REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE:	Italy
Principal Investigator[1]**:**	Catello Leonardo Matonti
Affiliation:	DIMEAS, Politecnico di Torino
Address:	Corso Duca degli Abruzzi 24 10129 Torino Italy
Other researchers:	Jost von Hardenberg, Politecnico di Torino & ISAC-CNR, Italy (ccjh) Marcello Romano, Politecnico di Torino, Italy
Project Title:	Climate impacts of space-based geoengineering: EC-Earth simulations for optimal non-uniform radiative forcing by a Planetary Sunshade System

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** ………….	
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 ☒	NO ☐

Computer resources required for project year:	**2025**	**2026**	**2027**
High Performance Computing Facility [SBU]	19,000,000		
Accumulated data storage (total archive volume)[2] [GB]	40,000		

EWC resources required for project year:	**2025**	**2026**	**2027**
Number of vCPUs [#]	0		
Total memory [GB]			
Storage [GB]			
Number of vGPUs[3] [#]			

Continue overleaf.

[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

1. Introduction

1.1 Background and motivation

According to recent scientific research studies, anthropogenic climate change insight reaches a no-return point in absence of actions [1].

In particular, according to this IPCC Sixth Assessment Report (AR6) [2] a projection of future warming of 1.5° will generate significantly increased risks and adverse impacts. If warming were to exceed 2°, the prospects for climate resilient global development decrease. This is due to increased interactions of climatic and non-climatic risks, which create compound, cascading events that strain management options. The conclusion of AR6 is that we are now faced with a narrow window of opportunity to undertake substantial climate actions.

To mitigate global warming, a space-based reversible solar geoengineering infrastructure has been previously proposed to reduce the oncoming solar radiance by setting a 'solar-light umbrella', called a Planetary Sunshade System, between the Sun and Earth [3-7]. The planetary sunshade design would strongly depend on the mitigation scenario chosen; generally, most space-based solar geoengineering research efforts set a uniform shading at the upper range of potential intervention levels, such that the global solar irradiance reduction is about $\delta Q/Q = 1.7$ %, corresponding to the mitigation of the effects due to a doubling carbon dioxide concentration in atmosphere [8].

Starting from 2010, the Geoengineering Model Intercomparison Project (GeoMIP) simulated a series of standardized climate model experiments to evaluate impacts of solar geoengineering. In particular, solar reduction experiments have been conducted too, namely G1, G1ext, G2 and G6Solar [9].

1.2 Planetary Sunshade System

A planetary sunshade is a space-based system for achieving solar geoengineering. The system is made up of a single very-large surface, likely resulting from the on-orbit assembly of a multitude of modular satellites. Each satellite composing the sunshade is assumed to have a large planar shading surface, that we call a solar-sail.

The photo-gravitational Circular Restricted Three Body Problem (CR3BP) is used as a preliminary model to investigate the dynamics of a planetary sunshade system. In particular, the two primaries are two-point masses representing the Sun's and the Earth's center of mass (CoM), considering a constant distance between them equal to 1 astronomical unit (AU). The two primaries perform circular orbits about their common CoM. In this model, a solar-sail satellite is attracted to each of the primaries and is affected by the Solar Radiation Pressure effect (SRP). The SRP is the force produced by sunlight photons impinging on the surface of the satellite, and whose direction can be modelled, in first approximation, parallel to the solar-sail surface normal $\hat{n}$.

In particular, the sunshade surface would be orthogonal to the Sun-Earth line to maximize and shade. Then, it is positioned along the same line on the optimal L_1^* equilibrium point of the rotating Sun-Earth system, given from the balance of the forces due to the Sun and Earth gravitational attraction, centrifugal force, and solar radiation pressure. Considering a solar reduction of δQ/Q=1.7%, the optimal of L_1^* is at a distance $d_{L_1^*}$=2.36 [Mkm], about 0.9 [Mkm] further respect to the classic L_1. Mass M and radius R are respectively equal to M=2.847e+11 [kg] and R=1.436e+03 [km].

Subsequent figure 1,2 shows a visualisation of the planetary sunshade located at optimal L_1^* with the acting forces and the shadow cones produced of umbra, penumbra and antumbra (not in scale). In this case, the Earth would be totally inside the antumbra cone, while the umbra cone terminates at a distance from Earth d_{UE}=2.053e+6 [km]. Then, a visualisation of the actual umbra, penumbra and antumbra shading intensity is visualised along the Sun-Earth plane from the sunshade to the Earth CoM.

Similar considerations can be extended to objects with a different, or even more complex, shape. Each architecture would produce a different shading on Earth and so its corresponding climate impact. Furthermore, we can produce non-uniform shading patterns by utilising a swarm of solar sail satellites, controlled passively with the solar radiation pressure by changing the attitude of each satellite [10]. In this way, the total shading pattern is calculated from the sum of the ones produced by each solar sail satellite.

Furthermore, this preliminary analysis set the basis to investigate the dynamics of a planetary sunshade system in the Sun-Earth-Moon Bi-Elliptic Restricted Four Body Problem (BER4BP).

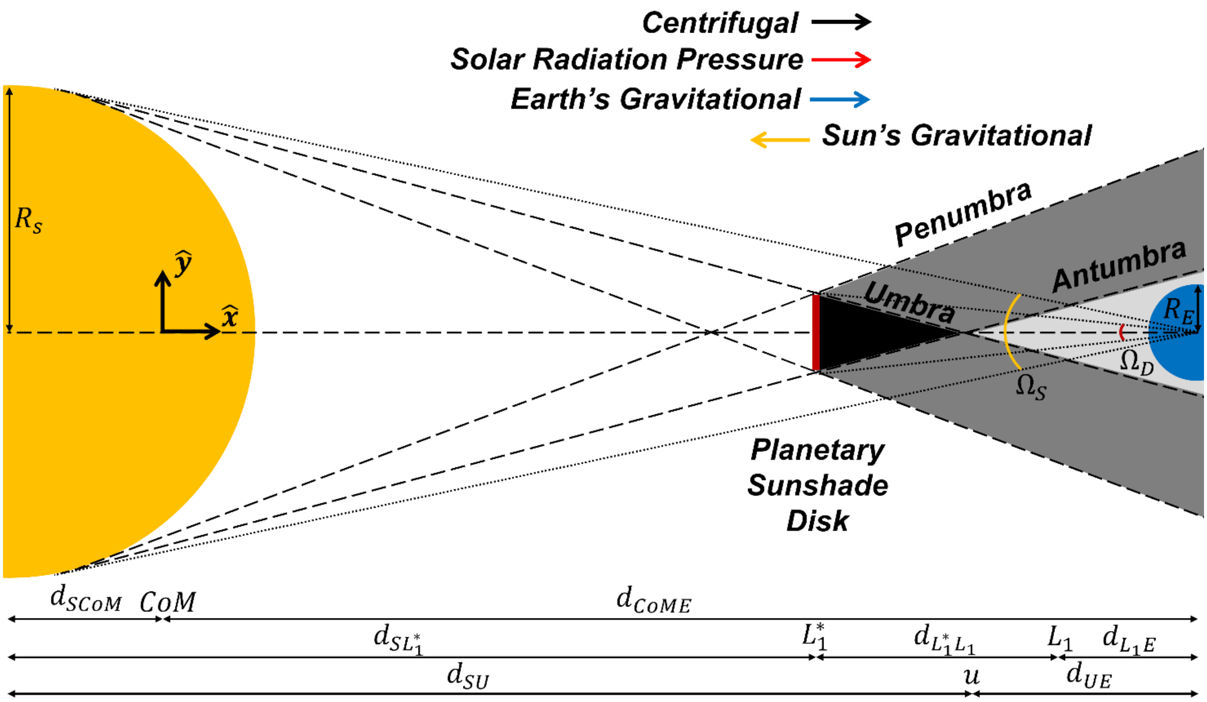

Fig.1 The Planetary Sunshade Principle

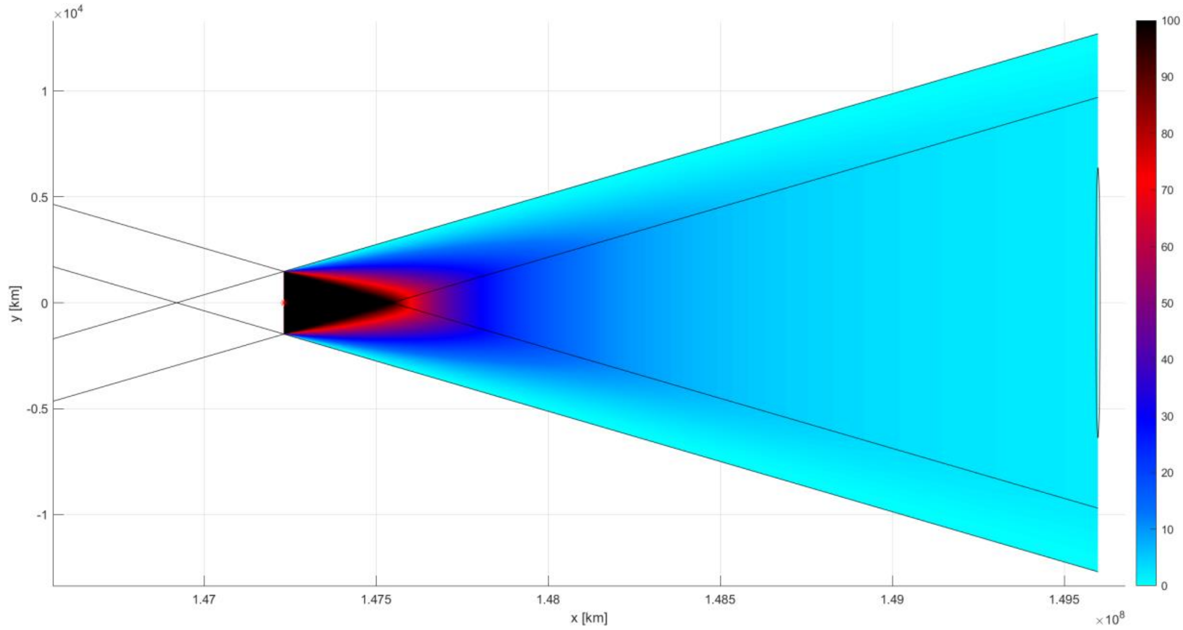

Fig.2 Actual umbra, penumbra and antumbra shading intensity

1.3 Scientific goals of the project

The GeoMIP experiments G1, G1ext, G2 and G6Solar considered an instantaneous or gradual variation of the solar constant, and so not addressing the possibility of non-uniform radiative forcing through differential shading.

In this project, we aim for the first time, through a global climate model, at addressing three core questions regarding the use of a Planetary Sunshade System as a space-based geoengineering strategy for solar radiation management: (a) What is the climate impact on Earth of different insolation patterns? (c) Which are the effects during the transition phase before final deployment of the planetary sunshade? (d) And finally, can we prove the reversibility of this mitigation strategy?

2 Proposed Activities

2.1 Model

We plan to perform model experiments with EC-Earth3 [11], a state-of-the-art developed by a consortium of European research institutions which participated in CMIP6. EC-Earth3 comprises of the atmospheric model ECMWF IFS cy36r4, the ocean model NEMO3.6 [12] including the LIM3 sea ice component [13], the land surface scheme H-TESSEL [14] and the coupler OASIS3-MCT [15]. Since we build on existing simulations carried out for CMIP6, we use the standard resolution of EC-Earth3: a spectral truncation of TL255 with 91 vertical levels for the atmosphere and an ORCA1 grid with 75 vertical levels for the ocean. This corresponds to a horizontal resolution of about 80 km in the atmosphere and 100 km in the ocean, with a grid refinement to about 40 km in the tropical ocean. While the next generation version of EC-Earth (EC-Earth 4) is in development, in this project we prefer to rely on EC–Earth3 which has now an extensive literature and can serve as solid reference model.

2.2 Optimal choice of non-uniform radiative forcing

Different non-uniform radiative forcing strategies are proposed and tested, in terms of maps of solar insolation as its daily average respect to latitude and day of the year. First, solar insolation maps are analysed respectively with a focus on the equator, south pole, north pole, both poles and all world.

Subsequently, according to the climate impact of these first test-cases, two more suitable patterns are identified, both as linear combinations of the previous ones or by adding some tuning to them.

2.3 Simulations

To address the scientific goals outlined above, we carry out simulations with EC-Earth3 for one standardized future emission scenario, represented by Shared Socioeconomic Pathways (SSPs) from the Scenario Model Intercomparison Project [16] as part of CMIP6:

• SSP245: As an update to scenario RCP4.5, SSP245 with an additional radiative forcing of 4.5 W/m^2 by the year 2100 represents the medium pathway of future greenhouse gas emissions. This scenario assumes that climate protection measures are being taken.

We will consider a planetary sunshade deployment and assembly scenario of 40 years, and so with an increasing insolation from 2040 to 2080. Then, the effects are evaluated for other 100 years. In this timespan, the 50 years from 2080 to 2130 are considered as a full operative scenario. Finally, for the last 50 years from 2130 to 2180, it is investigated the reversibility by simulating the dismission of the planetary sunshade system.

3 Justification of the computer resources requested

First runs on the new Atos machine have determined that the optimal configuration for the standard resolution of couple EC-Earth3 model (TL255L91-ORCA1L75) is obtained using five nodes (490 cores for IFS and 148 cores for NEMO, with one core each for the runoff mapper and the XIOS server). We estimate that one model year using the standard configuration of EC-Earth 3 will use about 19,000 SBU. Accounting for 6 hourly outputs for IFS and monthly outputs for NEMO, we estimate a need for about 40 GB of storage per model year.

In summary, for the experiments performed within the project the following resources will be required:

Experiment	Total Model Years
Model implementation testing and tuning	20
SSP245 (2040-2180) – equator coverage	140
SSP245 (2040-2180) – north pole coverage	140
SSP245 (2040-2180) – south pole coverage	140
SSP245 (2040-2180) – north and south coverage	140
SSP245 (2040-2180) – all world coverage	140
SSP245 (2040-2180) – linear combination	140
SSP245 (2040-2180) – tuning	140
Total model years	1000
Total SBU	19,000,000
Total Storage	40 TB

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