The Role of the Southern Ocean in the Earth System (RoSES) – Challenge 3	
Closing date	19 September 2019
Funding available	£650k
Funding mode/stream	Strategic Programme Area
NERC Core or UKRI/Collective Fund budget	NERC Core
Project duration	3 years
Funding partners (if applicable)	N/A
Start date requirements (if applicable)	N/A
Call aims and objectives	The aim of this Research Programme is to provide the scientific basis to inform international climate policy of the role of the Southern Ocean (SO) carbon system in 21st century climate change. Proposals are invited to address **Challenge 3** of the programme: **Develop key policy-informing metrics of the integrated efficiency of the SO carbon sink and its role in 21st-century global climate change.** Applicant will be expected to draw on outputs from Challenge 1: Design and implement the optimal approach to assess the state, variability and climatic drivers of the contemporary SO carbon sink and Challenge 2: Define, quantify and provide mechanistic understanding of the key processes controlling the rate of SO carbon uptake of the RoSES programme which were funded under the programme's first funding round.
Eligibility criteria	Standard eligibility criteria apply. Applicant can be named on two proposals, but only once as PI.
Call specific requirements	Applicants should draw on the outputs of Challenge 1 and 2 projects which were funded after the programme's first call for proposals.
Contact	Jennifer Morris

The Role of the Southern Ocean in the Earth System (RoSES)

Announcement of Opportunity

Issued on 25 June 2019
Full Proposals deadline 16.00 on 19 September 2019

1 Summary

Proposals are invited to address Challenge 3 of the Role of the Southern Ocean in the Earth System research programme.

The outcome of this Research Programme will be the provision of the scientific basis to inform international climate policy on the role of the Southern Ocean carbon system in 21st century climate change.

It is expected that this announcement will lead to the funding of 2 proposals that address Challenge 3 of the programme. Up to £650k is available for this call.

Proposals for this call are invited from eligible UK researchers (see NERC Grants Handbook for standard eligibility criteria.

The closing date for proposals is 16:00 on 19 September 2019.

2 Background

The Southern Ocean (SO) is one of the most important and poorly understood components of the global carbon cycle that profoundly shapes Earth's climate. It is the primary hot spot for the oceanic sink of anthropogenic CO_2, having captured half of all human-related carbon that has entered the ocean to date[1] [2]. This vast anthropogenic perturbation to the SO carbon system is activating a range of complex climate feedbacks (e.g. a rising atmospheric CO_2-induced acceleration of the westerly winds over the SO, which may in turn be driving increased SO outgassing and raising atmospheric CO_2 concentrations further[3]) that are likely to exert a decisive control on the evolution of oceanic carbon uptake, atmospheric CO_2 and global climate

[1] Mikaloff Fletcher, S. & twelve others, 2006: Inverse estimates of anthropogenic CO2 uptake, transport, and storage by the ocean. Glob. Biogeochem. Cyc. 20, doi:10.1029/2005GB002530.
[2] Frölicher, T. & five others, 2015: Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. J. Clim. 28, 862-886.
[3] Le Quéré & eleven others, 2007: Saturation of the Southern Ocean CO2 sink due to recent climate change. Science 316, 1735-1738.

over the 21st century[4] [5]. Many of these climate feedbacks are poorly understood and quantified, yet evidence from our planet's past global climatic transitions (e.g. the end of the last glacial period) suggests that they can induce changes in atmospheric CO_2 as large as those caused by human activities since the industrial revolution[6] [7]. As the focus of major knowledge gaps and a central player in global carbon and climate dynamics, the SO carbon system is regularly singled out as the 'Achilles heel' of the Earth system models upon which humankind relies to understand contemporary climate change, predict its future evolution, and define international climate policy[8] [9].

Inadequate understanding and unconstrained model representation of the SO carbon system constitute a critical uncertainty in climate projections for the 21st century. Investigations of the present magnitude of the SO carbon sink and its recent decadal variability yield wildly different estimates, yet unanimously show that the regional budget is the sum of large, uncertain outgassing and uptake terms that are both comparable in magnitude to the CO_2 emissions from the world's most polluting economies and highly sensitive to climate change[8] [10]. In the Paris Agreement, 195 nations committed to undertaking rapid reductions in their greenhouse gas emissions to hold the global-mean temperature to well below 2°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change. The effectiveness of this Agreement is, however, acutely vulnerable to future changes in the SO carbon system that are not captured by rudimentary representations in the present generation of Earth system models. Even modest variations in the SO's outgassing or uptake terms may lead to a significant shift in the reduction of global anthropogenic CO_2 emissions required to meet long-term temperature goals, and produce a geopolitically challenging imbalance between the integral of national sources and the desired evolution of atmospheric carbon.

The evolution of the SO carbon sink over the 21st century has been the subject of a persistent, heated debate in the scientific literature[3] [8] [10] [11] [12]. This is reflected in the SO accounting for most of the uncertainty in Earth system model predictions of global oceanic carbon uptake, which differ by up to approximately 2 Pg C yr-1 (i.e. the present net global oceanic carbon uptake) by 2050. The debate is fuelled by a paucity of essential carbon system observations in the SO, which makes the region the most glaring biogeochemical 'data desert' in the world ocean; and by a damaging lack of understanding of the fundamental processes controlling the size of the SO carbon sink, which raises large uncertainties in the nature and magnitude of associated climate feedbacks – particularly as global emissions start to decline toward zero. Now, the advent of novel autonomous robotic platforms and biogeochemical micro-sensor technologies, in which the UK has played a world- leading role, makes it possible to tackle these issues directly for the first time,

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[4] Schwinger, J. & eleven others, 2014: Nonlinearity of ocean carbon cycle feedbacks in CMIP5 Earth system models. J. Clim. 27, 3869-3888.

[5] Kessler, A. & J. Tjiputra, 2016: The Southern Ocean as a constraint to reduce uncertainty in future oceancarbon sinks. Earth Syst. Dyn. 7, 295-312.

[6] Martínez-García, A. & eight others, 2014: Iron fertilization of the Subantarctic Ocean during the last ice age. Science 343, 1347-1350.

[7] Watson, A. & two others, 2015: Southern Ocean buoyancy forcing of ocean ventilation and glacial atmospheric CO2. Nature Geosci. 8, 861-864.

[8] Lenton, A. & sixteen others, 2013: Sea-air CO2 fluxes in the Southern Ocean for the period 1990-2009. Biogeosci. 10, 4037-4054.

[9] Heinze, C. & seven others, 2015: The ocean carbon sink – impacts, vulnerabilities and challenges. Earth Syst. Dyn. 6, 327-358.

[10] Landschützer, P. & eleven others, 2015: The reinvigoration of the Southern Ocean carbon sink. Science 349, 1221-1224.

[11] Zickfeld, K. & three others, 2008: Comment on 'Saturation of the Southern Ocean CO2 sink due to recent climate change'. Science 319, 570b.

[12] Takahashi, T. & seven others, 2012: The changing carbon cycle in the Southern Ocean. Oceanog. 25, 26- 37.

and settle the debate once and for all.

3 Scope of Call

3.1 Programme Objectives

The overarching objective of RoSES is to provide the scientific basis to inform international climate policy on the role of the SO carbon system in 21st century global climate change. By substantially reducing uncertainty in 21st century global climate change projections through improved assessment of the SO carbon sink, RoSES will bolster the UK's capacity to credibly encourage other nations to strengthen their emission reduction ambitions through the 5-year review and 'ratchet' mechanism. This is a stated diplomatic priority for the UK (Prime Minister's speech to COP21 summit in Paris, 30 November 2015).

The exceptional significance of the SO in the global carbon cycle stems from the region hosting most of the vertical flow between the surface and deep layers of the world ocean[13]. Deep waters enriched in carbon and nutrients upwell to the surface in the Antarctic Circumpolar Current, powered by the strong westerly winds that blow incessantly over the SO. Some of these waters flow southward, cool, form sea ice and sink to the abyss, producing northward-flowing Antarctic Bottom Water. The remainder flow northward, freshen and subduct to intermediate depths at the northern edge of the SO as Antarctic Intermediate Water and Subantarctic Mode Water. These two circulation pathways form the lower and upper limbs of the SO overturning circulation, and act to draw carbon into the ocean interior and to feed the rest of the ocean with the nutrients that sustain global primary productivity and ecosystems[14] [15].

The sign and magnitude of the SO's contribution to global atmospheric CO_2 are set by the difference between the carbon content of upwelling and downwelling waters. This difference is determined by the sum of a complex, poorly understood array of biological, chemical and physical processes that collectively modify the carbon content of water parcels during their characteristically approximate 1 year-long journey through the upper ocean. On reaching the surface, upwelled waters experience air-ice-ocean gas exchanges, which transfer CO_2 into or out of the atmosphere. The high nutrient content of those waters fuels biological carbon fixation through the growth of phytoplankton, but this growth is regulated by upper-ocean turbulent flows (which shape the light and nutrient conditions for growth) and ultimately limited by the widespread shortage of the micronutrient iron. Grazing by zooplankton stimulates biological carbon export through the sinking of organic particles, which are broken down into inorganic carbon by remineralisation processes in the deep ocean. All these processes are strongly seasonal and episodic, and their effect on carbon content is dependent on their relative phasing and interactions with other processes[5]. In the pre-industrial period, this suite of processes made the SO a strong source of carbon to the atmosphere, but in recent decades the rising concentrations of anthropogenic CO_2 in downwelling waters have likely reversed the region's contribution to a sink of unknown magnitude[8]. During the 21st century, however, the SO carbon sink could revert to a source if the local biological carbon fixation and export decreased substantially[16].

The alarming uncertainty in the contemporary size and future evolution of the SO carbon sink stems from two factors:

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[13] Rintoul, S. & A. Naveira Garabato, 2013: Dynamics of the Southern Ocean circulation. In Ocean Circulation and Climate: A 21st Century Perspective, Academic Press, Oxford, U.K.
[14] Sarmiento, J. & three others, 2004: High-latitude controls of thermocline nutrients and low-latitude biological productivity, Nature, 427, 56–60.
[15] Marinov, I. & three others, 2006: The Southern Ocean biogeochemical divide. Nature 441, 964-967
[16] Hauck, J. & seventeen others, 2015: On the Southern Ocean CO2 uptake and the role of the biological carbon pump in the 21st century. Glob. Biogeochem. Cyc. 29, 1451-1470.

1. the acute sensitivity of observational estimates of the contemporary sink to methodological detail, which precludes assessment of the sink's variability and feedbacks with the wider climate system[10];
2. the existence of critical and uninformed differences in the representation of biogeochemical processes and their interaction with the overturning circulation in Earth system models[16].

Both of these factors are caused, at root, by the scarcity of biogeochemical observations. There is a fundamental mismatch between the annual time scale of upper-ocean carbon content change and the much shorter, summer-biased timing of the ship-based observations that are used to investigate its drivers. Year-round measurements of how the SO carbon system operates are key to determining the sequence of processes controlling the carbon content difference between upwelling and downwelling waters, so that an integrated view of the SO carbon sink and its vulnerability to perturbations in climatic forcing can be developed with robust analytical approaches and credible, mechanistically constrained models.

To address this requirement, the overarching objective of the programme will be addressed through the delivery of three inter-related research challenges. Challenge 3 is the subject of this call. Challenge 1 and Challenge 2 were funded as part of this programme's first call for proposals.

***Challenge 3*:** (2 proposals to be funded at a maximum cost to NERC of £325k each)
Develop key policy-informing metrics of the integrated efficiency of the SO carbon sink and its role in 21st-century global climate change.

If international climate policy is to succeed at stabilising atmospheric CO_2 concentrations and global warming below dangerous levels, it requires a quantitative assessment of the SO carbon system's impact on 21st century climate projections and their uncertainty ranges. Specifically, determining whether the policies arising from the Paris Agreement are likely to lead to the desired outcomes demands that:

- the evolving contribution of the SO carbon system to global atmospheric CO_2 be continuously monitored, supporting Article 4's requirement of signatories to reduce emissions so as to achieve a global balance between sources and sinks of atmospheric carbon;
- the commitment to future warming associated with anthropogenic perturbations to the SO carbon system be assessed, by e.g. identifying crucial tipping points in the system or other events that may lead to irreversible change and permanent loss or damage.

To meet these policy needs, it will be critical to develop and exploit key metrics that quantify the integrated effects of the SO carbon system on Planetary Vital Signs[17]. Key metrics are to encapsulate how changes in the biological, chemical and physical elements of the SO carbon system influence global climate, and might involve, for example, the upper-ocean mixed layer depth[16], extent of sea ice[18], strength of the overturning circulation[19], rate of biological export[20], and partitioning of nutrients within the water column[21].

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[17] Briggs, S. & two others, 2015: Planetary vital signs. Nature Clim. Change 5, 969-970.
[18] Ferrari, R. & five others, 2014: Antarctic sea ice control on ocean circulation in present and glacial climates. PNAS 111, 8753-8758.
[19] Anderson, R. & six others, 2009: Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO2. Science 323, 1443-1448.
[20] Kwon, E. & two others, 2009: The impact of reminerlization depth on the air-sea carbon balance. Nature Geosci. 2, 630-635.
[21] Ito, T., & M. Follows, 2005: Preformed phosphate, soft tissue pump and atmospheric CO2. J. Mar. Res. 63, 813-839.

Challenge 3 will directly connect the step change in scientific understanding of the SO carbon system achieved by RoSES to the goals of international climate policy-makers by, first, synthesising the new major insights on the system's operation from Challenges 1 - 2; and, second, using these as a basis to develop key metrics of the system's integrated efficiency and climate impacts. Significant contributions to this Challenge may come from multiple approaches, such as analyses of available carbon system-related data and proxies, the development and application of new theoretical frameworks, or investigations with a hierarchy of models of varying complexity (ranging from conceptual models to ocean general circulation models, and extending to IPCC-class Earth system models such as UKESM). ORCHESTRA simulations using ocean circulation models will be made available to RoSES for biogeochemical development or analysis.

This Announcement of Opportunity is for proposals to address Challenge 3 only. Details of Challenge 1 and 2 have been included for information as proposals to address these Challenges have already been funded. For further information on the expected outputs, from Challenges 1 and 2 to ensure their exploited in the delivery of Challenge 3, please contact the lead PI's (contact details in Section 8).

***Challenge 1*:** (proposal funded – PI Professor Corinne Le Quere)

Design and implement the optimal approach to assess the <u>state, variability and climatic drivers</u> of the contemporary SO carbon sink.

The SO is widely recognised as the largest oceanic sink of anthropogenic CO_2. In contrast, the strength, variability and biogeochemical controls of the SO's cycling of 'natural' (i.e. pre-industrial) carbon are poorly observed, modelled and understood, despite its decisive role in determining the sign and magnitude of the region's net contribution to global atmospheric CO_2 change[22]. Estimates of the size and recent variability of the regional carbon sink from atmospheric and oceanic observations differ wildly, are highly approach-dependent, and fail to constrain the system's climatic drivers[3 10]. Climate-scale models indicate a much more modest response of the SO carbon sink to climatic forcing perturbations than is suggested by observations, and provide no consensus on the sink's evolution over coming decades[8 17]. This points to serious structural deficiencies in the models, and opens up a fundamental and dangerous gap in our ability to predict and understand 21st century global climate change.

Challenge 1 will address this gap by developing, formally contrasting, and reconciling multiple approaches to the estimation of the SO carbon sink from diverse atmospheric and oceanic observations. This groundwork will lead to an assessment of the size, variability and climatic drivers of the contemporary SO carbon sink, and to the design and implementation of the optimal strategy to monitor the carbon sink in decades to come.

***Challenge 2*:** (two proposals funded – upper limb PI Dr Adrian Martin; lower limb PI Professor Karen Heywood)

Define, quantify and provide <u>mechanistic understanding of the key processes</u> controlling the rate of SO carbon uptake.

The rate of SO carbon uptake is set by the difference between the carbon content of upwelling and downwelling waters across both limbs of the overturning circulation. This difference is determined by a complex sequence of biological, chemical and physical processes with strong seasonality and highly episodic behaviour. These include: air-sea gas transfer, which controls the equilibration of CO_2 in upwelled waters with the atmosphere; sea ice formation and melting, which regulate gas transfer and biological production; iron supply and light levels, which influence the rate of nutrient utilisation and carbon fixation by phytoplankton; and grazing, which affects biological production and the sinking of organic carbon. Climate-scale models of the SO carbon

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[22] Ciais, P. & fifteen others, 2013: Carbon and other biogeochemical cycles. In Climate Change 2013: The Physical Science Basis. IPCC Fifth Assessment Report. Camb. Univ. Press, Cambridge, U.K.

system differ widely in their assessment of which processes are dominant in setting the system's efficiency and of how the balance between those processes is established[8 16]. The damagingly wide range of projections reflects the large uncertainties in current representations of biogeochemical processes in the models, which suffer from a critical lack of constraints by targeted, year-round observations.

Challenge 2 will tackle this fundamental weakness by:

- obtaining first-of-a-kind, systematic, year-round measurements of the processes controlling the rate of carbon uptake in each limb of the SO overturning circulation;
- using these observations to define the key processes that must be correctly characterised in models of the SO carbon system, quantify their contribution to the system's efficiency, and assess how models must represent their mechanistic operation.

3.2 Proposal Requirements

Proposals will be required to address the deliverables of Challenge 3:

Challenge 3 deliverables

- Definition of the key metrics of the integrated efficiency and climate impacts of the SO carbon system, to feature in future global climate monitoring programmes.
- Assessment of the consequences of contemporary changes in the SO carbon system for the stabilisation of atmospheric CO_2 and global warming over the 21st century.

Successful Challenge 3 grants will be expected to have established a formal partnership with the U.K. Met Office to (i) inform the accuracy of the 21st-century climate projections of UKESM and other CMIP6 models developed for IPCC AR6 (ca. 2020), which will be used in defining international global climate policy; and (ii) guide and support future developments of UKESM.

4 Programme Requirements

4.1 Programme Funding

Up to £650k is available for this call to fund 2 research project (at £325k each), to address Challenge 3.

The NERC funding contribution for proposed projects will be at 80% of FEC with the exception of facility costs, which will be paid at 100% and must be included within the funding limit.

Proposals should include formal requests (and access costs) for any other NERC Services and Facilities (e.g. aircraft, HPC, isotope analyses), where relevant.

All costs associated with facilities should be included within the Directly Incurred Other Costs section of the Je-S form.

Associated studentships may not be included in proposals.

4.2 Implementation and Delivery

All proposals are required to involve a minimum of 2 eligible institutions. Proposals will also be expected to include a range of both senior and early career scientists.

Proposals may be up to 36 months in duration. Proposals addressing Challenge 3 are expected to exploit the outputs from Challenges 1 and 2.

All proposals must include milestones and deliverables to ensure that NERC and the Programme Advisory Group can monitor the delivery of the science outputs.

It is highly desirable for proposal teams to be inter-disciplinary, and should also work with international project partners where appropriate.

4.3 Knowledge Exchange and Impact

Knowledge exchange (KE) is vital to ensure that environmental research has wide benefits for society, and should be an integral part of any research.

All applicants must consider how they will or might achieve impact outside the scientific community and submit this with their application as a Pathways to Impact statement, with associated delivery costs where relevant. Pathways to Impact activities do not have to be cost-incurring; it is not a requirement to include funded activities. Any funds required to carry out any proposed, outcome-driven activities identified within the Pathways to Impact **must** be fully justified within the Justification of Resources statement.

The Pathways to Impact will identify those who may benefit from or make use of the research, how they might benefit or make use of the research, and methods for disseminating data, knowledge and skills in the most effective and appropriate manner.

An acceptable Pathways to Impact is a condition of funding. Grants will not be allowed to start unless unacceptable Pathways to Impact are enhanced to an acceptable level within one month of notification of the panel outcome.

All funded projects may also be required to engage with programme-wide KE activities, in which case appropriate funding for which will be provided by the programme.

4.4 Data Management

The NERC Data Policy must be adhered to, and an outline data management plan produced as part of proposal development. NERC will pay the data centre directly on behalf of the programme for archival and curation services, but applicants should ensure they request sufficient resource to cover preparation of data for archiving by the research team.

4.5 NERC Facilities

Prior to submitting a proposal, applicants wishing to use a NERC service or facility must contact the facility to seek agreement that they could provide the service required. Applicants wishing to use most NERC facilities will need to submit a mandatory ‘technical assessment’ with their proposal. This technical assessment is required for aircraft but not for NERC Marine Facilities (NMF – Shiptime and/or marine equipment) and HPC. For NERC, this means a quote for the work which the facility will provide. A full list of the Facilities requiring this quote can be found on the NERC website. The costs for the service or facility (excluding NMF and HPC costs) must be included within the Directly Incurred Other Costs section of the Je-S form and also within the facilities section of the Je-S form. Further information on NERC services and facilities can be found on the NERC website.

4.6 Programme Management

It will be a condition of grant awards that the lead PIs of the awarded grants will work closely for the life time of the programme with the defined Programme Management arrangements.

4.7 Reporting requirements

As with all NERC grants holders, there will be a requirement to report through the UKRI reporting system; this is required annually and continues for up to five years post grant end.

5 Application Process

5.1 Full Proposals

Closing date: 19 September 2019

Full proposal must be submitted using the Research Councils' Joint Electronic Submission system (Je-S). Applicants should select Proposal Type - 'Standard Proposal' and then select the Scheme – 'Directed' and the Call – 'Role of Southern Ocean AUG19'.

This call will close on JeS at 4pm on 19 September 2019 and it will not be possible to submit to the call after this time. Applicants should leave enough time for their proposal to pass through their organisation's Je-S submission route before this date. Any proposal that is incomplete, or does not meet NERC's eligibility criteria or follow NERC's submission rules (see NERC Grants Handbook), will be office rejected and will not be considered.

All attachments, with the exception of letters of support and services/facilities/equipment quotes, submitted through the Je-S system must be completed in single-spaced typescript of minimum font size 11 point (Arial or other sans serif typeface of equivalent size to Arial 11), with margins of at least 2cm. Please note that Arial narrow, Calibri and Times New Roman are not allowable font types and any proposal which has used either of these font types within their submission will be rejected. References and footnotes should also be at least 11 point font and should be in the same font type as the rest of the document. Headers and footers should not be used for references or information relating to the scientific case. Applicants referring to websites should note that referees may choose not to use them.

Applicants should ensure that their proposal conforms to all eligibility and submission rules, otherwise their proposal may be rejected without peer review. More details on NERC's submission rules can be found in the NERC research grant and fellowships handbook and in the submission rules on the NERC website.

Proposals for this call should be submitted in standard grant format following the requirements outlined in Section F of the NERC research grant and fellowships handbook.

Please note that on submission to council ALL non PDF documents are converted to PDF, the use of non-standard fonts may result in errors or font conversion, which could affect the overall length of the document.

Additionally where non-standard fonts are present, and even if the converted PDF document may look unaffected in the Je-S System, when it is imported into the Research Councils Grants System some information may be removed. We therefore recommend that where a document contains any non-standard fonts (scientific notation, diagrams etc), the document should be converted to PDF prior to attaching it to the proposal.

No associated studentships can be requested under this call.

5.2 *Eligibility*

Normal individual eligibility applies and is in Section C of the [NERC research grant and fellowships handbook](). Research Organisation eligibility rules are in Section C of the handbook.

NERC research and fellowship grants for all schemes may be held at approved UK Higher Education Institutions (HEIs), approved Research Council Institutes (RCIs) and approved Independent Research Organisations (IROs). Full details of approved RCIs and IROs can be found on the UKRI website.

Investigators may be involved in no more than two proposals submitted to this call and only one of these may be as the lead Principal Investigator.

6 Assessment Process

Proposals will be considered by an Assessment panel made up of international experts and members of the NERC Peer Review College where possible. Funding recommendations will made by the panel.

The assessment criteria to be used will be as follows:

- Research Excellence
- Fit to Scheme

Feedback will be provided to both successful and unsuccessful applicants.

NERC will use the recommendations of the Assessment panel along with the overall call requirements and the available budget in making the final funding decisions.

7 Timetable

Closing date for full proposals:	19 September 2019
Assessment panel meets:	October 2019

8 Contact

For all enquiries, please contact:

Jennifer Morris

roses@nerc.ukri.org

For information on Challenge 1 and 2 projects please contact:

SONATA – Professor Corinne LeQuere, C.Lequere@uea.ac.uk

CUSTARD – Dr Adrian Martin, adrian.martin@noc.ac.uk

PICCOLO – Professor Karen Heywood, K.Heywood@uea.ac.uk