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Predictive Displacement Theory (PDT): An AI-Assisted Framework for Forecasting Jellyfish Movement Based on Citizen Observations and Environmental Drivers

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Abstract Jellyfish blooms are increasing in frequency and intensity across the Mediterranean Sea, posing growing challenges to tourism, fisheries, public safety, and coastal ecosystem monitoring. Despite the rise of citizen science platforms and the availability of real-time environmental data, no operational system currently exists to forecast jellyfish movement. This paper introduces the Predictive Displacement Theory (PDT), the first proposed framework for forecasting jellyfish drift by combining user-submitted sightings with environmental drivers such as wind, wave direction, sea surface currents, and atmospheric pressure. The concept is designed to operate through an AI-assisted application that ingests real-time observations and oceanographic data to generate short- and medium-term forecasts of jellyfish aggregations. As a proof of concept, the framework was retrospectively tested on the 2020~2023 *Pelagia noctiluca* blooms in Greece, with a focus on the Corinthian Gulf during 2021 and 2022, using Windy.com datasets and geo-referenced observations from the iNaturalist platform and a Facebook group. Even without AI support, the model predicted southward jellyfish movement with up to 90% accuracy over five-day periods. These findings demonstrate the viability of PDT and its potential to evolve into the first real-time jellyfish forecasting system, supporting both ecological forecasting and timely public warning mechanisms.

Keywords Jellyfish blooms; Predictive Displacement Theory; AI-assisted forecasting; Citizen science; Coastal ecosystem management

1 Introduction

Jellyfish blooms have emerged as one of the most visible and disruptive phenomena in coastal marine ecosystems, particularly in semi-enclosed basins such as the Mediterranean Sea. In recent decades, reports of large jellyfish aggregations have increased in both frequency and spatial extent, attributed to a combination of climate change, overfishing of natural predators, eutrophication (Fernández-Alías et al., 2024), and changing oceanographic conditions (Gravili, 2020). These blooms not only disrupt local food webs but also interfere with human activities, including fisheries (Palmieri et al., 2015), aquaculture operations, power plants, and especially tourism, where jellyfish stings can deter swimmers and reduce coastal revenue.

In the Mediterranean, species such as *Pelagia noctiluca* have become increasingly dominant (Bordehore, 2023) during summer months, forming large swarms that drift with currents and winds. However, despite their growing impact (Praved et al., 2021), there is currently no operational system capable of forecasting jellyfish movement in real time (Marambio et al., 2021). While citizen science platforms such as iNaturalist have improved spatial data availability, and while environmental datasets on wind, waves, and currents are widely accessible through services like Windy and Copernicus Marine, these data streams remain unconnected in any unified forecasting framework (Avazbek Furqat o’g’li et al., 2022) for jellyfish behavior.

This paper introduces the Predictive Displacement Theory (PDT) as a novel theoretical and technical framework aimed at filling this gap. PDT proposes that jellyfish movement in coastal systems follows semi-deterministic paths (Edelist et al., 2022) influenced by physical oceanographic forces and initial population inputs. By leveraging citizen-submitted sightings as anchor points and combining them with dynamic environmental vectors, PDT offers the basis for an AI-powered forecasting system (Castro-Gutiérrez et al., 2024) capable of predicting jellyfish aggregations (Marambio et al., 2021) over short (1~3 days) and medium (up to 10 days) timescales.

To test the viability of this framework, we retrospectively applied PDT principles to a well-documented case: the widespread blooms of *Pelagia noctiluca* in the Greece but focused on the Corinthian Gulf between 2021 (Taklis, 2022) and 2022 (Taklis, 2023). Using geo-referenced observations from a facebook group, iNaturalist platform and environmental data from Windy.com, we simulated the southward movement of jellyfish swarms under realistic meteorological conditions (Berline et al., 2013). While the test did not include machine learning, it successfully replicated bloom drift with high accuracy, supporting the foundation of PDT as a predictive tool (Gauci et al., 2020).

This paper presents the theoretical foundations of PDT, outlines its operational structure, and discusses the potential for its evolution into the first real-time jellyfish forecasting system, designed for use by scientists, coastal managers, tourism operators, and the general public.

Unlike traditional hydrodynamic or ecological models, which depend heavily on numerical simulations and extensive in-situ oceanographic datasets, PDT provides a lightweight and adaptive framework by directly coupling citizen science observations with real-time environmental drivers. This integration of participatory data and open-access oceanographic streams represents a novel approach to forecasting jellyfish movement, bridging the gap between community monitoring and applied ecological modeling.

2 Methodology

2.1 Overview of the PDT framework

The Predictive Displacement Theory (PDT) (Castro-Gutiérrez et al., 2024) is based on the hypothesis that jellyfish blooms do not disperse randomly (Edelist et al., 2022) but follow movement corridors shaped by environmental forces, such as wind, sea surface currents, and wave dynamics (Castro-Gutiérrez et al., 2022). PDT treats each jellyfish sighting as an origin point for displacement modeling, where jellyfish swarms are passively transported through marine physical vectors (Fossette et al., 2015). The proposed system is designed to operate as a modular forecasting tool that combines three data layers: Citizen science input: georeferenced observations submitted by users (Gutiérrez-Estrada et al., 2021) via a mobile or web-based app. Environmental data streams: real-time meteorological and oceanographic parameters from open-access platforms. AI or rule-based simulation engine: a model that processes the above inputs to generate spatial forecasts of jellyfish movement. The initial implementation of PDT relies on vector-based simulations, but future versions are intended to incorporate AI models trained on historical bloom data.

2.2 Data Sources

2.2.1 Citizen observations

Jellyfish sighting data were sourced from the Facebook group "Jellyfish in Greece," a public citizen science community where users submit reports including date, location, photographs, and species-level identifications. For the purposes of this study, records of *Pelagia noctiluca* from the Corinthian Gulf between 2021 and 2022 were extracted, filtered for accuracy, and aggregated to identify spatiotemporal patterns and likely bloom initiation zones.

Data quality was ensured through a multi-step filtering process. Duplicate reports and those lacking geolocation or time stamps were removed. Only records supported by photographic evidence were retained, and species-level identifications were cross-validated using community consensus on iNaturalist and additional expert review. This reduced the dataset to 150 verified observations between 2020 and 2023, with higher concentrations during June to September. Reports were aggregated into weekly intervals and mapped to subregions of the Corinthian Gulf to establish bloom initiation zones and subsequent displacement patterns.

2.2.2 Environmental data

Environmental inputs were retrieved from Windy.com and related APIs, including: Wind speed and direction at 10 m altitude; Surface current velocity and direction; Wave height, period, and direction; Sea surface temperature (SST); and Atmospheric pressure maps.

These variables were extracted at a 3-hour resolution, interpolated where necessary, and matched to the timing and location of citizen observations.

2.3 Displacement modeling process

The PDT simulation applies a simplified particle advection model in which each sighting is treated as a release point for a virtual jellyfish swarm. The swarm is then projected forward using a composite vector equation:

$$D = \alpha W + \beta C + \gamma V + \delta T$$

Where: D is the displacement vector; W = wind vector; C = current vector; V = wave vector; T = temperature gradient; α–δ are weighted coefficients reflecting the relative influence of each factor.

In the absence of AI, coefficients were manually calibrated based on observational alignment with bloom progression over time. Each sighting generated a prediction envelope, producing a forward simulation of likely jellyfish distribution for the following 1~5 days.

2.4 Limitations and assumptions

This pilot version of PDT assumes passive drift behavior for jellyfish swarms and does not account for: Vertical migration patterns (Malul et al., 2024) (e.g. diel movement (Hays et al., 2012)); Active swimming behavior in some species; Biological factors like reproduction or bloom collapse; Coastal geomorphology (e.g. barriers, eddies, bathymetric influence). In addition, the current approach is deterministic and not probabilistic, which may limit its precision during periods of highly variable weather.

3 Results

To evaluate the feasibility of the Predictive Displacement Theory (PDT) as a forecasting framework, we retrospectively applied its core principles to the extensive blooms of *Pelagia noctiluca* that spread through the Aegean Sea in the Corinthian Gulf between 2020 and 2023. These blooms were among the most persistent and widely reported in recent Mediterranean history, significantly impacting tourism, fisheries, and public safety across coastal regions of Greece.

3.1 Observation dataset

Over 150 georeferenced *Pelagia noctiluca* observations were retrieved from the Facebook Group “Jellyfish in Greece” and iNaturalist platform, concentrated in the summer months (June to September) from 2021 to 2022. These included user-submitted photos and estimated abundances along northern and southern shores of the Corinthian Gulf. Sightings showed clear temporal clustering, often appearing in bursts following periods of sustained northerly winds and calm sea states.

3.2 Environmental drivers

Environmental data collected from Windy.com revealed recurring meteorological patterns during peak bloom events: Northerly winds exceeding 20 km/h sustained for 24~48 hours. Weak east-to-west surface currents within the semi-enclosed Gulf. Warm sea surface temperatures exceeding 25 °C. Low wave energy in the southern coastline areas.

These conditions were considered favorable for jellyfish drift from the south-eastern coasts toward south-western regions, particularly from Kiato to Derveni.

3.3 Forecasting simulation

Using the PDT model in a manual, rule-based mode (without AI), jellyfish sightings were treated as initial displacement nodes. Based on contemporaneous wind, current, and wave data, forward trajectories were simulated for 5-day intervals during peak bloom periods.

Key outcomes include: Southward movement predictions aligned with observed bloom locations in 2021 and 2022 with up to 90% spatial accuracy over 5-day windows. The strongest predictive alignment occurred during episodes of northerly winds combined with low wave heights (<0.8 m), which facilitated passive surface drift. Areas such as the southern Corinthian Gulf coastlines consistently received aggregations 2 to 4 days after initial observations were reported along southern shores. While the forecasting in this phase did not use AI or machine learning, the results demonstrated strong correspondence between predicted and actual bloom displacement.

4 Discussion

The retrospective application of the Predictive Displacement Theory (PDT) to the *Pelagia noctiluca* blooms in the Greece from 2020 to 2023 and specifically in the Corinthian Gulf from 2021 to 2022, provides a promising indication that jellyfish movement can be forecast with reasonable accuracy using a combination of citizen science data and environmental information. Despite the absence of artificial intelligence in this initial phase, the model's ability to predict southward drift with up to 90% accuracy over a five-day period demonstrates the potential of PDT as a foundation for real-time forecasting tools.

The integration of citizen observations with open-access environmental data streams such as those provided by Windy.com offers a cost-effective and scalable method for ecological monitoring. Public contributions through platforms like iNaturalist not only enhance spatial coverage but also improve temporal resolution, which is critical for capturing dynamic bloom behavior.

The Corinthian Gulf's physical characteristics, including its semi-enclosed geography and prevailing current and wind patterns, make it particularly suitable for applying the PDT framework. The consistent pattern of northerly winds driving jellyfish swarms toward the southern coastline is well captured by the model, reflecting the semi-deterministic displacement corridors hypothesized in the theory.

Looking ahead, incorporating artificial intelligence and machine learning techniques will be essential for refining the model, enabling automated data processing, and producing probabilistic forecasts. Such advancements could facilitate real-time alerts for stakeholders, including coastal managers, fisheries, and the general public. To achieve this, future development should focus on expanding training datasets, improving data validation protocols, and integrating additional environmental variables such as vertical water column profiles and biological behavior patterns.

Limitations of the current study include the assumption that jellyfish move primarily as passive drifters, without accounting for vertical migration, active swimming, or biological life cycle events. Furthermore, finer-scale coastal geomorphological features were not included in the model, which may affect local swarm behavior nearshore.

Overall, this study lays the groundwork for the first operational jellyfish forecasting system. By combining community science with environmental modeling, PDT offers a novel approach to managing the increasing ecological and socio-economic impacts of jellyfish blooms in the Mediterranean and beyond.

While the retrospective validation of PDT demonstrates strong predictive potential, several limitations should be acknowledged. First, the reliance on citizen science introduces seasonal and geographic biases, as reports are concentrated during summer months and near populated coastal areas, leaving offshore and winter dynamics underrepresented. Second, data sparsity and uneven spatial coverage may limit the accuracy of predictions in under-sampled regions. Third, the integration of real-time AI poses computational and logistical challenges, including automated data validation, continuous assimilation of environmental streams, and the infrastructure required to support large-scale forecasting applications. Addressing these limitations will be critical for scaling PDT into a fully operational forecasting tool across the Mediterranean.

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