFCs in the stratosphere and the consequences for ozone depletion were confirmed by the experimental observation of the Antarctic ozone hole. Pyle's studies have shown that, without the Montreal Protocol, an Arctic ozone hole, similar to that seen in the south, would have occurred during the last decade with large increases in UV and additional impacts on human health. Many millions of skin cancers are avoided annually as a direct result of the reduction in UV dosage due to the measures put in place by the Protocol [12, 14]. The Protocol has also had a major impact in reducing climate change through the phase-out of ODS which are also greenhouse gases.

NCAS' research has not only provided critical scientific inputs into the Montreal Protocol, which continues to have major long-term impacts on the habitability of the planet, but also provided a platform to directly influence government policy in every country in the world through the role of Pyle as co-chair of the Scientific Assessment Panel. Tina Birmpili, Executive Secretary of the United Nations Ozone Secretariat, said "*We, in the ozone community, are so proud to have Professor John Pyle guiding the decision making of the parties to the Montreal Protocol ... His work has vastly contributed to our global efforts to protect the ozone layer*".[15]

5. Sources to corroborate the impact

[7] Corroboration available from Executive Secretary to the UNEP Ozone Secretariat

[8] United Nations Environment Programme – Kigali 15.11.2016
"Report of the Twenty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer"
conf.montreal-protocol.org/meeting/mop/mop-28/final-report/English/MOP-28-12E.pdf

[9] UN Environment OzonAction – About Montreal Protocol "Phase down of HFCs – The Kigali Amendment" resources/factsheet/kigali-amendment-montreal-protocol-hfc-phase-down

[10] World Meteorological Organization – 2014 Report by the Scientific Assessment Panel (SAP) 19.12.2014 "Scientific Assessment of Ozone Depletion: 2014"
https://www.esrl.noaa.gov/csd/assessments/ozone/2014/

[11] World Meteorological Organization – 2018 Report by the Scientific Assessment Panel (SAP) 01.2019 "Scientific Assessment of Ozone Depletion: 2018"
https://ozone.unep.org/sites/default/files/2019-05/SAP-2018-Assessment-report.pdf

[12] United Nations Environment Programme – Quito 15.11.2018
"Report of the Thirtieth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer" Report of the Thirtieth Meeting of the Parties to the Montreal Protocol

[13] International Institute for Sustainable Development Reporting Services – 05.11.2018 "30th Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer" https://enb.iisd.org/ozone/mop30/

[14] Our World in Data – Impacts on Skin Cancer Risk 06.2018 "Ozone Layer"
https://ourworldindata.org/ozone-layer#impacts-on-skin-cancer-risk

[15] United Nations Environment Programme – Ozone Secretariat 14.07.2018
UNEP award to "SAP Co-Chair John Pyle, Awarded for Scientific Leadership"
https://ozone.unep.org/sap-co-chair-john-pyle-awarded-scientific-leadership

Centre: National Centre for Atmospheric Science
Title of case study: Drought Monitoring and Early Warning for African Food Security

1. Summary of the impact

Over 200 million people in sub-Saharan Africa depend on rainfed, subsistence agriculture. Accessible climate services are key to managing the weather-related risks faced by these farmers along with reliable, local monitoring supporting risk management, including weather-index insurance (WII) and agricultural decision-support. Nationally trusted monitoring and forecasting products enable governments to mobilise aid. NCAS research by the Tropical Applications of Meteorology from SATellite data (TAMSAT) group have demonstrably improved Africa's resilience to drought. During 2015-2016 TAMSAT rainfall estimates informed the Food and Agriculture Organisation's (FAO) response to a severe drought in the Horn of Africa, and since 2014, payouts from TAMSAT-based insurance have compensated over 2 million farmers affected by adverse weather.

2. Underpinning Centre activities

NCAS research has produced robust estimation of meteorological, hydrological and agricultural risk across Africa, via the TAMSAT programme and other related underpinning activities. We have provided underpinning research and capability for TAMSAT since 2014 by supporting *Emily Black* and *Matt Young* via National Capability programmes and most recently a work package within ACREW, a National Capability Official Development Assistance research programme.

At the heart of TAMSAT is a high-resolution rainfall dataset, spanning all of Africa from 1983 to the present day. The dataset is updated throughout the year, now that Africa-wide rainfall estimates are issued every five days (http://www.tamsat.org.uk). Recent developments of TAMSAT's rainfall estimation technique, carried out through NERC, NCAS and EU projects, have substantially improved the utility of the dataset. The original TAMSAT dataset contained a persistent dry bias and the aggregation of regions into 'calibration zones' resulted in spatial artefacts. NCAS worked to develop a revised calibration technique that has eliminated these issues, increasing the skill of the dataset and user confidence. Additional advances have seen the disaggregation of previous 10-day rainfall accumulations into daily rainfall estimates, improving the relevance of TAMSAT data for monitoring short-term risk and for deriving cumulations over bespoke periods.

The wide uptake of TAMSAT data stems in part from the historical calibration approach, which allows us to meet user demands for real-time observations that reliably identify anomalous conditions. Alternative methods that ingest real-time rain gauge observations can have a latency of up to six weeks and suffer from instabilities caused by missing rain gauge records. Such instabilities lead to large biases in estimated trends and create difficulties with identification of anomalous conditions, making these alternative methods unsuitable for weather-index insurance (WII). The WII compensates farmers for the effects of adverse weather conditions when a weather threshold is breached.

Prompted by the need to anticipate risk, the TAMSAT Agricultural Early Warning System (TAMSAT-ALERT) was developed by NCAS through a series of NERC projects and the ACREW National Capability programme. TAMSAT-ALERT is a statistical and land-surface modelling framework that provides an assessment of agricultural risk based on monitoring of the growing season, the historical climatology and the meteorological forecast. TAMSAT-ALERT can be used for assessing the seasonal risk of low yield and for decision-support within seasons, such as when to plant and when to apply fertilisers.

Although rainfall monitoring plays a crucial role in early warning of drought, it is ultimately soil moisture deficit (agricultural drought) rather than rainfall deficit (meteorological drought) that affects crop yields. The importance of determining an agricultural drought has motivated the development of a novel technique, which estimates soil moisture: data assimilation principles are used to calibrate a land-surface model, integrating TAMSAT rainfall estimates with reanalysis and remotely sensed surface soil moisture. Calibration of crop specific parameters allows the derivation of the agricultural risk metrics used by international organisations, including the FAO and Red Cross.

TAMSAT tools and datasets can, in principle, be applied to manage risk on scales from individual communities to continents. The scaling of risk assessments does raise questions about interactions between agricultural and meteorological drought and the representativity of broad scale forecasts for individuals. NCAS' ongoing underpinning research is supporting the use of TAMSAT across these scales, and is extending the utility of TAMSAT for local to international applications through stakeholder co-development.

3. References to the underpinning work

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4. Details of the impact

The growing applications of NCAS drought monitoring and forecast services stem from (i) the longevity of the TAMSAT rainfall dataset; (ii) its skill in reliably monitoring rainfall; (iii) the near-real time release of the data; (iv) the skill of TAMSAT-ALERT in reliably forecasting agricultural drought metrics (including soil moisture) and; (v) the investment of NCAS staff in building capacity to utilise the data within African organisations. As a result, the impact extends beyond rainfall estimation to supporting agricultural decision-making and risk mitigation initiatives.

Financial sector: insurance

Due to TAMSAT's near-real time availability and its skill in detecting anomalous conditions, TAMSAT data is increasingly used by the financial sector to provide WII to farmers across Africa. This includes Africa Risk Capacity (ARC) who provide financial tools to all African Union countries to manage natural disaster risk, and the business OKO bringing insurance to farmers in Mali [3]. Since 2013, Zambia-based Risk Shield Consultants have exclusively used TAMSAT rainfall estimates to insure farmers across Africa in Angola, Botswana, Ghana, Kenya, Lesotho, Malawi, Mozambique, Namibia, Nigeria, Rwanda, Sudan, Tanzania, Uganda, Zambia and Zimbabwe [4]. Through Risk Shield Consultants, TAMSAT data has been used in the Zambian Government's Farmer Input Support Programme, insuring over 2 million farmers since 2017 [5].

The impact of this programme was evident during the 2017-2018 rainy season, when adverse weather conditions were determined by TAMSAT data. This resulted in insurance payouts of more than $3 million, an amount unprecedented for this type of insurance at the time, enabling farmers to purchase new seed and food for their families. A quote from the director of Risk Shield Consultants, Agrotosh Mookerjee, explains the significance of TAMSAT data in WII: "*Index insurance products based on TAMSAT data have triggered approximately 12 million US dollars in pay-outs over 2015-2019 in micro-insurance schemes. These products have reduced the climate risk faced by smallholder farmers in Africa and also enabled farmers to have better access to agricultural inputs, credit and access to off-takers due to the presence of the insurance products. These achievements would not have been possible without timely access to the accurate TAMSAT satellite data. The TAMSAT data has been crucial for the development and implementation of weather-index insurance products and the quality of the insurance products, which millions of smallholder farmers are now able to access* " [4].

Anticipating risk and evidence based decision support

TAMSAT-ALERT has been adopted by regional centres in East Africa to enhance their seasonal outlook bulletins for the region, including by ICPAC (Climate Predictions and Applications Centre), the National Drought Management Agency and the Kenya Meteorological Department. TAMSAT-ALERT seasonal outlooks have also informed World Food Programme bulletins for Zambia [6] and National Drought Management Agency announcements in Kenya [7]. Planting date decision-support, based on TAMSAT-ALERT predictions, is now provided to more than 500,000 farmers in Kenya following successful trials by the One Acre Fund. Despite its infancy, the demand for reliable, local and up-to-date rainfall forecasting has seen these and other TAMSAT-ALERT activities becoming fully operational in 2019.

Rainfall monitoring

Owing to its longevity and short latency, TAMSAT data are used in a range of pan-African governmental and non-governmental climate services for rainfall monitoring and as inputs into agricultural models. Examples include Enhancing National Climate Services

(ENACTS) [8], Rainwatch and the Africa Risk Capacity (ARC) [8], as well as multiple NMHS, regional centres and charities, such as Hydrogeologists Without Borders who aim to improve the sustainable management of water sources in developing nations. Through ENACTS, TAMSAT data is combined with rain gauge measurements to provide high quality rainfall information to improve national drought contingency planning in Mali, Ghana, Zambia, Rwanda, Madagascar, Tanzania and Ethiopia, and regionally across West Africa [8]. In turn, ENACTS formed an integral component of the 2018 Climate Smart Agriculture Project of the Year award-winning project, Rwanda's Climate Services for Agriculture [9], which aims to improve the accessibility of climate information to improve agricultural planning and food security.

Capacity building

TAMSAT enables Africans to benefit from scientifically credible information on drought. We also help to build the capacity of NHMSs to develop and exploit TAMSAT-based products. NCAS has offered internships and research supervision to more than 15 African students from 10 countries - many of whom now hold senior positions in African NHMSs. Having completed his dissertation with the TAMSAT group in 2015, Mr Edson Nkonde is now head of the Zambia Meteorological Department (ZMD) and has worked with TAMSAT collaborators (Risk Shield Consultants and the World Food Programme) to enhance the use of satellite products for climate services, including the launch of Zambia's WII scheme. Uptake of TAMSAT data represented a major change of policy in Zambia. NCAS has facilitated workshops and contributed to WMO courses throughout Africa. These activities have resulted in a growing community of NHMS staff capable of exploiting available data to improve climate services.

As a matter of policy, all TAMSAT code and datasets are freely available without licensing restrictions and were developed to operate on low-specification laptops (of the power used by NHMSs). Supporting our user community in this way has enabled commercial, governmental and non-governmental organisations to provide robust monitoring and forecasting services. The approach saw TAMSAT shortlisted for an open data award in 2019.

5. Sources to corroborate the impact

Summary
[1] https://www.dropbox.com/s/yrtveffrgya6q6u/fao_bulletin.pdf?dl=0
[2] https://www.dropbox.com/s/w4q1eaxztcjkumo/fisp_statement.pdf?dl=0

Financial sector
[3] https://www.oko.finance/blog-1
[4] https://www.dropbox.com/s/tcp8zq1dyo4a25k/risk_shield_letter.pdf?dl=0
[5] Examples :
http://www.parliament.gov.zm/sites/default/files/images/publication_docs/MINISTERIAL%20STATEMENT%20BY%20THE%20%20MINISTER%20OF%20AGRICULTURE%2C%20MR%20KATAMBO%2C%20ON%20FISP.pdf ;
https://indexinsuranceforum.org/project/zambia ;
https://www.musika.org.zm/headlines/fisp-electronic-voucher-program-to-promote-diversification/ ; http://www.times.co.zm/?p=80609

Anticipating risk
[6] https://www.dropbox.com/s/a2d1johplc7eu9b/WFP_report.pdf?dl=0
[2] https://www.dropbox.com/s/z0yikibe39ifmst/2019%20-10%20Kitui%20Bulletin.pdf?dl=0

Rainfall monitoring

[7] https://worldpolicy.org/wp-content/uploads/2016/03/The-ENACTS-Approach-Transforming-Climate-Services-in-Africa-One-Country-at-a-Time.pdf
[8] http://www.africanriskcapacity.org/wp-content/uploads/2018/06/COP6_FINAL-REPORT_EN_20180507.pdf
[9] https://ccafs.cgiar.org/news/media-centre/press-releases/rwanda-climate-services-agriculture-project-awarded-first-ever#.XI9p3aecZSw

Centre: National Centre for Atmospheric Science
Title of case study: New estimates of extreme winds and waves for oil and gas platform design

1. Summary of the impact
Estimates of extreme wave heights are used by the oil and gas industry in the design and maintenance of offshore oil and gas platforms. A new method has been developed by NCAS and BP to estimate extreme wave heights from multi-century climate model simulations. These new extreme wave estimates are now widely used by BP and other companies and have led to a *"huge reduction in the uncertainty of abnormal wave loads"* for their North Sea and Caspian platforms. Additional work to assess extremes for design criteria in the Caribbean has also been undertaken by NCAS.

2. Underpinning Centre activities

NCAS has undertaken research evaluating extratropical and tropical storms in high-resolution climate models (*Len Shaffrey, Kevin Hodges*), and research into global climate modelling as part of the NCAS HRCM (High-resolution Climate Modelling) programme (Lead: *Pier Luigi Vidale, Reinhard Schiemann, Bennoit Vanniere, Alex Baker, Marie-Estelle Demory*). This activity was heavily supported by the NCAS Computational and Modelling Support team (*Grenville Lister*), the Centre for Environmental Data Analysis and the JASMIN data centre (*Bryan Lawrence*), which enabled the long climate simulations to be performed, archived and analysed.

For over 15 years, NCAS has been a world leader in developing and analysing higher resolution coupled climate models through its HRCM programme. Working jointly with the Met Office, we have led the development of higher-resolution versions of the HadGEM1 [1] and HadGEM3 [5] Met Office global coupled climate models. Increasing resolution improves the fidelity of climate model simulations and leads to a better representation of extreme weather, such as extratropical and tropical storms [2, 6]. Present-day and future simulations with higher resolution climate models allow us to better address questions concerning present-day risks from extreme weather, and the potential impacts of climate change.

As part of our Climate and High Impact Weather science theme, we have evaluated the representation of extratropical and tropical storm in a wide variety of datasets including observational reanalysis, the HRCM high-resolution climate models, and the climate models used in the IPCC (Intergovernmental Panel on Climate Change) assessment reports. We also maintain and develop tools such as the Hodges (1995) tracking scheme [4], which identifies and tracks extratropical and tropical storms in reanalyses and climate models.

A key insight from our research is that increasing the resolution of climate models leads to substantial improvements in the representation of extreme weather, such as extratropical and tropical cyclones (2,6). Large ensembles of present-day simulations with high resolution climate model simulations can provide multi-century datasets of extreme weather, which are then used to assess risks. This is particularly true for extreme risks that are difficult to assess, due to either i) short observational records and/or ii) the complex manner in the risks that are generated (both of which are true for extreme winds and waves in the North Sea). Despite improvements, biases still remain in high resolution climate models so it is important to fully evaluate biases and potentially develop calibration schemes.

3. References to the underpinning work

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[6] Roberts, M. J., Vidale, P. L., Mizielinski, M. S., Demory, M.-E., Schiemann, R., Strachan, J., Hodges, K., Bel, R. and Camp, J. (2015) Tropical cyclones in the UPSCALE ensemble of high resolution global climate models. Journal of Climate, 28 (2). pp. 574-596. doi: 10.1175/JCLI-D-14-00131.1

4. Details of the impact

BP has been extracting oil and gas in the North Sea for more than 50 years, and is the operator for over a dozen installations in the West Shetland and Central North Sea areas. In Norway, BP (as AkerBP) is the operator for the Valhall, Ula, Ivar Aasen, Alvheim and Skarv installations. These assets require substantial capital investment, for example, the new Clair Ridge facilities in West Shetland required investment in excess of £4.5 billion [7]. BP and the wider Oil and Gas industry use estimates of very extreme (typically 1-in-10000 year) wave heights to design and manage risks to offshore oil and gas installations. Current industry methods are based on estimating extremes by statistically extrapolating from observed wave heights. The uncertainties in these estimates are very large due to i) sampling uncertainties that arise from extrapolating short observational records of observed waves; and ii) epistemic uncertainties that arise since statistical models poorly represent the physical processes that govern the heights of very extreme waves. These very large uncertainties present a massive challenge for BP and the wider Oil and Gas industry, since assessments of environmental risks from abnormal wave loads are critical to the safety of personnel, the resilience of offshore platforms and maintaining oil and gas production.

To address these challenges, BP approached NCAS in 2012 and a Knowledge Transfer Partnership (KTP, 2014-2016) was established to develop a new physically based method to estimate extreme wave heights. Known as the NS1200, the KTP's dataset consists of 1,200 years of modelled North Sea wave heights generated using calibrated surface winds and pressures from an ensemble of historical HiGEM high-resolution climate simulations [1, 3]. The calibrated output from HiGEM was used to drive the WaveWatch 3 spectral ocean wave model to produce 1,200 years of North Sea waves. The ability of the NS1200 dataset and HiGEM model output to represent observed extreme storms, winds and wave were evaluated extensively. We used the TRACK storm tracking software [4] to identify the paths of extratropical storms and measurements of wave heights taken at BP North Sea platforms. Development of the NS1200 dataset was peer-reviewed during the project through a series of meetings with other North Sea operators (Shell, Maersk, Conocophilips, Equinor, and Woodside), the UK Health and Safety Executive, and the Norwegian Petroleum Directorate.

The value of the research was highlighted by BP as follows: "*The project led to a huge reduction in the uncertainty of abnormal wave loads affecting our permanently manned installations and informed significant mitigation measures, now being implemented to keep our people safe on platforms West of Shetland and the central North Sea*." [8]

The NS1200 dataset has been widely adopted within BP to assess the design criteria and safety parameters for their North Sea platforms. This has led to a *"huge reduction in the uncertainty of abnormal wave loads"* affecting North Sea and Norwegian BP offshore platforms. As a measure of the extent of NS1200's impact, the outcomes have been disseminated widely within the Oil and Gas industry (see list of industry events in reference [9]). In addition, the NS1200 dataset has been shared with other North Sea operators. This has led to *"safer operating practices"* at major North Sea installations (see Testimonial letter.

Since HiGEM is a global high-resolution climate model, it produces output for other regions. Therefore, it is possible to assess risk in other locations of interest for BP and other Oil and Gas companies. BP has used the 1,200 year HiGEM output to assess environmental risks for a £4.6 billion Azeri Central East project in the Azerbaijan sector of the Caspian Sea. In addition, a joint NCAS and BP project (fully funded by BP) is underway (2018-2020) to produce a similar dataset but for hurricanes in the southern Caribbean. This work uses the 25km resolution HadGEM3 simulations (Mizielinski et al. 2014) to assess extreme risks to offshore installations.

5. Sources to corroborate the impact

[7] BP report on Clair Ridge production and financial investment. https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-starts-up-clair-ridge-production.html

[8] Testimonial letter from BP Metocean Team Leader

[9] List of Oil and Gas industry events and presentations on the NS1200 dataset:
i) International Association of Oil and Gas Producers workshop on "Our Future https://www.iogp.org/our-future-climate/
ii) 2018 Offshore Structural Reliability Conference https://www.api.org/products-and-services/events/calendar/2018/osrc

Centre: National Centre for Atmospheric Science
Title of case study: New international standards to deliver global reductions in aviation soot

1. Summary of the impact

NCAS developed methods to quantify and standardise the measurement of non-volatile particulate matter (nvPM) from aircraft engines. The International Civil Aviation Organisation (ICAO), which is the global regulator for the aviation industry, used our methods to update standards for aircraft emissions that affect local air quality, and to introduce new international measurement and emission standards for large aircraft, impacting an industry worth $100B pa. This has affected global aircraft engine design and regulation and been realised through; i) two new international standards for nvPM measurements, ii) technical advice in ICAO regulatory documents, iii) the introduction of mass and number emission limits from new aircraft engines to reduce global aviation soot.

2. Underpinning Centre activities

NCAS has a long-term programme of research in measurement of atmospheric particles and aerosols, including technology development, approaches to calibration and service provision to the community. We use this capability to undertake research on topics ranging from urban air quality through to the global scale interactions between aerosols and clouds. Our expertise was translated to the aviation sector to support the development of new regulations on aircraft emissions of particles. Our underpinning research activities allowed us to:

- Identify suitable measurement technologies and sampling protocols.
- Validate the proposed methodologies and develop software for producing quality assured data.
- Undertake measurements of real engine emissions, in turn allowing ICAO to set current and future emission limits.
- Quantify the uncertainties in the particle sampling framework and the values reported by engine manufacturers to ICAO.

NCAS scientist *Paul I. Williams*, is a globally recognised expert publishing in the field of aerosol measurement and aircraft emissions [e.g. 1,2,3], and was invited to contribute research project designs, execution and report writing to the International Civil Aviation Organisation (ICAO). The reference Petzold *et al.* [1] described the technologies available for aircraft emission measurements, without which a measurement standard could not have been defined. NCAS activities in aerosol counting and sizing made a key contribution by providing equipment and analysis of the data contained in the paper, leading to recommendations and the development of the measurement standards.

The European Aviation Safety Agency (EASA) funded the majority of the research through a series of programmes (SAMPLE I-III, 2009-2014; EASA specialist support I – IV, 2014 – 2019). Later programmes required assessment of the losses and uncertainties in the proposed methodology. Williams provided key aerosol measurements, quantified the number and aerosol sizes from engine emissions and evaluated the aerosol losses and uncertainty in the sampling systems. Without this underpinning expertise in aerosol counting and sizing [3], the final recommended design, and ultimately the standard, would not have been complete.

NCAS developed a loss and uncertainty model for the sampling system, in parallel with the US aviation regulators, in order to report uncertainties with emission data to ICAO. In 2016, Dr Williams highlighted a fundamental flaw in the error analysis of the uncertainty calculations, and developed a new methodology based on Monte Carlo modelling approaches. This was adopted and is now used in the ICAO regulatory documents for calculating uncertainties.

The research led to the design of the EU nvPM reference system for nvPM measurement. The reference systems for the EU, North America and Switzerland were used to make measurements of engines during the later SAMPLE projects [3-6]. ICAO used this data to set emission standards for new aircraft engines. Capitalising on past expertise in the field of aerosol technology and new expertise in aerosol loss and uncertainty modelling, NCAS contributed data on number and mass concentration emissions and associated uncertainties, which were used by ICAO to set engine emissions limits.

3. References to the underpinning work

[1] Petzold, A., Marsh, R., Johnson, M., Miller, M., Sevcenco, Y., Delhaye, D., Ibrahim, A., Williams, P. I., Bauer, H., Crayford, A., Bachalo, W. D., and Raper, D. Evaluation of methods for measuring particulate matter emissions from gas turbines. (2011) *Environmental Science and Technology*, **45**, 3562 – 3568. dx.doi.org/10.1021/es103969v

[2] Williams, P. I., et al. Impact of Alternative Fuels on Emissions Characteristics of a Gas Turbine Engine – Part 2: Volatile and semi-volatile particulate matter emissions (2012). *Environmental Science and Technology*, **46**, 10.1021/es301899s

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[5] Crayford, A., Johnson, M., Llamedo, A., Williams, P. I., Madden, P., Marsh, R., and Bowen, P. (2013) SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Third Specific Contract– Final Report. https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc03

[6] Crayford, A., Johnson, M., Sevcenco, Y. A., Williams, P. I., Madden, P., Marsh, R., and Bowen, P. J. (2015) SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Fifth Specific Contract– Final Report. https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc05

4. Details of the impact

Previous international regulations on particulate emissions from aircraft engines had not been updated since the 1970s. The regulation, based on a metric called “smoke number” (used as a measure of visibility), was no longer suitable to address current local air quality (LAQ) and human health. A new metric and standard was called for by the International Civil Aviation Organisation (ICAO) in 2009 for engines rated above 26.7 kN of thrust. This represents the engines used in the global commercial, non-propeller air fleet. ICAO sets the global standards for safety and environmental performance of the world’s aviation industry.

As a result of internationally recognised expertise in characterising the chemical and physical properties of aerosol particles [7], NCAS was approached by EASA and ICAO to collaborate on the technical design of a new nvPM sampling system and the production of a methodology for making nvPM measurement standard. Dr Williams’ contribution underpinned the technology and methods for size and number concentration measurements and validated the losses and uncertainties in the sampling system [8]. Membership of the international standards agency SAE provided Dr Williams a platform to advocate for, develop and approve the standards for nvPM measurement and reporting [9]. This also supported NCAS’ contribution to the writing of official ICAO Annex documents [10], leading to significant, technological, environmental, and economic impacts, summarised as, and expanded on under the three headings.

- Two international standards for nvPM measurements and an updating of the ICAO regulatory documents (Annex 16, Vol II, Appendices 7 & 8), which all large engine manufacturers must use to report their nvPM emissions to the ICAO.

- Setting a new nvPM mass emission index limit (EI_m– kg nvPM/kg of fuel burnt) for in-production engines and reporting number EI_n(number concentration nvPM/kg fuel burnt) to ICAO from 2020, with in-production nvPM number limits legally enforced from 2023.

- Manufacturers have agreed to a reduction in the mass and number emission limits for new aircraft engines designs from Jan 2023 of ~ 30% compared with in-production engines, and a reduction in global aviation soot emission.

Technological impacts:
As a result of this research, two new international standards and updated regulatory documents have been produced [7, 8, 10, 11, 12, 13].

- **ARP 6320:** Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines [12]
- **ARP 6481:** Procedure for the Calculation of Non-Volatile Particulate Matter Sampling and Measurement System Losses and System Loss Correction Factors [13]
- Technical contributions to the ICAO regulatory documents Annex 16, Vol II, Appendices 7 & 8 [8,10]

Engine manufacturers are required to follow the ICAO Annex for reporting and emission standard compliance. 192 countries are signatories to ICAO, and these new technological standards ensure that from 2020, all in-production engines over 26.7kN of thrust (all commercial jet engines, excluded turboprop and turbofan engines) operating in those national airspaces must conform to these standards of reporting and emission levels.

Environmental impacts:
NCAS assisted ICAO in determining the limits of nvPM permissible by aircraft engines [14], which was approved by ICAO in Feb 2019 [15]. New regulatory mass limits for particle emissions were enforced from January 2020 for in-production engines with in-production particle number limits to be enforced from 2023. New limits have been agreed for all new engines designs from January 2023, a reduction of approximately 30% for both aerosol number and mass. These emission standards facilitate a gradual reduction in the emission levels of aircraft as the levels set by ICAO are periodically adjusted to reduce emissions [8]. The emission standard was approved by ICAO in February 2019 [15]. Aircraft operate globally and hence the environmental impact beneficially affects all airports, and surrounding communities that are served by commercial jets.

Economic impacts:
The economic impact of this work is on an engine manufacturing industry with annual global revenue measured in the 10's of $bn. Failure to report as per the ICAO documentation on engine emissions, or to meet the emission standards that NCAS has helped develop, would mean engine manufacturers would be unable to sell their engines. As an indication of scale, in 2017 and 2018, Rolls Royce reported in their public annual report sales of large engines as £2.1bn and £2.4bn respectively [16]. GE Aviation 2018 annual report gives a combined sales and service of $22.7bn, with our estimated sales of new engines for this manufacturer in the range $2.3 – 4.5bn (since these figures are not reported separately). Since the standards will be in place for at least a decade, the cumulative economic impact of the industry that this research now helps regulate in terms of environmental performance is likely to easily exceed $100bn.

5. Sources to corroborate the impact

[7] Testimonial letter from EPA confirming Dr Williams' involvement, validating and developing the uncertainties and losses, and contributing to the standard writing. In addition, evidences the change in metric from visibility to local air quality.

[8] Testimonial letter from EASA confirming Dr Williams' involvement in the standard development and writing and contribution to ICAO documents. EASA letter also confirms regulators commitment to reducing emission standards. Letter also confirms Dr. Williams' contribution to the EU reference system design and uncertainty analysis.

[9] Testimony letter SAE confirming membership of, and voting rights on, the SAE committee.

[10] Letter of invitation from ICAO to contribute to regulatory documents Annex 16, Vol II, Appendix 7.

[11] Evidence by description of scope in EASA reports: https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc03 and https://www.easa.europa.eu/document-library/research-projects/easa2010fc10-sc05, see executive summary on web pages or Page 7 of downloadable PDFs).

[12] ARP 6320: https://www.sae.org/standards/content/arp6320/

[13] ARP 6481: https://www.sae.org/standards/content/arp6481/

[14] Evidence by statement in EASA report - https://www.easa.europa.eu/document-

library/research-projects/easa2010fc10-sc05, see executive summary on web page or Page 7 of downloadable PDF).

[15] Press release from ICAO: https://www.icao.int/Newsroom/Pages/Sustainable-aviation-takes-significant-step-forward-at-ICAO.aspx?from=groupmessage&isappinstalled=0

[16] Rolls Royce annual report 2018 https://www.rolls-royce.com/investors/annual-report-2018/annual-report-archive/annual-reports.aspx(see page 27 of the PDF).

Centre: National Centre for Atmospheric Science
Title of case study: Recent air pollution actions and the 2019 UK Government Clean Air Strategy

1. Summary of the impact

NCAS research has influenced actions to improve air quality in the UK for nitrogen oxide (NOx) and volatile organic compounds (VOCs). Real-world transport emission estimates have been used to motivate reductions in urban NO_2 and inform litigation on diesel engine emissions. Insight into sources of VOCs led to proposals in the 2019 Clean Air Strategy for reductions in domestic sector emissions. A body of research has underpinned recommendations in multiple expert reports published by Defra, been extensively cited in Parliamentary select committees, and has facilitated direct advice to Defra, including at Ministerial level, to BEIS and to the Cabinet Office.

2. Underpinning Centre activities

Air pollution forms one of the three NCAS science themes and capability to study air pollution processes is included with its services and facilities. NCAS undertakes research that encompasses laboratory studies of gas and particle reactions, through to field studies of air pollution processes and modelling of air pollution transport and effects. This has generated a substantial body of research (~ 450 peer reviewed publications 2013-2020) addressing contemporary issues associated with atmospheric chemistry and air pollution, delivered by ~20 research staff with open-ended roles.

Underpinning research quantifying the emissions and atmospheric behaviour of two key classes of air pollutants, nitrogen oxides (NOx) and volatile organic compounds (VOCs) have been central to generating the impact reported here. A body of research by *James Lee* and co-workers highlighted that emissions of NOx in the urban environment substantially exceeded the amounts reported in national and London emissions and that are used for pollution forecasting and policy-setting. Lee developed the first top-down estimates of urban NOx emissions using eddy covariance measurements from tall towers (notably the BT Tower in London) [1] and from low flying aircraft detecting emissions at a city scale. This latter work identified that in central London private cars contribute relatively limited amounts of NOx, relative to other diesel power users. Using large decadal datasets drawn from across Europe, in 2017 *Sarah Moller* and *Alastair Lewis* identified that future policy projections of urban NO_2 began deviating from observations around 2010 and that the policy models used across Europe for estimating direct tailpipe NO_2 required substantial revision, research later highlighted by a House of Commons inquiry [2].

Alastair Lewis, James Allan and co-workers used underpinning research capabilities from the NCAS Atmospheric Measurement Facility (AMF) to quantify emissions of evaporative and unburnt diesel fuel and aerosol emissions from wood-burning and cooking processes in central London. This identified that for some pollutants emissions were up to 70 times greater than assumed in the UK National Atmospheric Emission Inventory and that the diesel fleet and domestic combustion could impact significantly on secondary ozone and particle ($PM_{2.5}$) concentrations. NCAS research into the impacts of ethanol, identified that is now the most abundant VOC found in UK urban air, a result of an increase in domestic solvent consumption sources and a reduction in hydrocarbon emissions from the fossil fuel and transport sectors [4]. NCAS supported a long-term research activity to quantify emissions of VOCs from the industrial and domestic sectors [5], a combination of National Capability activity with external industry funding and collaborations with Ricardo plc. *Lewis* identified the growing significance of domestic emissions of VOCs, trends driven by increases in population and solvents within consumer product. With support from BEIS *Alastair Lewis* and *Ruth Purvis* made long-term measurements of NOx and VOCs at two rural candidate shale gas locations in Lancashire and North Yorkshire [6]. This research identified the air quality impacts of shale gas industries operating under UK conditions, with NCAS identifying that in a UK context enhancement in NOx from operational and supply-chain activities were a significant environmental impact.

3. References to the underpinning work

[1] J.D Lee, C. Helfter, R.P. Purvis, S. Beevers, D.C Carslaw, A.C. Lewis, S.J. Moller, A. Tremper, A. Vaughan, E.G Nemitz. (2015) Measurement of NO_x fluxes from a tall tower in central London, UK and comparison with emissions inventories. *Environmental Science and Technology*, **49**, 1025-1034. 10.1021/es5049072, PDF version

[2] S Grange, S.M Moller, A.C Lewis and D.C Carslaw. (2017). Lower vehicular primary emissions of NO_2 in Europe than assumed in policy projections. *Nature Geoscience*, **10**, 914-918. 10.1038/s41561-017-0009-0, https://tinyurl.com/txg7zau

[3] R.E. Dunmore, J.R. Hopkins, R.T. Lidster, J.D. Lee, M.J. Evans, A.R. Rickard, A.C. Lewis, J.F. Hamilton. (2015) Diesel-related hydrocarbons can dominate gas phase reactive carbon in megacities. *Atmospheric Chemistry & Physics*, **15**, 9983-9996. 10.5194/acp-15-9983-2015

[4] R.E Dunmore, L.K Whalley, T Sherwen, M.J Evans, D.E Heard, J.R Hopkins, J.D Lee, A.C Lewis, R.T Lidster, A.R Rickard, & J.F Hamilton. (2016) Atmospheric ethanol in London and the potential impacts of future fuel formulations. *Faraday Discussions.* **189**, 105-120. 10.1039/C5FD00190K

[5] C.M Wang, B Barratt, N Carslaw, A Doutsi, R.E Dunmore, M.W Ward & A.C Lewis. (2017) Unexpectedly High Concentrations Of Monoterpenes In A Study Of UK Homes. *Environmental Sciences: Processes and Impacts*, **19**, 528-537. 10.1039/c6em00569a

[6] Purvis, R.M., Lewis, A.C., Hopkins, J.R., Wilde, S., Dunmore, R.E., Allen, G., Pitt, J., Ward, R.S., Effects of 'pre-fracking' operations on ambient air quality at a shale gas exploration site in rural North Yorkshire, England. (2019) *Science of the Total Environment,* **673**, 445-454. 10.1016/j.scitotenv.2019.04.077

4. Details of the impact

Air pollution generates substantial costs to the economy through health costs, lost productivity (e.g. ill health / time off work, building damage) and damage to crops and ecosystems. Policy interventions have led to reductions in some key air pollutants over the last decade, particularly for NO_2, which is now declining in many cities. NCAS research has been central to the UK evidence base on which timely action was taken on NO_2 by vehicle manufacturers, central Government and at city level. Our research has shaped actions introduced by Government through its NO_2 reduction plans, the 2019 Defra Clean Air Strategy, influencing strategies for the monitoring of emissions from shale gas, and guiding Defra policies to reduce domestic sector emissions of VOCs through concepts such as consumer product labelling.

NCAS is the most significant institutional contributor to the Defra Air Quality Expert Group (AQEG), the independent body that provides scientific advice to Government on matters relating to air pollution. *Alastair Lewis* (member since 2012, Chair since 2019) and *James Allan* (member since 2016) are public appointments; *Sarah Moller* led the Scientific Secretariat 2012-2018, becoming a joint NCAS / senior Defra Fellow in 2019 and is now *ex officio*. Moller, Lewis, and Allan have provided underpinning research and commissioned analysis for 11 Defra reports in this evaluation period [7] on i) Fine particulate matter, ii) emissions inventories and ambient measurements, iii) the evidential value of compliance monitoring, iv) the effectiveness of paint and surface removal of NOx, v) impacts of urban vegetation on air pollution, vi) impacts of shipping emissions on air quality, vii) impacts of agricultural emissions air quality, viii) sensors for air quality, ix) The effectiveness of air quality interventions, x) Non-exhaust emissions from road transport, xi) VOCs in the UK . NCAS research papers are cited more than 100 times in these reports. Based on research expertise, and supported by a range of research outputs, Lewis and Moller provided evidence to the 2017 joint Defra / DSHC / DfT Parliamentary Inquiry on "Improving Air Quality" [8], and recommendations from NCAS were cited ten times in the final House of Commons report. Research by Lewis on the use of low cost sensors to measure air quality more widely was also then cited in the official Government response to the Committee.

The research by *James Lee* relating to urban NOx emission fluxes informed the UK strategies for NOx emission estimation [9] and been included as part of the evidence base for the national plans for NO_2, and underpinning city-level action including the introduction of the ULEZ in London. Research on excess diesel NOx emissions has formed part of the evidence considered in two Judicial Reviews of the Defra air quality NO_2 reduction plans. It has also been included as technical information in on-going litigation related to Volkswagen diesel engine emissions, where *Lewis* is engaged as expert advisor [10]. This High Court action is the largest consumer class action in UK legal history.

Research by *Lewis* in 2016 highlighted discrepancies in emissions and impacts of VOC from the diesel transport sector [11] and from domestic solvent emissions. This research was then incorporated in the revision of UK emissions inventories and led directly to policy proposals to reduce domestic sector VOC emissions in the Government Clean Air Strategy (2019) [12] and proposals from Ricardo plc for a reformed national measurement network. NCAS presented evidence at an industry - Ministerial Round-table on VOC emissions and the research was highlighted as a driver for urgent action on indoor air quality in the Chief Medical Officer annual review in 2017 [13, 14]. The research led to a substantial change in approach to reduce VOC emissions, arising from a combination of specific papers (e.g. 11,12) and the broader advice provided to Defra, including directly to ministers and to industry and trade bodies.

Further shaping of policy and wider public discourse has been achieved through i) a synthesis of air pollution impacts for the Cabinet Office National Risk Assessment by Lewis and Moller [15] ii) advice on indoor air pollution, forming part of the Chief Medical Officers 2017 report, iii) advice to the Met Office and Environment Agency on air pollution monitoring and forecasting, iv) support for the Royal College of Physicians 2020 review of air pollution impacts and v) multiple public engagement activities and coverage of research in the media [e.g 16]. The scientific evidence underpinning national strategies on air pollution is naturally drawn from multiple sources, however NCAS has contributed more than any other in terms of size of the body of work and breadth of topics addressed. NCAS can point to its leading role in providing critical evidence that has supported actions on diesel NOx emissions, and has been the prime source of research and evidence that has led to new approaches to VOC emissions controls being proposed by government.

5. Sources to corroborate the impact

[7] Multiple AQEG evidence reports on Defra website citing NCAS research papers https://uk-air.defra.gov.uk/data/openair

[8] 2018 Environment Food and Rural Affairs Committee (multiple NCAS citations). https://publications.parliament.uk/pa/cm201719/cmselect/cmenvfru/433/43305.htm and https://publications.parliament.uk/pa/cm201719/cmselect/cmenvfru/1149/114902.htm

[9] Linking Emission Inventories and Ambient Measurements (2015), Department of the Environment Food and Rural Affairs. https://uk-air.defra.gov.uk/library/reports.php?report_id=828

[10] Letter of engagement as expert, Freshfields, Bruckhaus and Deringer on behalf of Volkswagen Group.

[11] Letter: Ricardo plc - Referencing the influence of NCAS research on changes to the National Atmospheric Emissions Inventory.

[12] Policy paper: Clean Air Strategy 2019, Department of the Environment Food and Rural Affairs. Clean-air-strategy-2019.pdf

[13] Chief Medical officers report (NCAS citations and text). CMO_Annual_Report_2017__Health_Impacts_of_All_Pollution_what_do_we_know.pdf

[14] Letter: Defra - From evidence team on the impact of the body of research to policy and advice contained in the Clean Air Strategy related to VOCs

[15] Letter: Met Office / Cabinet Office - confirming contributions to Natural Hazards Partnership and National Risk Register.

[16] Clean air strategy: What you need to know about the UK's latest pollution policy. Alastair Lewis and Sarah Moller, The Independent 2018. https://www.independent.co.uk/environment/clean-air-strategy-environment-air-pollution-co2-emissions-diesel-a8365511.html

Centre: National Centre for Atmospheric Science
Title of case study: Improving Applications of Forecast Information for Aid Decision Making

1. Summary of the impact
NCAS has provided tailored meteorological forecast information to a range of humanitarian agencies in anticipation of, and in response to, impending monthly and seasonal-scale precipitation and weather extremes such as El Nino and La Nina. These agencies have used our bespoke products to position aid resources and respond to weather impacts, mitigating damage and safeguarding lives and livelihoods. Humanitarian agencies have allocated an additional £90 million for African aid in response to El Nino, which shows continued support for meteorological forecast products and recognises their value.

2. Underpinning Centre activities
International aid agencies, such as the Department for International Development (DFID) and the Red Cross, use various data sources to enable informed reactive and proactive decisions for distributing aid resources in response to natural hazards. For meteorologically-driven hazards, such as floods and droughts caused by El Nino events or shorter-lived extremes such as cyclones, forecasts are a vital source of information. While many global agencies access sub-seasonal and seasonal forecast information, poor communication and understanding of forecasts inhibits their effective use. Agencies in developing countries face the additional challenge of poor availability of forecasts, particularly impact-based forecasts (e.g. for floods). NCAS researchers have worked alongside such agencies to supply monthly and seasonal meteorological forecasts, which provides decision makers with robust, reliable and succinct information.

Monthly or seasonal forecasts predict the likelihood of temperature and rainfall extremes. For most tropical developing countries, the frequencies of these extremes are controlled by well-known climate phenomena, such as the Madden-Julian Oscillation, the El Niño-Southern Oscillation and the Indian Ocean Dipole. NCAS research has examined how these phenomena affect temperature and rainfall in South Asia, East Africa and South America. Our work has identified the countries and sectors most at risk from El Niño [1] and La Niña [2] events, analysed forecast accuracy for East African temperature and rainfall [3]. We have also designed a novel method for combining forecasts from several models, weighting each by their historical performance, to deliver improved predictions of temperature and rainfall extremes around the globe.

These activities have been performed as part of National Capability (NC) funded research by *Nicholas Klingaman, Linda Hirons, Andrew Turner* and *Steve Woolnough* into the effects of tropical variability (e.g. Madden-Julian Oscillation, El Nino-Southern Oscillation, [e.g. 4,5]) on sub-seasonal and seasonal temperature and rainfall variability in a range of developing countries, particularly those in South Asia [6]. The NC-funded ACREW programme, funded as Official Development Assistance, sees NCAS researchers evaluating sub-seasonal and seasonal forecasts of tropical rainfall. We also produce Climate Outlooks, funded by DFID, which are bespoke monthly and seasonal forecasts of the risk of temperature and rainfall extremes in approximately 50 developing countries (2015-2019). DFID have also supported NCAS to investigate novel methods for producing multi-model ensemble-based forecasts of temperature and rainfall, as well as the information design and communication of forecast information through the Outlooks via two 12-month research projects (2017-18 and 2019-20). Lead NCAS researchers on these projects are *Nicholas Klingaman, Linda Hirons, Hannah Young, William Keat* and *Emma Suckling*.

3. References to the underpinning work

[1] Hirons, L. and Klingaman, N., (2015) *El Niño 2015/2016: impact analysis of past El Niños.* Report. Evidence on Demand 10.12774/eod_cr.august2015.hironsletal

[2] Hirons, L. and Klingaman, N.,(2016) La Niña 2016/2017: historical impact analysis. Report. Evidence on Demand 10.12774/eod_cr.february2016.hironsetal4

[3] Young, H. and Klingaman, N.P. (2019) Skill of seasonal rainfall and temperature forecasts for East Africa. Under review for Weather and Forecasting. https://drive.google.com/file/d/1SeLZnK2jQNMnsbKMBbtwDF11T-HkU3ZA/view

[4] Guo, L., van der Ent, R., Klingaman, N., Demory, M.-E., Vidale, P. L., Turner, A., Stephan, C. and Chevuturi, A. (2019) Moisture sources for East Asian precipitation: mean seasonal cycle and interannual variability.Journal of Hydrometeorology, 20. pp. 657-672. ISSN 1525-7541 10.1175/JHM-D-18-0188.1

[5] Hirons, L. C., Klingaman, N. P. and Woolnough, S. J. (2018) The impact of air–sea interactions on the representation of tropical precipitation extremes. Journal of Advances in Modeling Earth Systems, 10 (2). pp. 550-559. ISSN 1942-2466 10.1002/2017MS001252

[6] Klingaman, N. P., Weller, H., Slingo, J.M. and Inness, P.M. (2008) The intraseasonal variability of the Indian summer monsoon using TMI sea surface temperatures and ECMWF reanalysis. Journal of Climate, 21 (11). pp. 2519-2539. ISSN 1520-0442 10.1175/2007JCLI1850.1

4. Details of the impact

In response to forecasts of a substantial El Nino event in summer 2015, *Klingaman* provided a report to DFID encompassing (a) a review on how previous El Nino events affected approximately 50 developing nations, including impacts on sectors such as disease, water and food security and conflict; and (b) predictions of the impacts of the then-forecast 2015-16 event. From this initial report, a rolling monthly analysis of seasonal forecast information (called Outlooks) was supplied to DFID, as well as a further review and analysis for the 2016-17 La Niña event. DFID commissioned ongoing monthly analyses of seasonal forecasts of the likelihood of temperature and rainfall extremes in 50+ developing countries, as well as two one-year research projects to understand the accuracy of seasonal forecasts and improve the communication of forecast information and associated uncertainty. A further El Nino impacts report – covering an updated literature review and seasonal forecast information – was provided prior to the 2018-19 event [7].

The investment from DFID in the production of these reports has been £330,000 over the past four years. It was noted by Yves Horent, Senior Humanitarian Advisor in Africa division that "*If this work affects even one decision that we make, it is excellent value for money.*" Philip Rundell, Humanitarian Adviser in the Humanitarian Response Group in the Conflict, Humanitarian and Security Department (DFID CHASE) commented that the Outlooks are "*a critical resource for us … based on the great work that NCAS perform*." [8]

Our research has led to recommendations that improve the content and information design of the Outlooks that support DFID, including (a) increasing the number of seasonal forecast models, (b) designing improved multi-model weighting systems that account for each model's historical performance, (c) better highlighting changes in the risk of extremes and; (d) more consistent messaging through a controlled vocabulary. The forecast information is fed into the Humanitarian Early Warning Note, which has a wide distribution across DFID country offices and beyond to a range of international actors (in total between 400-500 people). The 2015-16 El Nino forecast and impacts report [1] was the primary piece of scientific evidence used by DFID to negotiate a £90million of additional UK Government aid in 2015 to support sub-Saharan African countries experiencing heatwaves and droughts in 2015-16 [9, 10a 10b].

In November 2018, Klingaman presented the 2018/2019 El Nino forecast and impacts report to the United Nations Global ENSO Analysis Cell, which included representatives from the Office for the Coordination of Humanitarian Affairs (OCHA), the Food and Agriculture Organisation (FAO) and the World Meteorological Organisation (WMO). The Cell used the meteorological and impact information from the report in their disaster risk reduction planning.

DFID commissioned NCAS to provide more detailed reports on the state of the major wet seasons in sub-Saharan Africa, including rainfall, soil moisture, vegetation health and the prognosis for regional agriculture and cattle grazing. These reports were commissioned in response to concerns over agricultural productivity in Senegal and Mauritania (2018) and eastern Africa (2019). The latter report was quoted in a DFID submission to the Secretary of State on the drought in Ethiopia, which is DFID's largest aid mission.

As the work becomes more refined and procedural, the migration of the operation will transition from NCAS to the UK Met Office, who will produce an operational tool for this forecast data based on the "best practice" procedure developed through the research.

5. Sources to corroborate the impact

[7] SHEAR Annual Review (2018): http://iati.dfid.gov.uk/iati_documents/46299653.odt
Selected quotes:
(page 4, item 7):
"The [Climate Outlook research] has been instrumental for layering weather information over other risk data to identify the humanitarian risk in contexts of concern and help decision-making on whether to issue specific alerts in the monthly Humanitarian Early Warning Note (HEWN)".

(page 6):
Under SHEAR Applied and Innovations component, further work has been advanced around scientifically based forecast information on climate and weather patterns to assist better programming and decision making by DFID and partners. This is being well received by the Humanitarian Early Warning Network (HEWN) in particular in DFID participates. Examples include … [mentions our Climate Outlooks and El Nino report]

(page 10):
The support on Monthly Climate Outlooks and El Nino impact analysis are further examples of how SHEAR has further developed partnerships and improve products that are having an impact in practice, both within and beyond DFID.

(page 16):
DFID direct commissioned work (such as the El Nino impact update analysis, and the monthly Climate Outlook for Humanitarian actors) have been conducted in a timely and effective manner.

[8] Testimonials from DFID staff on value of Outlooks and the underpinning research

[9] Klingaman NP, Young H, Black A, Charlton-Perez A, 2018: Final report from "Supporting the Use of Subseasonal to Seasonal information in DFID (SUSSD)". Project report. https://drive.google.com/file/d/13hzpOA6zEe3r2UQRsUR1elO8rthxPPW9/view

[10] DFID annual report 2015-16
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/538878/annual-report-accounts-201516a.pdf

[10a] Page 11: £90million of additional UK Government aid in 2015 to support sub-Saharan African countries experiencing heatwaves and droughts in 2015-16

[10b] Page 23: *"The 2015–16 El Niño effect was one of the worst weather events on record, affecting 60 million people worldwide. The UK has been at the forefront of preventing and preparing for the effects of El Niño in the world's poorest places, by pre-positioning medicine and food supplies so they can quickly be delivered to those in need, and helping people to earn a living so they can provide for their families. The UK commissioned scientific work, and regional weather updates were used to prepare contingency plans and target aid in the countries most at risk. As a result, many countries were able to act quickly, including Ethiopia and Kenya. Overall, DFID has allocated £154.7 million to provide urgent aid attributable to El Niño response in 2015 and will continue providing support in 2016.*"

Centre: National Centre for Atmospheric Science

SECTION A: NARRATIVE

1. Context, Mission and Strategy

1.1 History and Mission

The National Centre for Atmospheric Science (NCAS) is NERC's research centre for atmospheric science, created by NERC in 2001 because NERC's Council recognised the enduring need for what is now termed National Capability in atmospheric science. NCAS is charged with providing facilities, long term science leadership and advice to support the academic research community, government departments and agencies, UK industry and the general public. Atmospheric science underpins the understanding and prediction of weather hazards, air quality and climate change and variability. It depends critically on large infrastructure at a national or international scale, including facilities to observe the atmosphere, to manage massive data volumes and to make predictions using high performance computing. For these reasons, NERC considered that the UK's national capability needs in atmospheric science could only be met by establishing a research centre. NCAS was created as a distributed organisation, with a lead contracting university sub-contracting other universities and organisations to deliver the National Capability. Since 2005 the University of Leeds has been the lead contractor.

The mission of the National Centre for Atmospheric Science is to:

- undertake and lead strategic and directed research;
- provide facilities and education to support atmospheric and wider environmental science;
- apply expertise and exploit facilities to support business and government.

Figure 1: The NCAS mission.

1.2 NCAS in Context

Fundamental and international-scale research in atmospheric science in the UK is primarily supported in two ways: by NERC (and its inter-linkages to other parts of UKRI) and by the Met Office. Figure 2 shows the breakdown of UK atmospheric science R&D spend (mid-evaluation, 2014-15). The diverse and distributed landscape for UK atmospheric science requires NCAS to have responsibility for *coordination* of effective collaborations across the UK sector. This is enabled by:

- NERC's enduring commitment to long-term atmospheric science research exemplified by its creation of and support for NCAS.
- The NCAS organisational model, predominantly delivered through a consortium of universities, ensuring science is closely linked to, and benefits from, the HEI sector.
- An NCAS strategy based on partnership and collaboration. Critical to this are a broad and deep relationship with the Met Office and other major collaborations such as with Defra, BEIS and industry.

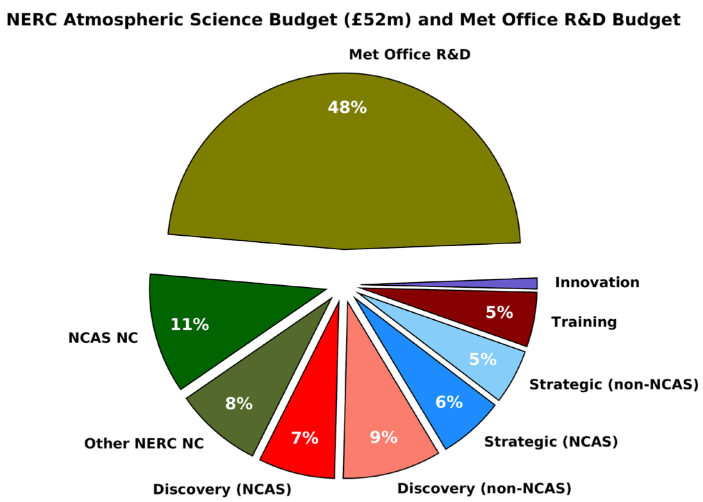

Figure 2: UK atmospheric science R&D budgets.

1.3 NCAS Structure and Organisation

NCAS has two major roles: to pursue original research and its consequences, and to provide services. NCAS has two “divisions”: *Science and Impact* and *Services, Facilities and Data*. Within *Science and Impact*, since 2018 NCAS has organised all of its activities under three themes (Figure 3).

NCAS Science Themes

- Climate and High-Impact Weather
- Long-Term Global Change
- Air Pollution

Figure 3: NCAS science themes.

NCAS Large Research Infrastructure, Services and Facilities (including Data)

- The Facility for Airborne Atmospheric Measurements (FAAM), managing access to NERC’s large atmospheric research aircraft;
- The Atmospheric Measurement and Observations Facility (AMOF - about to be launched following the merger of the Atmospheric Measurement Facility and the NERC Facility for Atmospheric Radar Research), managing access to major ground-based observing systems including NERC’s radars;
- The Centre for Environmental Data Analysis (CEDA), providing management services and NERC’s JASMIN super-data-cluster;
- The Computational Modelling Services, supporting users of large atmospheric computational models.

Figure 4: NCAS Large Research Infrastructure, Services, Facilities and Data.

The NCAS science themes provide coordination of virtually all NCAS science activities and ensure that the science and associated strategies remain at the international cutting edge, regardless of the funding sources. Each theme has a *Theme Leader* whose responsibility is to provide coordination and oversight, reporting to the NCAS Management Board. Individual research projects and programmes exist within and across themes; projects are where budgets are held and where staff and resources are managed.

Within *Services, Facilities and Data*, NCAS provides facilities to the community illustrated in Figure 4. Each facility is led by a Head who reports to the Management Board.

NCAS Corporate Services provides administrative services to run NCAS (including finance, administration, people management, communications, IT, training and events) and also performs a community role providing related services to the research community. The overall NCAS organisational structure is shown in Figure 5.

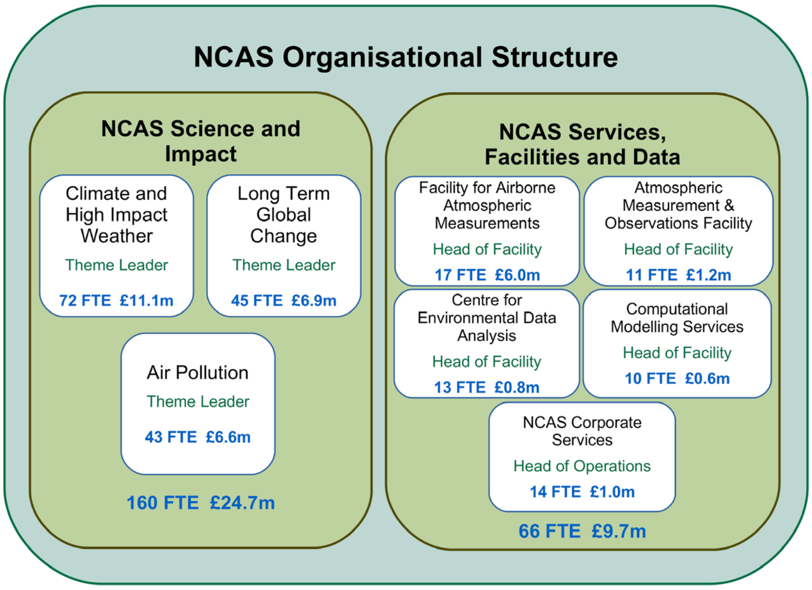

Figure 5: The NCAS organisational structure.

NCAS has approximately 220 staff FTEs, comprising ~120 open-ended roles and approximately 100 staff engaged on fixed term grants and contracts. Staff are principally embedded within the universities of Leeds, York, Manchester and Reading, with staff also located at Cranfield Airport (for FAAM) and the Rutherford Appleton Laboratory (for CEDA).

1.4 The NCAS Management Board and NCAS Governance

1.4.1 NCAS Senior Management

NCAS Management Board Appointment and Responsibilities

- NERC appoints the NCAS Executive Director and through the NERC-Leeds contract requires the University of Leeds to employ the director. The term of appointment is open ended. The NCAS Director chairs the NCAS Management Board.
- The NCAS Director and the NERC Director of Strategic Partnerships appoint four additional executive members of the NCAS Management Board.
- The executive members may appoint additional non-executive members of the board from outside and within NCAS. Currently there are three non-executive members appointed through external advertisement and one appointed through advertisement across the NCAS staff.
- The NCAS Management Board is responsible for:
  - Strategy development and delivery plans.
  - Policies and procedures.
  - Setting the NCAS budget plan.
  - Oversight of managers and budgets
  - Performance reporting, including reporting to the NCAS Centre Assurance Board (CAB)[1].
  - Development and oversight of NCAS partnerships.
  - Strategic oversight of NCAS communications.
  - Ethical and legal standards.
  - Risk management.
  - Oversight of health and safety and people management standards.
  - Accountability to the Chief Executive Chair.
  - Reporting on activities and performance.
  - Reviewing and implementing internal and commissioned advice.
  - Horizon scanning.

[1] The NCAS Centre Assurance Board provides the NERC Executive Chair with assurance concerning the management and governance of NCAS. Through the NERC-Leeds contract, NERC may take action it deems necessary as a result of the CAB process.

Figure 6: NCAS Management Board: appointments and responsibilities

Throughout most of the evaluation period NCAS was managed by an Executive Committee composed of science and facility leaders. This was replaced by the NCAS Management Board in October 2018. The Board is composed of the NCAS Executive Director (chair), four other NCAS executive members with science, facility and organisational responsibilities, and three external, non-executive members. Details of the NCAS Board are given in Figure 6.

1.4.2 NCAS Governance

NCAS Governance

- NERC appoints the NCAS Executive Director and requires the executive director's institution to employ the director and host the NCAS headquarters. The arrangement is open-ended but can be terminated by NERC. The Executive Director chairs the NCAS Management Board.
- The NCAS Executive Director and the NERC Director for Strategic Partnerships jointly appoint the other executive board members from within NCAS.
- The NCAS executive board members appoint the non-executive members of the board externally and from within NCAS.
- The NCAS Management Board is collectively responsible for reporting to the NCAS Centre Assurance Board (CAB). The CAB is chaired by the NERC Chief Operating Officer or NERC Director for Strategic Partnerships.
- The NCAS Centre Assurance Board provides the NERC Executive Chair with assurance concerning the management and governance of NCAS. Through the NERC-Leeds contract, NERC may take action it deems necessary as a result of the CAB process.

Figure 7: NCAS governance

NCAS is not a legal entity which necessitates a bespoke governance arrangement, different to that of a wholly-owned NERC centre or an independent legal entity. The governance arrangements for NCAS are described in Figure 7. The overall NCAS structure is shown in Figure 8, including the governance and management relationships.

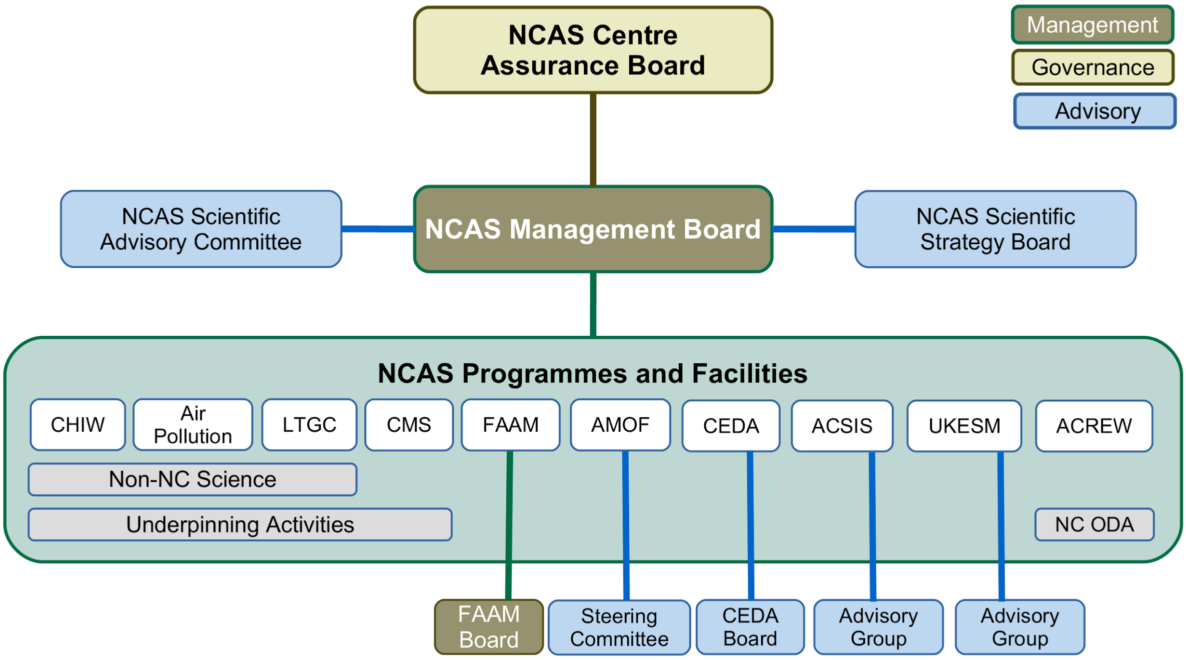

Figure 8: Overall NCAS organisational structure.

1.4.3 The NCAS Internal and External Advisory Structure

NCAS advisory structures have been strengthened during the evaluation period, in order to better address the requirements for research, service provision and overall centre performance. The Board receives external advice via an annual meeting of the NCAS Scientific Advisory Committee (chaired by Professor George Craig, University of Munich and with many overseas members). Internally, the Board receives advice on its science strategy from the NCAS Science Strategy Board (chaired by Professor John Pyle and with members including, amongst others, the *Theme Leaders* and other senior NCAS scientists). The Science Strategy Board meets three times per year.

NCAS frequently seeks focused strategic advice on emerging and topical issues and on how it serves its community. This is delivered up to six times per year through the NCAS Research Forum series. Our services and facilities receive dedicated external advice from steering committees and boards are mandated by NERC and adapted to meet NCAS requirements.

1.4.4 NCAS as a Distributed Centre

The University of Leeds has been the lead NCAS partner since 2005, enabled by the NERC collaboration agreement involving 10 other universities. The STFC also contributes to NCAS in a similar way but under a Service Level Agreement (SLA). Over the evaluation period, NCAS has consolidated its organisation around 6 sites - Leeds, Cranfield (FAAM), Manchester, Reading, Rutherford Appleton Laboratory (AMOF and CEDA) and York. 86% of the "permanent" staff are at these sites. Six other universities - Birmingham, Cambridge, Hertfordshire, Oxford, Surrey and UEA - provide specialist expertise to NCAS.

NCAS is also currently seeking to expand its activities in Scotland beyond existing collaborations, for example by developing a collaboration with the University of Edinburgh on data science.

1.4.5 Status of NCAS and its Staff

In order to evaluate NCAS it is essential to appreciate its status and that of its staff. Although NCAS is not a legal entity, the roles of NCAS and its staff, acting on behalf of NERC, are nevertheless exactly the same as those of NERC-owned centres (e.g. BAS) or centres which are independent legal entities (e.g. NOC). Functions which require a legal entity, such as financial transactions, ownership of assets and employment of staff are undertaken by the various NCAS host organisations.

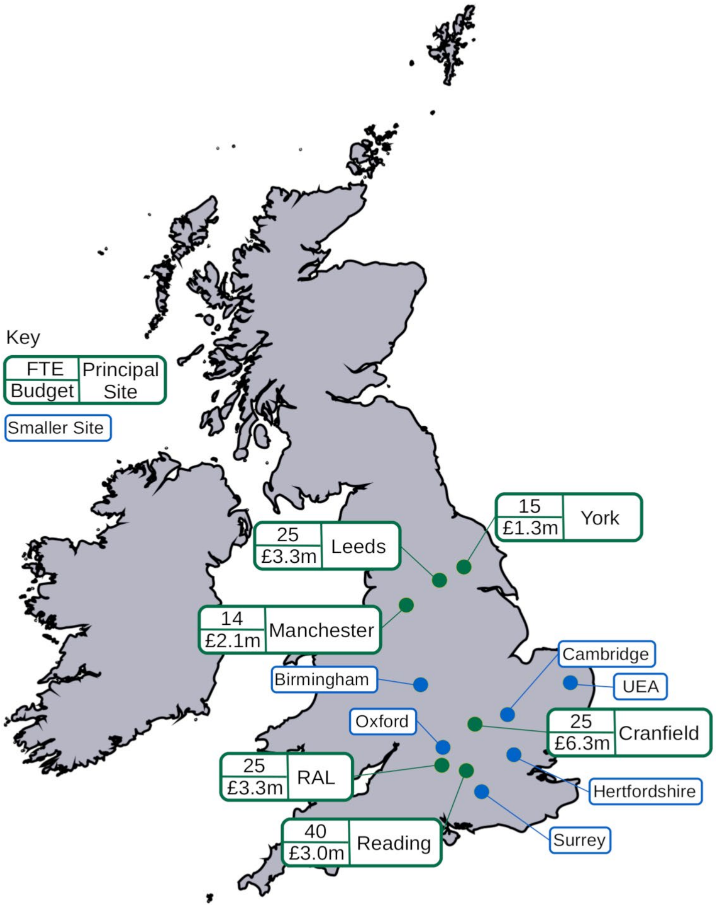

Figure 9: NCAS geographical distribution.

NCAS staff are *named individually in the NCAS sub-contracts to universities*. Almost all staff who are supported by NERC national capability funding are engaged on open-ended contracts, meaning that NCAS is committed to their roles unless circumstances change significantly. NCAS income is considered to be NERC national capability funding plus any other income won by a researcher who is a named member of the NCAS staff. The majority of the NCAS science staff are supported in part by competitively won income, with a small number of open-ended staff funded entirely from external sources. NCAS uses its size to help support open-ended commitments to staff where possible, smoothing short-term funding fluctuations. This enables its staff to plan long-term careers (see also section 2.1.2).

All NCAS contracts make it a requirement of funding that staff and host institutions comply fully with the NERC ethics policy (https://nerc.ukri.org/about/policy/policies/nerc-ethics-policy/). All the contributing NCAS host institutions do this by applying their own equivalent policies. NCAS can and does monitor this.

NCAS staff have roles (specified in the sub-contracts) which consist entirely of duties and functions which support the NCAS national role. We stress that although the NCAS staff are predominantly employees of universities, NCAS does not support academic university roles. A small number of staff hold joint appointments where NCAS makes an open-ended commitment to less than 100% FTE and the staff member additionally holds a part-time academic role. NCAS values such appointments because of the enhanced NCAS-university collaboration. The NCAS funding and staff support model ensures that:

- It is clear and transparent which achievements have been made by NCAS;
- Such outputs and achievements are distinct and separate from university academic activities;
- NCAS does not claim any credit for achievements which are HEFCE-funded.

The evaluation of NCAS research is therefore made on the same basis as that of NERC wholly-owned or independent research centres.

NCAS works with a small number of university academic staff to assist with local line management and to provide other advice. NCAS is currently updating its mechanisms for this, creating a small group of individuals who will become “Strategic Associates”. **No Strategic Associates are included in the NERC evaluation of NCAS**.

1.5 The NCAS Science and Impact Strategy

1.5.1 Science Strategy

The previous NCAS strategy, for 2010-17, was described in detail in the 2012 NERC evaluation. Between 2010 and 2017 NCAS science was organised along discipline lines. NCAS had three science “directorates”: NCAS-Climate, NCAS-Weather (latterly NCAS-Atmospheric Physics) and NCAS-Composition, which delivered a science strategy under four science challenges:

Challenge 1: Identify & model the processes governing climate variability & change on regional & local space and time-scales from months to decades; quantify and reduce the uncertainty in predictions on these scales.

Challenge 2: Identify and model the processes that govern climate on multi-decadal to centennial time-scales; quantify and reduce the uncertainty in predictions for the next century.

Challenge 3: Improve the prediction of human exposure to air pollution and the attribution of contributing sources.

Challenge 4: Improve the capability for predicting high impact weather.

These science challenges were chosen in response to the priorities set out by NERC in its strategy 2007-12. Towards the end of the evaluation period, NCAS has evolved its strategy and organisation to address applications and challenges of contemporary societal importance. Consequently, since 2017, the NCAS science strategy and internal organisation have been focused around the three themes (Figure 3).

The current strategy was developed in consultation with the atmospheric science research community and stakeholders, including using residential workshops. An objective of our strategy development process was to ensure maximum community buy-in to NERC’s commissioning of national capability. The three themes now reflect the central societal topics where atmospheric science is required and where NCAS expertise can contribute as part of multidisciplinary teams. In each area a critical mass of researchers is engaged in fundamental and applied research (funded by NERC and other external organisations) and underpinning science (long term science developments which are required to enable the wider research community activities, funded by NERC National Capability).

1.5.2 Impact Strategy

NCAS delivers impact to stakeholders using a range of mechanisms, with a focus on providing advice to key government departments. This is enabled by investment in strategic relationships, joint appointments, and the leadership of various Government expert committees by NCAS staff. In this evaluation period we have deepened our connections to Defra on science and evidence for air quality policy, with DFID in providing advice associated with meteorological hazards, agriculture and aid in Africa, and with BEIS on the atmospheric impacts of the UK oil and gas industry. These government users of our research provide funding to support interactions in addition to our own institutional investments. We have continued to support our excellence in the science of stratospheric ozone depletion, including providing staff, modelling and new measurements to underpin the most recent UNEP/WMO ozone assessment (2018). NCAS has increased its emphasis on delivering impact for business, including the application of climate science to support infrastructure resilience and new measurement standards that are reducing pollution emissions from aviation.

In some cases impact is delivered by NCAS teams drawing on our major infrastructure (using FAAM, AMF, models) and our science programmes collaborate with governments to deliver major pieces of work. Air quality and oil and gas emissions are examples where NCAS science has been co-designed and co-delivered. In other cases we have supported the bottom-up growth of specialist impact activities, particularly in the Overseas Development Assistance space, that are now self-sustaining and impact-focused activities in their own right. NCAS supports individuals who have highly specialist skills to work with international projects and stakeholders, for example through providing time and resources for engagement with end-users such as UNEP, WMO or industry.

1.6 NCAS Achievement of Strategic Aims

1.6.1 Achievement of Research Strategic Aims

NCAS has sought to strike a balance between support for the most academically impactful sub-disciplines and the requirement for a balanced portfolio of research and support, addressing wider NERC and UK needs. Thus we are equally committed to working at the international forefront in climate science (where journals have high impact factors and the community is large) and in observational science (where there are fewer journals, a smaller community and the investment in terms of person time per paper is greater). Equally, we have balanced the use of existing infrastructure (which sometimes can be exploited relatively quickly) with pioneering use of new infrastructure and technology (which can require greater resources but can lead to otherwise unobtainable breakthroughs). Our investments in each of challenges 1-4 have been approximately equal: ~51% of our research resources in our two climate science challenges, ~27% in air quality and ~22% in weather science.

NERC Underpinning and Programme Funding

Underpinning activities
"Long-term activities, platforms and technical capability and other activities that Centres will provide that are critical to achieving the strategic outcomes of NERC and support the delivery of environmental science and NPG for the wider NERC community"

Programme activities
"Strategic national capability science outcomes that the centres will deliver over the next five years and looking to a 10 year horizon".

Figure 10. NERC Programme and Underpinning national capability

NERC national capability funding is at the core of NCAS science strategy delivery. This is sub-divided by NERC into: *Underpinning activities* and *Programme activities* (Figure 10). NERC then further sub-divides its national capability science funding into ~60% for activities in single research centres and ~40% for cross-centre research. During the evaluation period, NCAS science funding under the single centre heading of "*Programme*" has declined to zero (because of overall flat-cash funding and the imperative for NCAS of maintaining its underpinning of the wider community). Consequently, NCAS strategic science has been predominantly enabled through either cross-centre support or through externally-won funding. National Capability funding to NCAS has accounted for only ~25% of the achievements described below, emphasising the critical role that competitively-won income has played in allowing NCAS to deliver its science.

Challenge 1. Climate Processes, Variability and Change on Time-scales of Days to Decades

NCAS has committed approximately 205 person years to this challenge during the evaluation period and its staff have authored or co-authored ~375 peer reviewed related publications, cited >10,000 times.

Reliable forecasting of extreme weather is of huge societal and commercial benefit. NCAS has contributed significantly to substantial increases in seasonal forecast skill of European climate projections and has demonstrated how such forecasts can now produce statistically skillful seasonal predictions for UK weather. A wide-ranging set of NCAS contributions to the NERC ACSIS project have improved understanding of seasonal variability in the North Atlantic. This includes the impact of El Nino in the North Atlantic, how the stratosphere contributes to wintertime seasonal forecast skill, and the role of springtime North Atlantic sea surface temperatures in driving summertime circulation over Europe. NCAS has delivered new insights into the roles of land surface exchanges and convective organisation in the variability and predictability of Sahel rainfall using pioneering high resolution modelling coupled with observational studies. Global modelling has also contributed substantially to establishing that global warming will very likely lead to increasing frequency of extreme El Nino and La Nina events.

Challenge 2. Climate Processes and Uncertainty on Time-scales of Decades to Centuries

NCAS has committed approximately 250 person years to this challenge during the evaluation period and its staff have authored or co-authored ~450 peer reviewed related publications cited >13,000 times.

In partnership with the Met Office, NCAS has led the development of a world-leading Earth System model, UKESM1. The model represents a major advance on its predecessor HadGEM2-ES, with enhancements to all component models and new feedback mechanisms. These include: a new core physical model with a well-resolved stratosphere; terrestrial biogeochemistry with coupled carbon and nitrogen cycles, much improved aerosol schemes; and ocean biogeochemistry coupled to the atmosphere. This NCAS-led initiative has provided the UK climate science research community with its own open, world-leading simulation infrastructure.

NCAS has delivered new science describing the sensitivity of the climate system to greenhouse gases and other forcing, including identification of a new climate feedback from coupling between changes in atmospheric circulation and changes in stratospheric ozone. NCAS has made substantial progress in understanding how small variations in solar output influence surface weather and climate, allowing future impacts of greenhouse gas increases and solar output to be placed into context. Intercomparison of observations and model experiments have revealed complex interactions between the tropical atmospheric circulation and the mid-latitude jetstream, affecting European weather.

Challenge 3. Prediction and Attribution of Human Exposure to Air Pollution

NCAS has committed approximately 240 person years to this challenge during the evaluation period. NCAS staff have authored or co-authored >450 peer reviewed related publications, which have been cited over 7500 times.

A major achievement has been the substantial NCAS contributions to the £11m NERC Air Pollution and Human Health (APHH) programme, including large bilateral community field experiments in Beijing and Delhi in 2016, 2017 and 2018. APHH illustrates the national role that NCAS plays in delivering air pollution science with global reach. The science highlights of this work include the identification of a novel VOC-NOx chemical environment in Beijing with major implications of future emission controls, the elucidation of a direct feedback between aerosol pollution and the worsening of air quality through stable boundary layers, and quantification of the role of biogenic emissions in summertime to urban aerosol pollution in China. NCAS has delivered on its 2013 evaluation goals for developing new technologies, publishing >40 papers on new and improved methods for chemical analysis of particles and gases and pioneering in the emerging field of low-cost sensors. NCAS has worked with industry to quantify and attribute pollution to sources, leading to multiple patent submissions and commercialisation. A particular achievement has been the methodology to quantify urban fluxes of pollution emissions, now routinely undertaken at the NCAS observatory on the BT Tower and used by DSTL.

Challenge 4. Processes Controlling High Impact Weather

NCAS has committed approximately 195 person years to this challenge during the evaluation period. NCAS staff have authored or co-authored approximately 280 peer reviewed related publications which have been cited >4,000 times.

Sting jets are features of extratropical cyclones which cause severe damage to infrastructure, as in the Great Storm of October 1987. NCAS research has transformed understanding of sting jets, leading to diagnostic tools to enable their precursors to be predicted. Observations using FAAM revealed the distinct properties of sting jets while model simulations were used to explain how these high winds are brought down to the surface, creating severe wind hazards. NCAS science has demonstrated that the proportion of North Atlantic cyclones with sting jets may increase from 33% in the current climate to 45% for the future climate.

NCAS research has improved weather forecasting across Africa, where phenomena ranging from sudden violent thunderstorms to multi-year droughts cause great stress on vulnerable populations. Analysis of TAMSAT satellite data has shown how decadal drying in East Africa is caused by a shorter rainy season, rather than less rain. Advances in computing have led to progress through high-resolution large-area simulations, explaining observations of convective storm outflows that influence the entire West Africa monsoon. In the GCRF Africa SWIFT project, NCAS is analysing the first-ever large-domain convection-permitting weather forecasts over Africa, building on the proven potential of such models in the tropics.

1.6.2 Achievement of Impact Strategic Aims

We have chosen six impact case studies for this evaluation based on advice from the NCAS staff impact group, and from external experts. Our six case studies demonstrate that the centre achieves impact across its portfolio of activities. We considered >20 staff-submitted impact activities, and examples not submitted as case studies included (i) the commercialisation of measurement technologies with two SMEs, (ii) supporting BEIS, Oil&Gas UK and UNEP to quantify methane leakage from offshore installations, (iii) working with the insurance sector to improve the quantification of climate and weather-related risk, (iv) supporting improved UK weather forecasting with the Met Office and independent assessment of BBC forecasts, (v) extensive support for the IPCC (see section 4.2.8), and (vi) public understanding of science using mechanisms including schools and festivals outreach, broadcast and print, and social media.

NCAS Submitted Impact Cases

- The Montreal protocol and stratospheric ozone depletion
- Science underpinning the development of the 2019 Defra Clean Air Strategy
- Weather forecasts supporting crop insurance for African farmers
- Designing future global regulations associated with aviation soot emissions
- Communicating extremes of weather in Africa and supporting overseas aid
- Estimating extreme winds and waves for oil and gas platform design

Figure 11: NCAS submitted impact case studies

NCAS has historically delivered significant impact in relation to emergency response with FAAM. NCAS was central to supporting the decisions to reopen European airspace following the Eyjafjallajökull eruption in 2010, and the re-occupation of the TOTAL Elgin Gas Platform following a major uncontrolled release in 2012 (case studies in the 2013 evaluation). Generating impact in an emergency response context is by its very nature highly unpredictable, but NCAS continues to enhance its preparedness to support the UK when required, investing in the FAAM short-notice operational capability and new instruments and agreements with NOAA, the Met Office and the CAA for joint working in emergencies.

1.7 Approach to Open Access

NCAS follows the Open Access publication policies of the university and STFC employers. All published papers are expected to be green or gold open access, and funds are provided by the employers to pay the appropriate page charges. If the cost of gold open access proves prohibitive, pre-publication copies are deposited in the University or research council's open repository.

NCAS is also committed to making all its experimental measurements open and usable by all, and is engaged in a wide-ranging project to ensure that all observational data follow FAIR principles (findable, accessible, interoperable and reusable); data are provided in a standard format (CF-NetCDF) with extensive, standardised metadata to enable the data repository (CEDA) to catalogue and describe the data for maximum ease of discovery. Processing software and calibration data are also provided via github.

NCAS also supports open-access community atmospheric models, notably UKCA, used for wide ranging chemistry-climate simulations and the Master Chemical Mechanism (MCM), the global benchmark explicit representation of tropospheric gas phase reactions, with research, regulatory and industry users in more than 40 countries.

1.8 Future Research Strategy

In setting a science strategy, NCAS anticipates delivery using predominantly funding from external competitive sources. The NERC national capability Programme funding will make up a small but crucial core element and national capability Underpinning funding ensures we continue to provide long-term support for the wider community as well as our own research. NCAS will continue to be heavily dependent on large infrastructure including FAAM and AMOF, HPC and the JASMIN super-data-cluster.

Climate and High Impact Weather Theme

High Impact Weather (HIW) is defined as weather events of exceptional intensity and/or duration, usually having high socio-economic impacts. Society needs improved early warnings, risk assessments and more information on the impact of climate change on HIW. The CHIW strategy will address these by using observations and weather and climate models to understand processes and evaluate predictions of HIW and HIW risk. The focus will be on: (i) cyclonic storms, (ii) persistent high impact weather (e.g. droughts and heat waves), (iii) convective storms, and (iv) large scale modes of variability. Other hazards will also be addressed under this programme, including dispersion of volcanic ash and gases.

Long Term Global Change Theme

Human activities are now the major driver of changes in global atmospheric composition and its interactions with Earth's climate. Over the next evaluation period we will aim to meet the scientific needs of society for robust adaptation and mitigation policies and responses. Evidence is required to address fundamental questions such as: how are atmospheric composition and climate changing?; how will long-term changes in gases and aerosols affect global weather, climate and air quality?; how do uncertainties in models affect our predictive capability, and how can models and observations be combined to provide robust information? The focus will be on (i) changes in atmospheric composition, (ii) changes in aerosols and clouds, and (iii) climate projections.

Air Pollution Theme

Human and ecosystem exposure to air pollution is a critical global environmental burden; reducing it brings benefits for health, quality of life and economic development. The users of our science are diverse, from needing kerbside predictions through to knowledge of hemispheric-scale impacts. The drivers of air pollution are different in developing countries to those found in Europe, China or North America, and the NCAS science strategy reflects this. The largest science uncertainties lie in predicting the effects of pollution on people in cities, in estimating emissions (now and in the future), and in how the local composition of air pollution affects health and ecosystems. The NCAS focus will be on (i) emissions and trends, particularly from diffuse sources, (ii) urban scale air pollution, (iii) health effects of individual pollutants and (iv) interactions and feedbacks between air pollution, dynamics, natural processes and trans-boundary effects.

Underpinning Science Priorities

Long Term Observations and Datasets

NCAS's strategy for long-term observations is to concentrate on a small number of high-quality activities that contribute to high-value national or international networks. In atmospheric chemistry, NCAS will support greenhouse gas monitoring at Weybourne (ICOS), halocarbon measurements at Cape Grim and the IAGOS/Caribic in-service aircraft, reactive gas measurements at Cape Verde (WMO GAW) and long-term measurements of urban air quality using the newly established NERC Air Quality supersites and the BT Tower. Cloud and aerosol profiles are measured using radar and lidar at Chilbolton (CLOUDNET/ACTRIS) and in situ by IAGOS. The NCAS wind profiler at Aberystwyth provides real-time data through EUMETNET to the international meteorological community. NCAS also supports the Climate Research Unit at UEA in maintaining the CRUTS and CRUTEM long-term gridded surface climate datasets.

Physical Science

Our strategy is focused on the study of critical chemical reactions at a molecular level and their representation in mechanisms and models. A priority is the further development of the open-access model MCMv4.0 that will underpin UK capability to simulate air pollution in a changing environment, and laboratory science using smog chambers that allows collection of new physicochemical data on aerosols, and gases including emerging pollutants. We foresee a growing requirement for scalable and traceable methods that can exploit sensors, and NCAS will use both lab and field experiments to advance capability in this area.

Numerical Modelling and Evaluation

Our numerical modelling strategy is closely connected to enabling the maximum exploitation of CMIP6 and future IPCC model intercomparisons. We will continue to invest significant effort in the UKESM long-term Earth system model development with the Met Office. We will continue to develop and enhance the UKCA aerosol modelling component and make a priority of developing and evaluating convection-resolving modelling using global and regional climate models and models for high-impact weather prediction.

Modelling Support

NCAS will continue its support for the NERC community using large computational models, and invest a significant technical effort into new model capabilities and facilities for users to exploit model output. This includes the transitioning and porting of models to new architectures (including HPC), managing workflows across multiple HPC platforms and developing model output standards. As our science moves into the "exascale" era when traditional algorithms for exploiting ever faster HPC will no longer be an option, we will invest effort with our partners (especially the Met Office) in enabling the exploitation of the next generation of HPC systems.

Education and Training

NCAS has a key role in providing training and support to the next generation of atmospheric scientists as well as supporting its own staff development. NCAS will focus its investments in training on providing education that benefits from scale, and particularly activities which would be unsustainable for individual universities with small cohorts. We will aim to expand international participation in our training at the PhD-level, and broaden what NCAS offers to include CPD training courses to practitioners, and skills courses in areas such as data science. Education and training also forms an integral part of several large competitively-won projects such as the GCRF Africa-SWIFT.

2. People

2.1 People Management Principles: The NCAS Deal

The relationship between NCAS and staff is set out in a document called *The NCAS Deal*, developed more than 10 years ago to help support the somewhat unusual legal and organisational structure of NCAS. The Deal sets out to staff that NCAS considers its responsibilities as being exactly the same as if it were the legal employer, and describes the commitments NCAS makes and the expectations it has in return. The Deal is attached to the NERC-Leeds contract for NCAS and also appended to each sub-contract.

2.1.1 Employment Conditions

As it is not the employer of its staff, NCAS does not legally control factors associated with pay, promotion, requests for flexible working or other circumstances. However we provide direct advice and support on these issues, and indeed on occasion mandate their implementation through the NCAS sub-contract to each university. Each staff member is named on a NCAS sub-contract, setting out their job descriptions, expectations, grades, and other circumstances that we expect the employer to respect. Where NCAS identifies issues around pay and promotions, it makes direct recommendations to the employer to ensure equality between employers, and monitors employers' compliance with their obligations towards staff with disabilities. NCAS provides employers with unambiguous flexibility to accommodate requests for changes in working patterns, for example to/from flexible/part-time working, and direct financial support for staff absent with long-term illness or on maternity, paternity or adoption leave. Over this evaluation period NCAS has enabled >100 staff requests for changed working patterns and a recent survey has shown that virtually all staff make use of the facility to work flexibly. We are currently in dialogue with staff to understand how NCAS may better support the career development of those with caring responsibilities, and this forms part of a broader organisational objective to support well-being in the workplace.

2.1.2 Career Pathway

NCAS staff span the full spectrum of grades and job-types found within universities and research institutes. NCAS has staff on both fixed term and open-ended contracts, although only uses fixed-term where there is a specific and justifiable reason to do so, and the staff member is aware of these reasons. NCAS and its sub-contracted employers comply with all the requirements of the 2019 UKRI Concordat to Support the Career Development of Research staff, and NCAS has a transparent process that allows staff on fixed-term contracts to be considered for transfer to open-ended roles. Whilst NCAS is limited in size, and the number of roles at more senior career stages constrained, we support staff in developing their profile and leadership skills, including via training courses and the development of collaborations and external engagement. NCAS is proud of how it has developed and mentored staff who have joined as early career researchers and who have advanced to a point where they move on to hold professorial appointments in universities; this includes staff that have taken career breaks and worked part-time. We see NCAS as providing a valuable, and different, career pathway for researchers in atmospheric science.

2.1.3 Early Career Staff

NCAS is committed to the development of its Early Careers scientists and ensuring they have the skills and support needed to make the best of their career in atmospheric science. Staff have access to the NCAS training programme which ranges from the fundamentals of atmospheric science, to field work skills and modelling. We strongly encourage our early career staff to develop their own skills and knowledge by sharing their expertise with others, through involvement in the development and delivery of our training programme. We have a policy to support staff who wish to undertake external training and are extending the support on offer to our early career staff who wish to take on leadership responsibilities. Staff are supported and mentored when applying for early career and career-establishing research funding, and staff have successfully applied for and held NERC Advanced fellowships, Royal Society fellowships and ERC Starter Grants during this evaluation period (see Section B).

2.1.4 Staff Recruitment and Succession Planning

All new posts, or existing posts which arise as vacancies, are openly advertised. Recruitment processes follow HR and EDI best practices and are implemented by host institutions with NCAS having a full say in the conduct, including panel membership. During the evaluation period NCAS has found that substantial, long term posts attract many excellent applicants, including a good proportion from overseas. We find that positions in NCAS are attractive because the critical size of NCAS allows us to offer greater continuity and breadth of opportunity. The success of the NCAS recruitment policy for research posts is reflected in the quality of the evaluation submissions. The NCAS Management Board is responsible for succession planning at senior levels and is currently planning two senior level successions over the next two years.

2.1.5 Student Supervision

NCAS is not a degree-awarding body, but many staff are directly involved in the formal supervision of students, including at both undergraduate and postgraduate level (made possible since they hold university employment - a particular strength of the NCAS organisational model). The number of PhD students being directly supervised by NCAS staff has more than doubled over the last 5 years (99 students in the year 18/19), linked to an expanded role for NCAS in supporting the NERC DTP programmes across the UK, and the wider trend towards multiple PhD supervisors. Wherever practical we include our PhD students as members of the NCAS community of researchers, for example through participation in conferences and meetings, in outreach, communications and consultations. Staff involved in PhD student supervision undergo the local training required by the awarding institution. NCAS offers a wide range of training courses to PhD students and typically trains 200 such students per year.

2.1.6 Exchanges with Business, Industry and Public bodies

NCAS's strategy is to concentrate on key stakeholders, particularly the Met Office and Defra, with whom we have long-term collaborations (section 4.1). Examples are a joint post with Defra in the area of Air Quality policy and NCAS staff working on the Earth System Model who are based at the Met Office. We also have a Visitor Programme, which funds collaborative exchanges, either by NCAS staff to external institutions or by external staff to work at NCAS. Applications are invited from all staff twice a year for a Visitor Grant, and 3-5 visits a year are funded. These may have an academic, service or impact focus.

2.2 Equality, Diversity and Inclusion

The NCAS Directors are committed to developing NCAS as an organisation that treats its staff fairly and respectfully and embeds principles of equality, diversity and inclusivity in every aspect of its working practices. NCAS follows Athena Swan and Race Equality Charter guidelines in developing its policies and strategies. (Note that NCAS cannot formally affiliate with Athena Swan because it is not a separate institution, but the universities and STFC that employ staff are all affiliated to AS and several have silver/gold status).

2.2.1 Equality, Diversity and Inclusion Policies and Practice

The direct consequence of NCAS being neither a legal entity nor employer is that whilst NCAS cannot directly replicate employers' E&D assessments and policies, we aim to apply all the best practices and adhere to our own set of principles for the fair and equitable treatment of staff. NCAS ensures all staff involved in assessments have had EDI and GDPR training from employers. In addition, all staff involved in decision-making associated with the NERC evaluation also underwent additional UKRI training. We are particularly conscious of the need for fair and equal access to resources, facilities, equipment and infrastructure, based solely on criteria of strategic need and science excellence. We embed principles of equal and fair access in our internal decision-making at Board level, and then cascade this to individual facilities and programmes, with external oversight provided by independent advisory committees.

The NCAS Equality and Diversity Group, chaired by an NCAS Board member and drawing its membership from across all sections of NCAS, is charged with monitoring all NCAS policies and procedures for Equality, Diversity and Inclusion compliance and best practice. This is a crucial part of the NCAS operational model, since NCAS cannot directly impose policies, but NCAS can and does monitor host institution performance and does enable the institutions to implement best practice. Good examples are:

- We replicate as far as we are able schemes such as Athena Swan.
- Our approach to flexible working, where NCAS is able to ensure that *all* its staff are able to work flexibly (the staff survey demonstrates that virtually all staff make use of this).
- Where staff have taken periods of leave (e.g. parental, illness, caring), NCAS agrees new or interim arrangements with the staff member to assist with their return and ensures that these are implemented locally.
- Regarding matters of staff wellbeing, NCAS works with the local employer's policies and through flexibility and individually tailored considerations, enables the employer to fully meet the staff member's needs.
- NCAS makes very heavy usage of video conferencing. We have pioneered this partly because of our distributed nature but also to assist staff with caring and other responsibilities to take part in meetings and conferences. All NCAS-organised conferences have this option.

2.2.2 Equality and Diversity Assessment

A consequence of the structure of NCAS means that we do not have a right to collect or hold data on protected characteristics; this right resides solely with employers. There are also similar consequences relating to GDPR which limit the information that NCAS as a corporate body (legally the University of Leeds) can retain on staff, and this is particularly relevant to the assessment of E&D and protected characteristics. The quantitative information that NCAS has available for assessment is therefore limited to information that staff have *voluntarily* chosen to share, through a secure fully anonymised survey. We note limitations in our assessment of some protected characteristics since as a small organisation, there are particular risks of identification of individuals.

A summary of key NCAS staff statistics (based on voluntarily contributed staff returns) is shown in the Figures 12 and 13.

2.2.3 Equality, Diversity and Inclusion Data

Equality & Diversity Survey Outputs

Disability	
Yes	9
No	80
Prefer not to say	5

Gender	
Man	62
Woman	31
Prefer not to say	1

Caring responsibilites	
None	41
For a child or children (under 18 years)	41
For a disabled child or children	1
For a adult (disabled, ill, or elderly)	6
Prefer not to say	10

More than one response per person is possible

Ethnicities	
English / Welsh / Scottish / Northern Irish / British	66
Any other White background	18
Other	7
Prefer not to say	3

Flexible Working Ability	
Yes, frequently	76
Yes, sometimes	16
No, but I don't need this option	2

Extended Leave	
Maternity leave	6
Paternity leave	16
Shared parental leave	8
Special leave (over one month)	1
Extended sick leave (over one month)	1

Full / Part Time	
Full-time	79
Part-time (greater than or equal to 0.5 FTE)	13
Part-time (less than 0.5 FTE)	2

Total number of responses **94**

Figure 12: Results of the NCAS equality and diversity voluntary survey.

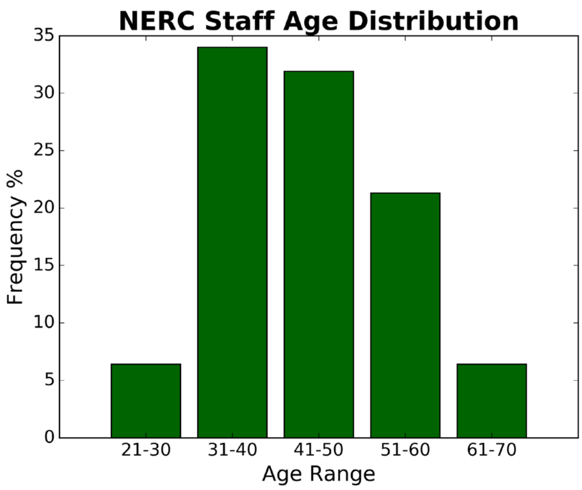

Figure 13: NCAS age distribution from the voluntary survey.

2.3 The NCAS Evaluation Code of Practice

Development of the Code of Practice (CoP) has been led jointly by two NCAS Executive Directors, one of whom (Professor Lesley Gray) chairs the NCAS Equality and Diversity Group (NEDG) and led the development of the Equality Impact Assessment (EIA) with contributions from a sub-group of NEDG. All members of NEDG were consulted on an early draft of the CoP.

Communication of the CoP was through a series of e-mails to staff providing details of the evaluation process (staff on leave of absence were also informed by letter if an affirmative response was not received to the e-mails). A dedicated section of the NCAS Staff Portal has also been developed, including the Code of Practice, the EIA, several additional documents explaining the aims of the Evaluation (including the NERC Guidelines), copies of all relevant staff communications, together with details on how staff can provide feedback on the process, including confidential communication to discuss eligibility or numbers of outputs submitted. To assess the effectiveness of the implementation of the CoP we undertook an analysis of the research outputs submitted to this evaluation and found no evidence of bias in the selection of outputs on the basis of gender or age.

3. Income, infrastructure and facilities

3.1 Income Generation and Staffing Strategy

Over the evaluation period available funding has declined in real terms and in line with its other programmes, NERC has implemented a policy of flat-cash funding for its national capability. We believe uniquely amongst research centres in the UK, NCAS has responded to this funding environment by:

- Growing other income sources to offset (and more) the decline in national capability funding;
- Enabled by this, only terminating activities if this is justified on strategic rather than purely financial criteria.

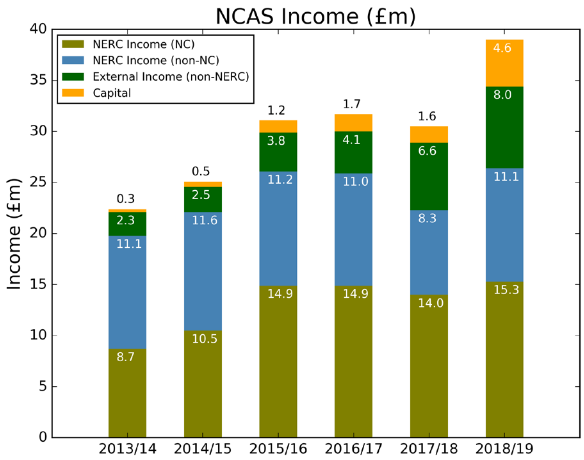

Figure 14: NCAS income.

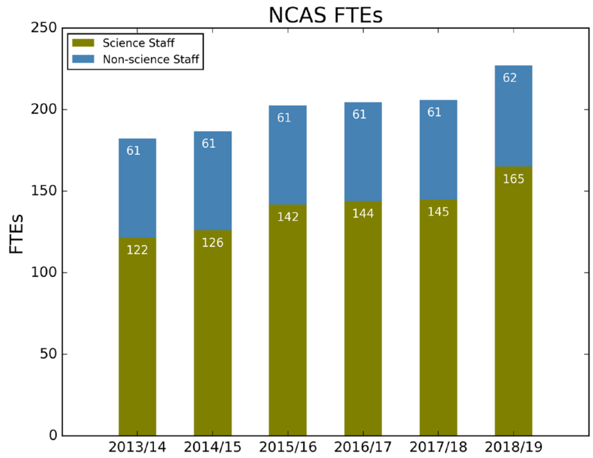

Figure 15: NCAS staff FTEs.

With this approach, NCAS has been able to grow all of its activities and maintain a thriving research programme based principally on competitively-won income, underpinned by a crucial core of NERC national capability funding.

An essential component of this strategy is the development of our body of expertise. The ability of NCAS to respond to new opportunities and initiatives is, we believe, particularly high because we invest in our workforce and retain essential skills even in times of financial constraints. This investment in people is impossible without maintaining a balanced budget and NCAS has consistently demonstrated the capability to achieve this with ambitious income generation targets.

3.2 Infrastructure Development

3.2.1 NCAS Headquarters

Throughout the evaluation period NCAS has continued the development of its status as a distributed but single research centre. A crucial step has been the establishment of an NCAS Headquarters with its own building, able to fulfil its national role impartially. In 2018, NCAS opened its headquarters building at Fairbairn House, adjacent to but separate from the University of Leeds campus. The refurbishment of the building was supported by NERC and the University of Leeds. Fairbairn House accommodates the central NCAS corporate services (administration, finance, people services, communication, training), the NCAS science activities based within Leeds and state-of-the-art national training facilities.

Figure 16: NCAS headquarters building Fairbairn House

3.2.2 Development of the Facility for Airborne Atmospheric Measurements

The evaluation period has seen substantial developments in the Facility for Atmospheric Measurements. At the beginning of the period FAAM was managed by NERC as a joint facility of NERC and the Met Office. FAAM staff were employed NERC and the Met Office. The aircraft was owned and operated by BAE Systems and its sub-contractors. NERC had a 10 year contract with BAE Systems from 2005-2015 for all aircraft services. Over the evaluation period, responsibilities for FAAM have gradually been passed to NCAS, with the process completed in 2019. In 2014 it became clear that BAE Systems no longer wished to own the aircraft. NCAS and NERC made a successful case to government for £10m capital funding to purchase the aircraft, to maintain the aircraft for a further 5 years and to construct a fit-for-purpose building for FAAM alongside Cranfield Airport. Over the period 2014-19 the NERC employees at FAAM were transferred to NCAS/University of Leeds employment. In 2019, the Met Office withdrew as a FAAM partner and it became necessary for NERC to assume full responsibility for FAAM. NCAS took on the employment of the remaining FAAM staff through the University of Leeds and negotiated a new five year aircraft services contract with BAE Systems for the period 2019-24.

The usage of the FAAM aircraft by the NERC community has grown, such that demand now exceeds availability. A programme of scientific instrument development has been pursued, overseen by working groups of FAAM and external community scientists. The facility is now clearly in the top three internationally, working at a similar level to facilities managed for NSF in the USA and HALO in Germany. Comprehensive planning and design work by NCAS with BAE Systems, with extensively community consultation, has established a roadmap for facility development over the next 15-20 years. This involves ambitious upgrades of the science instrumentation, especially in the area of remote sensing, and a comprehensive “Mid-Life Upgrade” of the aircraft itself. Funding for these initiatives is currently being sought, and FAAM has a position high on the UKRI list of infrastructure priorities.

3.2.3 Development of the JASMIN Facility

Massive increases in environmental data have led to two separate problems which can be summarised as: “disparate communities, common data” (e.g. multiple disciplines sharing data) and “common communities, disparate data” (e.g. scientists requiring access to data distributed globally). JASMIN provides a “Data Commons” solution to both these problems by providing a venue for data products to be assembled, shared, and manipulated by both disparate communities and those who need to assemble vast amounts of data from distributed sources. The need for, and architecture of, JASMIN, was identified in a series of e-science grants which began with “The NERC DataGrid (2002-2006)” followed up with NCAS NC funding.

JASMIN is one of the largest repositories of online environmental data in the world and provides unique facilities for exploiting that data. It consists of a massive disk store, supported by tape systems, alongside a large batch compute cluster, and a community cloud. The NCAS data centre (shared with NCEO), the Centre for Environmental Data Analysis (CEDA) is one of the tenants of the community cloud, with most CEDA services delivered via virtual machines managed by CEDA independently of the JASMIN team.

JASMIN hosts the CEDA archive, allowing users direct access to petabytes of data from Earth Observation satellites, climate models, and numerous heterogeneous ground and aircraft observations. Since commissioning in early 2012, JASMIN usage has grown year on year. As of November 2019 a total of 211 group workspaces are in use, with 13.5 petabytes of data serving a total of 2617 account holders of whom 1460 have JASMIN login access. The JASMIN Cloud currently has 52 tenancies, half of which are external and therefore serve their own users (who do not need JASMIN accounts).

3.2.4 Infrastructure Development for Air Pollution and Weather Science.

In both Air Pollution and Weather science, a continuing programme of capital investment in instrumentation (£250 k p.a. for ground-based and £250 k p.a. for FAAM (£500 k since 2017) has allowed the Facilities and the science programme to remain competitive and innovative. Larger capital awards such as £1.1M from ACSIS for FAAM, and £1.47M in transformational capital from Services and Facilities, have allowed step changes in observational capability. For access to capital, NCAS has an open process whereby any staff member can propose a piece of investment, either directly or through the NCAS instrument community working groups. Access to the Facilities themselves is mainly through grants, ensuring an open and fair application process and maintaining science quality.

3.2.5 High Performance Computing

NCAS is NERC's largest HPC user, with extensive relevant technical knowledge, and NERC has chosen to place its HPC budget within NCAS since 2014/15. NCAS has led NERC's HPC strategy since 2015. HPC provision comes from the UKRI ARCHER system and from a share of the Met Office HPC system (referred to as MONSooN) available to joint NERC/Met Office projects running under the Joint Weather and Climate Research Programme (JWCRP). Since 2017/18 this has been enhanced by a further service from the Met Office (NEXCS) available to all NERC users. In its role of managing the NERC's HPC budget, NCAS has also managed on NERC's behalf the strategy for development of the ARCHER/MONSooN/NEXCS provision to NERC users. NCAS has represented NERC in the negotiations leading to the ARCHER2 HPC system to replace ARCHER in the first half of 2020.

3.3 NCAS Exploitation of Infrastructure

3.3.1 Air pollution science

This area is critically reliant on access to laboratories, large simulation facilities and access to cutting edge measurement instrumentation (e.g. optical absorption, spectroscopy, mass spectrometry and chromatography). We have worked with our university partners to co-develop a laboratory science infrastructure that is world class, that have high utilisation rates, excellent cost efficiency and gain scientific leverage through collaborative working. NCAS has co-supported a 60m^3 environmental chamber for the study of gas and aerosol properties in Manchester, and a temperature and pressure controlled photoreactor reactor in Leeds. Both provide infrastructure that is shared Europe-wide through the programmes EUROCHAMP and ACTRIS. The NCAS long-term science needs were central to the design of a shared NCAS/University of York atmospheric chemistry building, which opened in 2014 following ~£1.5M in donations from the Wolfson Foundation and philanthropic donors, with further investment from NERC in 2016.

NCAS has invested (>£0.5M) in its WMO Global Atmosphere Watch observatory on Cape Verde, upgrading instruments and containerised laboratory space in 2014-5. In 2017 NCAS led a £4.3M capital programme for NERC, creating air pollution urban supersites in Birmingham, London and Manchester. NCAS has invested in the capability to build novel atmospheric chemistry instruments and shares technology development labs in Manchester (focusing on aerosols) and York (focusing on gases).

3.3.2 Weather Science

There is extensive use of observational facilities in the Climate and High Impact Weather theme. Research is conducted with the FAAM aircraft, which has a world-leading capability for *in situ* cloud measurements, complementing the remote sensing capabilities of aircraft such as the German HALO and contributing to ambitious joint experiments like the 2016 NAWDEX campaign. FAAM supported NCAS scientists in making ground-breaking measurements in India through the INCOMPASS project, and will play a major role in the future NERC Clouds and Climate strategic programme.

The NCAS ground-based observational programme exploits the NFARR and AMF facilities, (soon to be merged as AMOF). During the evaluation period, NCAS completed a re-design and upgrading of AMF to make it more responsive to community needs. A highlight from the past 7 years was establishing a triple-frequency scanning radar capability at Chilbolton, which will be further augmented by installation of an X-band radar on the main dish in 2022. Chilbolton's status as a Centre of Excellence on cloud and aerosol science means that it will offer a node of the ACTRIS Cloud Remote Sensing Topical Centre, as well as providing long-term measurements. In both AMF and NFARR, dedicated instrument scientists provide expertise needed to manage the equipment, as well as contributing to the science.

3.3.3 Climate Science

The principal infrastructures underpinning this area of NCAS science are High Performance Computing and JASMIN. NCAS develops and maintains community access to large models, including in particular, the UKESM Earth System Model. NCAS both facilitates the wider community usage and also make its own use of this and other large model capabilities. NCAS is a major user of the ARCHER and NECXS HPC systems and for several joint projects with the Met Office exploiting Earth System Models, NCAS is also a large user of MONSooN. Although NCAS manages the budgets for all these systems, allocations of HPC time are made by a separate HPC committee managed by NERC. For 2018/19, atmospheric science accounted for 46% of NERC's usage of ARCHER, of which 16% was used by NCAS. For the same period, atmospheric science applications accounted for 88% of NEXCS usage of which 45% was by NCAS.

A particular strength of NCAS climate modelling has been the development of high resolution global models under the joint NCAS/Met Office High Resolution Climate Modelling (HRCM) project, working at the frontier of weather-resolving climate models. Within HRCM, the 2016-19 PRIMAVERA/HighResMIP project has produced over 5000 years of climate simulation at resolutions spanning from 135 to 25km, all submitted to the the IPCCs CMIP6 project. All PRIMAVERA/HighResMIP simulations are held on JASMIN for analysis worldwide (over 150 users from 19 European groups and 18 international groups). During 2016-19, HRCM has produced 45 peer-reviewed publications with a further 25 submitted before the IPCC CMIP6 deadline.

4. Collaboration and Contribution to the Research Base, Economy and Society

4.1 Key research collaborations

Major collaborations, involving close working with complementary organisations, are integral parts of the NCAS research strategy. NCAS has a dual approach to these relationships: we support staff to prioritise collaborative working (e.g. by setting aside funds for two-way exchanges and visits) and by formalising key relationships with Memoranda of Understanding. NCAS currently has MoUs with the National Center for Atmospheric Research (NCAR), the National Oceanographic and Atmospheric Administration (NOAA - two separate MoUs), NASA, the Met Office, the Icelandic Meteorological Office, the University of Trento, the Royal Meteorological Society and several companies. NCAS has found that MoUs are an extremely effective way of sharing mutual understanding (e.g. organisational objectives, resources, ways of working) in order to promote maximum benefit from collaboration.

4.1.1 Met Office

The Met Office's research programme complements that of NCAS, engaging in numerous collaborations with NCAS. The UK Earth System Model (ESM) development, led by NCAS, is a formal collaboration between the NERC Centres and the Met Office. The JWCRP provides a framework for collaboration between the Met Office and the NERC Centres. Within this, the development and exploitation of climate and weather models based on the Unified Model underpins many of NCAS's scientific outputs. The development of the UK Chemistry and Aerosol Model (UKCA), which feeds into the ESM, is also an NCAS-Met Office collaboration. The Met Office was until 2019 a full partner in the FAAM aircraft, and is still an important user of the Facility with a long-term funding arrangement. The Met Office also collaborates with NCAS in field campaigns, for example COPE in 2013 (Cornwall), ICE-D in 2015 (Cape Verde), Monsoon in 2016 (India), CLARIFY in 2017 (Ascension Is) and Picasso in 2018-19 (Joint with Chilbolton radars).

Many NCAS staff have served on the formal advisory panels for the Hadley Centre (including by Prof John Pyle as Chair) and the Weather programme (MOSAC). Impact is delivered through specific projects like the development of a volcanic ash sensor for commercial aircraft, wider GCRF schemes to help deliver resilience to drought and high-impact weather in ODA countries, and through longer-term impact where the science done on microphysics and aerosols, for example, feeds into improved parameterisations in the UM and thereby into improved weather forecasts and climate projections.

4.1.2 Defra

There are strategic links between NCAS and government through Defra in the area of air pollution science. NCAS and Defra have supported joint staff appointments for nearly a decade that allow staff from NCAS to spend time most weeks embedded in Defra in Whitehall. Sarah Moller from NCAS is currently a Senior Research Fellow working part-time directly for the Defra CSA, and Alastair Lewis chairs Defra's science advisory group on air pollution, where James Allan is also a member.

4.1.3 BEIS

This period has seen NCAS develop new collaborations with BEIS supporting the science and impacts of emissions relating to the oil and gas industries. NCAS has been part of a long-term BEIS project to evaluate the impacts of shale gas in the UK, making measurements at prototype shale sites in Lancashire and North Yorkshire. NCAS has used the FAAM aircraft to pioneer new methods to quantify emissions and gases from offshore platforms and led directly to a close and direct collaboration with the BEIS Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) to develop new approaches to offshore emissions regulation.

4.1.4 Industry

NCAS uses its world-leading knowledge of atmospheric measurements to support a range of industries that rely on trace detection of gases and aerosols. NCAS has collaborated extensively with the aviation industry, supporting improved measurements and predictions of volcanic ash and with the ICAO on improved methods to quantify, and reduce, emissions from large aircraft engines. NCAS has strategic collaborations with two instrument manufacturers, Markes International and Syft Technologies who currently commercialise NCAS technology. NCAS has used mechanisms such as Innovate UK KTPs, the Small Business Research Initiative from the MOD, and direct external commercial funding, to support this work and collaborated with both DSTL and AWE plc on chemical hazard detection, supported by >£1M in external funding. NCAS uses its expertise in futures extremes of climate and weather to support industry in making assessments of insurance and infrastructure risk, and worked with BP, to help develop improved estimates of extremes of wave heights using high resolution climate models, underpinning the designs of large installations in the North Sea and Caspian Sea.

4.1.5 ECMWF

Although narrower in scope than the work with the Met Office, long-term collaborations are in place with ECMWF. Dr Paul Berrisford was until recently a joint appointment between NCAS and ECMWF to develop reanalyses (he has now transferred fully to ECMWF), while Dr Antje Weisheimer is a joint appointment between ECMWF and NCAS at Oxford working on stochastic parameterisation and predictability.

4.1.6 Environment Agency and SEPA

NCAS collaborates with the Environment Agency in England and with SEPA in Scotland in the area of weather radars. A series of deployments of the NCAS X-band radar have improved the analysis of radar rainfall data and for the agencies have provided operational capabilities of great relevance to flood warning, which would not otherwise have been available. NCAS and the EA are currently discussing how to further formalise this highly effective research-to-operations collaboration.

4.1.7 Overseas Development Partners

Atmospheric Science research can make substantial contributions to improving quality of life and supporting economic development in low and middle-income countries. The growth in UKRI focus on Official Development Assistance (ODA) has provided NCAS with major research and impact opportunities; ODA-related research now represents a substantial fraction of NCAS competitively-won income, from NERC, UKRI/GCRF and DFID. NCAS undertakes collaborative research on air pollution and rainfall prediction with partners in West Africa through the ACREW NC-ODA project, leads a major £8m NERC impact project on weather forecasting and applications (African-SWIFT) and with GCRF is working to develop new open-source methods for air pollution measurement. NCAS values highly its long-term relationships which have developed from ODA, exemplified by the successful multi-partner collaboration over the last 15 years with the Meteorological Service in Cape Verde (INMG), Max Planck Jena, and IFT Leipzig. This has delivered a continuously operating Global-status WMO-GAW observatory, and led to >100 publications since 2005.

4.2 Leadership in the Academic Community

4.2.1 Journal Editorships

During the evaluation period 25 NCAS staff have held positions as editors or co-editors of peer reviewed journals, including *Nature*, *Science*, *Quarterly Journal of the Royal Meteorological Society*, *Journal of Geophysical Research*, *Nature Scientific Reports*, *Analytical Chemistry*, *Advances in Atmospheric Science*, *Atmospheric and Oceanic Science Letters*, *Atmospheric Science Letters*, *Analytical Methods, Nature Scientific Data*, *Atmospheric Measurement Techniques*, *Geoscience Communications*, *Frontiers in Atmospheric Science*, *Advances in Meteorology*, *Atmosphere* and *Environmental Science Letters*.

4.2.2 Journal Reviewing

All but two of the staff submitted to this evaluation regularly review papers for leading scientific journals, including *Nature*, *Science*, *Journal of Geophysical Research*, *Atmospheric Chemistry and Physics*, *Journal of Climate*, *Quarterly Journal of the Royal Meteorological Society* and many others. The average number of reviews per person per year is 6.

4.2.3 Research Fellowships

Seven NCAS staff have held competitively won and externally funded fellowships during the evaluation period. These include ERC fellowships (Gregory, Edwards) and NERC Advanced fellowships (Hawkins, Klingaman) and NERC KE fellowships (Moller). It is an NCAS policy to encourage and assist our early career research scientists to seek fellowship support. This allows such staff to further their development as independent researchers whilst maintaining a close contact with long term NCAS strategic research. Fellowship holders are retain their open-ended positions within NCAS.

4.2.4 Advisory Roles

Excluding NERC advisory groups (where NCAS staff are often asked and expected to contribute), 28 NCAS staff members have been members of advisory boards and panels during the evaluation period. A majority of these are international, and in a number of cases staff have chaired advisory groups. Neely chairs the Interagency Committee on Hydrological Use of Weather Radar, Lewis chairs the Defra Air Quality Expert Group, Lawrence chairs the Independent Advisory Panel of the NCAR Computational Information Systems Laboratory, Jones chairs the Advisory Board Bjerknes Centre for Climate Research and Shaffrey chairs the European Climate Research Alliance. Other high profile advisory memberships include the Interim ACTRIS Council (Vaughan), CLIVAR Scientific Steering Group (Hawkins), Strategy Board of WCRP SPARC Programme (Gray), Met Office Scientific Advisory Committee (Mobbs, Vaughan), Met Office Hadley Centre Scientific Advisory Group (Sutton), the NHP Steering Group (Moller), the Cabinet Office Scientific Advisory Group in Emergencies (Mobbs) the Advisory Board of the Max Planck Institute for Meteorology Hamburg (Gregory). Lewis advises the Royal College of Physicians, NPL, UNEP GEOS-6, the National Nuclear Security Programme and has given evidence to House of Commons Select Committees and ministerial round-tables. Evans has been an Advisor to NASA on atmospheric chemistry modelling. In the course of their work for the Natural Hazards Partnership Moller and Mobbs are chapter authors in the National Risk Assessment. Pyle made major contributions to the 2014 and 2018 WMO/United Nations Environment Programme (UNEP) Scientific Assessments of Ozone Depletion.

4.2.5 Funding and Assessment Panels

In total, 29 NCAS staff members have been members of funding panels, with the majority of these staff being involved in overseas panels. High profile examples include the Academy of Finland (both Mobbs and Lewis have chaired, Lee and Alfara have been members), Deutsche Forschungsgemeinschaft and Deutsches Zentrum für Luft- und Raumfahrt (five staff on various occasions), several US Department of Energy review panels (Klingaman), NASA (Lewis, Evans), Swiss National Science Foundation (Burton), Belmont Forum (Weisheimer) and Norwegian Research Council (Shaffrey). Lewis has served as a UoA 8 sub-panel member for both REF 2014 and 2021.

4.2.6 Keynote Lectures

During the evaluation period, 28 staff have given a total of 59 keynote lectures at international conferences.

4.2.7 Awards and Prizes

Fourteen of the NCAS staff have received significant awards from external organisations during the evaluation period. These include CBE for Pyle, MBEs for Collier, Mobbs and Hawkins, the Royal Society Kavali Medal for Hawkins, the Royal Society Davy Medal for Pyle, the Royal Meteorological Society Fitzroy Prize for Gregory and the NERC International Impact Award 2015 for Pyle.

4.2.8 Contributions to the Intergovernmental Panel on Climate Change (IPCC)

NCAS is heavily committed to supporting the work of the IPCC in all its forms. Overwhelmingly the largest contribution is through the many NCAS climate science peer reviewed publications which form the basis of the IPCC reports (approximately 80 papers co-authored by NCAS staff are cited in the 5th Assessment Report). NCAS also supports the IPCC directly through authorship of the Assessment Reports. For the 5th Assessment report (i) Sutton, Guilyardi, and Gregory were lead authors for the report of Working Group 1, (ii) Gregory served on the writing team for the Summary for Policymakers, and (iii) an additional 10 NCAS staff served as Contributing Authors to various chapters. For the 6th Assessment Report, Hawkins and Turner are lead authors for the Working Group 1. In addition, the UKESM1 global Earth System Model, jointly developed by NCAS and the Met Office with input from other NERC centres, is one of the principal models contributing to the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 6 (CMIP6). These structured model simulations, agreed globally by the WCRP, form a basis for the IPCC 6th Assessment Report. In addition, NCAS is a key partner in Earth System Federation Grid, which distributes and archives the multi-petabyte CMIP5 and CMIP6 climate model datasets that support the IPCC process.

4.3 Sustainability of the Discipline and Support for the Community

NCAS takes extremely seriously its role in supporting UK atmospheric science, across the NERC-funded community and elsewhere in the UK. This commitment is firmly rooted in the NCAS origins. In 2001 NERC’s Science and Technology Board put forward a proposal to Council to create a research centre in atmospheric science.

> "*The NERC Centres for Atmospheric Science (NCAS)* [NCAS changed its name in 2007], *is being established to carry out NERC's core strategic programme in atmospheric science. NCAS will deliver, for the first time, a coordinated and integrated atmospheric science core strategic research programme, contributing to NERC's mission, by: developing and using state-of-the-art modelling and observational capability, so as to advance atmospheric science leading to improved understanding and predictability of the Earth System …. Atmospheric science is a small but high achieving component of the science funding NERC provides to the community; a highly regarded example is UGAMP* [the predecessor of the NCAS climate programme and the CMS support service]. *However there has been a significant loss of coordination caused by atmospheric science, unlike other areas of NERC science, not having a dedicated research centre.*"
>
> **NERC Science and Technology Board, October 2001**

Evidence of the NCAS commitment to its community includes:

- NCAS has protected and maintained its commitment to Underpinning Long Term Science against a background of declining baseline funding.
- NCAS takes a major leadership role in NERC's Long Term Science Multiple Centre programme, leading the cross-centre ACSIS and UKESM programmes.
- NCAS delivers a range of large infrastructures and services and facilities to a wide range of users in the UK.
- NCAS has a team dedicated to the organisation and management of community research events, such as the national Atmospheric Science Conference.
- NCAS prioritises the provision of early career training for atmospheric scientists and works with PhD students right across the UK.

4.3.1 The NCAS Research Forum

The NCAS Research Forum is a long-standing activity, consisting of invited gatherings of typically 25-40 members of the research and stakeholder communities brought together to produce a short report on the initiation and implementation of new research developments in the community. Typical examples include:

- *NCAS/Defra Sensor Research Forum*, October 2019. To develop a common understanding between Defra, researchers and other users concerning the state of science around small air pollution sensor.
- *The role of mixed-phase cloud systems on cloud-radiation feedbacks and climate sensitivity*, March 2017. To determine a way forward for improving the representation of cloud and aerosol processes in climate models.

4.3.2 Interdisciplinarity

An important role for NCAS is to promote interdisciplinary research and this is reflected in the NCAS leadership of the ACSIS and UKESM programmes and in the diverse ODA activities within and beyond the NCAS ACREW programme. NCAS has strong linkages with China, India and many African countries, ranging from air quality and human health to severe weather hazards. NCAS uses its long term strategy and science programmes to build linkages with organisations in other countries and other disciplines which can subsequently be used by the wider UK community (the African SWIFT GCRF programme being a good example).

4.4 Society and Outreach

Hawkins undertakes globally recognised work on climate change communications (awarded MBE 2020, and the Royal Society Kavli Medal 2018). Hawkins' climate spiral design was on the shortlist for the Kantar Information is Beautiful Awards 2016 the design having been featured in the opening ceremony of the August 2016 Summer Olympics (Rio de Janeiro)

Moller and Lewis promote debate around contemporary issues associated with air pollution, making multiple TV and Radio contributions (BBC 2,4,5, World Service, Inside Science, The Inquiry, Costing the Earth, Newsnight, Trust me I'm a Doctor, Channel 4 News), and publish regularly though The Conversation, reaching more than 350,000 readers in the evaluation period. Lewis worked with Aardman Animations and broadcaster Marcus Brigstocke to produce a short animated film on indoor air pollution, released at the 2018 Hay Festival. Mobbs frequently appears on the Paul Hudson Weather Show on BBC radio, along with several other NCAS colleagues. NCAS work monitoring volcanic emissions in Iceland using the FAAM aircraft was featured extensively on BBC news channels.

The NCAS Communications team alerts staff to opportunities that will further their science communication capabilities, and offer guidance through our own training, networks and knowledge-transfer sessions. We seek funding and opportunities for our staff, and also provide advice to those who lead applications themselves. NCAS generates media coverage about notable science achievements and initiatives where possible. NCAS is proactive in bringing its activities to the attention of the media and the wider public, working closely with the Science Media Centre. We frequently publish news articles on our website (www.ncas.ac.uk) and bring these to the attention of the media. Typical recent examples include:

- Rapid action needed to protect ozone layer against new source of illegal chemical emissions - NCAS scientists have assessed the impacts of a new source of an ozone-destroying chemical.
- Why climate science needs to learn from risk assessment - NCAS' Rowan Sutton recommends that climate scientists need to spend more time considering all plausible future climate scenarios rather than just the most likely.

ENVIRONMENT COMPONENT DATA

Total income (funding and capital): £m

2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
22.44	25.07	31.10	31.64	30.47	38.90