EVALUATION OF NERC CENTRES 2020: BRITISH ANTARCTIC SURVEY EVIDENCE SUBMISSION

1. LIST OF RESEARCH OUTPUTS

Type of output	Title of output	Year	Journal title	DOI
D – Journal article	A 120-year record of resilience to environmental change in brachiopods	2018	Global Change Biology	10.1111/gcb.14085
D – Journal article	A 308 year record of climate variability in West Antarctica	2013	Geophysical Research Letters	10.1002/2013GL057782
D – Journal article	A 30-Year Simulation of the Outer Electron Radiation Belt	2018	Space Weather	10.1029/2018SW001981
D – Journal article	A Cold Limit to Adaptation in the Sea	2016	Trends in Ecology and Evolution	10.1016/j.tree.2015.09.014
D – Journal article	A cool temperate climate on the Antarctic Peninsula through the latest Cretaceous to early Paleogene	2014	Geology	10.1130/G35512.1
D – Journal article	A draft fur seal genome provides insights into factors affecting SNP validation and how to mitigate them	2016	Molecular Ecology Resources	10.1111/1755-0998.12502
P – Devices & products	A ground-based radar for measuring vertical strain rates and time-varying basal melt rates in ice sheets and shelves	2015	Journal of Glaciology	10.3189/2015JoG15J073
D – Journal article	A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years	2013	Journal of Geophysical Research Atmospheres	10.1029/2012JD018603
D – Journal article	A new diffusion matrix for whistler mode chorus waves	2013	Journal of Geophysical Research: Space Physics	10.1002/jgra.50594
D – Journal article	A Predominant Reversal in the Relationship between the SAM and East Antarctic Temperatures during the Twenty-First Century	2013	JOURNAL OF CLIMATE	10.1175/JCLI-D-12-00671.1
D – Journal article	A temperate former West Antarctic ice sheet suggested by an extensive zone of subglacial meltwater channels	2014	Geology	10.1130/G35980.1
D – Journal article	Absence of 21st century warming on Antarctic Peninsula consistent with natural variability	2016	Nature	10.1038/nature18645
D – Journal article	Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century	2013	Nature Geoscience	10.1038/ngeo1787
D – Journal article	Acclimation and thermal tolerance in Antarctic marine ectotherms	2014	Journal of Experimental Biology	10.1242/jeb.089946
D – Journal article	Adaptation of proteins to the cold in Antarctic fish: A role for methionine?	2019	Genome Biology and Evolution	10.1093/gbe/evy262
D – Journal article	Additive effects of climate and fisheries drive ongoing declines in multiple albatross species	2017	Proceedings of the National Academy of Sciences of the United States of America	10.1073/pnas.1618819114

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D – Journal article	Adult acclimation to combined temperature and pH stressors significantly enhances reproductive outcomes compared to short-term exposures	2015	Journal of Animal Ecology	10.1111/1365-2656.12316
D – Journal article	Age-related variation in reproductive traits in the wandering albatross: Evidence for terminal improvement following senescence	2013	Ecology Letters	10.1111/ele.12092
D – Journal article	An initial assessment of Antarctic sea ice extent in the CMIP5 models	2013	Journal of Climate	10.1175/JCLI-D-12-00068.1
D – Journal article	Anomalously high geothermal flux near the South Pole	2018	Scientific Reports	10.1038/s41598-018-35182-0
D – Journal article	Antarctic Crabs: Invasion or Endurance?	2013	PLoS ONE	10.1371/journal.pone.0066981
D – Journal article	Antarctic last interglacial isotope peak in response to sea ice retreat not ice-sheet collapse	2016	Nature Communications	10.1038/ncomms12293
D – Journal article	Antarctic sea ice increase consistent with intrinsic variability of the Amundsen sea low	2016	Climate Dynamics	10.1007/s00382-015-2708-9
D – Journal article	Antarctica: The final frontier for marine biological invasions	2019	Global Change Biology	10.1111/gcb.14600
D – Journal article	Arctic Sea Ice Loss in Different Regions Leads to Contrasting Northern Hemisphere Impacts	2018	Geophysical Research Letters	10.1002/2017GL076433
D – Journal article	Asia's shrinking glaciers protect large populations from drought stress	2019	Nature	10.1038/s41586-019-1240-1
D – Journal article	Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing response, and state dependence	2013	Journal of Geophysical Research Atmospheres	10.1002/jgrd.50153
D – Journal article	Basal freeze-on generates complex ice-sheet stratigraphy	2018	Nature Communications	10.1038/s41467-018-07083-3
D – Journal article	Basal melting of Ross Ice Shelf from solar heat absorption in an ice-front polynya	2019	Nature Geoscience	10.1038/s41561-019-0356-0
D – Journal article	Basal terraces on melting ice shelves	2014	Geophysical Research Letters	10.1002/2014GL060618
D – Journal article	Bed conditions of Pine Island Glacier, West Antarctica	2017	Journal of Geophysical Research: Earth Surface	10.1002/2016JF004033
S – Research data sets & databases	Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica	2013	Cryosphere	10.5194/tc-7-375-2013

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S – Research data sets & databases	Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica	2013	Cryosphere	10.5194/tc-7-375-2013
D – Journal article	Biodiversity in marine invertebrate responses to acute warming revealed by a comparative multi-omics approach	2017	Global Change Biology	10.1111/gcb.13357
D – Journal article	Carry-over effects from breeding modulate the annual cycle of a long-distance migrant: An experimental demonstration	2013	Ecology	10.1890/12-2177.1
D – Journal article	Channelized ice melting in the ocean boundary layer beneath Pine Island Glacier, Antarctica	2013	Science	10.1126/science.1239373
D – Journal article	Chemical fingerprints encode mother-offspring similarity, colony membership, relatedness, and genetic quality in fur seals	2015	Proceedings of the National Academy of Sciences of the United States of America	10.1073/pnas.1506076112
D – Journal article	Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem	2015	Science Advances	10.1126/sciadv.1500050
D – Journal article	Climate change drives expansion of Antarctic ice-free habitat	2017	Nature	10.1038/nature22996
D – Journal article	Climate change selects for heterozygosity in a declining fur seal population	2014	Nature	10.1038/nature13542
D – Journal article	Climate-linked iceberg activity massively reduces spatial competition in Antarctic shallow waters	2014	Current Biology	10.1016/j.cub.2014.04.040
D – Journal article	Climatically sensitive transfer of iron to maritime Antarctic ecosystems by surface runoff	2017	Nature Communications	10.1038/ncomms14499
D – Journal article	CMIP5 diversity in Southern Westerly jet projections related to historical sea ice area: Strong link to strengthening and weak link to shift	2018	Journal of Climate	10.1175/JCLI-D-17-0320.1
D – Journal article	Comparison between POES energetic electron precipitation observations and riometer absorptions: Implications for determining true precipitation fluxes	2013	Journal of Geophysical Research: Space Physics	10.1002/2013JA019439
D – Journal article	Connectivity in the cold: The comparative population genetics of vent-endemic fauna in the Scotia Sea, Southern Ocean	2016	Molecular Ecology	10.1111/mec.13541
D – Journal article	Constraints on soluble aerosol iron flux to the Southern Ocean at the Last Glacial Maximum	2015	Nature Communications	10.1038/ncomms8850
D – Journal article	Critical Southern Ocean climate model biases traced to atmospheric model cloud errors	2018	Nature Communications	10.1038/s41467-018-05634-2
D – Journal article	Decadal freshening of the Antarctic bottom water exported from the Weddell Sea	2013	Journal of Climate	10.1175/JCLI-D-12-00765.1

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D – Journal article	Decadal-scale progression of the onset of Dansgaard-Oeschger warming events	2019	Climate of the Past	10.5194/cp-15-811-2019
D – Journal article	Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation	2014	PLoS ONE	10.1371/journal.pone.0109183
D – Journal article	Diverse landscapes beneath Pine Island Glacier influence ice flow	2017	Nature Communications	10.1038/s41467-017-01597-y
D – Journal article	Dynamics of mixed convective-stably-stratified fluids	2017	Physical Review Fluids	10.1103/PhysRevFluids.2.094804
D – Journal article	Eddy Saturation of Equilibrated Circumpolar Currents.	2013	Journal of Physical Oceanography	10.1175/JPO-D-12-095.1
D – Journal article	Eddy-induced variability in Southern Ocean abyssal mixing on climatic timescales	2014	Nature Geoscience	10.1038/ngeo2200
D – Journal article	Emperor penguins breeding on iceshelves	2014	PLoS ONE	10.1371/journal.pone.0085285
D – Journal article	Energization of the Ring Current by Substorms	2018	Journal of Geophysical Research: Space Physics	10.1029/2018JA025766
D – Journal article	Evidence for a palaeo-subglacial lake on the Antarctic continental shelf	2017	Nature Communications	10.1038/ncomms15591
D – Journal article	Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet	2013	Nature Geoscience	10.1038/ngeo1977
D – Journal article	Evidence of an active volcanic heat source beneath the Pine Island Glacier	2018	Nature Communications	10.1038/s41467-018-04421-3
D – Journal article	Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks	2017	Nature	10.1038/nature24458
D – Journal article	Evolution of the Southern Annular Mode during the past millennium	2014	Nature Climate Change	10.1038/nclimate2235
D – Journal article	Extinction risk and conservation of the world's sharks and rays	2014	eLife	10.7554/eLife.00590.001
D – Journal article	Extreme relativistic electron fluxes in the Earth's outer radiation belt: Analysis of INTEGRAL IREM data	2017	Space Weather	10.1002/2017SW001651
D – Journal article	Extreme spikes in DMS flux double estimates of biogenic sulfur export from the Antarctic coastal zone to the atmosphere	2019	Scientific Reports	10.1038/s41598-019-38714-4
D – Journal article	Foehn jets over the Larsen C Ice Shelf, Antarctica	2015	Quarterly Journal of the Royal Meteorological Society	10.1002/qj.2382
D – Journal article	Formation of electron radiation belts at Saturn by Z-mode wave acceleration	2018	Nature Communications	10.1038/s41467-018-07549-4
D – Journal article	Future circulation changes off West Antarctica: Sensitivity of the Amundsen Sea Low to projected anthropogenic forcing	2016	Geophysical Research Letters	10.1002/2015GL067143

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D – Journal article	Global biogeographic patterns in bipolar moss species	2017	Royal Society Open Science	10.1098/rsos.170147
D – Journal article	Global diversity and oceanic divergence of humpback whales (Megaptera novaeangliae)	2014	Proceedings of the Royal Society B: Biological Sciences	10.1098/rspb.2013.3222
D – Journal article	Global Model of Plasmaspheric Hiss From Multiple Satellite Observations	2018	Journal of Geophysical Research: Space Physics	10.1029/2018JA025226
D – Journal article	Global morphology and spectral properties of EMIC waves derived from CRRES observations	2014	Journal of Geophysical Research: Space Physics	10.1002/2014JA020064
D – Journal article	Global phenological insensitivity to shifting ocean temperatures among seabirds	2018	Nature Climate Change	10.1038/s41558-018-0115-z
D – Journal article	Heat Flux Distribution of Antarctica Unveiled	2017	Geophysical Research Letters	10.1002/2017GL075609
D – Journal article	Heat flux variations beneath central Greenland's ice due to anomalously thin lithosphere	2013	Nature Geoscience	10.1038/ngeo1898
D – Journal article	High basal melting forming a channel at the grounding line of Ross Ice Shelf, Antarctica	2016	Geophysical Research Letters	10.1002/2015GL066612
D – Journal article	Holocene dynamics of the Southern Hemisphere westerly winds and possible links to CO2 outgassing	2018	Nature Geoscience	10.1038/s41561-018-0186-5
D – Journal article	Hydrography and circulation in the Filchner Depression, Weddell Sea, Antarctica	2014	Journal of Geophysical Research: Oceans	10.1002/2014JC010225
D – Journal article	Hypoxia impacts large adults first: Consequences in a warming world	2013	Global Change Biology	10.1111/gcb.12197
D – Journal article	Iceberg killing fields limit huge potential for benthic blue carbon in Antarctic shallows	2017	Global Change Biology	10.1111/gcb.13523
D – Journal article	Ice-shelf buttressing and the stability of marine ice sheets	2013	Cryosphere	10.5194/tc-7-647-2013
D – Journal article	Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise	2019	Nature Climate Change	10.1038/s41558-018-0356-x
D – Journal article	Influence of Sea Ice-Derived Halogens on Atmospheric HOx as Observed in Springtime Coastal Antarctica	2019	Geophysical Research Letters	10.1029/2019GL083825
D – Journal article	Investigating vegetation-climate feedbacks during the early Eocene	2014	Climate of the Past	10.5194/cp-10-419-2014
D – Journal article	Krill (Euphausia superba) distribution contracts southward during rapid regional warming	2019	Nature Climate Change	10.1038/s41558-018-0370-z
D – Journal article	Krill faecal pellets drive hidden pulses of particulate organic carbon in the marginal ice zone	2019	Nature Communications	10.1038/s41467-019-08847-1
D – Journal article	Lack of long-term acclimation in Antarctic encrusting species suggests vulnerability to warming	2019	Nature Communications	10.1038/s41467-019-11348-w

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D – Journal article	Late cretaceous winter sea ice in Antarctica?	2013	Geology	10.1130/G34891.1
D – Journal article	Latest Cretaceous-earliest Paleogene vegetation and climate change at the high southern latitudes: Palynological evidence from Seymour Island, Antarctic Peninsula	2014	Palaeogeography, Palaeoclimatology, Palaeoecology	10.1016/j.palaeo.2014.04.018
D – Journal article	Low atmospheric CO 2 levels during the Little Ice Age due to cooling-induced terrestrial uptake	2016	Nature Geoscience	10.1038/ngeo2769
D – Journal article	Macrofossil evidence for a rapid and severe Cretaceous-Paleogene mass extinction in Antarctica	2016	Nature Communications	10.1038/ncomms11738
D – Journal article	Major advance of South Georgia glaciers during the Antarctic Cold Reversal following extensive sub-Antarctic glaciation	2017	Nature Communications	10.1038/ncomms14798
D – Journal article	Marine ice regulates the future stability of a large Antarctic ice shelf	2014	Nature Communications	10.1038/ncomms4707
D – Journal article	Mechanisms driving variability in the ocean forcing of Pine Island Glacier	2017	Nature Communications	10.1038/ncomms14507
D – Journal article	Microplastics in the Antarctic marine system: An emerging area of research	2017	Science of the Total Environment	10.1016/j.scitotenv.2017.03.283
D – Journal article	Millennial changes in North American wildfire and soil activity over the last glacial cycle	2015	Nature Geoscience	10.1038/NGEO2495
D – Journal article	Millennial timescale regeneration in a moss from Antarctica	2014	Current Biology	10.1016/j.cub.2014.01.053
D – Journal article	Minimal change in Antarctic circumpolar current flow speed between the last glacial and holocene	2014	Nature Geoscience	10.1038/ngeo2037
D – Journal article	Missing driver in the Sun-Earth connection from energetic electron precipitation impacts mesospheric ozone	2014	Nature Communications	10.1038/ncomms6197
D – Journal article	Modeling Satellite Gravity Gradient Data to Derive Density, Temperature, and Viscosity Structure of the Antarctic Lithosphere	2019	Journal of Geophysical Research: Solid Earth	10.1029/2019JB017997
D – Journal article	Modelling present-day basal melt rates for Antarctic ice shelves using a parametrization of buoyant meltwater plumes	2018	Cryosphere	10.5194/tc-12-49-2018
D – Journal article	More losers than winners in a century of future Southern Ocean seafloor warming	2017	Nature Climate Change	10.1038/nclimate3377
D – Journal article	Nitrogen Inputs by Marine Vertebrates Drive Abundance and Richness in Antarctic Terrestrial Ecosystems	2019	Current Biology	10.1016/j.cub.2019.04.038
D – Journal article	Not poles apart: Antarctic soil fungal communities show similarities to those of the distant Arctic	2016	Ecology Letters	10.1111/ele.12587
D – Journal article	Observations and Modeling of Increased Nitric Oxide in the Antarctic Polar Middle Atmosphere Associated With Geomagnetic Storm-Driven Energetic Electron Precipitation	2018	Journal of Geophysical Research: Space Physics	10.1029/2018JA025507

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D – Journal article	Observed vulnerability of Filchner-Ronne Ice Shelf to wind-driven inflow of warm deep water	2016	Nature Communications	10.1038/ncomms12300
D – Journal article	Ocean forcing of glacier retreat in the western Antarctic Peninsula	2016	Science	10.1126/science.aae0017
D – Journal article	Oceanic and atmospheric forcing of Larsen C Ice-Shelf thinning	2015	Cryosphere	10.5194/tc-9-1005-2015
D – Journal article	Oceanography and life history predict contrasting genetic population structure in two Antarctic fish species	2015	Evolutionary Applications	10.1111/eva.12259
D – Journal article	Oxygen depletion recorded in upper waters of the glacial Southern Ocean	2016	Nature Communications	10.1038/ncomms11146
D – Journal article	Past penguin colony responses to explosive volcanism on the Antarctic Peninsula	2017	Nature Communications	10.1038/ncomms14914
D – Journal article	Persistent regimes and extreme events of the North Atlantic atmospheric circulation	2013	Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences	10.1098/rsta.2011.0471
D – Journal article	Pine Island glacier ice shelf melt distributed at kilometre scales	2013	Cryosphere	10.5194/tc-7-1543-2013
D – Journal article	Plants and soil microbes respond to recent warming on the Antarctic Peninsula	2013	Current Biology	10.1016/j.cub.2013.07.011
D – Journal article	POES satellite observations of EMIC-wave driven relativistic electron precipitation during 1998-2010	2013	Journal of Geophysical Research: Space Physics	10.1029/2012JA017998
D – Journal article	Polar zoobenthos blue carbon storage increases with sea ice losses, because across-shelf growth gains from longer algal blooms outweigh ice scour mortality in the shallows	2017	Global Change Biology	10.1111/gcb.13772
D – Journal article	Potential sea-level rise from Antarctic ice-sheet instability constrained by observations	2015	Nature	10.1038/nature16147
D – Journal article	Pteropods counter mechanical damage and dissolution through extensive shell repair	2018	Nature Communications	10.1038/s41467-017-02692-w
D – Journal article	Radiative Effects of Secondary Ice Enhancement in Coastal Antarctic Clouds	2019	Geophysical Research Letters	10.1029/2018GL080551
D – Journal article	Rapid cross-density ocean mixing at mid-depths in the Drake Passage measured by tracer release	2013	Nature	10.1038/nature12432
D – Journal article	Rapid iceberg calving following removal of tightly packed pro-glacial mélange	2019	Nature Communications	10.1038/s41467-019-10908-4
D – Journal article	Rapid sea-level rise along the Antarctic margins in response to increased glacial discharge	2014	Nature Geoscience	10.1038/ngeo2230
D – Journal article	Rapid thinning of Pine Island glacier in the early holocene	2014	Science	10.1126/science.1247385

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D – Journal article	Rates and mechanisms of turbulent dissipation and mixing in the Southern Ocean: Results from the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES)	2013	Journal of Geophysical Research: Oceans	10.1002/jgrc.20217
D – Journal article	Reconstruction of changes in the Amundsen Sea and Bellingshausen Sea sector of the West Antarctic Ice Sheet since the Last Glacial Maximum	2014	Quaternary Science Reviews	10.1016/j.quascirev.2013.10.016
D – Journal article	Reconstruction of changes in the Weddell Sea sector of the Antarctic Ice Sheet since the Last Glacial Maximum	2014	Quaternary Science Reviews	10.1016/j.quascirev.2013.07.020
D – Journal article	Reframing the carbon cycle of the subpolar Southern Ocean	2019	Science Advances	10.1126/sciadv.aav6410
D – Journal article	Regional Antarctic snow accumulation over the past 1000 years	2017	Climate of the Past	10.5194/cp-13-1491-2017
D – Journal article	Regular patterns in frictional resistance of ice-stream beds seen by surface data inversion	2013	Science	10.1126/science.1243903
D – Journal article	Relationship between soil fungal diversity and temperature in the maritime Antarctic	2016	Nature Climate Change	10.1038/nclimate2806
D – Journal article	Retreat of Pine Island Glacier controlled by marine ice-sheet instability	2014	Nature Climate Change	10.1038/nclimate2094
D – Journal article	Rock comminution as a source of hydrogen for subglacial ecosystems	2015	Nature Geoscience	10.1038/ngeo2533
D – Journal article	Sequence of events from the onset to the demise of the Last Interglacial: Evaluating strengths and limitations of chronologies used in climatic archives	2015	Quaternary Science Reviews	10.1016/j.quascirev.2015.09.018
D – Journal article	Similarity of organized patterns in driving and basal stresses of Antarctic and Greenland ice sheets beneath extensive areas of basal sliding	2014	Geophysical Research Letters	10.1002/2014GL059976
D – Journal article	Simulating the Earth's radiation belts: Internal acceleration and continuous losses to the magnetopause	2014	Journal of Geophysical Research: Space Physics	10.1002/2014JA020092
D – Journal article	Southern Hemisphere westerly wind changes during the Last Glacial Maximum: Model-data comparison	2013	Quaternary Science Reviews	10.1016/j.quascirev.2012.12.008
D – Journal article	Southern Hemisphere westerly wind changes during the Last Glacial Maximum: Paleo-data synthesis	2013	Quaternary Science Reviews	10.1016/j.quascirev.2013.01.017
D – Journal article	Southern ocean mesopelagic fish comply with Bergmann’s rule	2018	American Naturalist	10.1086/695767
D – Journal article	Space weather impacts on satellites and forecasting the Earth's electron radiation belts with SPACECAST	2013	Space Weather	10.1002/swe.20023
D – Journal article	Stabilization of dense Antarctic water supply to the Atlantic Ocean overturning circulation	2019	Nature Climate Change	10.1038/s41558-019-0561-2

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D – Journal article	Strong contribution of diatom resting spores to deep-sea carbon transfer in naturally iron-fertilized waters downstream of South Georgia	2016	Deep-Sea Research Part I: Oceanographic Research Papers	10.1016/j.dsr.2016.05.002
D – Journal article	Strong sensitivity of Pine Island ice-shelf melting to climatic variability	2014	Science	10.1126/science.1244341
D – Journal article	Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier	2017	Nature	10.1038/nature20136
D – Journal article	Substorm-induced energetic electron precipitation: Impact on atmospheric chemistry	2015	Geophysical Research Letters	10.1002/2015GL065523
D – Journal article	Summer Drivers of Atmospheric Variability Affecting Ice Shelf Thinning in the Amundsen Sea Embayment, West Antarctica	2018	Geophysical Research Letters	10.1029/2018GL077092
D – Journal article	Surface-water iron supplies in the Southern Ocean sustained by deep winter mixing	2014	Nature Geoscience	10.1038/ngeo2101
D – Journal article	Tectonic development, sedimentation and paleoceanography of the Scan Basin (southern Scotia Sea, Antarctica)	2014	Global and Planetary Change	10.1016/j.gloplacha.2014.06.007
D – Journal article	Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the Last Interglacial	2014	Quaternary Science Reviews	10.1016/j.quascirev.2014.08.018
D – Journal article	Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and the onset of deglaciation on the maritime-Antarctic and sub-Antarctic islands	2014	Quaternary Science Reviews	10.1016/j.quascirev.2013.12.001
D – Journal article	The Amundsen sea low: Variability, change, and impact on Antarctic climate	2016	Bulletin of the American Meteorological Society	10.1175/BAMS-D-14-00018.1
P – Devices and products	The BAS ice-shelf hot-water drill: Design, methods and tools	2014	Annals of Glaciology	10.3189/2014AoG68A030
D – Journal article	The characteristics of the lower stratospheric gravity wavefield above Halley (75°S, 26°W), Antarctica, from radiosonde observations	2017	Journal of Geophysical Research: Atmospheres	10.1002/2017JD027079
D – Journal article	The contribution of zooplankton faecal pellets to deep-carbon transport in the Scotia Sea (Southern Ocean)	2015	Biogeosciences	10.5194/bg-12-1955-2015
D – Journal article	The diurnal variability of atmospheric nitrogen oxides (NO and NO 2) above the Antarctic Plateau driven by atmospheric stability and snow emissions	2013	Atmospheric Chemistry and Physics	10.5194/acp-13-3045-2013
D – Journal article	The Dominant Role of Extreme Precipitation Events in Antarctic Snowfall Variability	2019	Geophysical Research Letters	10.1029/2018GL081517
D – Journal article	The dynamics of Van Allen belts revisited	2018	Nature Physics	10.1038/nphys4350

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D – Journal article	The far reach of ice-shelf thinning in Antarctica	2018	Nature Climate Change	10.1038/s41558-017-0020-x
D – Journal article	The Holocene retreat dynamics and stability of Petermann Glacier in northwest Greenland	2018	Nature Communications	10.1038/s41467-018-04573-2
D – Journal article	The importance of geomagnetic field changes versus rising CO2 levels for long-term change in the upper atmosphere	2014	Journal of Space Weather and Space Climate	10.1051/swsc/2014016
D – Journal article	The influence of the Amundsen-Bellingshausen seas low on the climate of West Antarctica and its representation in coupled climate model simulations	2013	Journal of Climate	10.1175/JCLI-D-12-00813.1
D – Journal article	The interplanetary magnetic field influences mid-latitude surface atmospheric pressure	2013	Environmental Research Letters	10.1088/1748-9326/8/4/045001
D – Journal article	The role of ocean dynamics in king penguin range estimation	2019	Nature Climate Change	10.1038/s41558-018-0388-2
D – Journal article	The seasonality of Antarctic sea ice trends	2014	Geophysical Research Letters	10.1002/2014GL060172
D – Journal article	The sensitivity of West Antarctica to the submarine melting feedback	2017	Geophysical Research Letters	10.1002/2017GL072514
D – Journal article	The Southern Ocean ecosystem under multiple climate change stresses - an integrated circumpolar assessment	2015	Global Change Biology	10.1111/gcb.12794
D – Journal article	The spatial structure of Antarctic biodiversity	2014	Ecological Monographs	10.1890/12-2216.1
D – Journal article	Thick and deformed Antarctic sea ice mapped with autonomous underwater vehicles	2015	Nature Geoscience	10.1038/ngeo2299
D – Journal article	Threatened species drive the strength of the carbonate pump in the northern Scotia Sea	2018	Nature Communications	10.1038/s41467-018-07088-y
D – Journal article	Three-dimensional mapping by CryoSat-2 of subglacial lake volume changes	2013	Geophysical Research Letters	10.1002/grl.50689
D – Journal article	Trends in Antarctic Peninsula surface melting conditions from observations and regional climate modeling	2013	Journal of Geophysical Research: Earth Surface	10.1029/2012JF002559
D – Journal article	Turbulence Observations Beneath Larsen C Ice Shelf, Antarctica	2019	Journal of Geophysical Research: Oceans	10.1029/2019JC015164
D – Journal article	Twentieth century increase in snowfall in coastal West Antarctica	2015	Geophysical Research Letters	10.1002/2015GL065750
D – Journal article	Two-phase change in CO2, Antarctic temperature and global climate during Termination II	2013	Nature Geoscience	10.1038/ngeo1985
D – Journal article	Understanding the structure and functioning of polar pelagic ecosystems to predict the impacts of change	2016	Proceedings of the Royal Society B: Biological Sciences	10.1098/rspb.2016.1646

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D – Journal article	Unprecedented springtime retreat of Antarctic sea ice in 2016	2017	Geophysical Research Letters	10.1002/2017GL073656
D – Journal article	Unravelling the relative roles of top-down and bottom-up forces driving population change in an oceanic predator	2016	Ecology	10.1002/ecy.1452
D – Journal article	Uplift and tilting of the Shackleton Range in East Antarctica driven by glacial erosion and normal faulting	2017	Journal of Geophysical Research: Solid Earth	10.1002/2016JB013841
D – Journal article	Variability in Basal Melting Beneath Pine Island Ice Shelf on Weekly to Monthly Timescales	2018	Journal of Geophysical Research: Oceans	10.1029/2018JC014464
D – Journal article	Variability in transport pathways on and around the South Georgia shelf, Southern Ocean: Implications for recruitment and retention	2014	Journal of Geophysical Research: Oceans	10.1002/2013JC009348
D – Journal article	Vigorous lateral export of the meltwater outflow from beneath an Antarctic ice shelf	2017	Nature	10.1038/nature20825
D – Journal article	Warming by 1°C Drives Species and Assemblage Level Responses in Antarctica's Marine Shallows	2017	Current Biology	10.1016/j.cub.2017.07.048
D – Journal article	Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning	2016	Nature Geoscience	10.1038/ngeo2749
D – Journal article	West Antarctic ice loss influenced by internal climate variability and anthropogenic forcing	2019	Nature Geoscience	10.1038/s41561-019-0420-9
D – Journal article	West Antarctic Ice Sheet retreat driven by Holocene warm water incursions	2017	Nature	10.1038/nature22995
D – Journal article	West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability	2018	Nature Geoscience	10.1038/s41561-018-0207-4
D – Journal article	Whales from space: Counting southern right whales by satellite	2014	PLoS ONE	10.1371/journal.pone.0088655
D – Journal article	Widespread Antarctic glaciation during the Late Eocene	2017	Earth and Planetary Science Letters	10.1016/j.epsl.2016.10.045
D – Journal article	Widespread Biological Response to Rapid Warming on the Antarctic Peninsula	2017	Current Biology	10.1016/j.cub.2017.04.034
D – Journal article	Wintertime controls on summer stratification and productivity at the western Antarctic Peninsula	2013	Limnology and Oceanography	10.4319/lo.2013.58.3.1035
D – Journal article	Year-round records of sea salt, gaseous, and particulate inorganic bromine in the atmospheric boundary layer at coastal (Dumont d'urville) and central (concordia) East Antarctic sites	2016	Journal of Geophysical Research: Atmospheres	10.1002/2015JD024066
D – Journal article	Zooplankton and micronekton respond to climate fluctuations in the Amundsen Sea polynya, Antarctica	2019	Scientific Reports	10.1038/s41598-019-46423-1
D – Journal article	Zooplankton Gut Passage Mobilizes Lithogenic Iron for Ocean Productivity	2016	Current Biology	10.1016/j.cub.2016.07.058

2. IMPACT CASE STUDIES

Centre: British Antarctic Survey (BAS)
Title of case study: **Monitoring Wildlife from Space: Driving Practice and Public Awareness in Conservation**

1. Summary of the impact

BAS Researchers have led the development of methods using high-resolution satellite imagery to detect, study and monitor remote wildlife. These methods are cost-effective, enabling greater coverage than traditional approaches and are used by conservation organisations to monitor penguins, whales and albatrosses. Satellite provider 'Maxar Technologies' have donated imagery for conservation purposes, and political and management organizations have endorsed the methods and used the results. Based on BAS work, the threat status of emperor penguins has been changed from "Least-concern" to "Near-Threatened" by IUCN, and BAS has provided evidence to support further re-grading to "Vulnerable". The increased knowledge of emperor penguins has been instrumental in initiating the process to make emperors the first Antarctic Specially Protected Species. Wide media coverage has enabled the science to percolate into public consciousness, reaching 3,000,000,000 people in over 40 nations.

2. Underpinning Centre activities

BAS scientists have been the first to successfully employ very high resolution (VHR; pixels <1m) satellite imagery to identify, count and study a number of species of wildlife. This "Wildlife from space" project followed on from the use of medium resolution Landsat satellite imagery (pixels ~25m) to identify emperor penguin colonies (2009) from the red colouration of the guano by BAS scientists Fretwell and Trathan [1]. This paper was cited by Landsat as one of the "Top Ten Stories of Landsat's 40 Years". The use of higher resolution imagery and automated processing algorithms has enabled wildlife to be identified in remote and inaccessible areas where other survey methods are expensive and logistically challenging. Surveys can also happen at higher frequencies and with minimal disturbance to the animals.

These breakthroughs have led to several landmark findings for emperor penguins where Fretwell and Trathan have played leading roles, including a doubling of the official population estimate in 2012 [2], identifying changes in breeding behaviour in 2014 and 2015 [3, 4] and re-assessing their vulnerability to climate change in 2019 [5].

The methods developed for emperor penguins have been transferred to a number of other species: In 2014, a BAS team (Fretwell, Staniland, Forcada) developed new monitoring techniques for large whales [6], proving the applicability of VHR imagery to robustly count surface whales. So far 8 species of large whales, eg fin whales and southern right whales, have been counted in this way, and machine learning algorithms to automatically detect these species have been developed by BAS PhD students Bowler, Cubaynes and Gill under Fretwell's supervision (2016-2019).

We have also developed and tested satellite survey techniques for great albatross species. This included the first census of a whole species from space by counting individual animals by BAS scientists Fretwell and Phillips in 2017 (with support from Canterbury Museum, NZ), and the discovery of a previously unrecorded population decrease in the northern royal albatross [7]. Subsequently, between 2017 and 2018, Fretwell and Phillips completed satellite surveys for Birdlife International, RSPB and Dept. of Conservation (NZ) on albatrosses on 6 remote islands in the Southern Ocean that were inaccessible to ground visits, providing population data for the first time in 30 years and underpinning assessment of trends.

Since 2015, Fretwell, Trathan and Staniland have also developed methods to count ice seals and monitor two *Pygocelis* penguin species. At present, they are developing a collaboration to provide a pan-Arctic walrus census to WWF using VHR satellite imagery (Fretwell and Staniland), and are

working with the Alan Turing Institute to use Artificial Intelligence and machine learning to automate the process of counting wildlife in imagery (Fretwell and Hosking).

3. References to the underpinning work

[1] Fretwell, P.T. & Trathan, P.N. 2009. Penguins from space, faecal stains reveal the location of emperor penguin colonies. Global Ecology and Biogeography 18, 543-552. doi.org/10.1111/j.1466-8238.2009.00467.x
[2] Fretwell, P.T., LaRue, M.A., Morin, P., Kooyman, G.L., Wienecke, B., et al. 2012. An emperor penguin population estimate, the first global, synoptic survey of a species from space. PloS one 7, e33751. doi.org/10.1371/journal.pone.0033751
[3] Fretwell, P.T., Trathan, P.N., Wienecke, B., Kooyman, G.L. 2014. Emperor penguins breeding on iceshelves. PloS one 9, e85285. doi.org/10.1371/journal.pone.0085285
[4] LaRue, M.A., Kooyman, G., Lynch, H.J., Fretwell, P.T. (2015) Emigration in emperor penguins: implications for interpretation of long-term studies. Ecography, 38: 114–120, 2015. doi.org/10.1111/ecog.00990
[5] Fretwell, P.T., & Trathan, P.N. 2019. Emperors on thin ice: three years of breeding failure at Halley Bay. Antarctic Science. doi.org/10.1017/S0954102019000099
[6] Fretwell, P.T., Staniland, I.J., Forcada, J. 2014. Whales from space, counting southern right whales by satellite. PloS one 9, e88655. doi.org/10.1371/journal.pone.0088655
[7] Fretwell, P.T., Scofield, P., Phillips, R.A. 2017. Using super-high resolution satellite imagery to census threatened albatrosses. Ibis, 3159 (3) 481-490. doi: 10.1111/ibi.12482
[8] Cubaynes, H.C., Fretwell, P.T., Bamford, C., Gerrish, L., Jackson, J.A. 2018. Whales from space: Four mysticete species described using new VHR satellite imagery Marine Mammal Science 35,(2): 466-491. doi.org/10.1111/mms.12544
[9] Fretwell PT, Jackson JA, et al. (2019) Using remote sensing to detect whale strandings in remote areas: The case of sei whales mass mortality in Chilean Patagonia. PLoS ONE 14(10): e0222498. doi.org/10.1371/journal.pone.0222498

4. Details of the impact

4.1 Impacts on investment and practice of NGOs and businesses:

The remote sensing methods developed by BAS have influenced operational practice and investment decisions of NGOs and businesses, including:

- The use of satellite imagery for the direct monitoring of wildlife, as developed by Fretwell and colleagues, has become a standard practice for several NGOs:
  - The International Whaling Commission (IWC), the Inter-American Tropical Tuna Commission (IATTC) and Birdlife International have endorsed it [A1-3].
  - WWF, RSPB, Italian marine conservation organisation Tethys and the International Fund for Animal Welfare (IFAW) have commissioned work using this methodology to answer their research questions [B1-4]. The methodology is particularly valuable in remote areas where traditional, aircraft or ship-based surveys are expensive (in terms of fuel, time, carbon footprint, bureaucracy) or prohibited (eg North Korea, Bering Straits, Persian Gulf).
  - A number of NGOs (WWF/RSPB/MAVA/IFAW/Pelagos Marine Sanctuary) have made investments to further develop the approach (>GBP170,000 up to 2019). [C].

The UK Polar Program Lead at WWF testifies: *"Collaboration between BAS and WWF, using remote sensing to monitor change in emperor penguin colonies, is critical for the conservation of Antarctica's most iconic species."*

- After personal negotiation between Fretwell and the commercial satellite provider Maxar Technologies (formerly DigitalGlobe), they have opened their archive of VHR satellite imagery for the study of whales, albatrosses and seals, allowing free access to VHR imagery. To our knowledge this is the first time that conservation practitioners have been able to access large volumes of VHR satellite imagery free of charge. So far, this has led to 80,000km^2 of free imagery becoming available to scientists and conservation managers [D].

4.2 Impacts on public policy, services and the environment:

UK POLICY: Engaging Parliament in conservation matters, and changing purdah guidelines:

- Our 2009 emperor penguin paper [1] stimulated Parliamentary Questions about the effect of climate change on future levels of emperor penguin populations [E]. The Head of the Foreign and Commonwealth Office's (FCO) Polar Regions Department states: "*One of the consequences was a commitment we made at the FCO to intensify our financial support for collecting evidence on emperor penguin population levels.*" [F]
- Our work with whales [6] was cited in the UK parliamentary briefing notes in November 2017 (POSTNOTE 566, p2/Reference 35) on a report on Earth Observation.
- In 2017 our Albatross science paper [7] was one of two works cited by the chief executive of the Royal Statistical Society in an open letter calling for changes in purdah guidelines. This followed restrictions on reporting of that paper by media channels due to an upcoming general election. After this letter, and consultation with the Science Media Centre, the guidelines were changed in 2018 to enable such non-political science papers to be published.

INTERNATIONAL POLICY:

Facilitating change in conservation status of emperor penguins:

(i) at the International Union for Conservation of Nature (IUCN):

- The findings from our emperor penguin work [1], have kick-started a process that has led to the IUCN changing the threat status of emperor penguins from "Least concern" to "Near Threatened" in 2012.
- Based on our further work [2;3] highlighting the increased vulnerability of emperors to climate change impacts, the UK (through Trathan's involvement in the IUCN Penguin Specialists Group) is leading an initiative to drive forward the change in status of emperor penguins from "Near Threatened" to "Vulnerable" at IUCN. [F]

(ii) within the Antarctic Treaty System (ATS):

IUCN as a UN body is very important for *global awareness raising* of vulnerabilities; however protection of Antarctic penguins is managed under the jurisdiction of a different set of international treaties, ie the ATS. To ensure *legally binding* conservation measures can be put in place under the ATS, the UK (through BAS science) is leading international policy initiatives to have emperor penguins designated as an "Antarctic Specially Protected Species". To initiate this, the UK delegations to the ATS (led by the FCO and including BAS scientists Hughes and Trathan) have submitted papers to the 2019 Antarctic Treaty Consultative Meeting, referencing [2] and [3]. The papers were accepted in July 2019. The Head of FCO's Polar Regions Department states: "*So far no other species has gone through this process, hence BAS is helping to set a precedent for use of this conservation mechanism.*" [F]

Underpinning legal accountability action towards US Government:

As an immediate consequence of the publication by BAS of catastrophic breeding failure in emperor penguins [5], the Center for Biological Diversity filed a lawsuit against the Trump administration on 31 July 2019 for failing to act on a petition to protect emperor penguins under the Endangered Species Act. [G]

Initiating new areas of work in International Organisations:

- After the success of the penguins from space paper [1] the Scientific Committee on Antarctic Research (SCAR), led by the German government, developed an international wildlife remote sensing special interest group to use and promote the remote sensing of wildlife in Antarctica. The head of this action group states: "*Your paper* [1] *has been a key trigger in setting up the International Action Group under the umbrella of the Scientific Committee on Antarctic Research in 2012. This Action Group meets once a year, reports to the SCAR Chief Executive and promotes the use of remote sensing of wildlife in Antarctica. Outputs the group has achieved so far include exerting pressure on [..] the UK to instigate marine protected areas, facilitating the collection of Sentinel2 satellite imagery over Antarctica to enable further remote detection of wildlife. It is very important [..] for SCAR to get such data about abundance of birds and seals and changes between the years. [..] We currently lack baseline and impact data to manage the protection of bird and mammal populations in the Antarctic. 'Wildlife from space' project is essential to fill this knowledge gaps*." [H]

- After negotiations with the Scientific Committee of the IWC in 2017 involving BAS scientists Fretwell, Cubaynes and Jackson, the IWC endorsed the methodology of counting baleen whales by satellite and suggested specific populations in ten global areas that would most benefit from being counted in this way (as surveying them in other ways would be highly challenging due to remoteness or access limitation, political unrest, or territorial dispute). Work has already started in one of these areas (Gulf of Penas) to use satellite imagery provided to quantify whale strandings and understand their causes [9].

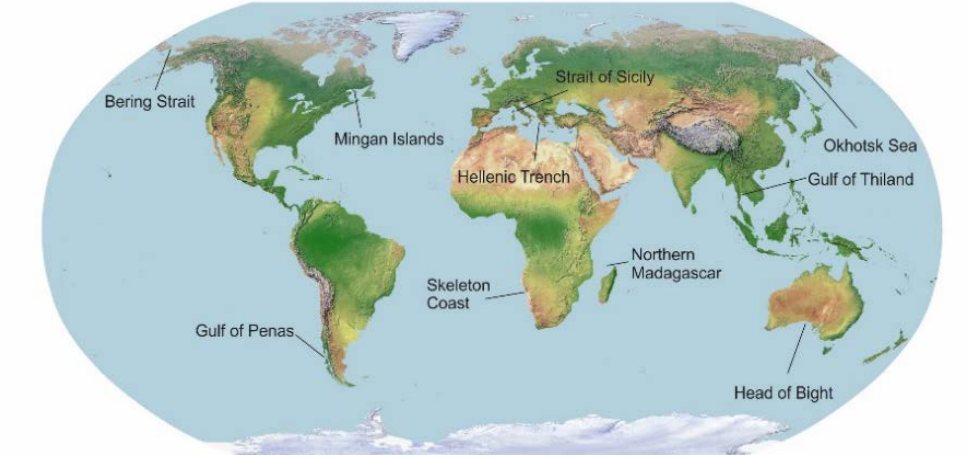


Figure 1: World map indicating ten priority areas proposed by the IWC for satellite whales survey based on the work of BAS scientist

4.3 Impacts on society, culture and creativity:
The science and use of technology described in Section 2 has been taken up extensively in the media:

Cartoon by Kipper Williams referencing [4], in E&T Magazine, 6 June 2017

Between 2009 and 2019 the work has been referenced over 1,600 times in news items across broadcast, radio, TV, as well as several thousand online reports in over 40 countries, with a reach of 3,200,000,000 viewers. One single story alone (following publication of the Albatross paper [7]) generated 700,000 page impressions on the BBC website. Highlights have included headline stories on the BBC 10 O'clock News (June 2009, April 2019, both viewed by 8,000,000 people), BBC News (April 2012, viewed by 11,000,000 people), various broadcast BBC Radio stations (October 2019, listened to by 20,000,000 people), Sky (April 2019, viewed by 3,200,000 people), CBS (April 2019, viewed by 1,600,000 people) and NBC (April 2012, online readership 32,000,000). Eight of our ten papers are rated in the top 1% of media impact globally. The responsible BBC Science correspondent testifies: *"Peter Fretwell's research is a guaranteed big-hitter in media terms. The last three stories featured on the BBC that were originated with Peter all acquired very high page-impression counts. [..]* [His story on] *Albatrosses counted from space* [generated] *700,000 page impressions. Half a million page impressions is good business in terms of reader engagement."*
It was referenced in two BBC documentaries: Earth from Space (April 2019; also available on DVD) and Dangerous Earth-Iceberg* (Dec 2016), as well as online and other broadcasters such as National Geographic (Nov 2016), What on Earth (March 2017), Weekly Dive (May 2012) and in light entertainment TV shows such as "QI" (Jan 2012), "Absolute Genius with Dick and Dom" (February 2013) and "The One Show" (June 2017), overall viewed by more than 15,000,000 people. Fretwell and Phillips worked closely with the BBC documentary "Earth from Space" to build storylines about penguins, whales and albatrosses around the technology, and discussing how these species are now routinely monitored by remote sensing. The Episode Producer for "Earth from Space" at the BBC Natural History Unit testifies: *"We have collaborated with Peter Fretwell on a number of sequences for the BBC1 documentary 'Earth From Space'. [..] The series was initially*

screened in the UK in April 2019 and has now been distributed and screened across the globe. Peter's research has been key, is giving us a new outlook and understanding of distribution and behaviour of Emperor Penguins in Antarctica and we have been working with him closely to build the first 'time-lapses from space' of Emperor penguin colonies, something that is really unique and will help further the understanding of these birds for our BBC1 audience."

The work has been referenced in 4 books: after several visits to BAS by the authors and intense interaction with Fretwell, 6 pages in James Cheshire and Oliver Uberti's book "Where animals go" (pp128-133, published 2016 – print-run ~50,000 copies in 5 different countries: UK, US, France, Germany, Spain) were dedicated to the fate of emperor penguins and albatrosses, and a double page spread to emperor penguins in Yann Arthus-Bertand's book "The Earth From Space" (pp 154, published 2013 – print-run of 40,600 copies in 6 countries (France, Germany, UK, Italy, Spain, US)). The BBC book, also called "Earth from Space" from the TV series (pp 66+67 &124-127, published 2018) highlighted BAS images and discussed the BAS research on emperor penguins and whales from space.

Fretwell has given a number of high impact talks at public events such as the 2014 Christmas lecture at the RGS (700 people (RGS members and general public), Cambridge Science Festival (March 2016; 250 people (general public)) and 12 invited talks at national and international universities (2010-2019; 300 people (university staff and students)). He has also given presentations to many VIPs and ministers including Jo Johnson (2017) and Ed Miliband (2009) on the subject.

5. Sources to corroborate the impact

[A] Endorsement of further development and use of BAS-developed methodology by
[A1] IWC: Report of the IWC Scientific Committee from its Annual Meeting held from 9-21 May 2017, ISSN 1561-0713, p55 / SC/67a/HIM02
[A2] IATTC (managing fisheries worth >USD5.8B): "Review of potential line-transect methodologies for estimating abundance of dolphin stocks", 2018 ISSN 1561-0713,]", p1
[A3] Birdlife International: "Important Bird Areas of Antarctica – Final Report", pp75, 103, 222, 224
[B] Evidence of use of BAS-developed methodology by NGOs to answer research questions:
[B1] WWF have commissioned BAS scientist Trathan to lead a project, entitled "MPAs in the Weddell Sea and Scotia Sea: *Pygoscelis* and *Aptenodytes* penguins", using this methodology. The outputs are publically available, see [5]
[B2] RSPB have commissioned a project, entitled "Estimating the population size of northern royal albatross at the Chatham Islands using satellite imagery", using this methodology. The outputs are publically available, see [7]
[B3] Tethys have commissioned a project, entitled "Developing and evaluating mitigation strategies to reduce the risk of ship strikes to fin and sperm whales in the Pelagos Sanctuary", using this methodology. The outputs are publically available, see [8]
[B4] IFAW have commissioned a project, entitled "Use of Satellite Imagery to Detect Blue Whales off the South Coast of Sri Lanka", using this methodology.
[C] Overview of investments made by NGOs to further develop the approach
[D] Maxar Technology blog, and Maxar contact: Senior Corporate Sustainability Manager
[E] Transcript of Prime Minister's Question time: Hansard Vol. 497 19/10/09, 293465; Col 1239WA
[F] Letter from FCO, Head of Polar Regions Department
[G] Intent to file lawsuit as immediate result of publication of [5]; confirmation of filed lawsuit
[H] Letter from Head of SCAR international wildlife remote sensing special interest group
* Clips from the documentary are available on BBC iPlayer. You may need to create an account to view them - this is free if you have a TV license.

Centre: British Antarctic Survey (BAS)
Title of case study: Increasing Safety in Polar Maritime Activities through Sea Ice Information

1. Summary of the impact

BAS provides sea ice information that minimises delays, improves efficiency, evaluates and mitigates risk to vessels and the environment, and supports compliance with maritime regulations - now reaching several thousand users across commerce, tourism, defence and rescue each month. In addition, since 2018 BAS has enabled vessels to assess their limits of operation in ice and conform with the new International Maritime Organisation (IMO) Polar Code through the POLARIS risk system.

2. Underpinning Centre activities

Context

With increased focus on shipping activity, growth of commercial fishing and tourism in both polar regions, and an expansion of natural resource exploration, more ocean-going vessels are transiting through hazardous ice infested waters today than in previous decades. This raises concerns about safety, especially in areas remote from search and rescue (SAR) facilities, and about potential damage to the environment.

In 2015, the International Maritime Organization (IMO) formally adopted the new Polar Code with binding regulations in order to promote safety and reduce the potential for environmental pollution from the increasing number of vessels operating in Arctic and Antarctic waters. This code came into force in 2018.

Since 2005, BAS expertise within the Mapping and Geographic Information Centre (Andrew Fleming (**AF**), Andreas Cziferszky (**AC**), Louise Ireland (**LI**)) has been used to develop tools that allow easy access to operational information for ship operators in the Arctic and Antarctic: Polar View offers a near-real-time sea ice information service, and POLARIS adds capabilities to satisfy new IMO regulatory demands.

2.1 Polar View

AF has led the implementation of a coordinated sea ice service for the Antarctic Polar View project from concept to operations since 2005. Following earlier fragmented efforts by national ice services in the Arctic, AF proposed and implemented a new integrated service for the Antarctic.

- AF proposed the new Polar View Antarctic service and won funding from ESA to implement it.
- AF and AC designed and implemented near real time processing chains (including data ingestion, radiometric and geometric corrections, transformation to digital formats for low-bandwidth distribution) for all SAR (Synthetic Aperture Radar) and other satellite imagery acquired over the Antarctic.
- AF and AC implemented new automatic and manual methods to extract information (e.g. position of sea ice edge) and validate other sea ice information (e.g. Copernicus / OSI-SAF sea ice data).
- AC and AF designed and maintain integrated delivery of sea ice information; using modern open standard geospatial web services and considering low bandwidth communications links.
- AF and AC extended the Antarctic integrated sea ice service to the Arctic, providing the first integrated operational sea ice service for both poles.

2.2 IMO Polar Code and POLARIS

To comply with the new IMO Polar Code, members of the International Association of Antarctic Tour Operators (IAATO) are required to include detailed information about the ship's ice limitations in the

Polar Ship Certificate and the Polar Water Operational Manual. At the request of IAATO, **AF** and **LI** have implemented the Polar Operational Limitation Assessment Risk Indexing System (POLARIS) to determine the ship operational limitations in ice [1]. POLARIS information provided by BAS satisfies the IMO Polar Code requirements and is used for voyage planning and real-time decision making on the ship bridge.

- AF and LI have assessed and adapted the POLARIS method to cope with different ice classification information available in the Antarctic. The POLARIS information provided by BAS includes a risk score that is calculated using sea ice concentration and ice type information from US National Ice Center ice charts to determine areas where the ship is within its operational limits (example given in Figure 1).
- LI and AF calculated POLARIS results for 2010-2015 and based on this, the BAS POLARIS product determines the probability of an increased or unacceptable level of risk for each calendar month (Figure 2). This information is used for voyage planning and defining areas of safe operation for ships of different ice classification.
- LI and AF implemented additional information required for the IMO Polar Code as part of a study for the European Space Agency [2]. This included calculation of MDLT (Mean Daily Low Temperatures) from long term meteorological observations on the Antarctic coast.

BAS now makes current and historical POLARIS information available to all IAATO members. Access to this information allows polar ship operators to comply with the new regulations of the Polar Code and be issued with their Polar Ship Certificate (PSC). This is a mandatory document for every ship entering polar waters where the Polar Code is applicable.

Fig 1

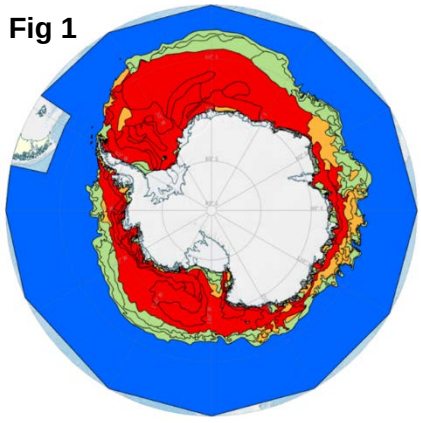
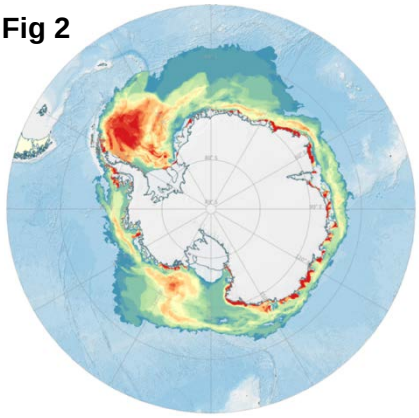


Fig 1: IMO Polar Code POLARIS output provided by BAS for PC6 class ship on 8/11/19. Red = Operation not permitted; Amber = Limited speed operation permitted; Green = Operation permitted

Fig 2: Probability of operation not permitted for PC6 ship in Nov. Blue = 1%, Red = 100%

Fig 2



3. References to the underpinning work

[1] Polar View & BAS (2016). IAATO & IMO Polar Code Antarctic Pilot Study. Report to International Association of Antarctic Tour Operators. 04/2016. Supplied on request.
[2] BAS & Polar View (2018). IMO Polar Code Data Availability Study. Report to ESA as part of Polar Code Decision Support Service study. 04/2018. Supplied on request.

4. Details of the impact

The tools and reports described above have added value to maritime operators and industries with activities in the polar regions in several ways:

4.1 Enhancing safety, reducing cost and lowering environmental risk of ship operations in hazardous polar waters

The Polar View service provided by BAS is used by a range of different sectors including:

- *National Programmes/Agencies*: e.g. Australian Antarctic Division, the US Antarctic programme, the US National Ice Center
- *Tourism*: e.g. Quark Expeditions, International Association of Antarctic Tour Operators
- *Commerce*: e.g. Sovcomflot
- *Defence*: e.g. Royal Navy, Joint Operational Meteorology and Oceanography Centre
- *Rescue and marine safety organisations*: e.g. RCCNZ (Rescue Coordination Centre New Zealand), US Coast Guard, AMSA (Australian Maritime Safety Authority)

A measure of the reach of this service is provided by the number of downloads of image products and access from unique IP addresses: The Polar View website regularly receives over 6,000 visits each month. Approximately 16,000 satellite image products are downloaded each month, increasing to over 22,000 products per month during peak shipping activity in the austral summer months (January and February).

Safety: Sea ice and icebergs are significant hazards to shipping as highlighted by the sinking of the MS Explorer in 2007 and entrapment of the Akademik Shokalskiy in 2014. The Polar View service allows ship operators to avoid areas which pose greater risk. Search and rescue (SAR) assets for the polar regions are very remote and rescue coordination centres require good information to plan SAR efforts. The BAS Polar View service has been used on several occasions to assist with rescue efforts, including by RCCNZ during rescue of the stricken Russian fishing vessel Sparta in the Ross Sea in 2011, during efforts coordinated by AMSA to help the Akademik Shokalskiy in 2014 which was stuck in heavy pack ice, and during a SAR operation for a missing French helicopter off the Antarctic coast in 2010.

Efficient ship operations: Operating in ice-infested areas frequently results in costly delays and more CO_2 emissions because of the need to travel through ice at slower speeds. This significantly increases fuel burn due to the resistance of sea ice. Less time spent moving through ice also reduces the amount of damage to a ship hull and minimises maintenance costs. Two users of the Polar View Antarctic service (Australian Antarctic Programme (AAP) and BAS) indicated significant cost savings due to availability of sea ice information. One estimated savings of approximately GBP150,000 per season, the other a saving of USD10,000 and 33.3tCO_2e per day whilst in sea ice (the equivalent of the carbon footprint of operating BAS's Signy station for 10 months). The Operations Manager of the AAP states: "*The Australian Antarctic program's shipping capability is a significant expense and the ability to undertake safe and efficient ice navigation is an important component of its cost management. The Polar View consortium is a key component of the AAP's suite of tools that improves the safety of our operations in the Southern Ocean*."

Environmental protection: The Arctic Marine Shipping Assessment (p5) states "*The most significant threat from ships to the Arctic marine environment is the release of oil through accidental or illegal discharge*". Polar View provides better knowledge of sea ice conditions which leads to safer operations, reducing the risk of accidents and resulting environmental damage. The Administrative Director of IAATO states: "*Polar View provides a valuable tool for the many member-companies of our association* [45 in 2019] *who operate passenger vessels in Antarctic waters. Good, near real-time sea ice information is extremely useful for safety as well as environmentally responsible and economically sound vessel operations*."

4.2 Enabling compliance with IMO Polar Code for ship operators

The International Code for Ships Operating in Polar Waters (IMO Polar Code), in effect since 2018, introduces new binding regulations for ship operation in the polar regions. Access to sea ice information is key to safe and efficient navigation in polar waters and the new code states that "Ships shall have the ability to receive up-to-date information including ice information for safe navigation." (MEPC 68/21/Add.1 Annex 10, section 9.2.1, p23).

The IAATO Director of Operations states *"The assessment of IMO Polar Code and provision of POLARIS by BAS has been important to our organization. It provided vital information allowing us to understand the regulations relating to sea ice in the new IMO Polar Code. Without the POLARIS information, vessels operated by IAATO members would not be issued with their Polar Ship Certificate and would not be permitted to operate in the polar regions.*

While IAATO was participating in the development of the Polar Code, the interaction with BAS assisted IAATO immensely. [..] having this data readily available saved Operators a massive amount of time and effort, both in person research hours and possible unforeseen changes during a vessel build." [A]

5. Sources to corroborate the impact:

[A] IAATO letter

Centre: British Antarctic Survey (BAS)

Title of case study: **Reducing Risks to Satellites through Daily Space Weather Forecasts**

1. Summary of the impact

BAS advises Government on the impact of space weather which led to its inclusion in the Cabinet Office National Risk Register of Civil Emergences. BAS has also developed a state-of-the-art model of the Earth's radiation belts and transitioned it into an operational system that forecasts the risk of damage to satellites. Our new forecasts enable satellite operators to take mitigating action and reduce the risk of loss. The archive of forecasts, and identification of new risks posed by 'Electric Orbit Raising', enable satellite designers to develop more resilient satellites and the space insurance industry to assess the level of risk more accurately. The BAS model has been licenced to the UK Met Office for use in their national space weather forecasting.

2. Underpinning Centre activities

2.1: Space weather forecasting

Severe space weather can cause electricity blackouts, loss of satellites, disruption to aviation and communications and a wide range of other essential services. The economic impact could be as high as USD2,000,000,000,000. Forecasting can help mitigate this impact.
From 2011 to 2017, the Science Leader for Space Weather and Atmosphere at BAS, Prof Richard Horne (RH), has led two EU projects called SPACECAST and SPACESTORM to develop a space weather forecasting system. The projects have delivered a three-hour forecast of high energy electrons in the Earth's radiation belts which is converted into a risk index for satellite operators. The forecasting system is fully automatic and is updated every hour. It operates 24 hours a day, 7 days a week. It became publicly available from 1 March 2012 and is at present freely accessible via the web. The research the forecasting system is based on is described in publications [1] and [2]. The system has three unique features:

i. It uses physics-based models derived from many years of research at Halley, Antarctica [1].
ii. It is the only system to provide a forecast of the entire outer radiation belt, including geostationary orbit where most commercial satellites operate, and medium Earth orbit where the GPS satellites operate.
iii. It is truly international, led by the UK and with 6 research groups across Europe, 2 European companies, 4 groups in the USA, and data from Japan.

This forecasting work was expanded and further improved between 2017 and 2019 through ESA funding to a consortium of researchers from BAS (led by RH), the Met Office and the Belgian company DH Consultancy, for the development of a new prototype space weather forecasting system ('SARIF'). The project incorporated end-user feedback on the previous system and used an updated version of the BAS radiation belt model, developed by Glauert, which has been compared successfully against independent data [3]. The SARIF system has been released in July 2019, and provides the following improvements:

a. The forecast horizon was increased from 3 to 24 hours, as requested by satellite operators.
b. The risk of satellite charging and ionising dose are provided along four different types of orbits, instead of being averaged over geostationary orbit alone.
c. The risks can be compared against NASA and ESA design standards, which was not possible in other systems, and SARIF shows when those standards have been exceeded.
d. The risk is displayed as a high-level traffic light system, as requested by the operators, with the ability to drill down for more detailed information.
e. The system holds a searchable archive of data which can be used by designers and space insurance to resolve the cause of a satellite anomaly.

RH has also collaborated with the Judge Business School at Cambridge University (with involvement of BGS, RAL, Met Office, Airbus, and Universities of Oxford and Cape Town) to determine the financial impact of severe space weather. For the USA, it was determined as ranging between USD6,000,000,000 and USD42,000,000,000 per day depending on the severity of the event [4]. Additional work identified that new investment in enhanced forecasting could reduce the financial impact to the UK from GBP2,900,000,000 to GBP900,000,000 [5].

2.2: Electric Orbit Raising of satellites

The detailed understanding of radiation belts has enabled RH to identify and quantify an additional major risk to satellite operations, relating to radiation exposure and associated damage to components during a new, slower way of raising satellites into orbit ('electric orbit raising'). RH and his team (with involvement of SES Global, Cambridge University's DAMPT, DH Consultancy and ESA) showed that radiation exposure during electric orbit raising is equivalent to 6.7 years operation at geostationary orbit [6], and is a major issue for a spacecraft with a typical design life of 15 years, causing premature deterioration of components and reduction to available power due to damage to solar arrays [7].

3. References to the underpinning work

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[3] Glauert, Sarah A., Horne, Richard B., Meredith, Nigel P.. (2018) A 30-year simulation of the outer electron radiation belt. *Space Weather*, 16. 1498-1522. Doi:10.1029/2018SW001981
[4] Oughton, Edward J., Skelton, Andrew, Horne, Richard B., Thomson, Alan W.P., Gaunt, Charles T.. (2017) Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. *Space Weather*, 15. 65-83. Doi:10.1002/2016SW001491
[5] Oughton et al. (2018): A Risk Assessment Framework for the Socioeconomic Impacts of Electricity Transmission Infrastructure Failure Due to Space Weather: An Application to the United Kingdom Edward J. Oughton; Doi:10.1111/risa.13229
[6] Horne, Richard B., Pitchford, David. (2015) Space weather concerns for all-electric propulsion satellites. *Space Weather*, 13. 430-433. Doi:10.1002/2015SW001198
[7] Lozinski, Alexander R., Horne, Richard B., Glauert, Sarah A., Del Zanna, Giulio, Heynderickx, Daniel, Evans, Hugh D.R.. (2019) Solar Cell Degradation due to Proton Belt Enhancements During Electric Orbit Raising to GEO. *Space Weather*, 17. 1059-1072. Doi:10.1029/2019SW002213

4. Details of the impact

4.1 Impacts on public policy and services:

BAS science and expertise have informed the UK Government of the importance of space weather for national security, leading to its inclusion in the National Risk Register of Civil Emergencies:

Since 2010, RH has been a member of the Space Environment Impacts Expert Group (SEIEG) [A], which meets twice a year at the Cabinet Office and provides advice to Government on Space Weather. It also provides the core membership of any Scientific Group for Emergencies during a space weather emergency (and in turn provides advice to the Government's emergency response committee COBR). As part of this role, RH has influenced the following:

- **Severe space weather has been recognised as a significant risk and has been included on the Cabinet Office's 'National Risk Register of Civil Emergencies 2012' at the same level as heat-waves and emerging infectious disease**. This, and updates of this risk register, has been underpinned by evidence provided by RH. The Head of Government Resilience Service at the Met Office states: "The evidence you have provided to
  - to the House of Commons Select Committee on Defence [B],
  - to the Cabinet Office Civil Contingencies Unit and to the Government Office of Science and the NATO Parliamentary Assembly Committee on Energy and Environmental Security [C] [..]

  has played an important role in the recognition that space weather poses a significant risk, and in its inclusion in the Cabinet Office's 'National Risk Register of Civil Emergencies 2012'. Since the inception of SEIEG in 2011, you have been a consistent and authoritative voice within SEIEG providing expert knowledge to support the various updates of the NSRA [National

Security Risk Assessment]. You were also an important contributor to the Royal Academy of Engineering Report "Extreme Space Weather: impacts on engineered systems and infrastructure" published in 2013, which remains to this day the most important reference document on the impacts of space weather globally." [D]

- **Strategic government funding decisions have been influenced through raising awareness amongst 3 Government Departments (BEIS, MOD, DfT) of the risks posed by space weather to their operations and to the UK.** The Chief Scientific Advisors of these departments have testified to the importance of space weather for the UK and their operation in letters of support for a GBP20,000,000 proposal ('SWIMMR') about space weather to the UKRI Strategic Priorities Fund. RH led the scientific input into this proposal for NERC in 2018. This new strategic funding stream has been approved and was announced by the Prime Minister on 23 September 2019. [E]

Following inclusion of space weather into the National Risk Register, the government devised a National Space Security Policy in 2014. Its implementation has been supported through BAS-led EU projects: Objective 1 of the policy is 'To make the United Kingdom more resilient to risks to space services and capabilities, including from space weather'. A main policy outcome is given as to 'Strengthen our ability to understand and forecast space weather events and their effects' (p4).

- Improved forecasting (as provided by BAS research, see Sections 2a-e and [3]) is highlighted as a means to promote resilience (p13). The role RH played as one of only 2 UK researchers who lead EU space weather projects as Principal Investigators (see Section 2.1) is acknowledged (pp13-14) [F]

Following inclusion of space weather into the National Risk Register, the UK government commissioned the Met Office to provide operational space weather forecasting. BAS-developed models are now made available to improve national space weather forecasting:

- The MET Office, who own the risk of Space Weather on behalf of the UK government, have licensed the BAS radiation belt model [1; 2] for forecasting radiation belts as part of their operational space weather forecasting system. [G]

MOD worst-case scenario planning has been influenced, and MOD-requirements have been incorporated in follow-on projects:

- DSTL's Space Weather Lead testifies: "The information provided by SEIEG (of which you are a member), has helped to define reasonable worst-case scenarios for table-top planning exercises for both the Government Chief Scientific Advisor (GCSA), in 2015, and MOD's CSA in 2017. [..]
  I was very pleased to see that your dialogue with Airbus, who operate MOD's Skynet satellites, have led you to develop specific features such as risk indicators that you have now incorporated into your SaRIF tool. These are important aspects of developing a research capability so it can be effectively exploited." [H, I]

4.2 Impacts on Industry

Satellite operators, manufacturers and insurers use the searchable archive of space weather provided by the BAS-led EU/ESA projects to

- **evaluate space weather threats on assets:** Satellite manufacturer UTC Aerospace Systems' Speciality Engineer states: "The ability to reconstruct relevant/recent time histories has become increasingly necessary in attempts to evaluate the space weather threat on specific assets [..]. The SPACESTORM work [..] has demonstrated particularly useful in this regard." [J]
- **investigate satellite anomalies, assess satellite susceptibility to space weather, inform insurance decisions and set reserves:** Insurer ASIC's Space Underwriter states: "We use the searchable archive of SPACECAST when we are informed of a satellite anomaly and are still awaiting the anomaly investigation report from the satellite operator. This allows us to quickly check whether an anomaly could potentially be linked to a space weather event. By monitoring these occurrences we can gain an appreciation as to whether particular satellites, or satellite

types, are more susceptible to space weather events than others which is a valuable input to our decision-making when we are approached to consider insuring the satellite for another year of service.

If we identify susceptibilities we can question the satellite operator or satellite manufacturer more closely to understand what steps they are taking to ensure their design is more robust in the future. Such informed decisions can help us avoid a claim.

Furthermore, design deficiencies that leave a satellite susceptible to space weather events are one of the Realistic Disaster Scenarios (RDS's) against which Lloyd's will judge whether a syndicate has sufficient reserves set aside to pay it's claims in the event of a worst-case loss. In that regard, ensuring that we are not overly exposed to these events by analyzing your searchable archive to evaluate when damage is likely linked to space weather events, has a direct financial benefit to the syndicates that form ASIC in ensuring that we maximize working capital." [K, L]

Satellite operators use forecasting for situational awareness, anomaly attribution and operations planning:

Satellite operator SES's Senior Satellite Engineer states: "Your Radiation Belt Model [..] has greatly improved the ability of satellite operators to maintain situational awareness of the space radiation environment. The improved accuracy of the modelling greatly increases the value of the predictions in the operational context. However, by far the most important advance has been the capability of the physical models to provide electron flux forecasts not just at GEO, but at LEO and MEO – both orbital regimes being of greatly increased importance now [..].

The availability of 'whole magnetosphere' modelling/forecasting offers us a great improvement in our visibility of the dynamics of the space environment in orbits [..] where we are greatly concerned about the risk to space-craft [..]. The capabilities offered by your SARIF system allows us to perform anomaly attribution for satellites in non-GEO orbital regimes." [M]

Airbus Defence and Space, who operate the Skynet 4 and 5 series of satellites to provide services to the MOD, state: "In particular, the high-level display of risk due to space weather [in the BAS model] and the ability to drill down for more information is very important. The forecasts from the BAS model are now one of the sources of information we use in planning our operations." [I]

Satellite manufacturers, operators and insurers recognise need for increased shielding based on identification of new risk of electric orbit raising:

Satellite designers at OHB in Germany, Europe's third-biggest satellite manufacturer, used RH's work on electric orbit raising to **brief their customers and management**.
Their Space Radiation Analyst states: "I cited your publication internally and externally many times to highlight the general risks and specifically the threat of adverse space weather due to long duration EPOR periods. I used it in particular to point out that Electrical Propulsion satellites are exposed up to 50% more total dose than Chemical Propulsion satellites, and therefore need more shielding against radiation. Internally I referenced to your paper with customers and internal management meetings, externally I cited your paper at presentations at the European Space Weather Week, SpaceMon workshop and at the International Astronautical Congress (IAC). [..] I would like to encourage you to continue the research in this topic, which is of utmost importance for all satellite manufactures." [N]

Satellite operator SES used BAS research to **improve satellite procurement specifications**. Their Senior Satellite Engineer states: "SES has expended considerable effort in reviewing and improving the Satellite Requirements Specifications that we use as part of the contractual documentation for a new satellite procurement; this has been necessary partly because of the move from conventional orbit raising to Electric Orbit Raising (EOR). The improvements that we have made to these requirements specifications are expected to have a long-term positive economic impact on our business, because of the satellite lifetime and performance improvements that will result. The output from BAS, specifically the results of the SPACECAST and SPACESTORM projects, has been instrumental in our work. Quite simply we have leveraged the BAS work in order to improve our ability to act as an Intelligent Customer to the satellite manufacturers." [M]

Insurers use RH's EOR work to **ensure satellite designs are robust enough to withstand the prolonged exposure.**
ASIC's Space Underwriter states: "When we first started to receive presentations from satellite operators and satellite manufacturers about their EOR solutions, we were disappointed with the lack of detail in their responses about space weather impacts. [..]

Your work in this area (including [6]) has allowed us to identify and quantify this issue and question satellite manufacturers in more detail to ensure that we are satisfied with the robustness of the design. I referenced your SpaceSTORM work during a presentation I gave at the Risk Management for Electric Propulsion panel of the International Electric Propulsion Conference held in Kobe, Japan in 2015 which helped prove to the industry that insurers were taking these issues seriously." [L]

The value of BAS space weather forecasting is recognised by insurance industry through a prize:
In recognition of the value of his work on space weather forecasting for insurers, RH was awarded the Lloyd's 2014 Science of Risk Prize (runner-up, Natural Hazards category, GBP1,000, including presentation about the scientific work with Q&A to insurance industry at award ceremony). [O]

4.3: Impacts on Public Understanding of Science

RH has been recognised as a space weather expert in the national and international media

Audio/visual media

- RH appeared with Prof Brian Cox on BBC2 'Stargazing Live - back to Earth', January 2014 (viewed by 2,000,000 people)
- RH was interviewed about his group's space weather research at Halley Station on Peter Gibbs' programme 'Back to the Ice' on BBC Radio 4, March 2016 (listened to by 1,000,000 people), and on the BBC Horizon Programme 'Ice Station Antarctica'*, May 2016 (viewed by 3,000,000,000 people, the most-watched Horizon programme of 2016)
- RH was interviewed about space weather on a BBC TV Programme on weather presented by Matt Taylor, broadcast 18 times between December 2017 and January 2018 on several national and regional BBC News Channels (including News 24 channel), viewed by approximately 17,000,000 people.
- RH was interviewed by the European Space Agency on Space Weather on 8 November 2018, broadcast on YouTube (viewed by 1,994 people)

Printed/online media

RH's work has been the subject of numerous articles in print and online news; in 2018 alone, RH's work has been referenced 153 times in online news items in 21 countries. For example, the press release 'Satellites more at risk from fast solar wind than a major space storm', of 3 September 2018, has been referenced in 20 media articles in 17 countries, including in Daily Mail Online (circulation: 37,000,000), Science Daily (online circulation: 3,000,000), Europa Press (online circulation: 1,800,000) and several outlets from China and India with online reach of 19,000,000.

5. Sources to corroborate the impact

[A] Composition of Space Environment Impacts Expert Group: footnote 11 (p 23) on the Space Weather Preparedness Strategy; **[B]** Report on advice provided by RH directly to House of Commons Select Committee on defence; **[C]** Letters of invite and thanks from NATO Parliamentary Assembly Committee on Energy and Environmental Security; **[D]** Letter from Head of Government Resilience Service at Met Office; **[E]** Letter of support from BEIS, MoD, DfT; **[F]** National Space Security Policy, April 2014, pp13-14; **[G]** Licensing Agreement with MET Office; **[H]** DSTL/MoD letter; **[I]** Airbus letter; **[J]** UTC letter; **[K- REDACTED**; **[L]** AISC letter; **[M]** SES letter; **[N]** OHB letter; **[O]** Award letter of Lloyd's 2014 Science of Risk Prize

* Clips from the documentary are available on BBC iPlayer. You may need to create an account to view them - this is free if you have a TV license.

Centre: British Antarctic Survey (BAS)

Title of case study: **Understanding Extreme Space Weather Events on Centennial Timescales Increases Resilience and Inspires Creative Industries**

1. Summary of the impact

BAS results on 1 in 100 year radiation exposure levels for low, medium and high Earth orbits have been used by satellite operators, designers and insurers to help develop satellites more resilient to extreme space weather events and minimise the risk of loss and damage. BAS results have also been incorporated into the UK National Security Risk Assessment and the US Space Weather Benchmarks Phase 1 report. We have created commercial and cultural impact by converting naturally occurring radio waves which increase particle radiation levels into weird and wonderful noises known as 'sounds of space'. These have been used in a world-renowned space simulation video game and in performances that fuse music, dance and science.

2. Underpinning Centre activities

The Space Weather and Atmosphere (SWA) team at BAS, led by Prof Richard Horne (RH), conducts research into how solar variations affect the Earth's space radiation environment, upper atmosphere and polar regions. Our research has shown that very low frequency radio waves in space are responsible for the formation and decay of the Earth's radiation belts and lead to the production of the enhanced fluxes of energetic electrons observed during extreme space weather events. In a recent set of studies, team member Dr Nigel Meredith (NM) focused on quantifying the fluxes of energetic electrons likely to be found during such extreme space weather events (2a), which subsequently has informed risk mitigation in satellite design and operation. NM also develops global models of Earth's naturally occurring radio waves which are an essential contributor to extreme space weather. He has used recordings of these waves to develop better awareness and public understanding of this aspect of the science (2b).

2a: Extreme space weather events

Our growing satellite infrastructure is vulnerable to the damaging effects of severe space weather, and, in particular, to enhanced fluxes of energetic electrons.

Energetic electrons affect satellites in two principle ways. Electrons with energies in the range from ~1keV to ~100keV, affect the current balance to the satellite surface. This may result in a high level of *surface charging*. Higher energy electrons can penetrate surface materials and embed themselves within insulators, leading to *internal charging*. Discharge of either type of charging can damage satellite components.

There are currently 2218 operational satellites in Earth orbit. In 2018 the total global revenues from the satellite industry were USD277,400,000,000, showing the importance of the industry to the economy. BAS research has sought to determine the conditions that would occur in a 1 in 100 year-event to determine the likely impact of an extreme event. There is no simple answer to this question since the severity of any given event depends on both location and electron energy. Therefore, between 2014 and 2017, analyses were undertaken by BAS for different electron energies and orbit types.

To obtain information on the 1 in 100 year space weather event as a function of electron energy and satellite location, NM (with support from RH and John Isles at BAS) conducted independent extreme value analyses of:

- 20 years of relativistic electron flux data at geosynchronous orbit (GEO) [1],
- 16 years of energetic electron flux data in low Earth orbit (LEO) [2],
- 10 years of internal charging current data from medium Earth orbit (MEO) [3], and
- 14 years of relativistic electron flux data from highly elliptical Earth orbit (HEO) [4].

The principle findings were:

- the 1 in 100 year flux of E > 2MeV electrons at GEO is 7 times larger than previous estimates [1]. This important result allows spacecraft operators to better trade-off risk versus the increased cost of protecting future satellites from worst-case conditions.
- the largest flux of E > 2MeV electrons observed at geosynchronous orbit in a 20 year period (between 01/95 and 06/14) occurred on 29/07/04 and our analysis estimated this to be a 1 in 50 year event. Five days later, during the enhanced fluxes associated with this extreme event, the geosynchronous satellite Galaxy 10R lost its secondary ion propulsion system reducing its lifetime significantly and resulting in an insurance claim of USD75,300,000. [1]
- the determination of the 1 in 100 year fluxes of E > 30keV and E > 300keV electrons, responsible for *surface* and *internal* charging respectively, in LEO as a function of orbital position [2]. This work extends the scope beyond the GEO regime to LEO (and potentially low-MEO) where the future large satellite constellations such as SpaceX Starlink and Oneweb are expected to operate.
- the 1 in 100 year internal charging currents behind *0.5mm* (typical for lightly shielded cables) and *1.5mm* of aluminium (typical for better protected equipment within the body of the spacecraft) shielding in MEO is *2.4* and *1.6 times* the current NASA guidelines for safe levels of operation respectively. [3]
- the determination of the energy spectra, essential for the calculation of radiation effects on satellite components, of the 1 in 100 year relativistic electron fluxes throughout the Earth's outer radiation belt from 0.69 to 2.05MeV [4]. The Senior Engineer for Spacecraft Survivability of satellite operator SES said "*This is important because the more damaging charging / ESD [electrostatic discharge] events are observed to occur when the electron flux spectrum hardens*". [B3]
- the 1 in 100 year flux of relativistic electrons at equatorial MEO, a region that had previously been poorly characterised but which is increasingly used operationally, is a factor of 3 to 4 times larger than that at GEO, depending on energy. [4]

2b: Earth's natural radio waves

Earth's naturally occurring radio waves play a pivotal role in the dynamics of the Earth's radiation belts [5], and are responsible for the build up of large fluxes of high energy electrons observed during extreme space weather events. Some of these waves are detected and recorded by Very Low Frequency (VLF) receivers at BAS's Halley Research Station in the Antarctic. The SWA team use the VLF data primarily for understanding the science of space weather storms, but, as a remarkable spin-off, conversion of these radio waves to sound reveals a series of weird and wonderful noises known as the 'sounds of space'.

NM has taken these fascinating recordings and worked with artists and audio engineers to develop novel outreach. In one project, he worked with an artist-engineer, a composer and two dancers leading to a multi-disciplinary performance involving soundscapes, animations, contemporary dance and music. As part of this project NM extended the database of eerie 'sounds' to include recordings from near-Earth space, other planets and other astronomical objects, including merging black holes and colliding neutron stars. In a separate project, NM worked closely with audio engineers at the videogame company Frontier Developments plc, to incorporate the audio recordings from the VLF receiver at Halley into a new exploration gameplay in the space simulation video game *Elite Dangerous* [6].

3. References to the underpinning work

1 Meredith, N. P., R. B. Horne, J. D. Isles, and J. V. Rodriguez, Extreme relativistic electron fluxes at geosynchronous orbit: Analysis of GOES E > 2 MeV electrons, *Space Weather*, 13, 170–184, doi: 10.1002/2014SW001143, 2015

2 Meredith, N. P., R. B. Horne, J. D. Isles, and J. C. Green, Extreme energetic electron fluxes in low Earth orbit: Analysis of POES E > 30, E > 100 and E > 300 keV electrons, *Space Weather*, 14,136-150, doi: 10.1002/2015SW001348, 2016a

3 Meredith, N. P., R. B. Horne, J. D. Isles, K. A. Ryden, A. D. P. Hands and D. Heynderickx, Extreme internal charging currents in medium Earth orbit: Analysis of SURF plate currents on Giove-A, *Space Weather*, 14, 578-591, doi: 10.1002/2016SW001404, 2016b

4 Meredith, N.P., R. B. Horne, I. Sandberg, C. Papadimitriou and H. D. R. Evans, Extreme

relativistic electron fluxes in the Earth's outer radiation belt: Analysis of INTEGRAL IREM data, *Space Weather*, 15, 917-933, doi: 10.1002/2017SW001651, 2017
5 Horne, R. B., N. P. Meredith, S. A. Glauert and T. Kersten, Wave-driven diffusion in radiation belt dynamics, in *Waves, Particles and Storms in Geospace: A Complex Interplay*, eds. G. Balasis, I. A. Daglis and I. R. Mann, Oxford University Press, 2016, doi: 10.1093/acprof:oso/9780198705246.001.0001
6 Meredith N.P., Turning the sounds of space into art, *Astronomy and Geophysics*, doi: 10.1093/astrogeo/atz097, 2019

4. Details of the impact

4a: Impact on policy, regulation and business practice

Our key findings, outlined in Section 2a, enable satellite operators, engineers and insurers to better assess the likely extremes to be encountered in various satellite orbits. Satellite operators and engineers use this information to help assess the impact of extreme events on the satellite fleet and to help improve the resilience of future satellites by better design of satellite components if required. Furthermore, published information on the likely magnitude of extreme events is very useful for satellite insurers.

The determination in 2015 of the 1 in 100 year flux of relativistic electrons at GEO [1], the location of the major telecommunications satellites, had a range of immediate impacts. The revised value, which is 7 times that estimated from an earlier study, has been:

- used by the Met Office to update the UK Cabinet Office and National Security Risk Assessment in 2017 [A]. The Head of Government Resilience Service at the Met Office states: "*The contribution of your work to the update of this assessment is particularly important as the UK's military secure satellite communications satellites, Skynet, are in GEO orbit.*" [A]
- included in the US Space Weather Phase 1 Benchmarks report (2018, p18) produced by the Space Weather Operations, Research, and Mitigation Subcommittee of the US National Science and Technology Council. This council, which coordinates science and technology policy in the US, is chaired by the US President.
- used by SES Global, a major satellite operator, to improve the definition of spacecraft technical requirements and in the evaluation of satellite proposals received from manufacturers. Their Senior Engineer for Spacecraft Survivability said: "*Our experience coupled to the analysis you have performed has allowed us to greatly improve our understanding of the worst case conditions that our spacecraft must be designed to survive. This has allowed us to carry out the important trade-offs required to maximise spacecraft survivability whilst avoiding the high cost of additional unnecessary mitigation*." [B1] "*I am using your work to feed into the Requirements Specifications that we submit to spacecraft manufacturers, and to help assess the robustness of the design proposals that they provide to us*." [B2]
- used by Atrium Space Insurance Consortium (ASIC), a consortium of ten Lloyd's of London insurance syndicates, in dialogues with clients [C]. ASIC's Space Underwriter said "*having papers such as Meredith et al., [2015] helps us to show manufacturers and operators why we have to take resilience against extreme space weather seriously and to support our line of questioning whether they are doing all they can to ensure satellites have sufficient design margins*."

More generally, the 1 in 100 year event levels in LEO, MEO, GEO and HEO, as a function of electron energy, serve as space weather benchmarks. In particular:

- they are being used in the revision of the UK National Security Risk Assessment [A]. The Head of Government Resilience Service at the Met Office states: "*Given that the UK Government is currently considering constellations of satellites at these lower orbits, this work is important in determining the risk the environment poses to these constellations.*" [A]
- the more recent results from HEO have been included in the US Space Weather Phase 1 Benchmarks report (pp4,5,18&19)
- they are being used by satellite operators to provide feedback to satellite manufacturers based on the on-orbit performance of their products. The Senior Engineer for Spacecraft Survivability at

SES said: "*During 2015 and 2016 SES participated in a technical review of the design practices and assumptions used by a major satellite manufacturer in its internal charging analysis. This customer-driven review led to changes in the way the manufacturer performs design analyses and was strongly aided by the worst-case event analysis performed by Nigel Meredith at BAS*." [B3]

- they are being used by satellite operators and satellite equipment manufacturers for:
  - the purposes of situational awareness and operational risk assessments. The Staff Engineer for Speciality Engineering at UTC Aerospace Systems said: "*In my responsibilities and research in space systems design, requirements verification and on-orbit operations I consistently rely upon your recent research involving long-term datasets in LEO, GEO and MEO. .. I continue to use [your work].. as my credible comparison for design and operational environments*." [D]
  - post event analysis. The Staff Engineer for Speciality Engineering at UTC Aerospace Systems said: "*I continue to rely on your work in answering the common qualitative, system-independent questions such as 'How severe was the environment?' and 'How many times has the system encountered such an environment?' Your work, and the support of BAS, enables me to respond in a quantitative manner, based on credible science*". [D]
- they are being used by ASIC to support space Realistic Disaster Scenarios (RDS's). ASIC's Space Underwriter said: "*Your analysis also supports the space RDS's in use at Lloyds. Lloyds uses the RDS's to judge whether a syndicate has sufficient reserves set aside to pay claims in the event of a worst case loss*." [C]

4b: Impact on culture and creative professionals

A novel international art-science co-practice has been created and exhibited internationally.

In 2014 NM started collaborating with Cambridge-based artist-engineer Diana Scarborough (DS) to produce soundscapes combining 'sounds of space' with original visual sequences [e.g., E]. In 2016 NM and DS included leading Australian composer Kim Cunio (KC) and professional London-based dancer Becky Byers (BB) in the collaboration to develop this work into a truly multidisciplinary show. The first show, which included a scientific presentation followed by a performance with animation, contemporary dance and soundscapes, was performed at the Cambridge Science Festival in March 2018 (in front of 65 people (general public)). Following on from the positive feedback on this event, KC travelled from Australia to play 'live' in the second show. This event, which was performed at the BAS Aurora Innovation Centre in November 2018 in front of an audience of 100 people (artists, scientists and public), was streamed live on the BAS YouTube channel and can be viewed in its entirety there (12,365 views, note that here and hereafter all online views are as of 31/12/19) [F].

In October 2019 a new immersive performance of the 'sounds of space' was showcased at the Cambridge Festival of Ideas in front of an audience of ~100 people (general public). At this innovative event BB together with a second professional dancer, Felix Denton, danced amongst the audience as they responded to the sound-led, data-driven journey from Antarctica to beyond the galaxy [G].

NM has also presented an audio-visual installation on the 'sounds of space' at the Cambridge Science Festival in March 2019 (attended by ~1000 people (general public)). NM and DS have given joint science-art talks on the 'sounds of space' at the Polar Educators International Workshop at Christ's College Cambridge in April 2019 (to 30 people (international education professionals) and at the Bluedot Festival, Jodrell Bank Observatory in July 2019 (attended by a full-house of 200 people (general public)).

NM has promoted this exciting collaboration by writing a cover article for the April 2019 issue of Astronomy and Geophysics [6] (viewed by 3360 people on line), and through an interview by BBC Earth for a podcast in May 2019

[H].

In a parallel development, 9 1-minute short films, based on the animations, music and space 'sounds' from the show, were shown as part of a film installation at the world famous Venice Biennale. The installation, screened between 8/5/19 and 4/6/19 at the historic Palazzo Pesaro Papafava, was part of 'Alive in the Universe', an art-film project that explores our emotional explanation of the *Universe* through arts and ideas.

BAS 'Sounds of Space' Data has been incorporated into a space simulation video game

Elite Dangerous is a space-flight simulation video game in which players take control of their own starship and can fight, explore and travel throughout a realistic three-dimensional model of the Milky Way galaxy. *Elite Dangerous*, launched in 2014, is the fourth game in the *Elite* video game series and, as of 15/1/19, cumulative sales of *Elite Dangerous* had exceeded 4,300,000 franchise units.

To feed into the development of a new gameplay, NM provided the *Elite Dangerous* team with over 200 one-minute audio files from Halley, including many different varieties of space 'sounds' called 'whistlers' and 'chorus'. NM worked closely with the team, going through his carefully selected sound clips and discussing how they might best be implemented in the game. As a result, in any one of over 400 billion stellar systems, players can now use a new analysis mode to discover more about their surroundings. The new mode, called the Full Spectrum System Scanner, features the simulated sounds of radio emissions from exoplanets in remote stellar systems based on the Halley VLF recordings.

The update, entitled *Elite Dangerous: Beyond – Chapter 4*, was released on 11/12/18. As a mark of recognition for excellence in gaming, it was nominated for "Best Evolving Game" at the 15th British Academy Games Awards on 4/4/2019, [I]. Following on from the success of the 'sounds' in the game, a dedicated Elite Dangerous livestream (6,058 views), featuring NM and Frontier Development's lead audio designer Joe Hogan, was broadcast on 7/11/19 about the 'sounds of space' and how they have been woven into the very fabric of the game [J].

This collaboration sparked media interest and stories resulting from interviews with NM were published in Polygon, a major US gaming website [K] and the Earther, an online environmental news website in the US [L]. The latter story has had over 65,700 views and the associated audio files have had over 121,000 hits on the sound cloud [M].

5. Sources to corroborate the impact

[A] Letter of support: Head of Government Resilience Service, Met Office
[B] Letters of support: Senior Engineer Spacecraft Power/Thermal Subsystem and Spacecraft Survivability, SES Global [B1:2019; B2:2015; B3: annotation to case study draft]
[C] Letter of support: Space Underwriter, Atrium Space Insurance Consortium
[D] Letter of support: Staff Engineer Speciality Engineering, UTC Aerospace Systems
[E] https://vimeo.com/246720784 – 1,143 views
[F] recording of the live stream of the 'Sounds of Space' performance from the BAS Aurora Innovation Centre, 16/11/18
[G] Sounds of space at the Cambridge Festival of Ideas, Astronomy & Geophysics Forum, 5/11/19
[H] BBC Earth podcast, Looking up, 9/5/19
[I] Letter of support: Product Manager, Frontier Developments
[J] The sounds of space, Elite Dangerous livestream, 7/11/19
[K] Polygon News Story, Elite's new exploration system brings even more real world science to the game, 4/12/18
[L] Earther News Story, Listen to the creepy noises picked up at a space weather station in Antarctica, 26/12/18
[M] Halley VLF recordings on the Sound Cloud

Centre: British Antarctic Survey (BAS)
Title of case study: Enabling Sustainable Fisheries Management in the Southern Ocean

1. Summary of the impact

Fisheries in the Southern Ocean were unregulated before 1982, resulting in over-exploitation. They are now well managed, allowing sustainable fishing for long-term food security while protecting the biodiversity integral to the ecosystem.

BAS's decades-long Ecosystems programme supports and influences UK policy decisions, shapes international marine conservation regulations, and informs international commercial fishing practices in the Southern Ocean worth USD1,000,000,000. The Ecosystems team's research papers, collaborations and long-term studies of species' response to environmental change in British Antarctic Territory and the Overseas Territory of South Georgia and the South Sandwich Islands contribute to strong UK geopolitical leadership in the region.

Successes include a 99.5% reduction in seabird mortality associated with fishing at South Georgia, voluntary action by the international krill fishery to protect penguin feeding grounds, and diversification of the product portfolio for a technology provider.

2. Underpinning Centre activities

Four key BAS activities contribute to the sustainable management of fishing by the international fleet in the Southern Ocean:

- **Long-term scientific research** on krill, birds and seals, including: the design and execution of annual surveys of krill biomass; biennial surveys for mackerel ice fish stock assessments; and regular monitoring of seabirds and seals. Analyses of these data generate the knowledge and insight which underpin fishery management decisions.
- **Expert advice** to the Foreign & Commonwealth Office and the Government of South Georgia and South Sandwich Islands (GSGSSI) to support legislation and administration in UK Overseas Territories.
- **Leadership** within the international Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). For example Dr Mark Belchier chaired the CCAMLR Scientific Committee from 2016-19 and Dr Jon Watkins convened the working group on Acoustic Survey and Analysis Methods from 2010-2014. In the last decade BAS contributed 133 working papers to CCAMLR scientific working groups, which is 19.7% of the total number submitted by 25 member states (compared to 16.6% by all US scientists combined).
- **Engaging with fishing industry and NGOs** to reduce the ecological impacts of fishing. For example, BAS brought these groups (including WWF, the Association of Responsible Krill Fishing Companies (ARK) and Pew) together in 2014 and 2019 to address future management of the Antarctic krill fishery. Dr Phil Trathan provided independent expert advice to a coalition of fishing companies and environmental NGOs which resulted in a measure to protect penguins during the breeding season. Dr Simeon Hill is a member of an expert panel that provides transparent expert scrutiny of the effectiveness of this measure.

2.1 Context and background

The Southern Ocean, which surrounds Antarctica, is rich in high value fishery species such as mackerel icefish, Patagonian toothfish and Antarctic toothfish, as well as Antarctic krill, a food source for penguins, other seabirds, seals, whales and humans.

South Georgia and the South Sandwich Islands constitute a UK Overseas Territory (OT) in the Southern Ocean with a Maritime Zone (MZ) covering more than 1,000,000km^2 (striped yellow in Fig 1). It is home to some of the best managed fisheries in the world.

Commercial fishing in the wider Southern Ocean, amounting to 10% of the world's marine area (lime green area in Fig 1), is regulated by the international Commission for the Conservation of Antarctic

Marine Living Resources (CCAMLR). This body makes decisions by consensus based on the advice of scientists from member states. At the core of CCAMLR's principles is the recognition that fisheries management should be based on sound understanding of the ecosystem in which the fisheries operate.

Compliance with CCAMLR regulations is enshrined in UK law through the Antarctic Act (2013), administered by the Polar Regions Department of the Foreign & Commonwealth Office (FCO).

Over 99% of the global annual krill catch, worth over USD500,000,000, is harvested in the Antarctic Peninsula Region and Scotia Sea (striped purple/red in Fig 1), including the South Georgia MZ. Fishing licences for toothfish, krill and icefish generate over 70% (GBP6,000,000) of the Government of South Georgia and the South Sandwich Islands' (GSGSSI's) revenue (Fig. 2).

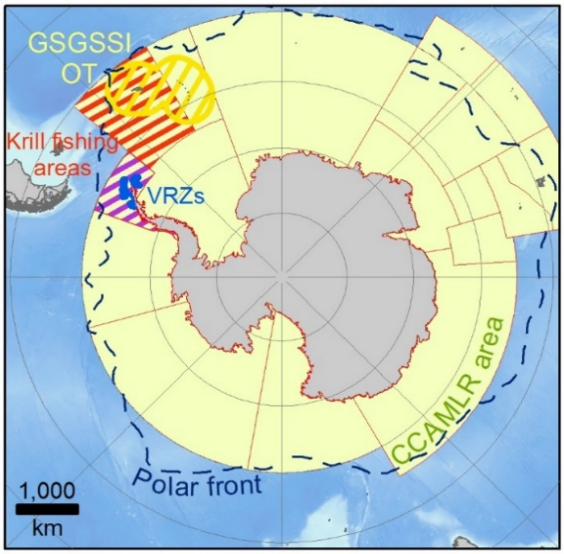


Fig 1: *Southern Ocean showing CCAMLR areas, lime green area; Maritime Zone of GSGSSI, a UK Overseas Territory, striped yellow; main areas for krill fisheries striped red/purple; krill fisheries Voluntary Restriction Zones (VRZs) in blue.*

In the face of overfishing and growing demand for food worldwide, BAS scientists work with CCAMLR, GSGSSI, the fishing industry, and environmental NGOs to deliver sustainable fisheries and environmental protection. Many current GSGSSI and CCAMLR management policies are directly based on BAS science [eg 1-7] which is detailed in Section 4.

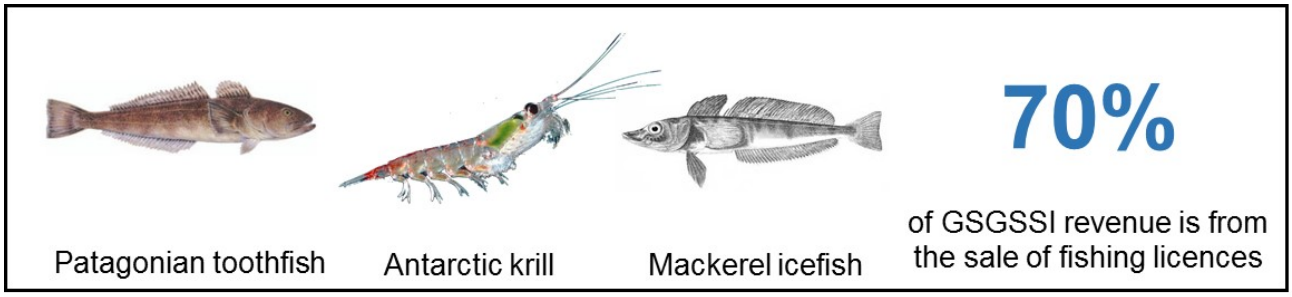


Fig 2: *Most of the revenue of GSGSSI is provided by toothfish, krill and icefish fisheries. Each of these species is the subject of BAS research.*

3. References to the underpinning work

[1] Everson I (1977) Southern Ocean fisheries survey programme. The living resources of the Southern Ocean. FAO, Rome, Italy, 142 pp.
[2] Fielding S et al (2014) Interannual variability in Antarctic krill (*Euphausia superba*) density at South Georgia, Southern Ocean: 1997-2013. *ICES J Mar Sci*, 71(9). 2578-2588. doi.org/10.1093/icesjms/fsu104
[3] Trathan PN et al (2001) The CCAMLR-2000 krill synoptic survey: a description of the rationale and design. *CCAMLR Sci*, 8. 1-23.
[4] M. Belchier et al (2017) Report of the UK groundfish survey at South Georgia. *WG-FSA-17/44*. CCAMLR, Hobart, Australia: 38 pp.
[5] Phillips RA et al (2010) Ingestion of fishing gear and entanglements of seabirds: Monitoring and implications for management. *Biol Conservn*, 143(2). 501-512. doi.org/10.1016/j.biocon.2009.11.020
[6] Fielding S et al (2011) The ASAM 2010 assessment of krill biomass for Area 48 from the Scotia Sea CCAMLR 2000 Synoptic Survey. *WG-EMM-11/20*. CCAMLR, Hobart, Australia: 10 pp.

[7] Hill SL et al (2016) Is current management of the Antarctic krill fishery in the Atlantic sector of the Southern Ocean precautionary? *CCAMLR Sci*, 23. 31-51.
[8] Trathan PN et al (2018) Managing fishery development in sensitive ecosystems: identifying penguin habitat use to direct management in Antarctica. Ecosphere 9(8): e02392. doi.org/10.1002/ecs2.2392.
[9] Afanasyev V (2004) A miniature daylight level and activity data recorder for tracking animals over long periods. *Mem Natl Inst Polar Res*, 58. 227–233.
[10] Clay et al (2019) A comprehensive large-scale assessment of fisheries bycatch risk to threatened seabird populations. *J Appl Ecol*, 56. 1882-1893. doi.org/10.1111/1365-2664.13407

4. Details of the impact

4.1 Influencing policy change - fishery legislation in the Southern Ocean:

Influencing regulation and strategy at CCAMLR:
Well-managed fisheries provide a stable supply of fishery products, economic benefits and a contribution to food security. CCAMLR's ecosystem approach to fisheries management maintains fish stocks and minimises impacts on the wider ecosystem. BAS has played a highly active role in CCAMLR's development and implementation of this evidence-based approach to date [A]. Examples include:

- BAS science informed the foundation of CCAMLR: For example, a 1977 report by a BAS scientist [1] established what are now the boundaries and subdivisions of the CCAMLR area (Fig. 1), used for catch reporting and setting catch limits.
- BAS provides long-term monitoring of the krill-based ecosystem in the Scotia Sea (striped red in Fig.1), where the krill fishery operates [e.g. 2].
- BAS is the main provider of fishery-independent data on the status of mackerel icefish, and toothfish stocks at South Georgia [e.g. 4].
- BAS scientists work with colleagues at the Centre for Environment, Fisheries and Aquaculture Science (Cefas) to provide stock assessments for icefish and toothfish.
- BAS scientists (Drs Sophie Fielding, Susie Grant, Simeon Hill, Philip Hollyman, Phil Trathan and Victoria Warwick-Evans) contribute to each stage in the development of legally binding regulations called "Conservation Measures" (CMs) (see Fig. 3).
- BAS expertise contributed to the advancement of the krill fishery management strategy agreed by CCAMLR in 2019. This aligns the management of this fishery with best practice from the finfish fisheries, including a regular cycle of revision of CMs (see orange arrow in Fig. 3). [A]

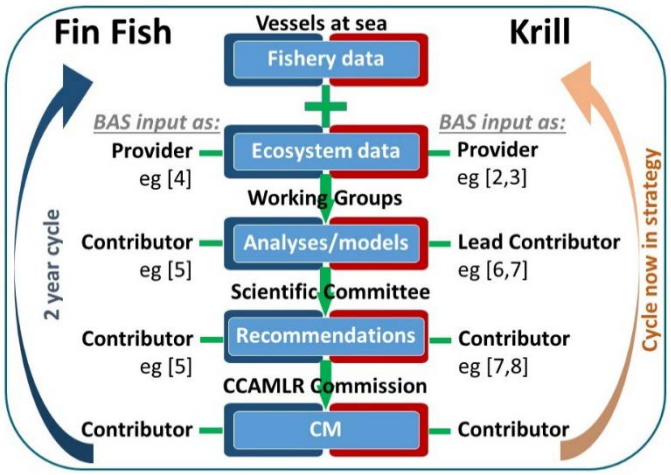


Fig 3: *The CCAMLR process for developing and updating Conservation Measures (CMs), showing its reliance on collaborative scientific input and indicating BAS inputs to all stages. Examples of BAS inputs to the various stages are shown in square brackets.*

Specific examples of CCAMLR CMs that have been informed by BAS data and expertise include:

- CM 51-01, which defines a catch limit for Antarctic krill. This was originally adopted in 2002 and revised in 2010 [based on e.g. 3,6]

- CM 51-07, which defines a spatial distribution of the Antarctic krill catch limit. Implemented in 2009 and renewed in 2016 [based on e.g. 7].
- CMs 42-01 and 41-02, which set sustainable mackerel icefish and toothfish catch limits at South Georgia and are regularly updated [based on e.g. 4] [A]

The FCO's Polar Regions Department states: "*sustained innovative work undertaken by BAS has ensured a substantial and invaluable role in supporting UK leadership in the Antarctic via 'soft politics through science'.*" [A]

Influencing fisheries policy and legislation at GSGSSI:

GSGSSI applies CCAMLR Conservation Measures with additional domestic measures to achieve a higher standard of ecosystem protection.
BAS is the main provider of ecological information to GSGSSI through its long-term monitoring of the krill-based ecosystem from two research stations on the South Georgia archipelago, and ship-based surveys and moorings throughout the territory.
GSGSSI states: "*This information is used to update our domestic fisheries policies and legislation.*"
For example:

- In 2019 BAS researchers (Drs Norman Ratcliffe, Andy Wood and Mr Kieran Love) provided tracking data showing that foraging distances from land of gentoo penguins may exceed 12nm (22.2km) in winter. This contributed to a change in GSGSSI fishery management policy, extending the fishery no-take zone from 22.2km to 30km from the shore.

GSGSSI states: "*The GSGSSI rely heavily on BAS scientific expertise to ensure that our policies and legislation are underpinned by the best available science but also to ensure that the high quality science conducted at South Georgia is visible and accessible and has a global outreach*." [C]

4.2 Improving animal welfare in a biodiversity hotspot

Seabird by-catch has been reduced:
BAS researchers have provided evidence of negative impacts of fisheries on seabirds. For example Prof Richard Phillips, and Drs Deborah Pardo and Wood identified when and where these long-lived charismatic birds are at greatest risk, and the consequences for populations breeding at South Georgia, a biodiversity hotspot [e.g. 5]. Over 40 BAS research papers since 2004 have examined seabird-fisheries overlap, impacts, and risk of by-catch (birds being caught by fishing gear). This research has led to strengthened regulations that have reduced by-catch by 99.5%.

GSGSSI states: "*Based on BAS evidence, international and domestic regulations have been amended, and consequently, incidental mortality of seabirds in South Georgia fisheries alone has been reduced from 6000 birds per annum in the late 1990s to <30 since 2015.*" [C]

4.3 Influencing companies – shaping fisheries practice, unlocking funding, expanding product portfolios

Product portfolio of an SME has been expanded:
Pioneering bird-tracking (geolocator) technology that was developed by BAS [9] to help understand interactions between fishing vessels and seabirds (see 4.2) has found application outside Antarctica. To meet international demand, the technology was licensed to an SME in 2011, contributing to product diversification

Industry has unlocked funds for science, following the "polluter pays" principle:
Trathan played a founding role in the establishment of the Antarctic Wildlife Research Fund (AWRF) [E] which awards grants (totalling USD1,000,000 to date) funded by the fishing industry to support scientific contributions to CCAMLR. As the first chair of AWRF's science advisory group he also shaped its science strategy.

Industry has altered its fishing practices to protect penguins:

The industry measure to protect penguins (voluntary fishing restrictions near breeding colonies) announced by ARK in 2018 was based on BAS science [8] and advice from Trathan.

ARK states: "*We thank BAS scientists for providing information about the location of penguin colonies, foraging ranges and dates of penguin breeding, which contributed greatly to the development of this initiative."* [i.e. the industry measure to protect penguins] [B]

4.4 Influencing marine stewardship – successful outcomes for consumer confidence

The Marine Stewardship Council (MSC) provides accreditation for fisheries judged to meet their sustainability standards. As consumers become more environmentally aware this becomes increasingly valuable for fishing companies. The certification and surveillance process for Antarctic fisheries draws heavily on evidence from BAS - for example:

- 2014. The South Georgia Patagonian toothfish longline fishery, which is managed with scientific support and advice from BAS, was re-certified by MSC.
- 2014-2019. The number of certified ARK-affiliated fishing companies increased from 2 to 5 (of a total of 7 Antarctic krill fishing companies) as a result of a recommendation made by an industry-science-NGO group convened by Hill and Dr Rachel Cavanagh [B]
- 2016. 21.7% of papers cited in the Polar ltd. mackerel icefish certification report and 10% of papers cited in the GSGSSI toothfish survellience report are BAS-led. Dr. Mark Belchier provided oral evidence.
- 2017. 20% of the 65 papers cited in the Monterey Bay Aquarium Seafood Watch report on Antarctic krill are BAS-led.
- 2018. The MSC certification report for the Pesca Chile krill fishing operation refers to 15 BAS-led papers and cites one of them [7] 15 times.

ARK states: "*Certification has been a significant step for several ARK members to access more exigent markets, as it demonstrates that their harvesting operations are environmentally responsible*". "[the 2014 BAS-led] *workshop recommended that ARK should encourage fishing companies to apply for certifications by MSC or Friend of the Sea. We now promote certification of our vessels and fishing practices."* [B]

5. Sources to corroborate the impact

1. List of krill projects and publications on the BAS website here:
2. Managing the fishery for Antarctic krill: A brief review of important environmental and management considerations. Published on the BAS web site as a business advisory resource.
3. South Georgia Patagonian toothfish fishery recertified with flying colours
4. South Georgia & the South Sandwich Islands Toothfish Fishery (48.3& 48.4) Management Plan 2018

Letters of support: [A] FCO Letter; [B] ARK Letter; [C] GSGSSI Letter; [E] AWR Letter

Centre: British Antarctic Survey (BAS)
Title of case study: Protecting Sensitive Species and Habitats in Antarctica and Beyond

1. Summary of the impact

The polar regions are under increasing threat from the effects of human activities and a changing climate. BAS's pioneering conservation biology research has provided critical expertise and evidence to support the UK Government's leadership role in influencing international policies and agreements to protect species and habitats in Antarctica, the sub-Antarctic and wider UK Overseas Territories. Successes include the designation of Marine Protected Areas covering over 3,300,000km^2 (equivalent to the size of India), now offering sanctuary to iconic species such as whales, penguins and albatrosses, and the adoption of international guidelines to prevent practices harmful to the endemic wildlife. Together these contribute to the delivery of UK commitments under global conservation targets such as the UN Sustainable Development Goals and the Convention on Biological Diversity Aichi Targets.

2. Underpinning Centre activities

For over 30 years, BAS's ecosystem research has supported the objectives of the UK Government in the Antarctic Treaty System (ATS) and international conservation agreements, and those of the governments of UK Overseas Territories including South Georgia and the South Sandwich Islands (SGSSI), British Antarctic Territory, Falkland Islands, St Helena, Ascension and Tristan da Cunha.

BAS research outputs, as well as individual scientific expertise, form the basis of UK contributions to the work of these bodies. Long-term ecosystem monitoring, eg of seabird and seal populations at biodiversity hotspots such as Bird Island and Signy, has provided scientific evidence to underpin the establishment of marine and terrestrial protected areas and spatial planning [1,2,3,4], and policies to ensure additional protection for individual species such as wandering albatrosses [5,6] and humpback whales [7] (see Fig 1). BAS scientists also hold leadership roles (detailed below) across a range of international science and governance bodies, further strengthening the UK's position at the forefront of science-based conservation.

The Committee on Environmental Protection (CEP) advises the Antarctic Treaty Consultative Meeting (ATCM) on matters relating to human activities and environmental impact in Antarctica. BAS scientists have contributed 98 papers (14% of the papers submitted from all 40 Parties, i.e. over 5x the average per Party) to the ATCM and CEP since 2013. Dr **Kevin Hughes** has been a *scientific advisor* since 2005, is currently *vice-chair* of the CEP and *convenor* of the CEP Subsidiary Group on Climate Change Response.

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is an instrument of the ATS, and governs the sustainable use of marine resources in the Southern Ocean. Since 2013, 195 papers authored by BAS scientists have been submitted to CCAMLR groups (11% of the papers submitted from all 25 Members, i.e. nearly 3x the average per Member), and have directly informed and influenced the agreement of conservation measures that protect Southern Ocean species and habitats. Key responsibilities held by BAS scientists included: **Dr Susie Grant** (*scientific advisor* since 2005, *vice-chair* of the Scientific Committee 2017, *convener* of the CCAMLR Workshop on Spatial Management 2018), and **Dr Philip Trathan OBE** (*senior scientific advisor* since 1992).

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) coordinates international activities to mitigate threats to albatross and petrel species worldwide. **Prof Richard Phillips** has been a *scientific advisor* to the UK Delegation to ACAP since 2004, and has played a leading role as *convenor* of the Population and Conservation Status working group. [D]

The International Whaling Commission (IWC) is responsible for the conservation of whales and the management of whaling. It addresses conservation issues such as bycatch and entanglement of whales, pollution and ocean noise. **Dr Jennifer Jackson** was *convenor* of the IWC Scientific Committee Working Group on Stock Definition (2012-2015), and is currently *chair* of the Southern Hemisphere Sub-Committee. [F]

3. References to the underpinning work

[1] Trathan PN et al (2014) The South Georgia and the South Sandwich Islands MPA: Protecting a biodiverse oceanic island chain situated in the flow of the Antarctic Circumpolar Current. Adv Mar Biol 69 15-78 . 10.1016/B978-0-12-800214-8.00002-5
[2] Hughes KA et al (2016) Assessing the effectiveness of specially protected areas for conservation of Antarctica's botanical diversity. *Conserv Biol* 30 113-20. 10.1111/cobi.12592
[3] Nolan ET et al (2017) Biological and physical characterization of the seabed surrounding Ascension Island from 100–1000 m. *J Mar Biol Assoc UK*, 97 647-659. 10.1017/S0025315417000820
[4] Augé AA, .. Phillips RA, .. Staniland IJ, .. Trathan PN, Croxall JP et al (2018) Framework for mapping key areas for marine megafauna to inform Marine Spatial Planning: the Falkland Islands case study. *Mar Policy*, 92 61-72. 10.1016/j.marpol.2018.02.017
[5] Phillips RA et al (2016) The conservation status and priorities for albatrosses and large petrels. *Biol Conserv* 201. 169-183. 10.1016/j.biocon.2016.06.017
[6] Pardo D et al (2017) Additive effects of climate and fisheries drive ongoing declines in multiple albatross species. *PNAS*, 114. E10829-E10837. 10.1073/pnas.1618819114
[7] Jackson JA et al (2014) Global diversity and oceanic divergence of humpback whales (Megaptera novaeangliae). *Proc R Soc Lond B*, 281. 10.1098/rspb.2013.3222
[8] Barnes DKA, et al (2019) Extremes in benthic ecosystem services; Blue carbon natural capital shallower than 1000 m in isolated, small and young Ascension Island's EEZ. *Front Mar Sci*, 6. 10.3389/fmars.2019.00663

4. Details of the impact

BAS conservation-biology research underpins UK leadership within the Antarctic Treaty System and other international agreements in line with the UN Sustainable Development Goals (SDG) and UN Convention on Biological Diversity Aichi Targets.

The Head of FCO's Polar Regions Department summarises the value of BAS contributions to its objectives: "*As one of the original 12 signatories to the Antarctic Treaty – a highly successful agreement that came into force in 1961 and now has 54 signatories – the UK continues to be a leader in the Antarctic Treaty System (ATS). Scientific research by BAS and its operational presence are therefore critical for informing UK Government policy objectives, including [..] the protection of the unique biodiversity and environments of Antarctica and the UK Overseas Territories. As an excellent example of 'soft politics through science', the work of BAS clearly demonstrates how research outcomes can be taken up by policy and business decision-makers [..]. The leadership of BAS scientists in key international roles within CCAMLR, CEP and ACAP is a major contribution to the UK's ability to drive forward its objectives for conservation and environmental stewardship in Antarctica.*"

Specific examples include:

Marine Protected Areas (MPAs) have been designated and marine spatial planning has been influenced, in line with UN SDG 14 and Aichi Target 11:
(Beneficiaries: Governments of UK and UK Overseas Territories; Wildlife)

MPAs and other spatial planning measures aim to protect precious sea life and habitats from damaging activity. In 2018, the UK government backed a global commitment to protect one third of the world's oceans by 2030. Between 2009 and 2019, **BAS research and expertise** (eg by Grant, Trathan, Peat, Barnes and Convey) **made key contributions to the establishment, review and monitoring of MPAs** covering over 3,300,000 km^2, **representing 12% of the total marine area currently protected globally** (Fig. 1), and helping to meet this commitment. Results include:

- Designation of the South Orkney Islands Southern Shelf in 2009 as the first CCAMLR MPA and the **first MPA to be entirely located in internationally managed waters**, subsequent reviews of this MPA and the establishment of a Research & Monitoring Plan. [A]

- Development of other CCAMLR MPAs (e.g. Ross Sea (designated in 2016), and in the Weddell Sea, East Antarctica, Antarctic Peninsula (proposals under consideration). [A]
- Implementation of the first Special Area for Scientific Study (SASS) for the Larsen C Ice Shelf in 2017, following a new conservation measure (CM 24-04) for areas exposed by ice shelf retreat in 2016. [A]
- Designation of SGSSI MPA in 2012 as one of the world's largest (>1,000,000km^2); its review in 2017 [1] leading to enhanced conservation measures. These include extended no-fishing zones (now 25% of the total MPA area), an extension to the krill fishery closed season to protect predators during the breeding season, a ban on the use and carriage of heavy fuel oil by vessels, and the prohibition of mineral or hydrocarbon exploitation. Government of SGSSI (GSGSSI) states: *"BAS scientific understanding of the ecology of the region, underpinned by its long-term ship-borne and terrestrial studies and the development of an extensive scientific literature, was the major contributor to the designation of the MPA."*
- Development of a Research & Monitoring Plan (RMP) and online Data Portal for the SGSSI MPA. GSGSSI states: "*The development and delivery by BAS of a public facing, web-based portal for the RMP is a major asset for MPA reviews and provides a model for how MPA management and review can be achieved in other UK overseas territories and beyond*."[B]
- Designation of a 440,000km^2 MPA in 2019 covering 100% of Ascension Island's Exclusive Economic Zone (EEZ). [8; C]
- Identification of important seabird and marine mammal areas for marine spatial planning in the Falkland Islands EEZ. [4]
- Identification and establishment of two MPAs on the Patagonian shelf in 2018. [4]
- Creation of a new 140,000 km^2 marine park around Diego Ramirez Island and Paso Drake Islands in 2019.

Details of which BAS staff members made which contribution to these can be found here.

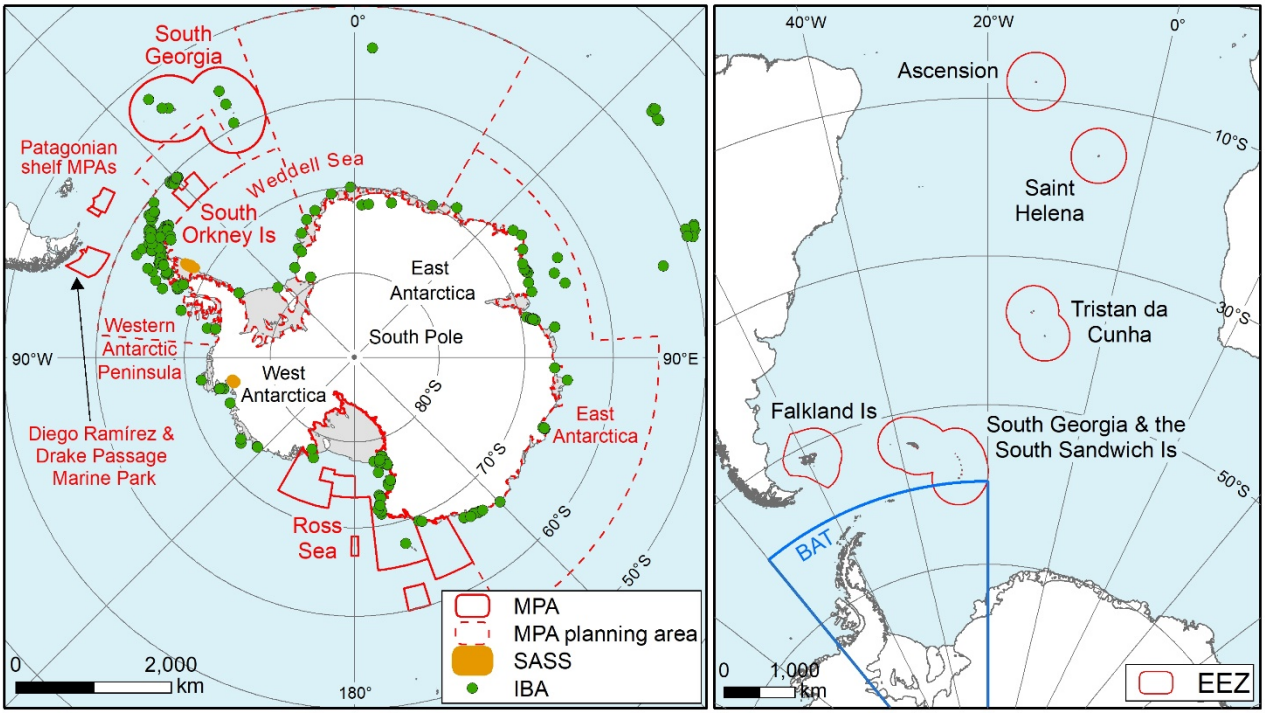


Fig. 1: Maps showing a) protected areas established as a result of BAS scientific advice (see text for abbreviations) b) British Antarctic Territory (BAT) and Exclusive Economic Zones (EEZs) of UK Overseas Territories, where BAS scientific advice has provided support for government objectives.

These areas give sanctuary to over 20 bird and whale species listed by IUCN as globally near-threatened or threatened (including Blue/Sei/Fin/Minke/Sperm Whales; Grey-

headed/(N/S)Royal/Antipodean/Sooty/Salvin's/Wandering Albatrosses; Rockhopper/Macaroni/ Emperor Penguins; Sooty Shearwater; White-chinned/Mottled Petrels), underpinning their recovery.

Other protected and managed areas have been designated:
(Beneficiaries: Wildlife, members of the ATCM, GSGSSI)

Important Bird and Biodiversity Areas (IBAs) and **Key Biodiversity Areas** (KBAs) are places of international significance for the conservation of birds and other biodiversity, which are used to implement spatial protection and management.

- Between 2012 and 2015, Phillips, Trathan, Fretwell and Ratcliffe provided data and expertise for identification of 204 IBAs for 20 bird species across the Antarctic (Fig 1a), all of which were recognised by the ATCM. Bird population data collected by BAS in 2018 led to the designation of a new IBA (AQ205) near Rothera Station, encompassing and protecting >10% of the global population of south polar skuas.
- Phillips, Ratcliffe, Staniland and Trathan contributed animal tracking and population data to identify marine IBAs and KBAs for seabirds and seals around South Georgia and the South Sandwich Islands (SGSSI). SGSSI government (GSGSSI) states: "*Of particular importance has been the ability to draw on the extensive BAS animal tracking datasets for South Georgia that have, for a range of species, provided high resolution data and analysis to identify 'hotspots ' of foraging activity. These data have been used directly in the designation of 'No Take Zones' (areas closed to all commercial fishing activity) and seasonal closures for the MPA and of important and key bird areas (IBAs and KBAs)*." [B]

Non-native species have been eradicated, and international guidelines to prevent the introduction of non-native species have been adopted*, in line with Aichi Target 9 / SDG 15.8:*
(Beneficiaries: Wildlife, all members of ATS/CEP)

- From 2012-15, Hughes successfully co-led with Spain and Argentina the eradication of a non-native grass from Cierva Point, Antarctic Peninsula. This removed a substantial threat to the survival of native grass species. [A]
- Hughes led the development of a Non-native Species Response Protocol (for use in the Antarctic Treaty area); included in the 2019 revision of the CEP Non-native Species Manual. The manual provides all parties working in these fragile regions with tools to minimise the risks to native biodiversity posed by invasive species.

UK leadership on climate change has been enabled*, in line with UN SDG 13.2: (Beneficiaries: UK Government, all member nations/organisations of SCAR, CEP and CCAMLR)*

FCO testifies: "*BAS science has played a major part in highlighting the threats of climate change to the Antarctic region and globally, particularly through its leadership role within the Scientific Committee on Antarctic Research (SCAR). BAS research and expertise has enabled UK leadership on climate change, including in the development of work programmes to respond to climate change that set benchmarks for all members of both the CEP and CCAMLR.*" [A]

Vulnerable species receive additional protection*, in line with UN SDG 14: (Beneficiaries: Wildlife, conservation organisations, government and population of Tristan da Cunha)*

- BAS has influenced conservation strategy and regulation to mitigate seabird by-catch through the Agreement on the Conservation of Albatrosses and Petrels (ACAP): The Chair of the Advisory Committee to ACAP states: "*Since 2004, Professor Phillips has [..] contributed BAS data to ACAP, making a major contribution to its strategic direction and implementation, and leading to improved regulations to mitigate seabird bycatch by fisheries in EEZs and the High Seas. Examples include*
    - *making it illegal to discard fish which still contains hooks, since these can get fed to seabird chicks by their parents;*
    - *measures (e.g. night setting, heavier line weighting and streamer lines) that minimise seabirds' access to fishing hooks close to the surface, thereby reducing the risk of hooking and drowning [..].*

  Research by BAS has been vital for documenting and identifying the drivers of population

declines in albatrosses and petrels in the Southern Ocean. Indeed, it led directly to the designation of the three albatross populations at South Georgia, among just nine worldwide, as global high priorities for conservation by ACAP." [5] [D] (addressing UN SDG 14.4)

- Scientific evidence provided by Ratcliffe at the request of the Government of Tristan da Cunha (2018-2019) led to the development of recently-implemented regulations to ensure sustainable harvesting of penguin eggs. [see details in reference letter E] (addressing UN SDG 14.7)
- BAS bird population data [e.g. 6] are used in IUCN Red List Assessments to determine the global conservation status of penguins, albatrosses (e.g. black-browed albatross) and other seabirds. Phillips and Trathan also provide expert input to the assessment process.

***Conservation success for southern humpback whale populations has been evidenced**, in line with Aichi Target 12: (Beneficiaries: Wildlife, conservation organisations, BBC, public)*

Since commercial whaling stopped in 1986, humpback whale populations have been recovering steadily in some areas, and less well in others. A global review of recovery was necessary in order to establish the correct conservation status of these populations under the US Endangered Species Act. In 2011, BAS ecologist Jackson and US (Scripps) PhD student Fleming completed this global review (started by Jackson when self-employed). As a consequence, 4 populations were listed as endangered, 1 as threatened and 9 – including all southern hemisphere populations – were considered sufficiently recovered that they are no longer in danger of extinction. Down-listing of recovering populations is important to free up resources towards more conservation-critical populations.

Identifying such conservation successes is also essential to spread hope. Jackson's work on southern right whales (together with Phillips's work on grey-headed albatrosses) was featured in episode 1 of the 2019 BBC series 'Seven Worlds, One Planet'. The final episode of the series concludes with this statement by Sir David Attenborough, which arose from Jackson sending the BBC series producer a 2015 IWC report she had led, summarizing Southern Hemisphere humpback whale recovery levels: "*In Antarctica, the international ban on whaling has meant that the great whales have returned to the Southern Ocean in numbers not seen for a century. So we can improve things – if we are determined to do so.*"[F]

5. Sources to corroborate the impact: [A] FCO Letter; [B] GSGSSI Letter; updated MPA legislation; [C] Ascension Letter; [D] ACAP Letter; [E] Tristan da Cunha Letter; [F] IWC Letter

Centre: British Antarctic Survey (BAS)
Title of case study: Influencing International Climate Policy through IPCC

1. Summary of the impact

Over the last 20 years, BAS has been a key contributor to reports of the Intergovernmental Panel on Climate Change (IPCC), which provide 195 Member Governments and 134 observer organisations with the authoritative consensus on the vulnerability of Earth's climate system to human influence. This has underpinned evidence-based development of international and national climate policies for adaptation and mitigation, and has helped the UK to become a global leader on climate policy. Since 2013, BAS scientists have also directly engaged nearly 900 international business and policy leaders in climate dialogue, including through events at the World Economic Forum.

2. Underpinning Centre activities

Coordination, authorship and scientific underpinning of IPCC assessments:
The IPCC is the leading authoritative international body for the assessment of climate change. It critically evaluates climate change research, from across the global peer-reviewed science literature, and draws out the key messages for its stakeholders.

Contribution of BAS scientists to IPCC reports
BAS's international reputation and the outstanding scientific profiles of its research staff have led to the nomination of BAS scientists by the UK Government to serve as authors on IPCC writing teams for nearly 20 years. After scrutiny by the plenary group of international governments that manages the IPCC process, more than 30 BAS staff were invited into the following prestigious roles for the Third, Fourth and Fifth Assessment Reports (TAR - 2001, AR4 - 2007, AR5 - 2013/14), and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC - 2019), including:

Coordinating Lead Authors (CLA): responsible for overseeing delivery of a chapter and ensuring coherency with other chapters. It requires scoping and structuring chapter content, planning the timeline and milestones, and overseeing the multiple revision phases leading to final delivery. Ultimately it involves presenting and defending the chapter to UN Governments at IPCC Plenary, and drawing out the policy-relevant messages in the Summary for Policymakers (SPM).

- *AR4-WG2 Ch15 Polar Regions; AR5-WG1 Ch4 Observations: Cryosphere:* D Vaughan
- *SROCC Ch3 Polar Regions:* M Meredith

Lead Authors (LA): responsible for producing assessment text covering broad areas of the chapters, and reviewing/revising in response to open scientific and Government review. LAs engage across the whole report to ensure consistency in these areas.

- *TAR-WG2 Summary for Policymakers, Technical Summary and Ch16 Polar Regions; AR5-WG1 Chapter Technical Summary, Summary for Policymakers:* D Vaughan
- *SROCC Technical Summary, Summary for Policymakers:* M Meredith
- *SROCC Ch3 Polar Regions:* H Pritchard

Contributing Authors (CA): responsible for producing text on key specific points, and revising in response to reviewers' comments.

- *TAR-WG1 Ch1 Climate System:* D Vaughan
- *AR4-WG1:* G Marshall (Ch3); D Vaughan, H Gudmundsson and A Jenkins (Ch4); D Vaughan (Ch10)
- *AR5-WG2 Ch28 Polar Regions:* D Hodgson; P Convey; E Murphy; P Fretwell; P Trathan
- *SROCC: Ch1 Framing and Context:* M Meredith*; Ch3 Polar Regions:* A Jenkins; A Meijers; P Holland*; Summary for Policymakers:* H Pritchard

The BAS Director of Science, D Vaughan, has now served in three such roles, in three successive assessments, and most unusually, has been a coordinating lead author for both WG1 (The Physical Science Basis) and WG2 (Impacts, Adaptation and Vulnerability).
Over 30 BAS Scientists have acted as Expert Reviewers of these reports, ensuring that they are comprehensive, objective and balanced.

Contribution of BAS science to IPCC reports

BAS scientific programmes have substantially improved understanding of the global impact of climate changes in the polar regions, and particularly the Antarctic; this breadth of understanding is picked up in the broad representation of BAS publications in relevant IPCC chapters. The contribution of BAS-authored papers in the 'Polar Regions' chapters from TAR to SROCC ranges between 4.3% (TAR) and 8.8% (AR5); compared with 1% of BAS-authored papers in the global polar climate literature in the same timeframe. This indicates that BAS papers have a disproportionately high impact on IPCC.

Engaging business leaders and the public in the science of climate change:

Workshops for Executives: BAS scientists have a long-standing collaboration with the Cambridge Institute for Sustainability Leadership (CISL) and regularly deliver workshops and practical sessions on climate change as part of CISL's executive programmes. These enable delegates to experience the significance of man-made climate change and appreciate the strength of scientific evidence.

World Economic Forum (WEF): Through the ICE-ARC EU funded project, BAS lead scientist J Wilkinson co-created the Arctic Base Camp Davos, at the World Economic Forum's annual meeting, Davos, Switzerland (2017-19). This innovative initiative has directly engaged world leaders in the science behind environmental change in the polar regions.

Ladybird Expert Book on Climate Change: BAS climate scientist E Shuckburgh has provided the scientific foundation for an easily digestible book that explains climate science and its significance in layman's terms.

3. Selected references to the underpinning work

[1] TAR WG2 Ch16: King, J., & Harangozo, S. (1998). Climate change in the western Antarctic Peninsula since 1945: Observations and possible causes. *Annals of Glaciology*, 27, 571-575. doi:10.3189/1998AoG27-1-571-575

[2] AR4 WG1 Ch3: Turner, J. , Colwell, S. R., Marshall, G. J., Lachlan-Cope, T. A., Carleton, A. M., Jones, P. D., Lagun, V. , Reid, P. A. and Iagovkina, S. (2005), Antarctic climate change during the last 50 years. *Int. J. Climatol.*, 25: 279-294. doi:10.1002/joc.1130

[3] AR4 WG2 Ch15: Vaughan DG, Marshall GJ, Connolley WM, Parkinson C, Mulvaney R, Hodgson DA, King, JC, Pudsey, CJ, Turner, J (2003) Recent rapid regional climate warming on the Antarctic Peninsula. *Climatic Change*, 60 (3). 243-274. doi:10.1023/A:1026021217991

[4] AR4 WG2 Ch4: Barnes, D. K., Hodgson, D. A., Convey, P. , Allen, C. S. and Clarke, A. (2006), Incursion and excursion of Antarctic biota: past, present and future. *Global Ecology and Biogeography,* 15: 121-142. doi:10.1111/j.1466-822X.2006.00216.x

[5] AR5 WG1 Ch4: Pritchard, H. D., Arthern, R. J., Vaughan, D. G., & Edwards, L. A. (2009). Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature*, 461(7266), 971-975. doi:10.1038/nature08471

[6] AR5 WG1 Ch5: Wolff, E. W., et al., 2010: Changes in environment over the last 800,000 years from chemical analysis of the EPICA Dome C ice core. *Quat. Sci. Rev.*, 29, 285–295. doi: 10.1016/j.quascirev.2009.06.013

[7] AR5 WG1 Ch13: Jenkins, A., P. Dutrieux, S. S. Jacobs, S. D. McPhail, J. R. Perrett, A. T. Webb, and D.White, (2010) Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. *Nature Geosci.,* 3, 468–472. doi:10.1038/ngeo890

[8] AR5 WG2 Ch28: Bednarsek, N., Tarling, G. A., Bakker, D. C. E., Fielding, S., Jones, E. M., Venables, H. J., . . . Murphy, E. J. (2012). Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, 5(12), 881-885. doi:10.1038/ngeo1635

[9] SROCC Ch3: Jenkins, A. et al., 2018: West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. *Nature Geoscience*, doi:10.1038/s41561-018-0207-4

[10] SROCC Ch4: Fretwell, P., et al., 2013: Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere*, 7, 375–393. doi:10.5194/tc-7-375-2013

[11] SROCC Ch3: Murphy, E.J. 2017. Restricted regions of enhanced growth of Antarctic krill in the circumpolar Southern Ocean. *Sci Rep*, 7(1), 6963, doi:10.1038/s41598-017-07205-9

4. Details of the impact

BAS science has influenced UK and global climate targets through contributing to IPCC reports, and enabled the UK to become a global leader on climate policy:

IPCC reports aim to provide 195 Member Governments and 161 observer organisations with the highest quality of scientific information on the Earth's climate system, and its vulnerability to increasing human influence. By contributing to these reports BAS science and expertise has underpinned international climate change negotiations and international and national climate policies, such as

- the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the agreements reached by its annual meetings (CoPs), including the UNFCCC Paris Agreement (CoP21, 2015) with the commitment to "pursue efforts to limit global temperature increase to 1.5°C."
- the UK Climate Change Act (updated in 2019 with the 2050 Target Amendment Order)
- the Scottish Climate Change Bill of 2018 [A]

The BEIS Head of Climate-International (UK IPCC Focal Point) testifies to the importance of IPCC reports for policy makers, and the value of BAS contributions (emphasis added):

"*IPCC [..]* ***reports are the most authoritative, comprehensive and influential sources of knowledge on climate science and they have informed both international climate negotiations and domestic policy formation****. [..] On the international front, the IPCC's recent Special Reports, and in particular the Special Report on the Ocean and the Cryosphere in a Change Climate (SROCC), featured heavily during this year's meeting of the UN Framework Convention on Climate Change [..]. The discussions and high-level statements at this meeting drew upon the findings of the SROCC, highlighting the important role the IPCC reports play in bringing the science to policy makers.*

The UK makes a considerable scientific contribution to the work of the IPCC through its expertise in the field of climate science, not least from within the ranks of BAS. We are in the top three countries with the most authors working on the IPCC's 6th Assessment Report and had a significant number of authors, working on the IPCC's recent Special Reports. More than 30 BAS staff have been selected to contribute to the preparation of IPCC reports. Most recently, BAS's Dr Michael Meredith was one of the Coordinating Lead Authors on the IPCC's Special Report on the Ocean and Cryosphere in a Changing Climate. The IPCC has also included 244 papers authored by BAS experts since its Third Assessment Report in 2001. ***We are therefore grateful for the excellent contribution of BAS both by furthering the scientific evidence base via research and also via direct contributions and involvement in the important work of the IPCC***." [B]

The DEFRA delegate to the UK delegation approving SROCC testifies about the role of BAS expertise in these impacts (emphasis added):
"*I have continued to productively engage with British Antarctic Survey scientists during various IPCC meetings and as a world leading polar and climate change research centre,* ***BAS is a key contributor to the IPCC process****.*

The IPCC is the leading authoritative international body for the assessment of climate change. Its reports are used to underpin the UK's National Adaptation Programme, which sets out the government's approach to dealing with current and future climate change and help form the scientific basis in the UK Climate Change Act. In June 2019, the UK became the first major economy to commit itself to a legally binding target of net zero emissions by 2050.

The IPCC reports have continued to provide key evidence to highlight the impacts of climate change on the ocean and the importance of ambitious global emissions reduction. This has led to the ocean becoming a focal topic at the 2019 UNFCCC COP25 Meeting in Madrid (the "Blue COP") and the COP26 in 2020, which will be hosted by the UK.

The deserved international reputation of BAS has led to the continual nomination of its scientists by the UK Government to serve as authors on IPCC writing teams for nearly 20 years. ***Their expertise and openness has been a vital conduit of information that has enabled the***

***UK to become a global leader on climate and ocean policy*.**"[C]

The importance of the contribution made by BAS authors is seen in not only the disproportionately high referencing of BAS papers in the polar/cryosphere chapters of the Assessment Report Working Groups and SROCC, but especially in how they filter through into the Summary for Policymakers issued for each report. These summaries, which are approved line-by-line by governmental plenary, draw policy makers' attention to the importance of polar regions in regulating and affecting the global climate system and interactions between the oceans and cryosphere. Most significantly, they contain specific statements that are traceable to sections of text that cite BAS research, and that evidence the increasing certainty and urgency in this timeframe from 2001 (TAR) to 2019 (SROCC). Eg {report sections} [D]:

On the causes and accelerating rate of climate change:

- TAR, WG2 – "Polar regions contain important drivers of climate change. Once triggered, they may continue for centuries, long after greenhouse gas concentrations are stabilized, and cause irreversible impacts on ice sheets, global ocean circulation, and sea-level rise (*medium confidence*)." {5.7 Technical Summary, 16.1.3.2, 16.2.3.4: *2 BAS-authored papers, incl. [1]*}
- AR4, WG1 – "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (see Figure SPM.3)." {3.2, 4.2, 5.5: *1 BAS-authored paper, [2]*}
- AR5, WG1 – "Concentrations of CO_2, CH_4, and N_2O now substantially exceed the highest concentrations recorded in ice cores during the past 800,000 years. The mean rates of increase in atmospheric concentrations over the past century are, with very high confidence, unprecedented in the last 22,000 years." {5.2, 6.1, 6.2: *7 BAS-authored papers, incl. [6]*}

On ecosystem impacts of climate change:

- AR4, WG2 – "In both polar regions, specific ecosystems and habitats are projected to be vulnerable, as climatic barriers to species invasions are lowered." {15.6, 15.4: *17 BAS-authored papers, incl. [3]*}
- AR4, WG2 – "With regard to changes in snow, ice and frozen ground (including permafrost), there is high confidence that natural systems are affected. Examples are: [..] changes in some Arctic and Antarctic ecosystems, including those in sea-ice biomes, and also predators high in the food chain" {1.3, 4.4, 15.4: *10 BAS-authored papers, incl. [4]*}
- AR5, WG2 – "Key regional risks: Polar Regions: Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies" {28.2-4: *54 BAS-authored papers, incl. [8]*}
- SROCC B5.3 – "Warming, ocean acidification, reduced seasonal sea ice extent and continued loss of multi-year sea ice are projected to impact polar marine ecosystems … The range of Arctic marine species is projected to contract, while the range of some sub-Arctic fish communities is projected to expand. In the Southern Ocean, the habitat of Antarctic krill…is projected to contract southwards" {3.2.2, 3.2.3, 5.2.3: *43 BAS-authored papers, incl. [11]*}

On ice sheet contributions to rapid global sea level rise:

- AR5, WG1 – "The average rate of ice loss from the Antarctic ice sheet has likely increased from 30 [–37 to 97] Gt yr^{-1} over the period 1992–2001 to 147 [72 to 221] Gt yr^{-1}*[ie by a factor of 5]* over the period 2002 to 2011" {4.4: *32 BAS-authored papers, incl. [5]*}
- AR5, WG1 – "Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. However, there is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century" {13.4, 13.5: *20 BAS authored papers incl. [7]*}
- SROCC A3.2 – "Sea-level rise has accelerated *(extremely likely*) due to the combined increased ice loss from the Greenland and Antarctic ice sheets (*very high confidence*). Mass

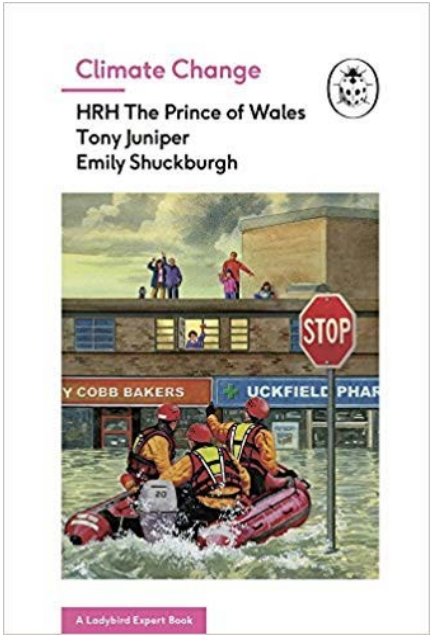
loss from the Antarctic ice sheet over the period 2007–2016 tripled relative to 1997–2006. For Greenland, mass loss doubled over the same period" {3.3.1; Figures SPM.1, SPM.2; SPM A1.1: *37 BAS-authored papers (3.3.1), incl. [9]*}

- SROCC A3.3 – "Acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea-level rise of several metres within a few centuries, is observed in West Antarctica and in Wilkes Land, East Antarctica (*very high confidence*). These changes may be the onset of an irreversible ice sheet instability" {3.3.1, Cross-Chapter Box 8 in Chapter 3, 4.2.3: *51 BAS-authored papers, incl. [10]*}

Business leaders have engaged with climate science:
Between January 2013 and December 2019, 874 business leaders from corporates such as Tata and Jaguar Land Rover from 44 nations, representing 125 companies, took part in climate change briefings led by BAS scientists and experienced scientific climate evidence first-hand at the BAS Ice Core Labs and Polar Aquarium. These workshops were part of executive programmes organised through the Cambridge Institute for Sustainability Leadership. Participants have testified: *"A transformative journey on sustainability that brings together the philosophy, the science and the data behind the sustainable development goals and leaves you inspired to take action and create a positive change."* [E]

Science Diplomacy: *BAS co-leadership of the Arctic Base Camp at the World Economic Forum (WEC) 2017-19:* At the Base Camp BAS scientists were part of a team briefing high-profile public figures on Arctic change, including former US Vice President Al Gore, Israeli Prime Minister Benjamin Netanyahu, activist Greta Thunburg and pop-star Ellie Goulding. Media coverage included BBC World Service, Reuters TV, Al Jazeera and 100 TV news outlets worldwide and the message reached over 30,000,000 people on social media. [F]

The public has been informed about climate change, and profit for a publisher and a charity has been generated through a Ladybird Expert book:
BAS scientist Emily Shuckburgh co-authored a Ladybird Expert book entitled 'Climate Change' with HRH The Prince of Wales, and Executive Director for Advocacy and Campaigns for WWF-UK Tony Juniper, which was published in 2017 and has been the second highest selling book in the Ladybird Expert series so far (13,000 copies sold by December 2019).
A copy of the book has been sent by the FCO to each embassy in London (120 copies have gone to these diplomats since 2017). The book has been translated into French, and an edition in English as a foreign language has also been published. Authors are donating their royalties to the Princes Trust, by 31/12/2019 having raised GBP12,000 for this charity.



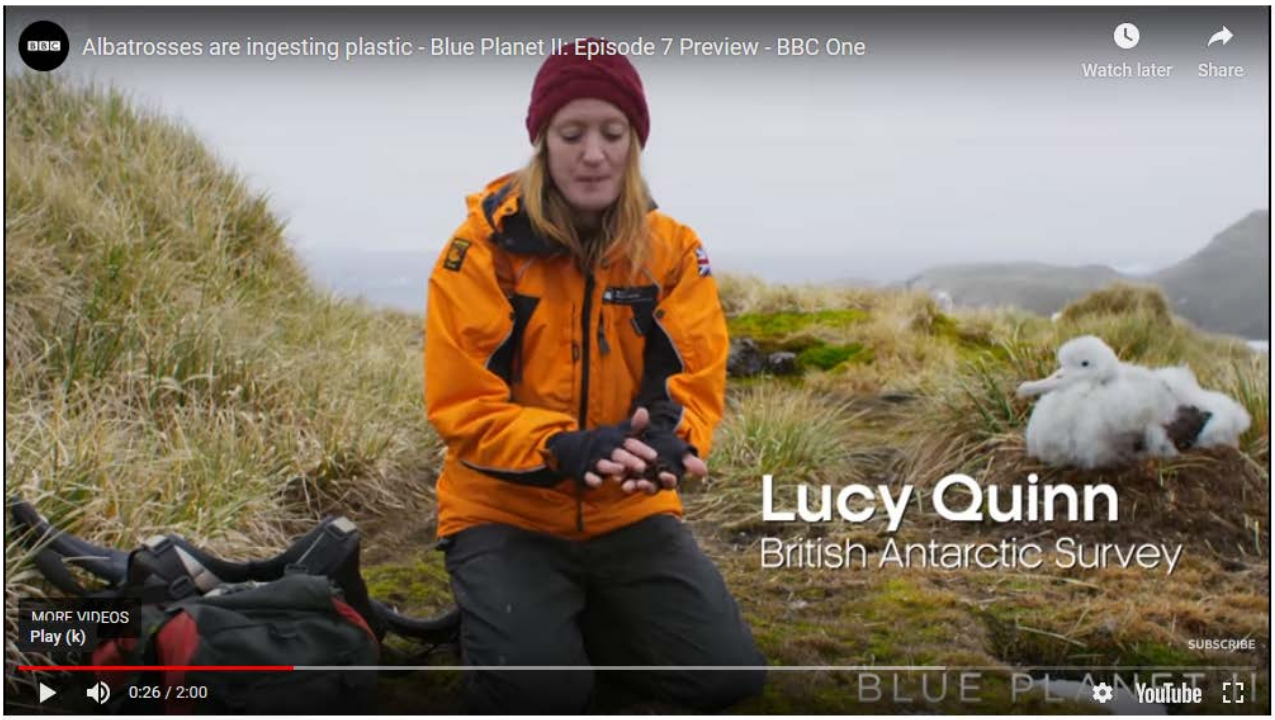
5. Sources to corroborate the impact

[A] Evidence that the IPCC reports are translated into 'UK Government Action' on climate change (p2 footnote 10 – links to "The average rate of ice loss from the Antarctic ice sheet has likely increased from 30 [–37 to 97] Gt yr–1 over the period 1992–2001 etc. etc. {4.4}"; p4 footnote 20 – links to "Concentrations of CO_2, CH_4, and N_2O now substantially etc. etc. {5.2, 6.1, 6.2}"
[B] BEIS letter
[C] DEFRA letter
[D] Links to statements extracted from the high-level Summaries for Policy Makers: TAR WG2, p16; AR5 WG1, p5; AR4 WG2, pp8,15; AR5 WG1, pp9,11,25; AR5 WG2, p24; SROCC, pp11,26
[E] Source to corroborate impact on business leaders: Project Manager, Exec Education, CISL
[F] Links to reports, programmes and statistics on all 3 years of the Arctic Bas Camp at WEC

Centre: British Antarctic Survey (BAS)
Title of case study: Changing behaviour – the Blue Planet effect

1. Summary of the impact

British Antarctic Survey's long-running collaboration with the BBC Natural History Unit has, over decades, generated international interest in the polar regions, and raised awareness of human impact in these climate-sensitive zones. *Blue Planet II* was the UK's most-watched TV programme of 2017. In the final episode zoologist Dr Lucy Quinn talks about albatrosses feeding their chicks plastic. This emotional sequence, filmed at Bird Island Research Station, became a key reference point in the media and public dialogue about plastic pollution stimulated by the landmark series. The 'Blue Planet effect' influenced parliamentary debate and changed business practices as well as consumer behaviour.



DEC 7, 2017. ALBATROSSES ARE INGESTING PLASTIC - BLUE PLANET II: EPISODE 7 PREVIEW - BBC ONE.
82,605 VIEWS.

2. Underpinning Centre activities

As part of its public engagement in research activities British Antarctic Survey runs an Antarctic media visits programme. In a competitive process, journalists and broadcasters put forward proposals to film, record or write about scientific research at the UK's Antarctic and Arctic research stations. Bids are assessed on their proposed science content, operational feasibility and global 'reach' (size, profile of audience at regional, national and international level).

The BAS Communications Team is the focal point for science-media collaborations. The Head of Communications, Linda Capper and the Senior Communications Manager Athena Dinar lead a proactive media relations programme that aims to promote and explain research outcomes and operational activity to different audiences.

Since the early 1990s BAS and BBC NHU have enjoyed a mutually beneficial relationship. Collaborations on landmark series narrated by Sir David Attenborough, including: *Life in the Freezer*

(1993); *Blue Planet I* (2001) *Planet Earth* (2006) *Frozen Planet 1* (2011); *Blue Panel II* (2017) *Seven Worlds: One Planet* (2019), have brought the polar regions into millions of homes around the world. This connection was strengthened when new polar research ship for Britain was named in honour of Sir David Attenborough.

Each of these documentaries has featured the wildlife around Bird Island Research Station, South Georgia. Located approximately 1000km south-east of the Falkland Islands, the island is accessible only by ship. The scientific research carried out at Bird Island is well-known to NHU. Its head, Dr Julian Hector, worked for BAS in the early 1980s, studying albatrosses at Bird Island. Multi-award-winning NHU cameraman Doug Allan, who has filmed in the polar regions for all the landmark series, spent his early career as a scientific diver and station leader with BAS.

For Blue Planet II, experts from the BAS Ecosystems team worked with the BAS Communications Team and NHU producers and researchers to develop story lines about albatrosses, penguins and seals that breed at Bird Island. A BBC two-person crew filmed at the station for 12 days in October 2016 (summer field season).

The NHU did not set out to make a documentary about plastic pollution. During planning discussions Professor Richard Phillips drew attention to the incidence of adult albatrosses returning from foraging trips and feeding their chicks with plastics and fishing hooks. Monitoring the levels of marine plastics and other anthropogenic debris associated with seabirds at Bird Island began in 1992.

As a result of these discussions NHU decided to include a sequence in the final episode where zoological field assistant (ZFA) and winter station leader Dr Lucy Quinn talks about albatross behaviour, and how plastic from the oceans ends up at their nest sites. Fellow Bird Island ZFA, John Dickens filmed Lucy on behalf of NHU. A blog by Lucy was published on the BBC website.

This final episode has been widely cited as a key moment sparking the 'war on plastics' and launching the 'Blue Planet effect'. [479]

3. References to the underpinning work

- **Science briefing – albatrosses**

https://www.bas.ac.uk/data/our-data/publication/albatross/

- **The science – impact of plastics on seabirds**

https://www.bas.ac.uk/project/higher-predators-long-term-science/

- **Science project**

https://www.bas.ac.uk/project/long_term_monitoring_of_plastics/

- Marine debris ingestion by albatrosses in the southwest Atlantic Ocean

Jiménez, S., Domingo, A., Brazeiro, A., Omar, D. and Phillips, R.A. (2015). *Marine Pollution Bulletin*, 96. 149-154. doi:10.1016/j.marpolbul.2015.05.034

4. Details of the impact

The original aspiration for BAS in the collaboration on *Blue Planet II* TV was to raise public awareness and understanding of the albatrosses of South Georgia, and the impact of plastics on these birds. A global audience was anticipated and achieved.

Blue Planet II was the most-watched TV show of 2017 in Britain. There were 37.6 million UK viewers (62% of the population). Over 200 countries broadcast *Blue Planet II*. To date it has been viewed more than 250 million times in China. BBC's estimated global audience is 376M per week. Within the UK the BBC has the highest cross-platform audience reach (81%). Its online, social media and global distribution through BBC Studios guarantees international exposure. Sales from global hits, including Planet Earth II, returned almost £1bn to the BBC in the past five years.

The clip was promoted widely by BBC and shared across social media by other media. For example: Sir David Attenborough introduces 'Albatrosses are ingesting plastic - *Blue Planet II*: Episode 7 Preview - BBC One; and MSN news.

Athena Dinar created a promotional campaign to coincide with transmission. She produced two video clips of Lucy Quinn and a news story for the BAS website, a series of posts for BAS social media channels (Facebook, Twitter and Youtube); and secured a speaking slot at the BlueDot Festival which is attended by 21,000 people.

Additonal media outputs 2017-19 – mentioning BAS and zoologist Lucy Quinn/albatross:

- 44 online print media articles and 57 individual broadcasts. Examples include: Express e-clip (21M), and Daily Mail online (48M); BBC1 Scotland (1.8M reach), BBC News at Six (4M); BBC News at 10 (6M); BBC London (5M reach), BBC Radio 5 Live (2M reach).

- On 4 December 2017 BBC Science Editor David Shukman interviews Dr Lucy Quinn for TV and online news. '*Shame and anger' at plastic ocean pollution*'.

- Viewer and TV critic reaction prompted countless articles about plastics in the oceans. The Radio Times quoted '*The episode, which depicted albatross parents unwittingly feeding their chicks plastic…*'

- In a video interview for Sky News Sir David Attenborough talks about a mother albatross and her chick. He said: *"There's a shot of the young being fed fish and what comes out of the mouth of the beak of the adult? Not sand eels, not fish, not squid – which is what they mostly feed on. It's plastic and it's heartbreaking.".*

- BBC News online on 19 November 2019. Science Editor David Shukman says,
"*In one of the most moving scenes, albatrosses were seen feeding their chicks a diet of plastic which would doom them to die*. "

The series won three BAFTA's, the Impact Award at the National Television Awards, an Emmy in the US; and in 2019 the Chatham House Prize was awarded to Sir David Attenborough and Dr Julian Hector. In a BBC Press Release Dr Julian Hector mentions his early career with BAS studying albatrosses.

The Blue Planet effect

The final episode *Blue Planet II* was widely reported as a key moment sparking the war on plastics. According to the BBC the series has had significant impact on viewers – 79% said they felt inspired by the series. There was a huge surge of interest in plastic recycling following the series finale. After the final episode, 25% of viewers reported that they had done something directly as a result of watching this programme. In a YouGov survey half of Britons (46%) expressed guilt about the amount of plastic they use, and 82% said they are trying to reduce the amount they throw away.

The Blue Planet II box set was Prime Minister Theresa May's official gift to China's President Xi Jinping, in connection with a $12bn trade deal between countries.

In a parliamentary debate **on the UK government's** Blue Belt programme **(12 Dec 2018) MP Zac Goldsmith makes a connection between the programme and South Georgia, stating "***Viewers of the extraordinary "Blue Planet II" series will know that the greatest gift that the Government can give the oceans lies further south…..*"

Businesses and media continue to make the link between the Lucy Quinn albatross clip and the need for behavioural change. Global Citizen online news site states: "*Once you've seen albatross parents feeding plastic to their chicks, there's no going back.".* The Financial Times reports consumer pressure on industry executives arising from the 'Blue Planet effect'.

The Waitrose Food and Drink Report 2018-19 states: ***"****It was the scene that changed everything: albatross parents unwittingly feeding their chicks plastic in the final episode of BBC One's Blue Planet II. [745]*

5. Sources to corroborate the impact

1. 23 October 2017 BAS news story: https://www.bas.ac.uk/media-post/bbc-blockbuster-blue-planet-ii-returns/

2. October 2017 Sir David Attenborough introduces 'Albatrosses are ingesting plastic - Blue Planet II: Episode 7 Preview - BBC One.

3. **VIEWERS REACT TO DAVID ATTENBOROUGH'S FINAL BLUE PLANET II CONSERVATION RALLYING CRY**
   https://www.radiotimes.com/news/tv/2018-08-29/blue-planet-2-plastic-waste-final-episode/

4. Friday 20 October 2017. Sky News https://news.sky.com/story/sir-david-attenborough-sea-plastics-impact-on-albatross-is-heartbreaking-11052475

5. November 2018. 88% of People Who Saw 'Blue Planet II' Have Now Changed Their Lifestyle
   https://www.globalcitizen.org/en/content/88-blue-planet-2-changed-david-attenborough/

6. October 2018. New publication by BAS plastics group. https://www.bas.ac.uk/data/our-data/publication/marine-plastics-threatens-giant-atlantic-marine-protected-areas/

7. November 2018 Waitrose Food and Drink Report 2018-19.
   https://waitrose.pressarea.com/pressrelease/details/78/NEWS_13/10259

8. **December 2018. Hansard – blue belt debate**
   https://hansard.parliament.uk/Commons/2018-12-12/debates/738FB752-531E-474C-80F0-7B6BFBD8762A/BlueBeltProgrammeSouthSandwichIslands

9. News consumption in the UK.
   https://www.ofcom.org.uk/__data/assets/pdf_file/0024/116529/news-consumption-2018.pdf

10. Dec 2019. Personal communication to BAS Head of Communications Dr Julian Hector, Head of NHU says,

"*As a young zoologist studying albatrosses I was not to know my generation of BAS scientists would be the last people to see breeding albatrosses in peak numbers. I left a piece of my heart in the South Atlantic. Today I lead the BBC Studios Natural History Unit and I have never relented making sure my programme makers culture a close partnership with the incredible people of the British Antarctic Survey. The greatest of British science informs the greatest of British creativity to bring the stories of Antarctic ecosystems to millions around the world*."

BRITISH ANTARCTIC SURVEY RESEARCH ENVIRONMENT SUBMISSION 2020

SECTION 1: Context, Mission, Strategy

Introduction

The British Antarctic Survey (BAS) delivers and enables world-leading interdisciplinary research in the Polar Regions. Its skilled science and support staff based in Cambridge, Antarctica and the Arctic, work together to deliver research that uses the Polar Regions to advance our understanding of Earth as a sustainable planet. Through our extensive logistic capability and know-how BAS facilitates access for the British and international science community to the UK polar research operation. Numerous national and international collaborations, combined with an excellent infrastructure, help sustain a world-leading position for the UK in Antarctic affairs. British Antarctic Survey is a component of the Natural Environment Research Council (NERC). **NERC** is part of UK Research and Innovation.

BAS provides the permanent UK presence in the British Antarctic Territory for the Foreign and Commonwealth Office (FCO). BAS is based in Cambridge and operates five aircraft and two ships - RRS *James Clark Ross* and RRS *Sir David Attenborough* (under construction); five permanent research stations in Antarctica (Rothera, Halley, Signy) and the sub-Antarctic (King Edward Point and Bird Island, South Georgia), plus the NERC Arctic station in Ny-Ålesund, Svalbard (Figure 1.1).

Mission

BAS has a dual role:

- To deliver a world-class programme of scientific research, national capability and long-term observations, concentrating on the regional and global role of polar processes in the Earth Systems.
- Through science and impact, to sustain for the UK an active and influential Antarctic regional presence, and a leadership role in Antarctic affairs.

This dual role is central to an MoU between the Department for Business Energy and Industrial Strategy (BEIS), the Ministry of Defence (MOD) and the Foreign & Commonwealth Office (FCO), reconfirmed in November 2019. Under this MoU BAS is required to deliver the UK's strategic footprint in the British Antarctic Territory (BAT) and South Georgia & the South Sandwich Islands (SGSSI), and maintain the UK's influence within the Antarctic Treaty System through its expertise in polar science.

With the advent of the new Director and senior leadership in 2013/4, a new vision for BAS was developed: **To be a world-leading centre for polar science and polar operations, addressing issues of global importance and helping society adapt to a changing world**. This vision unites both the science and operational side of BAS' responsibilities and underpins everything BAS does. It recognises the greater impact that the polar regions have on the entire planet, on its environment and its people.

BAS Mission:

BAS is a research-driven organisation recognised for:

- Commitment to excellence in science.
- Operational professionalism and innovation in everything we do.
- A partner of choice for science, operations and business wherever polar expertise can be applied.
- Safely delivering complex operations in extreme environments.
- Commitment to environmental stewardship of the polar regions.
- Developing our staff to reach their full potential.
- Sustaining an active and influential presence in Antarctica on behalf of the UK, and playing a leadership role in Antarctic affairs.
- Engagement with policy-makers, government and the public.

The internal BAS mission (see box) was defined to widen our role to emphasise our global reach and responsibility, and highlight our commitment to excellence in everything we do. We have new strategies for science, innovation and for logistic operations. The role of UK science in Antarctica is explained in this government handbook.

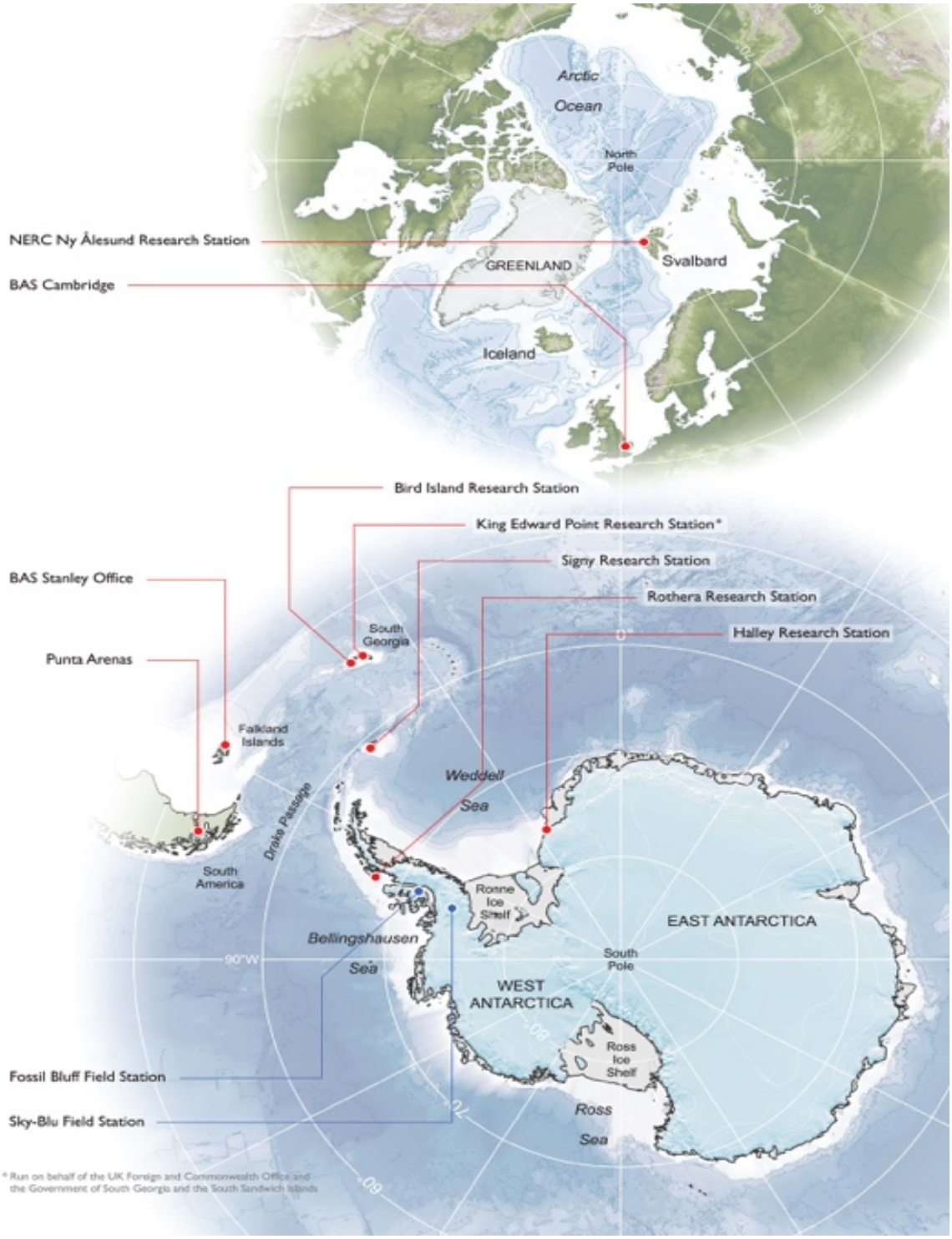


Figure 1.1: *Location of UK research stations in the Arctic and Antarctic*

Structure and governance

BAS is a complex and rapidly changing organisation, and over the past six years, BAS's organisational structure and governance has evolved to meet the challenges we face. BAS's new Director (Professor Dame Jane Francis) created a leadership team comprising Director of Science (Professor David Vaughan), Director of Innovation and Impact (Dr Beatrix Schlarb-Ridley), Director of Operations and Engineering (Simon Garrod), and Director of Corporate Services (Laura Dance). Director of the Antarctic Infrastructure Modernisation Portfolio (Jonathan Ager) was recruited in 2019.

The BAS Executive Team, the Science Strategy Team, and BAS Management Team support the Director and help provide the overall leadership, direction and management to the organisation to achieve its mission.

BAS employs more than 470 staff, including 137 scientists. Our workforce covers a wide range of disciplines, from mariners and pilots to ecosystem modellers and ice core scientists. During the 2018/19 Antarctic field season, of the 229 scientists who travelled 'south', 76 were from BAS, 101 were from other UK institutions and 52 were non-UK.

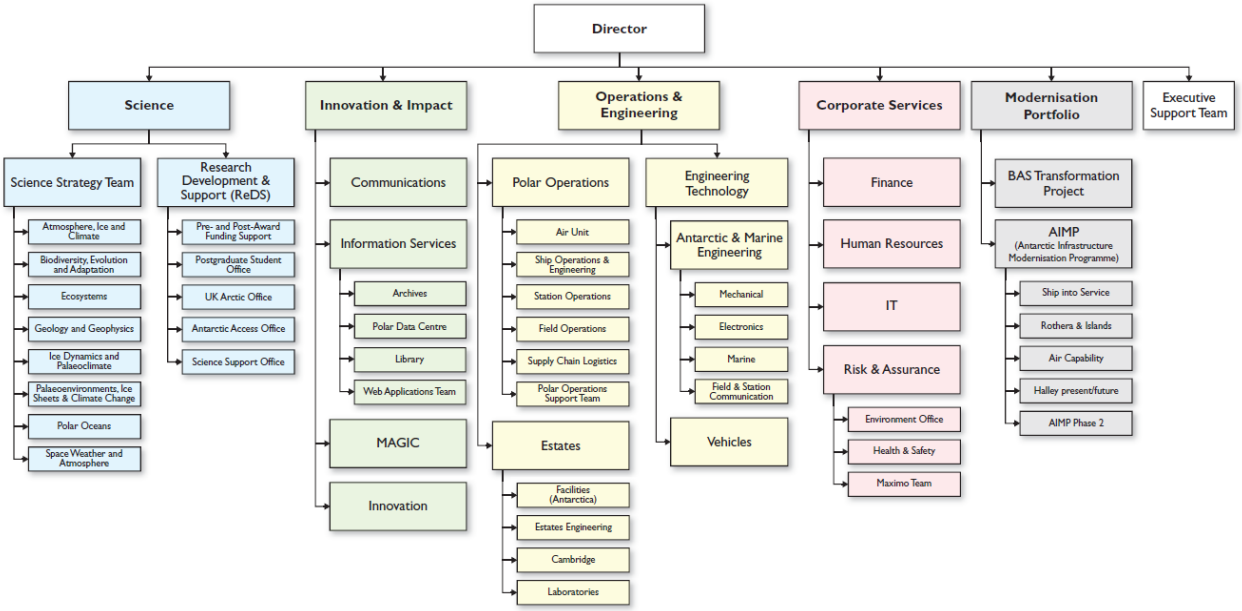


Figure 1.2: *Organisational Structure of BAS. Divisions such as Corporate Services and Innovation & Impact reach across all areas of BAS activity (MAGIC = Mapping and Geographic Information Centre)*

Significant changes since the last RCE

- In 2013, the new BAS Director initiated a new strategy, new organisational structure, renewed focus on diversification of funding sources to counteract flat-cash budgets. a new approach to innovation and impact activities, and enhanced staff development programmes to develop a more agile and flexible organisation.
- The BAS Partition, introduced in 2015/6, is a funding mechanism to reflect the dual role. It ring-fences funding (as a top-slice of the UK science budget) for Antarctic Logistics and Infrastructure (ALI), and includes logistic support for the whole UK community, plus government research required by the FCO from BAS. This is distinct from Non-ALI funding from NERC for BAS

science (National Capability, Section 3). The Partition has clarified the costs of each side of the dual role and has reduced internal funding competition between BAS science and logistics.

- National Capability*:* NERC clarified the purpose and funding associated with National Capability and commissioned long-term complex research via cross-centre (NC-LTSM), single centre (NC-SS), National & Public Good (NC-NPG) and NC-ODA science programmes. Institutional Funding delivers our science strategy through the Polar Science for Planet Earth science programme (Section 3). In addition, BAS scientists now win ~40% funding from a diversity of external competitively-won grants (e.g. NERC, EU, ESA, Darwin). Together this replaces the previous internally-allocated block funding.
- Antarctica and the Arctic remain the principal focus for BAS science but the scope of BAS's activities has increased geographically and scientifically to 'wherever polar expertise can be applied'. The re-allocation of some of BAS's NERC core funding for ODA activities encouraged BAS scientists to successfully develop new projects in remote environments, such as mountain glacier evolution in high-Mountain Asia, water supply assessment using polar equipment on Moroccan and Indian farms, and African reserves, and marine ecosystems and food security in UK's Atlantic Overseas Territories (UKOT).
- In 2015 the Antarctic Infrastructure Modernisation Programme (AIMP) was commissioned by NERC. This long-term programme will enable a world-leading capability to ensure that Britain remains at the forefront of climate, biodiversity and ocean research in the Polar Regions. Together with the commissioning of the *RRS Sir David Attenborough*, this modernisation programme represents the largest Government investment in polar science infrastructure since the 1980s (Section 3).
- BAS Transformation Programme – Fit for the Future - commenced in 2018. It aims to modernise, update and improve processes and systems across BAS to ensure the benefits of the AIMP are realised. This programme will also ensure that BAS can benefit from the new UKRI world.

Figure 1.3: *The main strategic goals for the BAS Transformation Programme*

Research Strategy

Our research strategy, *Polar Science for Planet Earth,* focuses on five key themes of global significance. Each theme crosses traditional disciplinary boundaries and requires a long-term strategic approach, that exploits the knowledge and expertise within our science teams. Each theme has a particular relevance or foundation in the polar regions but also has significance for the entire planet and the people living on it.

The five themes deliberately align with NERC's strategy stated in the Business of the Environment 2013, the NERC Delivery Plan 2019 and UKRI's Delivery Plan 2019.

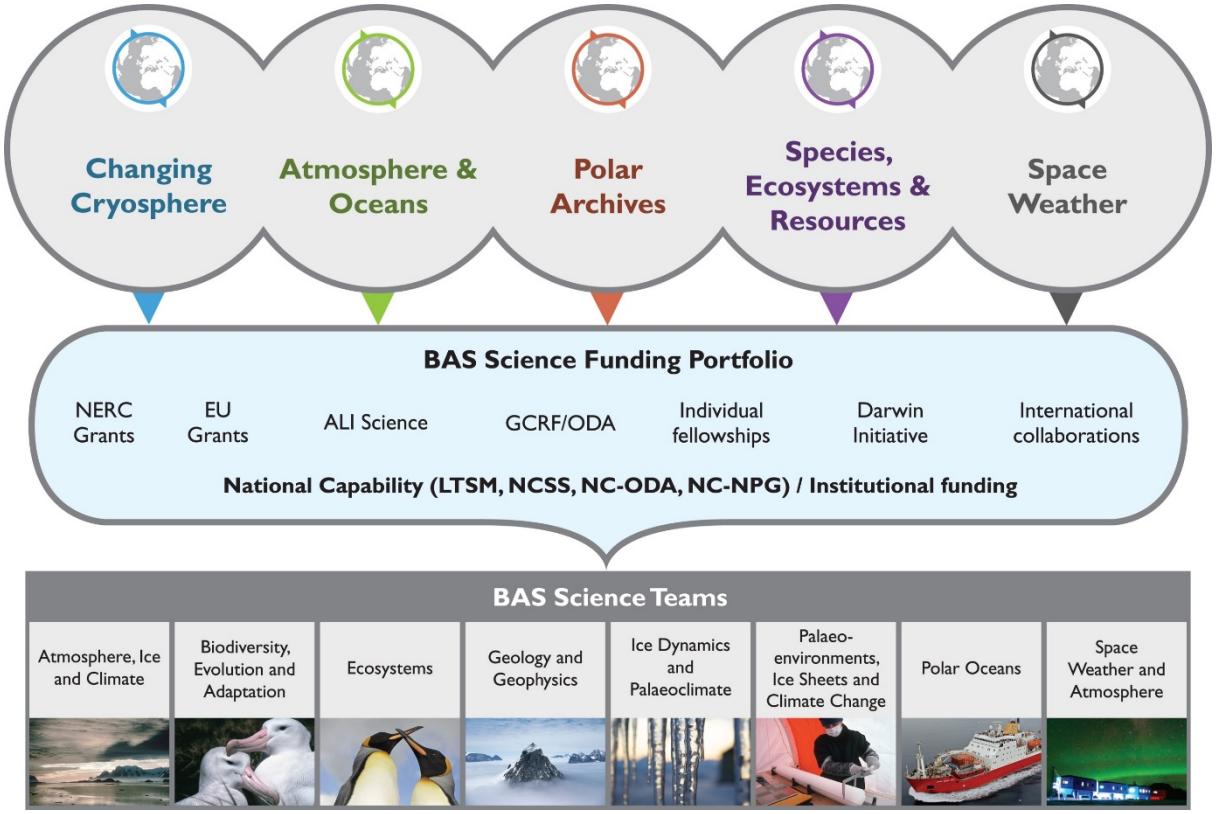


Figure 1.4: *Schematic illustrating the portfolio approach to five strategic themes that incorporate a mixture of scientific projects, technological development, observational/monitoring activities and engagement campaigns. The funding model is described in Section 3*

For each of these themes we seek to fill key knowledge gaps and develop new knowledge. Selected achievements in each theme are described below (with citation by reference number to example publications in the BAS RCE Excellence Submission):

Theme 1. Changing Cryosphere

Changes in the cryosphere are some of the most visible and influential impacts of climate change on our planet. We are studying key cryospheric components (sea ice, ice sheets, mountain glaciers) in both polar regions and High Mountain Asia to provide improved understanding of the processes that lead to cryospheric changes, and improved predictions of change and its impact on the global environment and human activities. We deliver this by developing and sharing innovative technologies (104, 136), understanding and quantifying key processes, and improving diagnostic and predictive models (87).

Recent BAS achievements include:

- clarification of the potential for collapse of marine ice sheets (1, 59, 60, 61,178).
- major advances in understanding the role of oceans in driving ice-loss from the Antarctic Peninsula (180, 11, 31, 36) and West Antarctic ice sheet (38, 89).
- the attribution of ice-sheet change, and its contribution to global sea-level rise, to anthropogenic influence (77, 37), and in particular to atmospheric circulation in the tropics (163).
- improved understanding of the regional patterns of sea ice change in the Arctic (175, 189) and Antarctica (5, 78).
- improved understanding of the influence geology exerts on ice-sheet morphology (92, 93, 161, 181).

(See impact case study (ICS) 7)

Theme 2. Oceans and Atmosphere

The globally-connected nature of the oceans and atmosphere makes the Earth System both dynamic and prone to change. We seek to understand the role of atmosphere and oceans in transporting heat around the planet, and the processes by which heat, carbon and momentum are transferred between ocean and atmosphere.

Recent BAS achievements in this area include:

- observation of change in polar oceans (115), and understanding of key processes in polar oceanography (9, 10).
- improved understanding of the major role played by the Southern Ocean in the uptake of heat and carbon (118, ORCHESTRA).
- the influence of Southern Ocean on global ocean circulation (113).
- identified key poorly understood polar processes in the atmosphere that limit the effectiveness of global models (6) and can cause dramatic local impacts (98, 99).
- improved understanding of atmospheric change (5).
- quantified the influence of key processes in Arctic (50, 157, 189, 50) and Antarctic (103, 99, 98) that impact global weather and climate patterns.

(ICS 7)

Theme 3. Polar Archives of Planet Earth

The ability of numerical models to predict future change on the planet is severely limited by a lack of real-world data for verification and testing. However, a wealth of data, recording both cause and response, exists in environmental and geological records. For example, in ice cores, there exists a unique and simultaneous record of greenhouse gas forcing and the temperature response. We seek to unlock the history of life, climate and the Earth, focussing exclusively on the proxies and periods that will inform understanding about the future warm world.

Recent achievements include:

- development of proxies of ice-sheet change (163, 90, 70, 74, 128, 158, 167, 168, 169, 170),
- ocean forcing on ice-sheet melt (64, 66),
- the location and strength of westerly winds in the Southern Hemisphere and their impact on carbon exchange (154),
- a history of thinning and retreat in the West Antarctic Ice Sheet (90) and its causes (63, 64).

(ICS 7)

Theme 4. Species, Ecosystems & Resources

Rapid rates of change in multiple stressors (ocean acidification, harvesting of marine resources, and climate change and consequential changes in ice conditions) in both polar regions are driving dramatic changes in the behaviour and physiology of species, on ecosystems and on biodiversity. We are working in both regions to understand the impact of change and the ability of species and ecosystems to adapt and/or migrate. This understanding will allow us to improve our predictive capacity and identify vulnerable habitats and species.

During the reporting period, we have had important successes in:

- quantifying changing environmental stress on species and communities (2, 7, 8).
- quantifying the adaptive responses of key species (18, 19, 20, 53, 57, 62, 85), and the underpinning physiological and genetic processes (47, 17, 44, 124,125).
- identifying, for the first time, the globally significant role played by the Southern Ocean zooplankton in mediating uptake of atmospheric carbon in the open ocean (105, 106, 107) and coastal shallows (3).
- improving the representation of biological systems in Earth System Models (191) and our predictions of future change in biodiversity across both polar regions (58, 132, 144) and globally (15, 134).
- state-of-the-art biophysical models to inform policy-makers on issues such as allowable catches, and establishment of Marine Protected Areas.

(ICS 5-8)

Theme 5. Space Weather

The polar regions provide a unique vantage point from which to observe our upper atmosphere and its interaction with the space environment. We use this vantage point, to quantify and minimise the risk of extreme space weather events on terrestrial (e.g., power distribution networks) and space

infrastructure (e.g., satellites) by observing space weather, quantifying its variability and understanding the processes involved.

Recent achievements include:

- ground-breaking statistical analyses to predict the likelihood of the most damaging space storms (55, 120).
- development and verification of the BAS Radiation Belt Model (BAS-RBM, 55,56), licenced to the UK Met Office to allow real-time operational space weather forecasts.
- significant improvements in our understanding of the Earth's van Allen radiation belts (56) and the processes by which solar flux influences weather on Earth (16, 24, 21).
- use of our data by the satellite operators, space insurers and designers to improve satellite design (82).

(ICS 3&4)

(Note: to meet the requirements of RCE, the 'Department/Units' to which the RCE Excellence Outputs are linked are a simplified version of the themes listed above.)

With the publication of the UKRI Strategic Delivery Plan and that of NERC in May 2019, BAS is currently in a process of reconsidering our research strategy and how this will need to be modified to deliver the UKRI and NERC strategies. We look forward to the launch of our first strategy as part of UKRI in 2020.

Research outputs and achievements during the RCE period

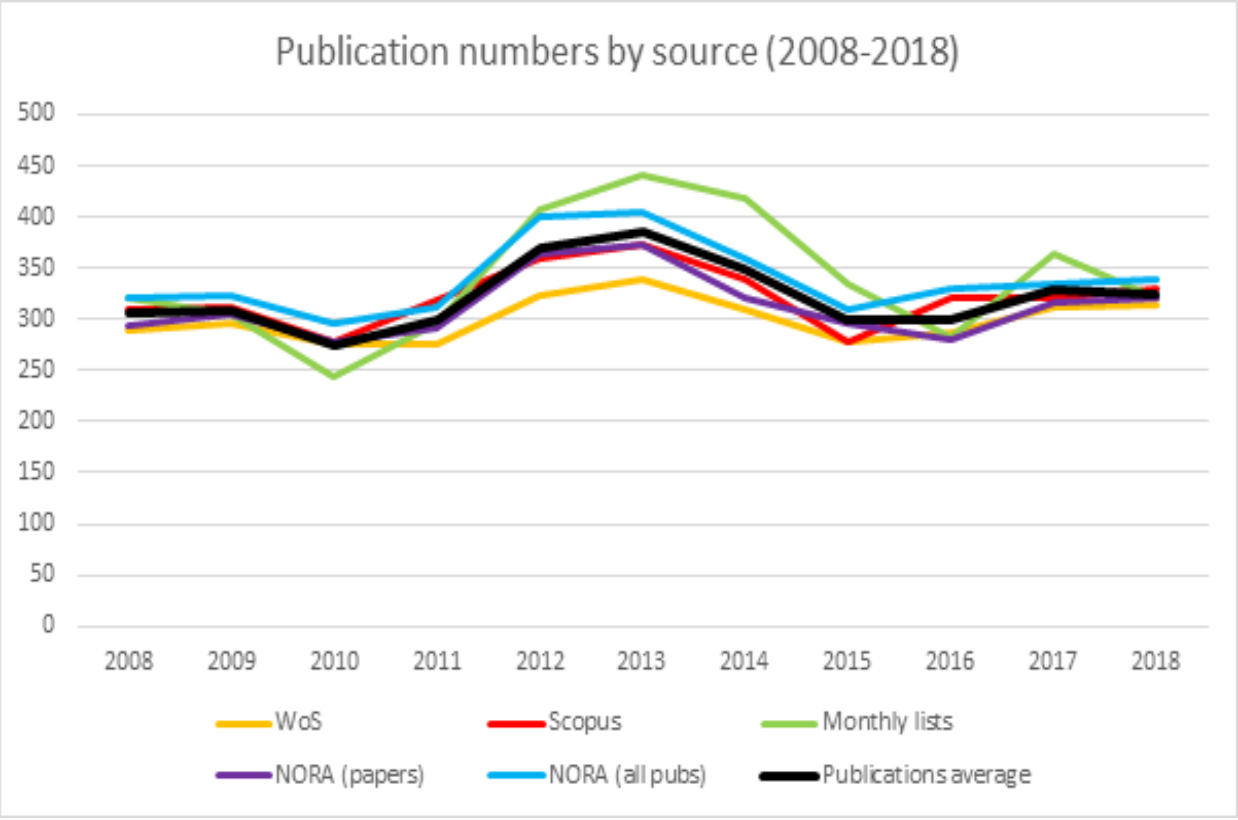


Figure 1.5: *Number of papers (co-)authored by BAS (from a variety of sources)*

Since 2013 we have published 19 items in Nature, 72 more in Nature-family journals (e.g. Nature Geoscience, Nature Communications), 10 in Science, and a further 9 in Science-family journals (e.g. Science Advances). Since 2013, BAS has published 2098 papers, acquired almost 33,000 citations, and has achieved an institutional h-index of 179 (Web of Science).

The BAS Science Strategy Team reviews BAS publications twice per year, analysing the number of papers published, citation rate, outputs of individual staff and identification of press releases etc. Overall, BAS researchers (av.80 ≥Band 5) publish more than 300 papers per year as authors and co-authors (see Figure 1.5). A notable success is the increasing number of publications by early career researchers, related to the increase in post-docs and PhD students on external grants and in DTPs/DTCs (Section 2).

Science Structure

A new science strategy and team structure was developed in 2014. Eight teams, each led by a Science Leader (SL) and Deputy Science Leader (DSL), deliver the interdisciplinary Polar Science for Planet Earth programme. Full details of the ambition and objectives of each team are published on the BAS website.

- Polar Oceans (Mike Meredith SL/Andrew Meijers DSL).
- Ecosystems (Eugene Murphy SL/Geraint Tarling DSL).
- Geology and Geophysics (Fausto Ferraccioli SL/Teal Riley DSL).
- Ice dynamics and palaeoclimate (Andy Smith SL/Louise Sime DSL).
- Atmosphere, ice and climate (Anna Jones SL/Tracy Moffat-Griffin DSL).
- Biodiversity, Evolution and Adaptation (Lloyd Peck SL/Pete Convey DSL).
- Space Weather and Atmosphere (Richard Horne SL/Mervyn Freeman DSL).
- Palaeoenvironments, ice sheets and climate change (Dominic Hodgson SL/Rob Larter DSL).

Science Teams provides a home for all scientists, from which they engage in one or more projects, including National Capability, institutionally funded or grant-funded. The team structure provides support for career development and team members hold specific roles (e.g. web editors, health and safety representatives). Teams meet on a monthly basis, and larger teams have subject-specific sub-groups.

Our Science Strategy Team (SST), chaired by the DoS, comprises science leaders from each Science Team, the Director of Innovation, and representatives from the BAS Research Development Support (ReDS) team, finance and early-career researchers. The SST formally reports to the BAS Executive Team, particularly for items such as risk reporting, staffing requests, bonuses etc. The DoS holds biannual Away-days, during which SLs/DSLs work through key issues for BAS science. The allocation of scientists' time is managed using the NERC Resource Management System (RMS). In 2019 BAS was involved in 187 separate projects with 11% drawing expertise from more than one BAS team (i.e. are interdisciplinary), and 57% are in collaboration with external Institutes.

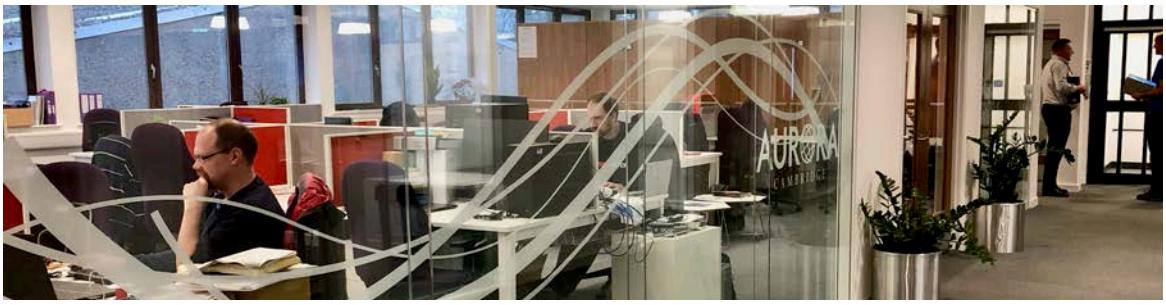
Delivering Impact

In 2014 BAS appointed its first Director of Innovation and Impact (DoI&I), Dr Beatrix Schlarb-Ridley, previously Business Innovation Manager for a University of Cambridge/UEA EU knowledge transfer project linking the region's top plant science research with businesses developing new products.

AURORA CAMBRIDGE

The **Aurora Innovation Centre opened in BAS in 2017. C**o-funded by BEIS/NERC and University of Cambridge, it has generated vibrant academic, business and policy partnerships that focus on excellent research and entrepreneurial activity in the areas of climate change, environmental stewardship and technologies for challenging environments. Within 2.5 years of completion, the Aurora Innovation Centre has become a successful self-funding facility, offering exhibition space show-casing BAS science and operational expertise, meeting facilities, and collaboration space hosting members from industry, third sector and academia.

Since its launch, Aurora has hosted 196 external meetings with over 8800 participants, raising the profile of UKRI, NERC and BAS. It has been a focal point for polar science meetings within the UK research community, and brought businesses and policy-makers into the heart of our organisation.



In 2014/15, the DoI&I developed 'Innovation through Partnership', the BAS Strategy for Innovation and Impact. The strategy defined four steps to achieve impact:

- *Knowledge of internal strengths:* we established a network of BAS Innovation Champions who map BAS's expertise and identify novel opportunities to turn this into impact through innovative work (e.g. Julius Rix developed novel sub-glacial rock-drill equipment with collaborators who are working on drilling on Mars, benefiting both areas of investigation; Simon Morley and David Barnes applied an ecosystem approach to assessing sustainability and vulnerability of fishing industries in several UKOTs).
- *Knowledge of the external landscape:* we actively participate in local, national and international strategic networks and commission market analysis, e.g. to understand which types of bioactives from polar organisms could address market gaps, and which BAS technology solutions could find application in non-polar remote environments (e.g. biopesticides; radars; autonomous weather stations; detection of wildlife, Rare Earths, plastics).

- *Formation of partnerships where values, strengths and needs are aligned,* such as with the Centre for Global Equality and the World Bank's Climate Innovation Centres on ODA work, and with Newton Technology Group for commercialisation of niche technologies
- *Joint translation of strengths into solutions, leading to impact:* supported by targeted pump-priming and collaborative work with stakeholders and end users, e.g. as described in ICS1 (Wildlife from Space) and ICS4 (Extreme Space Weather).

The BAS Strategy for Innovation and Impact has been revised to reflect opportunities arising from UKRI Industrial Strategy and the Global Challenge Research Fund, plus the Green Finance Strategy and the UK Government commitment to net zero emissions by 2050. BAS has focussed on developing new impact projects supporting the Sustainable Development Goals and net zero carbon targets. Examples include:

- An autonomous phase-sensitive radar, ApRES, originally designed to monitor changes in Antarctic ice shelves, has been used as a tool for groundwater monitoring with partners in Morocco, South Africa and India.
- Technologies developed to determine ice volumes in Antarctic ice sheets have been adapted to calculate the volume of freshwater locked up in Himalayan glaciers; this knowledge, combined with applying BAS expertise in regional climate modelling to the complex orography of the Himalayas, is being developed to underpin water management by governments and inform investment decisions for hydropower installations.
- A new initiative – the 1.5°C challenge – is BAS's response to the IPCC special report on the impacts of global warming of 1.5 °C. A steering group is tasked with investigating and reporting on how BAS will intensify engaging decision-makers in climate evidence and facilitate planning for net zero carbon by 2050.

Impact case studies (ICS)

Our Impact case studies reflect the breadth of BAS's influence and engagement with industry, policy-makers and the public, and the vitality and maturity of projects, which in many cases have been part of the long-term impact pipeline at BAS. They showcase new evidence that has arisen from established strengths capitalising on new opportunities. These are linked to the BAS Strategy for Innovation and Impact through alignment with strategic priorities (Figure 1.6).

	Environ-mental stewardship	Environ-mental sensing and autonomy	Deriving value from data and models	Technologies and materials for cold, remote and challenging environments	Climate and space weather science for risk mitigation
1: Wildlife from Space	✓	✓	✓	✓	
2: Sea-ice Information	✓	✓	✓	✓	
3: Space Weather Forecasting		✓	✓		✓
4: Extreme Space Weather Events		✓	✓		✓
5: Fisheries Management	✓	✓	✓		
6: Conservation of Species and Habitats	✓	✓	✓		
7: IPCC			✓		✓
8: Blue Planet Effect	✓		✓		

Figure 1.6: *Mapping of our impact case studies (left column) on to strategic priorities in the BAS Strategy for Innovation and Impact*

Research integrity

BAS's Research Ethics Policy shows our commitment to rigorously ethical research, following UKRI-NERC policies. The 'BAS Animal Welfare and Ethical Review Body' (AWERB) is charged with maintaining the highest standards of welfare in all animal experiments, include those covered by the Animals (Scientific Procedures) Act 1986, although we seek to apply the same standards in areas not covered by the Act, specifically in Antarctica. AWERB has external members including a Veterinary Surgeon, External Consultant and Lay Member.

Open research environment

BAS has made a strong commitment to publish in fully Open Access journals and has achieved around 80% since 2015 (see Part B). A principle of the Antarctic Treaty is that "scientific observations and results from Antarctica shall be exchanged and made freely available" (Article III). BAS hosts the UKRI-NERC Polar Data Centre for all UK polar science data. BAS publishes datasets as DOIs (Figure 1.7); e.g. BEDMAP2 topographic model of Antarctica was compiled from numerous datasets of scientific observations.

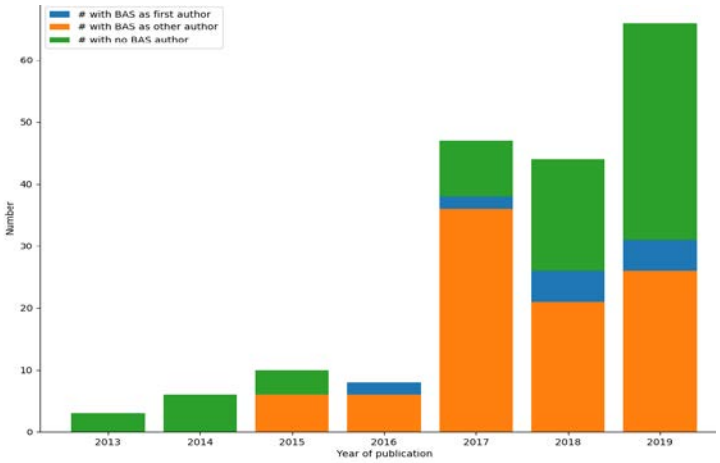


***Figure 1.7**. Number of DOIs issued by BAS Polar Data Centre. blue=BAS first author, orange=BAS co-author, green=no BAS author*

Interdisciplinary research

With the widest range of scientific fields of any of the NERC centres, BAS is naturally interdisciplinary across environmental science. The structure of our science teams was specifically designed to foster interdisciplinary working and introduce vitality within BAS, and with external experts, e.g. with social scientists and indigenous peoples of the Arctic.

The Aurora Innovation Centre brings contact with low-carbon businesses and entrepreneurs (e.g. Polysolar photovoltaic experts, Echion batteries developers, Entomics biotransformation specialists), and our DTCs have introduced BAS to new areas in, for example, machine learning (AI4ER).

The BAS Honorary Fellows scheme underpins collaborations with a variety of world-leaders in research e.g. Professor Klaus Dodds, Royal Holloway University, in geopolitics.

SECTION 2: PEOPLE

2.1 PEOPLE STRATEGY

Staffing strategy to support BAS Vision

Our staffing and development approach is captured in the BAS People Strategy. It sets out a forward-looking and ambitious agenda, responsive to change and designed to support staff in BAS, in all their diversity, to reach their full potential and deliver the BAS Vision.

Demographic profile and recruitment drivers

The evolving funding landscape has been a key driver for science recruitment since 2013. The increased focus on project funding (51% of total science funding on average 2013-9, vs. 21% in the previous RCE period) has increased the recruitment of fixed-term appointments (post-docs). This

has brought new skills to address opportunities such as machine learning, and has increased the percentage of Early Career Researchers (ECRs).

While the overall number of scientists has remained comparatively stable throughout the assessment period (average 126.2 full-time-equivalent (FTE) of a whole BAS workforce of average 403.0 FTE), the demographic profile has changed, see Figure 2.1:

Year	Full-time Equivalent	Part Time staff	Female scientists in senior roles (PB5/E and above)	ECRs (female)
2013/14	123.6	7	16	5(2)
2014/15	132.1	6	17	17(10)
2015/16	127.5	14	21	9(4)
2016/17	123.3	15	21	15(6)
2017/18	124.6	14	21	19(10)
2018/19	125.9	13	25	29(19)

Figure 2.1: *Science staff numbers over assessment period*

Facts to celebrate:

On average 39% of scientists are female, significantly higher than the UK average of 25% females in the primary science workforce. The proportion of females in higher bands has increased from 29% in 2013 to 52% in 2019, a trend resulting from BAS's conscious effort to increase gender diversity and address the leaky pipeline for female researchers.

The ratio of BAS ECRs (post-docs) to total science staff has increased significantly from 4% in 2013 to 23% in 2019. The percentage of female ECRs has increased from 40% in 2013 to 66% in 2019 (Figure 2.1).

Since 2013, the profile of our scientists has become more diverse with more staff from different cultural and ethnic backgrounds. On average 16% of scientists were non-UK, spread across 24 different nationalities (2013: 11%, 2019: 20%). BAME declaration increased from eight in 2013 to twelve in 2019. Bisexual/Gay/Lesbian declaration has increased from three in 2013 to eleven in 2019. Disability declaration has tripled from three in 2013 to nine in 2019. The data on BAME, sexual orientation and disability are organisation-wide: we cannot separate out science without compromising anonymity.

Trends to manage:

Since recruitment of new science staff has mainly been for post-doc positions, the average age of our Open Ended Appointments (permanent) science staff has increased from 43 to 49 years between 2013 and 2019. To address new funding opportunities that require leaders with new skill

sets, and succession planning for science staff close to retirement, we will recruit two new open-ended positions from 2020.

Converting opportunities and developing people through knowledge exchange

New skills are also introduced through knowledge exchange with other sectors. The embedding of innovative SMEs within BAS-AURORA (see Section 1), and frequent exchange opportunities with these and other organisations in the fertile Cambridge innovation landscape, ensures access for all staff to a broad knowledge exchange base. Understanding key stakeholder interests has also been facilitated through four secondments of scientists to public or international bodies (DEFRA, South Georgia Government (2), Niels Bohr Institute Copenhagen), and by hosting honorary appointments in BAS.

Recognising and rewarding staff

Reward structures play an important role in retaining our motivated workforce. These have become particularly important in BAS since 2018, when the formation of UKRI introduced dual pay scales, with pay harmonisation not yet achieved.

BAS has several schemes to acknowledge staff achievements:

One-off rewards/awards:

- Special Bonus Payments - BAS staff are nominated for one-off bonuses, generally in the range £300-£750. 31% of science staff received a bonus during the assessment period.
- BAS Prizes - Annually, BAS/BAS Club considers nominations for two prestigious awards: the Laws Prize for 'outstanding young scientists in recognition of their achievement', the Fuchs Medal to any BAS staff for 'devotion to the Survey's interests, beyond the call of normal duty'.
- Since 2018, BAS makes annual 'Going the Extra Mile' awards, a public thanks and gift voucher to individuals nominated by their peers. 5% of scientists have received this award to date.
- Thank-you vouchers: since 2018, BAS has used £50 vouchers to express appreciation to staff who have made important contributions; 16% of scientists have been awarded a voucher to date.

Celebrating Research

BAS science leaders select a Paper-of-the-Month from those published by BAS lead authors, chosen for its scientific quality and significance. Nomination and voting are a serious undertaking and the selected paper is promoted across BAS. Authors receive a personal commendation and thanks from the SST and DoS, and are mentioned in the BAS ICESHEET newsletter.

Additions to salary:

Salary flexibilities are delivered through Recruitment and Retention Allowances (RRA), and Supervisory and Responsibility Awards (SRA). 34% of scientists have received RRAs or SRAs during this assessment period.

Promotion:

Promotion is the key mechanism recognising achievement, skill and personal development. In 2018 NERC delegated management of its Merit Promotion Scheme to its Centres. Under BAS administration, the number of applications increased, especially from females (10 applications in

total 2013-17, 11 in 2018 alone under the BAS scheme). This bears witness to the effectiveness of the Leadership Programme launched in 2016 to develop aspiring women leaders at BAS.

BAS scientists (≥Band4) may also apply for Individual Merit Promotion (IMP), administered by BBSRC. This recognises outstanding personal contribution in their field. Seven BAS applications were made between 2013 and 2019, five were successful, including the first female IMP. BAS currently has 11 IMP Band3 and two IMP Band2 scientists.

	2013	2014	2015	2016	2017	2018	2019
B7 to B6	5(3)	4(1)	-	1(1)	4(0)	-	-
B6 to B5	-	1(1)	5(1)	3(2)	5(2)	8(4)	1(1)
B5 to B4	-	-	-	-	-	8(4)	9(3)
B4 to B3 (available from 2019 onwards only)							3(1)

Figure 2.2: *Applications for promotion by BAS science staff (successful applications in brackets)*

Supporting wellbeing

Wellbeing is an important focus in BAS. Initiatives include pilates, yoga and sessions on mindfulness, improving sleep, menopause and neurodiversity. BAS works closely with Mind to promote mental health. Five welfare officers and mental health first-aiders provide support and guidance to staff, and a welfare room offers a safe space whenever needed, and comfortable facilities for nursing mothers on Keep-in-Touch days.

BAS support for physical health includes preferential membership rates at the nearby Cambridge University's Sports Centre and a number of organised staff events, including:

- The biannual 'BAS-Handicap 10k Race', regularly attracting more than 30 runners and walkers of all abilities (Figure 2.3). Start times are staggered so that everyone finishes together.

***Figure 2.3**: BAS Midwinter Handicap 10k Race*

- The 'Race Antarctica' event, where teams in Cambridge and Antarctica accumulate 'race miles' through walking, running, swimming, cycling, rowing, skiing etc (Figure 2.4). Race Antarctica has been highly motivating to many at BAS.

***Figure 2.4**: 'Race Antarctica' at Rothera Research Station*

Supporting deployed staff:

Approximately 50% of BAS's Cambridge-based staff regularly work long periods away from home on stations, vessels or in field camps. Operational and HR teams are available 24/7 to provide support for them and their families, including tailored Emotional Resilience Programmes, Mental Health Awareness sessions and access to counselling.

2.2 Training and career development

Staff development and training is at the heart of our people strategy and a critical tool to delivering first-class science. All staff have access to structured activities to support their professional and

personal development and agree an annual development plan at appraisal. Time to complete these activities is allocated within normal working hours.

Training provision

A comprehensive training portfolio has been developed since 2013 (see Figure 2.5). Up to 2017, staff had access to additional NERC-run schemes:

- 'Leadership for NERC' – supporting the development of personal leadership skills among senior scientists.
- 'Growing Future Leaders' – a High Potential Development Scheme for Bands 6/5 staff who demonstrate potential to progress their careers rapidly to leadership positions.

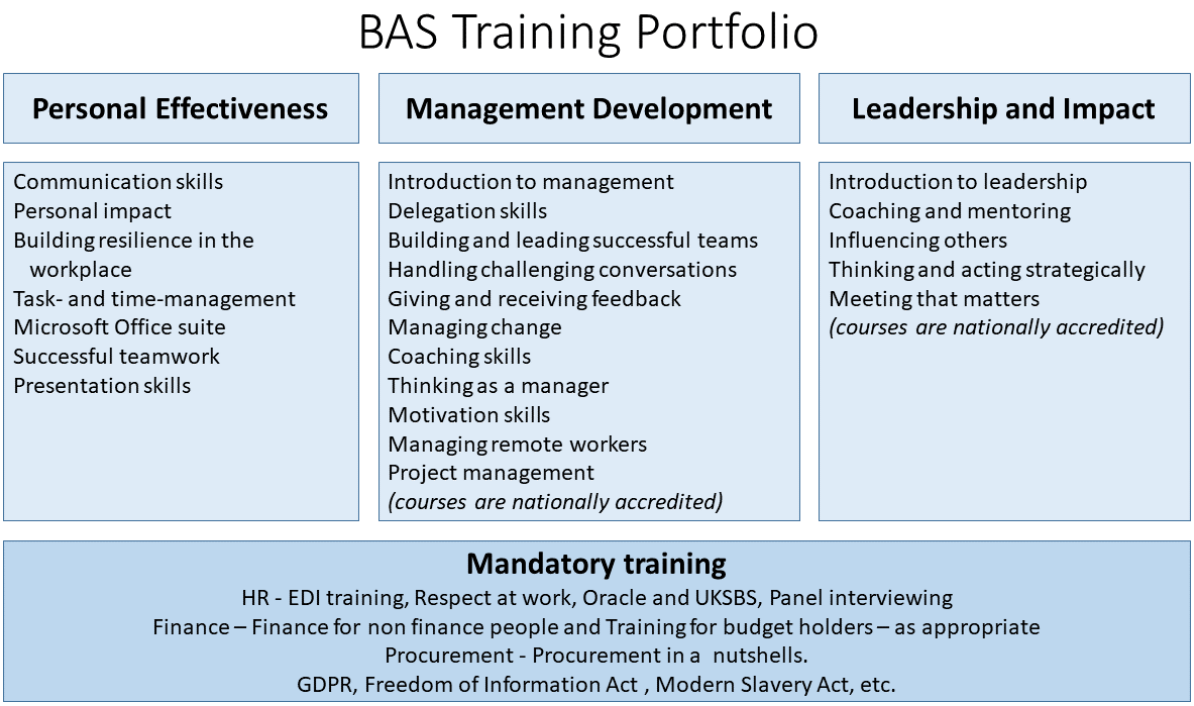


Figure 2.5: *BAS training portfolio*

Learning opportunities for innovation have been open to all BAS staff:

- Intrapreneurship training with Cambridge University's business school.
- Venture schools.
- Innovation toolkit training, including ODA focus.
- 'Knowledge snacks' with (inter)national entrepreneurs.

On average, scientists complete two to three training courses each year.

Career development support

All scientists benefit from individual quinquennial reviews with the Director and DoS to discuss short-, medium- and long-term plans and publication records. Annual appraisals with line managers also cover continuous career development.

Since 2015, staff can apply for mentoring, and seven scientists (six females) have been in formal mentoring relationships during the assessment period.

Opportunities for grants, fellowships and prizes are summarised in monthly funding bulletins and directly communicated to scientists for whom they are relevant. In addition to having access to an extensive self-help library of resources, staff writing proposals receive active support through:

- Grant writing workshops
- Internal peer review
- Budget planning with finance
- Presentation- and interview-practice for fellowships

In September 2019, following our commitment to the UK Concordat to Support the Career Development of Researchers, a Career Development Framework was developed. It moves from a training portfolio, as described above, to a structured progression of workshops, coaching and engagement activities, helping researchers take planned proactive steps to progress.

Support and integration for Early Career Researchers (ECRs)

ECRs are employed on Fellowships (currently 5) or fixed-term appointments (Post-Docs) mostly funded by grants.

In addition to the training resources and Career Development Framework described above, ECRs have access to:

- Vitae's Researcher Development Framework
- Guidance on Fellowships
- Reviews with internal and external experts in their field to discuss career aspirations and next steps

The perspectives of ECRs are embedded in BAS management. Several significant committees now explicitly seek ECR membership (e.g., Staff Forum, Transformation Programme Board), following the lead of the Science Strategy Team, which since 2014 has included an early-career member (on six-monthly rotation). This opportunity is valued by ECRs seeking insights into science strategy and leadership. Two former ECRs (both female) who previously participated in this programme are now Deputy Science Leaders.

Post-graduate research students (PGRs)

BAS has maintained a strong and vibrant research student community throughout the assessment period.

All BAS PGRs are registered with a partner university, have a BAS supervisor and belong to a BAS science team. Some are based full-time at BAS (currently 45), others visit regularly. We have nearly doubled our overall number of PGRs from 55 (2013) to 101 (2019).

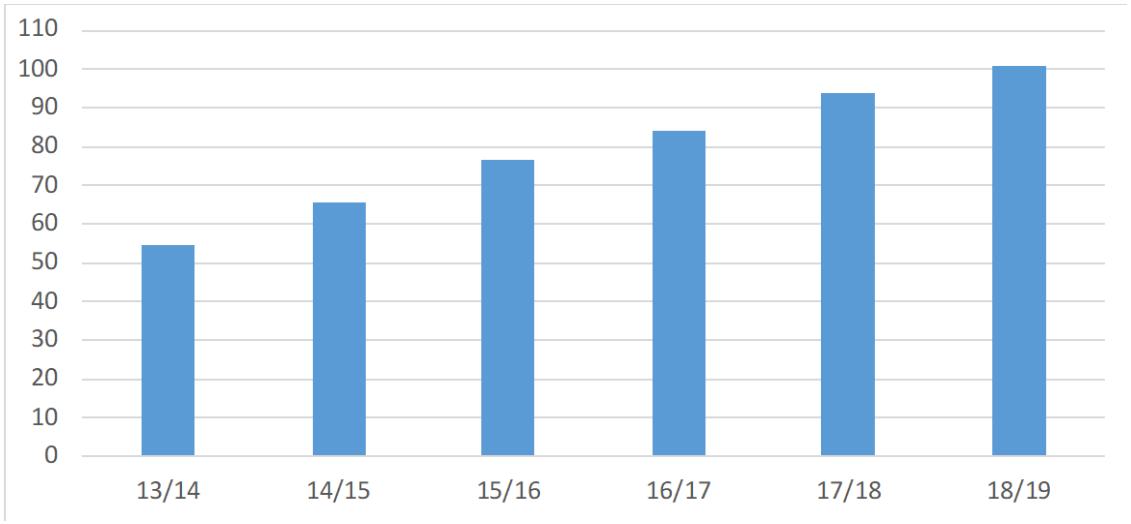


Figure 2.6: *Number of Ph.D. students (co-)supervised by BAS staff*

Over the first tranche of NERC DTPs, BAS hosted 41 students registered at seven different universities, with DTPs EnvEast, GW4+, SPITFIRE and Cambridge Earth System Science, and developed a particularly strong partnership with Cambridge University.

The strong link with NERC studentships is set to continue with the award of five host partnerships in the second tranche of NERC DTPs (start 10/2019; with ARIES, C-CLEAR, GW4+, Iapetus2 and INSPIRE, involving 16 universities; currently 2 BAS-hosted students).
BAS is also host partner in three Centres for Doctoral Training involving six universities, NEXUSS (NERC/EPSRC, 2 BAS-hosted students), AI4ER (UKRI) and SENSE (NERC) (both are yet to recruit).

BAS offers students a unique environment to develop research skills, and a wide range of project opportunities. BAS is involved in such a significant number of DTPs and CDTs in order to provide excellent opportunities across the range of scientific areas in which we are active.

Students are fully integrated into the core science teams and existing student cohort. They have regular supervisions and access to the entire research environment, including facilities, training, seminars and team meetings; many work in collaboration with an external CASE partner. In return, they bring invaluable new skills, insights and enthusiasm. Since 2013, BAS-hosted students have been lead authors on 44 papers and co-authors on 32 papers, and we pride ourselves in a 100% on-time PhD completion rate. Students further demonstrate their success with 64% continuing in academia, 15% working in industry/commerce and 11% in government/NGOs.

We provide five training courses for students through the year, ranging from a one-day induction course to a ten-day Advanced Training Course in Svalbard on “Safe and effective fieldwork in the polar regions”.

Students are supported by their supervisor/s and a dedicated Postgraduate Student Office. They are provided with both a Student Handbook (updated annually) and ‘BAS Code of Practice for Research Students’. They have access to a variety of learning and development opportunities:

Fieldwork	Induction and training courses to cover teamwork, safety, first aid, survival in remote conditions.
Teaching	All students have the opportunity for teaching at their registered university and occasionally at Cambridge University.
Science meetings	Monthly meetings providing an opportunity for students to share their research with peers and receive feedback.
Student science symposium	Annual event for students to showcase their work and meet other young polar science researchers.
Seminar series, representation in fora, and social activities	BAS PhD students organise their own seminars and social activities and join relevant fora (e.g. Science Strategy Team, Lab Forum, Staff Forum, Innovation Champions, Vitae's Researcher Development Framework).
Mentoring scheme	All students have access to mentoring through the BAS mentoring scheme and their research group. Female students with a male supervising team have access to a female mentor. All students have access to NERC and BAS Welfare Services.

Figure 2.7: *A selection of activities to support BAS PGRs*

2.3 Equality, Diversity and Inclusion (EDI)

BAS hosts a vibrant and diverse community of staff and students. Over 70% of respondents to BAS's 2016 Staff Survey felt that EDI values were supported and promoted across BAS; 78% felt that people with diverse experiences and background could contribute and thrive in BAS culture. In 2015 BAS joined the Employers Network for Equality and Inclusion (ENEI), and works with staff to promote a culture of tolerance and respect.

EDI engagement and support activities

Gender:

Significant progress has been made in gender equality of leadership in BAS: in early 2013, the Director and all Science Leaders were male. Since summer 2013, BAS has its first female Director, and in 2019 two of the four Deputy Directors and one of the eight Science Leaders were female. In 2017 a 'Women and Leadership' Scheme was introduced, taken up by 21 women so far. In 2013, we started a 'Women in Science' group (now Women@BAS). We hold an Athena Swan bronze award (2015, renewed in 2018). A snap-shot of gender balance across key BAS teams is given in Figure 2.8.

Internal Committee	Role	Total No and % Females
BAS Executive Team	Develop BAS' strategy and ensure sustainable activities	12 (25% F)
BAS Management Team	Responsible for all aspects of management	12 (25% F)
Science Strategy Team	Develop science strategy that puts BAS at the forefront of polar science	18 (28% F)
Staff Forum	Review and recommend changes/improvements to people policies and practices	17 (61% F)
Local Joint Consultative Committee	Provide dialogue between the Unions and BAS leadership	13 (77% F)
Women@BAS	Provide a forum for staff to share insights into issues that traditionally affect women in all functions at BAS to enhance improvement	44 (81% F)

Figure 2.8: *Gender diversity in key BAS teams*

Transgender:

BAS contributed to the development of the RCUK Guidance on Supporting Transgender Employees in the Workplace (launched 2017). We supported one staff member through transition (2013-2017). The support plan included:

- Paid time-off for medical appointments, treatment and surgery
- Welfare provisions, including time-off for counselling sessions
- Increased flexibility during a phased return to work

LGBTQ+:

BAS staff were instrumental in the 2018 international launch of 'Pride in Polar Research'. We now have an LGBTQ+ and allies' network, and central gender-neutral toilets.

Ethnic minorities and disabilities:

In 2019, BAS started a 'Diversity in Polar Science' initiative, encouraging students from ethnic minorities and with disabilities to consider careers in polar science. In December 2019, BAS hosted ten students from ethnic minorities for a citizen science project.
Since 2014, medical screening only occurs for posts with planned fieldwork requirement, increasing employment opportunities for disabled applicants.

To support all protected characteristics, an EDI Forum was set up in 2019, working closely with Women@BAS, the Staff Forum, the four EDI Champions (representing the Directorate, Science,

Operations, and ECRs) and leadership teams. In 2019, all staff were invited to demonstrate their support for diversity and inclusion by 'Taking the Pledge' and wearing the BAS EDI lanyard. Over 120 staff have participated so far.

EDI in recruitment

BAS follows NERC recruitment and selection policies and procedures. All panel members and senior managers undertake mandatory training in 'Recruitment and Selection', 'Bullying and Harassment' and 'Unconscious Bias', and all staff complete an online 'Equality and Diversity' module. 98% of panels arranged since 2013 had female representation: 62% had one, the remainder two, female members. All adverts include a positive recruitment statement for under-represented groups, Athena Swan charter member logo and links to family-friendly policies and flexible working arrangements.

As signatory members of the Disability Confident Scheme we are committed to the employment and career development of disabled people. As part of this commitment we

- Operate a guaranteed interview scheme for disabled applicants who meet the minimum criteria for the role.
- Advertise in the disability press (e.g. Diversity Review Magazine and Living with Disability).
- Have an online profile on Vercida, an employment platform for people with disabilities.

Flexible arrangements to support inclusion

BAS fully supports the UKRI policies on flexible working. 86% of scientists have opted into our flexi-time system, and 13 scientists currently have part-time roles. In the reporting period, 19 requests for flexible working arrangements were submitted by scientists, all were granted. Bespoke flexibilities are arranged for those returning from parental or long-term sick leave. In the 2016 staff survey 83% of respondents 'appreciated and valued BAS flexible working practices and the ability to increase working hours after a period of working reduced hours'.

To support flexible working, meetings are arranged wherever possible at times when staff with caring responsibilities can attend:

- Training sessions are delivered as short sessions to accommodate part-timers.
- Science seminars are held in early afternoon to maximise availability and attendance.
- Staff briefings by Directors take place late morning/early afternoon and are recorded and put on the internal web site to be available to all staff even in Antarctica and on ships.

Financial and practical support has been given to carers who requested to take their children to conferences. Where part-time work or protected characteristics have an impact on internal deadlines or processes, flexibilities and additional support are offered.

The processes by which EDI has been considered in the Census and selection of outputs for this RCE submission are described in the Code of Practice. Two of the eight impact case studies have been co-authored by junior scientists, enabling them to gain leadership experience.

SECTION 3: Income, infrastructure and facilities

Introduction

For most of the review period BAS has been operating in a flat-cash funding environment for science. To manage this challenge, we have successfully diversified our science funding sources, and have engaged with new science partners. Grant application and success rates have been maintained (Figure 3.1) but, with lower support costs from other (non-UKRI) sources, we have struggled to balance our budget. Although we have been successful in a bid for Arctic science with Canada through the UKRI Fund for International Collaboration and UKRI Strategic Priorities Funding for space weather research, polar science does not easily face UKRI most urgent priorities. We are thus about to develop a new strategy for BAS science to align with UKRI areas of research, including, for example, AI and environmental resilience linked to our new CDT in Artificial Intelligence for Environmental Research (AI4ER), and solutions-focussed environmental science featuring, for example, blue carbon assessments for overseas territories, and assessment of the impacts of geo-engineering solutions.

Income

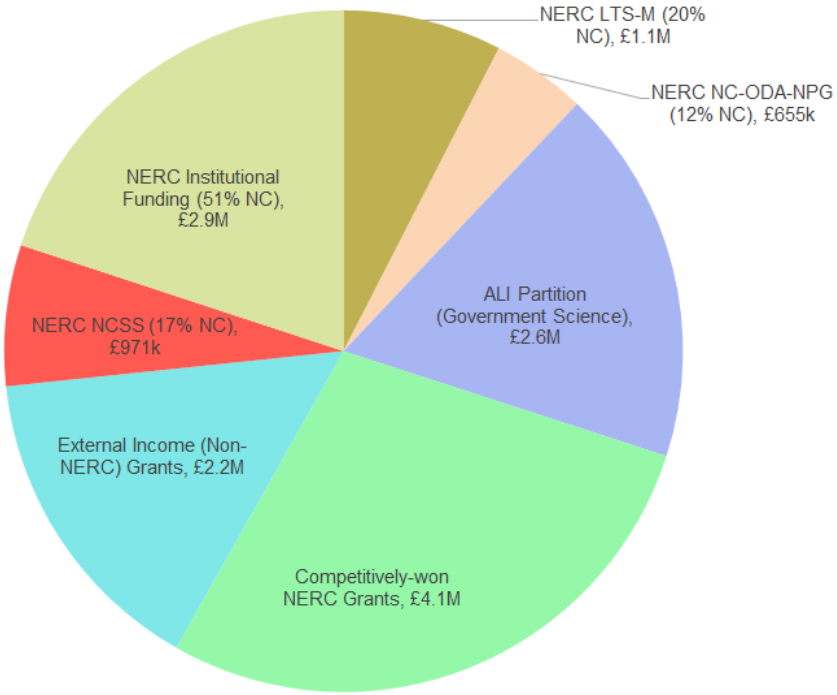


Figure 3.1: *Sources of income for BAS science 2018/19*

The landscape of BAS's science funding has changed enormously through the RCE period due to the Partition and NERC's commissioning of National Capability. It is currently as shown in Figure 3.1.

BAS's science income of £14.5m (FY 18/19) comprises:

- £5.6m from four strands of National Capability (NC) funding
- £6.3m external funding (i.e. competitively-won grants from NERC and other sources)

- £2.6m ALI Partition funding

UKRI-NERC's National Capability funding supports large-scale, complex and long-term science that makes high-quality contributions to UK environmental science.

Our NC commissioned income streams, which started in 2016, (Figure 3.1) comprise:

- **Long Term Science Multiple (NC-LTSM):**
  2016/17-20/21, total funding to BAS £5.5m (18/19 £1.1m).
  BAS is a partner in three LTSM multi-institutional, five-year programmes: ORCHESTRA, UKESM, ACSIS (Section 1).
- **Official Development Assistance (NC-ODA):**
  2017/18-19/20, total funding £1.5m (18/19 £0.563m),
  BAS' expertise is applied to developing world science issues in marine ecosystem management and high-mountain water resources.
- **Institutional Funding (IF):**
  IF (£2.9m) is the only funding stream for BAS science (apart from overheads) that is not tied to particular science tasks and therefore it is used to develop new research topics and the preparation of proposals, undertake pump-priming and responsive research, develop people and skills, and support our world-class research environment. RCE outcome determines the allocation of IF.
- **Science Single Centre (NCSS):**
  2018/19-22/23, total funding £4.1m (18/19 £0.971m) (Excludes CPOM allocation).
  NCSS supports a portfolio of:
  - Four sets of *Sustained Observations* providing long-term Antarctic datasets that underpin the work of BAS and the wider research community.
  - Four *Key Capabilities* that are funded by BAS NC and available to UK researchers for collaborative research, with marginal costs supported by users/grants.

Sustained Observations		
Rothera Time Series (RaTS)	Dataset used by oceanographers and biologists	Provides a year-round comprehensive set of oceanographic measurements, recording the impact of climate change in the most rapidly warming area in the Southern Hemisphere (contributes to ICS 7)
Scotia Sea Open-Ocean Biological laboratories (SCOOBIES)	Informs ocean modelling and change assessment	Provides three moorings measuring carbon flux, ocean acidification and micro-plastics transport in largest hotspot of primary productivity in the Southern Ocean. (ICS 7)
Ocean Forcing of Ice-sheet Change (OFIC)	Ocean and ice-sheet predictive models and sea-level projections	Provides *in situ* measurements of ocean-heat delivery and ice-shelf melt at the most rapidly-changing parts of the Antarctic ice sheet. (ICS 7)

Space Weather Observatory (SWO)	Real-time assessment of severe space weather risk, development of mitigation guidelines, and forecast capability	Provides real-time observation of space weather events and upper atmospheric processes to improve understanding of Sun-to-Earth processes. (ICS 3&4)
Key Capabilities		
Ice-core acquisition and analysis facility	UK's only capability to recover and analyse ice cores (up to 1000m). Ice core drills and state-of-the-art laboratories in Cambridge provide a wide range of climatologically and environmentally-relevant chemical, gas and stable isotope analyses. (This capability will be augmented through recent competitively-won capital funding).	
Sub-glacial access and sampling	World leading hot-water drilling through ice, accessing the ocean cavity and seabed beneath ice shelves and the subglacial environment, includes borehole sensors and cameras, water-sampling, and down-hole sediment corers	
Airborne geophysics	Instrument suite (gravimeter, magnetometers, ice-penetrating radar and LIDAR capability) and operational and analysis expertise. Widely employed on NERC and other grants and in support of other programmes e.g., Thwaites programme.	
Airborne meteorological and atmospheric instrument suite (MASIN)	Delivers an instrumented aircraft with suite of atmospheric instruments and scientific expertise to support grants, collaborations, and strategic programmes	

Figure 3.2: *BAS NCSS Sustained Observations and Key Capabilities*

National and Public Good (NC-NPG):
2018/19-22/23, total funding £0.468m (18/19 £0.092).
These activities are in five policy areas as in Figure 3.3.

Policy area	Primary customers	BAS Lead	Activity
Climate Change (IPCC support)	BEIS	Michael Meredith	Coordinating Lead Author for the 'Special Report on Oceans and Cryosphere in a Changing Climate'. Hamish Pritchard is Lead Author (ICS 7)
Sea Level Rise	Environment Agency, DEFRA, EU.	David Vaughan	Evidence for EA and DEFRA on sea level rise, coastal vulnerability and future coastal impacts (ICS 7)
Sea-Ice Information	UK Space Agency, ESA, International Ice-Charting Working Group	Andrew Fleming	BAS are co-founders of Polarview, providing sea ice information to polar shipping. NPG funding supports development of the service. (ICS2)
Space Weather	UK Meteorological Office, Cabinet Office Civil Contingencies	Richard Horne	BAS' world-leading models of the Van Allen radiation belts provide forecasting of space weather and its impacts on technology. Models are being incorporated

	Unit, UK Insurance Industry and Satellite Operators		into the UKMO space weather forecasting service and outputs provided to satellite operators. Informs UK Government on the risks posed to UK economy and national security. (ICS 3)
Antarctic Treaty System	Foreign and Commonwealth Office	BAS Director, Jane Francis	All BAS science teams provide scientific evidence to enable UK FCO to maintain a leadership position within the Antarctic Treaty System (ATS). (ICS 5&6)

Figure 3.3: *BAS science areas contributing to NC-NPG*

Science for government (ALI Partition funding)

Total funding for Antarctic Infrastructure and Logistics (ALI) within the Partition is ~£39m p.a. This covers Antarctic logistics support for UK scientists (£32m), Corporate Services (£2m), and government science. BAS scientists undertake research to underpin UK government (e.g. FCO, DEFRA, EIS) requirements, funded by £2.6m p.a. from the (non-NERC) ALI Partition budget.

This science activity specifically includes:

- Maintaining meteorological and climate observations at UK Antarctic Stations.
- Long-term ozone and atmospheric monitoring at Halley VI Research Station.
- Antarctic topographic, geologic and thematic mapping.
- Ocean ecosystem observations and analyses.
- On-demand scientific advice to support national and international policy-making. For example, BAS plays an important role for the UK in:
  - Antarctic Treaty Consultative Meetings (ATCM).
  - Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES).
  - Scientific Committee on Antarctic Research (SCAR).
  - Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).
  - International Whaling Commission (IWC).

BAS also provides direct advice to the All-Party Parliamentary Group for Polar Regions, FCO, UK Science Minister, Cabinet Office and others.

BAS science also supports:

- The UK's leadership role on ecosystems science and management that underpins the decisions made by CCAMLR. (ICS 5&6).
- Delivery of the UK's leading role in setting the direction of international science through prominent leadership in SCAR, and support for UK FCO in providing advice to the Antarctic Treaty System (since 2013, 293 BAS-authored papers have been submitted to the ATS, at least three times more than the average contribution by ATS members (ICS 6).
- Providing expert advice to UK Government departments, e.g. BAS has provided evidence to Select Committees on topics such as the Arctic, climate change, plastics, invasive species, biodiversity in UKOTs; are on the Advisory Board and participate in meetings of the All-Party Parliamentary Group on the Polar Regions; and contributed material to answer parliamentary questions, particularly on climate change.

Additional Funding

In addition, BAS receives other NERC funds (£6.6m) for infrastructure, the provision of specific services (e.g. programme coordination), overhead top-ups, and innovation that supports science activity. In particular, these include:

- **Large-Scale Research Infrastructure NC-LRI:** LRI funds BAS logistics to operate NERC's Arctic research station on Svalbard (£0.18m) and operating costs for Arctic cruises by BAS ships (£0.2m).
- **NERC Service Level Agreement (SLA) UK Arctic Office:** NERC Arctic Office (1.5 staff, £0.1m) supports UK researchers in the Arctic, provides advice to policy makers, and develops international scientific cooperation e.g. UKRI-FIC with Canada for science in the Arctic.

Figure 3.4: *Ny-Ålesund international research village, Svalbard. Arrow highlights the UK Arctic research station*

- **UKRI-NERC SLA UK-EISCAT:** UK EISCAT Support Group (BAS 0.4 staff and Rutherford Appleton Laboratory) facilitates UK Arctic research on atmosphere and space weather using world-class high power ionospheric radars provided by a European consortium (£0.2m).
- **NC-Services Facilities & Data – UK Polar Data Centre (PDC):** PDC is the focal point for UK Arctic and Antarctic environmental data management, supporting data management and policy compliance for UK researchers (£0.4m).
- **Innovation Funding:** NERC Innovation Funding (ramped down from £1m p.a. to £0.25m p.a.) underpins the work of the Innovation Champions and Innovation Team, and provides innovation vouchers (see below).

BAS facilitates high-risk, high-reward testing of early ideas through internally-funded Innovation Vouchers, which have initiated several ongoing avenues of innovation:

- Investigating microplastics in Southern Ocean fish.
- Exploring the potential for vertical hydroponic food production in Antarctic Research Stations.
- Quantifying polymer contamination with drones.
- Using AI to maximise the value of environmental data sets.

BAS has won additional **NERC and UKRI innovation funding** in the following areas:

- Market research for cold-active enzymes.
- Testing an Antarctic fungus as a winter-time biopesticide.

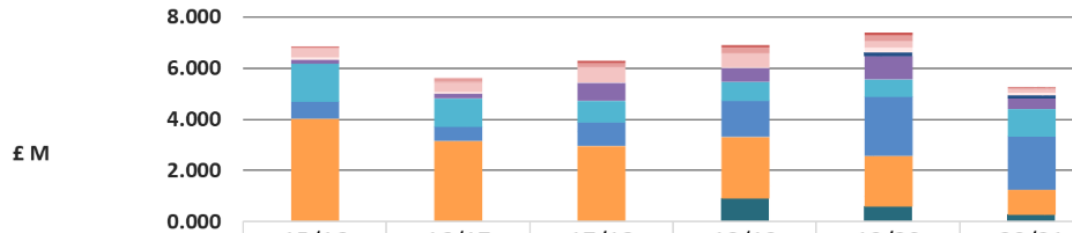
- Establishing the feasibility of using autonomous ground-penetrating radar (ApRES) for groundwater monitoring with Moroccan partners.
- Identifying high value products from polar algae.
- Collaborative development and testing of cold-compatible batteries with two industrial partners.

A number of additional funding streams have supported innovation described in our RCE:

- Collaborative EU and ESA proposals (e.g. SPACECAST/SPACESTORM) led by BAS experts underpin ICS 3&4.
- NGOs such as WWF and RSPB have funded work contributing to conservation biology (ICS 1&6).
- Cambridge University provided funding in 2013 to pump-prime innovation projects with BAS as part of the AURORA Innovation Centre. Of 29 applications, ten were funded, six led to joint PhD student projects, and one contributed to ICS 1.

Centre for Polar Observation and Modelling (CPOM)

CPOM is a distributed NERC Centre on satellite observation and modelling of polar ice sheets and sea ice to incorporate into global and Earth System Models, and deliver projections. Originally partnered by both BAS (ice sheets) and NOC (sea ice) 2014-19, CPOM will be financially and scientifically incorporated into BAS in 2020. (NB: CPOM is not in this RCE submission, and is not currently eligible for Institutional funding).



	15/16	16/17	17/18	18/19	19/20	20/21
TOTAL	6.795	5.601	6.265	6.867	7.356	5.245
Other	0.011	0.000	0.073	0.075	0.109	0.034
Foreign Private sector	0.009	0.157	0.188	0.227	0.208	0.059
Foreign Public sector	0.385	0.383	0.554	0.554	0.260	0.111
UK Private Sector	0.088	0.069	0.020	0.020	0.201	0.102
Other Research Councils					0.132	0.132
UK Government	0.152	0.180	0.700	0.540	0.893	0.418
European Commission	1.481	1.072	0.837	0.745	0.693	1.032
NERC Strategic Research	0.664	0.587	0.922	1.386	2.288	2.074
NERC Discovery Science	4.005	3.153	2.971	2.377	1.960	0.999
NERC Top-Up (JeS only)				0.943	0.612	0.284

Figure 3.5: *Recent competitive funding secured by BAS science with distribution between major funding sources Note: This table includes only support won through openly competitive proposals; the sum of 'NERC Strategic Research' and 'NERC Discovery Science' is thus less than that given in Part B for 'NERC competitive funding', as the latter includes various 'commissioned' activities (SLAs and National Capability, and some funds disbursed to partner institutes).*

Competitively-won funding

BAS scientists have maintained external income for science in recent years, despite decreasing Research Council funding (Figure 3.5).

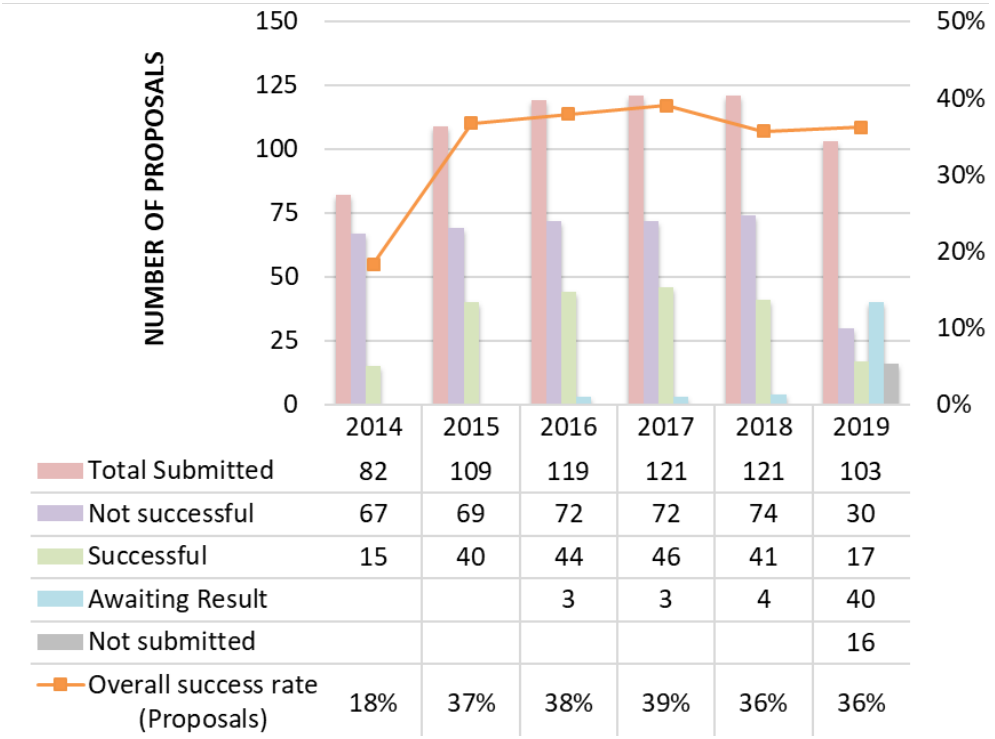
Focus is now more on NERC strategic programmes e.g. success with NERC/NSF Thwaites Programme, successful Highlight Topics (e.g. ROSES), and recent Strategic Programme Areas (e.g. Reducing Uncertainties in Climate Models from Clouds). BAS's cap for NERC standard grant proposals is 6.

The majority of competitively-won grants come from a variety of NERC funding streams and approximately one third from other sources e.g. EC, Office of Naval Research, ESA, DEFRA, FCO. The five largest research grants during the RCE period are listed in Figure 3.6.

	Title	Project name
NERC Strategic	Thwaites 6 projects	Thwaites Glacier programme, ITGC (total to BAS)
NERC Large Grant	FISS	Ice shelves in a warming world: Filchner Ice Shelf system, Antarctica
NERC Large Grant	BEAMISH	Basal Conditions on Rutford Ice Stream: Bed Access, Monitoring and Ice Sheet History
NERC Strategic	Rad-Sat	Modelling radiation belt electrons to protect satellites from space weather
EU	Ice-Arc	Ice, Climate and Economics – Arctic Research on Change

Figure 3.6: *Top five research grants to BAS within the RCE period*

BAS maintains significant EU funding (of order £1m p.a.) with recent success in the EU-TipES Consortium, studying tipping points in the Earth System. BAS science teams have diversified funding to develop a wider and more resilient funding portfolio including, for example: EU-BEST, Darwin Plus, Turing Centre.



	2014	2015	2016	2017	2018	2019
Total Submitted	82	109	119	121	121	103
Not successful	67	69	72	72	74	30
Successful	15	40	44	46	41	17
Awaiting Result			3	3	4	40
Not submitted						16
Overall success rate (Proposals)	18%	37%	38%	39%	36%	36%

Figure 3.7: *Six-year trends in numbers of proposals submitted by BAS per calendar year, with outcomes*

Fellowships

BAS is placing an increased emphasis on hosting individual fellowships, whether by incoming or existing staff. Currently, BAS hosts three Marie-Curie Fellows (including one prestigious Global Fellow), one NERC Independent Research Fellow, and one Royal Society Fellow. Two staff are currently preparing for interviews for UKRI Future Leaders Fellowships.

Infrastructure and facilities

BAS Cambridge is the centre for coordinating and supporting UK Antarctic science and operations, and for the UK Arctic Research Station. Offices, science and engineering laboratories provide the focal point for UK's polar research effort.

A controlled environment facility provides the following facilities, available for collaborative use by all UK polar scientists (all upgraded in 2016-19, funded from NERC capital allocation):

- UK's only polar aquarium (£1.2m).
- Experimental rooms with controlled environment to simulate polar conditions (£0.2m).
- Cold storage facilities for sediment and ice cores, and biological material (£0.4m).

Specialist laboratories include:

- State-of-the-art ice core analysis laboratory (upgraded in 2019/20, £0.3m).
- Micro-Molecular facility.
- Geology laboratory.

- Suite of biological laboratories (upgraded in 2016/17, £0.1m).
- In 2019 a prestigious award from the Wolfson Foundation of £0.6m supported capital investment in Cambridge for a Polar Sediment Core Facility.

BAS operates three research stations in the Antarctic and two on sub-Antarctic South Georgia, and one in the Arctic. Research platforms include the ice-strengthened RRS *James Clark Ross* (until 2021, replaced by the RRS Sir David Attenborough) and a fleet of five polar-adapted aircraft and various off-the-shelf and specialised vehicles. Rothera Station hosts the Bonner Laboratory, equipped for marine sciences and diving operations.Halley station has a state-of-the-art atmospheric chemistry laboratory (CASLab).

These facilities, together with instruments listed in NCSS-Key Capabilities (Figure 3.2), serve all UKRI grant holders. In addition, BAS operates for UKRI-NERC the Collaborative Antarctic Science Scheme CASS (£0.05m). This provides funds each year for ~5-6 UK researchers to access NERC-BAS Antarctic research stations and marine science cruises for the purpose of conducting small-scale, polar field science projects by joining field programmes already scheduled.

Antarctic Infrastructure Modernisation Programme (AIMP)

The AIMP will transform how BAS enables and supports frontier science. Commissioned in 2015 by NERC, this £300m investment will deliver a world-leading capability to ensure that Britain remains at the forefront of climate, biodiversity and ocean research in the polar regions. The programme involves the replacement of two ageing polar ships with the new polar ship (RRS *Sir David Attenborough*) and modernisation of station facilities to accommodate the new vessel and enhanced logistics handling capabilities. A new science support building at Rothera (Figure 3.8) will provide UK scientists with state-of-the-art facilities for their polar research.

Future projects, pending funding, include a replacement for the ageing intercontinental aircraft to transport people and cargo from Chile/Falklands to Rothera, enhanced runway facilities, modern station accommodation, modernised facilities in Cambridge, and planning for replacement of Halley station to maintain science and the UK presence in the eastern part of the British Antarctic Territory.

Partnering with business sectors

Construction and Technical Advisor contracts with BAM, SWECO, Ramboll and others are delivering the modernisation of NERC-BAS research stations and bringing in knowledge, expertise and innovation to help BAS realise its commitment for zero carbon operation before 2050. In turn, these organisations derive corporate benefit and value from their association with BAS. Evidence of this can be seen in video content including BAM's BAS Construction Partnership - Digital Construction 2019, and Ramboll's sustainable solutions campaign. Both BAM and Ramboll are enthusiastic partners, keen to promote their involvement with BAS.

Figure 3.8: *New Discovery science support building, Rothera, currently under construction*

SECTION 4: Collaboration and contribution to the research base, economy and society

4.1 Key collaborations, networks and partnerships

Successful partnerships are fundamental to BAS's role as a world-leading centre. Every aspect of BAS activity is a collaborative effort. Key stakeholder groups include:

- National and international polar research community – to drive forward frontier science.
- UK Government departments – to promote geopolitical and policy interests.
- Corporate stakeholders – to ensure public accountability.
- Media – to promote and explain polar science in a way that is meaningful to everyday lives.
- Museum & education sectors – to deliver shared ambitions for public engagement in research.
- Business – to share knowledge, expertise or services that benefit business operation or the economy.
- BAS staff, including Antarctic contract employees, mariners and former employees.

Whilst engagement with each of these key groups has different 'desired outcomes', collaborations are designed to ensure that all parties benefit from sharing knowledge, capability and (in many cases) access to polar infrastructure.

The polar research community – enabling frontier science

BAS has developed around 70 formal agreements (MoUs) since 2013. These support scientific projects, including 12 framework agreements with key institutions to support key science programmes in the Arctic (e.g., AWI for MOSAIC), and in Antarctica (e.g., NSF/USAP for ITGC), and many others as developing research partners, notably Korean Polar Research Institute, Polar Research Institute of China.

Our 'National Capability Science' portfolio funded by UKRI-NERC is the framework for sustained observations focussed on crucial Earth System indicators in Antarctica. Multi-partner collaborations such as ORCHESTRA and the Rothera Time Series benefit from access to polar infrastructure and expertise. Research activities and outcomes illustrate how the UK research base works collectively to advance knowledge about our changing world.

In 2019, BAS and Cambridge University's Earth Sciences Department signed an agreement to facilitate mutual access to laboratories and to co-develop a Cambridge Hub for Palaeoclimate and Palaeoenvironmental Research (CHPPR).

BAS Operational teams coordinate and enable large-scale multi-partner polar science missions (e.g. US-UK International Thwaites Glacier Collaboration). Partnering with colleagues from the COMNAP network (Council of Managers of National Antarctic Programmes) enables efficient and effective deep-field support that benefits the research community.

Working with Government – promoting UK geopolitical and policy interests

Relationships with the FCO Polar Regions Department and the BAS Review Group (BAS, UKRI-NERC, FCO, BEIS, Cabinet Office, MOD) support and inform ministerial level structures and help promote UK sovereignty in relation to the governance of British Antarctic Territory.

On behalf of the UK, BAS has supported the signing and now delivers on ministerial-level agreements to collaborate in polar research (e.g., Argentina 2018, Chile, 2018, Canada, 2013). **These** international agreements help reinforce the UK's influence across the world.

Regular dialogue with policy officials within UK Government departments, including the FCO Polar Regions Department, the Department for Business, Energy and Industrial Strategy (BEIS), and the Department for Environment, Food and Rural Affairs (DEFRA), drives forward national strategic priorities. (See ICS 6).

4.2 Engaging with our community

Our approach

Our communications and engagement strategy reflects and supports the BAS Vision and Mission, as well as Government & UKRI-NERC ambitions for public engagement in research. The activities we deliver are shaped by insights from national and international reports on public attitudes to science and news consumption (e.g. Reuters Institute for the Study of Journalism annual Digital News Survey Reports).

Engagement campaigns are designed and evaluated using the OASIS method. Global news distribution is achieved using Eurekalert (Over 6,000 registered reporters – 78% in USA) and Meltwater (800 journalists receive BAS Press Releases). Meltwater is used to generate media monitoring reports. Google Analytics and social media insights provide evaluation performance and impact of BAS online channels.

Engagement is embedded within the culture of our organisation. Over 50% of our workforce act as 'Ambassadors' for BAS and for polar science. Around 90 members of staff are quoted in the media each year; and approximately 85 give school or community talks.

Public engagement and educational campaigns relating to major projects are delivered in partnership with others who share common goals.

The 'channels' used to engage with different audiences include:

- **Proactive media relations** – each year BAS distributes around 15 press releases which generate approximately 12,000 individual items of news coverage, with a typical global audience reach of 24 billion.
- **Events and exhibitions** – examples include Science Museum for Antarctica Live (2018 attracted 2000 visitors); Blue Dot Festival (audience size 20,000+); Cambridge Science Festival 2018 – Antarctica Uncovered (attracted 2000 people to BAS); New Scientist Live 2016, 2017, 2019.
- **Formal and informal learning** – online resources to inspire young people in STEM include www.discoveringantarctica.org.uk and Polar Explorer Programme (PEP). The PEP 2017/18

impact survey show 100% of teachers involved agree pupil enjoyment and engagement in STEM subject lessons increased.

- **Science and art collaborations** - BAS collaborates regularly with artists to reach new audiences. One of its projects, Data as Art: the aesthetics of water, involves glass artist and Royal College of Art MPhil candidate Wayne Binitie, BAS ice core scientists Dr Robert Mulvaney, BAS creative services manager Pete Bucktrout, and Graham Dodds from Arup.Their most recent output is Ice Floor, an exhibition in Arup's London offices from November 2019 to February 2020.
- **Hosted visits to BAS Cambridge and Antarctica** – included the globally influential University of Cambridge Institute for Sustainability Leadership (CISL) is a regular visitor as part of its programme for developing leadership and solutions for a sustainable economy. Antarctic media visits included the Financial Times (2017), BBC Horizon (Weatherman Peter Gibbs revisits 2016 and Ice Station Rescue 2017), BBC Natural History Unit (see ICS 7&8).
- **Online** – website and social media (see below).

The following two activities illustrate the breadth of BAS community engagement:

1. A new polar research ship for Britain – 2015-present

This multi-partner campaign is designed to gain widespread recognition of the UK's investment in a new polar research vessel (RRS *Sir David Attenborough)* and its associated projects. Campaign partners include BEIS, UKRI-NERC, FCO, Cammell Laird and STEM Learning Ltd. It is aligned to national campaigns such at GREAT Britain, Engineering Take a Closer Look, and the Polar Explorer Programme (PEP). Highlights that demonstrate audience reach and diversity include

Keel-laying ceremony in October 2016

- 170 invited guests from the worlds of science, engineering, Government and industry.
- 800 members of Cammell Laird's workforce.
- Over 350 individual items of regional, national and international media coverage.
- Reach - over 350 million people on five continents; over 3 million social media followers.

Hull launch in July 2017

- 300 invited guests from programme partners, politics, academia, and industry.
- 3000 people from the Cammell Laird and subcontractor workforce attended.
- Keynote speeches including **Sir David Attenborough**, Minister of State the Rt Hon **Claire Perry** MP, Chief Executive of UKRI **Sir Mark Walport**.
- Over 750 individual news items were published or broadcast – doubled from 2016.
- Reach (media) - over 1 billion people around the world – three times more than 2016.
- Social media reach - over 380,000 individuals and over 7000 engagements (likes, etc).
- Over 11,000 people watched 'splashdown' live on the BAS website.

Royal ceremonial naming September 2019 – three-day celebration

- 10,000 visitors (including from overseas), including 600 invited stakeholders; 1500 school children.
- 16 exhibition areas – 12 from BAS; NOC and BGS; 12 public talks.
- over 3000 individual news articles.
- Global media reach – 4 billion.
- 181 articles were shared 53.7k times on social media.

"The Royal Research Ship Sir David Attenborough will form part of this vital infrastructure and marks a great step forward for polar research of national and global importance. This ship will be a vehicle of international research partnerships, continuing the UK's reputation for research and innovation excellence."
Sir Mark Walport, UKRI

***Figure 4.1**. Highlights from the SDA 2018 hull-launch and 2019 naming*

2. Digital engagement – boosting the power of and impact from our online channels

We rebuilt our public-facing website in 2014-15. Using new digital tools we were able, for the first time, to create visibility for our research projects, collaborations, and the opportunities for the science community to access to the UK's Antarctic research infrastructure.

Highlights:

- 40 BAS researchers were trained and empowered to publish details about their research projects and collaborations on our website. (In 2014, there were only three).
- Between 2015 and 2019, the science content on the rebuilt website attracted over 400,000 unique page views. Over 100,000 of those views were directed at polar fieldwork opportunities.

- At peak times, the number of unique users to the site doubled. For example, in July 2014 the number of unique monthly visitors was 75,000. By July 2016, this number was 140,000 (source Google Analytics).

Growing our online communities

Our science, public, business and family communities make extensive use of social media channels.

- In 2015, we rebranded our Facebook, Twitter, LinkedIn and Youtube channels to give them a consistent look and feel.
- Content was re-organised to target distinct audiences. In addition to our aim to post content that is user-focussed, our goal is to drive traffic to more detailed content on the BAS website.
- In 2015, we had around 7,000 followers on BAS Facebook and Twitter channels; by 2019, there were over 30,000 on each of those channels.

4.3 Contributions to and recognition by the research base

BAS is committed to being active and prominent within the various scientific communities in which we work. Some of these communities have a particular polar focus, while many more are disciplinary. BAS staff are encouraged to contribute; for example, by convening conferences, and taking on editorial roles. A 2019 survey of BAS staff showed:

- *Editorial Roles* - In total, BAS Scientists held 71 Editorial roles, of which 56 were as editors for peer-review journals. 46% of Band 5-2 science staff held some editorial role, and 60% of Band 3-2 held such roles.
- *Roles on grant awarding committees* - 33% of all scientists (60% of Band 3-2) have served on Grant Awarding Committees in the UK and overseas. 66% of scientists Band 3 and above have held roles on Grant Awarding Committees.
- *Prizes awarded* - 23% of all scientists have been awarded a prize or award during the period. These have included those awarded by Her Majesty the Queen:
  - Most Distinguished Order of Saint Michael and Saint George (Dame Prof. J. Francis)
  - OBE (Prof. D. Vaughan, Dr E. Shuckburgh, Dr Phil Trathan)
  - Polar Medal (Prof. D. Hodgson, Dr K. Newsham, Dr S. Fielding)
  - Clasp to the Polar Medal (M. Pinnock, Dr R. Mulvaney, Dr A. Smith).

  Academic prizes include:
  - Lloyds Science of Risk Prize – Prof. R. Horne.
  - Silver Medal for Outstanding Marine Biologist – Prof. L. Peck.
  - James Dungey Award of the Royal Astronomical Society – M. Clilverd.
  - Challenger Medal – Prof. M. Meredith.
  - Chapman Medal of the Royal Astronomical Society – Dr M. Freeman.
  - Tinker-Muse Prize for Science and Policy in Antarctica, Tinker-Muse Foundation (include £100k prize money) – Prof. M. Meredith.
  - Weyprecht Prize – Dr E. Thomas.

- *Honorary Appointments* - BAS Science Staff held 56 Honorary and Visiting academic positions, including 18 Honorary and Visiting Professorships (e.g., 12 held in UK HEIs). Dame Jane Francis is Chancellor of Leeds University.
- *National/International committees or advisory groups* - 75% of scientists, Band 5 and above are members of national/international committees and advisory groups. In total, BAS staff held 233 posts, of which 41 were as chair or co-chair.
- *Convening conferences, workshops or sessions* - 58% of all BAS scientists have convened conferences, workshops or sessions, many undertaking several such duties during the period of assessment.
- *Chairing conferences or attending invited lectures* - 55% of scientists have chaired conferences or given invited lectures. 30% of scientists at Band 2-5 have chaired 5 or more conference sessions and invited lectures since 2013.
- *Refereeing papers* - 60% of scientists have reviewed over 10 journal papers, and 10% more than 50, in the review period.

Committee, board or group	Owner	BAS role	BAS Representative
NERC Science Board	NERC	Member	Prof. D. Vaughan
Advisory Board to the All-Party Parliamentary Climate Change Group (APPCCG)	DEFRA	Member	Dr E. Shuckburgh
Space Environment Impacts Expert Group	UK Cabinet Office	Member	Prof. R. Horne
NERC Training Advisory Board	NERC	Member	Dr. A. Crame
Antarctic Climate Change and the Environment Expert Group	SCAR[1]	Chair	Prof. J. Turner
SCAR Horizon Scan Committee	SCAR	2 members	Prof. J. Francis, D. Vaughan
Scientific Committee for the Bayer Climate Prize	Bayer Foundation	Member	Prof. J King
Scientific advisory group	Alfred Wegener Institute	Vice Chair and member	Prof. M. Meredith
SuperDARN Executive Committee	The Super Dual Auroral Radar Network	Member	Dr A. Kavanagh
Working Group	Antarctic Treaty	Chair (First female)	Prof J. Francis

[1] The Scientific Committee on Antarctic Research (SCAR) is an inter-disciplinary committee of the International Science Council (ISC).

	Consultative Meeting (ATCM)		
Population and Conservation Status Working Group	Agreement on the Conservation of Albatrosses and Petrels	Co-convenor	Prof. R. Phillips
Seabird Group	Conservation of Arctic Flora and Fauna	Member	Dr N. Ratcliffe
Scientific Committee Working Group on Stock Definition, Southern Hemisphere Sub-Committee	International Whaling Commission	Chair	Dr J. Jackson
CEP / Subsidiary Group on Climate Change Response	Committee on Environmental Protection	Vice-chair / Convenor	Dr K. Hughes
Committee on Meteorology and Oceanography of the Southern Hemisphere	American Meteorological Society	Member	Dr G. Marshall
EISCAT Council	European Incoherent Scatter Radar Association	UK Delegate for NERC	Dr M. Freeman
Council of the Geological Society of London	Geological Society of London	Member	Dr R. Larter
International Commission on Polar Meteorology	ICPM/IAMAS	President	Dr J. Turner
Southern Ocean Observing System scientific steering committee	SCAR/SOOS	Member	Prof. M. Meredith
Antarctic Climate Change in the 21st Century (AntClim21)	SCAR	Chair	Dr T. Bracegirdle
The International Commission on Polar Meteorology	International Association of Meteorology and Atmospheric Sciences	Member	Dr S. Hosking
CCAMLR Commission	Commission for the Conservation of Antarctic Marine Living Resources	Advisor	Dr Phil Trathan
CCAMLR Scientific Committee	CCAMLR	Chair	Dr M. Belchier

Special Report on Oceans and Cryosphere in a Changing Climate (SROCC)	Intergovernmental Panel on Climate Change (IPCC)	Coordinating Lead Author and Lead Author	Prof. M. Meredith Dr H. Pritchard
MetOffice Hadley Centre - Science Advisory Group	BEIS	Member	Prof. D Vaughan
SuperDARN Executive Committee	Super Dual Auroral Radar Network	Member	Dr G. Chisham
Global Environmental Research Committee (GERC)	Royal Society	Secretary	Dr H. Winton Dr S. Hosking

Figure 4.2. *A selection of significant committee roles held by BAS scientists between 2013 and 2019 – see also ICS 7*

ENVIRONMENT COMPONENT DATA

1. Total income (funding and capital): £m

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
Antarctic logistics and infrastructure (ALI)	57.876*	42.108	60.145	83.849	116.585	115.190
Non logistics and infrastructure funding (non-ALI)		16.906	17.737	20.136	18.526	23.487

***** *Income was split into Antarctic Logistics and Infrastructure (ALI) and non-ALI post 2013/14*

2. Open access data

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
UKRI open access block grant awarded to the Centre (£k)	38.00	45.00	51.00	51.00	56.00	54.00
% of UKRI open access block grant spent (for years where block grant was received)	40%	61%	89%	100%	100%	100%
% **overall** open access compliance for UKRI-funded papers (as reported to UKRI)	80%	80%	77%	80%	80%	78%
% **gold** open access compliance for UKRI-funded papers (as reported to UKRI)	43%	45%	51%	51%	49%	68%
% **green** open access compliance for UKRI-funded papers (as reported to UKRI)	57.00	55.00	49.00	49.00	51.00	32.00