REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Ireland

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Project Title: Enhanced Climate Simulations of the North Atlantic

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.	**SP** spienola	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES **X**	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	80 million	90 million	80 million
Accumulated data storage (total archive volume)[2]	[GB]	50,000	50,000	50,000

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

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[1] The Principal Investigator will act as contact person for this Special 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.

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Extended abstract

The climate of Ireland and northwest Europe is dominated by the Atlantic Ocean and its interaction with the atmosphere (McCarthy et. al, 2015). For example, North Atlantic low-pressure systems are the main delivery mechanism for precipitation in Ireland. The AMOC exerts a strong warming influence on the North Atlantic and European climate through the equator-to-pole transportation of water (Zhang et al., 2019). The European and North Atlantic climate is heavily influenced by both the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO). Several studies have shown that the AMO influences the European summer climate, precipitation, and cold weather episodes during winter (e.g., Ruprich-Robert et al 2017; Peings and Magnusdottir 2014). Furthermore, the AMO "explains over 90% of the pronounced decadal temperature and summer precipitation variation" in Ireland (McCarthy et. al, 2015). The NAO strongly influences the North Atlantic storm track (e.g., Luo et al., 2010; Hall et al., 2014; Börgel et al., 2020) with extreme North Atlantic cyclones "occurring more (less) frequently during strong positive (negative) NAO phases" (Pinto et al., 2009). It is therefore vital for the assessment of national climate change that climate models demonstrate high skill in the representation of the North Atlantic Ocean, and associated atmosphere-ocean interactions.

The objectives of the proposed research are two-fold;

(i) investigate and improve the EC-Earth4 Earth System Model in the representation of the North Atlantic Ocean-Atmosphere System, and
(ii) contribute to the CMIP7 "Fast Track" project with high-resolution EC-Earth4 simulations

1. EC-Earth Climate Modelling System

The EC-Earth consortium contributed to Coupled Model Intercomparison Project (CMIP) Phase 6 via the EC-Earth v3 configuration (Döscher et al., 2021). The CMIP6 version of EC-Earth (v3.3) comprises the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) atmospheric model, the Nucleus for European Modelling of the Ocean (NEMO) model, the Louvain-la-Neuve sea ice model (LIM), the Tracer Model version 5 (TM5) atmospheric composition model, the Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS) vegetation model and the Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES) ocean biogeochemistry model. Coupling is provided by OASIS3-MCT [the Ocean Atmosphere Sea Ice Soil (OASIS) coupler interfaced with the Model Coupling Toolkit (MCT)]. EC-Earth (CMIP6 configuration, v3.3) is optimised for a standard horizontal resolution of T255 (~80 km) with 91 vertical layers for the atmosphere, and for 1 degree with 75 layers for the ocean. In addition, high-resolution configurations are available: 0.25 degrees and 75 layers in the ocean, and T511 (~39 km) and T799 (~25 km) in the atmosphere. The proposed PI contributed to CMIP6 (Nolan and McKinstry, 2020), using the resources of ECMWF Special Projects (spienola), by running the following:

- 7 × EC-Earth atmospheric–ocean–general circulation model Historical AOGCM/Veg simulations 1850–2014;
- 28 × EC-Earth AOGCM/Veg Scenario Model Intercomparison Project (ScenarioMIP) 2015–2100 SSP-RCP simulations; 7 × SSP1-2.6, 7 × SSP2-4.5, 7 × SSP3-7.0 and 7 × SSP5-8.5.

The full CMIP6 Scenario-MIP ensemble was analysed to assess where the CMIP6 EC-Earth contributions fit within the full ensemble. Figure 1 presents the global annual 2 m temperature anomaly (1850–2100) with respect to the pre-industrial 50-year mean 1850–1900. The mean of the full CMIP6 ensemble is presented alongside the individual EC-Earth ensemble members. A total of 206 (SSP1-2.6), 192 (SSP2-4.5), 183 (SSP3-7.0) and 203 (SSP5-8.5) CMIP6 ensemble members were analysed.

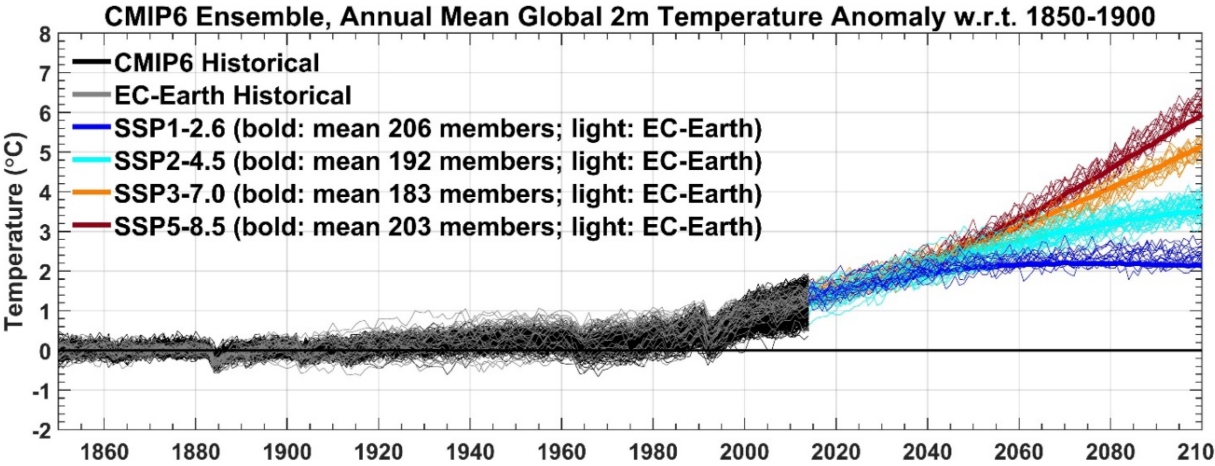

Figure 1. The CMIP6 global annual 2m temperature anomaly with respect to the 50-year mean 1850-1900. The EC-Earth ensemble members are presented alongside the CMIP6 mean to assess where the EC-Earth simulations fit within the full CMIP6 ensemble (analysis carried out by the proposed PI).

The CMIP6 version of EC-Earth (v3.3) was a substantial update on the CMIP5 version (v2.2). For example, all ESM components were updated with improved physical and dynamic features, new ESM components were included (e.g. PISCES biochemistry model in the ocean) and the atmosphere and ocean were simulated with enhanced spatial resolution. In addition, the EC-Earth CMIP6 ensemble size was substantially larger than that of CMIP5. Validations show that the CMIP6 EC-Earth model accurately simulates the global climate and outperforms the CMIP5 version for the majority of variables analysed. See Döscher et al. (2021) for a more comprehensive overview of the EC-Earth model, improvements compared with the CMIP5 version, validations and CMIP6 experiments. The next version of EC-Earth (v4) is currently being developed and is expected to similarly outperform the CMIP6 version.

2. EC-Earth (v4) Model Development

The project team will contribute to the development of the next version of EC-Earth (v4) in preparation for CMIP7, which in turn will inform the next round of IPCC AR7 reports.

The EC-Earth v4 model (currently in development) incorporates updated model components (e.g., OpenIFS 43r3v2, NEMO 4.2 with SI3 sea-ice model, XIOS 2.5+ and OASIS3-MCT 5.2) and will be run with enhanced spatial resolution.

After initial testing of EC-Earth4, it was determined that the following issues should be investigated with a view to improving the accuracy of the next generation EC-Earth v4 ESM in the simulation of the North Atlantic climate.

North Atlantic Cooling: Globally, most regions have observed a significant warming over the preceding decades. However, a region in the North Atlantic Ocean has been observed to cool, a phenomenon known as the "warming hole". Its emergence has been linked to a slowdown of the AMOC which leads to a reduced ocean heat transport into the warming hole region (e.g., Drijfhout et al. 2012; Caesar et al., 2018). The area of cooling is clear in Figure 2 (left panel) which presents the observed annual mean surface temperature change. The right panel of Figure 2 shows that the CMIP6 multi-model ensemble mean fails to capture this phenomenon. Figure 3 shows that the annual mean of the ensemble of CMIP EC-Earth (atmosphere 80km, ocean 1 degree) simulations also fail to capture the "warming hole" in the North Atlantic. The failure of the CMIP6 (and EC-Earth) models to capture this phenomenon is a significant research gap and will reduce the accuracy and confidence of North Atlantic climate projections.

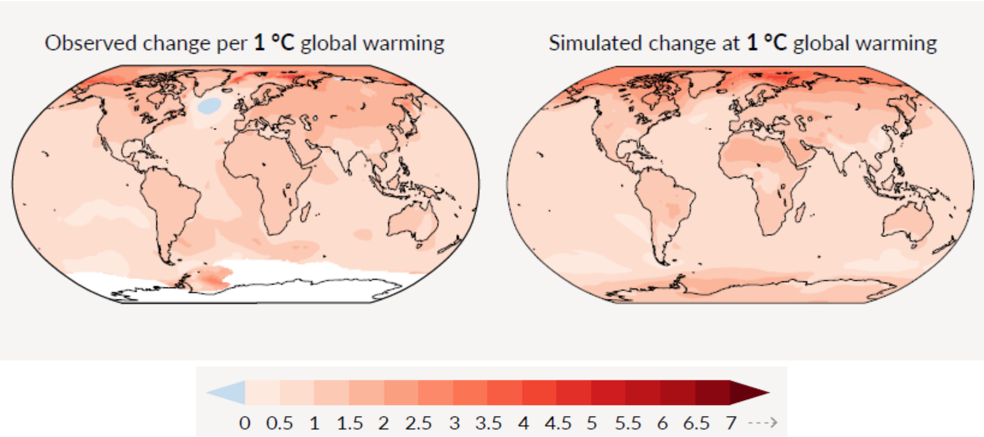

Figure 2 ***(taken from IPCC AR6 Summary for Policymakers, figure SPM.5).*** Comparison of observed and simulated annual mean surface temperature change. The left map shows the observed changes in annual mean surface temperature in the period of 1850–2020 per °C of global warming (°C). The right map is based on CMIP6 model simulations and shows change in annual multi-model mean simulated temperatures at a global warming level of 1°C (20-year mean global surface temperature change relative to 1850–1900).

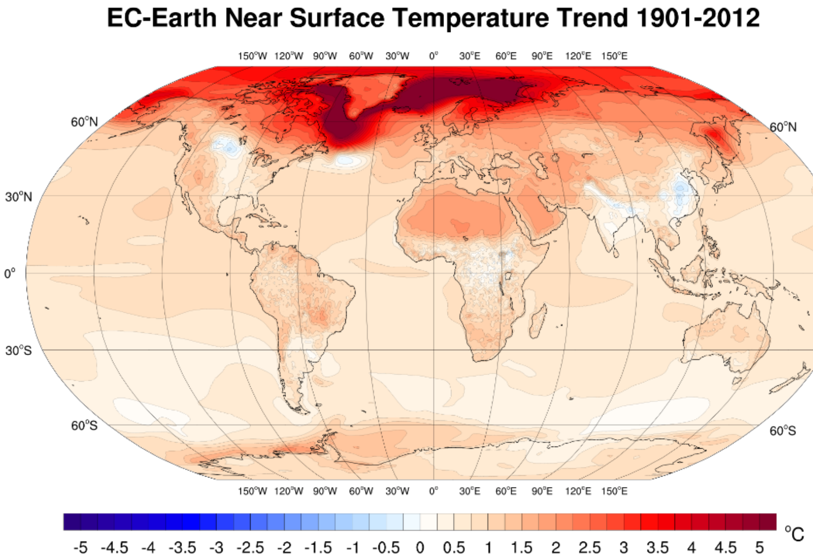

Figure 3. Change in annual multi-model (31 members) mean temperature trend as simulated by CMIP6 EC-Earth. A linear regression line was fitted to the annual temperature for the period 1901-2012 (analysis carried out by the proposed PI).

High resolution modelling: Studies have consistently demonstrated the added value of enhanced resolution in the simulations of the climate system, for example in the simulation of aspects of large-scale circulation, such as El Niño Southern Oscillation (ENSO) (Shaffrey et al., 2009), tropical instability waves (Roberts et al., 2009), the Gulf Stream and its influence on the atmosphere (Chassignet and Marshall, 2008; Kuwano-Yoshida et al., 2010), the global water cycle (Demory et al., 2014), extratropical cyclones and storm tracks (Hodges et al., 2011) and Euro-Atlantic blocking (Jung et al., 2012). In addition, the increased resolution enables more realistic simulation of small-scale phenomena with potentially severe impacts, such as tropical cyclones (Zhao et al., 2009), tropical–extratropical interactions (Haarsma et al., 2013) and polar lows.

More recent studies have showed that resolving ocean mesoscale eddies and narrow currents (e.g., gulf streams) improve large scale circulation of both the ocean and atmosphere. For example, global models with finer horizontal grids represent better many aspects of the circulation of the atmosphere (Jiaxiang et al., 2020; Schiemann et al., 2020) and ocean (Bishop et al., 2016; 5 Storkey et al., 2018). There is also evidence that enhancing horizontal resolution can reduce longstanding climate model biases in the AMOC (Chassignet et al., 2020; Roberts et al., 2020). Compared to CMIP5, there is improved consistency between recent observed estimates and CMIP6 simulations of changes in upper (<700 m) ocean heat content (IPCC, 2021). However, it is noted that “the structure and magnitude of multi-model mean ocean temperature biases have not changed substantially between CMIP5 and CMIP6 (medium confidence)” (IPCC, 2021). Priestley et. al (2020) showed that the CMIP6 models exhibit an overall improvement in the simulation of Northern Hemisphere (NH) extratropical cyclones compared to the previous generation of CMIP5 models with most improvements attributed to increased horizontal resolution (as opposed to model formulation and parameterizations).

Further improvements were found for very high-resolution (10-50km) (HighResMIP, Haarsma et al., 2016) coupled models (IPCC, 2021; Hewitt et al., 2017b; Roberts et al., 2019; IPCC, 2021). Haarsma et al. (2020) analysed the skill of a very high-resolution version of EC-Earth with a resolution of 0.25 degree in the ocean and ~40km for the atmosphere. The authors found that while increasing horizontal resolution does not result in a general reduction of biases, it potentially results in a better representation of tropical cyclones (see also Roberts et al., 2020) and ocean–atmosphere interactions (see also Tsartsali et al., 2020). The omission of specific tuning for the high-resolution version of EC-Earth v3 was attributed to the minimum improvements noted over the standard lower resolution version (Haarsma et al., 2020). It is important to note that model performance depends on model formulation and parameterizations as much as on resolution (IPCC, 2021).

Better representation of the AMOC - both its mean state and variability. This is a complex topic related to many processes and their parameterizations in nemo (e.g., the deep water formation in Labrador sea, mixing of eddy kinetic energy across the thermocline, sea-ice interactions). Döscher et al. (2021) showed that the ensemble mean of the AMOC stream function obtained from the EC-Earth3 CMIP6 ensemble features the expected overturning clockwise circulation. Compared to the 12-member ensemble mean of CMIP5 EC-Earth 2.3, the CMIP6 version has a stronger AMOC closer to observations. However, “there is a wide range of variability between ensemble members possibly because each member starts from a different initial condition that evolves differently depending on the state of the model's internal variability” (Döscher et al., 2021). The authors suggest that the “lowest AMOC strength values correspond with extended periods with absent deep-water formation and expanded sea ice in the Labrador Sea” (Döscher et al., 2021). Giving the importance of the AMOC to the North Atlantic climate, it is important that the AMOC is better resolved in EC-Earth v4.

Improved representation of the processes related to Sea Ice and the Greenland Ice sheet such as better snow parameterization on ice (e.g., snow albedo and snow melt), and freshwater runoff is expected to improve the accuracy of EC-Earth4 in the simulations of NAO, North Atlantic and Arctic ocean climates (Rahmstorf et al., 2015, Sévellec et al., 2017; Keil et al., 2020). A possible explanation for why EC-Earth is failing to capture the observed “warming hole” is poorly resolved freshwater fluxes from sea ice reduction and Greenland Ice Sheet runoff (Keil et al., 2020). While EC-Earth v3 currently includes a sea-ice model (LIM3 replaced with SI3 for EC-Earth v4), the coupling of the Greenland ice sheet is at an early stage, with more substantial development planned for EC-Earth v4. Improvements in the coupling of the Greenland ice sheet, along with improvements in modelling sea ice reduction, are expected to result in greater freshwater fluxes into the North Atlantic, in turn resulting in more accurate modelling of the AMOC and the “warming hole” (Rahmstorf et al., 2015, Sévellec et al., 2017; Keil et al., 2020). It is also important to note that freshwater fluxes are expected to be better resolved for higher-resolution models, leading to better representations of the AMOC and North Atlantic cooling.

Air-sea interactions, in particular the impact of wind stress.

The air-sea flux biases of CMIP6 were found to be similar to CMIP5 (IPCC, 2021). Important currents (e.g., Gulf Stream) are often found in erroneous locations in models, affecting SST and flux signatures (Beadling et al., 2020). However, it was found that their locations are improved in high-resolution ocean models (Chassignet et al., 2020; Hewitt et al., 2020). Furthermore, high-resolution coupled models were found to reduce the mean air-sea flux biases (Caldwell et al., 2019; Jackson et al., 2020). The IPCC (2021) conclude “In summary, there is very high confidence that air-sea heat flux and stress biases are reduced in coupled models with high ocean resolution over coarse resolution models”. Recent studies show that the role of wind stress in coupled models is larger than previously known (e.g., Elipot et al., 2017; Putrasahan et al., 2019). Better representation of the wind stress is expected to reduce biases in the simulation of sea ice as well as the subpolar ocean circulation. For example, Putrasahan et al. (2019) found that while freshwater is still the key to the reduction of AMOC seen in the higher-resolution model runs, "the freshening of the North Atlantic does not need to be directly caused by local freshwater fluxes. Instead, it can be caused indirectly through winds via a reduced wind-driven gyre circulation and salinity transport associated to this circulation".

3. Work Plan

3.1 EC-Earth v4 model development and validation experiments

The project team will collaborate with the EC-Earth consortium on the development of EC-Earth v4. It is envisaged that the project team will focus on ~4 main areas of model development with likely areas of focus the AMOC, "warming hole", atmosphere-sea interactions, Greenland Ice Sheet fluxes and ocean-ice interactions (as well as enhanced model resolution).

The PI will complete ongoing short-term validation experiments to ensure the added value of incremental model development. Long-term validations experiments will be completed for the latest "stable" versions of EC-Earth v4. To evaluate the impact of increased resolution on the representation of important North Atlantic climate processes, very high-resolution validation experiments will be completed (e.g., T799-25km in the atmosphere and 0.25 degrees in the ocean) and the results compared with the standard resolution configuration. The validation analysis will involve comparing the output of EC-Earth with observations (e.g., CRU) and re-analyses datasets (e.g., ERA5). The methods of Döscher et al. (2021) will be followed for validations of more complex processes such as the NOA and AMOC.

3.2. EC-Earth (v4) CMIP7 Fast Track Contributions

The future global climate will be simulated using the most up-to-date version of EC-Earth (v4.x). An ensemble of at least 2 historical and 4 (2 x 2 SSPs) future simulations will be completed for the period 1850-2100. An in-depth analysis will be completed to assess the impact of model improvements on the future North Atlantic climate.

The future global climate will be simulated using the most up-to-date high-resolution configuration of EC-Earth v4 (e.g., T799-25km in the atmosphere and 0.25 degrees in the ocean). An ensemble of at least one historical and 2 SSP simulations will be completed for the period 1950-2100. An in-depth analysis will be completed to assess the impact of enhanced resolution and model improvements on the future North Atlantic climate.

4. Justification of Compute and Storage Resources

The EC-Earth4 model was installed and scale-tested on atos using the intel compilers and intel-openmpi. The EC-Earth4 AOGCM configuration comprised the following components: OpenIFS 43r3v2, NEMO 4.2.0, XIOS 2.5+ and OASIS3-MCT 5.2. The system was tested using standard MPI and hybrid MPI-OpenMP (implemented within OpenIFS). Figure 4 presents timings for a one-month simulation. In all runs, the number of cores for XIOS was set to 1. For each node, numerous different allocations of cores between OpenIFS and NEMO were tested to quantify the optimal balancing of cores between model components. The figure presents the optimal timing for each node. The higher resolution versions of EC-Earth v4 were not available for testing at the time of writing, but experience with EC-Earth3 shows that increasing the spatial resolution by a factor of two results in an eightfold increase in required compute resources. For the current study, because EC-Earth4 is at an early stage of development, the exact spatial resolutions for OpenIFS are not yet decided (e.g., T255L1 vs. Tco199), but for the current study they will roughly correspond to 100km (low-resolution for testing), ~50km (standard resolution) and 25km (high-resolution). The scaling results of Figure 4, and additional scaling results for high-resolutions provided by EC-Earth partners, were used to provide the resource request of Table 1 using 4 nodes on the Atos system and the following SBU calculations:

$$\text{SBU} = \text{compute time [h]} \times \text{number of physical cores} \times 17.06$$

The low, standard and high-resolution simulations produce 20, 100 and 1000 GB of data per simulation year, respectively. Furthermore, storage resources of approximately 50 GB per simulation year will be required for short-term storage of run files and I/O data. Taking the above into account, we request 150TB of storage over the 3-year project timeframe. This estimate is an absolute upper value as data will be regularly deleted and the EC-Earth data will be transferred to local storage resources as the simulations complete.

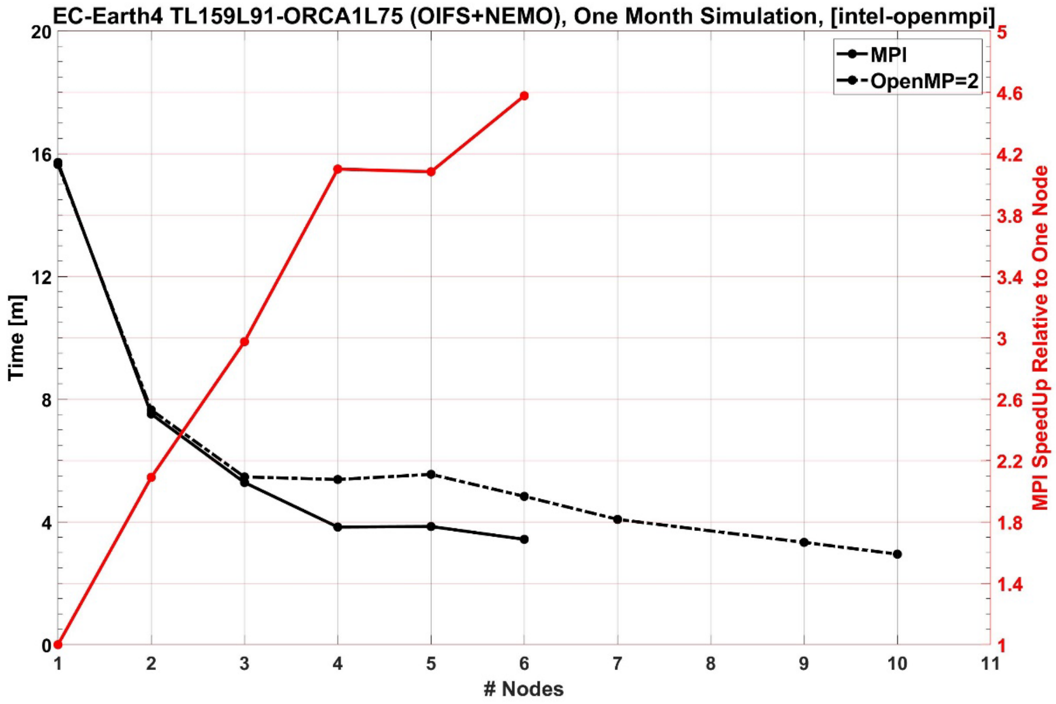

Figure 4. EC-Earth4 TL159L91-ORACA1L75 timings for a one-month simulation.

	Description	**Simulation time [hr]**	**Total SBUs = 4×128× [simulation_time_hr] × 17.06**	**Total Archive**
Experiment 1: EC-Earth4 short-term testing	1000 years testing of EC-Earth4 low-resolution 200 years testing of EC-Earth4 standard-resolution 50 years testing of EC-Earth4 high-resolution	4640	40.5 million	50 TB
Experiment 2: EC-Earth4 long-term validations	200 years testing of EC-Earth4 low-resolution 200 years testing of EC-Earth4 standard-resolution 200 years testing of EC-Earth4 high-resolution	11680	102 million	50TB
Experiment 3: EC-Earth4 CMIP7 Fast Track Contributions	2 × standard resolution EC-Earth4 AOGCM 1850–2014;	12045	105 million	50 TB

	4 × standard resolution EC-Earth AOGCM ScenarioMIP 2015–2100 (4 x SSP-RCP simulations; 2 × SSP1-2.6, 2 × SSP3-7.0). 1 × high resolution EC-Earth4 AOGCM 1950–2014; 1 × high resolution EC-Earth AOGCM ScenarioMIP 2015–2100 (likely SSP3-7.0)			
Total		**28365**	**247 million**	**150 TB**

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