IMPROVED TRANSDISCIPLINARY SCIENCE FOR EFFECTIVE ECOSYSTEM-BASED MARITIME SPATIAL PLANNING AND CONSERVATION IN EUROPEAN SEAS

Deliverable D6.4

Extended (regionalized) version of the Lagrangian drift module PELETS-2D

Funded by the European Union

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MARINEPLAN PROJECT SUMMARY

The diversity of terrestrial and marine life is dramatically affected by human interventions including climate change. Compelling and growing evidence shows that biodiversity underpins ecosystem functions and services, and consequently, human benefits depend on them. Thus, the importance of ecosystems in a good state cannot be underestimated and calls for an effective management of marine activities and sustainable use of marine and coastal resources.

Maritime Spatial Planning (MSP) is the main governance process that ideally balances economic, ecological and socio-cultural goals through the regulation of human uses at sea. As a future-oriented process, MSP is well-placed to realise sustainable marine futures. With global and regional conservation and green energy targets ahead, there is an urgent need to define pathways for a better alignment of MSP and systematic conservation planning, as part of the operationalisation of an Ecosystem-Based approach to MSP (EB-MSP).

The EU-funded MarinePlan project supports the implementation of EB-MSP through the development of a Decision Support System (DSS). It will offer guidance for an improved alignment of MSP, spatial conservation, and restoration interventions during the challenging times of ever-increasing pressures on marine ecosystems.

This main goal will be achieved through four specific objectives for the European seas:

#1 Co-develop with stakeholders the conceptual elements of the DSS (guidelines and tools) and derive best practice guidance for EB-MSP implementation.

#2 Develop quantitative metrics to operationalise Ecologically or Biologically Significant marine Area (EBSA) criteria and their application at various spatio-temporal scales.

#3 Implement and apply the DSS based on objectives #1 and #2, its guidelines, metrics, and tools at Planning Sites representing the diversity of European marine areas.

#4 Provide recommendations and improvements concerning the shortcomings, impediments to, and opportunities of prevailing governance processes to enhance the implementation of EB-MSP.

MarinePlan develops and applies the EB-MSP DSS within seven Work Packages and eight European Planning Sites. The Planning Sites range from coastal ecosystems to open ocean and the deep sea and from local to transboundary scales. Applying and validating the DSS incorporates realistic planning scenarios, key action points to achieve the EU Biodiversity Strategy, and policy recommendations on how to enhance EB-MSP implementation in European Seas. MarinePlan will communicate results to decision-makers at horizontal (between sectors) and vertical (from local to European) levels and enable the transfer of knowledge to areas in differing socio-ecological settings. The improved natural and social science base will ensure effective policymaking to support a greater coherence in implementing environmental policies as well as to enable streamlined planning for marine industries.

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Executive Summary

The MarinePlan project develops a DSS to promote the implementation of a coherent and adaptive EB-MSP framework in Europe. This DSS provides tools and guidelines that aim at helping member states to embed biodiversity conservation targets and ecosystem restoration measures in (trans)national MSP processes. Within this framework, maintaining the exchange between functionally connected parts of the ocean is recognised as a key component for underpinning the EB-MSP approach. It acknowledges that distant environments may function not just in isolation, but as part of a broader, interconnected system. The MarinePlan project therefore uses Lagrangian analyses to produce connectivity metrics for EBSAs and MPA networks in eight representative planning sites distributed across Europe. The Lagrangian analyses are driven by regional CMEMS reanalysis products which provide the physical forcing that is necessary to run offline particle transport simulations. The CMEMS products are particularly well-suited for this purpose as they offer high-quality, standardized oceanographic datasets for all MarinePlan planning sites. The Lagrangian particle transport model PELETS-2D is used to conduct these simulations. This deliverable outlines the basic principles of applying PELETS-2D to CMEMS datasets and describes the model's capabilities for connectivity assessments that support MarinePlan in achieving its objectives.

1 Aim of the Deliverable

The present deliverable aims at illustrating the operational readiness of PELETS-2D for simulating particle transport in all MarinePlan planning sites. It highlights an update over the previous PELETS-2D version by attaining compatibility with regional CMEMS ocean physics reanalysis products. The scope of PELETS-2D covers its performance in providing tailored solutions for assessing connectivity of EBSAs and MPA networks while considering variable oceanographic conditions. PELETS-2D therefore offers tools and functionalities to exploit large ensemble transport simulations, drift climatologies and multivariate statistics for

i) calculating cross-boundary exchange rates between multiple sources and sinks,

ii) estimating retention, travel and arrival times of water bodies and their constituents such as larvae, nutrients or harmful substances,

iii) assessing long-term trends and climate driven variability in dispersal patterns,

iv) identifying prevalent modes of current-driven transport, dominant corridors for particle dispersal as well as barriers to passive movement,

v) examining the role of extreme events and hot spots as well as the implications of alternate spatial prioritization scenarios,

vi) leveraging synoptic maps from observations of passive tracers or other Lagrangian indicators, and

vii) considering uncertainty in projected dispersal patterns and their temporal dynamics on a broader, system-wide scale.

The usage of CMEMS datasets ensures that the particle drift simulations are consistent across all MarinePlan planning sites, have at sufficient temporal and spatial coverage as well as an adequate resolution. They also guarantee long-term support, data continuity and access via standardized protocols beyond the project's runtime. The added value of this deliverable is the consideration of connectivity in MarinePlan's DSS multiplied by the impact of its application in systematic conservation planning and EB-MSP in Europe.

1.1 Contributors

Table 1. Names and roles of contributors to this deliverable.

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2 INTRODUCTION

MarinePlan is funded under the EU's Horizon Europe program. The project addresses the need for a cohesive and adaptive EB-MSP framework that aims at helping member states to fulfil the EU Biodiversity Strategy for 2030. Against this background, MarinePlan develops a DSS equipped with tools and guidelines for reconciling conservation and restoration measures with national and transnational MSP applications. A key pillar of this DSS explicitly recognises marine environments as functionally interconnected by ocean currents as these provide for the exchange of nutrients, larvae, and other ecologically important components. This way, connectivity contributes to resilience, biodiversity, climate regulation, food provision and many other important ecological functions and services that the project’s approach to EB-MSP is designed for to sustain.

Prioritizing a lasting preservation of marine functional connectivity requires an in-depth understanding of interlinkages between marine environments on various temporal and spatial scales. To achieve this goal, MarinePlan employs Lagrangian particle transport simulations to derive connectivity metrics for EBSAs and MPA networks in eight representative planning sites across Europe. These simulations are conducted with the drift model PELETS-2D, which also evaluates the particle trajectories in space and over time for the mapping of dispersal patterns, the detection of retention zones, the calculation of cross-boundary exchanges rates and the identification of dominant corridors and potential barriers to movement (Callies, 2021).

PELETS-2D is a Lagrangian drift model and toolbox written in Fortran 90 (Callies et al., 2011). The program is optimized to track large numbers of particles in parallel. Such ensemble simulations can be run either forward or backward in time. The particles are released from user-defined source regions, transects, or geographic locations at prescribed intervals or exact timings. For efficiency and versatility, the model accommodates multi-source and multi-sink tracking, i.e., the user can evaluate particle exchange between multiple origin and destination areas. An adaptive time-stepping method and stochastic diffusion component adjusts particle movements to changing current strengths and simulates small-scale turbulence, respectively. These features enhance the realism of particle dispersal, particularly in regions with complex hydrographic conditions.

As an offline model, PELETS-2D does not solve fluid dynamics equations in real time but depends on pre-computed current fields (Weisse et al., 2009). This makes the model very flexible in terms of processing diverse OCM datasets. As PELETS-2D operates on a two-dimensional horizontal plane, the physical forcing either represents the surface layer or depth-averaged values. This approach simplifies computations while capturing the essential dynamics of the particle trajectories (Callies et al., 2011). In MarinePlan, PELETS is driven by CMEMS reanalysis products, which provide consistent, standardized datasets of the required variables, like currents, temperature, salinity and water elevation.

CMEMS datasets are well suited for connectivity studies in MarinePlan’s diverse planning sites for several reasons. First, their high spatial and temporal resolutions capture the variability and fine-scale details of ocean currents that are necessary for taking the variety of hydrodynamic conditions into account. Second, CMEMS reanalysis products provide long-term historical data, which enables MarinePlan to conduct simulations over extended periods. This capability supports the analysis of both short-term events and long-term trends in connectivity, such as seasonal changes, climate-driven variability, and the impact of extreme events. Third, CMEMS data are consistently updated and accessible through standardized protocols. This ensures data continuity and allows MarinePlan to maintain high data quality for all planning sites.

In summary, drift simulations with PELETS-2D, driven by CMEMS data, enable MarinePlan to conduct detailed connectivity analyses across its European planning sites. By leveraging high-quality, standardized oceanographic data, MarinePlan's DSS provides a robust, data-driven framework to support effective EB-MSP, aligning with the EU Biodiversity Strategy's goals of fostering resilience, ecological coherence, and sustainable management of marine resources

3 METHODOLOGY

3.1 CMEMS DATA ACQUISITION

The CMEMS reanalysis products that are used to drive PELETS-2D simulations in MarinePlan's eight planning sites were downloaded at the Copernicus Marine Data Store. Below is a description of their key characteristics and limitations.

3.1.1. North-West European Shelf Physics *(Southern North Sea, Celtic Sea)*

This dataset captures the strong tidal forces and coastal mixing processes of the relatively shallow waters on the North-West European continental shelf and their interaction with the Atlantic. Its limited resolution may affect the accuracy of very detailed coastal studies. Some short-term tidal variations are not fully captured due to daily data.

- Product: NWSHELF_MULTIYEAR_PHY_004_009
- DOI: 10.48670/moi-00059
- Source: NEMO v3.6
- Horizontal Resolution: 1/9° longitude x 1/15°latitude (~ 7 km)
- Temporal Resolution: daily
- Z-Levels: 24
- Temporal Coverage: 1 Jan 1993 – 31 Dec 2022

3.1.2. Baltic Sea Physics Reanalysis (*Western Baltic Sea)*

Designed for the unique Baltic Sea environment, this dataset describes distinct salinity gradients, restricted water exchange, and circulation patterns. Boundary conditions for the transition to the North Sea may result in limitations on inflow and outflow accuracy,

- Product: BALTICSEA_MULTIYEAR_PHY_003_011
- DOI: 10.48670/moi-00013
- Source: NEMO v4.0 (Baltic-Nordic)
- Horizontal Resolution: 1/36° longitude x 1/60°latitude (~ 2 km)
- Temporal Resolution: daily
- Z-Levels: 24

Temporal Coverage: 1 Jan 1993 – 31 Dec 2021

3.1.3. Atlantic-Iberian Biscay Irish Ocean Physics *(Bay of Biscay)*

This dataset captures coastal upwelling, seasonal currents, and deep-water circulation in the Atlantic – Iberia Biscay Ireland – area. Boundary conditions in the region may not fully capture exchanges with neighbouring basins.

- Product: IBI_MULTIYEAR_PHY_005_002
- DOI: 10.48670/moi-00029
- Source: NEMO v3.6
- Horizontal Resolution: 1/12° longitude x 1/12°latitude (~ 6-9 km)
- Temporal Resolution: daily
- Z-Levels: 50
- Temporal Coverage: 1 Jan 1993 – 28 Dec 2021

3.1.4. Global Ocean Physics *(Azores)*

This dataset covers broad-scale global ocean current information, such as the North Atlantic Drif that influences the Azores. Its relatively coarse resolution does not capture very fine-scale features such as small-scale eddies or other local, costal phenomena.

- Product: GLOBAL_MULTIYEAR_PHY_001_030
- DOI: 10.48670/moi-00021
- Source: NEMO v3.1 (LIM 2 EVP)
- Horizontal Resolution: 1/12° longitude x 1/12°latitude (~ 8 km)
- Temporal Resolution: daily
- Z-Levels: 50
- Temporal Coverage: 1 Jan 1993 – 31 Dec 2019

3.1.5. Mediterranean Sea Physics *(Campania, Greek Seas, Western Mediterranean)*

This dataset captures the unique circulation patterns of the Mediterranean Sea including mesoscale eddies and seasonal stratification. The presence of complex coastlines and islands may lead to artifacts near boundaries. Analyses of long-term trends may require validation against observational data, given regional variability.

- Product: MEDSEA_MULTIYEAR_PHY_006_004
- DOI: 10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1
- Source: NEMO v3.1 (LIM 2 EVP)
- Horizontal Resolution: 1/24° longitude x 1/24°latitude (~ 4-5 km)
- Temporal Resolution: daily
- Z-Levels: 141
- Temporal Coverage: 1 Jan 1987 – 31 Dec 2020

3.2 Forcing Data Pre-processing

The transport algorithm of PELETS-2D operates on an unstructured, triangular grid, whereas CMEMS dataset are typically provided on a structured, rectangular grid, Consequently, the original CMEMS reanalysis products used in this project are pre-processed to be compatible with the PELETS-2D approach. This also includes vertical averaging of 3D-velocities profiles or extraction of the uppermost layer to allow for particle tracking in the two-dimensional model framework.

Adding a new forcing dataset to PELETS-2D involves several steps, from triangulating the original grid to interpolating the physical variables (Fig. 1), The core grid setup process starts with diagonally dividing each rectangular grid cell to create a mesh (Fig. 2). In a next step, program control files, that store grid element related information such as node and edge relationships, topology and coordinate transformation details, are generated. This setup also pre-calculates interpolation factors, optimizing computational performance. Next, a regular grid is defined to cover the study area, linking the unstructured grid data with a plotting routine. Following this, model boundaries are configured by selectively flagging edge labels as open for particle transport. The final step involves the actual transfer of the original CMEMS dataset to the unstructured PELETS-2D mesh and involves the interpolation of depth-averaged or surface layer velocity fields and other oceanographic variables (e.g., temperature, salinity) that are eventually stored as daily input files.

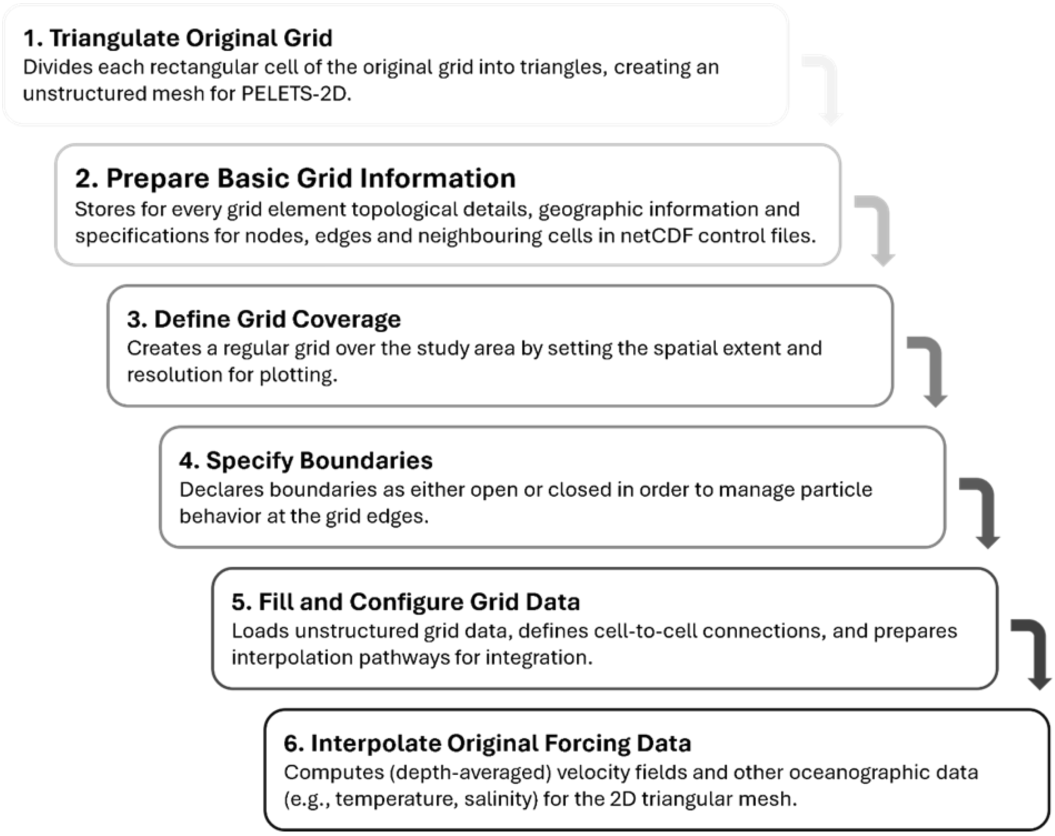

Figure 1. Basic steps for adding a new forcing dataset in the PELETS-2D framework.

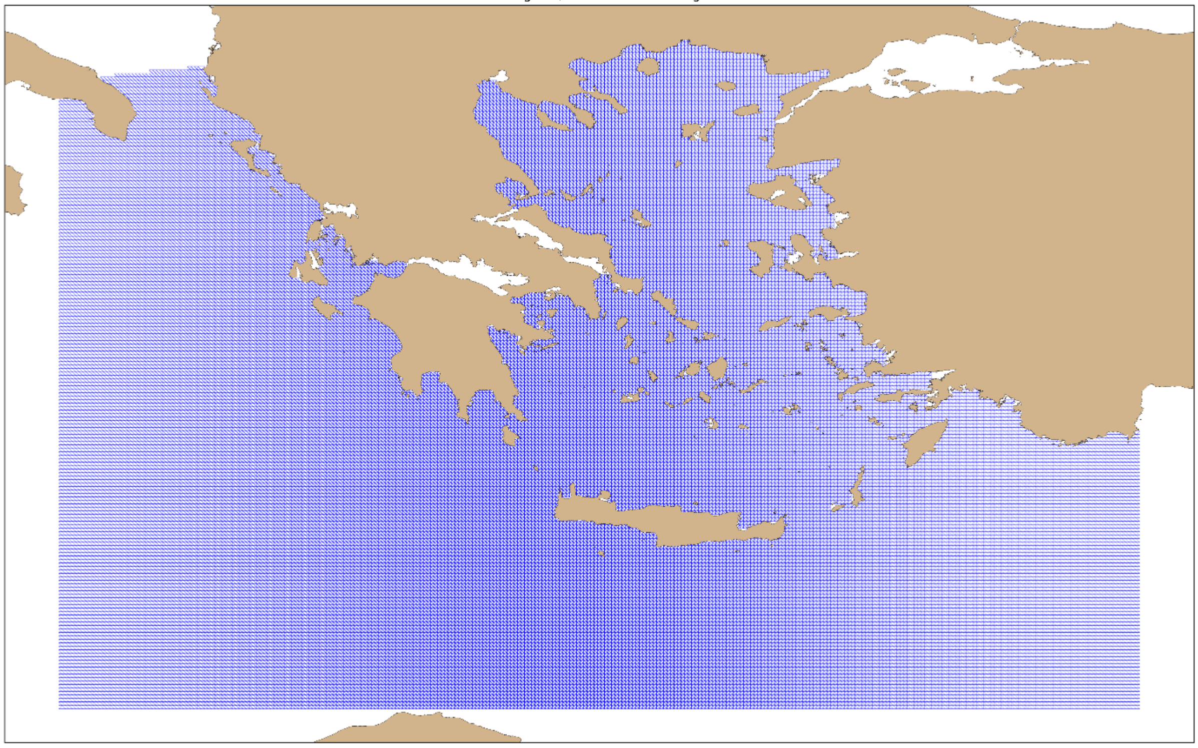

Figure 2. Example of CMEMS forcing data grid as used by PELETS-2D showing MarinePlan's "Greek Aegean – Ionian Seas" planning site.

3.3 Lagrangian Particle Tracking

In PELETS-2D, Lagrangian particle tracking is applied to model the movement of passive tracers, such as nutrients, larvae, or pollutants, in response to horizontal velocity fields. The choice of the horizontal pane (vertical average or surface layer) depends on whether neutrally buoyant or floating particles are considered. Depending on its purpose, a simulation is configured to run either forward or backward in time. For further customisations, several other setup options can be adjusted. Some of them are briefly explained below.

Particle Release: Particles can be released at specific user-defined times or intervals. For all release times, users can define exact event locations, transects, or multiple source regions across the grid. The initial distribution of particles may be chosen to vary by area, depth or be set as uniform across the sources.

Multi-Source to Multi-Sink Analysis: Unlike with the mandatory specification of sources for particle release, the specification of target regions is optional. If provided, PELETS-2D offers a suite of metrics to assess one-by-one source-sink relationships, including cross-boundary exchange rates as well as travel, arrival and residence times.

Wind Drift: For simulations of particles that drift at the sea surface an extra wind drift may be added as the percentage of 10-meter wind speeds (if provided along with the forcing data). The coefficient can be adjusted to represent types of particles with different buoyancy such as plastics or oil.

Numerical Integration: By default, PELETS-2D uses a forward Euler integration, which is a simple and computationally efficient approach to solve particle movement with reasonable accuracy. For higher accuracy, PELETS-2D offers a fourth-order Runge-Kutta scheme. This method provides a more precise solution, particularly in areas with rapid velocity changes, at a slightly increased computational cost.

Random Noise: White noise may be added to simulate more accurately the spread of particles over times. This noise component can be tuned to modify diffusion processes appropriate to reflect horizontal dispersion at a spatial scale of 1 km. Users may choose to draw random values from a normal or uniform distribution.

Adaptive Time-Stepping: This parameter specifies the time interval between updates of hydrodynamic fields. Re-definition provides an easy way for testing how time resolution of hydrodynamic fields influences the results.

External Parameters: Simulations may account for external parameters that are provided for each grid element. These parameters could represent for example habitat sensitivities, human pressures, or remote sensing observations. They shall be logged for each particle trajectory and are written to the output file.

Output and Storage: The output of particle drift simulations grows large if many particles are tracked over a long period of time. In PELETS-2D, users may choose to reduce the output by excluding the hourly particle positions which are stored by default. For simulations that also include many source and target regions, options to store a subset or a minimal selection of metrics or times is available.

Parallelisation: For running large ensemble simulations, PELETS-2D supports parallel processing with MPI.

3.4 PELETS-2D Toolbox

The PELETS-2D Toolbox offers a comprehensive suite of metrics and analysis tools to interpret particle drift simulations and assess marine connectivity. These metrics provide insights into dispersal patterns, connectivity strength, retention, and key transport pathways. Below is an overview of the key tools and metrics that are available in MarinePlan. Nearly all these analyses are also available as composites meaning that results of different simulations can be averaged.

Cross-Counts: Counts the number of particles that cross a specified boundary or reach a designated target region from a given source. Cross-counts quantify the immediate exchange of particles between regions, useful for assessing short-term connectivity.

Cross-Counts Cumulative: In addition to individual cross-counts, cumulative cross-counts track the total number of particles exchanged over a specified period, providing a broader perspective on connectivity over time. This is particularly useful for understanding sustained connections or gradual dispersal patterns.

Travel Times: Time it takes particles to move from a defined source region to a target region. The metric reveals the speed and directness of transport routes between regions helping to assess connectivity efficiency and potential ecological interactions. Shorter travel times often suggest stronger connections, while longer times indicate more diffuse dispersal. Percentiles of travel times provide a statistical summary of the distribution allowing for insights into the variability of transport rates between regions.

Arrival Times: Records the moment when particles reach a target region for the first time. Tracking arrival times is particularly useful for identifying when critical ecological resources, like larvae or nutrients, reach designated habitats. This metric is often applied to evaluate seasonal connectivity, recruitment potential, or time-sensitive transport.

Residence Times: Calculates the duration particles remain within a defined region before exiting. Residence time is essential for understanding retention areas, which are zones where particles (or organisms) tend to linger. This metric is critical in assessing where nutrients, larvae or pollutants are likely to accumulate and remain for extended periods.

Cross-Boundary Exchange Rates: Quantifies the rate of particle exchange between predefined boundaries or regions, which is particularly useful for examining source-sink relationships and inter-regional connectivity.

Hotspots Analysis: Identify regions with high particle density (hotspots) or frequent passage (corridors). These metrics help locate areas of frequent particle transit, which can inform MPA design and other conservation strategies.

FTLE: Quantifies the rate of separation of particles initially placed close together, providing a measure of flow divergence or convergence. This type of analysis is instrumental for identifying LCSs within flow fields as it uncovers hidden structures in Lagrangian flow. The metric is valuable for identifying dynamic structures in the ocean, such as retention zones, transport corridors, or areas which act as barriers to particle movement.

EOF: Decomposes complex flow patterns into a set of orthogonal modes, capturing dominant patterns of variability within the velocity fields. EOFs allow users to identify prevailing transport modes, seasonal shifts, and spatial structures in particle movement. This tool is especially useful for analysing long-term trends, climate-driven variability, or regional flow dynamics across large-scale simulations.

4 Discussion

PELETS-2D has been successfully applied to a wide range of research topics including the analysis of trends in chronic oil pollution (Chrastansky and Callies, 2009, Chrastansky et. al.,2009), weather related variations in litter transport (Neumann et al., 2014), effects of chemical dispersion on oil spill drift paths (Liu and Callies, 2019), use of synoptic maps for the identification of water masses in coastal seas (Callies et al. 2021), the study of algal blooms in marine systems (Teeling et al., 2012) and the dispersal of fish eggs in relation to the ecological effects of offshore wind farms (Gimpel et al.,2023). In the MarinePlan project, PELETS-2D is used to support the implementation of EB-MSP by integrating Lagrangian particle tracking with CMEMS reanalysis products. The application across multiple European planning sites enables a consistent and spatially comprehensive evaluation of marine connectivity. This section discusses the strengths and limitations of this approach.

4.1 Strengths and Contributions to EB-MSP

Integrating PELETS-2D outputs into MarinePlan's DSS has the potential to provide scientists and spatial planners with data-driven insights into ecosystem connectivity. This enables informed decision-making around MPA designation, management, and MSP that is aligned with the EU Biodiversity Strategy's goals. The suite of metrics provided by the PELETS-2D Toolbox, including cross-counts, cumulative counts, travel and arrival times, and advanced tools like FTLE and EOF analyses, offers a comprehensive framework for assessing connectivity. These tools help elucidate long-term trends, seasonal variations, and dominant transport pathways, making them a valuable resource for informed MPA network design and EB-MSP.

By addressing functional connectivity, the PELETS-2D model facilitates scenario development for conservation and restoration. This supports MarinePlan's emphasis on data-driven decision-making aligned with EBSA criteria, contributing to spatial prioritization and management scenarios that reflect ecosystem integrity and resilience against human impacts. In this context, large ensemble simulations are instrumental in assessing the impact of climate variability and change. As oceanographic and atmospheric conditions evolve, they yield probabilistic forecasts that reveal how marine species may redistribute in response to warming seas or how nutrients and pollutants might spread under altered currents or weather conditions. By simulating a broad spectrum of scenarios, large ensemble simulations capture a broad range of possible outcomes, thereby informing adaptive management practices for sustainable resource allocation, mitigation measures or disaster preparedness.

Utilizing CMEMS datasets, PELETS-2D integrates site-specific current fields to achieve precise particle drift simulations. They capture the variability in connectivity within and between EBSAs and MPAs of the diverse MarinePlan planning sites. The flexible setup allows for adjustments between vertical averaging and surface layer analysis and considers wind drift, adaptive time-stepping, and stochastic noise. These capabilities make it well-suited for tailoring the simulations to site-specific hydrodynamic conditions of shallow coastal to deep open ocean environments.

PELETS-2D's structure also accommodates multi-source and multi-sink tracking, enabling simulations with multiple origin and destination areas in parallel. Moreover, its modular input system further allows the model to adapt to a variety of spatial and temporal scales, accommodating specific data requirements across MarinePlan's planning sites. Together, these features make PELETS-2D a versatile and powerful tool for simulating particle transport, allowing MarinePlan to conduct detailed connectivity analyses across its diverse planning sites.

4.2 Challenges and Limits

The two-dimensional framework used by PELETS-2D ignores vertical dynamics by relying on depth-averaged or surface layer velocities. While this approach captures the essential horizontal dispersal patterns, it may overlook vertical processes that influence connectivity, such as diel vertical migration or stratification effects. This limitation could impact studies where vertical movement is a critical factor in connectivity.

As a passive particle tracking model, PELETS-2D also does not account for biological behaviours or ecological interactions, such as active swimming, predation, or habitat preferences. Consequently, while it offers a robust approximation of physical connectivity, it may lack the ecological depth required for studies focused on specific species or functional groups. This highlights a potential area for future model enhancement or coupling with biophysical models.

Running large ensemble simulations across multiple planning sites can create significant computational demands, especially when calculating detailed connectivity metrics across numerous source-target pairs. While PELETS-2D's support for parallelization addresses some of this burden, scaling simulations for extensive analyses or high-frequency output may still be challenging for some use cases.

While CMEMS datasets provide high-quality physical reanalysis products, their resolution may still limit the accuracy of connectivity metrics, particularly in highly dynamic or shallow coastal regions. Fine-scale oceanographic features such as small eddies or localized upwelling as well as detailed geographic structures like complex coastlines, little islands or small inlets may not be fully captured, potentially underestimating local retention or fine-scale connectivity. Future work could explore integrating higher-resolution, regional OCM datasets where available.

4.3 Future Applications and Improvements

The MarinePlan project represents a significant advancement in supporting EB-MSP, providing a transferable framework for assessing connectivity across different European seas. To further enhance the value of PELETS-2D for spatial planning and conservation, several potential improvements and applications are conceivable. To enhance ecological realism, future iterations of PELETS-2D could incorporate species-specific behaviours, habitat affinities, and mortality rates through targeted parameterizations. This would involve adding a behavioural module to simulate species-specific swimming, environmental cues, and dynamic responses to conditions like temperature or salinity. Habitat preferences could be integrated by weighting particle movement toward suitable areas using GIS-based habitat maps and environmental layers. Mortality could be modelled as time-dependent probabilities or linked to environmental extremes, reducing particle survival during simulations. These enhancements would require PELETS-2D to process spatially and temporally variable datasets, incorporate species life history traits, and expand post-processing tools to evaluate recruitment success and effective dispersal. Such upgrades would transition PELETS-2D into a hybrid eco-physical model, deepening its applicability for marine conservation and spatial planning.

Linking PELETS-2D to real-time or predictive oceanographic data would expand its utility for adaptive management. Real-time connectivity information could be valuable for responsive management of pollution events or tracking of invasive species. Extending the methodology beyond the current planning sites and incorporating longer-term historical or projected future climate scenarios could provide insights into connectivity changes over time. This would allow for evaluations of climate-driven shifts in connectivity and inform adaptive MSP strategies.

Currently, PELETS-2D provides a robust suite of tools for connectivity assessments, but additional metrics, such as density heatmaps or network analyses could add even more analytical power. Also, integrating 3D particle tracking would add another layer of ecological realism. Processes such as diel vertical migration or responses to habitat preferences and stratified water columns would improve model accuracy for coastal or deep-sea habitats. However, an increased data volume and processing time could pose challenges, particularly when evaluating climate-driven trends or conducting decadal-scale connectivity studies.

5 DELIVERY

The CMEMS forcing data translated for use in PELETS-2D encompass over 3 terabytes of data and thousands of files. These data are securely stored on the HPC infrastructure at Hereon, ensuring efficient access and management for particle drift simulations across all MarinePlan planning sites. GIS-compatible versions of the control files, containing grid-related information such as topologies and coordinate transformations, have been uploaded to the internal MarinePlan data repository to facilitate their integration into the planning sites' workflows.

To ensure effective use of PELETS-2D outputs, technical support is provided to the planning sites, assisting local teams in applying the model to site-specific scenarios. This includes guidance on adapting the data to regional conditions and tailoring simulations to address the unique ecological and management needs of each site. By bridging these technical and practical aspects, the deliverable enables planning sites to effectively utilize PELETS-2D outputs, sealing its integration into MarinePlan's DSS and EB-MSP initiative.

6 CONCLUSION

The MarinePlan project exemplifies a strategic approach to EB-MSP by incorporating advanced connectivity assessments through the PELETS-2D model. Utilizing high-quality CMEMS reanalysis datasets across various European marine planning sites, PELETS-2D supports DSS in providing robust, data-driven insights into marine ecosystem connectivity. The integration of particle tracking simulations enables a nuanced understanding of marine functional connectivity, informing the design and management of MPAs and facilitating alignment with EU Biodiversity Strategy goals.

PELETS-2D's suite of analytical tools, including metrics such as cross-counts, travel times, FTLE, and EOF analyses, offers essential support for spatial prioritization, conservation, and restoration measures. These metrics reveal long-term trends, seasonal connectivity patterns, and critical ecological corridors, providing valuable insights for MPA network design and EB-MSP. However, while PELETS-2D effectively captures horizontal dispersal patterns, its two-dimensional framework and reliance on passive particle tracking limit its ability to model vertical processes and species-specific behaviours. Addressing these limitations through potential future integration of 3D modelling, real-time data, and biological parameters would enhance the ecological realism and adaptability of connectivity simulations.

In summary, MarinePlan's application of PELETS-2D marks a significant advancement in supporting EB-MSP, providing a scalable, transferable framework for European marine conservation efforts. Future enhancements to PELETS-2D's capabilities would further strengthen its role in supporting efforts to preserve critical connectivity across marine ecosystems. This is essential for maintaining biodiversity and ecosystem resilience.

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Appendix 1 – List of Abreviations

MarinePlan	Improved transdisciplinary science for effective ecosystem-based maritime spatial planning and conservation in European Seas
DSS	Decision Support System
EB-MSP	Ecosystem Based – Maritime Spatial Planning
PELETS-2D	Program for the Evaluation of 2D Lagrangian Ensemble Transport Simulations
FTLE	Finite-Time Lyapunov Exponents
LCS	Lagrangian Coherent Structure
EOF	Empirical Orthogonal Function
OCM	Ocean Circulation Model
NEMO	Nucleus for European Modelling of the Ocean
EBSA	Ecological and Biological Significant Area
CMEMS	Copernicus Marine Environment Monitoring Service
GLORYS	Global Ocean Reanalysis and Simulations
HPC	High Performance Cluster
AZTI	Association for Research and Development of Natural Resources, Spain
Hereon	Helmholtz Centre Hereon, Germany
Thünen	Thünen Institute, Institute of Sea Fisheries, Germany
MII	Marine Institute, Ireland
RBINS	Royal Belgian Institute of Natural Sciences, Belgium
ICM-CSIC	Institute of Marine Science, Spanish National Research Council, Spain
UNINA	University of Naples Federico II, Italy
IMAR-UAZ	Instituto do Mar, Portugal
DTU-Aqua	Technical University of Denmark, Denmark
UAegean	University of the Aegean, Greece