REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation:	United Kingdom
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Project Title:	Arctic butterflies through accidental twins

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**N/A**	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	300M	0	0
Graphics Processing Unit Cluster-A	[GBU]	0	0	0
Graphics Processing Unit Cluster-B	[GBU]	0	0	0
Accumulated data storage (total archive volume)[2]	[GB]	100000	0	0

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

EWC resources required for project year:

		2027	2028	2029
Number of vCPUs	[#]	0	0	0
Total memory	[GB]	0	0	0
Storage	[GB]	0	0	0
Number of vGPUs[3]	[#]	0	0	0

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Extended abstract

Abstract

In this application, we request computational resources to use a novel coarse-graining framework to advance understanding of error-growth dynamics through the lens of turbulent energy cascades. First, we will exploit the set of "accidental twin" experiments in which butterfly-like perturbations were unintentionally introduced to the intended bit-identical IFS deterministic forecast and ensemble control. The unintended difference persisted for 18 months, from June 2023 to November 2024. By applying a newly developed coarse-grained error-flux diagnostic, we will evaluate the cascade of error across scales and thereby answer questions about the location dependence of intrinsic predictability and the state dependence of spectral error growth behaviour. In addition to understanding the resultant error-flux diagnostics for locations around the globe, we will have a particular regional focus on the Arctic. In this region we want to explore the physical mechanisms underpinning error growth, assessing when the Arctic behaves as a relatively isolated circulation system and evaluating implications for predictability and Arctic–midlatitude coupling. Therefore, to complement the *error* cascade analysis in this region, we will use coarse-graining to diagnose local *energy* cascades across a range of flow states, analysing data from ERA5, the IFS and the CARRA2 Arctic reanalysis. Our goal is to test whether the Arctic atmosphere can exhibit a distinct geostrophic-turbulence regime characterised by persistent vortices and predominantly upscale kinetic energy transfers

Scientific background

Accidental twins

In 1969 Edward Lorenz advanced a theory of turbulent error growth that had a deeply surprising implication for weather prediction. According to his model he predicted that there was a global fixed limit of predictability of two weeks, beyond which no increase in resolution or computational power could breach. This has been broadly supported since by various studies (Rotunno 2008, Judt 2020). Lorenz's model is a fundamentally spectral one, but through a newly developed coarse-graining framework for analysing error growth (Kouhen et al., in preparation), it is now possible to probe his theory in ways that have not been previously possible.

From June 2023 to November 2024, butterfly-like perturbations were unintentionally introduced to the intended bit-identical IFS deterministic forecast and ensemble control. This was caused by a discrepancy in how an orography file was read, resulting in an approximately 30 cm difference in the orography representation between the deterministic forecast and the ensemble control. This led the two to diverge in the manner of a classical twin experiment. This operational accident represents a valuable scientific opportunity to rigorously assess how tiny perturbations grow in a state of the art model using our new tools of analysis.

Through this analysis, we will be able to assess not just global or latitudinal error growth, but we will interrogate the space-local spectral behaviour of error growth. By connecting our results with Lorenz's theory, not only will we be able to access the detailed variation in the limits of predictability according to his theory, but we will be able to assess how or whether it applies under different dynamical regimes. In particular answering the question at the heart of our arctic analysis of whether a geostrophic regime has fundamental implications for predictability.

Recent work (Kouhen et al., in preparation) has derived an error-flux equation to partition observed error growth between various sources including advection and transfer across scales. This enables the first direct diagnosis of the direction and magnitude of nonlinear scale-dependent error growth. This has been implemented in the open-source software Flowsieve by Dr Kouhen, tested on ATOS, and is ready for application. Applying this novel analysis to this fortuitous dataset promises to test Lorenz's (1969) theoretical predictions and address more recent questions about the nature of error growth, in particular whether so called "up-amplitude" or "up-scale" error growth modes can be attributed to regime differences (Rotunno 2023).

Arctic Butterflies

In addition to a first global assessment of local error-flux statistics, we have identified the Arctic as a particular region of interest for understanding error growth. The Arctic exhibits circulation behaviour that differs substantially from that of the mid-latitudes, yet the dynamical nature of these differences remains poorly understood. Recent work suggests that Arctic circulation may alternate between two distinct regimes: one strongly coupled to the mid-latitudes and another that is comparatively isolated and dominated by long-lived vortices (Woollings et al, 2023). In the latter case, the flow may more closely resemble geostrophic turbulence, characterised by nonlinear interactions across scales and predominantly upscale energy transfers (Charney, 1971).

We will test this hypothesis using ERA5, operational IFS forecasts, and the new high-resolution pan-Arctic CARRA2 reanalysis. This work will provide the first systematic assessment of Arctic energy-cascade behaviour using coarse-graining diagnostics. A recently developed coarse-graining framework (Storer and Aluie, 2023) will be applied to diagnose local kinetic-energy transfers across a continuum of spatial scales and to quantify the direction and magnitude of scale interactions. Multi-year analyses will be used to characterise the climatological behaviour of energy transfers and its variations to determine whether signatures of geostrophic turbulence emerge systematically within the Arctic, which has not previously been assessed. Comparisons between ERA5, IFS, and CARRA2 will establish the robustness of the diagnosed cascade behaviour across datasets with differing resolutions, model formulations, and data-assimilation systems, with particular emphasis on the representation of small-scale processes and their upscale influence.

These analyses will provide a dynamical context in the Arctic region for the error-growth diagnostics undertaken in the accidental twin experiments, helping to assess whether geostrophic-turbulence regimes exhibit distinct pathways of perturbation growth and predictability in the Arctic.

The experiments proposed above form part of the NERC-funded project (UKRI 1288) 'Arctic Butterflies' and the Leverhulme Trust funded project 'Seamless Uncertainty QuantifiCation for Earth-System prediction' (SUQCES). Work involves shared methods, researchers and data, and so they have been combined in this application in order to make efficient use of the resources available.

B. Plan and justification of resources

The proposed work will apply a recently developed coarse-graining framework to three complementary datasets: ERA5 reanalysis, operational IFS forecasts, and the high-resolution pan-Arctic CARRA2 reanalysis. The computational cost is dominated by the repeated application of coarse-graining filters across multiple spatial scales, pressure levels, lead times and years of data.

For ERA5, we will analyse 45 years of daily data together with two years (2023–2024) of 6-hourly output, which will be shared across both components of the project. The coarse-graining framework will be applied to decades of data to characterise the climatological behaviour of energy transfers and their variability across different circulation regimes. Operational IFS forecasts will be analysed over approximately 10 years using archived 10 km resolution data, providing an assessment of cascade behaviour at higher spatial resolution and enabling direct links to be made with the accidental twin experiments described below. Finally, CARRA2 will be used to investigate Arctic dynamics at substantially higher resolution (2.5 km), allowing the role of mesoscale and sub-synoptic processes, and their potential upscale influence on the large-scale circulation, to be quantified.

The accidental twin experiment requires the analysis of the operational deterministic IFS forecast, the control member of the ensemble and their difference simultaneously. The accidental twin existed during the ECMWF cycle 48. That is, from June 27 2023 to November 12 2024. Forecasts were initialised four times daily during this period. In order to form a full picture of error growth, coarse-graining will be applied at multiple scales, lead times and pressure levels.

The estimated computational costs are summarised in Table 1. Cost estimates are based on benchmark tests performed on ECMWF computing facilities. A computational unit corresponds to processing a single timestep at a single model level; total costs are then scaled according to the number of years, temporal frequency, vertical levels, lead-times and datasets analysed, including both test and production runs.

Analysis name	Cost per unit (SBU)	Unit numbers	Total cost (SBU)
ERA5	400	59680	24M
IFS	1200	19345	23.2M
CARRA2	2400	21900	52.6M
TWIN	3800	50320	191M
Total			291M

The work plan is structured in stages. During the first phase, benchmark calculations and pilot analyses will be conducted on one year of data. The second phase will focus on the full multi-year ERA5 and IFS calculations, generating the diagnostics required for a climatological assessment of Arctic energy transfers and circulation regimes. During this phase, the accidental twin error diagnostic dataset will be generated in parallel. The final phase will concentrate on the computationally demanding CARRA2 calculations and targeted Arctic cyclone case studies.

All the requested resources will be used during the first year, when the ERA5, IFS, CARRA2, and accidental twin coarse-graining calculations will be performed. These calculations will generate the energy-transfer diagnostics that form the foundation for all subsequent analyses. The researchers for this work are already in post and preparing for the analysis, which will enable calculation to begin at the start of 2027.

The storage requirement is dominated by derived diagnostic fields generated from the ERA5, IFS, and CARRA2 analyses. Storage estimates are based on benchmark calculations of the coarse-graining workflow and include both intermediate outputs and final diagnostic products. For ERA5, approximately 0.48 GB of storage is required per processing unit, resulting in an estimated total of 28.8 TB. Corresponding estimates are 0.36 GB per unit and 7.2 TB in total for IFS, and 0.72 GB per unit and 16 TB in total for CARRA2. The larger storage requirement for ERA5 reflects the wider range of spatial scales that can be analysed in this comparatively coarse-resolution dataset, allowing more coarse graining scales to be retained while remaining computationally affordable. For the twin experiments, storage requirements are 1.04 GB per unit leading to an estimated 48 TB storage requirement. The total storage requirement over the duration of the project is estimated to be around 100 TB.

This storage allocation will allow both the processed fields and the derived energy-transfer diagnostics to be retained for reproducibility, intercomparison between datasets, and subsequent analyses of circulation regimes and error-growth behaviour.

Technical aspects

All the coarse-graining analyses described above will be achieved through the use of the open-source C++ software Flowsieve (Storer 2023). Flowsieve uses both MPI and OpenMP parallelism. It has been benchmarked extensively on ATOS, which has informed the above resource estimates. Further improvements to the efficiency and function of Flowsieve are currently underway. If these are completed during the project's lifetime, they will be used to increase the scientific yield of the resources allotted to us.

ERA5 and IFS data will be retrieved using MARS. CARRA2 will be retrieved from the CCDS. For long term data management, processed data will be transferred to the CEDA archive, where the datasets we produce, which we believe will be of significant scientific interest and use to the wider community, will be accessible.

References

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