EVALUATION OF NERC CENTRES 2020: NATIONAL OCEANOGRAPHY CENTRE EVIDENCE SUBMISSION

Submitted February 2020

1. List of research outputs

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	“Pomacytosis”—Semi-extracellular phagocytosis of cyanobacteria by the smallest marine algae	2018	PLoS Biology	10.1371/journal.pbio.2003502
D - Journal article	A continuous 55-million-year record of transient mantle plume activity beneath Iceland	2014	Nature Geoscience	10.1038/ngeo2281
D - Journal article	A general model for the helical structure of geophysical flows in channel bends.	2017	Geophysical Research Letters	10.1002/2017GL075721
D - Journal article	A global perspective on the trophic geography of sharks	2018	Nature	10.1038/s41559-017-0432-z
P - Devices and products	A Lab-on-Chip Analyzer for in Situ Measurement of Soluble Reactive Phosphate: Improved Phosphate Blue Assay and Application to Fluvial Monitoring	2017	Environmental science & technology	10.1021/acs.est.7b01581
D - Journal article	A new look at ocean carbon remineralization for estimating deepwater sequestration	2015	Global Biogeochemical Cycles	10.1002/2014GB005063
D - Journal article	A Rossby whistle: a resonant basin mode observed in the Caribbean Sea	2016	Geophysical Research Letters	10.1002/2016GL069573
D - Journal article	A sea change in our view of overturning in the subpolar North Atlantic	2018	Science	10.1126/science.aau6592
D - Journal article	A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation.	2018	Progress in Oceanography	10.1016/j.pocean.2018.01.011
D - Journal article	Abyssal deposit-feeding rates consistent with the metabolic theory of ecology	2019	Ecology	10.1002/ecy.2564
D - Journal article	Alternative Particle Formation Pathways in the Eastern Tropical North Pacific's Biological Carbon Pump	2018	Journal of Geophysical Research: Biogeosciences	10.1029/2018JG004392
D - Journal article	An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part III: Hydrography and fluxes	2016	Ocean Modelling	10.1016/j.ocemod.2016.02.004
D - Journal article	An evaluation of supervised and unsupervised classification techniques for marine benthic habitat mapping using multibeam echosounder data	2015	ICES Journal of Marine Science	10.1093/icesjms/fsu223
P - Devices and products	Application of marine radar to monitoring seasonal and event-based changes in intertidal morphology	2017	Geomorphology	10.1016/j.geomorph.2017.02.002
D - Journal article	Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014	2016	Journal of Geophysical Research: Oceans	10.1002/2015JC011579
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	10.1002/jgrd.50153
D - Journal article	Asymmetric transfer of CO2 across a broken sea surface	2018	Nature Scientific Reports	10.1038/s41598-018-25818-6

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D - Journal article	Atlantic Meridional Overturning Circulation slowdown cooled the subtropical ocean	2013	Geophysical Research Letters	10.1002/2013GL058464
D - Journal article	Attenuation of sinking particulate organic carbon flux through the mesopelagic ocean	2015	PNAS	10.1073/pnas.1415311112
D - Journal article	Behaviour of chromium isotopes in the eastern sub-tropical Atlantic Oxygen Minimum Zone	2018	Geochimica Et Cosmochimica Acta,	10.1016/j.gca.2018.03.004
D - Journal article	Benthic marine calcifiers coexist with CaCO3-undersaturated seawater worldwide	2016	Global Biogeochemical Cycles	10.1002/2015GB005260
D - Journal article	Big in the benthos: Future change of seafloor community biomass in a global, body size-resolved model	2017	Global Change Biology	10.1111/gcb.13680
D - Journal article	Biological effects 26 years after simulated deep-sea mining.	2019	Nature Scientific Reports	10.1038/s41598-019-44492-w
D - Journal article	Biological responses to disturbance from simulated deep-sea polymetallic nodule mining	2017	PLoS ONE	10.1371/journal.pone.0171750
P - Devices and products	Buzz off! An evaluation of ultrasonic acoustic vibration for the disruption of marine micro-organisms on sensor-housing materials	2016	Letters in Applied Microbiology	10.1111/lam.12671
D - Journal article	Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatran margin?	2013	Geology	10.1130/g34298.1
D - Journal article	Carbon sequestration in the deep Atlantic enhanced by Saharan dust	2017	Nature Geoscience	10.1038/ngeo2899
D - Journal article	Carbonate counter pump stimulated by natural iron fertilization in the Polar Frontal Zone	2014	Nature Geoscience	10.1038/ngeo2285
D - Journal article	Characterization of Convective Plumes Associated With Oceanic Deep Convection in the Northwestern Mediterranean From High Resolution In Situ Data Collected by Gliders	2017	Journal of Geophysical Research: Oceans	10.1002/2016JC012633
D - Journal article	Climate change and ocean acidification impacts on lower trophic levels and the export of organic carbon to the deep ocean.	2013	Biogeosciences	10.5194/bg-10-5831-2013
D - Journal article	Climate change threatens the worlds marine protected areas	2018	Nature Climate Change	10.1038/s41558-018-0149-2
D - Journal article	Climate-Driven Change in the North Atlantic and Arctic Oceans Can Greatly Reduce the Circulation of the North Sea	2018	Geophysical Research Letters	10.1029/2018GL078878
D - Journal article	CO2-brine flow-through on an Utsira Sand core sample: experimental and modelling. implications for the Sleipner storage field.	2018	International Journal of Greenhouse Gas Control	10.1016/j.ijggc.2017.11.019
D - Journal article	Coastal sea level rise with warming above 2 °C	2016	Proceedings of the National Academy of Sciences	10.1073/pnas.1605312113
D - Journal article	Coccolithophore calcification response to past ocean acidification and climate change.	2014	Nature Communications	10.1038/ncomms6363
D - Journal article	Coherent Circulation Changes in the Deep North Atlantic From 16°N and 26°N Transport Arrays	2018	Journal of Geophysical Research: Oceans	10.1029/2018JC013949

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D - Journal article	Coherent modulation of the sea-level annual cycle in the United States by Atlantic Rossby waves	2018	Nature Communications	10.1038/s41467-018-04898-y
D - Journal article	Continuous estimate of Atlantic oceanic freshwater flux at 26.5°N	2015	Journal of Climate	10.1175/JCLI-D-14-00519.1
D - Journal article	Control of Mode and Intermediate Water Mass Properties in Drake Passage by the Amundsen Sea Low	2013	Journal of Climate	10.1175/JCLI-D-12-00346.1
D - Journal article	Correcting datasets leads to more homogeneous early-twentieth-century sea surface warming	2019	Nature	10.1038/s41586-019-1349-2
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	Crustal manifestations of a hot transient pulse at 60°N beneath the Mid-Atlantic Ridge	2013	Earth and Planetary Science Letters	10.1016/j.epsl.2012.12.030
D - Journal article	Damaging sediment density flows triggered by tropical cyclones.Ê	2017	Earth and Planetary Science Letters	10.1016/j.epsl.2016.10.046
D - Journal article	Deep boundary current disintegration in Drake Passage	2014	Geophysical Research Letters	10.1002/2013GL058617
D - Journal article	Deep ocean communities impacted by changing climate over 24 y in the abyssal northeast Pacific Ocean	2013	PNAS	10.1073/pnas.1315447110
D - Journal article	Deep-sea hydrothermal vents as natural egg-case incubators at the Galapagos Rift	2018	Scientific Reports	10.1038/s41598-018-20046-4
D - Journal article	Dehydration of subducting slow-spread oceanic lithosphere in the Lesser Antilles.	2017	Nature Communications	10.1038/ncomms15980
D - Journal article	Detection and impacts of leakage from sub-seafloor deep geological carbon dioxide storage	2014	Nature Climate Change	10.1038/nclimate2381
D - Journal article	Detection of climate change-driven trends in phytoplankton phenology	2018	Global Change Biology	10.1111/gcb.13886
D - Journal article	Direct monitoring reveals initiation of turbidity currents from extremely dilute river plumes.	2019	Geophysical Research Letters.	10.1029/2019GL084526
D - Journal article	Dominant oceanic bacteria secure phosphate using a large extracellular buffer.	2015	Nature Communications	10.1038/ncomms8878
D - Journal article	Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave.	2016	Environmental Research Letters.	10.1088/1748-9326/11/7/074004
D - Journal article	Earthquake crisis unveils the growth of an incipient continental fault system.	2019	Nature Communications	10.1038/s41467-019-11064-5
D - Journal article	Earth's energy imbalance since 1960 in observations and CMIP5 models.	2015	Geophysical Research Letters.	10.1002/2014GL062669
D - Journal article	Ecological connectivity between the areas beyond national jurisdiction and coastal waters: Safeguarding interests of coastal communities in developing countries	2019	Marine poliocy	10.1016/j.marpol.2019.02.050

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D - Journal article	Eddy-induced variability in Southern Ocean abyssal mixing on climatic timescales	2014	Nature Geoscience	10.1038/ngeo2200
D - Journal article	Effectiveness of a deep-sea cold-water coral Marine Protected Area, following eight years of fisheries closure	2016	Biological conservation	10.1016/j.biocon.2016.05.030
D - Journal article	Effects of nutrient enrichment on surface microbial community gene expression in the oligotrophic North Pacific Subtropical Gyre	2018	ISME Journal	10.1038/s41396-018-0280-0
D - Journal article	Efficient removal of recalcitrant deep-ocean dissolved organic matter during hydrothermal circulation	2015	Nature Geoscience	10.1038/ngeo2543
D - Journal article	Episodic organic carbon fluxes from surface ocean to abyssal depths during long-term monitoring in NE Pacific	2018	PNAS	10.1073/pnas.1814559115
D - Journal article	Estimates of Future Warming-Induced Methane Emissions from Hydrate Offshore West Svalbard for a Range of Climate Models	2015	Geochemistry Geophysics Geosystems	10.1002/2015GC005737
D - Journal article	Estimating the Atlantic overturning at 26°N using satellite altimetry and cable measurements	2015	Geophysical Research Letters	10.1002/2015GL063220
D - Journal article	Evaluating the balance between vertical diffusive nitrate supply and nitrogen fixation with reference to nitrate uptake in the eastern subtropical North Atlantic Ocean	2013	Journal of Geophysical Research: Oceans	10.1002/jgrc.20416
D - Journal article	Export of nutrients from the Arctic Ocean	2013	Journal of Geophysical Research	10.1002/jgrc.20063
D - Journal article	Extreme air-sea interaction over the North Atlantic subpolar gyre during the winter of 20132014 and its sub-surface legacy.	2016	Climate Dynamics	10.1007/s00382-015-2819-3
D - Journal article	Extreme Variability in Irminger Sea Winter Heat Loss Revealed by Ocean Observatories Initiative Mooring and the ERA5 Reanalysis	2019	Geophysical Research Letters	10.1029/2018GL080956
D - Journal article	Faster growth of the major prokaryotic versus eukaryotic CO2 fixers in the oligotrophic ocean	2014	Nature Communications	10.1038/ncomms4776
D - Journal article	Fault-controlled hydration of the upper mantle during continental rifting	2016	Nature Geoscience	10.1038/ngeo2671
D - Journal article	Fe-XANES analyses of Reykjanes Ridge basalts: Implications for oceanic crust's role in the solid Earth oxygen cycle	2015	Earth and Planetary Science Letters	10.1016/j.epsl.2015.07.017
D - Journal article	Fine particle retention and deposition in regions of cyclonic tidal current rotation	2019	Marine Geology	10.1016/j.margeo.2019.01.006
D - Journal article	Flood hazard assessment for a hyper-tidal estuary as a function of tide-surge-morphology interaction	2018	Estuaries and Coasts	10.1007/s12237-018-0384-9
D - Journal article	Fluxes and fate of dissolved methane released at the seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard	2015	Journal of Geophysical Research: Oceans	10.1002/2015JC011084
D - Journal article	From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots.	2016	Global Change Biology	10.1111/gcb.13247
D - Journal article	Future Arctic Ocean primary productivity from CMIP5 simulations: Uncertain outcome, but consistent mechanisms.	2013	Global Biogeochemical Cycles	10.1002/gbc.20055

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D - Journal article	Future change in ocean productivity: Is the Arctic the new Atlantic!	2015	Journal of Geophysical Research	10.1002/2015JC011167
D - Journal article	Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios.	2018	Journal of Geophysical Research	10.1029/2018JC013866
D - Journal article	Gas and seismicity within the Istanbul seismic gap	2018	Scientific Reports	10.1038/s41598-018-23536-7
D - Journal article	Gelatinous zooplankton biomass in the global ocean: geographic variation and environmental drivers	2014	Global Ecology and Biogeography	10.1111/geb.12169
D - Journal article	Geographical CO2 sensitivity of phytoplankton correlates with ocean buffer capacity	2018	Global Change Biology	10.1111/gcb.14324
D - Journal article	Geographical, seasonal, and depth variation in sinking particle speeds in the North Atlantic	2016	Geophysical Research Letters	10.1002/2016GL069233
D - Journal article	Geological fate of seafloor massive sulphides at the TAG hydrothermal field (Mid-Atlantic Ridge).	2019	Ore Geology Reviews	10.1016/j.oregeorev.2019.03.005
D - Journal article	Global and full-depth ocean temperature trends during the early twenty-first century from argo and repeat hydrography	2017	Journal of Climate	10.1175/JCLI-D-16-0396.1
D - Journal article	Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard	2018	Nature Communications	10.1038/s41467-018-04692-w
D - Journal article	Global reductions in seafloor biomass in response to climate change	2014	Global Change Biology	10.1111/gcb.12480
D - Journal article	Global water cycle amplifying at less than the Clausius-Clapeyron rate.	2016	Scientific Reports	10.1038/srep38752
D - Journal article	Going with the flow: The role of ocean circulation in global marine ecosystems under a changing climate.	2017	Global Change Biology	10.1111/gcb.13586
D - Journal article	Greenland melt drives continuous export of methane from the ice-sheet bed	2019	Nature	10.1038/s41586-018-0800-0
P - Devices and products	High-resolution in situ measurement of nitrate in runoff from the Greenland Ice Sheet	2017	Environmental Science and Technology	10.1021/acs.est.7b03121
D - Journal article	Historical analogues of the recent extreme minima observed in the Atlantic meridional overturning circulation at 26°N	2015	Climate Dynamics	10.1007/s00382-014-2274-6
D - Journal article	How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean	2014	Geophysical Research Letters	10.1002/2013GL058799
D - Journal article	How to recognize crescentic bedforms formed by supercritical turbidity currents in the geologic record: Insights from active submarine channels,	2018	Geology	10.1130/g40095.1
D - Journal article	How well do global ocean biogeochemistry models simulate dissolved iron distributions?	2015	Global Biogeochemical Cycles	10.1002/2015GB005289
D - Journal article	Hypoxia causes preservation of labile organic matter and changes seafloor microbial community composition (Black Sea)	2017	Science Advances	10.1126/sciadv.1601897
D - Journal article	iMarNet: an ocean biogeochemistry model intercomparison project with a common physical ocean modelling framework.	2014	Biogeosciences	10.5194/bg-11-7291-2014

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D - Journal article	Impact of wave whitecapping on land falling tropical cyclones.	2018	Scientific Reports	10.1038/s41598-017-19012-3
D - Journal article	Impacts of climate change on marine ecosystem production in societies dependent on fisheries.	2014	Nature Climate Change.	10.1038/NCLIMATE2119
D - Journal article	Improved estimates of water cycle change from ocean salinity: the key role of ocean warming.	2018	Environmental Research Letters.	10.1088/1748-9326/aace42
D - Journal article	Investigating the predictability of North Atlantic sea surface height	2019	Climate Dynamics	10.1007/s00382-019-04814-0
D - Journal article	Investigation of subglacial weathering under the Greenland Ice Sheet using silicon isotopes	2019	Geochimica et Cosmochimica Acta	10.1016/j.gca.2018.12.033
D - Journal article	Iron Biogeochemistry in the High Latitude North Atlantic Ocean.	2018	Scientific Reports	10.1038/s41598-018-19472-1
D - Journal article	Iron fertilization enhanced net community production but not downward particle flux during the Southern Ocean iron fertilization experiment LOHAFEX.	2013	Global Biogeochemical Cycles	10.1002/gbc.20077
D - Journal article	Isotopic Composition of Atmospheric Nitrate in a Tropical Marine Boundary Layer	2013	Proceedings of the National Academy of Sciences	10.1073/pnas.1216639110
D - Journal article	Key Uncertainties in the Recent Air-Sea Flux of CO2.	2019	Global Biogeochemical Cycles.	10.1029/2018GB006041
D - Journal article	Krill faecal pellets drive hidden pulses of particulate organic carbon in the marginal ice zone	2019	Nature Comms	10.1038/s41467-019-08847-1
D - Journal article	Large salp bloom export from the upper ocean and benthic community response in the abyssal northeast Pacific: Day to week resolution	2014	Limnology and Oceanography	10.4319/lo.2014.59.3.0745
D - Journal article	Long-term variations in global sea level extremes	2015	Journal of Geophysical Research: Oceans	10.1002/2015JC011173
D - Journal article	Loop Current variability as trigger of coherent Gulf Stream transport anomalies.	2018	Journal of Physical Oceanography.	10.1175/JPO-D-18-0236.1
D - Journal article	Marine litter distribution and density in European Seas, from the shelves to deep basins	2014	PLoS ONE	10.1371/journal.pone.0095839
D - Journal article	Measurements and models of the temperature change of water samples in sea-surface temperature buckets	2017	Quarterly Journal of the Royal Meteorological Society	10.1002/qj.3078
P - Devices and products	Measuring currents, ice drift, and waves from space: the Sea surface KInematics Multiscale monitoring (SKIM) concept.	2018	Ocean Science	10.5194/os-14-337-2018
D - Journal article	MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting - Part 1: Theory.	2013	Geoscientific Model Development	10.5194/gmd-6-1851-2013
D - Journal article	Meridional heat transport variability induced by mesoscale processes in the subpolar North Atlantic	2018	Nature Communications	10.1038/s41467-018-03134-x
D - Journal article	Model sensitivity of the Weddell and Ross seas, Antarctica, to vertical mixing and freshwater forcing.	2015	Ocean Modelling	10.1016/j.ocemod.2015.08.003

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D - Journal article	Modelling Large-Scale CO2 Leakages in the North Sea.	2015	International Journal of Greenhouse Gas Control	10.1016/j.ijggc.2014.10.013
D - Journal article	Modelling ultrasonic laboratory measurements of the saturation dependence of elastic modulus: new insights and implications for wave propagation mechanisms	2017	International Journal of Greenhouse Gas Control	10.1016/j.ijggc.2017.02.009
P - Devices and products	Molding topologically-complex 3D polymer microstructures from femtosecond laser machined glass	2013	Optics Materials Express	10.1364/OME.3.001428
D - Journal article	Morphodynamics of submarine channel inception revealed by new experimental approach	2016	Nature communications	10.1038/ncomms10886
D - Journal article	Multidecadal accumulation of anthropogenic and remineralized dissolved inorganic carbon along the Extended Ellett Line in the northeast Atlantic Ocean	2016	Global Biogeochemical Cycles	10.1002/2015GB005246
D - Journal article	Multispecies diel transcriptional oscillations in open ocean heterotrophic bacterial assemblages.	2014	Science	10.1126/science.1252476
D - Journal article	Newly recognized turbidity current structure can explain prolonged flushing of submarine canyons	2017	Science advances	10.1126/sciadv.1700200
P - Devices and products	Nitrate drawdown during a shelf sea spring bloom revealed using a novel microfluidic in situ chemical sensor deployed within an autonomous underwater glider	2018	Marine Chemistry	10.1016/j.marchem.2018.07.005
D - Journal article	North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part II: Inter-annual to decadal variability.	2016	Ocean Modelling	10.1016/j.ocemod.2015.11.007
D - Journal article	Observations of a diapycnal shortcut to adiabatic upwelling of Antarctic Circumpolar Deep Water	2014	Geophysical Research Letters	10.1002/2014GL061538
D - Journal article	Observations of vertical mixing in autumn and its effect on the autumn phytoplankton bloom	2019	Progress in Oceanography	10.1016/j.pocean.2019.01.001
D - Journal article	Observed decline of the Atlantic meridional overturning circulation 2004-2012	2014	Ocean Science	10.5194/os-10-29-2014
D - Journal article	Ocean colour signature of climate change.	2019	Nature Communications	10.1038/s41467-019-08457-x
D - Journal article	Ocean impact on decadal Atlantic climate variability revealed by sea-level observations	2015	Nature	10.1038/nature14491
D - Journal article	Ocean Mixing beneath Pine Island Glacier Ice Shelf, West Antarctica	2016	Journal of Geophysical Research	10.1002/2016JC012149
D - Journal article	Ocean nutrient pathways associated with the passage of a storm	2015	Global Biogeochemical Cycles	10.1002/2015GB005097
D - Journal article	Ocean precursors to the extreme Atlantic 2017 hurricane season	2019	Nature Communications	10.1038/s41467-019-08496-4
D - Journal article	Ocean sprawl facilitates dispersal and connectivity of protected species.	2018	Scientific Reports	10.1038/s41598-018-29575-4

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D - Journal article	OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project.	2016	Geoscientific Model Development	10.5194/gmd-9-3231-2016
D - Journal article	On the fate of pumice rafts formed during the 2012 Havre submarine eruption	2014	Nature communications	10.1038/ncomms4660
D - Journal article	On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice	2017	Marine Policy	10.1016/j.marpol.2015.12.027
D - Journal article	Particle flux in the oceans: Challenging the steady state assumption	2017	Global Biogeochemical Cycles	10.1002/2016GB005424
D - Journal article	Persistent acceleration in global sea-level rise since the 1960s	2018	Nature Climate Change	10.1038/s41558-019-0531-8
D - Journal article	Photoheterotrophy of bacterioplankton is ubiquitous in the surface oligotrophic ocean	2015	Progress in Oceanography	10.1016/j.pocean.2015.04.014
D - Journal article	Potential impacts of climate change on the primary production of regional seas: A comparative analysis of five European seas.	2016	Progress in Oceanography	10.1016/j.pocean.2015.11.004
D - Journal article	Powerful turbidity currents driven by dense basal layers	2018	Nature communications	10.1038/s41467-018-06254-6
D - Journal article	Preconditioning and triggering of offshore slope failures and turbidity currents revealed by most detailed monitoring yet at a fjord-head delta	2016	Earth and Planetary Science Letters	10.1016/j.epsl.2016.06.021
D - Journal article	Prochlorococcus can use the Pro1404 transporter to take up glucose at nanomolar concentrations in the Atlantic Ocean	2013	PNAS	10.1073/pnas.1221775110
D - Journal article	Prodigious submarine landslides during the inception and early growth of volcanic islands	2017	Nature communications	10.1038/s41467-017-02100-3
D - Journal article	Projected Atlantic hurricane surge threat from rising temperatures	2013	PNAS	10.1073/pnas.1209980110
D - Journal article	Prospects for improving the representation of coastal and shelf seas in global ocean models	2017	Geoscientific Model Development	10.5194/gmd-10-499-2017
D - Journal article	Quantifying recent acceleration in sea level unrelated to internal climate variability	2013	Geophysical Research Letters	10.1002/grl.50731
D - Journal article	Quantifying the impact of riverine particulate dissolution in seawater on ocean chemistry	2014	Earth and Planetary Science Letters	10.1016/j.epsl.2014.03.039
D - Journal article	Rapid cross-density ocean mixing at mid-depths in the Drake Passage measured by tracer release	2013	Nature Letter	10.1038/nature12432
D - Journal article	Rapid emergence of climate change in environmental drivers of marine ecosystems	2017	Nature Communications	10.1038/ncomms14682
D - Journal article	Rapid mixing and exchange of deep-ocean waters in an abyssal boundary current.	2019	Proceedings of the National Academy of Sciences, 116 (27). 13233-13238.	10.1073/pnas.1904087116
D - Journal article	Rapid sea-level rise along the Antarctic margins in response to increased glacial discharge.	2014	Nature Geoscience.	10.1038/NGEO2230

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D - Journal article	Reconciliation of the carbon budget in the ocean's twilight zone	2014	Nature	10.1038/nature13123
D - Journal article	Reframing the carbon cycle of the subpolar Southern Ocean	2019	Science Advances	10.1126/sciadv.aav6410
D - Journal article	Regional variability of acidification in the Arctic: a sea of contrasts.	2014	Biogeosciences	10.5194/bg-11-293-2014
D - Journal article	Remineralization of particulate organic carbon in an ocean oxygen minimum zone	2017	Nature Communications	10.1038/ncomms14847
D - Journal article	Remotely induced warming of Antarctic Bottom Water in the eastern Weddell gyre	2013	Geophysical Research Letters	10.1002/grl.50526
D - Journal article	Resilience of benthic deep-sea fauna to mining activities	2017	Marine Environmental Research	10.1016/j.marenvres.2017.04.010
D - Journal article	Robustness and uncertainties in global multivariate wind-wave climate projections	2019	Nature climate change	10.1038/s41558-019-0542-5
D - Journal article	Role of zooplankton in determining the efficiency of the biological carbon pump	2017	Biogeosciences	10.5194/bg-14-177-2017
D - Journal article	Scaling up experimental ocean acidification and warming research: from individuals to the ecosystem.	2014	Global Change Biology	10.1111/gcb.12675
D - Journal article	Sea-level and deep-sea-temperature variability over the past 5.3 million years	2014	Nature	10.1038/nature13230
D - Journal article	Sea-level variability over five glacial cycles	2014	Nature Communications	10.1038/ncomms6076
D - Journal article	Seasonal intensification and trends of rogue wave events on the US western seaboard	2019	Nature Scientific Reports	10.1038/s41598-019-41099-z
D - Journal article	Seasonal variability of the East Greenland Coastal Current	2014	Journal of Geophysical Research: Oceans	10.1002/2013JC009279
D - Journal article	Self-sharpening induces jet-like structure in seafloor gravity currents	2019	Nature communications	10.1038/s41467-019-09254-2
D - Journal article	Single-taxon field measurements of bacterial gene regulation controlling DMSP fate	2015	The ISME Journal	10.1038/ismej.2015.23
D - Journal article	Spaceborne GNSS-Reflectometry for ocean winds: First results from the UK TechDemoSat-1 mission	2015	Geophysical Research Letters	10.1002/2015GL064204
D - Journal article	Spatial and temporal scales of variability in Tropical Atlantic sea surface salinity from the SMOS and Aquarius satellite missions	2016	Remote Sensing of Environment	10.1016/j.rse.2016.02.008
D - Journal article	Species replacement dominates megabenthos beta diversity in a remote seamount setting,	2018	Scientific Reports	10.1038/s41598-018-22296-8
D - Journal article	Species-specific growth response of coccolithophores to Palaeocene-Eocene environmental change	2013	Nature Geoscience	10.1038/ngeo1719
D - Journal article	Stability of dissolved and soluble Fe (II) in shelf sediment pore waters and release to an oxic water column	2017	Biogeochemistry	10.1007/s10533-017-0309-x

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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
D - Journal article	Sticky stuff: Redefining bedform prediction in modern and ancient environments	2015	Geology	10.1130/G36262.1
D - Journal article	Surface warming hiatus caused by increased heat uptake across multiple ocean basins.	2014	Geophysical Research Letters	10.1002/2014GL061456
D - Journal article	Talc-dominated seafloor deposits reveal a new class of hydrothermal system.	2015	Nature Communications	10.1038/ncomms10150
D - Journal article	Temporal Constraints on Hydrate-Controlled Methane Seepage off Svalbard	2014	Science	10.1126/science.1246298
D - Journal article	The 2008 Emiliania huxleyi bloom along the Patagonian Shelf: Ecology, biogeochemistry and cellular calcification	2013	Global Biogeochemical Cycles	10.1002/2013GB004641
D - Journal article	The accuracy of estimates of the overturning circulation from basin-wide mooring arrays.	2018	Progress in Oceanography	10.1016/j.pocean.2017.12.001
D - Journal article	The Arctic Ocean seasonal cycles of heat and freshwater fluxes: observation-based inverse estimates	2018	Journal of Physical Oceanography	10.1175/JPO-D-17-0239.1
D - Journal article	The biogeochemical impact of glacial meltwater from Southwest Greenland	2019	Progress in Oceanography	10.1016/j.pocean.2019.102126
D - Journal article	The chromium isotopic composition of seawater and marine carbonates.	2013	Earth and Planetary Science Letters	10.1016/j.epsl.2013.09.001
D - Journal article	The cold transit of Southern Ocean upwelling.	2018	Geophysical Research Letters	10.1029/2018GL079986
D - Journal article	The eastern extent of seasonal iron limitation in the high latitude North Atlantic	2019	Nature Scientific Reports	10.1038/s41598-018-37436-3
D - Journal article	The Greenland Ice Sheet as a hot spot of phosphorus weathering and export in the Arctic	2016	Global Biogeochemical Cycles	10.1002/2015GB005237
D - Journal article	The Impact of a Variable Mixing Efficiency on the Abyssal Overturning.	2016	Journal of Physical Oceanography.	10.1175/JPO-D-14-0259.1
D - Journal article	The impact of future sea-level rise on the global tides	2017	Continental Shelf Research	10.1016/j.csr.2017.02.004
D - Journal article	The impact of global warming on seasonality of ocean primary production	2013	Biogeosciences	10.5194/bg-10-4357-2013
D - Journal article	The impact of resolving the Rossby radius at mid-latitudes in the ocean: Results from a high-resolution version of the Met Office GC2 coupled model.	2016	Geoscientific Model Development	10.5194/gmd-9-3655-2016
D - Journal article	The importance of unresolved biases in twentieth-century sea-surface temperature observations	2019	Bulletin of the American Meteorological Society	10.1175/BAMS-D-18-0104.1
P - Devices and products	The measurement of pH in saline and hypersaline media at sub-zero temperatures: Characterization of Tris buffers	2016	Marine Chemistry	10.1016/j.marchem.2016.06.002

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	The North Atlantic Ocean Is in a State of Reduced Overturning	2018	Geophysical Research Letters	10.1002/2017GL076350
D - Journal article	The pervasive role of biological cohesion in bedform development	2015	Nature Communications	10.1038/ncomms7257
D - Journal article	The regulation of copper stress response genes in the polychaete Nereis diversicolor during prolonged extreme copper contamination.	2014	Environmental Science and Technology	10.1021/es503622x
D - Journal article	The role of biophysical cohesion on subaqueous bed form size	2016	Geophysical Research Letters	10.1002/2016GL067667
D - Journal article	The silicon cycle impacted by past ice sheets	2018	Nature communications	10.1038/s41467-018-05689-1
D - Journal article	The stabilisation and transportation of dissolved iron from high temperature hydrothermal vent systems	2013	Earth and Planetary Science Letters	10.1016/j.epsl.2013.05.047
P - Devices and products	The stoichiometric dissociation constants of carbonic acid in seawater brines from 298 to 267 K	2018	Geochimica et Cosmochimica Acta	10.1016/j.gca.2017.09.037
D - Journal article	The subpolar gyre regulates silicate concentrations in the North Atlantic	2017	Nature Scientific Reports	10.1038/s41598-017-14837-4
D - Journal article	The Surface-Forced Overturning of the North Atlantic: Estimates from Modern Era Atmospheric Reanalysis Datasets.	2014	Journal of Climate	10.1175/JCLI-D-13-00070.1
D - Journal article	The Weakly Stratified Bottom Boundary Layer of the Global Ocean	2018	Journal of Geophysical Research: Oceans	10.1029/2018JC013754
D - Journal article	Tide and skew surge independence: new insights for flood risk	2016	Geophysical Research Letters	10.1002/2016GL069522
D - Journal article	Tide-mediated warming of the Arctic halocline by Atlantic heat fluxes over rough topography	2015	Nature Geoscience	10.1038/ngeo2350
D - Journal article	Timescales for detecting a significant acceleration in sea-level rise	2014	Nature Communications	10.1038/ncomms4635
D - Journal article	Turbulence and mixing by internal waves in the Celtic Sea determined from ocean glider microstructure measurements	2015	Journal of Marine Systems	10.1016/j.jmarsys.2014.11.005
D - Journal article	Twentieth-Century Global-Mean Sea Level Rise: Is the Whole Greater than the Sum of the Parts?	2013	Journal of Climate	10.1175/JCLI-D-12-00319.1
D - Journal article	Twentieth-Century Trends in the Annual Cycle of Temperature across the Northern Hemisphere	2017	Journal of Climate	10.1175/JCLI-D-16-0315.1
D - Journal article	Unexpected Impacts of the Tropical Pacific Array on Reanalysis Surface Meteorology and Heat Fluxes	2014	Geophysical Research Letters	10.1002/2014GL061302
D - Journal article	Using global tide gauge data to validate and improve the representation of extreme sea levels in flood impact studies	2017	Global and Planetary Change	1016/j.gloplacha.2017.06.007
D - Journal article	Validation of an ensemble modelling system for climate projections for the northwest European shelf seas.	2015	Progress in Oceanography	10.1016/j.pocean.2015.07.002

Type of output	Title of output	Year	Journal title	DOI
D - Journal article	Vertical GPS ground motion rates in the Euro-Mediterranean region: New evidence of velocity gradients at different spatial scales along the Nubia-Eurasia plate boundary	2013	Journal of Geophysical Research: Solid Earth	10.1002/2013JB010102
D - Journal article	Vigorous Lateral Export of the Meltwater Outflow from beneath an Antarctic Ice Shelf	2017	Nature	10.1038/nature20825
P - Devices and products	Visualising the aspect-dependent radar cross section of seabirds over a tidal energy test site using a commercial marine radar system	2017	International Journal of Marine Energy	10.1016/j.ijome.2017.01.002
D - Journal article	Weighing the ocean with bottom-pressure sensors: robustness of the ocean mass annual cycle estimate	2014	Ocean Science	10.5194/os-10-701-2014
D - Journal article	Which Triggers Produce the Most Erosive, Frequent, and Longest Runout Turbidity Currents on Deltas?	2018	Geophysical Research Letters	10.1002/2017GL075751
D - Journal article	Will invertebrates require increasingly carbon-rich food in a warming world?	2017	American Naturalist	10.1086/694122
D - Journal article	Wind-wave-induced velocity in ATI SAR ocean surface currents: First experimental evidence from an airborne campaign	2016	Journal of Geophysical Research: Oceans	10.1002/2015JC011459

2. Impact case studies

Impact Case 1: Forecasting Oceans and Weather for Economic Benefit and Hazard Mitigation

Centre: National Oceanography Centre

1. Summary of the impact

Accurate high-resolution ocean models and ocean data are critically important to the UK's weather and ocean forecasting capabilities. Research conducted at NOC, in partnership with the Met Office, has greatly enhanced the UK's capability for long-range weather forecasting systems. This includes the ability to predict months to seasons ahead, leading to economic benefit across a wide range of sectors. Through our contribution to the European Copernicus service, NOC has provided the modelling capability for high-resolution ocean forecast and reanalysis information products used by key marine sectors, including for energy planning, government environmental policy and maritime operations.

2. Underpinning Centre activities

This impact arises from the expertise NOC has in high-resolution global and coastal-ocean model development, and in the generation and coordination of the observational data required for weather and ocean forecasting.

NOC is a world-leader in numerical modelling of the global ocean and shelf seas. This includes modelling the ocean circulation and heat transport, marine ecosystems, sea-ice, turbulence, surface waves, sediment transport, tides and storm surges. Much of our work is conducted in close partnership with the UK Met Office, who are fellow members of the Nucleus for European Modelling of the Ocean (NEMO) consortium.[R1]

NOC was a founder member of the NEMO consortium in 2008 and since then has worked to developed crucial aspects of the NEMO model and its configurations.[R2] The ¼° global ocean model configuration co-developed with the Met Office became part of the Met Office Global Seasonal Forecast System 5 (GloSea5) in 2013, substantially improving the UK's predictive skill. Key aspects of this improvement are directly attributable to the research conducted by NOC's Marine Systems Modelling Group (MSM). The model is now better able to represent the positions of the Gulf Stream and North Atlantic Current. This work markedly improved the predicted Sea-Surface Temperatures in the region, and led to enhanced simulation of the Atlantic Jet Stream and Atlantic anti-cyclonic "blocking" events in the atmosphere.[R2] These events govern anomalies in the North Atlantic Oscillation (NAO) and lead to extreme weather conditions in the UK, such as the cold winters in 2012/13. The Met Office implemented the higher resolution ocean model based largely on the results for improved blocking. This system now demonstrates "exciting levels of predictability" of the NAO.[R3]

NOC scientists have also made a critical contribution to the configuration of the NW European Shelf Sea models at 7km[R4] and 1.5km[R5] resolution, building on the operational shelf sea models co-developed by NOC and the Met Office. These configurations provide an unprecedented level of detail and process realism. They are used in both 7-day forecasts and multi-decadal reanalysis simulations of past conditions, run by the Met Office and served by the Copernicus Marine Environmental Monitoring Service (CMEMS).

The modelling systems and CMEMS described above require observational data to improve the fidelity of the hindcast simulations and constrain the forecasts. The international Argo Programme is arguably the most important data product available for constraining the sub-surface model behaviour in the open ocean and ocean-margins.[R6] NOC has a leading role in the international Argo programme in terms of float deployment, scientific steering, management of Argo data through the British Oceanographic Data Centre and high-level data products. Additionally, long-term observational data sets are key to model development in order to challenge their conceptual basis and in assessing

their accuracy. NOC leads or has a strong involvement in the key research programmes that maintain long term observations of the North Atlantic and enhance understanding through process studies. Key programmes include RAPID (for the Atlantic Meridional Overturning Circulation), OSNAP (for the sub-polar Gyre), FASTNet (shelf-edge exchange) and the Shelf Sea Biogeochemistry Programme (UK Shelf processes).

Key People King, Holt, Palmer, Moat, Sinha, Polton, Bruneau, Luneva, Wakelin, New, Megann, Blaker

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

R1 https://www.nemo-ocean.eu/

R2 Scaife, A.A. (2011) Improved Atlantic winter blocking in a climate model. Geophysical Research Letters. https://doi.org/10.1029/2011GL049573

R3 Megann, A., D. Storkey, Y. Aksenov, S. Alderson, D. Calvert, T. Graham, P. Hyder, J. Siddorn, and B. Sinha (2014), GO5.0: the joint NERC–Met Office NEMO global ocean model for use in coupled and forced applications, *Geosci. Model Dev.*, *7*(3), 1069-1092, doi:10.5194/gmd-7-1069-2014.

R4 O'Dea, E., R. Furner, S. Wakelin, J. Siddorn, J. While, P. Sykes, R. King, J. Holt, and H. Hewitt (2017), The CO5 configuration of the 7 km Atlantic Margin Model: large-scale biases and sensitivity to forcing, physics options and vertical resolution, *Geosci. Model Dev.*, *10*(8), 2947-2969, doi:10.5194/gmd-10-2947-2017.

R5 Tonani, M., P. Sykes, R. R. King, N. McConnell, A. C. Péquignet, E. O'Dea, J. A. Graham, J. Polton, and J. Siddorn (2019), The impact of a new high-resolution ocean model on the Met Office North-West European Shelf forecasting system, Ocean Sci., 15(4), 1133-1158, doi:10.5194/os-15-1133-2019.

R6 Roemmich, D., Alford, H., Claustre, H., Johnson, K, King, B. et al (2019) On the Future of Argo: A Global, Full-Depth, Multi-Disciplinary Array, Frontiers in Marine Science 6, article 439. https://www.frontiersin.org/articles/10.3389/fmars.2019.00439/full

4. Details of the impact

NOC generate significant impact through our contribution to weather and ocean forecasting and generation of information products. We also play a key role in advising UK and international programmes in determining best practice, and coordination and prioritisation activities.

Contribute to partnerships supporting ocean and weather prediction

NOC experts contribute to a number of key advisory partnerships including through the Joint Marine Modelling Programme (**JMMP**), National partnership for Ocean Prediction (**NPOP**), UK Integrated Marine Observing Network (**UK-IMON**), and the International **Argo** Programme. Contribution to and running of these activities are supported through NOC's National and Public Good funding.

JMMP focuses on the development and evaluation of configurations of the global ocean, sea ice and north-west shelf using the NEMO model. JMMP provides accessible modelling infrastructure and configurations required by the UK's operational prediction systems for ocean, weather and climate. JMMP also provides support to end users on technical issues and in running the model configurations to ensure that access to the model output is freely available.[S1]

NPOP's mission is to develop and promote marine products and services, with a focus on national and public benefit and stakeholder engagement.[S2] NPOP interacts closely with **UK-IMON** to ensure synergy with the observational community. The purpose of the UK-IMON is to draw together UK

marine observing programmes in order to create new knowledge and better evidence by making best use of all marine data. Marine data is expensive to collect, costing approximately £80 million per year in the UK, with increasing pressure to reduce these costs. The activity of UK-IMON, with NPOP is to ensure cost effective planning and prioritisation to support UK Government in effective planning and cost reduction.[S3]

Argo a global array of 3,800 free-drifting profiling floats continuously monitor the temperature, salinity, and velocity of the upper ocean, with all data being relayed and made publicly available within hours after collection. This programme is essential to weather and ocean forecasting. It is coordinated at an international level and NOC is the UK's representative and a member of the international Steering Committee.[S4]

Enhanced weather forecasting

As a result of the modelling improvements generated by the NOC Modelling team, the GloSea5 system now shows unprecedented levels of forecast skill and reliability for both the NAO and the Arctic Oscillation, allowing the UK to predict the mean winter NAO conditions 1-3 months ahead.[R3] so that suitable planning can be undertaken in advance of such events. The key configurations developed through the JMMP are used in operational forecast and reanalysis production centres. The improved seasonal weather forecasting derived from using the higher resolution global ocean model has substantial economic benefit across many sectors, including transport and energy.[R9-11] NERC's evaluation[R10] of the economic impact of this activity calculated that the incorporation of improvement ocean and atmospheric forecasting generated by NOC & NCAC have helped the Environment Agency, the NHS, local authorities, agriculture and transport to address weather-related challenges and realise benefits including:

- £76 million – 127 million/year reduction in flood damage.
- Reduction in the £500 million/day cost to the economy of heavy snow.
- Reduction in cold-related deaths among vulnerable people and in unnecessary stockpiling of road salt

This impact is only set to grow as this global ocean model becomes a component of the short-term Met Office global weather forecasting system in in 2021, as that system moves to being a coupled atmosphere-ocean system.

'*We write to confirm our strongest support for the Met Office – National Oceanography Centre collaboration on ocean modelling'*.[S5]

High-resolution ocean forecast and reanalysis information products

The NOC, in partnership with the Met Office, provide the modelling capability for high-resolution ocean forecast and reanalysis information products generated through the Copernicus Marine Environmental Monitoring Service NW European Shelf system (CMEMS-NWS). For instance, the 1.5km model[R5], operational in 2019, is the highest resolution model product from CMEMS across Europe. The observations and forecasts produced by the service support all marine applications, including:

- Marine safety
- Marine resources
- Coastal and marine environment

For instance, provision of data on currents, sea level and waves help to improve ship routing services, offshore operations or search and rescue operations, contributing to marine safety. The

service also contributes to the sustainable management of living marine resources, such as for aquaculture, fisheries management or regional fishery organisations decision-making process, and are used for water quality monitoring and pollution control. Information from the NWS model systems supported a comprehensive assessment of the state of the UK marine environment, as part of the Marine Strategy Framework Directive. In addition, Marine Scotland used these systems to support downstream model systems for coastal applications (e.g. aquaculture and harmful algal blooms)[S6] and for oil and other pollution spill response.[S7]

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

Evidence section A: Contribute advice to programmes

S1 JMMP http://www.jwcrp.org.uk/under/jmmp.asp

JMMP - Across the 'grey Zone' of ocean resolution – Hewitt et al. Ocean Modelling 2017 (PDF), https://www.ecmwf.int/sites/default/files/elibrary/2018/18413-across-grey-zone-ocean-model-resolutions.pdf

S2 NPOP, http://oceanprediction.org

S3 UK-IMON http://www.uk-imon.info/About.html

S4 International Argo: http://www.argo.ucsd.edu/members.html & Met Office Presentation 2015 on UK Argo http://www.argo.ucsd.edu/AST16_UKArgo.pdf

Evidence section B – Enhance weather forecasting

S5 The joint collaboration between the Met Office and NOC is essential to the development of the Met office's prediction and assessment capability, and NOC have made a substantial contribution to the development of GLOSEA Seasonal forecasting, CMEMS products and the Argo programme; as evidenced through the **Letter of support from the Met Office Senior Forecasting and Prediction Team.** Quotes: '*We write to confirm our strongest support for the Met Office – National Oceanography Centre collaboration on ocean modelling*'. '*Specifically, their work on the NEMO model and its configurations supports the on-going development of the GLOSEA seasonal forecasting system and the Copernicus Marine Environmental Monitoring Service products*.'

'*Moreover, their support for sustained observational programmes, such as ARGO, provides crucial data for forecast initialisation and reanalyses through data-assimilation methods. This in turn has significant societal benefit across many sectors including transport, energy and maritime operations.'*

The impact of this work is further substantiated through published articles on the links between the enhance forecasting capability and prediction of impact on the transport and energy sector. For the transport system, a statistically significant relationships has been shown between the observed and forecast NAO and road accident numbers, weather-related delays to flights leaving London Heathrow and weather-related incidents on the railway network[R9]. For the European Energy Industry, NAO forecasts translate into skilful predictions of both the winter wind speeds and temperatures, which are important for predicting how much energy can be produced from wind-driven sources, and what the overall energy demand is likely to be for the UK[R10]. Similarly, it has been shown that predictions based on the NAO forecasts can be used to predict the UK winter-mean gas demand and the number of extreme gas demand days[R11].

References (continued from section 3)

[9]Palin E.J., et al 2015 Skilful seasonal forecasts of winter disruption to the UK transport system. J. Appl. Met. Clim., doi:10.1175/JAMC-D-15-0102.1.

[10]Clark R. et al., 2017. Environ. Res. Lett., 12, 024002. Skilful Seasonal Predictions for the European Energy Industry

[11]Thornton H. et al, 2018 Skilful seasonal prediction of winter gas demand. Environ. Res. Lett.14, 2.

Evidence section C: Ocean forecast and reanalysis information products

The Copernicus Marine Service delivers information about the state of the ocean everyday to more than 10 000 users, on a full, open and free basis. More than 150 products are presents in the catalogue of the Copernicus Marine Service today and are grouped into physics, biogeochemical and wave products. These products are delivered via a user-friendly web portal marine.copernicus.eu upon registration. This can guarantee good statistics on the types of users and the products downloaded.

Data from CMEMS-NWS are widely taken up by 'Intermediate Users' who exploit the information across a diverse range of sectors. The latest available statistics show 97 users, representing 74 organisations in 20 countries, accessing the data in a month (of which half download the data daily), with 7,000 Tb of data downloaded each month, made up of 50,000 unique downloads of forecast data and 6,000 downloads of the reanalysis. Of these 44% are from Businesses/private companies, 28% Universities, 24% Public sector and 4% Foundations/Associations.

Download information by user is not available (due to GDPR and the spirit of free data access) but users can provide use case studies on the CMEMS website[S8]. To help with access to the information, we have given links to some example case studies of products and services from the website. Examples include NGO's defining gaps in biodiversity data for MPA's[S9], Marine Scotland for planning of oil spill response and Marine Spatial Planning[S6-7], and commercial companies conducting underwater noise mapping[S10], seismic ship operations[S10], and supporting aquaculture and fisheries in Ireland[S11] (PDFs available).

S6 http://marine.copernicus.eu/usecases/coastal-applications-using-scottish-shelf-model/, PDF CMEMS-NWS CS2

S7 http://marine.copernicus.eu/usecases/marine-scotland-oil-spill-response/ PDF CMEMS-NWS CS1

S8 Web site access to all case studies for CMEMS. Filter by European Northwest Shelf Sea, to filter out all cases directly using data and information products from the NOC activities. NOC data and modelling capability also underpins the other regional cases. http://marine.copernicus.eu/markets/use-cases/

S9 http://marine.copernicus.eu/usecases/oceana/ PDF CMEMS-MWS CS4

S10 http://marine.copernicus.eu/usecases/ocean-noise-mapping-support-eu-international-regulations/ PDF CMEMS-NWS CS3

S11 http://marine.copernicus.eu/usecases/support-seismic-ship-operation-sea-2/ PDF CMEMS-NWS CS5

S12 NERC Impact Report 2017: http://nerc.ukri.org/about/perform/reporting/reports/impactreport2017

Impact Case 2 : UK and Global Assessments of Future Climate

Centre: National Oceanography Centre

1. Summary of the impact

The National Oceanography Centre (NOC) supplied leading expertise and critical underpinning to the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports resulting in direct and identifiable policy changes by the United Nations and UK government during 2013-2019. NOC provided authoritative scientific evidence on sea level, ocean circulation, global temperature, ocean heat content and ocean biogeochemistry and contributed to delivery of UK climate model projections. NOC makes extensive contributions to the decadal reports of UK Climate Predictions (UKCP), and the Marine Climate Change Impacts Partnership (MCCIP), which are used by local government and the business community to plan for climate change adaptation.

2. Underpinning Centre activities

NOC ocean science has impact through sustained ocean observing programmes and ocean and climate modelling, comprising the most iconic and societally important manifestations of climate change: sea level rise, global temperature change, ocean heat and carbon uptake and circulation changes. NOC measurements and modelling contribute to the *detection* of change; they contribute to the *attribution* of change through development and validation of climate models, leading to *reduction in uncertainty* in model predictions. NOC observations, modelling and climate change research make a broad and distinctive contribution to climate assessments.

i) Sea-level rise is one of the most pressing global societal concerns. A significant proportion of the world's population lives close to the coast in vulnerable regions. Potential impacts of sea level rise are large: estimates for global annual flood costs without additional adaptation are up to US$ 14 trillion per year for global sea level rise of 1m by 2100[R1]. Definitive global sea-level data products as well as world-leading research and expertise stem from the NOC-hosted Permanent Service for Mean Sea Level (PSMSL[R2]), which operates under the auspices of the International Council for Science (ICSU). PSMSL generates climate-quality sea level time series from raw data supplied by the international tide-gauge network and is one of the main organisations supporting the Intergovernmental Oceanographic Commission (IOC) Global Sea Level Observing System (GLOSS) programme.

ii) Global surface temperature is a fundamental index of climate change. NOC works to understand, quantify and reduce biases in the marine component of the global surface temperature record[R3] to support evidence of recent change. Key activities are use of ship-based observations to generate definitive near-surface marine air temperature datasets to provide verification of the entire sea surface temperature (SST) record and validation of climate-quality SST from space-based satellite observations.

iii) Ocean heat content (OHC) directly impacts sea-level rise, and measurements from Argo drifting profilers have transformed our knowledge of the Variability and temperature of the upper ocean. NOC personnel are leading participants in the international Argo programme. NOC participation in the international GO-SHIP hydrographic programme enables quantification of deep ocean heat uptake and variability[R4].

iv) Heat carried by the oceanic Atlantic Meridional Overturning Circulation (AMOC) is responsible for mild winters in NW Europe. The longest and globally definitive measure of this, the world's most climatically active ocean circulation system is provided by RAPID-MOCHA-WBTS, a NOC-led international observing programme measuring the AMOC with a basin-wide mooring array at 26°N[R5].

v) Ocean biogeochemistry and carbon uptake is of very high relevance to climate change. NOC makes climate-quality measurements of air-sea CO_2 flux for the definitive SOCAT database and is

an international authority on the science of carbon uptake by the ocean[R6] and its impact on ocean acidification and global warming.

vi) During the 2013-2019 period NOC research into the effects of global climate change on UK regional climate[R7] had impacts on UK national government policy, local government and public sector bodies, and business and industry via contributions to and leadership of the official source material on climate change adaptation.

vii) NOC has made leading contributions to development and configuration of the ocean, ice and marine biogeochemistry components of the UK climate prediction models[R8].

Key personnel: Drs Bricheno, Aksenov, Coward, Megann, Sinha, Yool, Wolf, Brown, Henson, Yelland, Frajka-Williams, Moat, Rayner, Smeed, King, Desbruyères, McDonagh, Berry, Kent, Calafat and Jevrejeva; and Professors Holt, New, Holliday

3. References to the underpinning work

R1 Jevrejeva, S., et al., (2018). doi.org/10.1088/1748-9326/aacc76

R2 https://www.psmsl.org

R3 Kent, E. C., et al., (2013). doi:10.1002/jgrd.50152

R4 Desbruyeres, D., et al., (2017). doi.org/10.1175/JCLI-D-16-0396.1

R5 McCarthy, G. D., et al., (2015). doi:10.1016/j.pocean.2014.10.006

R6 Brown, P., et al., (2016). Impacts and effects of ocean warming on carbon management including methane hydrates. In: Baxter J. and D. Laffoley (Ed.) Explaining ocean warming: Causes, scale, effects and consequences. IUCN World Commission on Protected Areas, https://portals.iucn.org/library/node/46254

R7 Holt, J. et al., (2016). doi.org/10.1016/j.pocean.2015.11.004

R8 Williams, K. D., et al., (2018). doi.org/10.1002/2017MS001115

4. Details of the impact

NOC made key contributions to the Defra/BEIS-sponsored UK Climate Predictions 2009 and 2018 (UKCP18) and the MCCIP, which influence mitigation and adaptation policy of the UK Government and business community, through the UK Climate Change Risk Assessment. Specifically for UKCP18, NOC scientists are among the authors of the DEFRA/BEIS-sponsored UKCP18 Science Overview[S1] and Marine[S2] Reports. These are go-to documents on climate change adaptation for local government and businesses and underpin adaptation case studies with a variety of industrial and public sector partners. NOC science contributes to briefing for UK adaptation policy development, either directly to Parliament – e.g. the fisheries sector[S3], or via the MCCIP[S4].

NOC scientists provide important contributions to the annual State of the Climate Review, an annual publication from the Bulletin of the American Meteorological Society[S5], and the Met Office annual State of the UK Climate Report[S6]. These reviews report on the trajectory of changes to the climate system[S5] and summarise UK weather and climate[S6]. Contributions have been made to each review over 2013 – 2019.

NOC made major contributions to the IPCC Fifth Assessment Report (AR5), the Special Report on the impacts of global warming of 1.5°C (SR15) and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), leading to important policy changes by the United Nations (Paris Agreement) and the UK Government (Amendment to the 2008 Climate Change Act-CCA). The Paris Agreement committed signatory governments to emissions targets aimed at limiting anthropogenic

global warming to below 2°C. AR5 provided the evidence underpinning this agreement. The 2019 Amendment to the 2008 UK CCA commits the UK to zero net greenhouse gas emissions by 2050. The Amendment drew on evidence provided in the 'Net Zero' report and companion Technical Report, by the Committee on Climate Change (CCC). The CCC acknowledges SR15 as one a key document underpinning its recommendation that the UK aim for zero net emissions by 2050.

> *"The reports of the IPCC form the definitive scientific assessments underpinning the development of global and national climate change policy, and the substantial number of NOC staff holding lead and contributing author positions in AR5 and SROCCC reflects the world-class, influential scientific contributions of NOC across a wide range of policy-relevant science areas."*

NOC contributions:

(i) PSMSL data provides the fundamental basis for **all** historical global sea level reconstructions (1860-present) and in **all** IPCC reports, PSMSL tide gauge data (often supplemented by satellite altimetry) were used to estimate long-term sea level change

(ii) Surface temperature is the headline IPCC indicator of anthropogenic climate change: the very first Figure (SPM.1) of AR5. NOC led on identifying and correcting biases in historical *in situ* measurements of air and sea temperatures, quantifying observational uncertainties, and producing the single marine air temperature record presented in AR5. NOC research underpins the bias adjustments used in all AR5 instrumental estimates of global surface temperature.[S7].

(iii) The AMOC is another internationally accepted global climate indicator and features prominently in the AR5 WGI Summary for Policy Makers[S7]. AMOC change is one of 7 physical ocean changes highlighted in the SROCC Summary for Policy Makers[S8] And risk of AMOC collapse is discussed in SR15 Chapter 3[S9].

(iv) OHC measurements are a key element in the evidence for global warming. NOC is a major contributor to OHC observations via contributions to maintaining and extending the Argo array. Argo has doubled the accuracy of deep ocean temperature estimates, compared with the pre-Argo era.[S10]

> "*It is no exaggeration to say that the Argo array (where NOC plays a leading international scientific role) and the RAPID array (which is led by NOC, …) have revolutionised our knowledge of the ocean's role in climate since their inception in the early 2000s* "[S13]

post AR5: During 2013-2019, NOC extended its contribution to the IPCC in three areas: ocean/climate modelling, ocean ecosystems/biogeochemistry/carbon, and OHC observations.

(i) NOC ocean physical and biogeochemical modelling input heavily to design, development and testing of the UK Earth System modelling contribution to AR6[S11].

(ii) NOC contributes measurements to the SOCAT database of air-sea CO_2 flux, one of the observational pillars of the IPCC assessment of the ocean's role in the carbon budget.

(iii) NOC is contributing new gridded OHC products to a major international intercomparison of OHC products under the Global Climate Observing System (GCOS). This will be the definitive OHC resource for AR6.

The impact of NOC work to these internationally important programmes is succinctly captured by a representative from the MetOffice.

"In summary, NOC has been, and remains, a key global player in climate science, delivering impact by informing UK and international policy and planning in response to the risks and opportunities of climate change" [S13]

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

S1 Lowe, J. A., et al., (2018). UKCP18 Science Overview Report, https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

S2 Palmer, M., et al., (2018). UKCP18 Marine Report, https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Marine-report.pdf

S3 https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0604

S4 McCarthy, G. D., et al., (2017). Atlantic meridional overturning circulation. *MCCIP Science Review 2017*, pages 15–21, DOI: 10.14465/2017.arc10.002-atl.

S5 Blunden, J. and D. S. Arndt, Eds., (2019). State of the Climate in 2018. *Bull. Amer. Meteor. Soc.*, 100 (9), Si–S305, doi:10.1175/2019BAMSStateoftheClimate.1.

S6 Met Office State of the UK Climate Reports

https://www.metoffice.gov.uk/research/climate/maps-and-data/about/state-of-climate

S7 IPCC, (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., et al., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

S8 IPCC, (2019). Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, et al., (eds.)]. In press.

S9 Hoegh-Guldberg, O., et al., (2018). Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, et al,.].

https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter1_Low_Res.pdf

S10 Allison, L. C., et al., (2019). Towards quantifying uncertainty in ocean heat content changes using synthetic profiles. https://doi.org/10.1088/1748-9326/ab2b0b

S11 Kuhlbrodt, T., et al., (2018). The Low-Resolution Version of HadGEM3 GC3.1: Development and Evaluation for Global Climate. doi.org/10.1029/ 2018MS001370

S12 Bindoff, N. L., et al., (2019). In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. https://www.ipcc.ch/srocc/

S13 Letter of support from the Met Office.

Additional Evidence

S14 MCCIP report cards http://www.mccip.org.uk/impacts-report-cards/full-report-cards/ Also see recently latest report http://www.mccip.org.uk/media/1999/mccip-report-card-2020_webversion.pdf

S15 Confirmation letter from Matt Frost, MCCIP Chair

Impact Case 3: New generation of *in situ* environmental aquatic sensors

Centre: National Oceanography Centre

1. **Summary of the impact**

NOC have led the development of next generation *in situ* sensors critical for the measurement of pH, oxygen and nutrients in aquatic systems The impact of this work includes:

1. Enabling previously inaccessible sensing for industrial and regulatory stakeholders, as well as the Global Ocean Observing System.
2. Creation of commercially important products and a new start-up company, addressing global demand and a potential market worth >£300 M.
3. Delivery of sensors, training and capacity building to enable Official Development Assistance recipient nations to deliver water quality data to meet UN Sustainable Development Goal: 14.3.

2. **Underpinning Centre activities**

NOC have designed and built low-cost and high function devices that can address current under-sampling of the aquatic environment. The underpinning NOC activities include invention of new analytical methods, new hardware and software, with multidisciplinary elements spanning chemistry, electrochemistry, optics, microfluidics, metrology and engineering. This transformative technology has been delivered by a team of approximately 40 engineering and analytical staff working in state of the art multidisciplinary labs and workshops. The engineering and analytical science development programme is outlined within the Ocean Technology and Engineering Group (OTEG) technologies roadmap[R1], which is designed to address internationally prioritised gaps in capability for measurement technologies. The roadmap encompasses development programmes spanning 3 to 15 years, tackling some of the hardest metrology challenges known in oceanography and aquatic sciences. Funding for this has come from a succession of competitively won projects alongside National Capability providing continuity and long-term structure to this overarching programme.

NOC has created completely new sensor technologies, which have been developed to high technology readiness levels and are now used in a range of applications outside academia. Specifically this is: i) a robust microsensor for conductivity, temperature and dissolved oxygen (CTDO) that is, amongst other applications, a core component for the commercial Ecosub vehicle (See Impact Case 4), ii) a family of chemical reagent based, *in situ* analysers using microfluidics and lab on chip (LOC) technology to address high impact Essential Ocean Variables (EOVs), including three parameters of the Ocean Carbonate System[R2] (pH, Total Alkalinity, Dissolved Inorganic Carbon), Nutrients[R3] (Nitrate, Nitrate, Phosphate, Silicate) and trace metals[R4] (Iron, Manganese). This latter family of sensors has had impact in a wide variety of settings from offshore Carbon Capture and Storage reservoir integrity monitoring, to regulatory inland water quality assessment.

Underpinning technology developments have been protected where needed by patents e.g CTDO technology[R5] microfluidics[R6] and conductivity[R7].

Principal grants and personnel include:

- the EU ITN SenseNET (237868) and FP7 SenseOCEAN (614141) A training project and and innovation project that developed the underlying technology behind the LOC technologies.
- STEMM-CCS (654462) NOC-led project that enabled partnering with Shell and other stakeholders for CCS monitoring and sponsored the development of TA and DIC sensors
- CCS-MMV project, Energy Technologies Institute that supported the development and application of nutrient and pH sensors for CCS monitoring applications as well as partnering with BP, Sonardyne and Fugro
- NERC macronutrient cycles projects NOC worked with EA and DEFRA supporting the maturation of LOC nutrient sensors and development of Dissolved Organic Nutrient sensors.

- The NERC OCEANIDS programme including Autonuts and CarCASS which provide sensors as capital items at high technology readiness level (TRL 8) for the NERC Marine Autonomy Fleet (NMEP-MAS).

Key people: Prof's Mowlem, Connelly, Drs. Beaton, Loucaides, Cardwell.

3. **References to the underpinning work**

R1 OTEG roadmap

R2 Rerolle, V.M.C., et al., (2013) Development of a colorimetric microfluidic pH sensor for autonomous seawater measurements. Analytica Chimica Acta. **786**: p. 124-131.

R3 Beaton, A.D., et al., (2012) Lab-on-Chip Measurement of Nitrate and Nitrite for In Situ Analysis of Natural Waters. Environmental Science & Technology. **46**(17): p. 9548-9556.

R4 Geißler, F., et al., (2017) Evaluation of a Ferrozine Based Autonomous in Situ Lab-on-Chip Analyzer for Dissolved Iron Species in Coastal Waters. Frontiers in Marine Science,. **4**(322).

R5 PATENT - EP/E016774/1 (PI Hywel Morgan, University of Southampton, Matt Mowlem (NOC) Res-CoI and project coordinator) that pioneered the use of microfluidics and lab on chip for oceanography and linked to PhD studentships developing the CTDO technology. Formative in building relationship with Chelsea Technologies Group.

R6 PATENT - Floquet, C.F.A., H. Morgan, V.J. Sieben, I.R.G. Ogilvie, M.C. Mowlem, and L.R.G. Ogilvie, Absorption cell for measuring absorption of fluid analyte at sensing wavelength for microfluidc chemical analysis, has two windows adjacently placed to two ends of sensing channel that is transmissive to probe light. 2010. patent numbers: WO2011095821-A1; GB2490639-A; US2014176952-A1; US9025152-B2; GB2490639-B.

R7 PATENT - Morgan, H., M.C. Mowlem, X. Huang, and R.W. Pascal, Water parameter sensing apparatus for determining e.g., conductivity, temperature, in water by applying voltage signal between working electrode and reference electrode to provide conditioning waveform, wait time, and measurement function. 2012, Univ Southampton, patent numbers: WO2014044998-A1; US2015212040-A1; US9448200-B2.

4. **Details of the impact**

The underpinning work highlighted above has led to enduring collaborations between NOC and commercial companies, UK and international government agencies, and Governments and agencies in Small Island Developing States (SIDS).

(1) The robust microsensor for conductivity, temperature and dissolved oxygen (CTDO) has been developed for use on autonomous systems, with development tailored to address the cost and power constraints of these platforms. This sensor along with others NOC are bringing to market have had a direct economic impact on PlanetOcean and their ability to bring their EcoSub product to market.

Our long running collaboration with Chelsea Technolgies has resulted in the successful commercialisation of a number of products; the SenseOCEAN project led by NOC enabled the V-Lux system to be developed and brought to market, and more recently the STAFES project has resulted in two products, LabSTAF and AutoStaf being available for users.

ASV Ltd. is working with NOC to equip the C-Enduro and other Autonomous Surface Vehicles with the LOC chemical sensors as they see this as a key means of expanding their sales to both commercial and academic users.[S3]

(2) Working with the Cefas (Department for Environment, Food and Rural Affairs-Defra) we are deploying the new lab on chip technologies on a number of autonomous systems to enable more accurate, high precision, real time monitoring of the marine environment. This continuous monitoring is a policy requirement of the UK Marine Marine Strategy and the EU Marine Framework Strategy Directive. (https://www.cefas.co.uk/science/marine-monitoring/). NOC and Cefas are working together to combine autonomy with the NOC LOC system to reduce the cost burden of this monitoring.[S4] The sensor development programme has addressed key gaps in global ocean observing; a representative from the IOC comments on the NOC impact in a number of marine community areas:

(3) Through the Commonwealth Marine Economies Programme NOC have developed and deployed autonomous ocean acidification sensor systems as observation tools for ODA countries. Contained within a robust but lightweight frame, ocean acidity, temperature, salinity and dissolved oxygen can be measured at high frequency for a period of 2 months. These kits have been deployed in the Seychelles, Fiji, Dominica and Belize enabling the delivery of the first ever high resolution, long-term datasets of critical ocean health indicators. These data that can be submitted to the IOC; the mechanism through which countries will be assessed against SDG 14.3. NOC have provided training and capacity building in ocean acidification, sharing knowledge on how to monitor using autonomous sensors and how to interpret data. Training was delivered to government agency staff and university students.[S6]

To commercialise the NOC LOC, NERC pathfinder and follow on funding were used to arrange three IP auctions, two multiyear evaluations (2015-2018) with two large US corporations, a re-evalution of UK commercial partner options (2017-2018) and the launch of a UK spinout to commercialise the IP. The spinout company Solent Sensors will generate tax revenue for the UK, staff employment and export income, and is underpinned by investment from a Venture Capitalist[S7].

5. Sources to corroborate the impact

S1 Letter of support from Planet Ocean

S2 Letter of support from Chelsea Technology

S3 Letter of support from ASV.

S4 Letter of support CEFAS. (Full letter available on request)

Commenting on increasing use of autonomy for CEFAS objectives a CEFAS representative stated they:

S5 Letter of support from the IOC (full letter available on request):

S6 Letter of support University of the South Pacific.

S7 Letter of support from Venture Capitalist investing in Solent Sensors. Contains confidential information, but available on a restricted basis.

S8 There are a number of overseas contacts for the CMEP, depending on confirmation requirements. Therefore, please contact Chris Pearson (Head of the CMEP programme), who will direct you to the most appropriate contact.

Impact Case 4: Marine Autonomous Technology

Centre: National Oceanography Centre

1. Summary of the Impact

NOC has led the world in the development of Autonomous Underwater Vehicles (AUVs), enhancing the UK's marine science capability. In parallel NOC have collaborated with industry and government to stimulate uptake, and drive sector growth in, the development and use of small, low cost AUVs and surface vehicles for operational activities outside research. Working in partnership with business, we have significantly advanced the capability and provision of affordable ocean platforms, generating impact by:

- Creating space and support for innovation
- Enhancing the technical capacity and supporting growth of UK SMEs
- Generating advanced technology leading to a new spin-out company
- Increasing the monitoring capability of small island developing states.

2. Underpinning Centre Activities

Impact is underpinned by two strands of NOC's research and innovation activities:

1) Development of ocean observing platforms via the **Marine Autonomous Robotic Systems (MARS)** Team.

2) Provision of space, facilities and partnership opportunities for the marine robotics industry sector through the **Marine Robotics innovation Centre (MRIC)**.

The **MARS** fleet is one of the largest and most advanced Marine Autonomous Systems fleets in the world, having successfully secured £10M investment as part of the UK Government 'Eight Great Technologies' initiative and £16M through the Industrial Strategy Challenge Fund. Key to its success are the 45 engineers that develop, maintain and operate the vehicles on the behalf of the UK science community. The Autosub programme pioneered the development of AUV technology, transforming the UK's capability in autonomous ocean measurements, including 6000m depth capability[R1-2], optical seabed surveys[R3] and under ice capability[R4-5]. This capability was enhanced through the development of Autosub long range (ALR)[R1], with a range of 2000km, an endurance of 2 months and a depth rating of 6000m. ALR1500, will extend the range and endurance of ALR to 6000km and 6 months. The ALR vehicles can fitted with bespoke sensors and adapted depending on the deployment requirements.

In 2015 the NOC's **MRIC** was opened. Funded by a £3m government investment, the Innovation Centre was established for the emerging marine robotics sector. The vision was to accelerate exploitation of UK investment in autonomous technology through collaborative solutions, tackling key challenges in the ocean economy. MRIC provides space for companies to collaborate, with unique laboratory facilities, and access to input from world class researcher engineers. NOC staff work directly with companies enabling them to access funding and supporting SMEs in proposal writing. Working with the MRIC partners, NOC has successfully won 11 Innovate UK bids (100% success rate), resulting in projects valuing £7.675m with 30 partners from across industry, academia and government. MRIC partners also benefit from NOC's foresight and knowledge of the key potential transformative technology areas. For example, in 2010, NOC commissioned a market study into the viability of miniaturised AUV technology. At the time, commercial viability was limited by a lack of miniature sensors and suitable battery technologies. By 2015 the associated sensor technology, including that developed by the NOC sensors groupR6, made small AUV's more viable. NOC, with Planet Ocean, ASV Ltd. and University of Southampton obtained R&D funding to develop

micro-AUV'sR7 and the capability to launch and recover them from an Unmanned Surface Vehicle (USV). This work led to a new spin-out business, ecoSUB Robotics Ltd.

Key People: Prof. Griffiths, Horsburgh, Drs Phillips, Furlong, Ms. Gold, and Ms Cook, Messrs. Munafo, Fennuci, Thorn, Wood, Linton, Pearce, Rogers, Schink, Forshaw, West, Bell.

3. References to the underpinning work

R1 Roper, D. et al., (2017) Autosub long range 1500: An ultra-endurance AUV with 6000 Km range. In: OCEANS 2017, Aberdeen, 19-22 June 2017. 1-5.

R2 Furlong, M. E et al., (2012) Autosub Long Range: A long range deep diving AUV for ocean monitoring https://ieeexplore.ieee.org/abstract/document/6380737

R3 Morris, K.J et al., (2014) A new method for ecological surveying of the abyss using autonomous underwater vehicle photography

https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.4319/lom.2014.12.795

R4 Furlong, M. E. et al., (2018) OCEANIDS: Building Next Generation Maritime Autonomous Systemshttps://www.researchgate.net/publication/331295391_OCEANIDS_Building_Next_Generation_Maritime_Autonomous_Systems

R5 Wadhams, P., et al., (2005) A new view of the underside of Arctic sea ice https://doi.org/10.1029/2005GL025131

R6 Beaton, A. D., et al., (2012. https://doi.org/10.1021/es300419u

R7 ASV Global Demonstrates AUV Launch and Recovery System with C-Worker 5 ASV https://www.asvglobal.com/asv-global-demonstrates-auv-launch-recovery-system-c-worker-5-asv/

4. Details of the impact

Creating Space for Innovation

MRIC has had over 30 members across the full spectrum of Marine Autonomous Systems from end-users (e.g. BP, Shell, Chevron), platform developers (e.g. ASV, AutoNaut, Planet Ocean), software companies (TP Group, Seebyte), sensor developers (e.g. Sonardyne, Nortek) to regulators (MCA, DfT)[S1]. This facility creates the space for innovation, providing access to NOC's technical expertise, world class testing facilities, and opportunities for partnership. The indirect impact to partners includes business growth and the realisation of innovation opportunities[S2]. Selected examples of NOC's direct impact on three partners are described below. These are all created through enhanced funding, joint development of products and NOC's ability to demonstrate and showcase their products.

Enhancing the technical capacity and growth of UK SMEs

NOC, working with InnovateUK and Dstl, successfully generated a Government SBRI programme, leading to the investment of £1.2m in the development of two Unmanned Surface Vehicles (USV), the C-Enduro from ASV Ltd and the AutoNaut from MOST (AV) Ltd (Now AutoNaut Ltd.)[S3-4] NOC contributed to the development of the technology, were early adopters of both platforms and facilitated the promotion of the novel technologies through workshops, conferences, and demonstrator events, enabling both companies to engage with audiences in scientific, maritime and defence sectors.

AutoNaut were a small company when they joined MRIC, and have stated that without the early and continued support from NOC they would have been unlikely to have become the commercially viable company they are[S3]. AutoNaut now employs 12 people and has estimated that £500,000 of its growth

is directly attributable to their engagement with NOC, with a further £1M of indirect benefit to their business due to the MRIC.[S5] From the prototype vehicle that was developed under the SBRI programme AutoNaut have now developed a larger version that is being sold into international markets, and has been involved with projects for BP and the Big Ocean Clean Up.

ASV were one of the first members to join MRIC, within 2 years of the SBRI programme ASV had increased headcount from 30 to 55, and generated an estimated £1million in extra revenue.[S6] Today they are part of the L3Harris organisation and have over 100 employees.[S7] The collaboration with NOC was highlighted as a success case study for the SBRI Programme.[S5]

Generation of advanced AUV technology leading to a new start-up company

Working in partnership, we have developed a new range of small, low cost AUVs resulting in the generation of a new spinout company (ecoSUB Robotics Ltd.), employing five full-time staff, and seven local contractors. The initial ecoSUB product utilised MARS expertise in AUV technology, and funding secured through a joint InnovateUk project. In 2016, BP funded the NOC/Planet Ocean team to develop a new ecoSUB variant: ecoSUBm25, capable of diving to 2500m depth on missions of up to 30 hours. BP felt this had the potential of creating 50% cost saving in their operational maintenance budget by 2025. Seven months later NOC organised a demonstrator mission that proved to BP that ecoSUBm25 was well-suited to its future offshore maintenance plans. NOCs contribution has led to 2 new marine robotics products and a spinout company[S8.] In 2019, ecoSUB was named as one of the ECOs top10 Ocean influencer[S9]. Early adopters in the UK have included Universities, BP and Dstl through their Progeny funding framework. ecoSUBs are now selling internationally, with estimated sales of £5M per annum.

Increasing the monitoring capability of small island developing states (SIDS).

NOC, working with ASV/L3Harris, developed a Containerised Autonomous Marine Environmental Lab (CAMEL), providing access to low cost MAS that can be shipped to any port, and deployed from a quayside, beach or vessel. Funded through the Commonwealth Marine Economies Programme, the CAMEL includes a small ROV and AUVs (ecoSUB), and a USV with the capability to deploy a range of sensor payloads. This brings together the small, low cost robotic products generated through the MRIC partnerships, with the design and running of a containerised system by NOC, to enhance the capacity of SIDS to monitor their marine environments. CAMEL has been deployed in Belize and Dominica, to assess the impact of land-use changes on marine environments and to support marine spatial planning[S10]. Due to the ecoSUB's low cost (~ £10-30K), it has also proven attractive to developing nations. As part of the NOC led SOLSTICE-WIO project, funded by GCRF, NOC demonstrated how marine autonomous systems can be used in the West Indian Ocean to help nations like Tanzania, Kenya and South Africa understand their marine habitats.[S11]

5. Sources to corroborate the impact

S1 MRIC Members 2013-2109

ASV Global / L3Harris, AutoNaut, BP, BMT, Boeing, Blue Ocean Monitoring, Dept for Transport, MCA, Planet Ocean, Steatite, Seebyte, Sonardyne, Northrup Grumman, Shell, Chevron, QinetiQ, Smart Green, Shipping Alliance, MOcean, Deep Six, Hydriod, DuoDriveTrain, Atlas Elektronik, TP Group/Polaris Consulting, BAE, W-Sense, Liquid Robotics, Teledyne, South Coast Centre of Excellence for Sat Apps, Nortek, Saab Seaeye.

S2 Support statements - letters and emails available on request.

"The Marine Robotics Innovation Centre at NOC has been fundamental to the development of ecoSUB AUVs. The centre provides an excellent environment that facilitates collaboration between Planet Ocean and National Oceanography Centre engineers. We regularly benefit from access to a wide range of stakeholders, project and funding opportunities, all of which have informed and supported our R&D effort." *Planet Ocean Ltd*

"Completing our second full year as a member of the NOC Innovation Centre partnership, we find within this openly proactive business cohort every opportunity to rub shoulders with associated marine industry innovators, developers, and operators, including current and future business partners. Fully supporting the ethos of this partnership we have embraced the cooperative allegiance, supported development aspirations, and integrated well within this centre of Marine Scientific, Academic and Industrial expertise. Thales are set to continue for the foreseeable future and are proud to be a member of this valuable teaming community." *Thales UK, Defence Mission Systems*

"L3 ASV has been a member of the Innovation Centre since its inception and have benefited extensively from new partnerships, projects and connections developed within the Innovation Centre's family and the wider NOC." *L3 ASV*

S3 News story of the SBRI and surface vehicle development: https://www.noc.ac.uk/facilities/marine-autonomous-robotic-systems/asv/asv-development

S4 Pre-commercial procurement (PCP) brings unmanned oceanographic surface vehicles to the market, EU Digital Single Market News Article: https://ec.europa.eu/digital-single-market/en/news/pcp-brings-unmanned-oceanographic-surface-vehicles-market

S5 Press announcement of Autonaut Ltd joining MRIC and outlining their development on NOCs involvement https://www.oceannews.com/news/milestones/autonaut-ltd-formally-partners-with-noc-marine-robotics-innovation-centre; https://www.marinetechnologynews.com/news/autonaut-514332

Letter of support from Autonauts (available on request) qualifying NOCs contribution to their economic growth

'*AutoNaut's credibility and profile has been greatly increased by engagement with NOC MRIC. Exposure through marketing activities, VIP visits and events such as the annual Marine Autonomy and Technology Showcase (MATS) have undoubtedly helped further development commercially across the marine science, defence and energy sectors'.*

'In summary, without the early and continued support from NOC MRIC, it is unlikely that AutoNaut Ltd would have gone on to become the commercially viable company it now is. It is therefore difficult to put a value on the relationship. However, we estimate that £500,000 is directly attributable and the engagement has indirectly enabled a further £1m in business. It is anticipated that over the next 5 years we will see this rise to £2m'.

S6 ASV Success case study from Gov website: C-Enduro: A boat that goes the distance One of the SBRI Success story cased studies on SRBI https://www.gov.uk/government/case-studies/c-enduro-a-boat-that-goes-the-distance

Evidence quote SRBI Dan added: "SBRI has been fantastic for us. It's helped us move from an idea to a product that we know suits the need of the end user.

https://empowerednews.net/unmanned-underwater-vehicle-unmanned-surface-vehicle-market-to-2025/181650417/ Quote: '*Some of the remarkable partnership and collaboration in this industry includes the partnership of ASV Global with UK's National Oceanography Centre for development of containerized autonomous marine laboratory*.'

S7 Letter of support from ASV-L3Harris, selected quotes:

'The company's relationship with the NOC has been key to this growth through a number of key development projects, enabling engagement with the UK's marine science community and providing exposure to other key stakeholders.'

'The early and continued support and collaboration from NOC and its Marine Robotics Innovation Centre has been an important part of ASV Ltd's journey from micro-company to becoming part of a large, multi-national corporation.'

S8 Letter of support from Planet Ocean (available on request), selected quotes:

'*The NOC has always been enthusiastic and supportive of industrial partnerships, but the opening of the MRIC, which coincided with the launch of our Innovate UK-dstl project fundamentally made our project achievable The ability to co-locate our engineers on day one with the team from the well-established MARS group within NOC was essential to the timely delivery the project which has resulted in the establishment of not one but three Autonomous Underwater Vehicles which are now being sold.'*

'We have been able to establish a spinout Company, ecoSUB Robotics Ltd which will, in the near future be responsible for further developments, production and sales of ecoSUB AUVs. Through our engagements with the NOC we anticipate that over the next 5 years we will see sales of ecoSUB AUVs approaching £5m per annum.'

S9 ECOsTop10 Ocean influencers 2019 Awards: 'Ecosub is one of the most innovative and disruptive technologies to emerge in the last five years. It is already making an impact worldwide allowing access to measurements and data previously difficult or impossible to obtain, certainly at the price per data point. EcoSUB is also stimulating sensor manufacturers, software developers and end users to think smaller, smarter and more creatively' From:

http://digital.ecomagazine.com/archive/?p1=9890 ECOmagazine Nov2019, page 24

S10 Characterising the environmental sensitivity of Belizean coastal waters

http://projects.noc.ac.uk/cme-programme/news/characterising-environmental-sensitivity-belizean-coastal-waters

S11 https://www.solstice-wio.org

Impact Case 5: Marine Radar Remote Sensing

Centre: National Oceanography Centre

1. Summary of the impact

The NOC have been at the forefront of research and development of novel mapping capabilities using marine radars for well over 2 decades. The long term underpinning support of NERC NC funding has enabled the sustained development and refinement of new methods of remotely mapping water depths and currents from radar backscatter imagery. These methods have been applied in a number of sectors from marine renewable energy to coastal protection and are the subject of several revenue-generating licenses and have generated two patents. The methods now form the core business of a successful Liverpool based SME.

2. Underpinning Centre activities

NOC has worked with marine radar systems since the early 1990s due to their ability to image ocean wave fields over ranges of several km. This work was initially aimed at extracting nearshore 2D wave spectra and was first deployed during the 1994-5 Holderness projects. During that study it became clear that tidal fluctuations in nearshore waters were contaminating the wave spectra, so work began by Paul Bell to develop methods of extracting the water depth information from the recorded data[R1]. This work showed sufficient promise to be deployed as part of a number of research projects including COAST3D (1998-1999) studying nearshore sediment and hydrodynamics; Inlet Dynamics Initiative: Algarve (1999) studying a migrating tidal inlet; Further Algarve deployments in 2002, 2003 and 2005; the NOC Coastal Observatory – Hilbre Island (2004-2009); LEACOAST2 (2006-2008) studying hydrodynamics around offshore breakwaters; and FLOWBEC (2011-2014) studying marine energy test sites.

This range of different study sites enabled the algorithms to be refined in accuracy, robustness and transferability, leading to increasing interest from potential partners in terms of licensing opportunities and the development of further algorithms for high resolution mapping of intertidal areas, tracking of birds in flight and the detection of submerged migrating sediment dunes.

The high resolution intertidal mapping technique was initially developed and demonstrated on data from the Hilbre Island radar station, and results were so encouraging that funding was granted from NERC to cover international patenting costs[R2]. Sustained liaison between NOC and a Liverpool-based SME (Marlan Maritime), facilitated by NC funding, enabled the team to build a case for a PhD position, a subsequent KTP and the translation of the method into a commercial service[R3, R4].

With the gradual improvement in accuracy and robustness, a collaboration between NOC DRDC Atlantic (Canadian Navy), supported by NC funding enabled the first demonstration of remote bathymetry (water depth) mapping using radar data recorded from a moving vessel[R2]. With further investment from the UK's DSTL, NOC were able to refine and automate the wave inversion based mapping of depths and currents from moving vessels[R5, R6]. Trials aboard a Royal Navy vessel are now in the planning stages.

Key People: Drs Bell, McCann and Bird.

3. References to the underpinning work

R1 Bell, PS, 1999, https://doi.org/10.1016/S0378-3839(99)00041-1

R2 Bell PS & Osler JC, 2011, https://doi.org/10.1007/s10236-011-0478-4

R3 Bell PS, 2013 Inter-tidal Mapping: International Patent Application No. PCT/GB2014/050908, filed on Mar. 24, 2014, which claims priority from Great Britain Patent Application No. 1307303.6, filed Apr. 23, 2013. Resulting Granted Patents: US Patent 9792691; European Patent EP14718452.7A Implemented in UK, Germany, Netherlands, France, Belgium; Australia Patent AU2014259264B2.

R4 Bell, Bird & Plater 2016 - https://doi.org/10.1016/j.coastaleng.2015.09.009

R5 McCann DL, 2018, "Radar Image Processing", International Patent Application

PCT/GB2019/050258.

R6 McCann, David L. & Bell, Paul S. 2018 A Simple Offset "Calibration" Method for the Accurate Geographic Registration of Ship-Borne X-Band Radar Intensity Imagery. IEEE Access, 6. 13939-13948. https://doi.org/10.1109/ACCESS.2018.2814081

4. Details of the impact

There have been direct impacts of the work done at the NOC affecting a range of stakeholders; private companies, local government, and the MOD.

A partnership between Marlan Maritime Ltd (MM), began to look at potential for commercial opportunities around the use of the Marine Radar remote sensing techniques. Successful funding from the EU and an InnovateUK KTP led to the development of a high resolution "Temporal Waterline" Intertidal Mapping method – Patented in (2013)[S1]. MM reoriented their business to focus their business solely on services based on this work, developing "Synoptic"[S2].

The results from the first deployment of Synoptic together with a discussion between MM, NOC and Sefton Council resulted in Sefton Council deferring the original plan for replacement of the sea wall and instead planning a more cost-effective beach recharge. **A representative, at Sefton Council said** *"The Marlan Synoptic system enabled us to resolve some of the detail of our conceptual model which will fundamentally change the approach we take to the design of our coastal defence intervention and allows us to work with natural processes with far more confidence. I can't think of anything else that would have helped and still been affordable. As such we would have had to proceed with a more typical engineering approach which would have been more expensive and less sustainable"*[S3].

Following this work the first permanent installation at Rossall on the Wyre Coastline, monitoring sediment levels in front of £65M sea defences provided coastal managers with confidence to delay beach recharges in light of regular beach morphology & level updates. Initial estimates made by **Wyre Council suggest this could save £5M**. Not only did this save money, but MM were Co-awarded the only "highly commended" award by the Environment Agency for their Innovative Approaches award for Rossall Coastal Defences alongside Balfour Beatty & Wyre Council in 2019[S4]. **Analysis by Liverpool University of CO_2 reductions for a projected Crosby Scheme, based on the figures used in the Rossall design are a saving of over 10,000 tonnes CO_2**[S5].

These successful deployments and demonstrations have resulted in technologies developed by the NOC and operated by MM being included in **Natural Resources Wales best practice guide**[S6]. In 2019 MM's Synoptic service added to UK coastal framework agreement allowing purchase of services UK-wide by any UK coastal council. MM have estimated their **future potential export value at £8M pa** and expect to create and maintain 10-15 jobs in the UK[S2]. In 2017 The MM team won the Merseyside Innovation Award; 2018 The team secured the top prize in the 'Innovation' category at the prestigious Mersey Maritime Awards. Working with NOC has opened new markets for MM through our work in developing countries which will allow MM to grow its business into global markets[S7].

Marine radar deployments conducted by NOC in association with Cefas, investigating wave diffraction effects at the shore during the construction of the UK's first offshore wind farm (OWF) off the Norfolk coast, demonstrated that no impact could be observed in terms of adverse wave diffraction effects. Further, the report recommended "Defra's Marine Consents and Environment Unit are advised not to require developers of OWFs to monitor waves for diffraction/interference effects under a FEPA licence"[S8]. A substantial cost saving (for the UK taxpayer) in subsequent offshore wind farm projects - estimated at a minimum cost saving of >£100k per project based on current costs of using similar methods (own estimate).

A further example of an impact generated from the underlying research is a long running relationship between NOC and OceanWaveS GMBH (now part of Rutter Inc Canada). A licence has been in place with OceanWaveS since 2011, not only does this generate income to NOC (£35.5k to date) but allows customers of OceanWaveS to have a system for that is tested and trusted worldwide e.g. CEFAS, who operate a system monitoring the coastal region in front of Sizewell Nuclear Reactor.

Other uses of the NOC technology are in the defence sector. In 2018 NOC applied for a patent covering an automated method of calibrating radar associated navigation systems for applications on moving vessels. Further discussions with DSTL and representatives of Navy Command have recently led to a funding opportunity being created to support vessel trials of the remote mapping technique with the Royal Navy and development of a roadmap for implementation on the new all-digital radars installed across the RN fleet[S9].

5. Sources to corroborate the impact

S1 https://patents.google.com/patent/WO2014174240A1/en

S2 Managing Director, Marlan Maritime Ltd. (Contact for all matters relating to Marlan Maritime Ltd and their projects using NOC IP) Details on request

S3 Sefton Council contact (details available on request)

S4 Bird, C.O. et al, 2019, "**Autonomous monitoring of nearshore geomorphology and hydrodynamics to assist decision making in coastal management, using shore-based radar systems: A case study on the Fylde peninsula, UK**", Institution of Civil Engineers Coastal Management 2019 Conference, 24-26th September 2019, La Rochelle.

S5 Fulton et al, 2019, A Simplified Environmental Assessment Methodology as an Alternative to Life Cycle Analysis. Journal of Environment & Development, DOI: 10.1177/1070496519867435

S6 Natural Resources Wales Evidence Report 243 (2018) "Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to Inform EIA of Major Development Projects" https://cdn.naturalresources.wales/media/689058/guidance-on-best-practice-for-marine-and-coastal-physical-processes-baseline-survey-and-monitoring-requirements-to-inform-eia-of-major-developement-projects.pdf

S7 Letter of support Marlan Maritime Technologies Ltd. Full letter available on request.

"We are continuously working with the NOC on collaborative scientific projects and have recently been award an Innovate UK Demonstrate Impact grant to install a system in Mozambique. This project, alongside another in St Vincent and the Grenadines will be the first overseas installations, providing case studies to kick-start overseas operations and expansion of the business into global markets. " MM. (S7)

S8 CEFAS (2005). Assessment of the significance of changes to the inshore wave regime as a consequence of an offshore wind array. Contract AE1227. Research project final report. September 2005. http://randd.defra.gov.uk/Document.aspx?Document=AE1227_4775_FRP.pdf

S9 DSTL Contact for MarCE task 2.023. Details on request

Impact Case 6: Protecting People and Coasts

Centre: National Oceanography Centre

1. Summary of the impact

In the UK, £150 billion of assets and 4M people are at risk from coastal flooding, which has been exacerbated by rising sea level. It is predicted that the global cost might reach in the order of £77 trillion annually over the 21st Century, with 800 million people at risk. Research at NOC has transformed our understanding of risks associated with coastal flooding and storm surges, and has generated/installed the infrastructure needed to reduce this risk by providing:

- Evidence of best practice and cost avoidance for managing coastal hazards through advice to UK government and regulatory bodies
- Effective coastal planning for wave overtopping through development of novel low-cost technology and advice to UK coastal planners
- Improved monitoring of coastal flooding and tsunami risk to Small Island Developing States (SIDS) through installation of 'fit for purpose' tide gauges and training

2. Underpinning Centre activities

This Impact is underpinned by three strands of NOC's research and engineering activities, through:

- enhanced understanding of sea-level rise, storm surges, tsunami prediction and coastal inundation
- provision of expertise in the development and implementation of coastal monitoring systems
- development of new, accessible technologies with benefit beyond academia

NOC has a strong track record of using applied research to advise government[R1,S1] and regulatory bodies[S2] on UK climate change impacts and adaptation, building on decades of research into storm surge forecasting and extreme sea level statistics. NOC Scientists delivered the operational models for waves and storm surges that are the core of the coastal flood warning system[S3], and tools based on our data and climate model simulations supports advice to government on sea level extremes. Further work using complex mathematical models shows the sensitivity of storm surge generation to tiny errors in modelled weather systems, which gives a better understanding of worst case scenarios. This research influenced government policy for coastal defence and helped to establish the framework for replacing the Thames Barrier[R2].

NOC engineers develop and install innovative technology approaches to the monitoring of sea level, storm surges and tsunamis. NOC led the design and installation of the UK Tide Gauge Network (1980-2016), and has been measuring sea levels is some of the remotest places on Earth for 30 years. Through the Governments Commonwealth Marine Economies Programme, NOC has used this expertise to support Caribbean SIDS with their design and installation of coastal monitoring and defence systems[S4]. The proximity of Caribbean SIDS to the Hurricane Belt renders them vulnerable to storm surges, whilst regional seismic activity elevates their inundation risk by tsunamis. NOC scientists have also developed a new automated process of quality control for high-frequency tide gauge data[R3]. This process could greatly improve the data available for scientists researching high frequency sea-level variations, such as wind waves and tsunamis. Furthermore, NOC were involved in the design of the telemetry technology for the Indian Ocean tsunami monitoring System[R4], which improved the speed of tsunami detection in the Indian Ocean.

The cost of coastal monitoring, can be prohibitive for many countries, restricting access to vital information for decision makers. There is, therefore, a need for low-cost, low maintenance

technology for coastal monitoring. In response to this, NOC, in partnership, have developed a range of new coastal monitoring systems. These include radar gauges, operational tsunami-capable sea level monitoring systems and wave overtopping sensors (WireWall).

Wirewall represented a new approach to coastal wave hazard monitoring[R5]. This involved radically adapting low-cost capacitance wire technology, used to measure waves in the open ocean, to deliver a system capable of making the first wave-by-wave field measurements of wave overtopping volumes and speeds[R5]. System validation was undertaken with HR Wallingford in their flume facility prior to field deployment[R6]. These advances in technology mean existing wave height sensors can now measure at the high frequencies (a few 100 Hz) required to obtain overtopping data, to initiate a step-change in coastal hazard monitoring capabilities[R2].

Staff involved - Brown, Hibbert, Wolf, Wilson, Horsburgh, Palmer, Woodworth, Pugh, Jones, Yelland Pascal, among others.

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

R1 Environment Agency (2019) Coastal flood boundary conditions for the UK: update 2018. User guide, SC060064/TR7. https://www.gov.uk/government/publications/coastal-flood-boundary-conditions-for-uk-mainland-and-islands-design-sea-levels

R2 Contributions to 21st century projections of extreme sea-level change around the UK 2019, Howard, T., M.D Palmer & L.M. Bricheno, Environ. Res. Commun. 1, 095002

https://iopscience.iop.org/article/10.1088/2515-7620/ab42d7/pdf

R3 Williams, J., A. Matthews and S. Jevrejeva, 2019, Development of an Automatic Tide Gauge Processing System, Research & Consultancy Report No. 64

https://eprints.soton.ac.uk/431968/1/NOC_R_C_64_Final.pdf

R5 Brown J, Yelland M, Pascal R, Pullen T, Bell P, Cardwell C, Jones D, et al. (2018) WireWall: a new approach to coastal wave hazard monitoring. In: Protections 2018, 3rd International Conference on Protection against Overtopping, Grange-Over-Sands, UK, 6 - 8 June 2018.

R6 Pullen T, Silva E, Brown J, Yelland M, Pascal R, Pinnell R, Cardwell C, Jones D (2019) WireWall – laboratory and field measurements of wave overtopping. Proceedings of Coastal Structures, Hannover, Germany, 30 September – 2 October 2019, 10pp.

R7 Batstone C, Lawless M, Tawn J, Horsburgh K, et al. (2013) A UK best-practice approach for extreme sea level analysis along complex topographic coastlines. Ocean Engineering, 71, 28-39.

4. Details of the impact

Evidence of best practice and cost avoidance through advice on adaptation for government and regulatory bodies

Coastal flooding is the second most severe risk on the UK's national risk register. Research at the NOC has led to sustainable coastal defence policies and improved, effective and reliable coastal flood warning systems. For instance:

i) Working with JBA Consulting and Lancaster University, NOC have developed effective statistical techniques, produced a national database of extreme sea levels and developed reliable methodology for the estimation of extreme sea-level probabilities at high spatial resolution along coastlines[R7]. These methods are considered the industry best practice in coastal engineering for estimating extreme sea levels, and have been adopted by the Environment Agency (EA)[R1]

ii) NOC contributed to the TE2100 plan, commissioned to assess the effects of climate change on extreme sea levels in the Thames Estuary. Our monitoring and prediction of tidal and storm surges and expert advice to the EA helped inform decisions on when to close the Thames Barrier, preventing flooding that would cost the local economy £94 million per day[S5].

iii) Though the National Hazards Partnership[S6], NOC science on coastal hazards is translated into products and information in support of Government, such as Daily Hazard Assessments[S6a], the National Risk Assessment and Natural Hazards Trump Cards[S6b].

iv) NOC scientists have contributed to the national Marine Climate Change Impacts Partnership Report Cards[S7]. The 2018, State of the UK Climate Report, co-authored by NOC[S8], was referenced by the Committee on Climate Change in their Parliamentary report.

v) NOC contributed to the Office for Nuclear Regulation (ONR), Technical Assessment Guide on Coastal Flood Hazards[S2]. This provides guidance for ONR Inspectors on the assessment of site-specific studies to quantify threats from external hazards at nuclear sites.

Effective coastal planning for wave overtopping, through development of novel low-cost technology

Seawall construction costs at least £10K per mile in the UK. With 2000 miles of coastal defences we need to reduce costs while maintaining flood resistance. Previously, crucial data on the overtopping speed was not available resulting in a three-fold overestimation of the threshold for public safety, leading to the use of large safety margins at increased cost. NOC and its partners*, developed WireWall, to collect site-specific data to calibrate industry estimates of overtopping, allowing the flood alert threshold to be refined.

At Crosby, the 900 m seawall is nearing the end of its design life. Deployments of WireWall at this site provided the North West and North Wale Coastal Group with the site-specific data and calibrated overtopping tools that they need to design a new, cost-effective seawall, with evidence of local overtopping events being incorporated into the Sefton Council business case to rebuild the sea wall[S9].The deployment of WireWall at Crosby is the first step towards the development of a UK wide overtopping monitoring system that could improve regional shoreline monitoring programmes.

The engagement activities that ran alongside WireWall deployments (twitter, YouTube[S10]) increased research and hazard awareness in the local and wider coastal community[S11]. The project's Wider Interest Group expressed interest in deploying WireWall at various sites around the UK and abroad.

Improved monitoring of coastal flooding and tsunami risk for SIDS

The effectiveness of the Caribbean Early Warning System for coastal hazards (ICG/Caribe-EWS) was limited by an inadequate distribution of sea level monitoring stations and insufficient funding. This hindered the improvement and validation of hurricane forecasts and prevented local agencies from predicting tidal variability to facilitate navigation in heavily-used ports. Working in partnership with local authorities, NOC installed bespoke tide gauges in the key vulnerable and commercially important SIDS of St Lucia, Belize and Dominica[S4]. The gauges were equipped with dual sensor technology for added resilience, and free satellite-linked data transmission to deliver real time observations to local, regional and global operational monitoring centres. In each case, NOC conducted scoping visits to evaluate the monitoring and training needs, and designed bespoke monitoring equipment to meet the specific requirements of local stakeholders.

In St Lucia, NOC installed a renewably-powered gauge, coupling above-water radar sensors with underwater pressure sensors, for added resilience. NOC and ICG/Caribe-EWS co-convened a training course to upskill delegates from 8 Caribbean countries in tide gauge maintenance. Eleven months later, this gauge detected and withstood Hurricanes Irma and Maria.

In Belize, NOC installed renewably-powered gauge sensors beneath the quay in Belize City, whilst designing bespoke steelwork to accommodate sensors on an offshore atoll. This enabled the Belize Met Service to monitor and predict tidal conditions mitigating the risk to navigation. In 2018, the Belize City tide gauge detected a tsunami generated by an earthquake north of Honduras.

In Dominica, Hurricane Maria obliterated the tide gauge systems in 2018. NOC engineers installed a bespoke system that would fold to the quayside during hurricanes, to avoid future destruction. NOC and ICG/Caribe-EWS ran further training for delegates from Belize, Dominica, St Lucia and 12 other Caribbean states in data processing and tidal analysis. Through the ICG/Caribe-EWS, NOC continue to provide ongoing support regionally, to embed the technology and processes within local and regional operational systems.

5. Sources to corroborate the impact

S1 Palmer M, Howard T, Tinker J, Lowe J, Bricheno L, Calvert D, Edwards T, Gregory J, Harris G, Krijnen J, Roberts C. (2018) UKCP18 Marine Report, Met Office Hadley Centre, Exeter.

S2 ONR Expert Panel Paper No: GEN-MCFH-EP-2017-2 "Analysis of Coastal Flood Hazards for Nuclear Sites", http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013-annex-3-reference-paper.pdf & ONR Technical Assessment Guide, TAG13 (NS-TAST-GD-013 Annex 3 R1, 2018): http://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013-annex-3.pdf

S3 Protecting homes and lives from Coastal Flooding, Runner up in the NERC Impact awards (societal Impact), 2015 https://nerc.ukri.org/latest/events/impact/finalists/

S4 Hibbert A, Jones DS, Pugh J (2017) Commonwealth Marine Economies Programme NOC Deliverable Reports - Tide Gauge Installation and Training, St Lucia, 32pp; Tide Gauge Installation, Belize, 26pp.; Tide Gauge and GNSS Installation, Dominica, 24pp

S5 Quote from NERC Impact Report 2017 *'The Thames Barrier safeguards the lives and livelihoods of around 1.25 million Londoners, with every day of flooding prevented worth £94 million to the local economy. Monitoring and prediction of tidal and storm surges by the National Oceanography Centre plays a key role in informing decisions on when to close the Barrier.'*

S6 National Hazards Partnership (NHP), http://www.naturalhazardspartnership.org.uk/. *The NHP, is a consortium of public bodies that provide information, research and analysis of natural hazards for the development of more effective policies, communication and services for civil contingencies, and the responder community across the UK*.

S6a http://www.naturalhazardspartnership.org.uk/products/dha/;

S6b http://www.naturalhazardspartnership.org.uk/wp-content/uploads/NHP_trumps_1.pdf

S7 Links to the MCCIP scorecards http://www.mccip.org.uk/impacts-report-cards/. http://www.mccip.org.uk/ http://www.mccip.org.uk/impacts-report-cards/full-report-cards/2020/. *The MCCIP Report Cards collate and synthesise evidence on UK climate change impacts and adaptation in a timely, impartial and independent manner, for dissemination to a wide range of stakeholders including government, its agencies, local authorities, and the general public*.

S7a Confirmation letter from MCCIP Chair

S8 Kendon, McCarthy, Jevrejeva, Matthews, Legg (2019) "Progress in preparing for climate change 2019 Report to Parliament". State of the UK climate 2018. International Journal of Climatology, 39, S1, 1-55. https://doi.org/10.1002/joc.6213

S9 Letter of Support from the North West and North Wales Coastal Group. Quotes: '*The new measurements provide invaluable information about the wave overtopping behaviour at Cosby. We*

now have a credible understanding of the flood hazard for the existing scheme to better manage our hazard response activities.' Sefton Council. *'The New Understanding gain from deployments in Cosby are of great value to Selton Council, who are in the process of developing a business case for a new coastal scheme.*' Chair of the Northwest and North Wales Coastal Group, Wyre Council

S10 Social media: The WireWall project twitter feed, @WireWall_NOC, had over 300 followers after 1 year, https://twitter.com/wirewall_noc. A series of wave overtopping clips archived alongside the Northwest regional monitoring programme, with over 2000 views in a few months of release. https://www.youtube.com/playlist?list=PLEG2kTxO5bksR1bhXXbE_Id-wFQ7vOmf_

S11 The project was highly commended in the Dredging and Ports Construction Awards 2018, received the Mersey Maritime Award for Positive Impact 2018 and was a finalists as Knowledge Business of the year at the Echo Regional Business Awards 2018. Members of the team and wider interest group were interviewed resulting in published articles in Nature and Environmental monitor

https://www.nature.com/articles/d41586-019-00720-x, https://www.fondriest.com/news/wirewall-measuring-flood-risk-in-real-time.htm.

S12 There are a number of overseas contacts for the CMEP, depending on confirmation requirements. Therefore, please contact the Head of the CMEP programme, who will direct you to the most appropriate contact.

Impact Case 8: Marine geohazards and threats to critical global infrastructure

Centre: National Oceanography Centre (NOC)

1. Summary of Impact

The global seafloor network of telecommunications cables carries >99% of all digital communications, including financial trading (£trillions/day) and the internet, while subsea pipelines connect offshore energy supplies. These networks are essential for economic development, underpinning our daily lives; yet are vulnerable to natural hazards, which can sever trading links or release environmentally-harmful products. To assess these hazards, NOC develops novel technology, analyses global trends in infrastructure damage, and makes detailed measurements of marine geohazards to enable offshore industries and policy makers to make more informed decisions, design more resilient routes, minimise environmental impacts, maintain global connectivity, and promote economic growth.

2. Underpinning Centre activities

The Marine Geohazards research team at NOC has made significant step-changes in the quantification of how turbidity currents behave, which is crucial information for understanding how they interact with strategically important seafloor infrastructure. NOC is focused on the development and deployment of emerging technology to make direct measurements of active seafloor processes in the ocean. This includes characterisation of past geohazard events to better understand risks posed to coastal communities and seafloor infrastructure. Such processes, including submarine landslides and avalanches of sediment called turbidity currents, also transport globally important volumes of sediment, organic carbon and pollutants and hence are important to our fundamental understanding of the oceans.

The NOC is the lead Research Organisation for the “National Centre of Excellence for Geohazards”, established in 2014, funded by Industry and NERC Innovation funding. This has facilitated development and field trials of a number of new sensors enabling measurements of seafloor hazards not possible with existing sensors[R1,2]. The work has catalysed collaboration with Sonardyne to develop next generation sensors[R3]. Ongoing research includes testing passive sensors (including hydrophones and geophones[R4]) to make measurements of seafloor hazards offshore Angola and Taiwan.

With further funding from NERC, Royal Society and industry, these sensors enabled the first detailed measurements of deep-sea turbidity currents in settings offshore Angola, California and British Columbia. This work revealed that these currents represent a greater hazard to seafloor infrastructure than previously thought[R3].

NERC-funded research leveraged industry data that records the timing, location and inferred cause of breaks to the global network of seafloor cables. This provided valuable information about the effects of earthquakes and tropical cyclones on seafloor slope stability and offshore sediment transport. This remarkable dataset has been used to increase our understanding of how these processes work in the deep sea[R1,4,5].

This data, along with existing data sets, have improved impact assessments for seafloor structure by providing the basis for the development of depth-resolved numerical models. These models allow us to better understand how sediment is transferred from onshore to offshore systems, which is necessary to understand particulate, organic carbon, and pollutant fluxes[R6].

NOC research has led to better understanding of the recurrence, preconditioning, triggering and magnitude of large geohazards (such as submarine landslides that may initiate tsunamis) through novel geochemical and statistical analysis of seafloor bathymetry, subsurface geophysics, and

sediment cores. This research is largely funded through NERC and EU sources, but also the Commonwealth Marine Economies Programme to provide guidance to developing countries on the threats posed by offshore geohazards[R6] Information has been provided to the UK Cabinet Office through NOC's position on the Natural Hazards Partnership (steering group to the Cabinet Office), DEFRA (via NERC Arctic Research Project) and through a three-year Knowledge Exchange Fellowship held by Mike Clare.

Key people: Mike Clare, Mike Clare, James Hunt, Ed Pope, Maarten Heijnen, Peter Talling, Matthieu Cartigny

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

R1 Clare, M.A., et al., (2017). Direct monitoring of active geohazards: emerging geophysical tools for deep-water assessments. http://nora.nerc.ac.uk/id/eprint/517514/7/NSG17-0010_GoldOpenAccess.pdf

R2 Clare, M.A., et al., (2015). Quantification of near-bed dense layers and implications for seafloor structures: new insights into the most hazardous aspects of turbidity currents. In Offshore Technology Conference. https://www.onepetro.org/conference-paper/OTC-25705-MS

R3 Azpiroz-Zabala, M., et al., (2017). Newly recognized turbidity current structure can explain prolonged flushing of submarine canyons.

https://advances.sciencemag.org/content/3/10/e1700200?rss=1&intcmp=trendmd-adv

R4 Pope, E.L., et al., (2017). Damaging sediment density flows triggered by tropical cyclones. . https://www.sciencedirect.com/science/article/pii/S0012821X16306112

R5 Pope, E.L., Talling, P.J. and Carter, L., (2017). Which earthquakes trigger damaging submarine mass movements: Insights from a global record of submarine cable breaks?. https://www.sciencedirect.com/science/article/pii/S0025322716300093

R6 Clare, M.A., et al., (2018). Complex and cascading triggering of submarine landslides and turbidity currents at volcanic islands revealed from integration of high-resolution onshore and offshore surveys. Frontiers in Earth Science, 6, p.223.

4. Details of the impact

NOC-led advances in monitoring technology, developments in numerical modelling, and increases in knowledge about the real-world behaviour of deep-sea processes have been translated to a range of offshore industries that include telecommunication cable operators[S1], engineering consultants[S2,5], offshore survey companies[S3], technology and sensor developers[S4], and oil and gas operators[S6].

The global economy relies on uninterrupted use of a network of telecommunication cables on the seafloor; they carry ~99% of all inter-continental digital data traffic worldwide. Submarine cables have considerable strategic importance to the UK because this data traffic includes the internet, defence information, financial markets and other services that underpin daily lives. Repairs for telecommunication cables have cost up to £100m, with further costs resulting from the loss of connection. In 1929, all cables connecting the UK to USA were broken in a few hours by an undersea landslide, a repeat event today would have serious consequences to the UK. Similar events have occurred worldwide, such as offshore Algeria (1954, 1980, 2003), and Taiwan (2006, 2009, 2015).

NOC have assessed why, how often, and where the seafloor cables are broken by natural causes (primarily subsea landslides and sediment flows). This work is based on a global analysis of an industry database of cable breaks, provided by Global Marine Systems[R4,5]. Geographic 'pinch points' at risk from specific hazards were identified, helping partners identify resilient routes in the deep-

sea[S1]. This reduces costs involved in repair and ensures global trading and communication links are unbroken.

"*Such information is essential for improving subsea cable routes and has been instrumental in the design of one new cable route through the cable-congested Strait of Luzon between Taiwan and the Philippines. The redesign allowed the cable to cross the highly active Gaoping Canyon at a location where turbidity currents waned to speeds that were not damaging to cables."*[S1]

A briefing document was provided to the Cabinet Office and Department of Digital, Culture, Media and Sport setting out the basis for why submarine cable breaks should be included in the UK National Risk Register[S7].

NOC engages directly with the offshore hydrocarbon industry (Exxon, Chevron, ENI) on jointly funded projects to better reduce the risks posed by natural hazards to seafloor infrastructure. Offshore oil and gas production relies on an array of expensive seafloor infrastructures to transport hydrocarbons. These infrastructures are weak points in subsea field developments as they are exposed to the impact of seafloor flows[S8]. The damage caused to offshore pipelines by such flows exceeds $400m per year, with reputational damage to operators potentially far exceeding that[R2]. NOC research enables industry to assess the risk posed by turbidity currents, and demonstrates how to model their impact, and effectively design infrastructure for safe, uninterrupted operations, without the need for total avoidance. NOC research will enable significant cost reduction in future and minimise the loss of hydrocarbons to the environment[R2; S1,6]. The work NOC has done to directly measure turbidity using new sensor technology and working with industry partners (Fugro, Sonardyne, Atkins) has led to new tools used by those partners:

"The collaborative relationship between Atkins and NOC (e.g. through NERC Innovation projects) has successfully and significantly contributed to the knowledge base that now guides the development of offshore and seabed infrastructure" [S2]

Geohazards & Ground Modelling, Atkins

The NOC in collaboration with industry partners Sonardyne are looking at the commercialisation of the new sensor technologies developed by NOC.

"Close cooperation between Sonardyne and Dr Clare's group will result in new understanding of sediment transport and characterisation on the academic side, and productionalised devices on the commercial side, especially with respect to environmental risks to infrastructure."[S4]

The knowledge, from both direct measurements and enhanced models have been used to develop the best practice for turbidity current hazard assessment. A new method for assessing submarine landslide hazard, lead-authored by Mike Clare of NOC, is now incorporated into national hazard planning in Canada[S8].

"In conducting our national assessment, and designing our database, we have made considerable efforts to use the classifications schemes provided in Clare et al., 2018. So we are one of the first Geological Surveys to implement this NOC- generated recommendation."[S8]

5. Sources to corroborate the impact

S1 General Manager of the International Cable Protection Committee (full letter of support available on request)

"There is no doubt that the research supported by NERC has provided new knowledge that is of direct value to the submarine cable industry and advances marine science."

S2 Technical Authority for Engineering Geomorphology, Geohazards & Ground Modelling, Atkins (full letter of support available on request)

"The collaborative relationship between Atkins and NOC (e.g. through NERC Innovation projects) has successfully and significantly contributed to the knowledge base that now guides the development of offshore and seabed infrastructure (and specifically seabed pipelines, export power cables and telecommunication cables). We hope very much that the excellent research being conducted at the NOC and with their various research partners, and in turn the support to industry, will continue."

S3 Service Line Director, Marine Geoconsulting, Europe and Africa & Mr Grant Lewis, Engineering Geology and Geohazards Team Leader (full letter of support available on request)

"Direct measurements of turbidity currents by the NOC, such as density and velocity, have been and are extremely valuable in developing more credible inputs to forward-looking numerical models. This also allows back-calculation of deposit geometry to check against the as-sampled conditions to validate models".

S4 Doppler Group Manager, Sonardyne International Ltd (full letter of support available on request)

"Monitoring sediment transport and geohazards in the offshore energy environment are of direct relevance to Sonardyne's main marker, developing markets (specifically renewable energy) and in-house R&D priorities (including) field deployments of acoustic instrumentation toward this purpose, and subsequent data capture and analysis. Sonardyne sees this as an important opportunity to maximise synergies between leaders in the UK research base and British industry and as such is fully aligned to the principles of joint research and innovation outlined in the UK's Industrial Strategy. In this context, we are potentially interested in being involved in the commercialisation of this research at the appropriate time."

S5 Chief Technical Director, HR Wallingford

"The work completed by Dr Clare and associates provides access to published modern datasets on turbidity current behaviour in a comparative range of submarine settings. The summary paper on geophysical tools for monitoring geohazards with which we were directly associated also provides a helpful reference source. Overall the work will help to quantify impacts on subsea infrastructure and enable validation of existing models, point to further model developments for use by industry, and identify gaps to be filled by future field, laboratory and modelling initiatives."

S6 Team Lead, Process Stratigraphy Project, ExxonMobil Upstream Research (full letter of support available on request)

"Over the past few years (circa 2013), sediment transport and geohazards research at NOC has had a broad impact on oil and gas exploitation with new avenues of research and important implications for our business (e.g., Hodgson et al., 2018)"

S7 Parliamentary Office of Science and Technology (POST) Briefing note 31 (2019).

S8 Marine Geoscience Projects Lead - Natural Resources Canada & Geological Survey of Canada

" In summary, the collaboration with NOC has given us exciting direct measurements of delta failure and turbidity current activity, but also allowed us to even get into these fjords with multibeam and sub-bottom profiling systems, moorings, and coring devices to conduct surveys for other types of marine geohazards. We have considered or implemented the results in several of our outputs. We very much hope to continue the collaboration with NOC."

Impact Case 9: Habitat mapping & policy advice

Centre: National Oceanography Centre

1. Summary of the impact

To achieve responsible marine spatial management, policy-makers need robust evidence of biodiversity and human impacts, as well as cost-effective methods to monitor the marine environment. Research into seafloor biodiversity and the development of novel habitat mapping approaches at NOC provides governments, industry, trans-national bodies and coastal communities worldwide with essential knowledge, independent advice and state-of-the-art tools to understand and monitor their seabed environment, and to design appropriate management and conservation strategies.

2. Underpinning Centre activities

Development of robust and cost-effective approaches for habitat mapping

The exceptional collaboration between environmental researchers and engineers at NOC drives innovations in robotic technologies and analytical methodologies. This allows scientists to extend observational capacity in space and time, develop novel mapping approaches for inaccessible areas and to reduce costs of benthic investigations. The marine realm is vast, covering ~70% of the planet, yet only a fraction of it has been investigated or even mapped to a fit-for-purpose resolution. In order to achieve sound stewardship and responsible management, new observational and mapping approaches are needed that can integrate information across scales, maximising observations and minimising cost, while being statistically robust and scientifically objective. Within the framework of the ERC Starting Grant project CODEMAP (Grant no 258482), the NERC NC programmes MAREMAP and CLASS, the NERC project AESA, and a series of DEFRA-funded projects, NOC developed: (1) new approaches for nested habitat mapping, imaging benthic processes at the scale they occur[R1]; (2) novel techniques to map vertical and overhanging cliffs in the deep sea[R2], a type of habitat overlooked by traditional methods that often hosts vulnerable marine ecosystems; (3) new methods to harvest the richness of photographic data collected by AUVs[R3] in a cost-effective way; (4) new statistical approaches to habitat mapping[R4], both based on a top-down analysis of full-coverage acoustic data, and a bottom-up spatial modelling of species distributions.

Fundamental and applied research into seafloor biodiversity and ecosystem function, its spatial distribution and its evolution under natural and anthropogenic disturbance scenarios

NOC has a long-standing expertise in research and habitat mapping with the aim to understand the dynamics and spatial distributions of life on the seafloor[R3]. Programmes such as MAREMAP, and the EU FP7 projects HERMIONE, FixO3 and MIDAS have supported evidence-gathering and repeat observations[R5] in a wide range of benthic environments. Many of these environments host Vulnerable Marine Ecosystems and species/habitats of conservation interest (OSPAR, EU, CBD), or are located in areas earmarked for the development and extraction of marine resources. The new National Capability programme CLASS includes a specific research project, delivered through long-term observations at a series of fixed point observatories, many of which are in Marine Protected Areas (MPAs).

Marine habitat mapping in developing island and coastal states, overseas territories and the high seas

The growth of the blue economy is an evolution that is not just reserved to the developed world: particularly island and coastal states are rapidly realising the potential of their marine environment. However, the near-complete lack of robust baseline data to inform their marine strategies and spatial planning calls for urgent action. As part of a series of OT and ODA-based programmes (SOLSTICE, CME, ACCORD, Blue Belt), NOC combines marine habitat mapping research[R4] with knowledge

exchange and training activities in countries such as Belize, Malaysia, Tanzania, British Virgin Islands, Kiribati[R6], Vanuatu and Dominica. The habitat mapping work is based on low-cost solutions, but incorporates the latest technology where possible, and focusses on the investigation of areas with direct importance for marine spatial planning such as fish habitat, coral reef extent and health assessments, and blue carbon stocks.

Key People: Huvenne, Le Bas, Wynn, Strong, Robert. Ruhl.

3. Reference to the underpinning work

R1 Wynn, R.B., et al. (2014). Autonomous Underwater Vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. *Marine Geology,* 352, 451-468. Doi:10.1016/j.margeo.2014.03.012

R2 Robert, K., et al. (2017). New approaches to high-resolution mapping of marine vertical structures. Doi :10.1038/s41598-017-09382-z

R3 Benoist, N.M.A., et al. (2019). Monitoring mosaic biotopes in a marine conservation zone by autonomous underwater vehicle. Doi:10.1111/cobi.13312

R4 Hogg, O., Huvenne, V.A.I., Griffiths, H., Linse, K. (2018). On the ecological relevance of landscape mapping and its application in the spatial planning of very large marine protected areas. Doi: 10.1016/j.stotenv.2018.01.009

R5 Huvenne, V.A.I., et al. (2016). Effectiveness of a deep-sea cold-water coral Marine Protected Area, following eight years of fisheries closure. Doi:10.1016/j.biocon.2016.05.030

R6 Simon-Lledó, E., et al. (2019). Preliminary Observations of the Abyssal Megafauna of Kiribati. *Frontiers in Marine Science* 6 (605).

4. Details of the impact

Several governments and trans-national bodies rely on NOC for the direct delivery of scientific evidence in the form of habitat maps, reports, biodiversity information and evidence of anthropogenic impacts, particularly in MPAs. They trust NOC in its provision of advice and its demonstration of new technologies and improved practices. They also greatly value our collaborative activities, knowledge exchange and training.

Impacts on UK Government strategies and legislation regarding marine spatial planning and conservation

NOC provided direct evidence and input in the process of MPA designation, management and monitoring, most notably in December 2016, when R. Wynn was invited at a Parliamentary Environmental Audit Committee inquiry into MPAs[S1]. NOC research particularly supported the designation and monitoring of the Darwin Mounds[R5] and NW Rockall Bank Special Areas of Conservation (SACs), and the Greater Haig Fras and The Canyons Marine Conservation Zones (MCZs)[S2]. Furthermore, the NOC analysis on two recommended MCZs under project MB0120 was published in post-survey site reports in 2013, and the Western Channel and North-West of Jones Bank sites were subsequently designated as MCZs in 2016.

The UK Government's monitoring plans now include the use of AUVs for surveying and monitoring of MPAs, after NOC work at the Greater Haig Fras MCZ over the years 2012-2015-2018, funded by DEFRA, MAREMAP and CLASS, proved this a cost-effective approach[R1,3]. Representatives of the statutory nature conservation body JNCC and the scientific agency CEFAS participated in the expeditions, during which evidence was also collected supporting the designation and management of The Canyons MCZ[S3]. The work resulted in direct NOC input into DEFRA's autonomous monitoring plans for The Canyons and Greater Haig Fras MCZs[S4].

Impacts on methods, guidelines and standards

Through collaborative work, direct advice and secondments (e.g. between NOC and DEFRA), NOC has made a major impact on the Recommended Operational Guidelines (ROGs) of governments and trans-national bodies (e.g. International Seabed Authority, ISA) regarding the use of novel technologies and robust statistical approaches for benthic observations and surveys. Input was provided to JNCC on its guidelines for AUV and ROV use[S5], and similarly NOC reviewed the Australian field guide for AUV use[S6]. In March 2019, JNCC created a forum for scientists using marine imagery data, aiming to achieve a more streamlined, standardised approach: NOC researchers were explicitly invited to this 'Big Picture' initiative.

The research into seafloor habitat classification methods also led to the development by T. Le Bas of the low-cost software 'RSOBIA', an extension to the most commonly used GIS package ArcGIS[S7]. RSOBIA enables Object Based Image Analysis, a novel method for mapping marine habitats. Until recently, this method typically required expensive commercial software; RSOBIA made it accessible for most researchers. By August 2019, RSOBIA already counted >100 users, including (inter)national government bodies[S7], and industry.

Impacts in ODA countries

NOC's work in ODA countries delivers three important outputs[R6,S8]: (i) the provision of survey, data processing and analysis skills to in-country partners; (ii) high-quality/high-value data sets, often of essential ocean variables or of habitats of conservation or economic importance; and (iii) interpreted final products (reports, scientific papers, management tools) that are used directly by policy-makers. Projects in Cambodia & Malaysia (ACCORD), Tanzania (SOLSTICE), Dominica & Kiribati (CMEP) and the British Virgin Island (non-ODA funding from the FCO) had strong skills training and capacity building for in-country partners[S8,S9]. The work in BVI was particularly important as their request to claim their EEZ has been declined because they currently lack the ability to monitor and manage their marine areas (a combination of skill shortages and scientific hardware). The NOC/BVI capacity building project partially addressed both shortcomings and was of direct impact to the BVI[S9]. In Kiribati, NOC training and support allowed the government to produce the first marine resource boundary map for the country, provided new baseline information for management and is influencing policy development for deep-sea mining[S10].

Impacts on the international regulation of deep-sea resource exploitation

The sustained influence of NOC staff and activities on the policy landscape for deep-sea mining has led to substantive impacts, particularly in mineral exploration and environmental management of deep-sea mining. NOC has been influential in the development of (inter)national regulations for the exploitation of minerals in areas beyond national jurisdiction (governed by the ISA) by translating scientific expertise into policy advice, as well as capacity building in developing economies. The UK Government has used this advice to inform their response to parliamentary questions and in the parliamentary select committee report on Deep-sea Mining[S10]. NOC has provided information and advice to industry, which has shaped the development of their environmental impact assessment process, e.g. UK Seabed Resources partnered with NOC in their Abyssal Baseline (Abyssline) Project.

5. Sources to corroborate the impact

S1 Provision of evidence by Prof Russell Wynn to Parliamentary Inquiry on MPAs

https://www.parliament.uk/business/committees/committees-a-z/commons-select/environmental-audit-committee/inquiries/parliament-2015/marine-protected-areas-revisited-16-17/publications/

S2 JNCC reports and management guidance for MPAs, illustrating NOC input to evidence, reports, imagery, video… :

http://archive.jncc.gov.uk/default.aspx?page=6531 (Darwin Mounds SAC)

http://archive.jncc.gov.uk/default.aspx?page=6556 (Canyons MCZ)

http://archive.jncc.gov.uk/default.aspx?page=6538 (North West Rockall Bank SAC)

http://archive.jncc.gov.uk/default.aspx?page=6533 (Haig Fras SAC)

http://archive.jncc.gov.uk/default.aspx?page=7135 (Greater Haig Fras MCZ)

S3 "*The Canyons MCZ is a challenging site for us to survey, as it is in deep water far from land and has a complex and rugged landscape. The equipment and expertise provided by NOC enabled us to gather high-quality data from this important site in a cost-effective way. These data are providing us with robust evidence about the location and extent of designated features such as cold-water coral habitats, which will enable us to make informed decisions about future site management*."

Defra Marine Evidence Manager, 2016

http://www.under-water.co.uk/robots-inform-protection-of-english-deep-sea-corals/

"*The surveys by ROV Isis, Autosub6000 and the RRS James Cook provide JNCC with invaluable information about the marine areas we have to monitor and manage. At JNCC, we do not have regular access to equipment with these advanced capabilities and depth ratings, and so are keen to explore their performance in relation to the monitoring of MPAs. We look forward to continuing and expanding our collaboration with the NOC*."

JNCC Marine Evidence Manager, 2018

https://jncc.gov.uk/about-jncc/jncc-blog/archive/rrs-james-cook-returns-from-successful-collaborative-voyage/

S4 Input to the Greater Haig Fras MCZ and Canyons MCZ Autonomous Monitoring Plans (currently confidential, available on request)

S5 https://hub.jncc.gov.uk/assets/f52a772a-1d81-4cab-b850-7a9e32d0fef6 (JNCC Guidance on AUV work);

https://hub.jncc.gov.uk/assets/4abdba96-8ade-468d-8f80-c23a6ad87dc5 (JNCC Guidance on ROV work)

S6 https://www.nespmarine.edu.au/field-manuals (Field manuals on marine observational techniques. Direct reference to NOC work, B.Bett and V.Huvenne invited to review Chapter 4 on AUVs. Note both were wrongly referenced as 'University of Southampton')

S7 https://conference.noc.ac.uk/product/rsobia-software which received following reactions:

"*RSOBIA fits nicely into our workflow here at NGU, providing a quick and easy solution for segmentation of multibeam and other seabed data using object based image analysis. We particularly like how RSOBIA offers both segmentation and classification tools within the same toolbox*." – **Representative Geological Survey of Norway**

"*I have found it (RSOBIA) straightforward to use. The software highlights similar areas of seabed in far greater detail than could be achieved by hand, and can turn weeks of work into hours/days when used correctly*" – **Representative, Channel Coastal Observatory**

S8 Griffin (2019). Marine Survey Capacity Building Activity Closure Report – a report by the British Virgin Islands Recovery and Development Agency with contributions from the National Oceanography Centre, UK, 24pp. This includes the following quote:

"I was very pleased to participate in this training opportunity with the NOC Team. …

From an environmental perspective, having the capacity to spatially conduct these surveys locally would be crucial for our us to indicate the state of our marine environment, identify healthy and vulnerable habitat, determine potential economic features and many other possibilities.

This marine survey training should allow for all the relevant agencies involved to implement the skills acquired to yield valuable information that is vital in our respective areas. I am looking forward to collaborating with these agencies with the assistance of the NOC team as we gain more insight of our Territory's marine resources." - **Geographical Information Systems Officer, Conservation Department**

S9 Support for NOC Knowledge Exchange work in Kiribati, supporting the country's environmentally sustainable approach to deep-sea resources (full Letters of Support available on request):

"*We wish to highlight that your work on developing a baseline data acquisition strategy for Kiribati has been very useful for this process. … This work will directly inform the developing policy and implementing regulations for seabed mineral exploration in Kiribati."* – **Legal Advisor, Commonwealth**

"*The Kiribati Government is in the process of setting up regulatory frameworks as depicted under the new enacted Kiribati Seabed Minerals Act 2017, with an aim to encourage investment within Kiribati and bring new national revenue, while maintaining appropriately high standards with regards the protection of the marine environment and socio-economic well-being of the people of Kribati. … The Deepsea Environment workshop conducted from the 10-21st November (and supported by the NOC) is the starting phase of establishing an environmental regulatory framework that will ensure a sustainable approach for such a development. The Ministry (MFMRD) therefore now wishes to request continuous technical assistance from NOC to support our efforts to develop the requisite environmental regulations…"* – **Representative A, Ministry of Fisheries and Marine Resources Development**

"*In addition to enhancing knowledge on the environment and species of the deep sea, the workshop had also addressed the skill gap of relevant officials … The Ministry of Fisheries and Marine Resources Development acknowledges that the sharing of information, procedure and skills in this 3-day workshop are very crucial in the study and development of our Kiribati Deep sea mineral. Therefore, the Ministry of Fisheries and Marine Resources Development deeply appreciate the opportunity and time given from National Oceanography Center for their assistance to Kiribati in this regard*." – **Representative B, Ministry of Fisheries and Marine Resources Development**

S10 Parliamentary select committee report on deep-sea mining:

https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/980/98007.htm

S11 There are a number of overseas contacts for the CMEP, depending on confirmation requirements. Therefore, please contact the Head of the CMEP programme, who will direct you to the most appropriate contact.

NOC Environment submission for NERC Centre Evaluation Exercise

A1 Context, Mission and Strategy

A1.1 The Ocean Agenda as Context

At the National Oceanography Centre (NOC) we are **passionate about the ocean**. There is only one ocean. A vast, interconnected system, divided into large basins and seas, covering 70% of the Earth's surface and 97% by volume of the biosphere. The ocean generates 50% of oxygen we breathe and provides the primary protein source for over a billion people.

The ocean is vital to the functioning of our planet. It regulates climate by taking up ~30% of anthropogenic carbon and 93% of the Earth's excess solar heat, which is redistributed within the Earth system, including through a surface to seabed overturning circulation.

In 2016 the Organisation for Economic Co-operation and Development (OECD) forecast that the value of the ocean economy would double by 2030 from $1.5 to $3 Trillion per year, equivalent to the economic output of the world's 7th largest economy. However, 80% of the direct economic benefit will depend on healthy marine ecosystems, which are increasingly under threat.

In an era of climate change, expanding global population and intense resource exploitation, it is essential that we have the capability to investigate the processes of change and variability operating over **long time scales** (seasons to millennia), and to coordinate **large scale observation and prediction** systems, so policy makers can make sound evidence-based decisions about the ocean.

The period of evaluation has seen a **dramatic transformation of public and political awareness of the importance of ocean issues**, as illustrated by:

- UN Sustainable Development Goal 14 explicitly recognising the ocean and seas;
- Intergovernmental Panel on Climate Change (IPCC) Special Report on Cryosphere and Oceans (2019);
- Negotiations on a new legally binding treaty under the UN Convention on the Law of the Sea (UNCLOS) for Sustainable Management of Biodiversity in Areas Beyond National Jurisdiction (BBNJ);
- UK led '30by30' initiative to protect 30% of the ocean by 2030;
- Declaration UN Decade of Ocean Science for Sustainable Development 2021-2030;
- High-Level Panel on a Sustainable Ocean Economy - 15 Heads of State/Government;
- UK Government Office of Science Foresight Report - Future of the Seas, 2018;
- Drafting UK International Ocean Strategy 2018/19 (stemming from Future of the Seas);
- G7 Future of the seas and oceans initiative.

The ocean is a scientific, technological, economic and geo-political frontier. The NOC **motivates and frames its science** by the fact that by 2050, human population will grow to nine billion, concentrating fastest in low-lying coastal zones. Consequently, attention is turning to the ocean and scientific evidence to:

- secure natural resources and protect future productive capacity of marine ecosystems;
- increase resilience to marine related disasters, especially flooding from the sea;
- make sense of global change and variability, climate and biodiversity.

A1.2 NOC's International Setting

Large-scale oceanography is **'big science'** and expensive. The G7 countries understand that this cannot be delivered through their respective university sectors alone. Consequently, each has a major national ocean research institute to provide long-term strategic vision, concentrated critical mass of expertise and sustained ocean observations, and to manage large research infrastructures.

In the UK, the NOC is that institution - one of only a handful of similar-scale institutions worldwide. We regard our immediate international peer group as: Woods Hole Oceanographic Institution

(WHOI, USA); Scripps Institution of Oceanography (SIO, USA); French Institute for the Exploitation of the Sea (IFREMER, France); Helmholtz Centre for Ocean Research (GEOMAR, Germany); Japanese Agency for Marine Earth Science and Technology (JAMSTEC, Japan).

All the top-tier institutes, including the NOC, have the following in common:

- critical mass of expertise over a broad ocean science discipline spread;
- global/multi-basin interests and capabilities (not only regional);
- major capability for technology innovation (each with its own distinctive niche);
- undertaking sustained ocean observations for the global ocean observing system;
- managing significant research infrastructures and deep-sea marine equipment;
- playing leading roles in international partnerships and coordination mechanisms.

A1.3 NOC Mission and Strategy

The **mission** of the NOC is ***making sense of changing seas for a sustainable future***. The three supporting pillars of this are:

- Undertaking and enabling world-class science and technology development (Excellence);
- Providing large research facilities and access to data and samples for UK science (Enabling);
- Creating value and public benefit by supporting development of public policy, hazard assessment, ocean governance and regulation, and development of a sustainable ocean economy (Engagement).

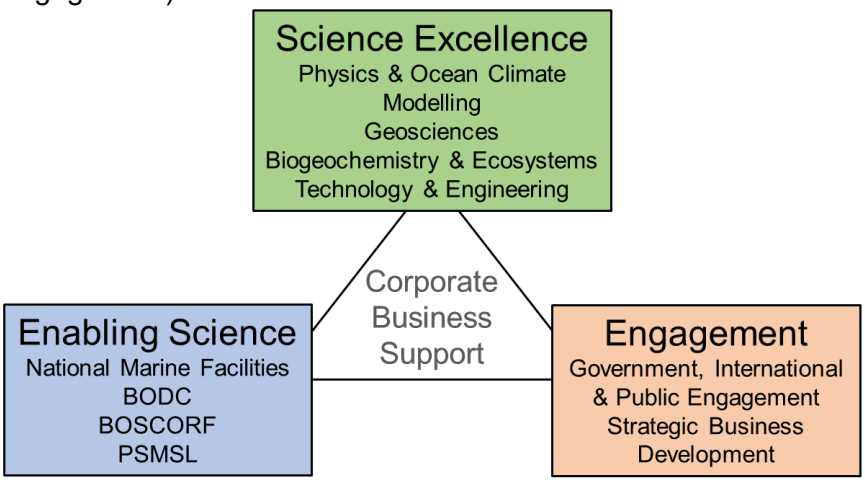


Figure 1. NOC structure runs through three interlinked pillars: Excellence, Enabling and Engagement; all underpinned by Corporate Business support. BODC = British Oceanographic Data Centre, BOSCORF = British Ocean Sediment Core Research Facility, PSMSL= Permanent Service for Mean Sea Level

The NOC is shaped by the nature of the ocean: its interconnectedness; its scale; the nature of challenges faced; and the science, technology and infrastructure needed. Consequently, as reflected in our strategy, we:

- embrace **cooperation and partnership** – no one country, let alone institution, can make progress alone – and our outlook is inherently international (e.g. 70% of our research publications have an international co-author).
- have a **large-scale long-term perspective** – key processes operate at basin-decadal scale. Sustained global observations, alongside global-scale models, provide the essential scientific methodology, hence why they feature so prominently in our work.
- value **big, diverse team** approaches to delivering science - not just individuals working in isolation. This extends to the engineering, technical and sea-going specialists without whom ocean-going science is impossible at scale.
- prize **technological innovation with a long-term vision** – the NOC pioneered development of Autonomous Underwater Vehicles (AUVs) for science (first sea trials in1996), having the vision then to recognize them as critical to tackling gross under-sampling of the ocean.
- commit to **open access** of data and information - international data-sharing has been

integral to the culture of oceanography for decades, it is essential for building the global- and basin-scale pictures of change and variability of the interconnected ocean.
- commit to **explaining the meaning of our science** and facilitating its use. We work hard at this because the role of the ocean for humanity has largely been overlooked, but is now changing rapidly; e.g. the BBC Blue Planet TV series raised concerns about mankind's impact on the ocean, highlighting plastic waste in particular.

Currently, the NOC has **646 staff** including 194 research scientists and technology developers, 91 of whom are Principal Investigator level (Fig. 2). Ocean science is **interdisciplinary,** so our scientists come from diverse discipline backgrounds: physics, biology, chemistry, earth sciences, mathematics and engineering.

Science and technology development is delivered through five operationally based groups: Marine Physics & Ocean Climate (MPOC), Marine Systems Modelling (MSM), Ocean Biogeochemistry & Ecosystems (OBE), Marine Geosciences (MG) and Ocean Technology & Engineering (OTE). However, collaborative cross-group working is embedded in all we do. As such, our outputs to the Centre Evaluation are submitted under two equal sized units:

1. **Ocean Physics and Climate** (encompassing MPOC, and physical aspects of MSM and OTE)
2. **Biogeochemistry: from surface to sea floor** (encompassing biology, chemistry and geoscience aspects of OBE, MG, OTE and MSM).

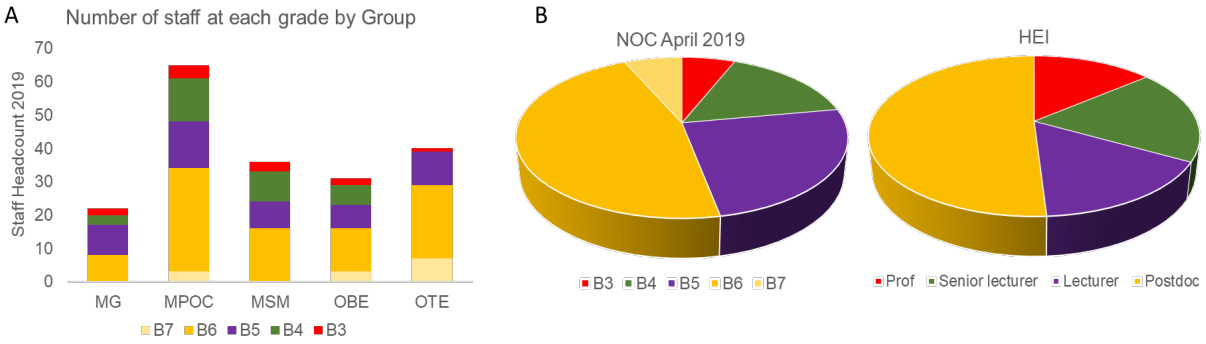


Figure 2: Number of staff at each grade within the five science groups (A), and overall balance of NOC science staff at each grade as compare to the related university sector (B). Note: B3 is the most senior level in NOC and equivalent to University Professor. B5 is the equivalent to University Lecturer. NOC has 1.13 postdoctoral researchers for every Principal Investigator (PI), compared to 1.04 for HEIs based on subject area.

This structure is intended to sustain and develop critical mass of scientific capabilities across the span of underpinning ocean science disciplines and provides a home-base for career development. The structure allows the NOC the flexibility to draw together experts to build large, time-limited, multi-disciplinary teams to deliver large-scale projects, programmes and partnerships in collaboration with others.

Most of our work is **team-based and interdisciplinary** and the NOC is pro-active in ensuring effective internal communication and planning of our involvement in large programmes. For example,

- The NOC Chief Scientist (Professor Angela Hatton) meets with Group Heads once a month, and convenes two workshops a year across all research groups to discuss the long-term strategy, current priorities, design and delivery of National Capability (NC) programmes, influencing or responding to emerging opportunities, staff development and recruitment, and diversification of income.
- As most major advances in oceanography require advanced technology, we have developed a Technology Roadmap. Working with external scientists and supported by a Technology Working Group (TWG) we are ensuring close linkage between future science needs and technology developments.
- Where stronger integration is needed, the NOC has deliberately invested in targeted leadership, including appointment of the Chief Scientist for International Development Science

(Professor Horsburgh) and the Chief Scientist for Marine and Autonomous Robotic Systems (Professor Wynn, and then Dr Palmer). The Associate Director Research (Professor Connelly) specifically leads on influencing and engagement in European Programmes and associated scientific collaborations.

A1.4 open Access and Integrity

The NOC endeavors to ensure our research outputs are accessible. Working with the National Oceanographic Library, we aim to ensure that all publications are gold open access or deposited in the NERC Open Research Access database - NORA (unless embargoed or restricted due to commercial sensitivity). Our overall open access compliance increased from 67% to 83% between 2013 and 2019, with 64% of publications gold compliant in 2019.

The importance of **open data access is exemplified** by the global Argo profiling float programme (4,000 profiling floats distributed globally, measuring heat content of the upper ocean with UK contributing 8% of the array). Data are available to researchers, operational agencies, and the public, usually within 24 hours of acquisition. Up to August 2019, Argo identified 3,834 research publications that depend on Argo data (http://www.argo.ucsd.edu/Bibliography.html). About 250 Argo papers have a lead author from the UK, but UK Argo implementation involved only eight participants (and just two researchers). The overwhelming majority of UK-led papers have therefore depended on Open Access data and NOC played a central role in availability of that data (https://www.ukargo.net.) Data generated by NOC is deposited with the British Oceanographic Data Centre (BODC), a facility run by NOC for all UK science (see later) and/or with other major specialist international data bases (such as Pangea).

Our core value of integrity encompasses research integrity. The public must have confidence in the conduct of science and actions founded on scientific evidence. During the evaluation period we have followed NERC-UKRI policies, but during our path to independence, we developed NOC policy and procedures (linked to policies on impartiality, conduct, sponsorship and whistleblowing). These cover research misconduct and wider issues important to maintaining the NOC's scientific independence and impartiality.

A1.5 NOC Independence

The evaluation period coincided with a protracted spell of organisational planning, culminating on 1 November 2019 in NOC becoming independent from NERC. The aim was to secure greater operational freedoms, to ensure we could remain a world-class scientific institution. NOC is now a non-profit distributing Company Limited by Guarantee with charitable status. It has a commercial Trading Subsidiary (NOC Innovations Limited). A charitable model was chosen specifically to safeguard against long-term mission drift, with our charitable objects fully aligned with the NOC mission.

The NOC is now overseen by a Board of Trustees (Chair John Hirst CBE) with a senior executive team led by the Chief Executive (Professor Ed Hill OBE), Chief Scientist (Professor Angela Hatton) and Chief Operating Officer (Julie Pringle Stewart) and Associate Directors spanning Research (Directorate of Science and Technology: DST), National Marine Facilities (NMF), Data & Information (D&I, including BODC), Government International & Public Engagement (GIPE), Strategic Business Development (SBD) and Corporate Business Support Services. During the evaluation period the CEO reported directly to the NERC Chief Executive/Executive Chair but is now accountable to the NOC Board. Professor Angela Hatton was appointed as Chief Scientist/Director of Science & Technology in 2016, succeeding Professor Ian Wright.

The drivers for change requiring greater freedoms were and remain:

- more complex multi-disciplinary grand scientific and societal challenges;
- rapidly developing need for advanced ocean measurement technologies;
- increasing opportunities in the growth potential of the ocean economy;
- ability to respond to a wider range of end-user of science and technology;
- access to new funding routes to increasing competitive funding, with 70% of NOC's science income now openly competed, compared to around 30% a decade ago;

- increasing global competition for scientific, technical specialist talent;
- need for closer professional working with business and other stakeholders.

NOC will use its freedoms to set attractive employment terms for staff, matched to business needs and to build unrestricted reserves to manage risks and invest in promising new areas.

A1.6 NOC Strategy

During the evaluation period, the NOC worked within the framework of the NERC/UKRI strategy (*Business of the Environment*) and latterly the *NERC-UKRI Delivery Plan*. These were interpreted in NOC's context and then evolved during our journey to independence. Hence three strategic documents have informed our approach and priorities over the period:

- NOC Strategy – *Taking the Lead* (from 2013);
- NOC Strategic *Business Case for Independence* from NERC (developed 2016-2018);
- NOC Strategy – *Making Sense of Changing Seas* (developed since 2018).

Our strategic goals for the coming five years are:

Goal 1: Undertake internationally excellent research and technology development to advance the frontiers of knowledge about the ocean;
Goal 2: Create public benefit from all of the NOC's capabilities;
Goal 3: Successfully translate world-leading and innovative research and technology developments to achieve wider impact;
Goal 4: Provide world-class underpinning capabilities that enable the UK and global scientific endeavour.

Enabled by:

Goal 5: Responsibly grow and diversify revenue to sustain our mission with a critical mass of scientific and technical capability;
Goal 6: Transform the way the NOC is governed and operated;
Goal 7: Invest and reinvest in the NOC and its people.

A1.7 Creating the Environment for Excellence, Innovation and Impact

NOC Values. As part of our change process, we worked collectively to **articulate our shared organisational values**. These are as important as our strategic goals to guide how we tackle the unexpected during rapid change. The six shared values are: Excellence, Empowerment, Integrity, Innovative thinking, Environmental responsibility and Working in partnership. The headline words are articulated in more detail below and in staff guidance notes.

Figure 3: NOC's shared values developed 'bottom-up' by staff

Two Sites, One NOC. The NOC is based at two purpose-built sites in Southampton (headquarters) and Liverpool. The infrastructure includes: 4000 m^2 office space (Southampton), 994 m^2 (Liverpool); 11 engineering workshops; 64 laboratories, with specialist facilities including high pressure testing facilities, instrument calibration, a glider test tank and ballasting facility amongst others; many of the facilities in Southampton, such as the cleanrooms and the micro-fabrication facilities are state of the art and also used by the University of Southampton.

There is regular **movement of staff between sites**, especially senior managers: e.g. open staff meetings led by the Chief Executive alternate between sites with live video links to the alternate site. Travel to collaborate is tensioned against remote dialogue facilitated by the NOC's video-conferencing facilities.

University co-location: The NOC is purposely co-located with the Universities of Southampton and Liverpool, both Russell Group Universities. Although our relationship with these universities is not exclusive, their vibrant local academic environments and large Graduate Schools are important parts of our research environment. With the University of Southampton, the NOC is a partner in the Southampton Marine & Maritime Institute.

NOC is proactive in **building and sustaining relationships with science users in government and industry** (Annex 1). The key to delivering impact is understanding user needs at the outset so that science outcomes can be shaped to both deliver great science and to address these needs. At the NOC, external engagement is supported by the Government, International & Public Engagement Teams (public sector & public) and the Strategic Business Development Team (business).

The NOC is supported by **Corporate & Business Service** support teams (headquartered at Southampton with local provision at Liverpool). In particular, the Science Programme Support Team assists researchers with costing and preparation of proposals.

A1.8 Science Excellence

Excellence underpins our research, from discovery science and transformative technology development to research that directly addresses the needs of government, business and the public. This is reflected in our scientific outputs. NOC generated 1461 peer-reviews publications during the Centre Evaluation period, with **108 papers published in Science or Nature group** journals. Our papers are widely cited, with **19.7 citations per publication** over the period.

Over the evaluation period, 22.9% of NOC's papers were in the top 10% of cited papers in our field (Table 1); higher than our key international peers, except Wood Hole. By 2019, this had risen to **25.2% of our papers in the top 10%** and 2.8% of our papers in the top 1% of papers in our field, positioning us above Woods Hole.

Table 1: Percentage of papers in the top 10% of cited publication in the research field

Institute	Country	% publications
NOC	UK	22.9
Woods Hole	USA	24.4
Scripps	USA	21
GEOMAR	Germany	20
IFREMAR	France	18.2
JAMSTEC	Japan	12.3

Our success allows us to attract excellent researchers from around the world, and enhances our collaboration with Universities, with a third of our staff originating from outside the UK, and 16 members of Staff with Honorary Professorships.

Our consistent strategic science priorities through the evaluation period have been

- Oceans & Climate: making sense of global change;
- Coastal and Shelf Seas: crowded waters where seas and people meet;
- Seafloor Resources, Habitats & Hazards: the deep-sea frontier;
- Technology development: transforming access to data: from gross under-sampling to data deluge.

Some highlight achievements against these goals and that exemplify our approach are:

Atlantic Overturning Circulation (RAPID-AMOC/OSNAP)

The NOC has leading roles in two international collaborative science programmes that are re-writing our knowledge of the large-scale Atlantic Ocean circulation. The RAPID programme, coordinated by the NOC and run in partnership with the University of Miami and NOAA, began in 2004 and observes the Meridional Overturning Circulation (MOC) in the **subtropical** North Atlantic. The RAPID array comprises vertical deep ocean moorings supporting instruments measuring temperature, salinity, velocity and oxygen between Morocco and Florida at 26°N. NOC scientists have worked in partnership with UK universities, Plymouth Marine Laboratory (PML) and EU partners, to build on the array, leveraging funding for additional research programmes.

The success of RAPID enabled the development of a second MOC array, the Overturning in the Subpolar North Atlantic Program (OSNAP) in the **subpolar** North Atlantic. OSNAP is a multi-national programme that began in 2014 and established a new deep ocean array that sits along a line between Canada, Greenland and Scotland. OSNAP's international partners include the US, Canada, France, Germany, the Netherlands and China. In the UK, OSNAP is led by NOC, in partnership with the Scottish Association for Marine Science (SAMS) and the Universities of Liverpool and Oxford. The first full OSNAP array results produced a sea-change in our understanding of the subpolar MOC, showing that convection in the Labrador Sea, a process previously thought to dominate, may actually play a minor role. This surprising new observation is being used to critically review essential processes in ocean and climate models used by the Met Office and other organisations around the world. Thus, NOC leadership in the RAPID and OSNAP observational programmes is essential for reducing the uncertainty in seasonal, decadal and longer term climate forecasts (See Impact Cases 1 & 2).

The Atlantic Ocean Observing System *(AtlantOS*)

The AtlantOS project ran between 2015 and 2019 and was one of the largest funded EC H2020 projects, bringing together 62 partners across 18 countries. AtlantOS was a multidisciplinary, large scale project centred around the coordination and enhancement of Atlantic Ocean observations. The NOC was a lead partner in the delivery of the project, led two work packages, and involved researchers from every research group in the organisation. The project had a global reach with partners from all of the nation's bordering the Atlantic. The NOC delivered key parts of the technology development, enhanced the global sea level measurement systems and developed key financial metrics around the operation of fixed-point observatories.

Shelf Seas Biogeochemistry Programme (SSB*)*

The SSB Programme was a multidisciplinary project funded by NERC and the Department for Environment, Food and Rural affairs (Defra) that finished in 2018. The NOC was one of the main delivery partners, bringing together modelling, analysis, data management and the application of autonomy through the use of Autosub and gliders to investigate controls on the major processes that control the fundamental biogeochemical processes in shelf sea areas. The programme linked the experts at the Universities of Aberdeen, Bangor, East Anglia, Edinburgh, Liverpool, Oxford, Plymouth, Portsmouth and Southampton with NOC, the Met Office, SAMS, the Centre for Environment, Fisheries and Aquaculture Science (Cefas) and PML. The NOC contributed to the delivery of both the scientific and infrastructure requirements of the project, through its research, data management, technology development and the major infrastructure of the NMF vessels and autonomous vehicles.

Strategies for the Environmental Monitoring of offshore Carbon Capture & Storage (STEMM-CCS)

Capturing carbon dioxide (CO_2) from industrial sources (such as power plants and cement manufacturers), then storing it offshore in depleted oil and gas reservoirs (or aquifers), is one of the leading contenders for mitigating the impacts of increasing CO_2. CCS is now one of the IPCC highlighted solutions, deemed necessary to limit global warming below 1.5ºC. The energy company Equinor has operated the world's longest-running offshore storage reservoir in the North Sea. However, there has not been a wider roll out of the technology, mainly due to public concerns over the safety and the start-up costs associated with offshore CCS. The STEMM-CCS project, coordinated by the NOC, brings together 13 academic and business partners from across Europe.

It aims to increase public confidence that a leak from a storage reservoir could be detected and quantified. The project has developed a suite of new technologies and techniques to detect an early stage accidental leak of CO_2 from a storage reservoir, and developed an online tool to be used by reservoir operators to cost monitoring programmes (See Impact Case 3).

Sensor Technology Development

Sensor development at the NOC is at the forefront of global innovations, addressing capability gaps for measuring ocean chemical, biological and ecosystem variables. This work, funded through a variety of research and development routes, engages 45 staff and 10 PhD students in a unique multidisciplinary team. Comprised of mechanical, electrical, electronic, software and systems engineers together with analytical chemists, biologists and application specialists. The team is focused on the creation of new highly capable but low-cost sensors to operate in the harsh ocean environment, including on small autonomous vehicles. Working in partnership with the Marine Autonomous & Robotic Systems (MARS) team, this creates a unique multidisciplinary environment, augmented by world leading laboratories, testing and workshop facilities, and draws in the very best engineers and scientists from around the world to the UK. The team has strong links with technology users and stakeholders globally, but particularly benefits from strong interactions with UK Government (e.g. Defra, Environment Agency, Cefas), industry (e.g. offshore industry and instrument manufacturers), and benefits from partnership with leading Higher Education Institutes (HEI). This led to development of 19 new sensors, the biggest portfolio of ocean sensors worldwide, eight patents and >80 journal publications (see Impact Case 3).

Most of the projects above are only possible because of the combination of multidisciplinary science and working partnership with universities, HEI's commercial organisations and government bodies and departments.

Our NC, such as the Climate Linked Atlantic Sector Science (CLASS) programme, deliver the UK Governments commitment to the Global Ocean Observing System (GOOS), and through them, we deliver to several internationally coordinated observing programmes, including the Global Ocean Ship-based Hydrographic Investigations Programme (GO-SHIP), the Integrated Carbon Observing System (ICOS), the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and the Global Sea Level Observing System (GLOSS). Working with the Met Office we fulfil the UK's commitments to international Argo, and drive NEMO model development (Nucleus for European Modelling of the Ocean), one of a small handful of physical ocean models used in a global context for IPCC-class climate simulations, operational forecasting and oceanographic research (See Impact Case 1 & 2).

The NOC benefits from external collaboration in many ways. We value support received from external senior scientists through collaboration, advice, mentoring and advocacy which helps ensure the quality of our science and enhance its impact. To acknowledge their contribution, in 2017 NOC instigated distinct categories of **NOC Fellows** (Visiting Fellow, Senior Visiting Fellow, Adjunct Fellow, Emeritus Fellow). The category of Honorary Fellow is the highest honour the NOC can bestow and so far has been awarded just twice: to Professor Peter Liss CBE, FRS (academic) and Sir Robert Margetts CBE, FREng (industrial).

A2 People

A2.1 Valuing our People

Being a people focussed organisation, the NOC takes the learning and development needs of staff seriously, and was successfully reassessed against the new Investors in People **(IIP) Standard in October 2018**. The IIP assessor described the NOC as a highly engaged organisation, with nearly 80% of respondents stating that '*my organisation is a great place to work*'. NOC was also short-listed for the IIP Standard Award (in the over 250 staff category) at the IIP 2019 Awards Event.
https://www.investorsinpeople.com/events/awards/

The NOC has established a set of **Values Awards** that are announced at annual 'Summer Celebration' events at both sites, organised by a cross-NOC team including the Investors in People Working Group, Communications Team, Events Team, and Estates; these awards recognise staff

who are considered to best embody the NOC Values by their peers. In 2019, 84 individual nominations were received and six awards made to staff at each site, with details published on the intranet.

The NOC has a Learning and Development (L&D) team that provides **personal development training,** open to all staff, and management development training, covering a broad range of topics including assertiveness, time management, difficult conversations, objective setting, personal development planning and review, change management, stress and resilience, and coaching and mentoring. Some examples of important training and mentoring schemes are listed below:

- The L&D team designed and launched a NOC ***mentoring scheme*** in 2017, and provided three skills workshops to help potential mentors understand the type of commitment they would be making and to develop their skills. The scheme has been widely supported: many senior staff signed up as mentors, supporting both NOC staff and external academics. Mentors have signed up from all parts of the organisation and across all grades.

- The NOC has provided two ***Management Development Programmes*****,** funded by the Apprenticeship Levy (at ILM Level 3 and Level 5) for those who want to complete a formal management qualification. Over 25 staff have signed up to date. The NOC has also provided a new '*Introduction to Science Leadership*' programme, widely supported by staff. The Director of Science and Technology has run an Early Career Researcher (ECR) programme since 2017, training staff in leadership, proposal writing, networking and creating a peer-to peer network. This is now being developed into a formal ECR training programme.

- Some 102 staff have attended a range of in-house **Health and Safety training** on manual handling, risk assessment and COSHH. A further 14 attended the NERC-funded Safety Management in Research Environments course. In recognition of the growing requirement for scientists and engineers to undertake overseas fieldwork, the organisation has invested £60k in Overseas Business Travel Safety Awareness training, with five sessions attended by nearly 60 staff.

To recognise the developing skills and talent of staff we have developed a new process for **Merit Promotion**, designed following wide consultation across the organisation. This replaced the previous process administered by NERC and is now seen as better able to recognise the diversity of DST roles. In 2018, 24 staff attended Merit Promotion Information Sessions and 29 applied for Merit Promotion, a marked increase on the 12 in 2017. We have quarterly Performance and Development Reviews aimed at developing clear objectives around the day today job, which feeds into long-term development and career planning goals, enabling managers to support staff in developing their careers and aiding staff retention.

We have a number of ways to reward, retain and develop our talented staff:

We recognise staff who are delivering above and beyond what is expected of their Band and job role and who have demonstrated high levels of impacts and success in their areas of work. These range from the ability to award thank you vouchers (£25 - £50) for a one-off event, nominated by any member of staff, bonus schemes awarding £250 - £750 for more exceptional efforts and pensionable Supervisory and Responsibility Allowances that reward staff who have themselves increased the responsibilities in their roles.

In addition, as we operate in a highly competitive environment for talent, we have used Recruitment and Retention Allowances to attract and retain staff who may normally be attracted to higher salaries outside the research environment, this is particularly relevant for some of the high-level technical, computing and engineering skills we require.

We actively support our staff in engagement with the wider scientific community, allowing our scientists to play key roles on a wide range of national and international science committees and bodies. Furthermore, we nominate our ECRs for relevant advisory committees and academic

activities. The NOC management view this as a key role for our scientists and is an important way we can aid our staff in developing their careers.

We have a young, dynamic workforce with 46% of researchers under the age of 40. To support our younger ECR's, we have developed tailored programmes such as the mentoring programme and the ECR training programme. We include ECR's on important internal committees, such as the Demand Management Committee, the Athena SWAN, Science Advisory Team and the Science Committee. The NOC has an annual ECR Award to recognise a piece of excellent research in the previous 12 months. It is, highly competitive and the judging panel includes external academics. The prize of up to £1,000 supports conference attendance, and the award is well regarded by staff. We also endeavour to support ECRs outside of the NOC: e.g. as part of the CLASS NC programme, NOC administers a fellowship scheme to support ECR working on Atlantic Ocean research. Four fellowships were awarded in Nov 2019 as part of the first phase of this programme, to ECRs at Universities of Bristol, Manchester and Southampton, and Flanders Marine Institute.

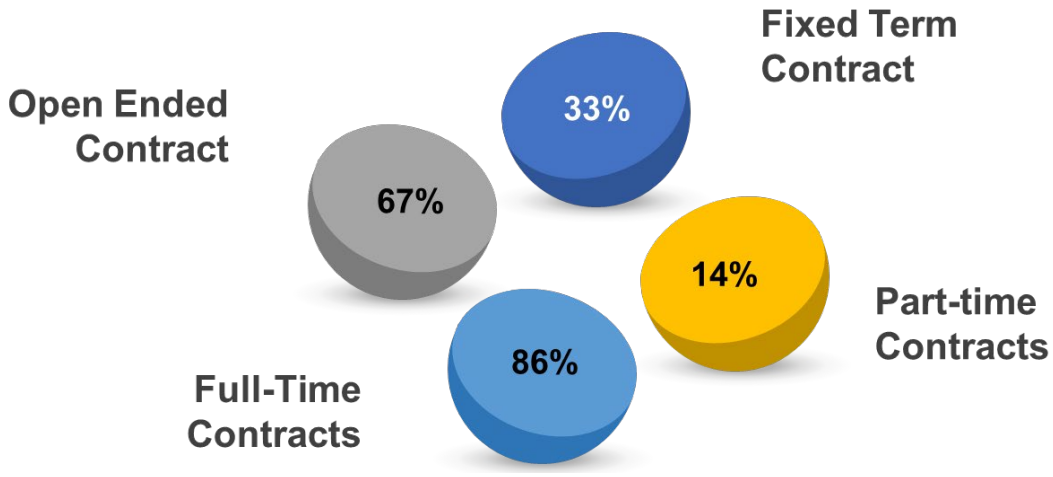


Figure 4 Balance of Full Time/Part time staff and Open Ended/Fixed Term Appointments for DST staff 2019

We offer **training and support in the development of competitive funding applications** and our ECR staff have been very successful in obtaining funding. During the review period, three female scientists secured or completed prestigious European Research Council (ERC) projects, with a combined value of €5.4M. Dr Veerle Huvenne completed her Starting Grant for the CODEMAP project in 2017, Dr Eleanor Frajka-Williams secured a Consolidator Grant for the TERIFIC project in 2018, and Dr Stephanie Henson secured an ERC Consolidator Grant for the GOCART project in 2017. Amongst our cohort of lead scientists under 40, 90% have secured competitive funding.

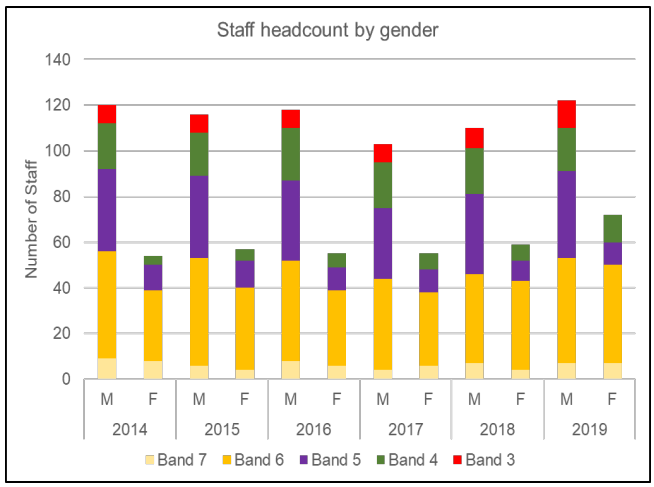
DST headcount has increased by 11% since 2014. We currently have 91 Principal Investigators, running 142 grant-funded projects varying in size from £50k to £24M. 37% of our staff are female, relative to 31% in 2014, with the number of female staff in DST increasing between 2014 (54) and 2019 (72). With such excellent staff NOC is proactive in development of policies and processes aimed at the retention of staff in a competitive environment for talent.

We have a sabbatical programme to allow staff (full and part-time, open ended and on fixed term appointments) the opportunity to study at other institutes for short- or long-term periods; for instance, Dr Veerle Huvenne has recently returned from a three week sabbatical in Italy. Two other members of staff Sveta Jevrejeva and Professor Mike Zubkov are on long-term sabbaticals to the Centre for Climate Research Singapore, and SAMS, respectively. We also have part-sabbaticals where staff spend a period of each month working at another organisation Professor Russ Wynn worked closely with Defra under this scheme for two years.

A2.2 Equality, Diversity and Inclusion

At the NOC we recognise that the success and overall competitiveness of our institute depends on our ability to embrace diversity and draw upon the skills, understanding and knowledge of all our employees, students and visitors. The potential opportunities and rewards are significant; therefore, we intend to ensure that Equality, Diversity and Inclusion (EDI) underpin our shared values. As a first step towards greater diversity we have chosen to adopt the Athena SWAN Charter, which recognises the advancement of gender equality through representation, progression and success for all: NOC became the 115th member of the Athena SWAN Charter in 2014.

When the new Director of Science & Technology arrived, it was clear to her that the processes in place had not effectively addressed gender equality issues. None of the B3 staff, and only 20% of the B4 staff, were female. Due to NOC independence we have been able to bring promotion and recruitment processes in-house. This has resulted in an increase in the number of female staff at B4 (improving from 5 males to every female in 2014 to 1.6 males to every female in 2019). We have now recruited the first female B3 in DST. This is a positive start, but there is still much to do.



The NOC **Athena SWAN Self-Assessment Team** (SAT) is represented by staff at all levels of the organisation, as well as PhD students, and is chaired by the NOC Director of Science & Technology. Recent activities include the delivery of an independent Gender Equality survey to understand the main challenges and gaps in the organisation. We had strong engagement from staff with ~60% taking part in the survey, reflecting the growing commitment across the organisation for greater gender inclusivity. The report was finalised in October 2019 and the SAT is in the process of analysing the data to produce a robust four-year Action Plan for implementation. The NOC originally planned to submit an application in November 2017, but we became aware that the Athena SWAN remit was expanding, so wanted to wait to ensure **all** NOC staff were included and that this was relevant to the newly independent NOC processes. This meant expanding our SAT and collating feedback from all employees and students. The new SAT is currently working towards an application for Athena Swan Bronze Award status in Nov 2020.

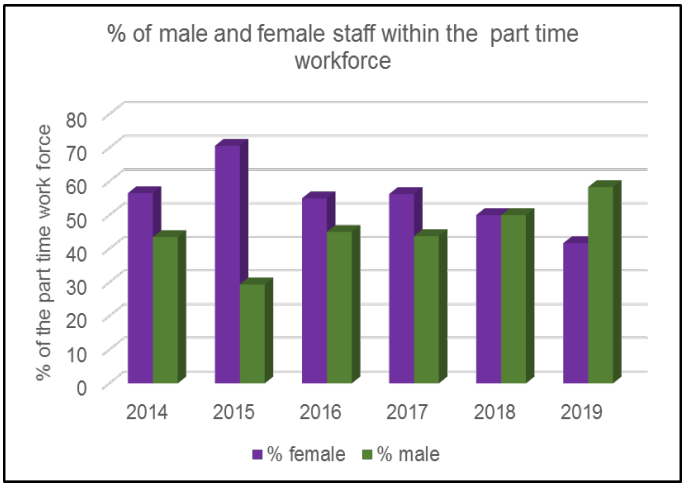
One of the highlight findings of the survey report was that 90% of staff would **recommend working at NOC** to a prospective staff member (92% amongst female respondents), and the vast majority (96%) of those who have worked at sea or undertaken fieldwork as part of their role at the NOC would recommend such experience to a colleague. It was also notable that 81% of staff were positive that the NOC recruits and selects staff fairly, without systematic gender discrimination.

The NOC also held well-attended **Gender Equality talks** in June 2019 for staff and students to coincide with the 100-year celebration of Women in Engineering, featuring inspirational speakers including NOC Board Member Sarah Kenney OBE (Chief Executive BMT Ltd), Professor Rachael James (University of Southampton) and Leigh Storey (Associate Director NMF). In Feb 2015, the NOC contributed three biographies to "*Women in Oceanography: a decade later*" a special issue of the journal *Oceanography* that assessed progress in gender equality since the original special issue on the topic a decade earlier. The NOC also celebrates its female scientists and engineers during the annual 'Women in Engineering' Day; e.g. for the 2018 edition, the NOC profiled seven DST and NMF-MARS engineers on the NOC website and on posters distributed around the building.

The NOC has provided three workshops on **Unconscious Bias** for senior scientists and engineers, with 47 attendees. A further 97 staff attended a session on Unconscious Bias as part of the Recruitment and Selection course. In addition, 27 sessions covering 231 staff have provided training on managing resilience, mental health awareness and disability awareness.

To enable staff to better **balance the requirements of their personal and professional life** we offer a number of avenues for staff, including flexible working, generous maternity and paternity conditions and childcare vouchers.

We are fully **supportive of our staff working part time**. Over the evaluation period, on average 11% of staff in DST worked part time, of which 55% were female and 45% male. However, this varied over time with males representing 29% of part time staff in 2015 increasing to 55% in 2019.



A2.3 Developing the Next Generation of Marine Scientists

To develop the next generation of scientists the NOC is actively involved in programmes that support PhD students at the start of their research career:

- The NOC and the University of Southampton together host the **Graduate School** of the National Oceanography Centre, Southampton (GSNOCS), which is arguably the largest concentration of marine science and technology postgraduates in Europe. There are currently around 170 PhD students at GSNOCS, with an annual intake of about 40, together with about 50 Masters students.
- The NOC has been or is currently a partner in six **NERC Doctoral Training Partnerships** (DTPs: SPITFIRE, INSPIRE, ENVISION, ARIES, Manchester and Liverpool DTP and the Oxford DTP) and three **industry-partnered Centres for Doctoral Training** (CDTs: NEXUSS, AURA and SENSE) led by HEI's. These cover environmental sciences, Unmanned systems science, offshore wind energy and Satellite Data use in environmental sciences.
- The NOC has been successful in **attracting funding for PhD students** by leading or partnering in more than seven EU Marie Skłodowska-Curie Innovative Training Networks: including £460k for IsoNOSE (ISOtopic tools as Novel Sensors of Earth Surface resources), £332k for RISES-AM (Responses to coastal climate change: Innovative Strategies for high End Scenarios – Adaptation and Mitigation), and £228k for Robo-academy to investigate AUV navigation.
- The NOC offers the **opportunity for students** from external organisations to participate in active research programmes both nationally and internationally; for instance, we have students working on the CLASS Programme, in association with researchers from NOC, Sea Mammal Research Unit (SMRU), SAMS, PML and the MBA. Internationally we have students associated with the CME programme; for instance, both Stacey Felgate and Sarah Cryer have been doing work in Belize for their PhD's.

A3. Income, Infrastructure and Facilities

A3.1 Income

Over the evaluation period, NOCs **annual income rose** from £46m rising to £60m. In that time, NERC NC funding increased from £22M to £24.5M, with the science component (NC-Science) increasing from £4.6M to £5.1M. It should be noted that this is just slightly below inflation (an inflationary-level increase would result in £25M and £5.2M respectively). These numbers demonstrate two key points: 1) 80% of the NC Funding awarded to NOC supports provision of services and facilities (e.g. ships, data) to the wider community; 2) Total NC dropped from 48% to 41% of NOCs overall Income during the evaluation period.

The breakdown of **science income** by major funders (Figure 7) shows that NC-Science represented only about 20% of NOC science income in 2019, and less than 10% of NOC income overall.

The share of competitively-won science income has grown steadily over the evaluation period - rising from 71% to 80% of all science revenue (Figure 7). NERC remains NOC's major funder (NC, Strategic Programmes and Discovery Science), but reducing as a share of the total from 56% to 47% as NOC has diversified its portfolio. Other funders are the EU, Government Departments and a growing share of private sector income.

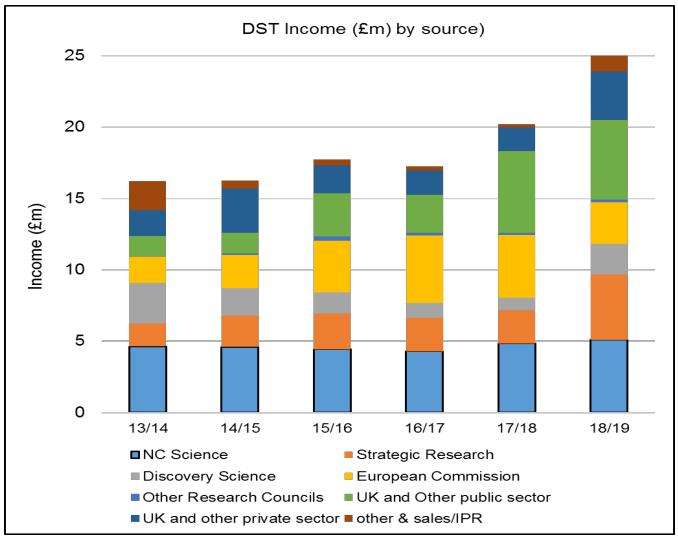


Figure 7. Changing science income 2013/14 to 2018/19

NOC's strategy in generating research income is to secure **a balanced portfolio,** enabling us to focus on the largest, most challenging science problems at basin-decadal scale, whilst also addressing important environmental challenges required by end-users.

The NOC has been active and influential in seeking funding through **NERC Large Grants, Highlight Topics and EU Horizon 2020 programmes** – all of which are better suited to larger scale science. As a result, the majority of the NOC research funding bids are collaborative with multi-institution partners e.g., the EU programmes AtlantOS (£20m across 64 partners); STEMM-CCS (£15 m across 13 partners)**.** In addition to numerous NERC and EU grants and EU grants, NOC's success in winning competitive funding includes winning funds from prestigious sources including:

- Five NERC Large Grants: only three Large Grants are funded each year across all environmental science, with 24% awarded to NOC in this highly competitive call;
- Seven Highlight Topics: strategic projects of up to £4m, with NOC involved in 20% of the projects funded through this call;
- Three European Research Council (ERC) grants: highly competitive personal fellowship awards funding pioneering research from any field.

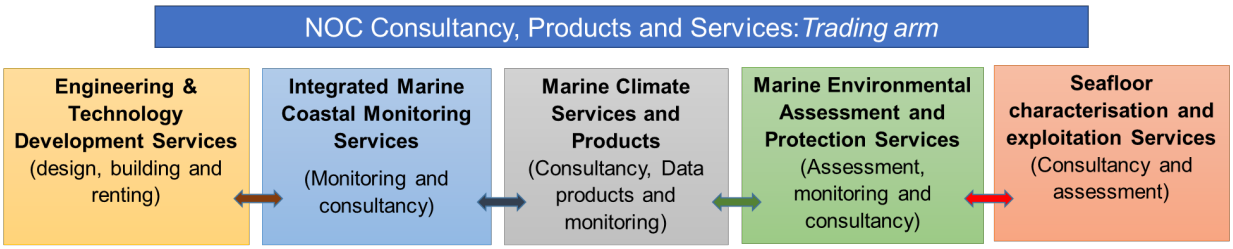
A3.2 Long-term Planning

NC science underpins distinctive aspects of the national science capabilities for which NOC is custodian: i.e. infrastructural sustained ocean observations; large ocean general circulation models; technology development capability. However, it is the NOC's success in leveraging revenue from other sources that is crucial to sustaining these capabilities for the benefit of UK science at the level and quality that could not otherwise be achieved by NERC NC funding alone. Moreover, the funding leveraged off NC-Science (e.g. from the EU) has brought funds into partners at British universities and institutions spreading further benefit of the NC investment. The STEMM-CCS project led by the NOC (Professor Connelly) had partners from the Universities of Southampton and Heriot-Watt along with PML, with funding to UK institutes €10.2m of the total €16m.

Financial sustainability is crucial (Strategy Goal 5). The NOC never returned unplanned deficits whilst part of NERC and is not permitted to operate deficits in future as a charity. Consequently, in conjunction with the science priorities, our bidding strategy emphasises ensuring that projects meet their full costs, and that any low-margin projects are offset by higher-margin work. Our portfolio of EU programmes is constructed so it can be matched with other funding sources. Based on its financial model, the NOC strategy is to diversify its revenue portfolio to generate higher margins, to build unrestricted reserves, to buffer risk and to reinvest in promising new areas.

A dedicated Strategic Business Development team has been recruited, tasked with building relationships with key industry partners. We have identified areas for future growth and income diversification - based in international strategic science agendas, scientific opportunity, and potential

to become financially self-sustaining, to generate high impact partnerships, products and services and non-traditional revenue.



Building on the achievements during the assessment period, our vision for the next five years is to become the world's most innovative oceanographic institution - both in what we do and how we do it. Whilst we may never be the best funded ocean research institute in the world, innovation and being the partner of choice will be key to our competitive edge. Furthermore, this will help the UK maintain its international standing in ocean science as emerging economies invest heavily in the field.

A3.3 Infrastructure, Facilities and Enabling the Wider Community

National-scale research infrastructures

As part of the NOC's national remit, we manage the UK marine scientific community **national-scale research infrastructures** and other facilities, on behalf of NERC. The NOC employs the specialist technical support teams, with a brief to operate and innovate, including:

- Two global-class research ships RRS Discovery and RRS James Cook and associated shore side support and logistics.
- National Marine Equipment Pool (NMEP) of ship-deployed marine equipment and including Europe's largest fleet of autonomous underwater and surface platforms and sub-sea gliders and deep sea Remotely Operated Vehicles (ROVs). This equipment pool is available to the NERC funded ocean science community, following approval by NERC's Cruise Programme Executive Board, as part of Marine Facilities Planning.
- Customs Warehouse facility at the NOC in Southampton, which allows suspension of import duty and VAT on equipment used at sea (outside UK territorial waters), representing an ongoing saving of £5m in suspended duty.



This infrastructure is used to lever additional capacity such as through international ship and equipment barter arrangements whereby access to international facilities is exchanged for access to UK facilities.

The NOC shares its wealth of knowledge the **nationally-pooled approach** to marine facilities around the world. NOC was a founding member of the European Ocean Facilities Exchange Group (OFEG), which has helped promote models of pooled equipment sharing. This pooling enables the UK to fully support the UK community across a breadth on disciplines – doubtless contributing to international analyses (e.g. UNESCO Global Ocean Science Report, 2016) placing the UK in the top three players internationally in the field of ocean science.

The Evaluation period has seen significant **capital investment** in scientific infrastructures, including:

- £75m investment in the new research ship RRS *Discovery*, which was delivered in 2013 and entering science service in 2014.
- £30m investment over the period to 2020 in marine autonomous and robotics platforms and sensors as part of the Eight Great Technologies initiative and subsequently the Industrial Strategy Challenge Fund.
- £1m per year investment in sustaining the NMEP advised by the independently-chaired Marine Facilities Advisory Board (MFAB) with UK science community representation.
- £0.75m per year investment in capital to support NOC science and IT equipment. The NOC continues its policy of ensuring seagoing equipment procured for NOC science is part of the NMEP so it can become available in due course to the entire science community.
- £0.65m approved for High Performance Computing costs relating to global-ocean and shelf-sea simulation modelling.

During the evaluation period, NERC moved to a **'flat cash' funding model** for the bulk of ship/NMEP operating costs ('owner and ready to go costs'), meaning that a funding gap is opening year-on-year between the cost of operating at full capability and available NERC NC funds. NERC has tasked the NOC to negotiate ship charters and equipment hire-out options in order to bridge the funding gap. The NOC has adapted to this model e.g. RRS *James Cook* has just completed a charter in December 2019 for the Canadian Government.

National-scale data infrastructures

Infrastructure providing for the long-term management of quality controlled, irreplaceable **ocean digital data and samples and metadata** is provided by the British Oceanographic Data Centre (BODC: digital marine data), the British Ocean Sediment Core Research Facility (BOSCORF), the Discovery Collections of deep-sea biological specimens which are all part of the NOC, and the Permanent Service for Mean Sea Level (PSMSL).

The **BODC** is an accredited data acquisition centre of the Intergovernmental Oceanographic Commission's International Ocean Data Exchange (IODE) worldwide network of ocean data repositories. BODC leads the UK's Marine Environmental Data Information Network (MEDIN) which provides access to all government marine data holdings and is regarded as an international model for national data sharing based on the principle of "collect once, use many times". The BODC is also the Global Data Assembly Centre for Seabed 2030, with the vision to map the entire ocean floor at high resolution by 2030 relative to the 15% mapped today.

Shared Library Facilities

The **National Oceanographic Library** (jointly funded with the University of Southampton) is an integral part of the research support provided to all our scientists. Library staff provide advice on copyright and open access and help with applications for UKRI gold open access funds and compliance. The team manages the NOC outputs for the institutional repository and ensures publications are made accessible as soon as possible. The Library ensures that staff have easy access to a wide range of literature through electronic and print formats and runs a range of workshops on research skills.

A4. Collaboration and Contribution to the Research Base, Economy and Society

A4.1 Engagement and Impact

The combination of world class facilities, scientists and technology developers greatly enables our engagement agenda. On top of our reputation for depth and breadth of intellectual capacity in ocean science, our superb physical environment and ease of hosting visitors, events mean that the NOC has considerable 'convening power' in the marine and maritime community. There is a regular flow of visitors from other research institutions and universities, from government, intergovernmental bodies and from industry.

As described in our Business Case for independence, the NOC plays an important role in marine research & innovation. Partnership and collaboration with both the academic community and with research users, is essential. We work closely with partners at a range of geographical scales from

local (where NOC sites are based) to national and international. These relationships take a diverse range of forms such as:

- Partners in co-delivery of NERC national capabilities (PML, SAMS, MBA)
- Partners in funded research projects (Research Institutes, Universities)
- Funder of projects delivered by NOC (e.g. NERC, UKRI, Government, Industry)
- Co-delivery of outputs/infrastructures, but funded separately (Met Office, ICOS)
- DTP's/CDT's (Universities, Industry)
- International Programmes with agreed aims, funded separately (e.g. GOOS, ICOS)
- Networks e.g. for influence, dialogue (e.g. POGO, European Marine Board)
- Suppliers e.g. technology, data International Comprehensive Ocean-Atmosphere Data Set (ICOADS)
- Local and regional business clusters (Maritime UK Solent, Mersey Maritime)
- NOC Marine Robotics Innovation Centre (30 partners) (see Impact Case 4).

Figure 8: Some examples of the NOC's collaborations over the assessment period. Centre circle: NOC internal collaborations; Middle circle: UK based collaboration; Outer circle: International Collaborations. See Annex A for detailed examples

Ocean science is in increasing demand to inform actions: policy, governance and business investment decisions concerning sustainable economic and human development. The NOC is an independent and trusted source of marine data, information and advice to our four key stakeholder groups: UK Government, industry, the marine science community, and the general public. As well as providing advice, we work in partnership to ensure that the work we do makes a difference and has impact. **Details of engagement and impact can be seen in Annex 1, Table 2 and the impact cases**.

A4.2 Measures of Esteem and Contribution to the Research Base

Our staff contribute in many ways to the effective functioning of the UK and international research endeavours, often in unsung ways through their participation in advisory bodies, peer review. We are proud of the work they do and the esteem in which they are held as evidenced by the invitations they receive to bring their expertise to bear in many different ways.

Awards and Honours

The NOC is proud of all its staff who have received recognition for their achievements in science and the enabling of science including:

- Member of the Order of the British Empire: Griffiths, Captain Plumley & Cooper
- Adrian Gill Prize of the Royal Meteorological Society 2015: Kent
- Merchant Navy Medal for Meritorious Service 2018: Captain Gatti
- EGU Fridtjof Nansen Medal: Huthnance
- BSRG Perce Allen Award 2015: Masson)
- BSRG Harold Reading Medal 2015: Clare
- Roland Goldring Award, 2019: Clare
- H. Burr Steinbach Scholar WHOI: Thorne
- Honorary Fellow Bangor University 2014: Hill
- Fellow of the Institute of Directors 2015: Hill
- SUT Oceanography award 2019: Holliday
- Geological Society Coke Medal: Murton
- Geological Society Distinguished Service Award: Day
- Challenger Fellowship: Henson, Firing
- IMP (individual Merit Promotion): Bacon, Anderson & Zubkov (renewal)
- Honorary Professor University of Southampton: Bacon, Hatton, Holliday, Gommenginger, Mowlem, Murton
- Honorary Fellow of the SAMS: Hatton.

Committees

Over the assessment period NOC staff have served on over 140 committees and advisory bodies. These are vital to the global endeavour by both overseeing the garnering of scientific consensus, developing strategic science agendas and enabling the translation of scientific evidence into actionable advice, some of the most significant of which were as follows:

International

European Space Agency Earth Science Advisory Committee (Gommenginger); IOC (Hill, Evans); EMB (Hill, Evans); World Climate Research Programme & Global Climate Observing System – Atmospheric Observing Panel for Climate (Kent); GOOS Steering Committee (McDonagh); Argo Steering Committee (King); Deep Sea Mining Stakeholders Group (Murton); Global Sea Level Observing System Group of Experts (Rickards, Jevrejeva); GO-SHIP Science Committee (Holliday); General Bathymetric Chart of the Oceans Guiding Committee (Allen); International Comprehensive Ocean-Atmosphere Data Set Steering Committee (Kent); International Ocean Carbon Coordination Project Scientific Steering Group (Connelly); IOC Tsunami Warning System (Hibbert); Joint World Meteorological Organisation/IOC Technical Commission for Oceanography and Marine Meteorology (Horsburgh); Nucleus for European Modelling of the Ocean Steering Committee (Holt); OceanSITES Ocean Fixed Point Time Series Committee (Lampitt); POGO (Hill);; World Register of Marine Species Steering Committee (Horton); IPCC Assessment Reports (Josey, Jevrejeva, Henson).

National

NERC Science Board (Hatton, Chair); Government Office of Science Future of the Seas Foresight Panel (Hill, Hatton); UK Marine Science Coordination Committee (Hill, Wynn); UK Overseas Territories Biodiversity Group (Strong); UK Office for Nuclear Regulation Climate Expert Panel (Horsburgh); Natural Hazards Partnership (Horsburgh); National Partnership for Ocean Prediction (Hill, Holt); UK Integrated Marine Observing Network (Palmer).

Editorships

Our scientists contribute to global dissemination of scientific results by serving as journal editors During the evaluation period these included: Ocean Science (Huthnance, Editor in Chief; Williams); Continental Shelf Research (Palmer, Lichtschlag); Frontiers in Marine Science (Connelly); Journal of Operational Oceanography (Wilson); Marine Geology (Wynn); Ocean Dynamics (Palmer). Guest Editors: Deep-Sea Research II (Huvenne), Frontiers in Marine Science (Calafat), Journal of

Geodesy (Williams); Journal of Marine Science and Engineering (Brown); Marine Geology (Huvenne); Natural Hazards and Earth System Sciences (Brown); Ocean Dynamics (Brown, Wilson).

Journal Reviewing

NOC staff have reviewed papers for all of the leading ocean, earth science and technology journals, covering the broad range of subjects that reflect the multi-disciplinary nature of NOC's expertise. These journals include Nature and the associated Nature-family, Science, Environmental Science and Technology, Optics Express, Journal of Geophysical Research, PLOS One etc.

Participation on National and International Grant Committees

NOC staff have reviewed funding proposals and participate in moderating panels for the following organisations: NERC, BBSRC, EPSRC, UKRO FLF, German Research Foundation - DFG; EPSRC; US National Science Foundation (NSF); Royal Society Wolfson Fellowship; Schmidt Ocean Institute; Dept of Energy; NordForsk; ANR-France; FORMAS Climate change review panel Sweden; and others.

A4.3 Engaging with Diverse Communities

Engagement of the public in ocean science is critical to inform public debate and maintain public confidence in science and policy founded on scientific evidence. It nurtures support and sympathy for ocean research and meeting our responsibilities for public accountability for the large volumes of public funding that support ocean science. The NOC engages within the ten principles of 'Ocean Literacy' (e.g. UNESCO, 2015) which enables us to reinforce key messages about the ocean, its benefits to humanity and our impacts on it and its ecosystems. This is growing more important as the ocean has attracted public attention, not least on account of the issue of plastics (the 'Blue Planet' Effect). The NOC has developed and put in place policies for engaging with the media and social media to ensure our scientific independence and impartiality remain assured as the territory becomes more complex. **Details of our public engagement activities can be found in Annex 2**.

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Table 2: Summary of impact cases submitted to the Centre Evaluation Exercise

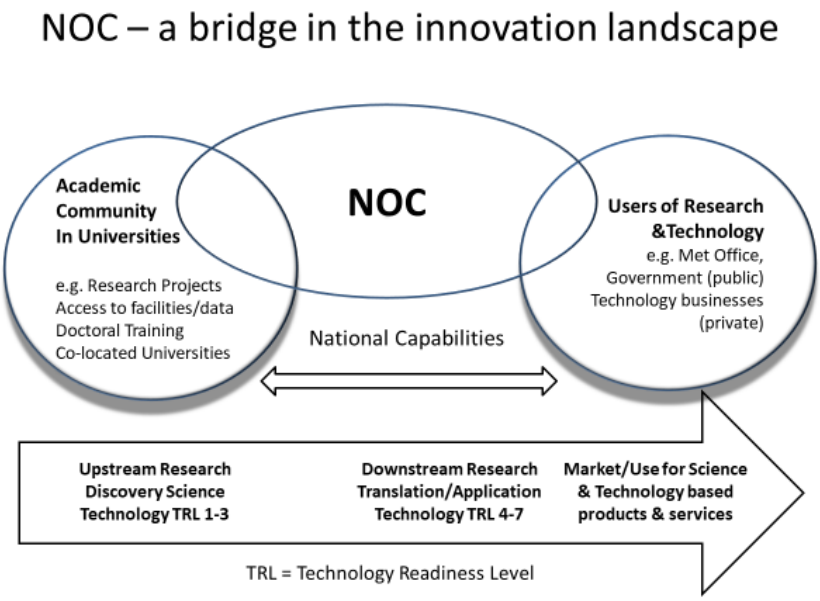
Impact Case No	Short name	Type of Impact	Beneficiaries
Impact Case 1	Operational Forecasting	Economic (cost avoidance) Societal Environmental	Met Office Government Bodies Industry (Energy, Shipping) Government (Marine Scotland, Defra) General Public
Impact Case 2	Climate Assessment	Policy & planning Societal Environmental	Met Office Government (Defra, BEIS) Intergovernmental (IPCC)
Impact Case 3	Aquatic Sensors	Economic Environmental Capacity building	Business (start up: Solent Sensors, Teledyne) Intergovernmental (IOC) ODA countries (e.g. Indian Ocean, Caribbean)
Impact Case 4	Marine Autonomous Technology	Economic Capacity building	Business (e.g. ASV, Autonaut, EcoSUB) ODA countries (e.g. Caribbean SIDS, West Indian Ocean)
Impact Case 5	Marine Radar Remote Sensing	Economic Policy & planning Capacity building	Business (Malan Maritime; Rutter Inc) Local Authorities (Sefton) Government bodies (NRW) ODA countries (West Indian Ocean, Caribbean)
Impact Case 6	Protecting People & Coasts	Societal Policy & planning Economic (cost avoidance) Capacity building Environmental	Local authorities (e.g Sefton Council) General Public Business (Balfour Beatty, HR Wallingford) Public bodies (ONR) Government/ government bodies (Cabinet Office, Defra/ EA) ODA countries (Caribbean SIDS)
Impact Case 7	National Security	Planning & procurement	Government: MoD
Impact Case 8	Marine Geohazards	Economic (cost avoidance) Risk Assessment Planning	Business (e.g. Sonardyne; HR Wallingford, Atkins, ExxonMobil, Chevron) Government (Cabinet Office-Risk register) International Bodies (ICPC) International Government bodies - Canada
Impact Case 9	Habitat Mapping	Policy & planning Societal Environmental	UK government bodies (JNCC, Cefas) International bodies (ISA) ODA countries (West Indian Ocean, Caribbean)

Annex 1: Examples of collaborations and partnerships

It is the collaborations and partnerships with users of research and technology that enable us to deliver impact by engaging in dialogue to understand the needs and drivers of end-users and intermediate end-users of research, technology development. To do this, the NOC plays an important role in the marine research & innovation ecosystem (Figure 9).

The NOC has developed policies and procedures for risk-based testing of collaborative projects and partnerships from different dimensions: reputational and ethical; deliverability; health & safety & welfare; financial sustainability. These are intended to be empowering whilst providing a clear governance framework for thinking through risks ahead of entering in to arrangements and with clear escalation for decision making in NOC up to and including the CEO and the Board.

Figure 9



Annex 1.1 Industry relationships

The following exemplify ways in which the NOC engages in a partnership approach with industrial end users (right hand side of Figure 9)

(a) NOC Marine Robotics Innovation Centre at Southampton: opened by Science Minister Jo Johnson in November 2015, today there 21 Innovation Centre partners (there have been 30 in total over the evaluation period) many of which are physically co-located with us. The Innovation Centre supports pre-commercial R&D and once companies have a product they must manufacture/market it offsite, making space for the upstream pipeline. It has attracted interest from UK Government and businesses, and internationally (including the OECD) in how to stimulate a business cluster.

- The essence of the model was providing flexible, attractive facilities to co-locate small businesses to work alongside the NOC, who bring expertise in various dimensions of autonomous technologies.
- A key example was the development of 'ecoSUB', a small AUV capable of meeting requirements for swarms of low cost, fast deployable AUVs for rapid response e.g. to oil spills. Once co-located the NOC has been able to develop joint projects (over £2.6m in Innovate UK funding) and to jointly exploit IP (see Impact Case 4).

(b) Project Partnerships: Since 2015, Knowledge Transfer Partnerships (KTP) have been used to facilitate technology transfer and as a means of developing long-term relationships.

- The NOC partnered with Marlan Maritime Technologies Ltd and the University of Liverpool in a KTP. Based on a NOC idea for cheaply and accurately mapping the shifting seabed of coastal waters using shore-based radar measurements of water wave to infer water depths

(needed for navigation and coastal engineering), the KTP focussed on developing the necessary software and techniques. It was ranked as 'Outstanding' by Innovate UK in 2018. This partnership was also integral to Marlan securing the Merseyside Innovation Award in July 2017 and the 'Innovation' award at the Mersey Maritime Awards in March 2018 (see impact Case 5)

(c) Visibility in the Marine Industries. Increasing, the visibility of the NOC within the maritime sector is important to promote us as a credible industry collaborator and source of great ideas that achieve results. For example:

- Membership of Industry Trade Associations: these provide access to networks and enables us to engage in discussion of strategic issues facing the sector. The NOC is an Associate Member of the Society of Maritime Industries; member of the World Ocean Council (global businesses) and the Institute of Marine Engineering Science & Technology.
- Hosting & Participation in Industry-led Conferences and Exhibitions: by far the most notable is Ocean Business held at the NOC in Southampton every 2 years in partnership with Intelligent Exhibitions Ltd; the NOC has also played an important supporting role at Oceanology International (IO) at the Excel Centre in London. For example, at OI 2018, NOC scientists and engineers chaired eight sessions and provided six speakers.
- Industry Awards The NOC's visibility is enhanced through industry sector recognition. Examples include:
  WIREWALL - based on highly innovative accurate measurements of wave overtopping of sea defences to optimise sea defence design and early warning, the impact of which is protection of coastal communities and reduce construction costs. WireWall was delivered in partnership with HR Wallingford, won the 'Positive Impact' category at the 2019 Mersey Maritime Industry Awards and received a special commendation in the 'Research Project/Team of the Year' category at the 2018 Dredging and Port Construction Awards (See Impact case 6).
  ANYTIDE is an app which includes free comprehensive tide information for over 1000 coastal points worldwide, widely used by the recreational sailing community it won the 'National Impact' category at the 2019 Mersey Maritime Industry Awards.

Annex 1.2 Academic
At the academic end of the bridge (Figure 9) are numerous collaborative partnership examples, including:

NOC Association. The NOC put in place an engagement forum, to provide an opportunity for the wider (mainly academic) community to understand and access NOC's national capabilities. The NOC-A was independently chaired during the period by Professor Peter Liss FRS and Professor David Thomas. Under NOC's new governance, the chair of NOC-A is an Observer on NOC's Board, with a view to providing an academic community perspective on NOC's support of the community through all of the NC funded activities.

The NOC engages in many global collaborative activities, which shape international research agendas and strategies. These entail not only individual scientist-to-scientist interactions, but depend on cooperation and networks of influence at intergovernmental and institutional-levels. To this end, NOC's International & Strategic Partnerships Office (ISPO) supports and facilitates at an institutional level, and on behalf of UK Government Departments (especially the FCO, BEIS and Defra). For Example:

- The NOC and University of Exeter are UK co-hosts for the Ocean Thematic Centre within the Integrated Carbon Observation System (ICOS), which is a European Research Infrastructure Consortium (ERIC), agreed through BEIS. The NOC is also a member of the European Multidisciplinary Seafloor and water-column Observatory (EMSO), which is also an ERIC.
- The NOC manages, researches and makes data openly accessible the PSMSL global data base of monthly mean sea levels from over 2,000 coastal and island tide gauges worldwide.
- The NOC is a founding member of the Partnership for Observation of the Global Ocean (POGO), comprising the world's 40 major ocean institutes. It coordinates between those

institutions that are at the front-line of delivering 'in-water' sustained ocean observations for the Global Ocean Observing System.

- The NOC is a founding and active member of the newly-reformed European Marine Board (EMB). EMB are responsible for preparing authoritative consensus led position papers, which have proven influential in developing EU funding calls. NOC CEO (Hill) was influential in shaping EMB's strategic forward look documents, Navigating the Future IV (2014) and Navigating the Future V (2019).
- On behalf of and liaising with the Foreign and Commonwealth Office (FCO), NOC leads the UK Delegation to the Intergovernmental Oceanographic Commission (IOC) of UNESCO, which is the UN competent body for ocean science and sponsor/co-sponsor of many key international ocean programmes, including the Global Ocean Observing System. The FCO views the NOC's role as essential in ensuring the IOC remains a technically motivated UN body
- Dr Elaine McDonagh (NOC) was elected by representatives of European and North American Member States of the Intergovernmental Oceanographic Commission to serve on the International Steering Group of GOOS. For other examples, see section A4.2 international committees.

Annex 1.3 Public sector

Returning to the 'user' end of the bridge (Figure 9) the NOC has important partnerships with **public sector users and intermediate users of scientific information**, expertise and advice. Within the United Kingdom NOC been supporting UK Government (and government bodies), advising on the scientific aspects of many ocean initiatives, including

Met Office: The NOC has a strategic relationship with the Met Office - an 'intermediate user of science', with the true end-users utilising Met Office products and services. The NOC develops and innovates ocean circulation models as part of the wider NEMO consortium. We contribute to the development of the NEMO-global ocean model (see Impact Case 2) and the NEMO shelf sea model (see Impact Case 1). The NOC also contributes the global intermediate-complexity biogeochemical model, MEDUSA to the Met Office climate model.

Intergovernmental Panel on Climate Change (IPCC): The NOC scientists contribute to the work of the IPCC in its production of periodic, authoritative, consensus scientific Assessment Reports (AR) on the state of the climate system. These assessments are central to informing global collective climate actions for mitigation under the UN Framework Convention on Climate Change (UNFCCC) and their Conferences of the Parties (COP) (see impact case 2).

UK Government: The NOC directly advises UK Government in many ways. For example,

- We supported BEIS with the UK-led 'G7 Future of the Seas initiative' which focussed on five strategic actions around ocean observing and monitoring activities. NOC's Chief Scientist is the UK scientific Lead for the G7 Expert Working Group, and BEIS has provided resources to recruit a G7 coordination post, based at the NOC. We continue to provide close support to the FCO with scientific and technical advice in negotiations on a new legally binding instrument under the UNCLOS for sustainable management of biodiversity in BBNJ areas.
- The NOC supported the **UK Government Office of Science** (GO-Science) Foresight Report: Future of the Seas, led by Government Chief Scientific Adviser Sir Mark Walport. Hill and Hatton were members of the Government Chief Scientific Advisor's Steering Panel and Hatton contributed to a special report on deep sea resources. Its public launch attracted worldwide media attention.
- NOC has provided input to the **UK International Ocean Strategy** (stemming from Future of the Seas Report) which is soon to published and led by the FCO.

We hosted the 24th Onsite Inspection Workshop of the **Comprehensive Test Ban Treaty Organisation** (see CTBTO, 2018), focussed on detection and response to potential under sea nuclear tests. This was an unusual community (to NOC). NOC researchers were provided valuable insights to aid their work, and contributed to the inspection handbook that resulted from workshop.

NATO and UK's security interests have shifted in recent years due to the geopolitical situation, renewed focus on naval power and threats in the North Atlantic and Arctic. Over this time, the NOC has increased its engagement with the defence sector. There is particular interest in autonomous technologies for surveillance and rapid environmental assessment. The NOC series of demonstrator missions for autonomous systems (MASSMO) have involved defence stakeholders including one linked to the 'Unmanned Warrior' NATO Exercise in 2016. We have an MoU with the Royal Navy and supports training needs regarding autonomous systems (see Impact Case 7).

The NOC is an important contributor to a number of international bodies focussed on environmental impacts, including; the UK **Marine Climate Change Impacts Partnership** (MCCIP), the **Natural Hazard Partnership**, and the **International Cable Protection Committee,** which brings together Government advisors and commercial companies who own or operate sub-sea telecommunications cables and pipelines (See Impact Case 8).

Foreign Secretary, Boris Johnson, visited NOC in 2018 to announce the development of the UK International Ocean Strategy.

Internationally, the evaluation period has seen increasing focus on end users being beneficiaries of **Overseas Development Assistance** (ODA). Projects, all of which require close working with 'in country' end users include:

- Commonwealth Marine Economies Programme (CMEP): Since 2015/6 NOC has been collaborating with the UK Hydrographic Office (UKHO) and Defra's Cefas in delivering the CMEP, designed to aid resilience and sustainable development of marine economic resources for Commonwealth Small Island Developing States (SIDS) and Coastal States. A major focus has been in the Caribbean and Belize. The NOC developed and deployed an innovative Containerised Autonomous Marine Environmental Laboratory (CAMEL) and training for rapid, low cost mapping and assessment of coastal marine environments (see Impact Case 4). The NOC has installed and trained users on equipment for improving risk management. Official Development Assistance (ODA) activity is feeding into advice to other parts of the UK Government. For example, the installed radar gauge systems for tsunami, surge and long-term sea level trends in Caribbean SIDS are now far superior to the UK's own aged network. The NOC has been working with Defra, Marine Scotland and the Environment Agency to pilot a long overdue UK upgrade.
- Global Challenges Research Fund (GCRF): In the GCRF-funded **SOLSTICE Programme,** NOC has worked with East African States (South Africa, Mozambique, Tanzania, Kenya) bordering the Western Indian Ocean (WIO). In recent years, the region has seen dramatic and often poorly understood reductions in key fisheries, due to the combined effects of climate change, natural ecosystem variability, overfishing and degradation of key marine habitats. SOLSTICE brings together recent advances in marine technologies, local knowledge and research expertise to address challenges facing the WIO region in a cost-effective way via state-of-the-art technology transfer, collaborative environmental and socio-economic research and hands-on training.
- Newton Fund: A collaborative project called '**Applying Nature-based Coastal Defence to the world's largest urban area'** (ANCODE), which is a partnership between NOC,

University of Liverpool, Netherlands Institute for Sea Research (NIOZ) and Sun Yat-sen University in China, has been short-listed for the £1M Newton Prize 2019.

Annex 2: Public Engagement

Public engagement is supported through individual funded projects and NOC's GIPE team (supported by the NOC events team and volunteers), who provide professional communications support to researchers and the NOC corporately. Forms of engagement include;

- Bringing the public to interact with NOC scientists (open days, ship port calls)
- Taking science to public venues (e.g. museums, public venues)
- Mainstream Media (press, radio, TV, web) and Social Media.

The NOC holds an **Annual Open Day**, at which staff give freely of their time to enable the general public to explore the on-site facilities, and take part in topical debates and hands-on activities. In 2019, Open Day events (see NOC Open Days, 2019) were held at both Liverpool and Southampton sites, attracting over 1800 attendees and were timed to coincide with World Oceans Day (Table 2).

NOC Events & Visitors	2015	2016	2017	2018	2019
NOC Open Day (Adults)	1,205	926	809	1,133	1,119
NOC Open Day (Children)	939	525	585	812	759
Total	**2,144**	**1,451**	**1,394**	**1,945**	**1,878**
Events Supported	100	104	105	145	217
Conference Delegates hosted	5,366	7,200	10,849	14,200	14,114
Outreach tours attendeeds	No Data	508	1,917	1,461	442
Marine Life Talk Evening Attendees	No Data	644	651	1,058	596

Table 2 NOC events- by the numbers

The NOC has supported NERC with two major **events based around the research ships**: *Discovery* in London (2017) and *Discovery* in Liverpool as part of NERC's 'Into the Blue' public engagement in NW England. The NOC hosts visits to the ships when (rarely) alongside in their home port of Southampton. For instance, during an eight day port call in 2017, 917 visitors from diverse groups such as Beavers, Cubs Scouts, Guides, Brownies, Sea Cadets, retired engineers, schools, film crew, and BEIS/UKRI/NERC toured *RRS James Cook.*

When ships undertake extended overseas port calls the NOC, at its own initiative, has instigated visits for local communities, schools and diplomats (strongly supported by respective British Ambassadors). Events have been held at port calls in Rio de Janeiro and Santos (Brazil), Punta Arenas (Chile), Cape Town (South Africa), Port Stanley (Falkland Islands) and Halifax (Nova Scotia, Canada).

Our engineers developed and now operate the Autosub Long Range, which since 2016 has been more commonly known amongst the general public as 'Boaty McBoatface'. Boaty is a highlight of our Engineering Workshop tours which are enjoyed by schools, business partners, government visits and interest groups.

Over the past two years, four NOC staff have been interviewed on BBC Radio 4 Flagship Today Programme – (Hill, Ocean Foresight Report; Hatton, Marine Plastics; Huvenne protecting cold water corals, Martin, Southern Ocean and climate change). In 2018 NOC scientists (Murton and others) were broadcast to around 18 million viewers of the BBC news at 6 discussing the discovery of large volumes of tellurium on a submarine seamount.

NOC actively supports the activities of other NERC Centres and Universities in the UK: NOC scientists showcased work at the RRS *Sir David Attenborough* launch; working with the University of Southampton on their annual open day; NOC scientists assist at the British Geological Survey BGS open science days.

From 2015 NOC has monitored it's mainstream and social media engagements; highlights are shown in **Table 3**.

NOC Mainstream and Social Media	2015	2016	2017	2018	2019
Stories issued to the media or added to the NOC website	125	72	65	57	61
Items of media coverage generated by NOC releases and direct pitches	420	108	816	1,612	1,849
Twitter: total followers	7,700	9,700	12,300	14,200	16,000
NOC mail: total subscribers	7,600	13,000	18,000	11,800	19,000
YouTube: total views	32,000	39,000	44,000	83,000	65,000
Website: unique page views	994,000	908,000	391,000	430,000	485,000

Table 3. NOC media engagement.

ENVIRONMENT COMPONENT DATA

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

Provisional pending the year end Charity Commission audit process

2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
60.5	55.8	51.7	56.2	59.9	69.6

2. Open access data

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	Notes
UKRI open access block grant awarded to the Centre (£k)	39	49	51.8	49.1	53.9	56.8	Data based on OA returns each year
% of UKRI open access block grant spent (for years where block grant was received)	100%	100%	100%	100%	100%	100%	
% **overall** open access compliance for UKRI-funded papers (as reported to UKRI)	67%	77%	82%	86%	80%	83%	Note: decrease in 2017/18 of open access occurred when RCUK changed licence requirements and Elsevier was no longer compliant for green open access
% **gold** open access compliance for UKRI-funded papers (as reported to UKRI)	38%	43%	40%	58%	61%	64%	
% **green** open access compliance for UKRI-funded papers (as reported to UKRI)	29%	34%	42%	28%	19%	19%	