

Building Ocean Intelligence Together

For the Blue Economy, Sustainable Development, and a Smart 21st-Century Society

Session schedule and Abstracts

Location: Workpia Yokohama, Japan

Dates: 11-13 November 2026

Session schedule

Wed. Nov 11, 2026

JST	(10:00 AM - 11:00 AM)	(11:00 AM - 11:30 AM)	(11:30 AM - 11:40 AM)	(11:40 AM - 12:40 PM)	(12:40 PM - 2:00 PM)	(2:00 PM - 3:30 PM)	(3:30 PM - 4:00 PM)	(4:00 PM - 5:30 PM)	(5:30 PM - 7:30 PM)
Room A (Oshidori) (2F)	**Registration**	**Opening (Plenary)** **Chair:** Swadhin Behera	**Summit Photograph**	**DITTO Past, Present and Future (Plenary)** **Chair:** Enrique Alvarez	**Lunch Break**	**Keynotes A1** **Chair:** Marina Tonani, Fei Chai	**Coffee Break**		**Dinner Reception**
Room B (Kujaku) (2F)						**Keynotes B1** **Chair:** Joanna Staneva, Yoichi Ishikawa		*Data, Observation & Modelling* **Oral A1 Environmental Variability and Prediction** **Chair:** Sigmund Kluckner, Hiromichi Igarashi	
Room C (201) (2F)								*Platforms, Digital Infrastructure & Interoperability* **Oral B1 Digital Infrastructure, Interoperability and AI-Enabled Platforms** **Chair:** Jon Blower, Naoki Hirose	
Room D (Icho) (3F)								*Cross-Sector Applications & Solutions* **Oral D1 Cross-Sector Applications & Solutions** **Chair:** Takashi Enomoto, Arne Jørgen Berre	

Thu. Nov 12, 2026

JST	(9:00 AM - 10:30 AM)	(10:30 AM - 11:00 AM)	(11:00 AM - 12:30 PM)	(12:30 PM - 2:00 PM)	(2:00 PM - 3:30 PM)	(3:30 PM - 4:00 PM)	(4:00 PM - 5:30 PM)
Room A (Oshidori) (2F)	**Keynotes A2** **Chair:** Fumio Inagaki, Swadhin Behera	**Coffee Break**	*All categories* **Demos A1** **Chair:** Akihiro Inomata, Laura Rogers	**Lunch Break**	*Data, Observation & Modelling* **Oral A2 Coastal Resilience & Hazard Mitigation** **Chair:** Joaquin Tintore, Urmas Lips	**Coffee Break**	*Data, Observation & Modelling* **Oral A3 Data-Driven Emulators** **Chair:** Alain Arnaud, Deanesh Ramsewak
Room B (Kujaku) (2F)	**Keynotes B2** **Chair:** Yasumasa Miyazawa, Bente Lilja Bye			*Other* **Oral/Panel C1 From Ocean Science to Ocean Policy** **Chair:** Michael Huang	*Platforms, Digital Infrastructure & Interoperability* **Oral B2 Digital Twin Infrastructure and Operational Services** **Chair:** Avichal Mehra, Shintaro Momose		*Platforms, Digital Infrastructure & Interoperability* **Oral B3 Ocean Digital Twins for Coastal Resilience, Ecosystems and Ocean Health** **Chair:** Ruoying He, Hakase Hayashida
Room C (201) (2F)					*AI, Automation & Optimization* **Oral C2 AI, Automation and Agent Platform** **Chair:** Patrick Heimbach, Fernando Mendez		*AI, Automation & Optimization* **Oral C3 AI, Automation & Optimization** **Chair:** Di Wan, Justin Buck, Takeshi Doi
Room D (Icho) (3F)					*OSID & IESS* **Oral D2 OSID & IESS** **Chair:** Alessandro Oggioni, Matthias Obst		*OSID & IESS* **Oral D3 OSID & IESS** **Chair:** Bruno Buongiorno Nardelli, Akira Nagano
Posters (3F)			*Everything else* **Posters 1**				

Fri. Nov 13, 2026

JST	(9:00 AM - 10:30 AM)	(10:30 AM - 11:00 AM)	(11:00 AM - 12:30 PM)	(12:30 PM - 2:00 PM)	(2:00 PM - 3:30 PM)	(3:30 PM - 4:00 PM)	(4:00 PM - 5:00 PM)
Room A (Oshidori) (2F)	*Data, Observation & Modelling* **Oral A4 Ocean Observing Systems and Data Quality** **Chair:** Sung Yong Kim, Yosuke Fujii	**Coffee Break**	*All categories* **Demos A2** **Chair:** Takehisa Yamakita, Ibrahim Hoteit	**Lunch Break**	*Data, Observation & Modelling* **Oral A5 Ocean Digital Twins, Data Architectures and AI-Enabled Approaches** **Chair:** Philipp S. Sommer, Tomoki Tozuka	**Coffee Break**	*Other* **Closing (Plenary)**
Room B (Kujaku) (2F)	*Asian Hub (DOM)* **Oral B4 - Asian Hub** **Chair:** Yushi Morioka				*Data, Observation & Modelling* **Oral B5 Coastal and Marine Ecosystems, Blue Carbon and Regional Ocean** **Chair:** Konobu Kimura, Fadli Syamsudin		
Room C (201) (2F)	*Data, Observation & Modelling* **Oral C4 Marine Biodiversity & Ecosystem Modelling** **Chair:** Cheng-Hao Lu, Qiang Deng				*ILIAD Discussion (PDII)* **Oral C5 A Federated Ocean-Earth Digital Twin Ecosystem: Connecting EDITO, Destination Earth and Open Standards** **Chair:** Bente Lilja Bye, Marco Oliveira		
Room D (Icho) (3F)	*Cross-Sector Applications & Solutions* **Oral D4 Cross-Sector Applications & Solutions** **Chair:** Matthew Palmer, Haruka Nishikawa				*Cross-Sector Applications & Solutions* **Oral D5 Corss-Sector Applications & Solutions** **Chair:** Klaas Deneudt, Michio Kawamiya		
Posters (3F)			*First two categories* **Posters 2**				

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Opening Remarks

Chair: Swadhin Behera

Welcome Address

Dr. Tomohiko Kawamura (President, JAMSTEC)

Opening Remarks

Mr. Tomohiko Arai (Deputy Director-General, Research and Development Bureau, MEXT)

Keynote Speech 1

Ms. Ekaterina Zaharieva (European Commissioner for Startups, Research and Innovation)

Keynote Speech 2

Ms. Charlina Vitcheva (Director-General, European Commission's Directorate-General for Maritime Affairs and Fisheries)

Keynote Speech 3

Dr. Robert Redmon (Director, NOAA Center for Artificial Intelligence)

Keynote Speech 4

Prof. Yutaka Michida (IOC/UNESCO Chairperson, The University of Tokyo)

DITTO Past, Present and Future (Plenary)

Chair: Enrique Alvarez

Welcome remarks

**Enrique Alvarez*[1] (1. OceanPrediction DCC (France))

DITTO in the Past: Origins, milestones and lessons learned

**Martin Visbeck*[1], John Siddorn[2] (1. OceanQuest (Germany), 2. NOC (UK))

DITTO in the Present: Progress, achievements and ongoing activities

**Joanna Staneva*[1], Fei Chai[2] (1. Hereon (Germany), 2. Xiamen University (China))

DITTO in the Future: Strategic priorities, opportunities and the way forward

**Marina Tonani*[1], Swadhin Behera[2] (1. Mercator Ocean International (France), 2. JAMSTEC (Japan))

Discussion and Feedback: Future priorities and opportunities for collaboration

*Nicolas Segebath[1], Ann-Christine Zinkan[2], All Participants (1. European Commission (Belgium), 2. NOAA (USA))

Keynotes A1

Chair: Marina Tonani, Fei Chai

Real time Bayesian inversion, prediction, and OED for tsunami early warning

*Omar Ghattas

Abstract: We address real-time Bayesian inverse problems governed by time-shift-invariant wave equations, with particular focus on tsunami source inversion and forecasting, and sensor network optimal experimental design. Efforts are underway to instrument subduction zones with ocean bottom acoustic pressure sensors to provide tsunami early warning. Our goal is to create a physics-based early-warning system that employs this pressure data, along with the 3D coupled acousticâ€“gravity wave equations, to infer the earthquake-induced spatiotemporal seafloor motion in real time. The Bayesian solution of this inverse problem then provides the seafloor forcing to forward propagate the tsunamis toward populated areas along coastlines and issue forecasts with quantified uncertainties.

In the context of the Cascadia Subduction Zone, a single forward wave propagation requires ~1 hour on a supercomputer. The Bayesian inverse problem, with a billion uncertain parameters, formally requires hundreds of thousands of adjoint wave propagations; thus real time inference appears to be intractable. We propose a novel approach to enable exact solution of the inverse and prediction problems in real time. The key is to exploit the time-shift-invariance of the parameter-to-observable map, which permits FFT diagonalization and fast GPU implementation. The result is that tsunami inverse problems with a billion parameters can be solved exactly in a fraction of a second.

This fast Bayesian inversion capability is then exploited to solve the optimal experimental design problem of placement of seafloor pressure sensors to maximize expected information gain in predictive quantities of interest. Time permitting, we discuss data-driven prior construction, goal-oriented dimension reduction, and construction of fast surrogates for the nonlinear shallow water equations, which are needed for representing nearshore tsunami dynamics.

This work is joint with Stefan Henneking, Sreeram Venkat, Bowen Shi, and Yuhang Li at UT Austin, and Alice Gabriel at UCSD.

Transforming Ocean Observation into Continuous Action through Fujitsu's Ocean Digital Twin

*Akira Karasudani[1], Akihiro Inomata[1] (1. Fujitsu (Japan))

Abstract: As societies face increasingly complex challenges, understanding the interdependencies among physical environments, ecosystems, infrastructure, human activities, and policies is becoming essential. Fujitsu's Digital Twin vision extends beyond the representation of physical assets to support informed decision making across social, economic, and environmental domains. Through initiatives such as Social Digital Twin and Digital Rehearsal, Fujitsu is exploring new ways to understand complex systems and evaluate actions before they are taken.

Building on this vision, Fujitsu is advancing Ocean Digital Twin technologies to make underwater environments more visible and understandable. Coordinated control of multiple underwater drones enables adaptive data collection across wide areas, while real-time sensing and rapid 3D reconstruction provide timely visibility into underwater conditions and evolving changes.

Through a hardware-agnostic approach, Fujitsu integrates multimodal data from underwater vehicles, cameras, sonar, environmental sensors, and other sources. The resulting digital representations can be continuously enriched through observation and operations, helping stakeholders improve situational awareness and make informed decisions regarding inspection, maintenance, environmental management, and other interventions. By applying Digital Rehearsal to these Ocean Digital Twin representations, stakeholders can evaluate possible interventions and their implications before actions are taken in the real environment. This creates a continuous cycle of observation, understanding, action, and learning.

This presentation introduces Fujitsu's latest Digital Twin vision and its application to the ocean domain. It will demonstrate how real-time observation, 3D visualization, and multimodal data integration can strengthen ocean intelligence and connect it with operational and societal decision making. Together, these capabilities contribute to more adaptive, resilient, and collaborative management of marine environments and infrastructure.

Digital-Twin of 3D Immersive Ocean Diagnostic and Prognostic System in the Western Pacific Marginal Sea

*Jianping Gan

Abstract: The western Pacific marginal sea (WPMS), spanning from tropical to high latitude region, is the transition zone between the Southeast Asia continent and open Pacific Ocean. WPMS is one of largest marginal seas in the world, surrounded by more than 15 countries with active socioeconomical development. WPMS covers bays, estuaries, shelf seas and interlinked semi-closed seas from the south to north that actively exchanges with the open western Pacific Ocean. WPMS is undergoing changes physically and biogeochemically in responses to changing climate and human activities. These changes exhibit spatiotemporally heterogenous in the multi-scale system. Diagnoses and prognoses of the status, health, resilience and future trend of WPMS are largely determined by the sustainability of the ocean in the interlinked spheric system that composes the lithosphere (land), the hydrosphere (oceans and rivers), the atmosphere, and the biosphere (living things). It is also controlled by the multi-scale processes of unique marginal sea characteristics internally and sea-ocean exchange externally. Based on complex integration of all streaming data from observation, earth simulator, analytics, visualization, machine learning and fundamental ocean and earth science, we have developed a comprehensive digital twin system, WavyOcean (http://wavyocean.hkust.edu.hk/), to resolve multi-scale processes from coastal oceans, seas to open ocean in the WPMS. WavyOcean innovatively developed an architecture of integrated land-ocean-atmosphere earth system; high-fidelity 3D immersive, GIS-BIM integrated visualization and diagnosis, comprehensive interactive analysis toolkit, high-performance rending for large-scale data and flexible cross-platform accessibility. The system let you see the unseen ocean, provides an innovative technology to make ocean transparent, and upgrade our holistic capability for understanding, prediction and management to the ocean.

From Ocean Forecasting to Predictive Digital Twins: Closing the Loop from Observations to Decisions

**Ibrahim Hoteit*

Abstract: Ocean forecasting has advanced considerably over the past two decades, driven by improvements in numerical models, observing systems, satellite remote sensing, data assimilation, ensemble methods, artificial intelligence, and high-performance computing. Ocean digital twins provide an opportunity to bring these elements together within an integrated framework that combines models and observations to represent and predict the evolving ocean state and ultimately support informed decision-making. Developing predictive digital twins requires the seamless integration of numerical models with in situ observations and satellite imagery, while quantifying and propagating uncertainties and enabling optimization and decision-making in real time.

In this talk, I will discuss our experience developing integrated ocean prediction systems, with particular emphasis on the Red Sea. Ensemble data assimilation provides a framework for integrating heterogeneous observations with numerical models, quantifying uncertainties in the ocean state, and propagating them into forecasts. I will

illustrate these developments through two applications. The first focuses on oil-spill monitoring and prediction, using satellite imagery for detection and atmospheric and oceanic forecasts to predict spill evolution and associated uncertainties. The second explores how environmental predictions and their uncertainties can be combined with optimization methods to design shipping routes that reduce environmental impacts, including emissions and underwater noise.

Building on these applications, I will discuss how ocean prediction systems can evolve toward operational digital twins that connect observations, prediction, and uncertainty quantification with optimization and decision-making under uncertainty. Closing this loop in real time presents significant computational and methodological challenges, and this is where AI can play an important role. AI can extract actionable information from satellite imagery, accelerate computationally demanding models, and enhance data assimilation, ensemble prediction, optimization, and decision support. I will conclude by highlighting the key challenges toward operational ocean digital twins capable of transforming observations and predictions into actionable information for real-time decision-making.

Keynotes B1

Chair: Joanna Staneva, Yoichi Ishikawa

OneArgo as a Core Component of GOOS: From Sustained Ocean Observations to Digital Twins for Society

**Toshio Suga*[1] (1. WPI/AIMEC, Tohoku University (Japan))

Abstract: Over the past quarter-century, the Argo program has fundamentally revolutionized our understanding of the global ocean, serving as a backbone of modern oceanographic and climate science. Achieved through unprecedented international cooperation and continuous technological innovations—such as advanced battery efficiencies, satellite communications, and robust sensor designs—the core Argo array has successfully maintained a fleet of thousands of autonomous profiling floats. This collective global effort has provided a wealth of high-quality, real-time data, completely transforming our ability to monitor ocean heat content, sea-level rise, and shifting salinity patterns. The rich scientific repository built by Argo has enabled thousands of peer-reviewed studies, refined climate projection models, and underpinned critical assessments by the IPCC.

Today, this foundational network is undergoing its most ambitious evolution yet into "OneArgo." Recognizing that the ocean’s challenges extend far beyond the upper two kilometers and physical parameters, the OneArgo design comprehensively expands the traditional array along two major frontiers: deep-ocean profiling down to six thousand meters and the full integration of biogeochemical (BGC) sensors to monitor ocean acidification,

deoxygenation, and carbon uptake. As a core component of the Global Ocean Observing System (GOOS), OneArgo represents the ultimate globalization of sustained ocean observing.

However, the true value of this vast, multidimensional data can only be unlocked when it is actively translated into actionable insights for society. In this context, the rapid advancement and implementation of the Digital Twin of the Ocean (DTO) is not merely an optional application, but a primary prerequisite. A functional DTO requires a continuous, high-fidelity stream of real-time physical and biogeochemical data to continuously synchronize its virtual models with the actual state of the ocean through advanced data assimilation, numerical modeling, and AI-driven predictive frameworks. Without the global, robust infrastructure of OneArgo, digital twins would lack the foundational truth needed for high-resolution forecasting. Conversely, without the analytical and predictive frameworks of a DTO, the full societal potential of OneArgo's multi-parameter data cannot be fully realized.

This presentation will review the historic milestones of the Argo community, outline the current implementation status and future vision of OneArgo, and demonstrate—drawing on emerging institutional frameworks like WPI-AIMEC—why the integration of observations, modeling, and AI through co-designed digital twin technologies is indispensable for addressing pressing societal needs, supporting the blue economy, and building a climate-resilient future.

Ocean Forecasting and Digital Twins: Towards a Federated Predictive Ocean

**Enrique Alvarez*

Abstract: Digital Twins of the Ocean (DTOs) are opening new opportunities to understand, explore, and manage the ocean by bringing together observations, models, data, knowledge, and applications. Their ultimate value, however, will depend on their ability not only to represent the ocean as it is, but also to help us explore what may happen next. In this context, Ocean forecasting has a fundamental role to play.

At the same time, Digital Twins can become a powerful accelerator for the evolution of ocean forecasting. The needs emerging from DTO applications — higher spatial and temporal resolution, faster delivery, local information, uncertainty estimates, seamless integration across scales, and interactive exploration — are pushing Ocean forecasting technology forward. In this sense, the DTOs are the best possible catalyst for a needed revolution in Ocean Forecasting and observation.

This calls for a different way of thinking about the relationship between forecasting systems and Digital Twins. Rather than developing a dedicated forecasting system for every Digital Twin, we should move towards a globally

built federation of interoperable forecasting services, where individual services can be discovered, accessed, combined and reused by multiple Digital Twins. A global, regional or coastal forecasting service should not belong to a single DTO: it should become a shared capability that can support many different applications and domains. Conversely, a Digital Twin may dynamically combine several forecasting services to address a particular decision or user need.

Artificial Intelligence will be an important enabler of this evolution. In particular, AI offers the potential to overcome one of the fundamental limitations of conventional forecasting: computational cost. By providing low-computing-cost capabilities, AI could make it possible to explore large-domain, high-resolution scenarios interactively. This would move us beyond the traditional question of "What will happen?" towards "What if?" — allowing users to investigate possible interventions, events and management strategies within the Digital Twin itself. And, in this new scenario, these "What if" questions could be solved in real time, not needing to rely on pre-established computations which could be ill-suited to the problem to solve.

The emerging vision is therefore of a globally built federated predictive ocean, in which observations, numerical models, AI and forecasting services are interconnected and can be shared across multiple Digital Twins. OceanPrediction DCC and other initiatives, such as FORESEA and CoastPredict, are already working in this direction. Many of these concepts will be tested in AFRICA, thanks to the OPERA (Ocean Prediction Enhancement in the Regions of Africa) project. Such an ecosystem would benefit both communities: Digital Twins would gain access to increasingly powerful predictive capabilities, while their demanding applications would drive the development of faster, more flexible, and more locally relevant forecasting services.

Therefore, the challenge ahead is not simply to build more Digital Twins or better forecasts, but to connect these capabilities into an interoperable ecosystem that can turn predictions more easily into actionable exploration of the ocean's possible futures, exploiting more efficiently the limited computational and observational resources we have.

Earth System Digital Twins: A New Frontier for Ocean Understanding

**Laura J. Rogers*[1] (1. NASA Earth Science Technology Office, USA)

Abstract: We are entering a pivotal moment in Earth science. Rapid environmental change, rising coastal risks, and intensifying societal demand for trusted Earth intelligence are reshaping how we observe, analyze, and understand our planet. Emerging Earth System Digital Twins (ESDTs) are opening the door to an entirely new class of scientific capability - dynamic, data-assimilative frameworks that merge measurements, models, and

intelligent analytics to reveal how Earth systems behave in real time and how they may evolve under different futures.

NASA's diverse portfolio places it at the center of this transformation. From spaceborne and airborne missions to field or ship based campaigns, from physics-based models to machine-learning emulators, and from advanced cloud architectures to open-data ecosystems, we now have the ingredients to generate more complete and more responsive representations of ocean and Earth system dynamics. Across hydrology, coastal processes, biogeochemistry, and atmosphere–ocean coupling, new missions and modeling approaches are producing richer, more continuous, and more interoperable streams of information. Advances in AI-enabled prediction, quantum-inspired sensing concepts, and adaptive observing strategies are accelerating what digital twins can capture and how quickly they can respond.

These breakthroughs reveal a rapidly expanding opportunity space. ESDTs can transform how we deliver environmental intelligence, enabling clearer insights for resource management, hazard planning, and real-time decision support. They promise to make complex systems more transparent, reproducible, and accessible to scientists, stakeholders, and communities.

Yet critical challenges remain. Interoperability across global data systems, unified standards for model-data fusion, scalable uncertainty characterization, and robust calibration frameworks are essential for reliable twin ecosystems. Supporting global, high-resolution systems requires major computational and architectural innovation. And as these technologies advance, so must our attention to equity, transparency, and accessibility.

This talk explores these opportunities and challenges, and highlights how today's scientific progress is shaping the next era of Earth system understanding.

Thirty Years of JAXA Earth Observation: From Monitoring to Prediction Toward Earth Intelligence

**Osamu Ochiai*[1] (1. JAXA (Japan))

Abstract: JAXA has a longstanding history of developing and operating Earth observation satellites. Since the 1990s, it has continuously advanced a diverse portfolio of observation systems spanning multiple sensing technologies. Many of these missions have now evolved into their second and third generations, enabling the establishment of nearly three decades of continuous global Earth observation records. These long-term datasets provide an invaluable foundation not only for scientific research but also for practical applications, including

disaster management, environmental monitoring, land and ocean observation, and the provision of greenhouse gas information to policymakers.

Currently, JAXA operates nine Earth observation satellites and sensors and provides a wide range of science-based data products to users worldwide. Since 2024, three new Earth observation missions have been successfully launched. EarthCARE, carrying the Cloud Profiling Radar (CPR), was launched in May 2024. ALOS-4, equipped with the Phased Array L-band Synthetic Aperture Radar-3 (PALSAR-3), was launched in July 2024. GOSAT-GW, carrying the TANSO-3 greenhouse gas monitoring sensor and the Advanced Microwave Scanning Radiometer-3 (AMSR3), was launched in June 2025. In addition, JAXA is developing two next-generation missions: the Precipitation Measuring Mission (PMM), featuring a Ku-band Doppler precipitation radar, and the Multi-footprint Observation Lidar and Imager (MOLI), which will be deployed on the International Space Station. Through these efforts, JAXA continues to advance satellite technologies, sensors, and data products to address global challenges such as climate change, extreme weather, and natural disasters.

Looking ahead, the value of more than 30 years of continuous Earth observation data extends beyond monitoring toward prediction and actionable intelligence. By integrating long-term satellite observations with Earth system models, data assimilation frameworks, and emerging artificial intelligence technologies, JAXA is working to enhance climate and environmental forecasting capabilities. This transition from observation to prediction represents a key step toward realizing "Earth Intelligence," delivering greater benefits to science, policy, and society through improved understanding and anticipation of our changing planet.

Oral A1 Environmental Variability and Prediction

Chair: Sigmund Kluckner, Hiromichi Igarashi

Seasonal prediction of wind/wave/current for ship operation planning

**Yasumasa Miyazawa*[1] (1. Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Japan))

Abstract: Prediction of oceanic states (wind, wave, and current) has been utilized for safe and efficient marine transportation. Predictability of wind in weather forecasting is generally lost within 10 days because of its chaotic nature, and that of wave and current is also significantly affected by wind variability. However, sub-seasonal and

seasonal predictability of the oceanic states in the time scale longer than 10 days has not been well utilized for marine transportation. Un-negligible biases and errors represented by available seasonal forecast data provided from atmosphere-ocean coupling physical models hinder the utilization of the seasonal forecast data. Furthermore, fully utilization of the seasonal forecast data requires intensive survey of possible applications based on in-depth discussion between users and forecast data providers. To resolve such difficulty and establish the practical application of seasonal prediction for marine transportation, recently we have launched a R & D program for developing a seasonal predication simulator in a framework of close collaboration among private ship management companies, R&D companies, universities, and research institutes including JAMSTEC. Here we introduce our plan and discuss some scientific and technical issues for skillful prediction.

Extreme Climate and Ocean Digital Twin by JAMSTEC/APL

**Takeshi Doi*[1] (1. JAMSTEC/APL (Japan))

Abstract: Every month, we produce two-year climate predictions in real time to investigate the seasonal predictability of the climate system and find ways to utilize seasonal climate forecast information. Although significant advances have been made in seasonal climate prediction and its social applications, more needs to be done to support users' behaviours and decision-making by connecting the value chain from the ocean observing system to numerical seasonal climate forecasts and end users. To this end, we are developing the 'Extreme Climate and Ocean Digital Twin' at JAMSTEC/APL. Moving beyond predicting three-month temperature and precipitation averages, we are beginning to provide information on the seasonal characteristics of extreme events, such as tropical cyclones, coral bleaching and heatwaves. Our forecast outputs are provided via a data server, and we are also developing a new visualization tool with a 'twin mode' to enable users to compare the real situation with virtual forecasts. These new digital tools could facilitate the collaborative development of the digital twin between scientists and specific end users. Intermediate users may be key.

JAXA Ocean Missions and its Applications to Model and Analysis

**Misako Kachi* (1. Japan Aerospace Exploration Agency (JAXA) (Japan))

Abstract: JAXA operates several ocean missions and produces various geophysical parameters related to ocean environmental monitoring, such as sea surface temperature (SST), ocean color, sea surface wind speed, sea ice concentration, sea ice motion vector, etc. Those ocean products are distributed to public on a near-real-time basis via internet. They are used not only for scientific purposes, such as climate studies, but also for operational applications in meteorological agencies, maritime safety, fisheries and navigation services for polar vessels. While satellite observations are essential in ocean environment monitoring, they have disadvantages that some

important parameters and information under the ocean surface cannot be observed by satellites. To demonstrate capability of satellite-based ocean data and enhance their effectiveness at the maximum, JAXA collaborates with model development organizations to utilize satellite data into their ocean models.

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) assimilates satellite-based SST into their high-resolution regional ocean model around Japan on a near-real-time basis to produce short-term forecast of ocean status, called JCOPE-T DA (Miyazawa et al., 2017, 2021) and JCOPE-T 1ks, to produce temporally gapless ocean information with higher accuracy. Analysis and forecast by JCOPE-T DA and 1ks are available from the JAXA web site (https://www.eorc.jaxa.jp/ptree/ocean_model/).

For long-term analysis of ocean state, an ensemble ocean analysis product, LORA Ver. 1.0, is created by a regional ocean data assimilation system, sbPOM-LETKF, which is developed by RIKEN under collaboration with JAXA (Ohishi et al., 2024). LORA Ver. 1.0 is also available via JAXA web site (https://www.eorc.jaxa.jp/ptree/LORA/index.html). RIKEN is currently developing the next version of LORA to extend its coverage to quasi-global area with 0.25-degree grid.

Modeling and prediction of Arabian Sea cyclonic storms using WRF modeling system

**KUVAR SATYA SINGH* (1. Vellore Institute of Technology (India))

Abstract: The present study examines the performance of high resolution WRF modeling system in simulation/prediction of Arabian Sea cyclonic storms. The model initial and lateral boundary conditions derived from the FNL analysis and integration using a double nested domains 15 km and 3 km. The initial conditions for the model was improved through three dimensional data assimilation technique by using satellite radiances with conventional observations from NCEP. The study also used regional background error statistics to improve the model initial condition. The model performance was evaluated by using 3 km results and compared with available observational datasets namely best fit data from the Indian Metrological Department (IMD) and CIRA - Cooperative Institute for Research in the Atmosphere. The statistical analysis was also conducted in this study in terms of bias, mean error, and standard deviation, and it exhibited the significance and importance of the prediction of Arabian Sea cyclones.

The Weather Extremes Archive

**Patrick Martineau*[1] (1. JAMSTEC (Japan))

Abstract: Climatic extremes, such as heat waves, cold spells, wet and dry spells, and marine heat waves, have significant socioeconomic and ecological impacts. Despite the existence of various disaster archives, no dedicated,

publicly accessible database comprehensively catalogs global climatic extremes. This project addresses that gap by developing an online archive of climatic extremes, designed to facilitate scientific collaboration, inform policymakers, and support media coverage. As a pilot project, we focus on heat extremes, with atmospheric heat waves and cold spells identified using ERA5 2-m air temperature, and marine heat waves identified using OISST sea surface temperature. In both cases, extremes are defined as highly unusual temperature anomalies that persist over time. They are further grouped into extreme events using connected component labeling to provide a spatiotemporally coherent representation of large-scale, persistent climatic anomalies. The archive comprises a static database of past events, presenting statistics on extremes, maps of affected areas, and timelines showing the evolution of each event, as well as an interactive analysis tool for data exploration.

Recent Thermal Shifts along the Moroccan Atlantic Coast (21°N–36°N): Insights from Sea Surface Temperature Variability and Anomalies, 1993-2026

**Karim HILMI* (1. Secrétariat d'Etat Chargé de la Pêche Maritime (Morocco))

Abstract: Monthly sea surface temperature (SST) data from the Copernicus Marine Service were analyzed for 1993–2026 along four cross-shore transects of the Moroccan Atlantic coast: T1 (32°N), T2 (26°N), T3 (24°N), and T4 (21°N). Each transect includes eight stations extending from the shelf to the open ocean, from 50m to 5000m depths. Their selection reflects the main oceanographic contrasts of the moroccan Atlantic coast/margin in the Canary Current upwelling system, including latitudinal changes in shelf–slope structure, coastline configuration, upwelling intensity, and cape-related circulation. The 1993–2026 records show a pronounced seasonal SST cycle superimposed on strong interannual variability. A persistent cross-shore thermal gradient is evident, with coastal stations generally cooler than offshore stations, consistent with wind-driven coastal upwelling and offshore export of upwelled waters. This gradient is particularly clear along T2, T3, and T4. Recent anomalies from September 2022 to June 2026 reveal marked regional contrasts. At T1, positive anomalies during late 2022–2023 are followed by cooling in 2024 and a pronounced cold event in autumn 2025. T2 shows widespread warming in 2023, especially offshore, followed by weaker near-normal to slightly negative conditions. T3 also exhibits coherent warming in 2023, peaking around mid-year, then weakening through 2024–2026. At T4, warming persists longer, into early 2024, before shifting toward predominantly negative anomalies, especially over the shelf and upper slope. Regionally, 2023 represents the most spatially coherent warm phase, whereas 2024–2026 are characterized by relative cooling and stronger spatial heterogeneity. This evolution suggests a recent reorganization of thermal conditions within the Moroccan upwelling system, potentially linked to changes in wind forcing, Ekman transport, upwelling intensity, and large-scale climate variability such as NAO, EA,

AMV/AMO, ENSO-related teleconnections….Further atmosphere–ocean investigations are currently underway to quantify these drivers and assess their impacts on SST.

Oral B1 Digital Infrastructure, Interoperability and AI-Enabled Platforms

Chair: Jon Blower, Naoki Hirose

A Metadata Application Profile for Machine-Actionable Ocean Workflows

Marco Oliveira[1], *_Artur Rocha_[1] (1. INESC TEC (Portugal))

Abstract: The reuse of analytical workflows in Digital Twin of the Ocean environments depends on more than access to source code, containers or workflow files. Users and software agents must also be able to identify a workflow, understand its purpose, assess where and when it is applicable, determine its inputs and outputs, and verify the conditions under which it can be used. This requires a consistent, machine-readable and machine-interpretable metadata model.

This presentation introduces the Application Package Metadata Application Profile (APKG-MAP), developed to describe executable Application Packages used in ocean and geospatial processing environments. The profile extends the metadata available in packaged workflows by combining information about identity and lifecycle, responsibility and governance, spatial and temporal applicability, and the executable interface of the workflow.

APKG-MAP reuses established RDF vocabularies, including Schema.org, Dublin Core Terms, DCAT, OWL-Time, GeoJSON, GeoSPARQL and Common Workflow Language terms, together with a dedicated Application Package vocabulary. It defines how these elements are combined, which properties are required or optional, and which cardinalities and controlled values apply. Descriptions are represented in JSON-LD, while SHACL shapes are used to validate conformance, completeness and consistency.

The profile is designed as a semantic contract for executable workflows. It enables Application Packages to be consistently described, queried, compared and evaluated for reuse across infrastructures. Its implementation in the ILIAD Application Package Registry demonstrates how the profile supports metadata-based discovery while preserving links to the underlying executable workflow.

The presentation will focus on the profile's requirements, conceptual structure, vocabulary reuse, validation model and implementation experience, and will discuss its contribution to extending semantic interoperability from ocean data to executable analytical workflows.

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A reuseable OSS Framework for building reliable and agentic digital twins

**Philipp S. Sommer* (1. Helmholtz-Zentrum Hereon (Germany))

Abstract: Agentic digital twins require more than conversational interfaces: they need reliable access to scientific methods, distributed infrastructures, and trusted data while remaining secure, maintainable, and reusable. We present an open-source framework for building such systems based on the Data Analytics Software Framework (DASF), a lightweight message-broker-based RPC framework that enables scientists to expose existing Python methods, workflows, and models as remotely callable services.

The approach is designed for interoperability across heterogeneous research environments. DASF-based agents can securely orchestrate tools and computations across institutional boundaries, including high-performance computing systems, local research infrastructures, and domain-specific services, without requiring inbound internet-facing ports. This allows agentic digital twins to combine distributed capabilities while keeping compute close to data and respecting institutional security policies.

A key strength of the framework is its open-source and reusable deployment model. DASF can be setup through standardized templates and Helm charts, supporting reproducible deployments across projects and institutions. This reduces implementation effort, encourages common architectural patterns, and enables scientific teams to build agentic systems without re-platforming existing applications.

We demonstrate the concept with iseapower.hereon.de, a decision-support tool for offshore wind farm maintenance, combining multiple infrastructures and frameworks. In this operational digital-twin context, a DASF-based AI agent can trigger analyses, plan maintenance workflows, and return results as native application views such as maps, plots, tables, and dashboards. The agent therefore becomes an additional interaction layer for science-based decision support rather than a detached chatbot.

The framework supports reliable, transparent, secure, and interoperable agentic digital twins that can be adapted to diverse scientific questions and stakeholder-driven decision processes.

Squidle+ and SquidJam: An Explorable, FAIR Digital Twin of the Ocean for AI-Ready Marine Imagery

*Dhugal John Lindsay[1] (1. JAMSTEC (Japan))

Abstract: The rapid growth of marine imaging — from towed cameras, ROVs and AUVs to citizen-science divers — has outpaced our ability to turn pixels into usable knowledge. Squidle+ (squidle.org) is a web-based, collaborative platform providing end-to-end management, discovery, annotation, and reuse of marine imagery, regardless of collection method, ecosystem, or data format. Rather than duplicating imagery, it links directly to existing cloud storage repositories, decoupling collection from delivery and enabling automated, set-and-forget ingestion.

A core strength is Squidle+'s map-based exploration interface: users can browse a world map of surveys, zoom into individual deployment tracks, and click through to seafloor imagery and photomosaics stitched from thousands of stereo pairs, all georeferenced and contextualised with annotation summaries. In this sense, Squidle+ already functions as an early, imagery-based digital twin of the seafloor — a persistent, explorable, spatially-indexed representation of real ocean environments that anyone can query and revisit.

Beyond exploration, Squidle+'s annotation framework is media-agnostic, spanning stills, video, and mosaics through one consistent interface, with QA/QC tools enabling human-human and human-algorithm cross-validation. Its vocabulary translation framework cross-walks between disparate labelling schemes (CATAMI, WoRMS, CAAB) via direct mapping, hierarchical traversal, and semantic matching, enabling cross-project synthesis, large-scale ML training, and national reporting. ML algorithms are treated as first-class "users," connecting researchers directly to validated training data through the same sharing framework used for human collaborators. Squidle+ now holds over 10.2 million images from 22,107 deployments, underpinning 50+ publications, including in Nature and Nature Ecology & Evolution.

This talk will also introduce SquidJam, a complementary tool for streamlining metadata ingestion and validation from historical survey platforms, flagging sensor gaps and timing errors before they propagate downstream. Together, Squidle+ and SquidJam show how open, FAIR imagery infrastructure can serve as both a practical building block and an early realisation of ocean digital twins.

Semantic Space Modeling of Ocean Environments Using a CityGML-Based Approach

*Seong Gon Kim[1] (1. Sfractum Co., Ltd. (Korea))

Abstract: This study proposes OceanGML, a semantic modeling framework for digital twins that integrates CityGML 3.0 with IHO S-100 standards. Unlike terrestrial modeling focused on discrete objects, marine environments demand a space-centric paradigm to represent dynamic, vertically stratified fluid domains. To overcome the limitations of static models, OceanGML implements a 4D (x, y, z, t) grid-based structure, enabling the seamless ingestion and synchronization of time-varying physical fields such as ocean currents, temperature, and salinity profiles.

The framework incorporates specialized modules—OceanTopography, OceanLinkBoundary, and OceanObjectGroup—that align with S-100 product specifications (S-101, S-102, S-104). By leveraging the S-100 Part 8 framework, the model facilitates the processing of high-resolution spatiotemporal data, allowing for the dynamic visualization and analytical query of volumetric physical properties. This semantic layering enables multi-stakeholder interpretations of the same ocean volume, from navigation corridors to complex ecological reserves. By effectively bridging the gap between raw geophysical sensor data and semantic spatial models, OceanGML provides a robust, standards-based foundation for advanced analytical ocean digital twins.

Semantic Digital Twins for Marine Observing Systems: a SOSA-based Approach to Machine-Actionable Platform Descriptions

**Alessandro Oggioni*[1] (1. National Research Council of it (CNR) (Italy))

Abstract: Marine observing infrastructures, including fixed platforms, moored buoys, and instrumented chains, generate vast amounts of heterogeneous data whose provenance, quality and context remain only partially machine-readable. This limits their discoverability, interoperability and reusability within marine data infrastructures.

This work presents a methodology for semantically describing marine observing platforms and their associated sensor systems using the Sensor, Observation, Sample and Actuator (SOSA) ontology and its extension SSN, complemented by PROV-O for deployment and calibration provenance, GeoSPARQL for geometric representation, and the NERC and QUDT vocabularies for standardized property types and units. The approach was evaluated through real-world case studies conducted at marine sites of the Integrated European Long-Term Ecosystem, Critical Zone and Socio-Ecological Research Infrastructure (eLTER RI).

The resulting RDF descriptions constitute semantic digital twins of observing systems, representing both the physical structure of platforms, including sub-components, sensor cages, mooring chains and anemometer masts,

and the full lifecycle of sensor instances, including acquisition, calibration history, deployment context and spatial position within a local coordinate reference system.

These machine-actionable descriptions support automated reasoning over sensor metadata. By linking sensor instances to manufacturer specifications, calibration records, deployment configurations and spatial context, reasoning agents can infer key information such as measurement accuracy and precision. Furthermore, the approach enables the integration of observations with established frameworks, such as the Essential Ocean Variables (EOVs) and the Essential Climate Variables (ECVs), by considering not only observed properties but also contextual information, including sampling frequency, sensor position in the water column and deployment characteristics. This enables the automated assessment of whether and to what extent an observation contributes to specific monitoring objectives.

The approach supports FAIR data principles and lays the groundwork for interoperable, machine-actionable and robot-ready marine observation registries within research infrastructures.

A Provenance-Preserving LLM-Assisted Interface for Heterogeneous Marine Observations in Digital Twins of the Ocean

**Jaronchai Dilokkalayakul*[1] (1. Graduate School of Information Sciences, Tohoku University (Japan))

Abstract: Digital Twins of the Ocean require interfaces that can integrate heterogeneous observations, support analysis, and preserve the provenance of system outputs. This is essential because DTO results may combine direct observations with processed products or analyses generated on demand. Each result must therefore remain traceable to its source data and processing history.

Marine ecosystem monitoring draws on information collected at different scales. Satellite-derived sea surface temperature describes broad surface conditions, while in situ CTD profiles capture changes through the water column. DNA-based community profiles add biological information from individual sampling sites. These sources are difficult to use together because they follow different formats, resolutions, identifier schemes, and scientific conventions. We therefore developed a provenance-preserving retrieval-augmented generation framework for coastal ecosystem monitoring.

Source-specific pipelines standardize key fields without discarding original metadata or provenance records. Related observations are linked through stable monitoring-event identifiers and represented as traceable evidence units in a shared knowledge base. The system retrieves evidence using both lexical and vector search, then

incorporates relevant precomputed analyses and reliability assurance. A locally deployed large language model uses this context to produce grounded answers with citations. It also indicates whether information is observed or derived and identifies where evidence is missing.

We evaluated seven system configurations through an ablation study to examine the contribution of individual components. Precomputed analyses improved the completeness of answers, particularly when reliability information was included. The main remaining limitation was incomplete retrieval when questions required evidence from multiple sources. The framework offers an auditable interface for connecting marine observations with analytical functions and user inquiries within Digital Twins of the Ocean. Future work will activate on-demand analysis and assess the system with marine ecosystem researchers.

Oral D1 Cross-Sector Applications & Solutions

Chair: Takashi Enomoto, Arne Jørgen Berre

AI/ML-Augmented Metocean Digital Twins for Predictive and Actionable Maritime Intelligence

**Ruoying He[1]* (1. North Carolina State University (USA))

Abstract: The maritime industry increasingly requires accurate, timely, and actionable insights to manage risks, optimize operations, and support sustainability. This presentation introduces an AI/MLaugmented Digital Twin of the Ocean (DTO) that integrates hyper-local, atmosphere–ocean–wave models with advanced data assimilation, cloud computing, and machine learning. By combining real-time observations with process-based modeling and AI-enhanced analytics, this framework creates a dynamic, interactive representation of the marine environment that can anticipate evolving conditions and support decision-making.

The talk will describe examples of how this innovation delivers predictive and actionable intelligence for a wide range of maritime applications, including port operations, offshore platforms, marine life protection, and search-and-rescue missions. Beyond operations, these systems also enable scenario testing to evaluate climate impacts, guide spatial planning, strengthen ecosystem resilience, and mitigate pollution risks.

Aligned with the UN Ocean Decade program DITTO and the IEEE P3501 standardization effort, this work emphasizes the importance of interoperability, engineering frameworks, and interface standards to ensure long-term scalability across science, industry, and policy. By advancing both the scientific foundations and practical implementations of DTOs, this research demonstrates how AI/ML-driven digital twins can transform metocean forecasting into predictive, decision-ready intelligence that supports a sustainable and resilient maritime future.

From Ocean Integration to Ocean Strategy: A Principles-Driven Framework for the Long-Term Success of Regional Digital Twins

*Joaquín Tintoré[1] (1. IMEDEA (CSIC-UIB) (Spain))

Abstract: Regional Digital Twins of the Ocean (RDTOs) offer a unique opportunity to transform ocean science by delivering measurable societal impact. Realizing this potential requires recognizing RDTOs not simply as complicated technological platforms, but as complex socio-technical systems. Despite advances in observing systems, modelling, and digital infrastructures, societal impact remains constrained by fragmented disciplinary and institutional silos, persistent "sea-blindness" in governance, and limited progress in ocean literacy and connecting people with the ocean.

Addressing these systemic barriers requires organizational transformation alongside scientific and technological innovation. Building on progress in ocean integration, the next step is a coherent Ocean Strategy. Here, strategy is understood as an integrative set of mutually reinforcing choices that aligns people, disciplines, and organizations around a shared purpose. Such a strategy must be principles-driven, since decision-making in complex systems requires enduring principles rather than fixed rules to guide short-term decisions while sustaining a clear long-term direction. If strategy defines the map, principles provide the compass for navigating uncertainty.

Drawing on Roger Martin's Strategy Choice Cascade, we develop an Ocean Strategy to guide the design and long-term success of Regional DTOs. We illustrate its implementation through the 17-year strategic evolution of the SOCIB Research Infrastructure and discuss the leadership and organizational changes required in two-sided scientific organizations balancing scientific excellence and societal impact.

Our analysis shows that the long-term success of Regional DTOs depends on a paradigm shift: from bureaucratic inertia to principle-based agile governance, from fragmented disciplinary efforts to symbiotic innovation ecosystems, and from scientific excellence alone to scientific excellence with societal impact. By aligning people around a shared purpose, such an Ocean Strategy builds trust, sustains communities of practice, connects people with the ocean, attracts the next generation, and enables Regional DTOs to evolve beyond technological platforms into socio-technical catalysts for ocean sustainability and human well-being.

Digital Twins at the Land–Ocean Interface: A Platform for Cross-Sector Dialogue and Public Engagement

*Francisco Werner[1] (1. Smithsonian Institution, National Museum of Natural History (USA))

Abstract: Beyond their role as scientific and decision-support tools, Digital Twins (DTs) have the potential to transform how museums and public institutions diffuse knowledge. Immersive and interactive DT environments can allow users to experience complex land–ocean systems in ways that static exhibits cannot, exploring how ecosystems function, how human activities influence environmental outcomes, and how alternative futures may unfold under different decisions. By making scientific knowledge tangible, participatory, and accessible, DTs can expand the traditional role of museums from repositories and interpreters of knowledge to active platforms for exploration, learning, and informed dialogue about the future. In this way, DTs align closely with the Smithsonian Institution's mission of the increase and diffusion of knowledge, creating new opportunities to connect research, education, resource management, and public engagement.

This presentation explores how Digital Twins can serve as a platform for addressing complex challenges at the land–ocean interface. By integrating observations, collections, historical records, socioeconomic information, predictive models, and stakeholder knowledge, DTs can enable users to explore alternative futures, evaluating potential synergies and tradeoffs to assess the consequences of management actions before they are implemented. Such capabilities support applications ranging from coastal resilience and ecosystem restoration to sustainable fisheries, biodiversity conservation, watershed management, and climate adaptation.

Drawing on emerging initiatives in coastal and ocean digital twinning, including applications spanning watershed-to-ocean systems from the Arctic to the tropics, this presentation argues that DTs can simultaneously advance science, support actionable solutions, and strengthen public engagement. By connecting discovery, decision-making, and education within a common framework, Digital Twins offer a powerful pathway for fostering more resilient and informed futures at the land–ocean interface.

Connecting the DOTs: An Exploratory Study of Global Activities and Collaboration Potential for Digital Ocean Twins

**Sigmund Kluckner*[1] (1. Sigmund Kluckner (Austria))

Abstract: Connecting the DOTs provides a global overview and interactive map of Digital Twins of the Ocean (DTOs), examining the current status of DTO developments, stakeholders, technologies, and opportunities for collaboration. The report reveals a rapidly expanding but highly fragmented landscape in which governments, research institutions, international organizations, and private-sector actors are developing ocean digital twins and related components, often using similar technologies, datasets, and objectives but with limited coordination.

A central finding is the strong and growing demand for international cooperation. Organizations consistently highlighted the need to share challenges, exchange experience, increase access to data and computational infrastructure, and avoid duplication through the reuse of models, workflows, and software components. International networks and standards initiatives are already creating momentum toward more connected and interoperable DTO ecosystems. The report argues that federated architectures, common standards, shared registries of models and datasets, and stronger cross-border partnerships will be essential to unlock the full value of DTOs for science, policy, and the blue economy.

At the same time, significant challenges remain. Technical barriers include limited interoperability between systems, difficulties integrating data and models, infrastructure constraints, uncertainty in model outputs, and the challenge of moving from static digital replicas to interactive digital twins. Organizational barriers include fragmented governance, inconsistent funding, data licensing restrictions, and uneven technical capacity across regions. These challenges are especially pronounced in areas with limited resources but growing demand for ocean information and decision-support tools.

The report concludes that realizing the full potential of DTOs will require coordinated international action, sustained investment, and a culture of openness and collaboration. Building on momentum within DITTO and related initiatives, there is growing interest in strengthening peer exchange, convening collaborative workshops, and establishing an active global community of practice that promotes the sharing of data, models, infrastructure, and expertise to accelerate DTO development worldwide.

Accelerating a Fully Coupled Earth System Forecast Model through an Efficient CPU-to-GPU Development Approach

**Yun-Chuan Shao[1]* (1. National Taiwan University (Taiwan))

Abstract: Over the past decade, limitations in GPU hardware and development technologies have made it difficult to migrate global numerical weather prediction models to GPU architectures. Although these models run efficiently on CPU-based systems, porting them to GPU typically requires substantial development effort to rewrite low-level code for specific GPU architectures. In addition, the high double-precision requirements of global numerical weather prediction models introduce challenges related to rounding errors and numerical accuracy during GPU implementation. Similar issues have been reported in GPU-based weather and climate

model development, particularly when different numerical precisions and CPU–GPU implementations are compared.

To address these issues, our team developed a CPU-to-GPU migration framework that combines OpenACC with the NVIDIA Collective Communications Library (NCCL). Using this framework, we upgraded the Central Weather Administration's Global coupled Earth system Prediction System, GEPSv3, from its original CPU-based high-performance computing platform to a GPU-based architecture. The proposed approach aims to reduce the need for extensive low-level code rewriting while addressing the inter-GPU communication and numerical-accuracy requirements of a fully coupled global ocean–atmosphere forecasting system.

A performance comparison was conducted between the original configuration using 496 CPU cores on the FX1000 system and the GPU-based configuration using 16 CPU cores and eight GPUs on an A100 node. For a 45-day integration of GEPSv3, the GPU-based configuration reduced the computational time by 86%, while the node-hour consumption was reduced to approximately 1.4% of that of the original CPU-based configuration. These results demonstrate that the proposed NCCL-OpenACC framework can substantially improve computational efficiency and reduce resource consumption, while providing an effective approach for migrating a fully coupled global ocean–atmosphere forecasting system from a CPU-based to a GPU-based architecture.

Impact of Coastal Upwelling on Biological Production: Numerical Modeling Investigation of the Situation on the Ghanaian Shelf

*Kwabena Danso[1] (1. Africa Centre of Excellence in Coastal Resilience, University of Cape Coast (Ghana))

Abstract: In Ghana and other countries around the Gulf of Guinea, the strength of upwelling is mostly assessed based on changes in sea surface temperature (SST). This approach ignores surface wind conditions that drive Ekman transport and the upwelling of nutrient-rich water, which stimulate biological production. Therefore, the purpose of this study was to evaluate a new index for assessing upwelling events on the coast of Ghana. The study utilised satellites measurements (wind, nitrate, etc.) from the Copernicus Marine Service from 1995 to 2021. The occurrence of upwelling was assessed using the Coastal Upwelling Transport Index (CUTI) based on the combined effect of alongshore wind and geostrophic velocities. Nutrient input associated with upwelling was assumed to be directly related to Biologically Effective Upwelling Transport Index (BEUTI); vertical transport of nitrate by upwelling into productivity euphotic zones of the ocean. A generalised addictive model was applied to investigate relationship between the strength of upwelling and abundance of three small pelagics (Sardinella maderensis, S. aurita, and Engraulis encrasicolus). Intense upwelling was predicted to occur in July, August and September of each year, with moderate to significant relationship between average CUTI (1.94 ± 0.37 m2 s-1) and the concentration of nutrients such as silicate (R2 = 0.70, p = 0.001), phosphate (R2 = 0.54, p = 0.007) and nitrate (R2 = 0.42, p = 0.022) in surface waters of the ocean. Consequently, nutrient input was also significantly high in July, August and September with BEUTI at 7.16 ± 3.45 STD mmol m-1 s-1 and had a strong relationship between abundance of S. maderensis (R2 = 0.193, p = 0.0279) and E. encrasicolus (R2 = 0.194, p = 0.0279). These results agree with previous reports on the characteristics of coastal upwelling in Ghana.

Thu. Nov 12, 2026

Keynotes A2

Chair: Fumio Inagaki, Swadhin Behera

From EDITO, the European Digital Twin of the Ocean, to ONE-DTO, the Collaborative, AI-Enabled Global Digital Twin of the Ocean

*Alain Arnaud[1] (1. Mercator Ocean International (France))

Abstract: EDITO is the core public infrastructure of the **European Digital Twin of the Ocean**: an open environment where data, models, computing resources, and applications converge to transform ocean observations into actionable knowledge. Building on **Copernicus Marine**, **EMODnet**, and Europe's research and innovation ecosystem, EDITO is progressively federating national and regional contributions into a shared European capability—while enabling countries and communities to retain their expertise, assets, and identity. It also connects with cutting-edge digital assets and programs, such as **Destination Earth** (with its Earth-system digital twins and data ecosystem) and **EuroHPC's** pre-exascale and exascale computing resources. Together, these infrastructures can link ocean, climate, weather, and human activities, support higher-resolution simulations, and make trusted European data and computing capacities accessible to a broader community.

Now, the **Digital Twin of the Ocean (DTO)** capability is central to **OceanEye**, Europe's flagship initiative to strengthen ocean observation and unlock ocean knowledge. At the**OceanEye International Alliance** launch during the **UN General Assembly** in New York on 23 September 2026, European Commission President **Ursula von der Leyen**stated: *"OceanEye can show us what is happening in the ocean right now. The Digital Twin of the Ocean can help us predict what may happen next."*

The DTO is the means to combine these observations, test scenarios, and convert a global flow of data into decisions for resilience, safety, restoration, and a sustainable blue economy.

Similarly, the **OceanEye International Alliance** represents the next step toward a fully federated and interoperable **One Digital Twin of the Ocean (ONE-DTO)**. This system should rely not only on sustained global observing systems but also on distributed, heterogeneous infrastructures. With the active contribution of the **International community**, it will connect data and services through open standards and provide interfaces tailored to national and regional needs. Rather than a single centralized system, it will be a **system of systems**,

combining shared foundations with specialized portfolios of applications—for example, an **Arctic DTO** addressing polar observation, forecasting, ecosystems, communities, and navigation.

To conclude, we must remember that **artificial intelligence (AI)** is already *completely* reshaping this ecosystem. New AI agents will not only help users find and interpret information; they will orchestrate models, trigger simulations, generate fit-for-purpose data products, and combine evidence across infrastructures. Interoperability may shift from traditional data sharing or federated infrastructure to **agents exchanging information dynamically**. This evolution can make digital twins more accessible and powerful—**provided that scientific validation, traceability, and human oversight remain embedded by design**.

The CoastPredict Programme; Innovative co-Designed Regional Digital Twins and Fit-for-Purpose Solutions for Coastal Resilience

**Joaquín Tintoré*[1], Nadia Pinardi, Villy Kourafalou, Giovanni Coppini, Mairéad O'Donovan, Emma Heslop, Aletta Yñiguez (1. IMEDEA (CSIC-UIB) (Spain))

Abstract: The triple crisis of climate change, biodiversity loss and pollution demands urgent action, above all for coastal communities facing increasingly severe hazards. Until recently, the tools to respond effectively at regional and local scales were not available. That has changed: advances in satellite and multi-platform observing systems, forecasting, data science and artificial intelligence, together with their integration into regional-to-local digital twins of the ocean have transformed our ability now to monitor and predict coastal conditions across all scales, from the nearshore to the open ocean. CoastPredict is a flagship GOOS programme endorsed by the UN Decade of Ocean Science for Sustainable Development, working with coastal countries to improve resilience to climate and ocean-related hazards. It brings together innovative ocean observing and forecasting capabilities in a regionally integrated, stakeholder-informed framework that strengthens science-policy collaboration. By connecting proven scientific tools with decision-making processes, CoastPredict supports early warning systems and climate adaptation planning for communities worldwide. Coastal digital twins combine real-world observations, high-resolution models and AI to replicate coastal conditions. They enable real-time monitoring, prediction and "what-if" scenario analysis to support decisions on extreme events, climate adaptation, hazard mitigation and coastal planning. They are an essential tool of the GlobalCoast, initiative under CoastPredict. GlobalCoast has grown into a bottom-up, co-designed network of 192 Pilot Sites (141 validated) across 77 countries and 30 regions of the global coastal ocean. It was built from local needs and existing capacities rather than top-down design. Sites prioritise long-term climate change impacts (59%) and disaster risk reduction with real-time forecasting (55%). They build on observing, remote-sensing and modelling capacity already in place

(71%, 61% and 56% of sites, respectively). The Pilot Sites will be linked through a shared cloud-based digital infrastructure to integrate observations, models, AI and end-user products. This infrastructure is currently in a prototype phase called ‘ProtoCoast’. By applying common, interoperable building blocks across contrasting coastal regimes, GlobalCoast offers a scalable pathway from operational oceanography to transferable coastal digital twin services. Examples of Pilot Digital Twins in specific global coastal ocean pilot sites will be presented and discussed.

Bridging the Physical and Virtual Ocean: A Cyber-Physical Approach to Marine Digital Twins

**Konobu Kimura*[1] (1. FURUNO ELECTRIC CO., LTD. (Japan))

Abstract: While the ocean surface is comprehensively observed via satellite technology, the underwater environment remains a largely unexplored frontier where real-time monitoring presents significant challenges. Since the commercialization of the world’s first practical fish finder in 1948, Furuno Electric has been relentlessly dedicated to the "visualization of the ocean." Acoustic technologies have since evolved from single-point, downward-looking echo sounders into advanced multi-dimensional sonars capable of simultaneously capturing wide-area volumes. Furthermore, the integration of ocean current profiling capabilities has continually expanded the methodologies available for marine sensing and resource exploration.

Today, rapid advancements in cloud computing and Artificial Intelligence are revolutionizing these traditional approaches. By seamlessly aggregating acoustic data from fishing fleets and smart buoys, dynamic, wide-area ocean monitoring can now be achieved. For example, AI-equipped sensors deployed on set nets automatically analyze net conditions and classify fish species in real time, directly optimizing the daily operational behavior of fishers. Concurrently, data-driven fishing ground forecasting systems have been commercialized. By analyzing global oceanographic data—including water temperatures, currents, and sea surface heights—these systems can predict high-probability fishing zones prior to departure. Notably, AI-optimized predictive models are increasingly reporting forecasting accuracies that surpass those of conventional physical models.

The next-generation marine digital twin is thus envisioned as a "cyber-physical" ecosystem: one that harmoniously integrates real-world acoustic sensing with virtual, AI-driven predictions. In this session, this synergy will be explored from the perspective of an industry manufacturer. Actual use cases will be presented demonstrating how these integrated technologies are practically implemented in the field, creating a robust bridge between the physical and virtual ocean to empower end-users and ensure sustainable maritime operations.

Research Information Infrastructure for AI-Driven Science: Integrating HPC, Research Data Management, and Advanced Analytics

*Shintaro MOMOSE[1] (1. NEC (Japan))

Abstract: The rapid advancement of artificial intelligence is transforming scientific discovery and industrial research. While high-performance computing (HPC) remains an essential foundation for large-scale simulation, modeling, and data-intensive computing, the importance of research data has grown significantly. In the emerging era of AI for Science, scientific competitiveness is increasingly determined not only by computational capability but also by the ability to manage, share, and utilize heterogeneous datasets generated across simulations, experiments, and observational facilities.

To address this challenge, NEC is developing a Research Information/Intelligence Infrastructure (RII), a data-centric research platform that integrates HPC resources, research data management, data sharing, provenance management, and AI-enabled analytics. RII aims to establish an environment in which research data can be continuously collected, curated, shared, and reused throughout the research lifecycle, supporting collaboration across computational and experimental domains while improving the accessibility and value of scientific data.

This presentation introduces the architectural concept of RII and discusses three fundamental capabilities required for next-generation research infrastructures: efficient movement of large-scale datasets across distributed environments, automated provenance capture to enhance reproducibility and transparency, and advanced data utilization through AI and optimization technologies. Together, these capabilities enable a seamless connection between data generation, management, and knowledge extraction, reducing barriers to data-driven research and accelerating scientific workflows.

The presentation also explores the evolving role of research data management as a key component of modern HPC ecosystems and discusses how integrated cyberinfrastructure can support AI-driven discovery, digital engineering, and future research environments in both academia and industry.

Keynotes B2

Chair: Yasumasa Miyazawa, Bente Lilja Bye

Weather Forecasts Supporting Ship Operation and Design in Maritime DX

*Ryo Kakuta[1] (1. Monohakobi Technology Institute, Japan (Japan))

Abstract: Japan's maritime transport underpins daily life and economic activity, and sustaining it requires a stable supply and operation of ships—a matter vital to the nation's economic security. Since October 2025, an industry–academia–government collaboration has been carrying out the R&D project "Development of Integrated Simulation Platform for Sustainable and Competitive Maritime Industry," selected under the Key and Advanced Technology R&D through Cross Community Collaboration Program (K Program). Over its five-year term, the project establishes an Integrated Simulation Platform that enables simultaneous consideration of ship lifecycle and supply chain at the initial development and design stages to optimize ship design and construction plans, thereby promoting the implementation of virtual engineering concepts and techniques into the maritime industry. In addition, regarding weather and sea condition predictions that impact safe and stable ship operations, a seasonal prediction technology covering one to three months in advance, including extreme phenomena such as typhoons, is being developed and integrated into the platform. This presentation introduces two efforts on using such weather and ocean data, from the standpoint of the maritime industry as the data user.

The first is the operational use of seasonal predictions. To apply one-to-three-month predictions to routing decisions, the required accuracy must be clarified and expressed as a quantitative requirement to forecast developers. For container ship operation in the North Pacific, we apply a cost-loss model, defining a "hit" as correctly anticipating, about one month in advance, whether weather severe enough to prevent a vessel from proceeding northward will occur, and derive the hit rate required for net cost reduction. The second is estimating future encountered weather and sea conditions. The conditions a vessel meets over its 20-year-plus lifecycle are key design inputs, informing main-engine sizing and fuel-tank capacity.

To obtain realistic profiles, we simulate operation in which routes follow predictions while encountered conditions reflect the actual weather and sea state, using a database of past forecast fields. Together, these efforts combine seasonal prediction with operational simulation to reproduce realistic ship–ocean interactions, forming a weather-informed digital twin that supports both the operation and the design of ships.

Environmental Impacts of Microplastics Beyond Biological Effects

*Atsuhiko Isobe[1] (1. Kyushu Univ. (Japan))

Abstract: As marine microplastics (MPs) are transported vertically via biological processes, the total amount of particulate organic carbon (POC) attached to MPs was estimated in the North Pacific Ocean, and its impact on the biological carbon flux was evaluated using the Martin curve (Martin et al., 1987). Observational data on marine MP concentrations ranging from 10 μm to 5 mm (Kuroda et al., 2025) were used to validate a three-dimensional model reproducing MP transport from the sea surface to 1000 m depth. The model incorporated riverine and fisheries-derived MP emissions, as well as ocean currents, windage, and Stokes drift to simulate transport. In addition, it concurrently included an algae ecosystem model for MP biofouling (Kooi et al., 2017) and a zooplankton ingestion process (Kvale et al., 2020, 2021). Ocean currents, wind, Stokes drift, water temperature/salinity were derived from reanalysis or satellite data, while ecosystem data such as phytoplankton concentrations were obtained from ESTOC reanalysis data (Osafune et al., 2015). Calculations assumed a plastic-free ocean prior to 1960 and hindcasted/forecasted in subsequent changes. Since MPs are less dense than seawater, POC aggregates containing MPs exhibit reduced densities and slower settling velocities, thereby inhibiting downward carbon flux. Furthermore, MPs from which biofouling has been removed through decomposition may return to upper ocean again, thereby inhibiting downward carbon flux over long timescales. The present-day downward carbon flux was estimated to decrease by several percent at depths of 500 m and 1000 m. Considering the projected decline in the coming decades, marine plastic pollution may need to be recognized not only as a threat to marine ecosystems but also as a potential player in the climate system.

Agentic Earth System Digital Twins: From Prediction to Collaborative Scientific Discovery

*Jennifer Sleeman[1] (1. APL, Johns Hopkins (USA))

Abstract: The landscape of Earth system modeling has advanced significantly with the advent of AI, giving rise to AI emulators, differentiable models, physics-informed models, and foundation models. These approaches are changing not only how we model and predict the Earth system, but also how AI can participate in the scientific process. As these capabilities mature, an increasingly important challenge is how to coordinate heterogeneous models, observations, experiments, and scientific reasoning across domains and scales. Agentic AI offers a new paradigm in which AI can progress from a scientific tool or assistant toward a collaborator capable of designing experiments, coordinating analyses, evaluating evidence, and helping scientists explore new hypotheses.

Within this emerging paradigm, we consider how Earth system digital twins can evolve from predictive representations toward environments for collaborative scientific discovery. We present an agentic digital twin

framework that treats scientific questions as executable workflows. Scientific questions are interpreted to identify the observations, models, and computational experiments needed to investigate them. Agents coordinate these workflows by acquiring data, executing and evaluating models, comparing experiments, and synthesizing results. When existing capabilities are insufficient, the framework can dynamically construct new AI models, allowing the digital twin's modeling capabilities to evolve as new scientific questions emerge.

We demonstrate this approach through an Earth system tipping-point digital twin that coordinates reduced-order models with AI-based methods for discovery and forecasting to investigate abrupt transitions and interactions across ocean, atmosphere, and land systems. Current applications include the Atlantic Meridional Overturning Circulation, the Amazon, and the West African Monsoon, providing environments for exploring hypothetical and counterfactual scenarios and, ultimately, interactions and cascading behavior across Earth subsystems. These capabilities point toward a broader role for digital twins in AI-enabled science: not only predicting how the Earth system may evolve, but enabling scientists and AI to collaboratively ask questions, conduct experiments, evaluate evidence, and discover new understanding.

From Demonstrators to Decisions: Digital Twins Delivering Ocean Intelligence for Shelf Seas

**Juliane Wihsgott*[1] (1. Plymouth Marine Laboratory (UK))

Abstract: Shelf seas are where society meets and interacts with the ocean. They sustain productive ecosystems and underpin energy security and global shipping. A growing number of sectors now compete for their space and resources. They are also changing rapidly, driven by climate change and human activity, and increasingly serve as the setting for climate mitigation itself, from offshore wind to marine carbon dioxide removal. This makes them difficult to predict: key processes are short-lived and can occur over fine scales, subsurface processes lie beyond the reach of Earth Observation, and human pressures add further complexity to an already shifting baseline. Meeting this challenge requires observations and models that continuously inform each other, rather than operating in isolation. The SyncED-Ocean demonstrator, one of the first operational Digital Twins of the Ocean (DTO) implementations, showed that this loop can be closed. During a two-month campaign in a dynamic coastal sea, in-situ and satellite observations informed a coupled physical- biogeochemical model. Machine learning, with human oversight, guided autonomous gliders to collect targeted subsurface observations, assimilated daily to improve forecast skill. But what changes when a DTO must serve multiple users, sectors, and pressures simultaneously? Mitigation measures are themselves interventions, and their effects must be detected, attributed and verified against natural variability. It will take multiple twins of infrastructure, ecosystems and interventions that work together as a system. This talk explores the case for building the next generation of DTOs

around questions, rather than data volume: defining the expected state, detecting departures from it, and knowing when additional sampling adds little value. Partnering with decision-makers will be key to ensuring DTOs inform real decisions.

Oral/Panel C1 From Ocean Science to Ocean Policy

Chair: Michael Huang

Opening Remarks

*Mitsutaku Makino[1] (1. OPRI (Japan))

From Research Project to Services: Copernicus Earth Observation Programme

*Alain Arnaud[1] (1. Digital Ocean Department, MoI (Japan))

The Demanding Issues on Ocean Observation in Asia and Pacific

*Yoichi Ishikawa[1] (1. Research Institute for Earth and Information Sciences, JAMSTEC (Japan))

Using AI for Research Trend Identification and Policy Evaluation

*Mengyao Zhu[1] (1. OPRI (Japan))

Panel Discussion

*Michael Huang[1], Enrique Alvarez2, Yoichi Ishikawa3, Mengyao Zhu1 (1. OPRI (Japan), 2. Mol (Japan), 3. JAMSTEC (Japan))

Closing Remarks

*Michael Huang[1] (1. OPRI (Japan))

Oral A2 Coastal Resilience & Hazard Mitigation

Chair: Joaquin Tintore, Urmas Lips

Multi-Scale Ocean Digital Twin with the Sanriku Coast as Its Base: A flagship project of AIMEC

*Michio Kawamiya[1] (1. JAMSTEC/Tohoku Univ. (Japan))

Abstract: The Advanced Institute for Marine Ecosystem Change (AIMEC), established in 2024, is a new research institute jointly hosted by Tohoku University and JAMSTEC. Its mission is to elucidate the mechanisms by which marine ecosystems respond to and adapt to changes in oceanic conditions resulting from global environmental change, and to enable projections about the future of these ecosystems. To fulfil this mission, three research clusters have been formed: Open Ocean, Coastal Ocean and Planetary Stewardship. Each cluster is guided by specific overarching research questions. The Planetary Stewardship cluster focuses on acquiring scientific knowledge to promote sound societal decision-making. To this end, AIMEC plans to develop a marine digital twin centred on the Sanriku coast. This project aims to solve real-world problems by providing numerical model-based and AI-assisted projections for coastal and open ocean environments, and by communicating with stakeholders in local governments, the fisheries industry and others. It is expected to become a flagship project of Cluster #3. This presentation will provide an overview of AIMEC and its digital twin project, presenting initial results.

Pumice drift simulation and visualization

**Haruka Nishikawa*[1] (1. JAMSTEC (Japan))

Abstract: Drifting pumice generated by submarine volcanic eruptions poses a serious threat to marine transportation, fisheries, and the tourism industry, particularly in volcanic countries such as Japan. When a submarine volcanic eruption occurs, predicting the distribution of drifting pumice is essential. Particle tracking experiments using ocean hydrodynamic models are useful for predicting pumice distribution. In such simulations, the choice of the horizontal diffusion coefficient plays an important role. However, the appropriate value of the horizontal diffusion coefficient is not uniquely determined. It must be selected to account for the effects of Stokes drift and other processes that cannot be reproduced by the model, such as finer-scale eddies, in order to improve the accuracy of pumice distribution predictions. Therefore, the appropriate horizontal diffusion coefficient depends on the model and its temporal and spatial resolution. We aim to develop a digital twin of submarine volcanic eruptions for the creation of realistic hazard maps. As part of this digital twin, we visualize particle tracking experiments performed using various ocean hydrodynamic models and different horizontal diffusion coefficients. Visualization is important not only for highlighting the differences among models but also as a key component of the digital twin. In particular, this study discusses the usefulness of visualization for the development of hazard maps.

DTO of compound coastal-fluvial floods

**Indiana Olbert* (1. University of Galway (Ireland))

Abstract: Floods are the most pervasive and costly weather-related natural disasters, and future climate may increase the flood risks and impacts. In estuaries the compound nature of coastal–fluvial flooding and the intricacies of built environments present challenges for flood understanding. Flood prediction requires integrated and multi-hazard multi-model and multi-observational approaches. This research aims to develop a Digital Twin for Ocean of coastal–fluvial floods using advanced physics-based and data-driven models.

The proposed DTO for compound flood modelling is a novel framework that integrates advanced data- and physics-based models with both in-situ and satellite observations. The ultra-high resolution hydrodynamic model is used to simulate a wide range of hydrological and coastal scenarios, as well as their combinations. Time series of water depths at each numerical grid point (6x6m) of an urban riverine–estuarine domain capture the evolution of flood events over the city-wide floodplains. Sentinel-1 SAR satellite products are used to validate historical flood events. The AI-driven component employs a range of machine learning and deep learning algorithms trained on outputs from hydrodynamic simulations of non-flood to extreme-flood conditions. Ultimately, the best-performing AI model is selected for each grid point individually and used to simulate water levels across the urban floodplains.

The AI-based component of DTO produces short-term flood predictions by integrating a variety of features, including meteorological and sea level conditions. The system's performance is demonstrated for the coastal city of Cork, the second-largest city in Ireland that is frequently affected by coastal flooding. Results show that the hydrodynamic model can reproduce historical flood events with a very high accuracy while several AI models are able to simulate coastal urban flooding when trained on hydrodynamic model outputs.
Reliable what-if scenario modelling of compound floods offers numerous societal benefits, including improved flood preparedness, greater confidence in decision-making and climate adaptation.

Dynamical Downscaling of Future Climate Projections Around Penghu Islands in the Southern Taiwan Strait

**Jo-Hsu Huang* (1. Institute of Oceanography, National Taiwan University (Taiwan))

Abstract: This study investigates projected ocean changes around the Penghu Islands in the southern Taiwan Strait under the SSP2-4.5 mid-21st century warming scenario, using two-stage offline nested dynamical downscaling of Taiwan Earth System Model version 1 (TaiESM1). The high-resolution model accurately reproduces many key regional oceanographic features. Our future projection suggests three major regional circulation changes. First, the upstream Kuroshio east of Luzon Island weakens due to an enhanced positive Pacific wind stress curl. This curl strengthens the anticyclonic loop current, which increases current curvature and reduces net westward Kuroshio intrusion. Second, the eastward Ekman current in the Taiwan Strait strengthens due to a weakened northeast winter monsoon. Third, the northeastward South China Sea surface current strengthens, driven by enhanced negative basin-scale wind stress curl. These shifts increase wintertime South China Sea water intrusion into the Taiwan Strait. Furthermore, the topographically induced upwelling surrounding the Penghu Islands significantly suppresses surface warming during summer and autumn. This upwelling generally moderates marine heatwave frequency and intensity. However, rising sea surface temperature variability still amplifies future marine heatwaves intensity. The coarse-resolution model overestimates the increase of regional sea surface temperature by up to 0.4°C, confirming the importance of dynamical downscaling. These findings provide valuable insights for future fisheries management and marine resource planning in the warming climate.

Unveiling Coastal Dynamics: Integrating Global Ice Extent and Climate Data to Improve Tide Predictions in the Bay of Bengal

**Kazi Rafid Raiyan* (1. Independent Researcher (Japan))

Abstract: Rising sea levels and extreme weather events are leading causes of increasing challenges in coastal regions, particularly in deltaic areas such as Bangladesh. These difficulties should be addressed effectively, and to do so, precise predictions of tidal height are crucial. This paper predicted daily high and low tides at coastal stations in Bangladesh utilizing various regression models, including Machine Learning (polynomial, support vector, XGBoost, random forest) and Deep learning (neural network).

The paper originated a novel dataset for Bangladesh that incorporates atmospheric data, tide height, and additionally, introduced a completely new feature, Ice extent, that has not been used in previous work to estimate tidal heights. The research indicated that including this new feature to predict tide height has improved the R2 score of regression models by 2%-5%. Eventually, after running all the models, the study found that the Neural regressor outperformed all the other models (with approximately 88%-94% R^2 score) in predicting tide height (HIGH) for all of the stations. However, XGB Regressor outperformed in some stations, such as Chitalkhali and

Kuakata (with around 83%-95% R2 score) for predicting tide height (LOW). In summary, This study provided detailed insights into the strenghts and weaknesses of various regression models, incorporated unique features and enhanced the prediction of coastal tide heights. Additionally, the method and findings of this study offer significant insight for developing strategies to manage coastal difficulties and adapt to climate change in an ever changing atmosphere.

An Integrated Digital Twin Framework for Hydro-Meteorological and Coastal Risk in the Bay of Bengal

Mohan Kumar Das (Hydro-Climate and Ocean Centre (HCO))

Abstract: The Bay of Bengal is a dynamic ocean,Äìatmosphere,Äìland system where extreme precipitation, monsoonal disturbances, river flooding, storm surges, and sea-level variability interact to generate compound hazards and cascading impacts across coastal Bangladesh. Fragmented observation and prediction systems constrain the representation of these interactions and the delivery of timely, impact-relevant information. This study develops an interoperable digital-twin architecture that combines satellite and in-situ observations, gridded meteorological products, numerical weather and climate simulations, hydrological information, and machine learning models. The methodology integrates data harmonization, data,Äìmodel coupling, event-based analysis, predictive modelling, and predictive analytics to connect environmental states with hazard evolution across the ocean,Äìatmosphere,Äìland continuum. Across 20 hydro-meteorological and coastal events during 2010,Äì2026, the system achieved a rainfall correlation coefficient of 0.67, an RMSE of 22 mm, and an event-detection rate of 77%, with a 60% improvement in overall predictive performance relative to the baseline system. It extended the useful forecast lead time to 8 hours and improved identification of compound events. The system linked environmental evolution with exposure and impacts, providing a science-to-society pathway from prediction to early warning and actionable decision support for communities, infrastructure, ecosystems, and coastal management. These results demonstrate the feasibility of connecting heterogeneous observations, predictive models, and impact information within a common digital environment, providing a practical route from fragmented systems toward functional digital-twin services for hazard forecasting, disaster preparedness, climate resilience, and sustainable coastal management in the Bay of Bengal.

Oral B2 Digital Twin Infrastructure and Operational Services

Chair: Avichal Mehra, Shintaro Momose

OPERA Project: Developing an African Digital Twin Ocean for Integrated Ocean Knowledge, improved monitoring and decision support

*Lillian Diarra[1] (1. Mercator Ocean International (France))

Abstract: African oceans and coasts are facing increasing pressures from climate change, illegal fishing, pollution, biodiversity loss, and rapid urbanisation. At the same time, advances in Earth observation, ocean modelling, artificial intelligence and cloud computing are transforming our ability to monitor, predict, and manage marine environments. These emerging technologies provide a unique opportunity to address Africa's growing need for accessible, integrated ocean information services tailored to regional priorities and at the same time contribute to global ocean knowledge.

Responding to this opportunity, the European-funded project - Ocean Prediction Enhancement in Regions of Africa (OPERA) is developing an African Digital Twin Ocean (African DTO), aligned with Priority 7 of the Ocean Decade Africa Roadmap (Digital Twin for Africa/ Knowledge Hub). Implemented by Mercator Ocean International through its coordinating role of the OceanPrediction Decade Collaborative Centre, OPERA will establish African Regional Centres of Excellence for digital ocean services, fostering collaboration between African and European partners.

Building on the technologies developed through the European Digital Twin Ocean (EDITO), the African DTO will provide an integrated digital ocean service platform. It will bring together and provide access to data from the ocean forecasting systems developed within OPERA, Copernicus Marine global products, additional local datasets as well as applications. By doing so, it will deliver interoperable ocean information services and decision-support tools for key areas such as disaster risk reduction, coastal resilience, and the sustainable blue economy. Through visual and customised interfaces, the African DTO will improve access and uptake of ocean knowledge for policymakers, researchers, practitioners, the private sector and coastal communities.

By delivering a prototype African DTO, OPERA will lay the groundwork for a scalable continental platform that can integrate future DTO initiatives, promote interoperability and innovation, and empower African stakeholders with digital tools and services to advance climate resilience and sustainable development.

EDITO: Building the Infrastructure of the European Digital Twin Ocean

*Elin V. P. Persson[1] (1. Mercator Ocean international (France))

Abstract: The European Digital Twin Ocean is a flagship initiative of the European Commission designed to transform ocean knowledge into actionable intelligence through advanced digital technologies, enabling evidence-based decision-making for policy, research, innovation, and societal engagement.

EDITO is the core infrastructure underpinning the European Digital Twin Ocean. Built upon established European assets, including the Copernicus Marine Service and the European Marine Observation and Data Network (EMODnet), EDITO integrates marine observations, forecasts, models, and thematic datasets into a common digital environment supporting data discovery, visualisation, application development, and scenario exploration. By combining high-resolution observation data and forecasts with cloud computing resources, collaborative development environments, and advanced analytical tools, EDITO enables the development of digital twin applications capable of supporting simulations, forecasting, and interactive "what-if" scenario analysis.

Following the initial development phase of the platform (2022–2025), EDITO2 (2025–2028) focuses on strengthening both the technical infrastructure and the user community. Key developments include enhanced data onboarding and validation processes, expansion of the EDITO data lake to incorporate biogeochemical, socio-economic, and citizen science data, and the development of more accessible user interfaces and visualisation tools.

Through open calls, co-creation activities, and dedicated user support services, EDITO fosters broad participation from the scientific and innovation communities. Through its open architecture and interoperable services, the platform supports international collaboration and interoperability across the growing ecosystem of ocean digital twins, contributing to activities and objectives pursued within the framework of the Digital Twins of the Ocean (DITTO) programme. Looking towards 2030, EDITO aims to deliver a fully operational and sustainable European Digital Twin Ocean that serves as a reference infrastructure for digital ocean solutions and democratised access to ocean knowledge in support of a healthy, productive, and resilient ocean.

From Copernicus Marine Operational Services to Digital Twin Ocean Components: The CLS Experience with EDITO

**Fabien Lefèvre* (1. CLS (France))

Abstract: The Digital Twin Ocean aims to make ocean data and services easier to access, use and combine. As part of Copernicus Marine and EDITO, CLS will deploy in the coming months several services developed within three Copernicus Marine Thematic Assembly Centres: Sea Level (SL-TAC), Waves (WAVE-TAC) and Multi-Observations (MOB-TAC). These deployments will bring operational Copernicus Marine expertise into the Digital Twin Ocean environment and help transform established production systems into on-demand cloud services.

For the Sea Level TAC, CLS will deploy MIOST (Multiscale Inversion for Ocean Surface Topography), the operational mapping system used within DUACS-NG (Data Unification and Altimeter Combination System - Next Generation). Integrated into EDITO, it will allow users to generate customized Level-4 sea level and wave products from multi-mission altimetry and SWOT observations for selected regions and periods.

For the Wave TAC, CLS will deploy the operational Level-3 Significant Wave Height production system and develop new user-oriented services, including wave propagation visualizations and a virtual buoy tool, making advanced wave products easier to explore and exploit.

For the Multi-Observation TAC, CLS will deploy two complementary services. ARMOR3D will provide on-demand regional 3D ocean fields, including temperature, salinity, currents and mixed-layer depth. SOCA will use artificial intelligence to generate virtual biogeochemical profiles by combining Argo measurements with ocean-colour and altimetry observations.

These deployments are both challenging and promising. They require adapting mature operational Copernicus Marine processing chains to cloud-native environments that support scalability, interoperability and user-driven applications. The presentation will discuss the opportunities and challenges associated with this transition and share lessons learned from the first deployment activities. It will illustrate how operational ocean services can evolve into reusable Digital Twin Ocean components, supporting future research, innovation and ocean applications within the EDITO ecosystem.

From SST Observations to Reusable Services for the European Digital Twin Ocean

**Vincenzo de Toma*[1] (1. Consiglio Nazionale delle Ricerche, Istituto di Scienze Marine (CNR-ISMAR) (Italy))

Abstract: Reliable, traceable, and fit-for-purpose sea surface temperature (SST) information is essential for transforming Digital Twins of the Ocean from integrated data environments into effective tools for climate monitoring, extreme-event assessment, and product evaluation. This contribution outlines a planned Copernicus Marine initiative, developed within a project proposal currently under evaluation, to deploy four mature SST workflows on the European Digital Twin Ocean (EDITO), translating established scientific methods into accessible, reproducible, and scalable digital services.

The proposed applications cover the full pathway from observations to user-oriented information. They include global monitoring of marine heatwaves and cold spells using near-real-time and multi-year SST analyses; detection and object-based tracking of Mediterranean marine heatwaves, including their evolution, propagation, merging, and splitting; production of monthly SST anomaly maps relative to the 1991–2020 climatology, initially for the Baltic Sea but applicable to other regional and global products; and fair intercomparison and quality monitoring of SST products against a common set of in situ observations and harmonised diagnostics.

Rather than forming a single monolothic system, the four applications will operate as independent, reusable EDITO processes. Each workflow will be containerised and reproducible, following common standards for data access, provenance, configuration, documentation, testing, and interoperability. The services will exploit Copernicus Marine datasets and deliver interactive notebooks, analysis-ready datasets, and web-ready outputs, as appropriate, through scheduled or user-triggered execution. Externalised configuration and product-agnostic interfaces will facilitate their transfer across regions and SST products.

Beyond their individual scientific applications, these workflows will demonstrate how mature Earth observation methods can be integrated into Digital Twin Ocean infrastructures as reusable analytical services. Collectively, they would improve access to climate diagnostics, strengthen the monitoring and characterisation of marine extreme events, and support consistent and transparent product evaluation. Their deployment would also provide feedback on platform integration, data access, scalability, and long-term reuse, supporting the evolution of interoperable digital-ocean platforms.

MeDITTO: Engineering an AI Agent Integration Layer for Interoperable Ocean Digital Twins

Simon Keeble[2], **Miguel Charcos-Llorens*[1] (1. SOCIB (Spain), 2. Blue Lobster IT Limited (UK))

Abstract: Digital twins of the ocean are proliferating, but each comes with its own data services, formats, and interfaces, and the cost of connecting them falls on every user. MeDITTO, a prototype within the SOCIB2030 strategic framework, developed collaboratively by Blue Lobster (UK) and SOCIB (Spain), demonstrates a different approach: AI agents, communicating over open protocols, serve as the integration layer, and natural language serves as the common interface to observations, models, and twins.

The platform gives researchers, managers and the public conversational access to SOCIB's multi-platform observing and forecasting system in English, Spanish and Catalan, returning live data as interactive plots, maps and species datasheets, adapted to user expertise. Three examples of SOCIB digital twins, within the MeDITTO prototype, run as first-class agents: ecological surveillance of the Cabrera National Park's protected waters, shoreline adaptation planning for the urban beach of Cala Millor, and meteotsunami early warning for Ciutadella Port.

Architecturally, a supervisor agent classifies intent and maintains shared session context, while specialist agents for catalogue, data, visualisation, knowledge, and species each own their tools, prompts, and model choices. Every digital twin is an independent agent reachable via the Model Context Protocol, so adding new twins, including external EDITO services, is a registry entry rather than a rewrite. The platform is self-hostable on an open-source substrate, routes across LLM providers rather than binding to one, and pairs per-agent tracing with an evaluation harness run in continuous integration, so agent behaviour cannot regress silently. Provenance follows the data: sources are referenced in responses, and quality and FAIR assessment surface alongside results. The design aligns with the EU AI Act and GDPR.

We present the working system, the architecture decisions that underpin it, and evidence that agent-based integration is a transferable pattern for the interoperable digital twin ecosystem DITTO is building.

Building the South Atlantic Digital Twin of the Ocean

**Segen Estefen* (1. National Institute for Ocean Research (INPO) (Brazil))

Abstract: The National Institute for Ocean Research (INPO) is leading a Brazilian initiative toward a Digital Twin of the South Atlantic, an interoperable and evolving environment that shall connect observations, numerical models, forecasting, artificial intelligence, high-performance computing, and visualization tools. The initiative will transform distributed scientific capabilities into actionable ocean intelligence and enable what-if scenarios for climate adaptation, marine spatial planning, disaster resilience, biodiversity conservation, maritime operations, blue economy, and evidence-based governance.

The South Atlantic presents a challenge for digital-twin development. It combines a vast spatial domain, critical ocean-climate processes, heterogeneous observing capacity, historical data gaps, and responsibilities distributed across multiple institutions. INPO's approach treats the twin not as a single model or platform, but as a federated ecosystem in which observations and simulations will be integrated across spatial and temporal scales, updated as new information becomes available, and adapted to different users and decisions.

A key enabling component is INPO's Ocean Data Storage and Distribution System (SADD), which transforms heterogeneous historical and contemporary observations into FAIR, interoperable data. Its cloud-based architecture connects data providers through standardized metadata, data harmonization, scalable storage, APIs, and AI. SADD will provide the trusted data infrastructure through which observations interact with models, forecasts, analytical services, and visualization environments. This infrastructure will be connected to forecasting environments which, in turn, will feed the Digital Twin of the South Atlantic, in a phased process.

The initiative is also an institutional innovation as INPO is articulating key players in Brazil from the public and private sectors, together with international partners, particularly through its formal partnership with Mercator Ocean International. Our aim is to support alignment with open standards and the global digital-ocean ecosystem. This combination of regional leadership, institutional federation, and interoperability offers a pathway toward an inclusive South Atlantic DITTO for a historically underrepresented ocean basin.

Oral C2 AI, Automation and Agent Platform

Chair: Patrick Heimbach, Fernando Mendez

MeDITTO: An AI-Agent Platform for Interoperable Digital Twins of the Ocean

Miguel Charcos-Llorens (1. SOCIB (Spain))

Abstract: Developing regional Digital Twins of the Ocean (DTOs) requires architectures integrating heterogeneous, distributed digital assets into actionable knowledge accessible to users with different levels of expertise. Building on more than 17 years of experience operating observing and forecasting systems, the Balearic Islands Coastal Observing and Forecasting System (SOCIB), in collaboration with Blue Lobster IT, is developing MeDITTO “Mediterranean Digital Twins of the Ocean”, a pilot within the SOCIB2030 strategic framework. This contribution presents MeDITTO, highlighting its agent-based orchestration, multimodal user interaction and distributed integration capabilities. We discuss key architectural choices, lessons learned, and pathways towards a scalable, secure, modular and interoperable framework for federating DTOs.

MeDITTO provides a unified platform to seamlessly discover, compose and execute DTOs, services, data, products, models and knowledge across regional and global ecosystems. A multimodal interface combines conversational natural-language interaction with interactive maps and visualisations, featuring a clear, intuitive design tailored to users with different levels of expertise and needs. It enables them to formulate complex questions and progressively explore and refine results through visual analytics. An orchestration layer coordinates specialised AI agents to discover available capabilities, invoke federated services, manage execution across hybrid cloud HPC infrastructures, and aggregate results using provenance-aware workflows. This agent-based approach keeps individual DTOs modular while communicating through a common interaction layer. MeDITTO will also provide a marketplace that interoperates with external DTO ecosystems such as EDITO and DITTO.

MeDITTO builds on SOCIB's active participation in European initiatives, particularly the EDITO Model Lab, adopting interoperability principles aligned with the European ecosystem. Integration with Destination Earth Data Lake is also being explored to test distributed access and execution workflows across heterogeneous infrastructures. Together, these developments and collaborations provide a testbed for evaluating scalability and standards-based integration approaches for hybrid infrastructures, connecting regional digital twin capabilities with broader European and global DTOs.

SURF AI Assistant: Multi-Agent AI for On-Demand Coastal Digital Twin Configuration and Scientific Workflows

**Francesco Trotta*[1] (1. CMCC Foundation – Euro-Mediterranean Center on Climate Change (Italy))

Abstract: Developing and operating Digital Twins of the Ocean (DTOs) requires expert knowledge across multiple stages, including experiment design, dataset selection, numerical model configuration, workflow validation, simulation, and scientific assessment. Although large language models offer new opportunities for AI-assisted scientific workflows, configuring operational coastal ocean models remains a domain-specific task requiring specialised expertise, traceability, and rigorous validation.

We present the SURF AI Assistant, a domain-specialised multi-agent framework integrated into the Structured and Unstructured grid Relocatable Ocean platform for Forecasting (SURF). SURF enables on-demand, high-resolution coastal Digital Twins through relocatable downscaling workflows based on the NEMO structured-grid and SHYFEM unstructured-grid ocean models. It supports the modelling lifecycle from data acquisition and preprocessing to simulation, validation and analysis, serving applications including coastal forecasting, oil-spill response, search and rescue, navigation, and maritime decision support.

The SURF AI Assistant orchestrates specialised agents representing expertise in atmospheric forcing, bathymetry, open-boundary conditions, numerical configuration, workflow validation, documentation, and scientific best practices. It combines retrieval-augmented generation with structured configuration schemas and deterministic validation rules, grounding recommendations in curated SURF documentation and operational knowledge. Through natural-language interaction, users define experiments, generate and iteratively refine configurations, and analyse uploaded observational and model datasets. Specialised agents extract metadata and selected physical properties on the fly to derive data-informed modelling parameters and recommend domain settings, forcing choices, boundary treatments, and validation criteria. Human experts retain control over all modelling decisions.

By embedding domain-specific AI within an operational coastal modelling platform, the SURF AI Assistant demonstrates a practical human–AI approach to reducing configuration complexity while improving reproducibility, transparency, and interoperability, lowering the barrier to trustworthy coastal Digital Twins for research, forecasting, and coastal management.

ROMSA: An Agentic AI Framework for Regional Ocean Model Setup

**Xing Zhou* (1. Fujian Ocean Innovation Center (China))

Abstract: Mechanistic coastal and regional ocean models remain essential for understanding and predicting ocean processes. However, setting up such models is still a highly specialized task that requires substantial technical expertise and practical experience. Recent advances in AI agents provide an opportunity to encode accumulated model setup knowledge and experience into agent skills, enabling a pathway toward automation of model configuration and setup.

Here we introduce ROMSA (Regional Ocean Modeling Setup Agent), an agentic framework designed to translate scientists' intent in natural language into a structured regional ocean model setup. ROMSA aims to lower the technical barrier to regional ocean modeling while retaining scientific oversight throughout the workflow. ROMSA adopts a multi-agent architecture. A questionnaire agent first interacts with the user to identify the scientific objectives and required model configuration, and then multiple model-building agents use the structured questionnaire output together with curated modeling knowledge, preprocessing tools, and established procedures to construct the numerical experiment.

Data-Driven Global Wave Model Based on a Multiscale Graph Neural Network

**Godai Sonoda* (1. FURUNO ELECTRIC CO., LTD. (Japan))

Abstract: Accurate wave forecasting is essential for maritime safety and efficient ship routing, and is a key component of ocean digital twins. Numerical wave models are widely used but require substantial computational resources, limiting their real-time use in ocean digital twins. To address this, data-driven models have been developed as fast surrogates. While various data-driven models have been proposed in atmospheric forecasting, they have been explored far less extensively in wave forecasting.

In this study, we applied a multi-scale graph neural network (GNN) to global wave forecasting, with a horizontal resolution of 0.5 degrees and a lead time of 10 days. Unlike conventional grid-based models, the GNN-based formulation can also be applied to unstructured meshes, although structured meshes are used here. In addition to wave variables, 10m wind components over ocean are used as inputs, and the model is trained on reanalysis data.

Using reanalysis winds as inputs, the model achieved an average RMSE of 0.19 m for significant wave height, 14.2° for mean wave direction, and 0.53 s for mean wave period at a lead time of 9.5 days. On a single NVIDIA A100 GPU, a complete 10-day global forecast takes about 100 seconds. Using forecast winds as inputs, the accuracy decreased due to wind forecast errors, yet this suggests that the model has acquired the ability to generate and develop wave fields in response to winds. Overall, machine learning can serve as a fast surrogate for physics-based wave models, well suited to operational digital twins. Furthermore, the GNN's applicability to unstructured meshes is expected to enable higher-resolution forecasting in coastal regions, supporting interoperable digital-twin applications.

The Marine Autonomous Systems Digital Twin (MAS-DT) - Using AI to aid in the piloting of ocean gliders

**Justin Buck*[1] (1. National Oceanography Centre (UK))

Abstract: The Marine Autonomous Systems Digital Twin (MAS-DT) project aimed to enhance ocean observation and forecasting by integrating digital twin technology with ocean modelling and marine autonomous systems. This approach demonstrated how a dynamic digital framework could optimise data collection and improve ocean model accuracy, delivering benefits for environmental science and operational forecasting.

At the core of the project was the development of a prototype digital twin to optimise ocean glider observations used by the UK Met Office. The system brought together multiple components: ocean glider operations from the National Oceanography Centre (NOC) under the Met Office Glider (MOGli) programme; earth observation data; and outputs from operational ocean models. These inputs were integrated within the NOC Command and Control (C2) infrastructure to create a four-dimensional representation of the ocean. A key feature was the Autonomy Engine developed by the Oxford Robotics Institute, which optimised glider missions based on defined objectives

and constraints such as battery life and speed. Supporting this, an Objective Generation User Interface enabled scientists to identify high-impact observation areas and define mission goals.

Stakeholder engagement played a central role, including a joint workshop with the Turing Research Innovation Cluster for Digital Twins (TRIC-DT), which explored interoperability, user interaction, security, and system resilience. Enhancing interoperability across environmental digital twins was identified as an ongoing priority.

Overall, the project successfully demonstrated a functional digital twin integrating marine glider operations with the AMM15 ocean model. It delivered key innovations such as a new user interface and integrated mission planning tools. However, challenges included defining effective in-water experiments, accounting for human factors, and improving understanding of data assimilation processes. These findings highlight opportunities for future development, particularly in adaptive observation systems.

Oral D2 OSID & IESS

Chair: Bruno Buongiorno Nardelli, Matthias Obst

The Coastal Zone Digital Twin: A Federated Bridge Between Land, Coast, and the Digital Twin of the Ocean

**Nicole Ramberg-Pihl*[1] (1. NASA Earth Science Technology Office (SSAI), USA)

Abstract: Coastal zones sit at the dynamic intersection of riverine, oceanic, atmospheric, and human systems, where flooding, erosion, and water quality degradation increasingly pose urgent risks to communities and economies. NASA's Coastal Zone Digital Twin (CZDT) is an extensible, AI accelerated Earth System Digital Twin designed to provide an integrated, real time understanding of these complex land to sea interactions. By maintaining a continuously updated digital replica of coastal and adjacent ocean environments—harmonizing satellite, airborne, and in-situ observations with high fidelity models—CZDT directly addresses fundamental questions that drive coastal resilience: What's happening now? What will happen next? What if conditions or decisions change?

As a component of emerging digital twins of the ocean, CZDT advances multi source data fusion, hybrid modeling, and federated interoperability across agency and partner systems. Remote sensing data from ocean focused missions provide Essential Variables such as sea surface height, shoreline position, turbidity, chlorophyll, and temperature, feeding a living digital replica capable of representing both terrestrial and marine processes driving coastal change. Surrogate models accelerate forecasting of storm surge, compound flooding, estuarine water

quality, and sediment transport, enabling rapid, interactive scenario exploration for emergency management, environmental stewardship, and infrastructure planning.

New agentic capabilities strengthen both science and usability. A data wrangling agent automates onboarding of new Essential Variables; retrieving, ingesting, and normalizing ocean and coastal datasets into the replica, while a natural language, LLM based interaction layer assembles CZDT subsystems on demand, allowing users to pose complex what-if questions without navigating rigid pipelines. Standards based interfaces, provenance tracking, and uncertainty quantification ensure scientifically defensible outputs that can be federated with other regional or global ocean digital twins.

Together, these innovations position CZDT as a foundational component in the broader digital twin ecosystem—linking land, coast, and ocean processes—and enabling richer, more actionable insight into the evolving coastal Earth system.

From observations to lessons learned; Implememting Improved Digital Twins to Support Offshore Energy Decision Making

*Thomas Mansfield[1] (1. Plymouth Marine Laboratory (UK))

Abstract: Environmental digital twins are increasingly supporting evidence-based decision-making across the lifecycle of offshore energy platforms. As these technologies mature, there is a growing need to move beyond proof-of-concept deployments to digital twins with improved reliability, transparency and long-term sustainability.

This paper builds on from the SyncED-Ocean digital twin deployment (Mansfield et al., 2025), which identified three key observations: applying engineering rigour to digital twin development, effective processes for balancing data timeliness with data quality, and maintaining appropriate human oversight despite increasing automation. The UK's EQUIFy and VALMAS programmes provide an opportunity for lessons to be learnt from these observations within active offshore energy initiatives.

To address the first observation, systems engineering approaches, particularly Model-Based Systems Engineering (MBSE), are being introduced. MBSE enables researchers, data managers, and domain experts to contribute to a shared system model, creating a single source of truth for requirements, interfaces, design decisions, and dependencies. This improves traceability throughout the digital twin lifecycle and supports the adoption of engineering best practice in environmental science projects.

The second observation is being explored through collaboration with environmental data-provider communities. Within initiatives such as the Western Channel Observatory, ERDDAP services and interactive visualisation tools support community-led quality assurance processes. Contributors can review datasets, apply SeaDataNet quality flags, increasing transparency around data quality while maintaining timely access to observations.

To progress the third observation, VALMAS's broad links to industry, academic and government organisations are helping shape future human-in-the-loop capabilities, recognising that trust in environmental digital twins depends not only on automation, but also on mechanisms for oversight, intervention, and accountability.

This work demonstrates how lessons from an operational digital twin deployment can be learned through an iterative process. Supported through a DAFNI Fellowship, this work continues to collect evidence on how environmental digital twins can evolve towards more robust, transparent, and sustainable socio-technical systems.

Future Perspectives for Intelligent Ocean Utilization Enabled by Ocean Digital Twins

**Issei Fukamizu* (1. Mitsubishi Research Institute (Japan))

Abstract: In recent years, marine technologies have advanced rapidly in support of the blue economy, which seeks to balance environmental conservation and economic development. Policy and technology trends suggest that labor-saving and unmanned technologies, such as autonomous ships and marine drones (e.g., AUVs and ASVs), together with AI, may play important roles in supporting the future marine industry. At the same time, real-world marine environments are highly complex and uncertain, and challenges remain for the practical implementation of these technologies.

Ocean digital twins are expected to serve as an important enabling foundation for addressing these challenges. By integrating marine environmental conditions, vessel behavior, sensor data, simulations, and AI-based analysis in a virtual environment, they are expected to enhance the efficiency and sophistication of risk assessment, operational planning, and decision-making.

This presentation reviews policy and technology trends related to autonomous ships, marine drones, and AI. It also reviews domestic and international initiatives on ocean digital twins and their potential applications, and discusses future directions for sustainable, intelligent ocean use.

Spatial Digital Twins for Coastal Resilience in Small Island Developing States: A Data Integration Framework

**Crystal Cooper*[1] (1. The University of the West Indies (Trinidad and Tobago))

Abstract: Like many other Small Island Developing States (SIDS), tt faces no shortage of challenges ranging from finite land space, to climate change mitigations, to city planning within the coastal zone, which is home to 70% of the population and 80% of the country's socio-economic activities as reported by the Central Statistical Office (CSO) and Integrated Coastal Zone Management (ICZM) Steering committee. The 2023-approved ICZM Policy Framework explicitly identifies the absence of a centralized coastal information management system as one of the key hindrances to effective management. This research is intended to readily address the latter gap through the development of a Spatial Digital Twin (SDT) of the coastal zone that serves multiple sectors and ministries and supports Sustainable Development Goals (SDGs 13 & 14) by combatting threats such as sea-level rise and coastal erosion. A SDT is a virtual representation of a connected physical asset and the transfer of data or information between these two state. The research utilizes a Geomatics Engineering lens to delineate a comprehensive SDT framework, highlighting Surveying types such as Remote Sensing, Photogrammetry and Traditional Land Surveying via drones, satellites and laser scanning etc., with data products such as LiDAR, orthomosaics and satellite imagery. The data amalgamation, hosting, monitoring, manipulation and implementation of the SDT shall be illustrated though a local case study. Not only can this research promote coastal resilience, but the framework can be used to develop a local centralized information system and be integrated in SIDS coastal management plans in the Caribbean and other small island regions alike.

An approach to forecast of super cyclone Amphan (2020) using WRF-ARW model at 1.667 km horizontal resolution

**Reshma Sini Manikantan[1]* (1. JAMSTEC (Japan))

Abstract: The present study investigates the role of the high-resolution (1.667 km) Weather Research and Forecasting (WRF-ARW) Model in the forecast of super cyclone Amphan (2020). The study analysed the dynamic of the ocean-atmosphere interaction using the WRF-ARW model coupled with the three-dimensional Price-Weller-Pinkel (3DPWP) model, and the role of time-varying sea surface temperature (SST) was examined using initial conditions taken from the fifth generation of the European Centre for Medium-Range Weather Forecasts Data. Three sensitive experiments (CNTL, SST, and 3D-PWP) were carried out using the WRF-ARW model on a moving nested domain platform with finer domain horizontal resolution of about 1.667 km. The initial and boundary conditions for the model simulations were taken from the National Centers for Environmental

Prediction final analysis data. The cyclone intensity, track, and structures were evaluated with the available observational data from the India Meteorological Department best track, satellite observations, and Doppler Weather Radar observations. Results indicated that the SST and 3D-PWP experiments showed a 25%-39% improvement in the MSW estimate and a 49%-55% improvement in the MSLP estimate compared to the CNTL experiment. There is no significant enhancement in the track estimate for the SST and 3D-PWP experiments. The study indicated that both SST and 3D-PWP experiments showed considerable impact on the structure characteristics in terms of reflectivity, latent heating, and temperature anomaly.

Connecting Atlantic and Pacific Ocean knowledge through digital twin capability: An ICES-PICES dialogue.

**Alondra Sofia Rodriguez Buelna*[1] (1. International Council for the Exploration of the Sea (ICES) (Denmark))

Abstract: Digital Twins of the Ocean are moving from concept and technical development towards operational capability. For this transition to support sustainable ocean governance, Digital Ocean Twins need more than interoperable data streams, models and platforms. They also need trusted institutional pathways that connect ocean data with advice on management of marine resources and space, governance needs, stakeholder uptake and decision-making.

This proposed panel discussion explores how international, intergovernmental marine science organizations can support this transition. ICES and PICES operate at the science-policy interface across the Atlantic and Pacific, bringing together scientific communities, data infrastructures, expert groups, advisory processes and intergovernmental networks. Together, they provide an ocean-scale perspective on how Digital Ocean Twins can be connected to trusted data flows, operational advice, capacity building and cross-basin learning.

The session creates a structured dialogue between ICES, PICES, DITTO actors, policymakers and data/infrastructure stakeholders on how Digital Ocean Twin capabilities can be used or applied within existing science-advisory and governance systems. Key questions include: how can Digital Ocean Twins support intergovernmental science advice; what standards and data life cycle practices are needed for trusted intra and inter-basin use; and what capacity is needed for uptake by scientists, advisors, managers and policymakers?

The dialogue aligns with the DITTO Summit 2026 ambition to move from concept to capability and to build operational, interoperable and user-driven digital twins that support sustainable governance, climate resilience and the blue economy. It also contributes to the UN Ocean Decade Digital Ecosystem vision of making ocean knowledge more accessible, interoperable, usable and actionable through trusted digital infrastructures and

international collaboration (UNESCO-IOC, 2025).By connecting Atlantic and Pacific experience, the ICES-PICES perspective can help identify practical pathways for making Digital Ocean Twins institutionally embedded and relevant for sustainable ocean governance at ocean-basin and global scales.

Oral A3 Data-Driven Emulators

Chair: Alain Arnaud, Deanesh Ramsewak

A Differentiable, Performance-Portable, Multi-Fidelity Computational Framework for Digital Twins of the Ocean

**Patrick Heimbach* (1. University of Texas at Austin (USA))

Abstract: We present an integrated computational framework for building digital twins of the ocean around a single differentiable modeling core. The core supports several coupled modes of operation: high-resolution, high-fidelity simulations that resolve ocean dynamics explicitly and low-resolution, parameterized models in which unresolved processes are represented by learned closures, implemented as neural operators trained online against the high-fidelity solutions. Because the hybrid data assimilation-machine learning framework is differentiable, these parameterizations are learned end-to-end and updated concurrently with the simulations they inform, allowing the coarse model to inherit dynamical consistency from its high-fidelity counterpart without a separate offline calibration stage. The framework is complemented by computationally efficient emulators trained on the high-fidelity model to further accelerate ensemble generation, uncertainty quantification, and scenario exploration (WHAT-IF experiments).

All components, the high-fidelity and parameterized simulation models, the online-trained neural operators, and the Sobolev-trained emulators, are automatically differentiable end-to-end and portable across heterogeneous HPC hardware, including GPUs, CPUs, and TPUs, using automatic compiler transpilation tools. This design allows a single codebase to move fluidly between resolutions and fidelities and to run efficiently across the diverse compute architectures found in modern, AI-puposed HPC and cloud environments. It is making accessible a vast range of compute systems and providing an efficient path toward operational, sensitivity-informed, data-driven digital twins of the ocean.

Differentiable Earth: Theory and Practice

**Takeshi Enomoto*[1] (1. Kyoto University (Japan))

Abstract: Many problems in Earth science are inverse problems that require parameter, initial, or boundary condition estimation given a model and data. The adjoint method has traditionally provided an efficient solution to these problems. In atmospheric and ocean prediction, variational data assimilation (VDA) utilizes an adjoint model. However, the development and maintenance of an adjoint model require significant effort compared to the popular ensemble-based approach. The rise of machine learning (ML) has renewed interest in this method: since both ML and VDA share a mathematical foundation in optimization, VDA can now directly leverage modern ML frameworks that offer automatic differentiation (AD). Unlike traditional source-to-source translators, AD generates derivatives for optimization without explicit adjoint code compilation. We argue that AD functions similarly to the systematic approach of building an adjoint using the Lagrange multiplier method (Thacker and Long 1988). In this talk, we demonstrate AD-based VDA (ADVDA) applied to idealized and intermediate complexity models. We show that ADVDA replicates results from hand-coded adjoints with comparable efficiency, and we examine ADVDA performance in the presence of discontinuities. These findings demonstrate the utility of ADVDA in solving inverse problems—provided careful attention is paid to technical challenges such as computational efficiency, memory management and discontinuities—and motivate us to build differentiable digital twins.

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Reconstructing the ocean state from observations through Physics-Informed Neural Networks

**Bruno Buongiorno Nardelli*[1]* (1. Consiglio Nazionale delle Ricerche - Istituto di Scienze Marine (Italy))

Abstract: No observing system can independently resolve the full ocean state across the spatial and temporal scales relevant to ocean dynamics. At the same time, numerical models remain affected by uncertain initial conditions, unresolved processes, parameterizations, and numerical errors. This contribution examines how physics-informed artificial intelligence can provide observation-based dynamically consistent reconstructions suitable for integration into future operational Digital Twins of the Ocean.

We present a series of applications combining satellite and in situ observations, numerical simulations, and neural-network architectures. These range from the reconstruction of three-dimensional structure of the ocean by combining surface observations and hydrographic profiles, to the super-resolution of sea-surface height and

temperature for improved surface-current estimation and physics-informed learning of lateral diffusion, to AI emulators of the diabatic quasi-geostrophic Omega equation solver.

Physical knowledge is incorporated through observational and architectural choices, as well as loss-function constraints enforcing governing equations, thermodynamic consistency, and static stability. Results show that these approaches can improve the representation of dynamically relevant structures while maintaining closer consistency with independent observations than conventional statistical reconstructions. In fact, neural networks should not be regarded merely as data-analogue generators: they learn nonlinear relations among features and can be constrained by established physical principles as well as be used to improve physical parameterizations. Physics-informed learning can therefore complement mechanistic modelling and data assimilation, supporting faster and higher-resolution ocean-state estimation. By connecting heterogeneous observations, physical models, and scalable AI components, these methods offer practical building blocks for operational, interoperable, and observation-driven ocean digital twins.

The Atlas of Ocean Microplastics (AOMI): Harmonized Observational Data for Marine Microplastic Research and Digital Twins of the Ocean

**Tahira Irfan* (1. Center for Ocean Plastics Studies, Research Institute for Applied Mechanics, Kyushu University (Japan))

Abstract: As research on ocean microplastics continues to expand, data remain highly fragmented across studies, regions, and methodologies, preventing synthesis, comparison and policy relevance of this data. Therefore, the Atlas of Ocean Microplastics (AOMI, https://aomi.env.go.jp/) was developed to provide a unified and accessible platform for marine microplastic data.

The AOMI dataset provides global measurements of microplastics collected historically by researchers worldwide, including particle counts (expressed as particle counts per seawater volume or survey area) and mass concentrations (expressed as mass per area). In addition, it also provides gridded data of microplastic surface distribution corrected for wind and wave driven mixing, following Isobe et al. (2021). The current dataset includes ~19, 351 points worldwide. While AOMI has improved data comparability, significant spatial gaps remain, especially in the East Asian Seas, the South China Sea, the Indian Ocean, and the Southern Ocean.

This presentation introduces AOMI, highlighting its structure, data integration framework, and ongoing development. The platform enables users to visualize spatial and temporal patterns of microplastic distribution and to access curated datasets for further analysis. We discuss progress achieved to date, key challenges in harmonizing heterogeneous environmental datasets, and future directions for expanding coverage and standardization.

Beyond its role as a global data repository, AOMI can provide an observational foundation for developing and validating digital twins of the ocean. Its standardized microplastic observations can be integrated with numerical ocean models, particle-transport simulations, and environmental datasets to improve representations of microplastic transport and distribution. Such integration can support model validation, identify observational gaps, and enable scenario-based assessments of microplastic accumulation. By connecting harmonized observations with dynamic ocean models, AOMI can support emerging digital twin applications and contribute to improved scientific assessment and evidence-based management of marine microplastic pollution.

Physics Informed Shallow Water Emulator

**Iuri Gorenstein*[1] (1. Universidade de São Paulo (Brazil))

Abstract: Numerical ocean models face a trade-off: low-resolution runs miss turbulence, while high-resolution ones require smaller time steps, making them slow and expensive. Neural Networks (NNs) can decouple spatial and temporal resolution, integrating with larger time steps and capturing both linear and nonlinear behaviors without explicit equations. This flexibility accelerates simulations and allows NNs to represent processes that traditional models might oversimplify in their higher-level description of the discretized physical equations. Yet it raises a critical question: How can we trust physics-uninformed models to produce stable, realistic long-term ocean simulations? This study aims to build a fully generalizable, point-wise, physics-informed NN embedded with the Regional Ocean Modeling System (ROMS) barotropic dynamics. Bridging the gap between traditional numerical models and NN algorithms, our results demonstrate that the NN emulator accurately reproduces the non-linear instabilities and eddy dynamics observed in barotropic flows, comparable to the original numerical solver.

A Physics-Guided Deep Learning Approach for Kuroshio Extension Prediction

**Yu-Xuan FU* (1. The University of Tokyo (Japan))

Abstract: The Kuroshio is a strong, warm current flowing past southern Japan. After leaving the coast, it continues eastward as the Kuroshio Extension (KE), whose path shifts north and south over years. These shifts redistribute ocean heat, affecting ecosystems, fisheries, and climate, making advance prediction valuable. The KE position depends on its recent state and remote winds over the central and eastern North Pacific. These winds generate slow ocean disturbances called Rossby waves that travel westward and can shift the KE east of Japan, offering an early signal. Testing this possibility is difficult because satellite records began in the early 1990s and contain few such shifts.

Therefore, we use monthly output from a completed 520-year simulation with the high-resolution, eddy-resolving Community Earth System Model (CESM-HR), from which a 370-year segment provides the long record needed to learn how KE latitude and remote wind forcing are connected. We predict the upstream KE latitude between 142° and 150°E at lead times of 6-48 months, after smoothing the monthly variations with a six-month running mean. The wind influence is represented by Ekman pumping, which describes wind-driven vertical ocean motion. Broad spatial patterns and slow variations are extracted, then combined with 48 months of KE latitude in a long short-term memory (LSTM) network. Satellite altimeter observations and atmospheric reanalysis winds are used for evaluation and forecast initialization.

CESM-HR tests show that a wind pattern raises correlation by 0.14 at 27 months across 10 initializations. At 48 months, a preselected wind-informed model reaches a correlation of 0.43 and reduces mean-square error by 18% compared with a persistence forecast. Initialized through July 2026, the models suggest a consistent southward tendency, although its robustness requires further evaluation. This physics-guided approach could support longer multiyear KE prediction and earlier warning of impacts on ecosystems, weather patterns, and fisheries around Japan.

Oral B3 Ocean Digital Twins for Coastal Resilience, Ecosystems and Ocean Health

Chair: Ruoying He, Hakase Hayashida

Empowering Africa's Blue Economy: Co-Designing the African Digital Twins of the Ocean

*Hassan Moustahfid [1] (1. UN Ocean Decade Africa Task Force/IOOS (USA))

Abstract: Africa faces pressing marine challenges, from coastal vulnerabilities to sustainable fisheries management and climate adaptation. Digital Twins of the Ocean (DITTO) offer a transformative, user-driven approach to addressing these issues. Globally, operational digital twins integrate real-time observations, AI, and advanced modeling to empower decision-makers, enhance disaster resilience, and drive sustainable blue economy

innovation. However, translating these global principles into a sovereign, interoperable African digital ecosystem requires a dedicated, regionally led co-design strategy.

To bridge the gap from concept to capability, the African Ocean Decade Taskforce and OceanPrediction DCC are convening a pivotal implementation workshop in Cotonou, Benin, in October 2026. Acting as a collaborative hub, this multi-stakeholder gathering will bring together African governments, researchers, operational agencies, industry partners, and Early Career Ocean Professionals (ECOPs) to construct an actionable DITTO roadmap tailored to the continent's unique environmental and economic landscape.

This presentation will unveil the immediate, fresh outcomes of the October workshop. The session will detail the co-designed regional architecture, exploring how it builds on Africa's existing high-performance computing (HPC) capabilities while harnessing complementary infrastructure from global partners, cloud ecosystems, and regional observing systems to support maritime development. Furthermore, we will present the workshop's consensus on priority cross-sector applications, such as fisheries management, hazard forecasting, and coastal infrastructure resilience, alongside proposed governance frameworks grounded in FAIR data principles and African data sovereignty.

By sharing these forward-looking strategies, this work will highlight how inclusive, regional co-design accelerates the deployment of functional, Earth-to-Society digital platforms. The anticipated Cotonou roadmap will provide a replicable model for developing user-driven, operational digital twins that directly empower Africa's blue economy, support resilient coastal communities, and solidify the continent's leadership within the UN Ocean Decade.

A Digital Twin System for Smart Aquaculture in Sansha Bay

**Qiang Deng* (1. Fujian Ocean Innovation Center / Xiamen University (China))

Abstract: This project, based on the needs of high-quality development of the marine economy in Fujian Province, takes Sansha Bay as a demonstration sea area and addresses multiple environmental risks such as extreme temperatures, sudden salinity changes, and red tides. It has constructed a digital twin system for intelligent prevention and control of aquaculture environmental disasters in bay areas. By integrating a high-precision three-dimensional monitoring network of temperature salinity profiles, a three-dimensional hydrodynamic ecological coupled model, a data driven short term early warning model, and the DeepSeek large language model, the system possesses real time dynamic simulation and multi source data assimilation capabilities. It can forecast water

temperature, salinity, and red tide probability for the next three days, and automatically generate tiered prevention and control strategies based on an intelligent knowledge base, forming a whole chain coordination mechanism of "monitoring—early warning—prevention and control—decision making". At the same time, the project establishes a three tier interactive platform for decision makers, managers, and farmers, enabling precise dissemination of risk prevention and control measures. Through full process application demonstration in Sansha Bay, it accumulates practical experience and explores promotion models, providing a demonstration model for bay type aquaculture areas to achieve a win win situation of "ecological security and production efficiency enhancement", and contributing to the creation of a new growth pole for the blue economy.

Enabling Nature-Based Coastal Adaptation through Digital Twin-driven What-if Scenarios for coastal vegetation restoration

Benjamin Jacob[1], *Kelli Johnson1 (1. Helmholtz-Center Hereon (Germany))

Abstract: Climate hazards increasingly threaten coastal ecosystems through the intensification of storm events, coastal erosion, and ecosystem degradation. Nature-Based Solutions (NbS), such as seagrass, saltmarshes or mangrove restoration, are increasingly acknowledged as pathways to enhance coastal resilience by dampening driving mechnisms of coastal impacts, while simultaneously supporting biodiversity conservation and carbon storage.

Despite that, effective implementation requires actionable insights on how to choose design, location, and characteristics of restoration measures. These insights can help to maximize ecosystem services such as coastal protection under varying environmental conditions.

Here, we present a Digital Twin of the Ocean (DTO) system aimed at aiding in decision support by integrating observations, numerical models and artificial intelligence (AI) enabling the execution What-if Scenario (WiS) to assess coastal resilience via seagrass restoration:

The DTO system combines regional coupled hydro-wave-sediment simulations with high-resolution coastal morphodynamical modelling to evaluate erosion risks and impacts under different seagrass scenarios. Thereby, considering vegetation characteristics such as meadow location, extent, shoot density to investigate their influence on coastal ocean kinematics and sediment dynamics. An AI-based emulator further enhances computational efficiency allowing the exploration of multiple restoration pathways within the DTO.

These systems have been implemented within the European Digital Twin of the Ocean (EDITO), via downstream interactive user interfaces facilitating the exploration of different vegetation WiS.

The results demonstrate that the effectiveness of seagrass restoration is highly dependent on local environmental conditions and implementation strategies. For example, erosion mitigation potential was identified when seagrass was positioned in areas exposed to high wave roller energy. Overall, the results indicate the need for site-specific assessments rather than generalized restoration approaches.

By translating complex model outputs into actionable metric-based information, the DTO enables the visualization and comparison of different restoration scenarios to support sustainable NbS implementation.

An Interactive Coastal Digital Twin of the Ocean for User-Driven What-If Scenarios and Nature-Based Coastal Resilience

**Ivan Federico*[1] (1. CMCC - Euro-Mediterranean Center on Climate Change (Italy))

Abstract: Coastal Digital Twins of the Ocean (C-DTOs) are evolving from numerical models into interactive decision-support systems that integrate Earth observations, in situ monitoring, physics-based simulations and Artificial Intelligence. Their objective is not only to reproduce coastal dynamics but also to enable users to explore what-if scenarios, evaluate adaptation strategies and support evidence-based coastal management.

We present an integrated Coastal Digital Twin architecture for coastal resilience. The framework combines multi-source observations, deterministic numerical models and AI-based services to represent the coupled dynamics of waves, hydrodynamics, sediment transport, coastal flooding and marine vegetation. Earth observations and in situ measurements underpin model calibration and validation, while AI accelerates computational workflows and scenario exploration. The architecture is relocatable across coastal environments and supports forecasting, event reconstruction and on-demand simulations.

The Digital Twin is implemented as an interactive, user-centred platform that enables users to configure, execute and visualize customized what-if scenarios through an intuitive graphical interface. Users can delineate intervention areas, modify nature-based or engineered coastal measures, define environmental forcing conditions and compare adaptation strategies. User-defined configurations are automatically translated into model-ready simulations, with results visualized through maps, time series and impact indicators for rapid evaluation of alternative interventions.

The framework is demonstrated through two operational applications. 1) The first supports seagrass restoration as a nature-based solution for coastal protection. Users can define the location, extent and characteristics of restored seagrass meadows and evaluate their effectiveness in reducing wave energy and circulation. 2) The second application focuses on natural dune systems, enabling users to investigate how different dune configurations influence coastal flood hazards by quantifying changes in inundation extent, water levels and flood dynamics.

These applications demonstrate how Coastal Digital Twins transform coastal models into interactive decision-support platforms where observations, process-based simulations and AI are integrated into a seamless workflow, enabling planners and coastal managers to efficiently evaluate adaptation options for resilient coastal management.

Digital Ocean Twins as a Medium for Scientific Communication

**Armando Jr Benavidez[1]* (1. Institute Of Science Tokyo; Nakamura Lab (Japan))

Abstract: Scientific communication is moving toward immersive, interactive media, yet most reef and ocean research still reaches audiences as static figures and text. Digital ocean twins, navigable 3D representations that fuse underwater photomosaics with broader spatial context, are themselves a communication medium and not only an analytical one. They preserve the georeferencing and structure that scientific work requires, while presenting it in an environment a non-specialist can enter and explore without instruction.

A digital twin is natively three-dimensional, and that 3D structure is precisely what virtual and augmented reality are built to render. Where a photograph or map flattens a reef, a digital twin preserves its geometry, so that it can be navigated and experienced rather than merely viewed. VR and AR excel at exactly the spatial and volumetric content that digital twins produce, making the twin a ready-made asset for immersive interaction. Delivered through virtual and augmented reality, it allows coastal managers to convene inside a shared spatial scene for remote decision-making; researchers can present findings via AR-assisted teleconferencing; and students can discover underwater habitats in interactive VR space. Presented this way, a digital ocean twin can give an audience the opportunity to move continuously across scales, from the structure of a single coral colony outward. The pairing of digital ocean twins with interactive VR and AR media offers a new channel to communicate reef science.

Ultimately, these photomosaic-based digital twins lower the engagement threshold, turning dispersed survey data into a cohesive experience that travels to entirely new audiences.

Enhancing Marine Biodiversity through Integrated Conservation Strategies: An Academic Framework for Digital Twin Integration

*LIBAN MOHAMUD JAMA[1] (1. Darul Hikmah University (Somalia))

Abstract: Marine biodiversity faces unprecedented threats from climate change, overexploitation, and habitat degradation, requiring robust and dynamic management frameworks. This presentation explores academic research into the implementation of integrated conservation strategies designed to safeguard marine ecosystems. Emphasizing data-driven methodology and regional oceanographic insights, the study highlights how combining rigorous ecological monitoring with strategic management models can enhance habitat resilience and protect critical marine species.

A central focus of this research is the potential for integrating localized marine biodiversity datasets into Digital Twins of the Ocean (DITTO) frameworks. Traditional conservation models often suffer from data fragmentation and delayed response times. By leveraging standardized observation data and academic research baselines, integrated conservation strategies can provide the foundational biological layers necessary for predictive modeling, real-time tracking, and scenario simulation. This linkage allows researchers and stakeholders to visualize the direct impacts of human activity and climate stressors on vulnerable marine protected areas.

Ultimately, this paper demonstrates that linking empirical fisheries science with digital infrastructure is essential for scalable ocean conservation. Integrating comprehensive biological datasets from university research initiatives into interactive digital twin platforms ensures that conservation strategies are not only proactive but also adaptive to rapidly shifting marine environments. This framework offers a scientifically rigorous pathway toward achieving global biodiversity targets through technologically empowered, evidence-based decision-making.

Oral D3 OSID & IESS

Chair: Alessandro Oggioni, Akira Nagano

Digital Twin applications for dynamic assessments of marine biodiversity in European coastal waters

*Matthias Obst[1] (1. Department of Marine Sciences, University of Gothenburg (Sweden))

Abstract: Biological monitoring needs to improve radically to serve our understanding of marine ecosystems and biodiversity under long-term global change and multiple stressors. Over the last decade, high-throughput monitoring technologies including genomics, hydroacoustics, telemetry, and computer vision have gained a lot of traction among marine scientists, but the quickly mounting volumes of data typically prevent scientists from obtaining deeper insights into ecosystem function and change. The European Digital Twin Ocean programme addresses this challenge and develops a

digital environment that brings together data and analytical services supporting effective monitoring, restoration, and management of marine ecosystems by 2030. In 2023, the DTO-BioFlow project was initiated to support the integration of biodiversity in the European Digital Twin Ocean. Based on the ongoing work in this project, this talk will introduce some important concepts for marine biodiversity and present demonstrator use cases developed for marine ecological research. Examples feature ecological power tools and predictive applications available as open-source services through the European Digital Twin Ocean platform EDITO. The services are currently used in management of marine protected areas, offshore wind test sites, aquacultures, and for predicting marine invasive species. We will present results of scientific studies using these DTO services, explain how this approach is new, and how it can support ecosystem management as well as nature positive development. We will also highlight the advantages of using the DTO and EuroHPC infrastructures for such computationally complex and demanding tasks.

Collection and Use of Fishing Vessel Data: Practical Use Cases in Japan

Takuto Hazama (1. FURUNO ELECTRIC CO., LTD. (Japan))

Abstract: In Japan and many other countries, the fisheries industry is placing greater importance on improving daily work through data use. This need is increasing because the industry faces issues such as changes in fishing grounds, labor shortages, and the need for better resource management. FURUNO is promoting the use of fishing vessel data to support sustainable fisheries, the growth of the fisheries industry, and the efficient use of fishery resources.

The aim of this presentation is to show how fishing vessel data can be collected and used in practical fisheries. It introduces “Ryoshi Diary,” a system that supports the process from data collection to the use of analysis results. The word “Ryoshi” means “fisher” in Japanese. The data include vessel position, time, fishing operation records, and data from marine electronic devices. The system collects data from devices on fishing vessels, stores the data in cloud services, and presents the results through web services. This allows users to check past results and compare fishing activities over time.

This presentation also describes two use cases in Japan. The first is a local project in which data from many fishing vessels were collected and used as regional fishing vessel data. Collecting data from many vessels over a short period made it possible to cover a wide range of fishing grounds. This result suggests that regional fishing vessel data may help users understand long-term trends in fishing grounds. The second is a single-vessel project using one bottom trawler, in which one fisher collected and analyzed fishing ground data for three years. In this use case, the data made it possible to study changes in catch composition and consider possible reasons for these changes. These use cases suggest that continuous collection and use of fishing vessel data can turn daily fishing activities into useful knowledge for sustainable fisheries.

Building Ireland’s Digital Twin of the Ocean: From Trusted Marine Data to Operational Decision Support

Gerald Lyons[1] (1. Marine Institute (Ireland))

Abstract: Ireland is advancing a Digital Twin of the Ocean (DTO) to support sustainable ocean management, marine spatial planning and climate resilience. Building on decades of marine observations, data stewardship and national monitoring programmes, the Marine Institute (MI) is developing an operational and interoperable DTO ecosystem that connects trusted observations, models, data services, analytics and decision-support tools. Rather than a single visualisation platform, Ireland's approach focuses on creating reusable digital capabilities that enable data, models and users to interact across multiple marine management applications.

The MI manages marine data through trusted pipelines, standardised metadata, and open publication services backed by internationally recognised quality and governance frameworks, including IODE accreditation and CoreTrustSeal certification. Adopting a cloud-first approach the MI is modernising spatial infrastructure, marine portals and digital services while enabling integration with emerging European data spaces and advanced analytics environments. These foundations support capabilities including real-time data integration, scenario modelling, immersive 3D visualisation, and AI-driven analysis.

As Ireland's National Oceanographic Data Centre and an active contributor to European marine data initiatives, the MI provides trusted and reusable data supporting applications across government, research, industry and society. These foundations are reinforced by a strong organisational data culture where stewardship, quality, interoperability and reuse are shared responsibilities.

Practical applications are already emerging through the recently launched cloud-native Marine Atlas, Ireland's maritime spatial planning initiatives, sea sensitivity assessments and marine policy development, demonstrating how trusted data and predictive capabilities can be translated into actionable decision support.

The presentation demonstrates how trusted marine data infrastructure, supported by strong organisational governance and data culture, can evolve into operational Digital Twin capabilities. Ireland's experience provides transferable lessons for the international DITTO community on the technical, organisational and governance foundations required to move from authoritative marine data services to interoperable, user-driven Digital Twins of the Ocean.

A Seagrass EOV and –Enabled Coastal Biodiversity Digital Twin

**Takehisa Yamakita*[1] (1. JAMSTEC/APMBON (Japan))

Abstract: Under GOOS/MBON, “Seagrass cover and composition” has recently been finalized as a BioEco Essential Ocean Variable (EOV), with percentage cover, species composition, and areal extent defined as core subvariables. In Japan, long-term monitoring is conducted across six regions under the Monitoring Sites 1000 program; however, its spatial coverage remains insufficient. Satellite remote sensing can help address this gap by enabling broad-scale mapping of ecosystem extent. Nevertheless, detecting and interpreting rapid, localized changes—such as the regional loss of seagrass meadows within a single year reported by Yamakita et al. (2016)—still require in situ verification.

We propose a high-throughput DT-BIO FLOW that integrates satellite and aerial imagery, field-based vegetation and community surveys, eDNA, fixed cameras, and citizen-science observations, including BIOME. Beyond mapping ecosystem extent, frameworks such as TNFD require assessments of ecosystem condition, species extinction risk, population dynamics, and ecosystem function. Meeting these requirements calls for high-resolution predictions of habitat suitability and responses to climate change and alternative nature futures. Because condition-, function-, and species-level assessments are often constrained by the availability of in situ observations, we emphasize the importance of distributed observation networks involving fishers, coastal managers, and citizen scientists, supported by robust quality-assurance procedures and tangible benefits for participants.

Data will be harmonized into Darwin Core–compliant Event, Occurrence, and Extended Measurement or Fact (EMoF) tables and published through OBIS to support standardization, quality control, provenance tracking, and reuse. We identify key infrastructure challenges, including the integration of heterogeneous data streams, iterative model updating, and uncertainty assessment. We also examine progress and challenges associated with Japan's pioneering blue-carbon credit schemes, including JBlueCredit®, and ocean-health index that capture co-benefits—such as biodiversity, fisheries, and water purification—beyond carbon sequestration alone. Finally, we discuss the framework's potential to support evaluation of marine protected areas, Nature Positive outcomes at OECM sites, TNFD-related reporting, and adaptive fisheries and coastal management, while identifying bottlenecks to operational implementation.

African Ocean Biodiversity Atlas: Advancing Digital Twins of the Ocean Through AI-Enabled Biodiversity Intelligence and Community Knowledge

*Peter Teye Busumprah[1] (1. Ocean Rock Base and Africa Ocean Alliance (Ghana))

Abstract: Digital Twins of the Ocean (DTOs) are transforming ocean science by integrating diverse datasets into dynamic digital environments that support ecosystem monitoring, forecasting, and evidence-based decision-making. However, significant data gaps and fragmented biodiversity information continue to limit the representation of African marine and coastal ecosystems within emerging global digital ocean infrastructures. Addressing these gaps requires interoperable platforms that integrate ecological observations, environmental data, and local knowledge into accessible digital systems.

The African Ocean Biodiversity Atlas (AOBA) is an AI-enabled geospatial platform designed to strengthen biodiversity intelligence for Africa's marine and coastal ecosystems while contributing to the development of Digital Twins of the Ocean. The platform integrates marine biodiversity records, habitat information, Earth observation data, oceanographic variables and community-generated observations within an interoperable framework aligned with international ocean data standards. Artificial intelligence and machine learning are applied to automate species distribution modelling, biodiversity hotspot mapping, habitat classification, ecological change detection, and environmental risk assessment.

A distinguishing feature of AOBA is the integration of Indigenous and local ecological knowledge alongside scientific observations, creating a more comprehensive digital representation of marine ecosystems. The platform supports community-led marine conservation, locally managed marine protected areas, ecosystem restoration, sustainable fisheries management, marine spatial planning, and biodiversity policy development by providing stakeholders with real-time, decision-ready information.

The African Ocean Biodiversity Atlas (AOBA) is a UN Ocean Decade endorsed project dedicated to integrating biodiversity data, advanced analytics, and community knowledge. It exemplifies how regional digital infrastructures can enhance the biodiversity component of Digital Twins of the Ocean. This initiative aims to foster more inclusive, interoperable, and scalable digital ocean ecosystems, thereby improving environmental monitoring, supporting climate resilience, and enabling informed decision-making for sustainable ocean governance across Africa.

Conceptual Design of a Digital Twin-Based Integrated Framework for Subsea Infrastructure Management

**Sujin Son*[1] (1. Sundosoft Co., Ltd. (Korea))

Abstract: With the expansion of offshore wind farms and subsea power and communication networks, various types of subsea infrastructure - including submarine cables, pipelines, and artificial reefs - are continuously increasing in Korean waters. However, information on these assets, such as location, burial depth, permitting, and maintenance records, is managed separately by different organizations, limiting efficient management and spatial decision-making. As marine biodiversity conservation becomes a significant issue in the installation and management of such structures amid the climate and biodiversity crises, the demand for systematic marine spatial planning (MSP) is expected to grow. This study defines subsea infrastructure as interoperable digital objects and designs a digital twin-based integrated framework linked with MSP.

The framework standardizes core data elements for submarine cables, pipelines, artificial reefs, and subsea structures, and represents each asset as an interoperable operational digital object by integrating location and facility attributes, permitting, inspection, maintenance, and risk information, together with heterogeneous geospatial data such as electronic navigational chart-based bathymetry, seabed topography, field survey data, and public water occupancy permits. The digital twin environment provides 3D visualization, spatial analysis, and site suitability assessment to support integrated management and spatial decision-making.

In particular, overlay analysis with key MSP layers - marine use zones, protected species habitats, marine protected areas, and regulatory zones for safety and defense - enables pre-installation review of spatial conflicts and risks, while supporting integrated management of existing facilities' conditions and maintenance histories. The framework thus consolidates distributed information into standardized digital objects, functioning as a decision-support system across the full lifecycle of planning, installation, operation, and maintenance.

In the second year, a pilot dataset will be developed for a demonstration area, integrating real-time monitoring, marine environmental observations, and field survey data to realize an operational ocean digital twin, ultimately supporting national subsea infrastructure management and marine spatial policy.

Demos A1

Chairs: Akihiro Inomata, Laura Rogers

European Digital Twin Ocean – Immersive Control Center

Camille Cherques (Mercator Ocean International (France))

Abstract: The European Digital Twin Ocean is a virtual replica of the ocean that will make ocean knowledge readily available to everyone via a free, public platform (EDITO). Its aim is to democratise access to ocean knowledge and aid decision-makers, researchers, innovators, and citizens with tools to shape a sustainable future. EDITO is a free, public pilot platform intended to evolve into a long-term European operational service by 2030, acting as a global benchmark for digital ocean solutions.

EDITO integrates and upgrades existing European assets, combining data from EMODnet and the Copernicus Marine Service into a single digital framework. EDITO enables the distribution of high-resolution ocean observation data, forecasts, and analysis, the ingestion of external data and tools, and links to advanced computing resources, such as cloud and high-performance computing (HPC), to support complex simulations and scenario modelling.

The proposed live demonstration will show concrete marine applications that support decision-making across environmental, economic, and operational contexts, showcasing what-if scenarios and operationally relevant use cases. As part of the demonstration, an interactive control centre is designed to provide the community with a hands-on experience.

The live demonstration will display marine environmental monitoring and coastal risk management scenarios accessing real-time operational ocean information. They will illustrate how the European DTO is helping transform ocean knowledge into actionable tools for policymakers, researchers and stakeholders. Visitors will interact in this immersive exhibition space with AI-driven marine forecasts, ocean governance dashboards,

predictive modelling tools highlighting ocean data in climate resilience strategies and simulation-based scenarios such as coastal restoration strategies, ship routing optimization, oil spill responses, and more.

Through a unique experience using cutting-edge visualization tools, the demonstration will provide an overview of the vast possibilities offered by the European Digital Twin Ocean to empower decision-making with practical insights and actionable strategy based on scientifically qualified solutions.

Smart Watershed Digital Twin for the Ocean-Based Blue Economy

Tetsu Hattori (PwC Consulting (Japan))

Abstract: This demonstration presents a Smart Watershed Digital Twin designed to support the development of "Umi-gyo," a Japanese concept that expands local economic activity by connecting fisheries with tourism, food, learning, recreation, and community engagement.

The digital twin visualizes and integrates the diverse demands of fishers, tourism operators, residents, visitors, municipalities, researchers, and businesses. It enables stakeholders to explore future scenarios for how coastal areas, fishing ports, and marine resources can be used in complementary ways.

Coastal communities contain multiple opportunities, including seagrass and seaweed bed restoration, sustainable fisheries, stock enhancement, recreational fishing, fishing experiences, marine tourism, coastal walks, environmental education, local cuisine, accommodation, and cultural activities. By treating these activities as an integrated Umi-gyo system, the approach strengthens fisheries while creating new sources of income, employment, and exchange.

The platform combines user needs—such as preferred locations, timing, expected value, required facilities, and acceptable conditions—with information on marine ecosystems, fishing grounds, seasonal changes, catch data, port infrastructure, visitor movements, walking routes, local events, restaurants, and accommodation.

This makes it possible to identify areas for seaweed bed restoration, sustainable fishing, tourism, learning, recreation, and community use, while coordinating activities by season and time of day. For example, restored seaweed beds can improve fish habitats and support fisheries, while also creating opportunities for underwater observation, fishing experiences, environmental education, local seafood dining, and coastal tourism.

The Smart Watershed Digital Twin therefore functions as a shared decision-making platform for designing the future use of the sea. By coordinating nature restoration, fisheries, tourism, food, education, and community

activities, it helps maximize environmental, economic, and social value. Ultimately, the concept aims to create a sustainable Umi-gyo model in which healthier marine ecosystems generate stronger local economies, and regional economic activity, in turn, supports continued restoration and stewardship through inclusive planning, adaptive management, and locally grounded collaboration.

Big Blue Cloud: Enabling User-Driven Ocean Digital Twins for Marine Protected Areas and Participatory Science

Jack Pan (Ocean Motion Technologies, Inc. (USA))

Abstract: Operational digital twins of the ocean require more than high-volume data -- they need accessible and traceable workflows that connect Earth observations, in situ measurements, model outputs, analytics, and the communities that use the resulting information. This live demonstration presents the Big Blue Cloud, a cloud-based open data science platform developed by Ocean Motion Technologies Inc. to support application-specific data-to-decision workflows for ocean research and management.

Two use cases will illustrate how a shared platform can support both formal conservation governance and participatory science. For the Ross Sea Region Marine Protected Area (RSRMPA), we will combine NASA Earth observations, in situ data, model products, and official management boundaries, explore conditions across space and time, and generate interactive visualizations and analytical products relevant to research, monitoring, and the 2027 decadal review. For IceEco, a NASA-supported coastal Greenland project with Scripps Institution of Oceanography collaborators, we will show how satellite products and observations contributed by expedition participants can be curated, compared, and visualized to investigate relationships among icebergs, glacial meltwater, phytoplankton, and seabirds.

Participants will follow a reproducible workflow from data discovery and ingestion through provenance tracking, multi-dataset analysis, visualization, and sharing. The demonstration will include configurable dashboards and machine-learning tools designed to lower technical barriers while maintaining transparency. Audience members will be invited to test queries and provide feedback on interoperability, governance, and co-design priorities.

Rather than presenting a single “monolithic” digital twin, this demonstration positions the Big Blue Cloud as reusable digital infrastructure for building user-driven ocean digital twins around specific management and research questions. It shows how researchers, managers, community partners, and the public can transform diverse observations into collaborative, actionable intelligence for environmental stewardship and resilience.

iSeaPower: An Interactive Decision-Support Digital Twin Platform for Offshore Management

Naseem Ali (Helmholtz-Zentrum Hereon (Germany))

Abstract: As Europe works toward climate neutrality by 2050, offshore wind is expanding rapidly increasing the need for integrated management and sustainable co-use of increasingly crowded marine space. The cost-efficient, and safe deployment, operation, and maintenance of offshore wind farms depend on reliable meteorological and oceanographic forecasts. In particular, the accurate identification of suitable weather windows is essential for safe and efficient offshore activities as forecast uncertainties lead to costly delays and increased operational risk. Simultaneously, offshore management increasingly requires decision-support tools that can integrate multiple activities, environmental conditions, and user requirements within a common digital framework. Consequently, decision-support systems can formalize key concepts such as accessibility, and approachability, and combine them with user-defined operational constraints, to improve the planning of activities ranging from routine inspections to major maintenance campaigns and coordinated operations. We introduce iSeaPower, a web-based Digital Twin of the Ocean (DTO) interactive decision-support platform for offshore renewable energy operations and multi-use applications. iSeaPower integrates model and observation data covering a wide range of temporal scales and translates them into actionable information for specific decision problems. Its modular architecture provides a basis for extension beyond individual offshore environment, and the co-use of offshore space, including combined activities such as offshore wind energy and aquaculture. For example, iSeaPower supports uncertainty-aware planning, and provides an interactive workflow that links geospatial selection, constraint definition, and decision outputs. The modular framework enables the integration of AI-based methods, and the intelligent exploration of complex operational scenarios. By integrating data, models, AI, and user interaction, iSeaPower supports adaptive DTO-based decision-making and enables users to explore heterogeneous data and operational scenarios across multiple spatial and temporal scales. Consequently, iSeaPower contributes to the DITTO vision of interoperable and user-driven Digital Twins of the Ocean that connect data, models, advanced digital technologies, and users to support ocean management.

Posters 1

[Poster 1-01] Automated Gap-Length-Aware AI-Based Imputation Framework for Multivariate Marine Observatories

Oriol Prat Bayarri (Politechnical University of Catalonia, UPC (Spain))

Abstract: Continuous in-situ data from marine observatories is vital for coastal monitoring but frequently suffers from gaps due to technical failures. We present an automated, scale-aware imputation framework that dynamically routes missing data to the optimal algorithm based on gap length. Using the 15-year OBSEA dataset as an operational demonstrator, the pipeline ingests raw data, applies rigorous real-time QARTOD quality control, and corrects sensor drift and biofouling to establish a high-fidelity physical baseline.
The framework classifies missing data into six duration categories. Micro-gaps (<6 hours) are resolved via fast linear bounding. Medium to extended gaps utilize advanced machine learning and deep learning models (such as XGBoost and SAITS) trained via auto-supervised residual learning. To mitigate platform-wide co-failures, the system integrates un-gapped external covariates—including CMEMS and ERA5 reanalysis—ensuring models maintain high accuracy when local predictors are unavailable. Gigantic gaps (>30 days) are seamlessly blended into bias-corrected climatology to prevent error divergence.

Benchmarking demonstrates that the SAITS algorithm achieves the lowest reconstruction errors, while the inclusion of external covariates reduces RMSE by over 25% compared to local-only models. Additionally, the homogenization process accurately recovers long-term environmental trends, such as a +0.090 °C/year warming signal. This transferable, FAIRcompliant framework balances computational efficiency with physical consistency, delivering a robust, gap-free multivariate dataset perfectly suited for Digital Twin of the Ocean initiatives, marine heatwave tracking, and advanced coastal climate monitoring.

[Poster 1-02] Toward generalizable deep-learning post-processing for seasonal and subseasonal wind forecasts

Alessandro Damiani (Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Japan))

Abstract: Reliable atmospheric forcing is essential for marine forecasting, offshore decision support, and operational ocean digital-twin systems. However, seasonal and subseasonal wind forecasts often contain systematic biases, imperfect representations of spatial variability, and limited probabilistic reliability, restricting their direct use in downstream ocean applications.

Here, we assess the generalizability of a previously developed deep-learning post-processing framework across different forecast systems and end-use requirements. Built on a single three-dimensional U-Net backbone, the framework employs two formulations. Regression-based ensemble correction produces continuous, spatially coherent wind fields for downstream physical applications, whereas ordinal probabilistic prediction provides direct information for risk assessment.

We evaluate both formulations across multiple subseasonal prediction systems and compare their performance with conventional statistical methods, including quantile mapping, and machine-learning baselines. Preliminary results show that the framework generally improves forecast skill and usability, although the gains vary across post-processing objectives, forecast leads, and prediction systems. This variability highlights the value of a flexible framework that can be configured for different forecast products and end uses.

Overall, the results demonstrate the potential of deep-learning post-processing to provide more reliable, application-ready atmospheric forcing for marine prediction and ocean digital-twin applications.

[Poster 1-03] An AI-Driven Operational ENSO Forecasting Framework for Climate-Resilient Digital Twins

Kalpesh R. Patil (Application Laboratory (APL), Research Institute for Earth and Information Sciences (REIS) (Japan))

Abstract: We present an AI-enabled operational forecasting system for the El Niño–Southern Oscillation (ENSO), representing a significant step toward an ocean digital twin capable of delivering seasonal ENSO forecasts from 2-months to 2-years in advance. The system employs seasonally optimized convolutional neural networks (CNNs) trained on long-term ocean reanalysis datasets using a customized loss function designed to improve the prediction of extreme ENSO events. Extensive validation demonstrates that the AI system consistently outperforms state-of-the-art dynamical prediction models, particularly at long lead times, while remaining consistent with leading statistical forecasting systems. Motivated by these results, we transitioned the framework into an operational forecasting system two years ago, issuing updated Niño-3.4 index forecasts on the 20th of every month for the upcoming seasons and extending up to two years ahead. To further enhance forecast robustness, the operational framework now incorporates a multi-source sea surface temperature (SST) ensemble. Recent forecasts, initialized from the latest seasonal conditions, consistently indicate the development of extreme El Niño conditions during the coming boreal winter, in agreement with forecasts from leading international climate centers. This operational AI forecasting capability provides an important predictive component for resilient climate and ocean digital twins, supporting climate services, early warning, risk-informed decision making, and evidence-based policy for climate resilience.

[Poster 1-04] From Ocean Blue Carbon Observation to National Spatial Planning: A Remote Sensing–Enabled Digital Twin for Taiwan

Po-Chun Hsu (Center for Space and Remote Sensing Research, National Central University (Taiwan))

Abstract: Taiwan's surrounding seas serve as a spatially heterogeneous regional carbon sink, yet their carbon uptake capacity is increasingly influenced by ocean warming, stratification, changes in circulation, and declining carbonate buffering. This study integrates multi-source remote sensing, ocean reanalysis, carbon-system diagnostics, and a national-scale digital twin framework to support operational blue carbon assessment and spatial planning. Long-term observations from 1998–2025 were analyzed for sea surface temperature, salinity, wind, mixed-layer depth, circulation, surface-water pCO_2, air–sea CO_2 flux, pH, and Revelle factor across five representative marine regions around Taiwan. Results show that the northwestern shelf and Penghu waters are the strongest and most stable carbon sinks, driven by winter cooling, vertical mixing, nutrient supply, and enhanced physical and biological pumping. The Kuroshio and Dongsha waters exhibit moderate but climate-sensitive uptake, whereas the southwestern region behaves as a transitional system with stronger seasonal switching between sink and near-neutral conditions. Concurrent decreases in pH and increases in pCO_2 and Revelle factor indicate a gradual weakening of carbonate buffering and potential future constraints on carbon uptake. These scientific outputs are integrated into a prototype digital twin platform built on standardized data services and a scalable Unity– Cesium–ECS architecture. GPU-enabled visualization supports dynamic geospatial layers, time-series tile streaming, and interactive exploration of blue carbon indicators. The platform is designed for scenario-based applications, including blue carbon restoration, development-impact assessment, land–sea ecosystem protection, carbon sink quantification, and spatial decision support. By connecting Earth observation, carbon-cycle science, and digital infrastructure, this framework demonstrates a deployable pathway from marine environmental intelligence to cross-sector governance, supporting net-zero planning, ecosystem resilience, and adaptive coastal management.

[Poster 1-05] Citizen Science–Driven Digital Twins for Coastal Monitoring and Risk Governance

Ronald Pelot (Dalhousie University (Canada))

Abstract: Digital twins have emerged as powerful tools for representing and understanding complex marine systems, yet their application to dynamic coastal environments remains comparatively underdeveloped, particularly when driven by citizen science observations. This paper presents an emerging initiative to establish a network of citizen science monitoring nodes across multiple coastal communities on the Eastern Shore of Nova

Scotia. Volunteers collect environmental observations using standardized protocols, including meteorological conditions (e.g., air temperature, wind speed and direction, precipitation), beach morphology (e.g., sediment grain size, dune position relative to the shoreline), coastal vegetation characteristics, and bird presence. These observations are stored in structured databases and will serve as continuous and periodic input streams to a digital twin representing the monitored coastal sites.

The proposed digital twin integrates these heterogeneous datasets with geospatial information and numerical environmental models to create a dynamic virtual representation of each coastal location. The model will provide community members, researchers, and decision-makers with near real-time visualization of current environmental conditions while supporting scenario analyses of coastal evolution under storms, sea-level rise, erosion, habitat change, and other climate-driven pressures. Additional data streams from government weather stations, water-level gauges, wave buoys, satellite imagery, drone surveys, and automated cameras can further improve temporal resolution and model fidelity.

Beyond environmental monitoring, the digital twin offers a platform for enhancing coastal literacy, supporting community engagement, and strengthening social licence for adaptation initiatives by making environmental change more transparent and accessible. It also provides a common evidence base for collaborative coastal risk governance, enabling stakeholders to evaluate the potential consequences of management decisions, compare adaptation strategies, and identify emerging vulnerabilities. The paper discusses the architecture of such a citizen science-enabled coastal digital twin, the data integration challenges involved, and its potential to bridge scientific modelling with community-based environmental stewardship and climate resilience.

[Poster 1-06] Environmental Digital Twin Framework for Offshore Wind Farms

Hamid Afshari (Dalhousie University (Canada))

Abstract: Digital twins (DT) are increasingly being adopted to support the planning, operation, and management of offshore wind farms (OWFs). While most existing DTs focus on the structural integrity and operational performance of turbines, comparatively little attention has been devoted to representing the complex bidirectional interactions between OWFs and their surrounding marine and atmospheric environments. We propose a conceptual framework for an environmental digital twin that captures both the influence of environmental conditions on wind turbine performance and degradation, and the impacts of wind farm operations on local atmospheric and oceanographic processes.

The proposed DT integrates physics-based simulation models with continuous streams of observational data to maintain an up-to-date representation of the coupled wind farm– environment system. Environmental inputs may include meteorological measurements, oceanographic observations, and ecological indicators. These data may be acquired through a combination of turbine-mounted sensors, oceanographic buoys, autonomous surface and underwater vehicles, satellite remote sensing, and aerial drones. Data assimilation techniques would serve to continuously calibrate and update numerical models, ensuring that the DT remains representative of current conditions.

The resulting framework provides a platform for advancing scientific understanding of the interactions between OWFs farms and the surrounding environment. By integrating diverse environmental datasets with dynamic simulation models, the DT enables improved assessment of wake effects, hydrodynamic changes, sediment transport, underwater noise propagation, water quality, and potential ecological responses under varying operational and environmental conditions. This capability can support cumulative environmental impact assessments, improve the transparency and traceability of environmental monitoring, and provide regulators, industry, researchers, and coastal communities with a common evidence base for evaluating project performance. As a living representation of an OWF, the environmental DT has the potential to strengthen stakeholder confidence, facilitate more informed decision-making, and contribute to the social licence necessary for the sustainable development and long-term acceptance of offshore wind energy.

[Poster 1-07] A machine-learning NEMO-emulator for regional ocean ensemble climate projections

Benjamin I. Barton (National Oceanography Centre (UK))

Abstract: Digital Twins of the ocean require computationally efficient methods to deliver timely climate projections and quantify uncertainty. This work explores the development of a forcingconditioned machine learning surrogate for regional ocean circulation that can emulate numerical model predictions at a fraction of the computational cost. A convolutional neural network based on a U-Net architecture is trained on ocean state variables and atmospheric forcing to predict the future surface ocean state. Initial experiments demonstrate the feasibility of learning the relationship between forcing and ocean response, providing a first step towards a fast surrogate model for regional ocean climate projections. Future work will extend the approach to three-dimensional predictions and investigate its use for generating large regional climate projection ensembles, supporting uncertainty quantification.

[Poster 1-08] Conditional Flow Matching-Based Surrogate Modeling of Lagrangian Transport for Floating Marine Debris in a Tide-Dominated Coastal Region

Myeongmo Kang (Department of Marine Environmental Science, Chungnam National University (Korea))

Abstract: Conventional Lagrangian particle tracking requires repeated spatiotemporal interpolation and numerical integration of hydrodynamic velocity fields, resulting in substantial computational cost. This study proposes a conditional flow matching surrogate model for floating marine debris transport in a tide-dominant coastal area. The surrogate learns a continuous-time vector field from Gaussian probability paths constructed around splineinterpolated reference trajectories. Four configurations were evaluated: an unconditioned model, early-time displacement conditioning, M2 tidal phase conditioning, and multi-tidal conditioning. Performance was assessed using root mean square error (RMSE), temporal changes in spatial particle distributions, and integration time. All models reproduced the dominant oscillatory behavior and overall transport direction of the reference trajectories, while RMSE decreased progressively from the unconditioned model to the multi-tidal conditioning model. The multi-tidal model achieved the lowest RMSE at every time step, demonstrating the benefit of incorporating multiple tidal constituents. For 10,000 trajectories, the surrogate required 0.20 s for integration compared with 6.05 s for the reference simulation, corresponding to a 30.25-fold speedup. These results demonstrate that conditional flow matching can provide an efficient surrogate for Lagrangian particle tracking.

[Poster 1-09] Graph Neural Networks for Nested Weather Prediction from Global to Regional Scales

Yuki Yasuda (Japan Agency for Marine-Earth Science and Technology (Japan))

Abstract: Digital twins of the ocean require accurate atmospheric prediction because ocean circulation is driven in part by surface wind stress and air-sea heat fluxes. Deep learning models have advanced rapidly in both atmospheric and ocean prediction, making them important components of Earth system digital twins. In the atmosphere, accurate prediction of extreme weather often requires kilometer-scale grids capable of resolving mesoscale structures. However, global prediction at such resolution remains computationally demanding. Limited area models (LAMs) offer a practical alternative by restricting high-resolution prediction to a regional domain and using lateral boundary conditions from a coarser global model. However, the use of deep learning in LAMs and their integration with global models remain underexplored.

This study develops a nested prediction system that combines a global model with a LAM over Japan. The global model is a message-passing graph neural network trained on the global reanalysis dataset (JRA-3Q). It operates at a horizontal grid spacing of approximately 125 km, and its predictions provide lateral boundary conditions for the LAM during both training and prediction. The LAM is based on a graph attention network and is trained on the regional reanalysis dataset (RRJ-Conv). It operates at a grid spacing of approximately 5 km. By nesting the two models, the system downscales coarse global predictions into highresolution predictions over Japan. We evaluate prediction accuracy at both global and regional scales using standard verification metrics, and we examine extreme weather over Japan through case studies. In the poster session, we will discuss the potential and limitations of this data-driven nested approach to regional weather prediction.

[Poster 1-10] [Withdrawn]From Data to Decisions: Digital Twin Applications for Ecosystem-Based Coastal Climate Adaptation and Resilience

Chinomnso Onwubiko (University of Cape Coast (Ghana))

Abstract: Coastal regions are increasingly exposed to climate-driven hazards, including flooding, erosion, sea-level rise and ecosystem degradation, creating interconnected risks for communities, infrastructure, biodiversity and local economies. Addressing these challenges requires decision-support approaches capable of integrating environmental, ecological, and socioeconomic information across sectors. Digital twins offer an emerging opportunity to transform diverse coastal datasets and modeling outputs into dynamic, scenario-based tools for climate adaptation and resilience planning.

This presentation explores the application of digital twin approaches to ecosystem-based coastal adaptation, with particular emphasis on integrating geospatial data, coastal vulnerability modeling, ecosystem service information, and stakeholder knowledge. Building on experience with GIS and the InVEST Coastal Vulnerability model for assessing the contribution of mangrove ecosystems to coastal flood-risk reduction, it proposes a pathway for translating conventional spatial and ecosystem-service modeling into more integrated digital representations of coastal systems. Such digital twins could enable users to explore alternative scenarios, including mangrove conservation and restoration, ecosystem degradation, coastal development, and changing climate hazards, and evaluate their implications for people, ecosystems, and infrastructure.

The proposed approach demonstrates the cross-sector potential of coastal digital twins by connecting climate adaptation, disaster risk reduction, nature-based solutions, ecosystem conservation, spatial planning, and

community resilience. Importantly, incorporating local and stakeholder knowledge alongside biophysical and socioeconomic data can strengthen the relevance and inclusiveness of digital-twin-supported decisions.

By moving beyond static vulnerability assessments towards interactive and scenario-based decision support, digital twins can help bridge the persistent gap between coastal data, scientific modeling, and practical action. The presentation highlights opportunities for applying this approach in data-constrained coastal regions, particularly in developing countries, to support more adaptive, ecosystem-informed, and climate-resilient coastal management.

[Poster 1-11] Climate change, flood induced disasters and their management in Nepal

Narayan Prasad Gautam (Tribhuvan University (Nepal))

Abstract: South Asian country Nepal, although being one of the less greenhouse gases emitting countries, has been affected by the adverse impacts of climate change. Studies have expressed concern that the general rise in temperatures at high altitudes poses a serious environmental and humanitarian threat in Nepal. It is a fact that such a threat extends from glaciers to the ocean. In this study, I have analyzed the future projection of climatic changes in Nepal and found that future temperatures will rise whereas precipitation will decrease for 2050. The results from this study have shown a great concern for the sustainability of water resources in the rivers of Nepal.

Water is one of the main natural resources of Nepal. This study has considered flood induced disasters and their management in Nepal. The yearly flooding is one of the catastrophic events that cause casualties in the country. The severe flood events generally appear in monsoon season that is June to September. Floods of 26-28 September, 2024 killed more than 250 people especially in the capital city Kathmandu and nearby regions. In Nepal, from the records of 1971-2018, flood is the first biggest cause for family and house damages. It is within the category of fourth most severe factors to cause casualties among different multihazard cases.

Therefore, a holistic approach is required for the implementation of flood disaster reduction works accommodating other basin communities, academia, scientific organizations, NGOs, volunteering organizations along with private sectors. It is a need of time to invest more in pre-disaster management programs and adopt best strategies. In a nutshell, active participation and cooperation among all stakeholders should be promoted in order to reduce casualties and property damages from the yearly occurring flood induced disasters and extreme cases of climate change in Nepal.

[Poster 1-12] Evolutionary code search for numerical simulation development

Dennis G. Wilson (Sakana AI (Japan))

Abstract: Digital twins depend on numerical models that are accurate, stable, and adaptable, yet developing and maintaining these models remains labor-intensive. We investigate whether evolutionary code search can automate part of this process by applying ShinkaEvolve, an open-source framework that uses large language models as mutation operators within an evolutionary search, to numerical simulation development.
We formulate simulation development as program evolution from observed trajectories. Candidate programs receive an initial state and generate future states autoregressively, allowing the search to modify executable simulation code rather than fit a fixed neural architecture. We benchmark the resulting programs on several spatiotemporal physical systems using a common rollout interface. Evaluation separates short-horizon prediction error from long-horizon stability and physical behavior.

Initial experiments establish the end-to-end feasibility of using ShinkaEvolve to generate, execute, and iteratively improve numerical simulation programs under a limited evaluation budget. The evolved artifacts remain explicit source code, making them directly inspectable and potentially easier to adapt than opaque learned surrogates. At the same time, the benchmark exposes practical challenges for evolutionary simulation development, including computationally expensive fitness evaluation, unstable rollouts, and the need for objectives that reward meaningful temporal evolution rather than persistence.

These results position evolutionary code search as a promising tool for constructing and updating numerical components of digital twins, including future ocean and Earth-system applications where models must evolve alongside observations and operational requirements.

[Poster 1-13] Digital Twins of the Ocean for Mediterranean Climate Adaptation: Integrating Coastal Monitoring and Decision Support

Drici Mohamed Anis (marine science and coastal environment (Algeria))

Abstract: Climate change is intensifying risks across Mediterranean marine and coastal systems through sea-level rise, coastal erosion, marine heatwaves, biodiversity loss, water stress, and increasing pressure on coastal livelihoods and infrastructure. Despite significant advances in climate science, translating scientific knowledge into effective adaptation policies remains fragmented across the region.

This study presents the Regional Climate Change Adaptation Framework for Mediterranean Marine and Coastal Areas (2026–2035), developed to strengthen the science–policy interface and support climate-resilient coastal governance. The framework identifies four strategic pillars: (1) adaptive governance and stakeholder engagement, (2) ecosystem-based and scalable adaptation solutions, (3) improved access to climate adaptation finance, and (4) evidence-based decision support through integrated monitoring, research, and climate information services.

A central component of the framework is the operationalization of scientific knowledge through enhanced vulnerability and risk assessments, coordinated coastal and marine observatories, accessible climate data platforms, participatory approaches, and regional knowledge-sharing mechanisms. It also promotes the conservation of blue carbon ecosystems and encourages coordination among local, national, and regional stakeholders to accelerate climate adaptation.

By integrating environmental observations, monitoring systems, climate information, and stakeholder engagement into a coherent regional framework, this work provides an important foundation for future Digital Twins of the Ocean in the Mediterranean. The proposed approach demonstrates how interoperable monitoring networks and decision-support systems can strengthen climate resilience, improve coastal governance, and bridge the gap between scientific research and policy implementation under rapidly changing environmental conditions.

[Poster 1-14] Recommended Practice for the Development of Digital Twins of the Earth.

Sigmund Kluckner (Sigmund Kluckner (Austria))

Abstract: Digital Twins of the Earth (DTEs) offer transformative capabilities for simulating, predicting, and delivering actionable information to support decision-making across planetary subsystems. However, current DTE initiatives are frequently restricted to domain-specific environments, resulting in varying scopes, disparate geographic resolutions, and inconsistent terminology. Because many of these systems are built from scratch, developers often underestimate the benefits of cross-domain interaction, creating isolated products.
Establishing standard engineering practices is therefore critical to build consensus alignment across architecture, syntactics, schematics, semantics, and legal interoperability layers, enabling digital twins to interact beyond proprietary boundaries.

To address this need, the IEEE P3501 Working Group is developing the Recommended Practice for the Development of Digital Twins of the Earth. The scope of this project covers the development processes for DTEs

and their subsystems, as well as reconfiguration pathways. Acting as a foundational "base" standard, it aims to establish a high-level vision for a global ecosystem of interoperable DTEs, including Digital Twins of the Oceans.

Currently, the working group has established a comprehensive Draft Outline to guide the standard's development. The standard is structured to cover foundational vocabulary, a step-by-step development process, guidance on leveraging the existing standards ecosystem, and principles for a federated system of twins. The document will include concrete example use cases like estuary salinity models, renewable energy planning or wildfire digital twins.

Moving forward, the working group's next steps focus on driving active content development through subgroups per section, as well as engaging external stakeholders from major global DTE development programs and communities like DITTO. A primary objective will be to demonstrate feasible interoperability across these mostly independent efforts. The group is also working on increasing its outreach and awareness activities through publications, project involvement and workshop organization with a broader audience.

[Poster 1-15] A data integration framework for procedural 3D models for the digital twins of the coastal ecosystems

Xian Qin (Hong Kong Metropolitan University (China))

Abstract: Coastal habitats are highly dynamic interfaces where terrestrial and marine processes intersect, making them challenging to monitor and manage. Coastal digital twins—virtual counterparts that mirror real-world states—offer a transformative approach, yet their creation depends on the effective fusion of diverse and inconsistent datasets. This study presents a comprehensive data integration framework designed to aggregate multi-source coastal data and drive the procedural 3D models for a high-fidelity, species-level digital twin. We utilize existing ecological scenes and established ecological process algorithms to drive procedural systems that replicate integrated phenological life-history events in synchrony with environmental triggers. These control procedural geometry updates, enabling users to witness detailed ecological processes. The entire visualization accurately mirrors the documented phenological patterns. The core advance lies in establishing a high-fidelity foundation of a species-level asset library. This framework provides a reusable blueprint for constructing science-grade digital twins of coastal habitats, enabling quantitative habitat assessment, scenario simulation, and immersive visualization for conservation and management.

[Poster 1-16] User-Centred Digital Twins of the Ocean for a Sustainable Blue Economy: Insights from an India–Europe World Café with ocean stakeholders

Mats Blakstad (SINTEF Digital (Norway))

Abstract: The transition towards a sustainable Blue Economy requires not only technological innovation but also greater collaboration between stakeholders who manage, use, and protect ocean resources. While Digital Twins of the Ocean (DTOs) and related digital decision-support tools have advanced rapidly in recent years, their successful adoption depends on how well they respond to the needs of key societal ocean stakeholders such as coastal communities, civil society, industry and policymakers. Too often, DTOs are developed without sufficient early engagement with the stakeholders expected to use them, creating a gap between technological capabilities and users' practical needs for real-world applications and hinders the potential impact of the tools. Structured dialogue between scientists and societal ocean actors beyond the scientific community is therefore essential for developing tools that can effectively address real-world governance challenges.

To this end, a World Café workshop in New Delhi (October 2026) was designed to convene a diverse group of Indian and European stakeholders working on sustainable ocean management. The event examined how data can be made more accessible and useful for the development of user-centred DTOs. The World Café was designed to convene a diverse group of Indian and European stakeholders working on sustainable ocean management, through utilizing a combination of short presentations and facilitated interactive table discussions to learn from their different development contexts. Europe has accumulated substantial experience in developing DTOs and the data infrastructures that underpin them, while India brings strong capabilities in developing scalable, cost-effective and adaptable digital solutions that can operate across diverse contexts, including data- and resource-constrained settings. These complementary strengths can help address challenges around data availability, accessibility, interoperability and usability. This contribution is an overview of lessons learned about user-centered DTOs from European-Indian collaborations that can be reapplied to new contexts and partnerships.

[Poster 1-17] Integrating Plankton Traits and Trophic Interactions into a Marine Ecosystem Digital Twin

Sang Ah Park (College of Natural Sciences, Seoul National University (Korea))

Abstract: Marine Ecosystem Digital Twins require more than spatially explicit observations of ecosystem states; they also need representations of the biological processes that regulate ecosystem dynamics. Our previous

experimental studies have investigated diverse interactions among bloom-forming dinoflagellates and their potential predators, providing quantitative information on feeding, ingestion, growth, survival, mortality, swimming behavior, and physiological traits.

These studies demonstrate that plankton interactions cannot be represented simply by prey abundance and predator abundance. Predator–prey interactions are strongly species-specific and can be mediated by prey traits and environmental conditions. For example, different heterotrophic protists showed contrasting feeding and growth responses to the kleptoplastidic dinoflagellate Shimiella gracilenta, while swimming and behavioral characteristics influenced predator–prey interactions. Studies of Alexandrium species revealed substantial interspecific variation in bioluminescence and its relationship with physiological and phylogenetic characteristics. Salinity experiments further demonstrated that environmental conditions can modify growth, cell characteristics, and bioluminescence of Noctiluca scintillans, Polykrikos kofoidii, and Alexandrium mediterraneum. More recently, experiments with Karenia bicuneiformis and Karenia selliformis demonstrated contrasting effects on heterotrophic protists and the copepod Acartia hongi, ranging from successful feeding and survival to strong mortality responses.

Based on these findings, we propose a trait-based plankton interaction module for integration into a Marine Ecosystem Digital Twin. The module links environmental conditions and species traits to physiological state, grazing interactions, population growth, and mortality, providing a mechanistic bridge between monitoring observations and ecosystem processes. This framework represents a step toward transforming experimentally derived ecological knowledge into dynamic, predictive components of a Marine Ecosystem Digital Twin. This research was supported by Korea Institute of Marine Science & Technology (KIMST) Promotion funded by the Ministry of Oceans and Fisheries, Korea(RS-2026-25538840, IncheonGyeonggi-Chungcheong Sea Grant).

[Poster 1-18] From Marine Ecosystem Monitoring to an AI-Enabled Digital Twin: An Integrated Framework for Ecosystem Knowledge, Prediction, and Decision Support

Gyung Soo Park (Department of Marine Biotechnology, Anyang University (Korea))

Abstract: Marine ecosystem monitoring programs generate extensive observations of environmental conditions, biological communities, and habitat characteristics, yet these data are often fragmented across surveys, disciplines,

and spatial and temporal scales. Consequently, monitoring results are frequently used for retrospective assessment rather than for integrated ecosystem understanding, prediction, and adaptive decision-making. This study proposes an AI-enabled framework for transforming long-term marine ecosystem monitoring data into a dynamic Digital Twin of the marine ecosystem.

The proposed framework consists of seven interconnected components: (1) systematic ecosystem observation, (2) an integrated ecosystem database linking environmental, biological, habitat, and human-pressure information, (3) an AI-based ecosystem knowledge platform, (4) ecosystem state assessment and anomaly detection, (5) ecological process and interaction models, (6) scenario-based simulation and prediction, and (7) decision support and ecosystem governance. Large language models, vector databases, geospatial analysis, and machine-learning techniques are incorporated to enable natural-language queries, automated report analysis, spatial pattern detection, and identification of ecological anomalies.

The framework is being developed using the long-term datasets of the National Marine Ecosystem Monitoring Program of Korea as a representative application. Rather than treating the Digital Twin as a simple three-dimensional visualization or data repository, we conceptualize it as an evolving digital representation that integrates observed ecosystem states with ecological processes and predictive models. The system is designed to progress from an AI-based marine ecosystem knowledge platform toward a fully integrated Digital Twin capable of scenario simulation and adaptive monitoring.

This approach provides a pathway for transforming conventional monitoring programs from data collection systems into intelligent, process-oriented, and decision-support platforms for ecosystem management and governance. This research was supported by Korea Institute of

Marine Science & Technology (KIMST) Promotion funded by the Ministry of Oceans and

Fisheries, Korea(RS-2026-25538840, Incheon-Gyeonggi-Chungcheong Sea Grant)

[Poster 1-19] Challenges in developing observation-informed, high-resolution coastal digital twins: A model case in Ofunato Bay, Japan

Helen Stewart (Space Environment and Energy Laboratories, NTT, Inc. (Japan))

Abstract: Japan's numerous coastal bays and inlets support fisheries, aquaculture, tourism, and coastal infrastructure that are central to regional economies. However, these environments are undergoing rapid change as ocean warming and shifts in regional circulation alter marine ecosystems and the distribution and productivity of fisheries resources [1]. Coastal digital twins could support adaptation by combining localized observations with satellite products, regional ocean datasets, and high-resolution numerical ocean models into integrated, predictive tools for environmental management. However, fragmented datasets, limited realtime data coverage, uncertain boundary conditions, and the need to represent interacting physical, biogeochemical, and ecological processes across scales remain major obstacles to implementing coastal digital twins [2].

Our group aims to develop coastal digital twins by combining observation-derived datasets with high-resolution ocean simulations. As an initial test case, we focus on Ofunato Bay, located in northeastern Japan. The bay has accumulated observational datasets, including multi-decadal hydrographic monitoring, current measurements, nutrient and chlorophyll records, and spatially resolved metagenomic surveys [3–5]. These datasets provide a basis for examining long-term changes in the bay's physical environment and ecosystems, which support oyster and scallop aquaculture. Ofunato Bay is influenced by interacting river discharge, seasonal stratification and engineered exchange through its narrow entrance [4–5], making it a complex test environment for coupled physical and ecosystem modelling. We discuss approaches for integrating these observations with numerical simulations and identify the remaining barriers to developing functional, observation-informed coastal digital twins.

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[Poster 1-20] [Withdrawn] Design of the Yucatan Shelf Observation and Prediction System

Alejandro Souza (Cinvestav (Mexico))

Abstract: The Yucatan Shelf is one of the largest shelfs in the world, it is a microtidal system. The Yucatan Current a western boundary current, interacts with the shelf generating upwelling, which sustain a large fisheries,

including the third largest octopus fisheries. In this region all the freshwater is from underground sources. This freshwater debauches at sea rich in nutrients from anthropogenic sources can lead to Harmful Algal Blooms. This shelf sea is located in the southern Gulf of Mexico, where Marine Heat Waves are becoming more common. So we have the need of designing a observing and forecasting system that will allow us to prepare early warnings to end users, mainly from the fishing communities and tourism industry.

[Poster 1-21] Digital Twin Readiness for Offshore Wind: Stakeholder-Driven Insights from Nova Scotia's Marine Environment

Madhulika Bhati (Dalhousie University (Canada))

Abstract: Nova Scotia's (NS) emerging interest in large-scale offshore wind development has intensified the need to understand how renewable energy expansion can proceed without compromising marine ecosystem integrity. In response, this study proposes the Digital Twin for Offshore Wind Farms and Marine Ecosystems (DT-OWF-MPA) as a conceptual framework for creating dynamic, data-driven virtual representations of offshore wind installations and the marine environments they influence. Using a systems-theoretical perspective, the research explores how DT could support environmental monitoring, predictive modelling, and the evaluation of ecological trade-offs within Marine Protected Areas (MPAs).

The study draws on multi-sector technical workshops, focus group discussions, and expert interviews to examine stakeholder perspectives on the anticipated value, feasibility, and governance considerations for DT adoption. Although the project does not develop an operational DT, stakeholder engagement reveals several critical socio-technical factors that must be addressed before meaningful implementation is possible. Participants emphasized the importance of integrating cultural and Indigenous knowledge systems into environmental assessment processes, improving occupational health and safety through predictive modelling of worker exposure and operational risks, and addressing region-specific geotechnical challenges. They also highlighted enabling conditions such as digital literacy, data accessibility, and transparent modelling practices, noting that the effectiveness of DT depends on diverse user groups' ability to interpret, engage with, and contribute to complex digital models.

These insights position DTs not only as environmental monitoring tools but as multidimensional platforms capable of supporting cultural inclusion, workforce safety, regional risk mitigation, and broader socio-technical

capacity building. At the same time, concerns related to fragmented data systems, institutional constraints, limited technical capacity, and the risk of opaque "black-box" models underscore the need for careful governance. The study concludes that technological sophistication alone is insufficient; meaningful adoption requires open data principles, transparent modelling, inclusive governance, and incremental pilot initiatives that build trust and cross-sector collaboration.

[Poster 1-22] From Ocean Data to Maritime Intelligence: Colombia's Path toward Operational Digital Twins

Claudia Patricia Urbano Latorre (Universidad Nacional de Colombia (Colombia))

Abstract: Colombia is developing a maritime intelligence ecosystem that demonstrates how digital technologies can transform oceanographic and meteorological information into practical, high-resolution services for maritime safety. The SIPSEM (Integrated Forecasting System for Maritime Safety) climate services ecosystem, led by the Colombian Maritime Authority (DIMAR), constitutes an innovative South American approach that connects observation, high-level modeling, predictive intelligence, and interoperability to support operational decision-making.

The system addresses a fundamental coastal challenge: global models and heterogeneous observations are often fragmented, siloed, or lack the resolution required for tactical maritime applications. SIPSEM responds through a multi-layer architecture that integrates Colombia's oceanographic and marine-meteorological observations with nested numerical models, data-driven intelligence, and digital dissemination.

At its modeling core, SIPSEM uses a cascading approach that links global atmospheric forcing with regional, coastal, and local configurations, progressively increasing spatial resolution from about 27 km to 750–150 m in critical port environments. This architecture enables high-resolution simulations, operational forecasting, and scenario-based analysis, linking large-scale environmental dynamics with the local conditions necessary for navigation, port operations, coastal protection, and emergency response.

A key innovation is its open, interoperable digital architecture. ERDDAP provides a flexible data integration and dissemination layer, connecting heterogeneous sources and formats via standardized services such as WMS and

interoperable interfaces. This architecture facilitates access to reusable data, geospatial integration, and the scalable delivery of environmental information across diverse platforms and user groups.

Through SIPSEM, Colombia demonstrates how a maritime authority can evolve from isolated datasets and models toward an operational, scalable ecosystem of digital twins. Port-scale modeling at the Port of Barranquilla illustrates how high-level numerical modeling, AI-driven predictive intelligence, and open digital infrastructure can combine to strengthen Colombia's maritime security, climate resilience, and emerging ocean intelligence capabilities.

[Poster 1-23] Accelerating Science-Based Coastal Protection: an AI Emulation Framework for Nature-based Solutions

Serena Maria Lezzi, **Ivan Federico* (CMCC - Euro-Mediterranean Center on Climate Change (Italy))

Abstract: Nature-based Solutions (NbS), such as seagrass meadows, are increasingly recognized as infrastructure for mitigating coastal hazards including extreme waves, storm surges, and shoreline erosion. However, designing and optimizing NbS interventions requires evaluating countless "what-if" scenarios with varying plant phenotypic traits, species compositions, and spatial meadow layouts. While physics-based numerical models accurately capture these complex ocean–vegetation interactions, their high computational cost creates a severe bottleneck that prevents their integration into real-time Digital Twins of the Ocean (DTOs). To overcome this limitation and enable rapid optimization of coastal resilience strategies, we present an AI-based surrogate modeling framework designed for ocean fields emulation within a DTO architecture. Multiple data-driven surrogate models, ranging from ensemble tree methods (Random Forest, LightGBM) to deep convolutional networks, have been evaluated to identify the optimal architecture for learning complex spatial flow regimes. A U-Net-like deep learning architecture provided best results. The model was trained on a synthetic dataset generated by the coupled SHYFEM-MPI circulation model and WAVEWATCH III wave model, incorporating the ocean–vegetation parameterizations of Shirinov et al. (2025). The dataset encompasses 28 distinct meadow configurations, where key benthic morphological parameters (shoot density, leaf length and thickness) are systematically varied.

The emulator acts as a fast, multi-variable surrogate, inferring vegetation-induced modifications across coastal ocean fields: significant wave height, mean wave period and direction, near-bottom orbital velocity, and currents. Implemented and validated across two pilot sites in Italy (Rimini and Manfredonia), the U-Net model accurately

reproduces wave attenuation and flow dynamics, showing strong generalization capabilities when predicting firstly seen intermediate benthic states.

By accelerating complex, physics-based simulations by several orders of magnitude, this work demonstrates how AI can bridge the gap between numerical modeling and interactive DTO platforms. This framework provides an automated, science-based tool to evaluate and deploy NbS for climate adaptation and coastal defense.

[Poster 1-24] Integrated Assessment of Seasonal Land Deformation and Long-Term Sea Level Rise in the Godavari Delta

Smriti Kumari (Indian institute of technology Kharagpur (india))

Abstract: The Godavari Delta covers area roughly of 4,100 to 5,100 sq.km, stretching over 170 km. It is the second largest delta in India and is known for intense fertility and paddy cultivation. It is formed where Godavari River enters the Bay of Bengal. The study area was latitude (16°40'N– 16°80'N) and Longitude (81°80'E–82°20'E) for seasonal land deformation. The sea level anomaly was calculated from latitude (15°N–18°N) and longitude(80°E–84°E).

Seasonal land deformation was analyzed using 32 Sentinel-1 SBAS interferogram pairs acquired between 2017 and 2024, representing four characteristic months (February, May, August, and November) each year. A representative multi-temporal deformation map was generated using a pixel-wise median composite to identify persistent deformation patterns. Long-term sea level variability was evaluated using Copernicus Marine Sea Level Anomaly (SLA) data covering the period 1993–2024.

Sea Level Anomaly (SLA) represents deviations of sea surface height from a reference mean sea level. The monthly mean SLA values were extracted for the region and analyzed over the study period. A linear regression model was applied to the time series to estimate long-term trend in sea level change. Each SBAS interferogram was examined to identify areas of maximum negative subsidence and positive as uplift. The maximum subsidence value and its corresponding geographic coordinates were recorded for every pair. Seasonal and annual variations were then compared to identify persistent deformation patterns and region with maximum subsidence was plotted.

The combined interpretation of land subsidence and sea level rise indicates that the delta is highly vulnerable to relative sea level rise. This increases the potential risk for coastal flooding, shoreline erosion and salt-water intrusion.

[Poster 1-25] Application of ROMS-CSTMS to Analyze Sediment Transport Dynamics in the Northern Bay of Bengal

Mohd Imaran (IIT Kharagpur and Swansat (India))

Abstract: The monsoonal rivers of India at its head are contributing to the sediment load and massive freshwater inflows into the Northern Bay of Bengal (NBoB). The integrated community sediment transport modelling system (CSTMS), a submodule of the Regional Ocean Modelling System (ROMS), was applied to analyze the spatial dispersal of cohesive (silt) and noncohesive (sand) sediment. We simulated the model under three alternative scenarios: (1) river-influenced, (2) non-river-influenced, and (3) non-tidal-influenced to understand the sediment dynamics close to the coast. The Ganges-Brahmaputra, Mahanadi, and Irrawaddy Rivers revealed a very high vertically averaged silt and very low sand at their mouths while the presence of the river was in simulation. Additionally, where the averaged silt concentration is very high, the bottom stress brought on by wave-current interaction is also strong. Furthermore, bottom stress is the major factor of sediment migration near the coast. Moreover, the averaged silt and sand are also noticeably less where the Ganges and Brahmaputra meet, as are the Mahanadi and Irrawaddy rivers when the rivers are not in the simulation. The ROMS-CSTMS model for the NBoB is then used to perform numerical simulations under three scenarios: with and without rivers and without tide. The findings show that patterns of sediment transport, erosion, and accretion are strongly impacted by bottom stress brought on by the interaction of waves and currents. A high sediment load can impact water quality and marine life; therefore, to manage the shoreline, plan the harbour, and dredge the silt deposited for the ship passages to the port, erosion and accretion of the shore and the sea bottom are crucial.

Fri. Nov 13, 2026

Oral A4 Ocean Observing Systems and Data Quality

Chair: Sung Yong Kim, Yosuke Fujii

A smart buoy network for digital representation of the Estonian marine areas

**Urmas Lips* (1. Tallinn University of Technology (Estonia))

Abstract: High-quality environmental and navigational information is essential for maritime safety and security, sustainable management of the marine environment, and the development of the blue economy. The Estonian MEREHUNT project is developing an integrated marine observing and data management system to support a future digital twin of Estonian marine areas.

During its first phase (2025–2027), MEREHUNT will develop and deploy up to seven prototype autonomous observing platforms of three types designed for different operational environments and measurement needs. Larger platforms will incorporate profiling systems for observing the vertical structure of the water column, while camera systems on most platforms will provide complementary information on sea state, marine traffic, and potential pollution events. The network will combine observations from the attached wave and current profilers and dedicated surface current recorders. Modular sensor integration will also enable testing of emerging technologies for variables that remain challenging to observe autonomously, including nutrients, pCO_2, etc.

The prototypes will be evaluated through concrete operational applications, including providing real-time environmental and navigational information for remote vessel piloting, detecting marine pollution, supporting drift forecasting, and improving characterization of hydrodynamic and biogeochemical conditions.

Observations will be integrated into a common data platform that provides data transmission, processing, quality control, storage, visualization, and fit-for-purpose services for different users, with connections to national, regional, and European marine data infrastructures. The system design builds on consultations with governmental agencies, maritime industries, offshore wind and aquaculture developers, environmental and rescue organizations, scientists, and the public. By integrating multi-purpose autonomous observations, interoperable data infrastructure, and operational demonstrations, MEREHUNT provides a practical pathway from marine monitoring toward a dynamic digital representation of Estonia's marine environment for data-driven decision-making.

The Fishing Vessel Ocean Observing Network: Advancing Collaborative Ocean Observations to Fill Critical Data Gaps and Improve Forecasts

*Shin Kida[1] (1. Kyushu University (Japan))

Abstract; Ocean observations are a foundation for our understanding of the marine environment and are essential for improving ocean forecasts and supporting sustainable management. Despite major advances in global observing systems, critical spatial-temporal data gaps remain, particularly in coastal and shelf regions as well as subsurface. These gaps limit forecast skill and increase uncertainty in scientific, operational, and policy decision-making. Fishing vessels offer a unique opportunity to help close these gaps because their activities overlap extensively with data-sparse regions. They can host a wide range of oceanographic sensors, while many fishing gear types routinely profile through the water column, providing cost-effective access to much-needed subsurface observations. By integrating ocean measurements with fishing operations, fishing vessels can substantially expand the coverage of existing observing systems. However, scaling these efforts globally requires addressing challenges related to diverse fisheries and fishing practices, heterogeneous data management and quality control, and sustained engagement with fishing communities. The Fishing Vessel Ocean Observing Network (FVON) was established to coordinate these efforts by maximizing the value of fishing vessel observations, developing best practices, and promoting the integration of observations into operational forecasting systems. Through partnerships among fishers, scientists, governments, and industry, FVON seeks to democratize ocean observations, improve ocean forecasts, support sustainable fisheries, and advance a data-driven blue economy. We will introduce FVON and highlight collaborative observing initiatives from around the world that demonstrate the value of integrating ocean observations with fishing operations, enabled by advances in sensor technology, and discuss recent progress, remaining challenges, and opportunities for expanding these efforts to help fill critical ocean data gaps and strengthen ocean forecasting.

Multi-system Observing System Experiment Database provided by UN Ocean Decade Project SynObs

*Yosuke Fujii[1] (1. JMA/MRI (Japan))

Abstract: “Synergistic Observing Network for Ocean Prediction (SynObs)” is a project of the United Nations Decade of Ocean Science for Sustainable Development. SynObs aims to identify the roles of individual ocean observing systems, assess their combined value for ocean/climate monitoring and prediction, and explore future designs of the ocean observing network that maximise synergy among diverse observation platforms. SynObs is currently conducting internationally coordinated multi-system observing system experiments (OSEs), known as the SynObs flagship OSEs. OSEs are observation sensitivity experiments carried out using data assimilation and

prediction systems. In the flagship OSEs, several ocean/climate prediction centers conduct OSEs using a variety of ocean-only or coupled ocean-atmosphere prediction systems under a pre-defined experimental setting. This activity aims to provide fair and scientifically consistent observation impact assessment which are robust among most prediction systems. All OSE results are stored in netCDF-format files agreed upon SynObs members and are aggregated on the Japanese DITTO server. Thus, SynObs adds a specific function which enable us to evaluate/design the ocean observing system for various purposes. For example, we confirmed that the multi-system ensemble spread of analysis SSH fields is increases when either satellite altimeter data or Argo data are withheld from data assimilation, implying that assimilating Argo data in addition to satellite altimeters is necessary to reduce uncertainty in the analysis sea surface height (SSH) fields. SynObs is now inviting volunteer groups to analyze the impacts of ocean observing systems using this database. It is also planned to improve the user interface of the DITTO to support the use of the SynObs OSE data.

Design of High-Resolution Physical Oceanographic Observing System and Numerical Simulation for Coastal Seas

**Kiyoshi Tanaka[1]* (1. University of Tokyo (Japan))

Abstract: Coastal seas, such as bays, estuaries, and nearshore areas within roughly 100 km of the coast, are expected to become increasingly important in oceanography. However, neither satellite observations nor autonomous observing platforms (e.g., Argo floats and gliders) are effective in these areas, where observations are required at spatial scales of 100–1000 m and temporal scales of hours to days.

To address this observational challenge, we have so far pursued three key approaches. The first approach involves establishing a continuous or high-frequency observation system in collaboration with local stakeholders, such as fishers. It is generally difficult to make high-resolution observations among many marine facilities, such as aquaculture facilities, using conventional research vessels (equipped with advanced instruments such ADCPs and CTDs). Therefore, we have established a sustainable observation and monitoring framework using fishing boats that can easily navigate among the facilities.

The second approach is to advance numerical modeling that includes not only an ocean circulation model but also an atmospheric circulation model, which compensates for the coarse resolution of observational data and also provides insights and forecasts to address societal problems in coastal seas. In the simulation of coastal circulation, one of the most difficult data to observe is, other than lateral boundary conditions, high-resolution wind stress data over the sea surface (surface boundary condition). This problem may be solved by driving an atmospheric

circulation model. In general, coastal sea circulation is crucially influenced by small-scale, short-term wind variations, which are induced by steep mountains and complex coastlines.

The third approach is to conduct atmospheric observations simultaneously. Proper validation of the simulated atmospheric circulation fields is essential. It should be noted that meteorological observations are usually not conducted on mountains or at sea, where we have been carrying out such observations.

Globally covered Argo float observations and a challenge of quality control with the signature method for improved RTQC profiles

**Shigeki Hosoda* (1. JAMSTEC, WPI-AIMEC (Japan))

Abstract: The Argo data—comprising global temperature and salinity profiles collected with uniform quality control—have been accumulating for over 25 years, and by 2025, the cumulative number of so-called "Core mission" profiles exceeded 3 million. The Argo data flow, which forms the backbone of the Argo program, is already well-established in collaboration with highly accurate data from ship observations and others; Data Assembly Centers (DACs) in various countries and float PIs conduct real-time (RTQC) and delayed-mode quality control (DMQC), respectively, performing both automatic and accurate quality checks before submitting data to the Argo Global Data Assembly Centers (GDAC). Because the Core mission profiles provide comprehensive global coverage, they enable the capture of seasonal variations on an ocean basin scale and the forecast data using data assimilation models, leading to a wide range of scientific outcomes and applications across various fields. The volume and scale of this accumulated Argo data are substantial for ocean observations, and it is becoming increasingly difficult for resources to provide quality-controlled data that meets the Argo data flow requirements within the specified timeframe. Furthermore, the RTQC data produced by automated processing—which is provided for forecasts requiring immediacy—is not being maintained at a sufficient research level. To address these points, attempts were made to create an available dataset bringing better quality-controlled RTQC data before submitting DMQC data, based on a method that defines profile data as a single function called a "signature" and determines the errors based on its features (Sugiura and Hosoda, 2022), as well as on a further development of this method (Kouketsu et al., 2026). Currently, the transition from the conventional Argo to the OneArgo—which includes BGC and Deep missions—is underway; applying this method to each parameter is effective, and further automation utilizing AI and ML is anticipated.

From Radiometric Intercomparison to Skin SST Retrieval: Algorithm Development Using INSAT- 3DR and Meteosat-8 TIR Observations

*Swadhin Satapathy[1] (1. National Institute of Science Education and Research (India))

Abstract: Accurate skin-SST retrieval at high temporal resolution from satellites remains a persistent challenge in remote sensing inversion, often neglected due to the inherent limitations of in situ observations and the widespread focus of many algorithms on bulk SST. Leveraging the continuous monitoring capabilities of geostationary satellites, we developed a robust skin-SST retrieval framework for INSAT-3DR and Meteosat-8. To ensure high-quality inputs for the retrieval framework, we performed a detailed intercomparison of the Brightness Temperatures (BTs) of the thermal infrared window channels using more than 1.5 billion collocated clear-sky observations over the Bay of Bengal. We applied a bias-correction scheme that significantly improved the consistency of observations and reduced the mean observation-minus-model (O-M) difference to zero. We address this inverse problem by integrating prior knowledge from a large ensemble of 10 years of ERA5 cloud-free datasets and using the RTTOV radiative transfer model to generate an extensive lookup table (LUT) that maps physical states to corresponding simulated BTs. We then implemented a Bayesian 1D-Var framework and developed a machine learning (ML) model that uses the LUT to learn complex patterns, thereby improving retrieval. We achieved correlations of 0.934 and 0.960 for 1D-Var and 0.942 and 0.957 for the ML retrieval for INSAT-3DR and Meteosat-8, respectively, when compared against ERA5 skin-SST. Comparison of the retrieved skin-SSTs with ISFRN shipborne radiometer skin-SSTs shows correlations exceeding 0.95 for both satellites, with biases of 0.2 K for ML and 0.1 K for the 1D-Var algorithm. Furthermore, incorporating the diurnal variations in skin-SST on a peak-warming day results in substantial differences of 35-40 W/m² in the estimated air-sea latent heat flux. By successfully leveraging a physically constrained dataset, our method significantly improves the accuracy of skin-SST retrieval, enabling improved ocean monitoring from geostationary platforms.

Oral B4 - Asian Hub

Chair: Yushi Morioka

Opening Remarks

*Yushi Morioka[1] (1. JAMSTEC (Japan))

Digital twin of the ocean as a catalyst for blue economy innovation

*Fei Chai[1] (1. Xiamen University (China))

Abstract: The global ocean economy is undergoing an urgent transition from an ecologically harmful, profit-driven model to a sustainable blue economy. Yet traditional maritime governance systems still struggle with real-time monitoring, cross-sector collaboration, and efficient decision-making, highlighting a pressing need for advanced digital solutions. The Digital Twin of the Ocean (DTO) offers a promising pathway forward. By creating dynamic, virtual replicas of marine environments, it integrates real-time observations with advanced modeling, supported by AI and supercomputing. Its multi-module architecture, encompassing data, models, analysis, and visualization, enables stakeholders to ask critical questions in the immediate ("What now?"), prospective ("What next?"), and hypothetical ("What if?") scenarios. Advanced DTO systems have the potential to support a wide range of blue economy sectors through full-lifecycle management, including aquaculture, offshore wind energy, shipping, disaster mitigation, blue carbon initiatives, and marine tourism. However, challenges remain in areas such as integrating heterogeneous data, improving model accuracy, and ensuring cybersecurity. Future development should focus on establishing unified mathematical frameworks, hybrid modeling techniques, edge-cloud computing systems, and enhanced interdisciplinary collaboration. With sustained investment and global cooperation, DTOs can become a cornerstone of a sustainable and resilient blue economy.

Toward a Digital Twin of the Indonesian Throughflow: From Multiscale Ocean Dynamics to Predictive Intelligence

*Fadli Syamsudin[1] (1. National Research and Innovation Agency, Indonesia (Indonesia))

Abstract: The Indonesian Throughflow (ITF) is the world's only tropical ocean gateway connecting the Pacific and Indian Oceans and plays a fundamental role in global heat redistribution, climate variability, and marine ecosystem dynamics. Despite its importance, continuously observing and predicting ITF variability across multiple temporal and spatial scales remains challenging. We propose a Digital Twin of the Indonesian Throughflow (ITF-Digital Twin) as an integrated framework combining observations, ocean reanalysis, numerical modelling, artificial intelligence, and process-based understanding to represent and predict the evolving ITF system.

As a scientific foundation for this vision, we investigate the multiscale modulation of Makassar Strait ITF transport by the Madden–Julian Oscillation (MJO) under different El Nino-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) states. Using 17 years (2004-2020) of high-resolution GLORYS12 reanalysis evaluated against INSTANT mooring observations, we characterize intraseasonal, interannual, and vertical variations in ITF transport. Results demonstrate that MJO-related transport responses are strongly state-dependent, with systematic differences in amplitude, timing, and vertical structure across ENSO-IOD regimes. These responses reflect interactions between intraseasonal atmospheric forcing, wind-driven ocean adjustment, and large-scale pressure-gradient variability controlling Indonesian Seas circulation.

These findings highlight a key requirement for an ITF Digital Twin: the ability to dynamically represent interactions between fast atmospheric forcing and slowly varying ocean-climate states. We envision a multi-layer system integrating in situ moorings and acoustic observations for sensing, satellite and operational products for spatial coverage, high-resolution models and reanalyses for physical state estimation, and artificial intelligence for adaptive prediction. Makassar Strait provides a strategic natural laboratory and observation–modelling node for this architecture.

This work represents a step toward an Indonesian Ocean Digital Twin, with future expansion across the interconnected Indonesian Seas and coupling with the wider Indo-Pacific climate system, supporting climate services, marine ecosystem and fisheries management, and early-warning applications.

Mutual benefits between fisher observations and ocean forecasting in coastal waters

**Naoki Hirose*[1] (1. RIAM, Kyushu University (Japan))

Abstract: Subsurface observations in coastal and shelf seas remain insufficient compared to profiling measurements in open oceans. To address this gap, we have developed a system that involves coastal fishermen in conducting in-situ measurements. By assimilating this observation data in real-time, we can provide valuable feedback on ocean predictions to support their fishing activities. We adapted the traditional full-scale conductivity-temperature-depth (CTD) instrument into a more conventional model dedicated to small-scale fisheries. This simple and smart CTD device allows Bluetooth communication with Android devices. Although its accuracy and pressure resistance were reduced to make it affordable, it remains effective for our data assimilation purpose. Along with acoustic current data, the accuracy of coastal ocean prediction models, particularly for velocity components, can be significantly increased. Using the intuitive and user-friendly forecasting app, cooperating fishermen have been able to reduce fuel usage, working hours, and gear damages,

thereby improving profitability and working conditions. This app has become an indispensable operational tool for Japanese coastal fishermen, motivating them to actively participate in ocean observations. The Smart Fisheries Network (SFiN) has grown remarkably through these efforts. Today, it encompasses more than 30 participating organizations and over 340 collaborating fishing vessels, spanning Japan from Okinawa to Hokkaido.

Building Blocks for a Philippine Coastal-Ocean Digital Twin: Insights from Remote Sensing, Modeling, and Machine Learning Twin: Insights from Remote Sensing, Modeling, and Machine Learning

**Ayin M. Tamondong[1]* (1. University of the Philippines - Diliman (Philippines))

Abstract: The Philippines is an archipelagic country whose coastal waters and marginal seas are closely tied to food security, livelihoods, biodiversity, disaster resilience, maritime activities, and the blue economy. These areas support fisheries and aquaculture, host important ecosystems such as coral reefs, seagrass beds, and mangroves, and help protect coastal communities. At the same time, they are increasingly affected by climate change, coastal development, pollution, extreme weather events, harmful algal blooms, habitat degradation, and competing uses of marine space.

Despite their importance, many coastal and ocean areas in the Philippines remain difficult to monitor on a regular basis. In-situ observations are often limited in coverage, while coastal and ocean datasets are often produced for specific projects, locations, and objectives. This makes it challenging to build a broader and more consistent picture of ocean conditions, environmental changes, and emerging risks across the country.

This presentation shares selected ocean-related research undertaken in different study areas in the Philippines. These include applications in coastal habitat mapping, coral bleaching detection, seagrass assessment, water quality monitoring, red tide prediction, storm surge simulation, oil spill and marine litter tracking, vessel monitoring, and fisheries-related oceanographic analysis. The studies use remote sensing, field data, geospatial analysis, physical models, and machine learning models to describe coastal and marine environments, examine environmental changes, and explore possible support for monitoring and decision-making.

While these studies were developed as separate research efforts, they offer useful examples of the kinds of data, methods, and applications that may be relevant to future coastal-ocean digital twin initiatives. The presentation therefore reflects on lessons from these Philippine case studies and discusses how such experiences may contribute to broader conversations on an Asia Hub for Ocean Digital Twins, especially for archipelagic and data-limited coastal regions.

Ocean Prediction and Services in Southeast Asia: Challenges and a Pathway toward Coastal Digital Twins

*Dhrubajyoti Samanta[1] (1. Nanyang Technological University, Singapore (Singapore))

Abstract: Southeast Asia's marginal seas lie at the crossroads of the Pacific and Indian Oceans and are among the most dynamically complex and hazard-prone coastal environments. Archipelagic geography, shallow shelves, narrow straits, strong currents, monsoon forcing, and climate variability interact across multiple timescales. Yet sustained in-situ ocean observations remain sparse and discontinuous, impeding model evaluation, prediction, and development of reliable ocean services. This presentation provides a Southeast Asian perspective on what is needed for Digital Twins of the Ocean to become genuinely useful. Instead of presenting an existing operational digital twin, we examine the scientific and service gaps that must first be addressed: sustained observations, data integration, realistic representation of regional ocean dynamics, global-to-local prediction, rigorous validation, and translation of forecasts into information that users can readily act on. Singapore, situated in shallow waters connecting the Malacca Strait, South China Sea, and Java Sea, provides a valuable testbed for addressing these challenges. Recent studies in Southeast Asia have demonstrated rapidly increasing marine heatwave frequency, duration, and subsurface extent, together with strong ENSO-driven ocean warming and pronounced regional sea-level variability. These changes emphasize the need for prediction systems capable of connecting large-scale climate drivers with local-scale coastal dynamics. Based on our regional studies of ocean circulation, sea-level variability, marine heatwaves, and ocean warming, we introduce an emerging Japan–Singapore collaboration that brings together complementary strengths in observations, regional process understanding, ocean-climate prediction, digital-twin development, and stakeholder co-design. Our goal is not simply to build another digital platform, but to create a pathway toward trustworthy predictions and decision-ready coastal services. Lessons learned from Singapore could help guide digital-twin development for the complex, data-sparse, and highly exposed marginal seas of Southeast Asia, supporting coastal planning, maritime operations, and climate-risk management. This effort also supports Singapore's Green Plan 2030 by enhancing coastal climate resilience.

Discussion

*Yushi Morioka[1] (1. JAMSTEC (Japan))

Oral C4 Marine Biodiversity & Ecosystem Modelling

Chair: Cheng-Hao Lu, Qiang Deng

Advancing Marine Ecological Monitoring through a Digital Twin of the Ocean Framework

*Morane Clavel-Henry[1] (1. GEOMAR (Germany))

Abstract: Long-term ecological monitoring provides essential information on patterns, trends, and variability in biodiversity of marine ecosystems, including highly pressured coastal environments. The Digital Twin of the Ocean (DTO) framework offers new opportunities to combine biological and environmental observations with modelling methodologies, enabling the generation of near-real-time, spatially upscaled ecological indicators. Within the EU-funded DIGI4ECO project, a digital platform is being developed to expand marine information across four dimensions (space and time). Here, the objective is to demonstrate how a DTO framework can enhance the value of marine observatories and their platform networks by connecting in-situ observations, modelling tools, and decision-support interfaces within a coherent digital framework. The presentation will showcase project activities structured around three core themes: (i) observed and predicted data; (ii) Big Data infrastructure and pipeline; and (iii) machine-learning approaches.

The first theme develops on acquisition, integration, and harmonisation of multi-source datasets, including imagery, computationally assisted environmental DNA (eDNA), historical archives, and sleeping data. These observations are complemented by models that support the spatial upscaling of species distributions and socio-ecological analyses, helping to fill data gaps and strengthen decision-support capabilities. The second theme focuses on the integration of cross-site, cross-sectoral data streams while ensuring compliance with FAIR data principles within the DTO framework. We will also highlight advances in autonomous data collection and transmission between observing assets, including interactions between fixed platforms and mobile robotic systems through docking technologies. The third theme presents developments in automated organism classification using image analysis and machine-learning techniques, as well as their integration with remote mission supervision and adaptive control of multi-parameter sensor systems.

Ultimately, the DTO services developed within DIGI4ECO are designed to support the expansion of datasets, the deployment of new marine observatories, and evolving monitoring requirements driven by international policies and directives.

Turning biodiversity data into dynamic digital ecosystems

**Klaas Deneudt*[1] (1. VLIZ (Belgium))

Abstract: Marine habitats present specific and one-of-a-kind issues when it comes to observing, mapping, and monitoring biodiversity in marine ecosystems. In spite of the fact that significant advancement has been made in

Europe to collect, harmonise, and make available data on marine biodiversity, a large portion of the data that is currently being collected is unavailable and inaccessible.

The core mission of the DTO-BioFlow Project is to unlock those “sleeping” biodiversity data, enabling the sustained flow of these and new data via primary integrators and EMODnet into the EU Digital Twin Ocean. It is working to create a digital replica of marine biological processes, transforming new and existing data flows into evidence-based knowledge.

The project aligns with the EU's Biodiversity Strategy and Nature Restoration Law and with the mission "Restore our oceans and waters by 2030", both of which advocate for the protection and restoration of land and sea regions.

Over the four years, the DTO-Bioflow consortium has been working on consolidating standards, quality control, communication protocols, harmonisation pipelines, data products, data models, ingestion procedures and incentives for sustainable connection to improve the interoperability and digitisation of biodiversity data. The project will also test out various technologies that are both affordable and adaptable to carry out species monitoring on a massive scale. The end-to-end approach will be demonstrated via a number of science-based use cases and via mechanisms to monitor, measure progress and drive community action towards increasing biodiversity data flows.

Toward a Digital Twin of Rocky Intertidal Ecosystems: From Long-Term Monitoring to Social Implementation

**Ken ISHIDA[1]* (1. JAMSTEC (Japan))

Abstract: With global climate change, the frequency and intensity of disturbances such as marine heatwaves and typhoons are increasing, severely impacting marine ecosystems and their services. There is, therefore, an urgent need to evaluate the impacts of these disturbances on ecosystems and predict their future states.

While constructing a "digital twin" is highly anticipated as a promising approach to this challenge, actual examples targeting coastal ecosystems remain virtually non-existent worldwide due to a severe lack of both environmental and ecological data.

In this presentation, we overcome this bottleneck by focusing on the rocky intertidal zone in Japan, where an exceptionally long-term dataset spanning over two decades across more than a hundred sites has been accumulated. Based on this rich data, we present a vision for building a rocky intertidal digital twin.

We also discuss the scalability of this model to wider geographical regions. To expand environmental data, we propose a correction model for nearshore-offshore data discrepancies. For ecological data, we plan to develop a method to extract biological information from publicly available photographs across the nation.

Furthermore, we outline the prospects for this concept to evolve beyond a purely academic proposal into a practical tool supporting socioeconomic benefits. In fisheries, it can ensure stable business management through future predictions for oysters and key seaweeds (such as Gloiopeltis and Analipus), while assisting decisions on shifting target species from declining to thriving ones. In coastal zone management, predicting biofouling organisms like barnacles can reduce port maintenance costs and enhance safety. Finally, in environmental impact assessments, this tool can contribute to corporate TNFD disclosures, future risk assessments of Marine Protected Areas (MPAs), and the selection of new candidate conservation sites.

A Coastal Ecosystem Digital Twin: Integrating Numerical Modeling and Interactive Visualization

**Takashi Nakamura*[1] (1. Institute of Science Tokyo (Japan))

Abstract: Conserving coastal ecosystems is essential for the sustainable use of the ecosystem services they provide. One serious barrier to coastal ecosystem conservation is that many people are unaware of the degraded state of these ecosystems, as underwater environments are not easily visible. Coastal ecosystem digital twins offer a means of visualizing these underwater conditions. They therefore have the potential to raise awareness of the state of coastal ecosystems and to promote conservation actions. In this context, we developed a coastal ecosystem digital twin that employs an integrated land–ocean–ecosystem model as its core engine and Cesium JS as its visualization platform.

For the integrated land–ocean–ecosystem model, we used the Soil & Water Assessment Tool Plus (SWAT+; Bieger et al., 2017) as the land model component to estimate nutrient discharge from rivers adjacent to the coastal waters. Both the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2008) and Simulating WAves Nearshore (SWAN; Booij et al., 1999), embedded in the Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modeling system (Warner et al., 2010), were used as the ocean model components. For the ecosystem component, we employed the Marine Coupled Pelagic–Benthic Ecosystem Model with Element Tracers (Marine CoMET; Nakamura et al., in prep.). To generate the initial and boundary conditions for biogeochemical parameters, we developed a machine learning model based on GLODAP, BGC-Argo, and satellite-derived chlorophyll-a products (Nakamura, in prep.).

Three sites—Shizugawa Bay, Tokyo Bay, and Sekisei Lagoon—were selected for developing the coastal ecosystem digital twin. We also developed a web application for interactively visualizing the coastal ecosystems at these three sites, built on Cesium JS and hosted on the academic cloud platform mdx I.

Impact of land mass effect on trace metal distribution: Insights from the Gough Island, South Atlantic

**Miranda Sitofile*[1] (1. Southern Ocean Carbon-Climate Observatory (SOCCO) & Stellenbosch University (South Africa))

Abstract: The Southern Ocean plays a significant role in absorbing around one-third of global carbon dioxide through the biological carbon pump and the solubility pump. The biological carbon pump system is regulated by the presence of the essential micronutrient iron, with some evidence of potential iron-manganese co-limitation. Iron and manganese are essential trace metals that have a crucial effect on the functioning of photosynthetic proteins in metabolic processes and the study of their biogeochemical cycles is of great interest. Within the Southern Ocean are regions such as island wakes, which are recognized for their high productivity, usually depicted by phytoplankton blooms, a phenomenon known as the "land mass effect", where the presence of land might contribute to increased availability of trace metals. However, the majority of observations are mostly focused on islands such as South Georgia, Crozet Island, and Kerguelen Island, whereas no observations have been made on the islands situated in the Atlantic sector of the Southern Ocean (Gough Island). This hampers our understanding of the land mass effect on significant micronutrients, as the islands differ from one another in terms of topography and the currents surrounding them, thus resulting in different distribution patterns of trace metals.

To address this gap, trace metal samples were collected during the 2023 and 2024 Gough Island cruises. These samples were collected upstream and downstream of Gough Island and were analyzed at Stellenbosch University. The data collected from these islands was utilized to examine the interplay between dissolved and particulate forms of trace metals and their distribution patterns. The chlorophyll-a distribution showed low concentrations, and furthermore, the climatology of geostrophic current velocity around the island indicated that water movement strongly influences the surrounding waters, with relatively high flow leading to continuous transport and dispersal of trace elements, weakening the chlorophyll signal typically associated with the Island Mass Effect.

The Role of General Authority of Maritme Science Researches and Aquatic life in Yemen in Research Development, promoting the blue Economy and Protecting Marine Environment by using GIS

**Mohammed Humran*[1] (1. TUOAA-GAMASR (Yemen))

Abstract: The Red Sea and Indian Ocean have become a key geostrategic arena marked by military competition and escalating maritime security threats, which increasingly endanger the marine environment through pollution and ecosystem degradation. This study applies an integrated scientific management framework supported by artificial intelligence, geographic information systems (GIS), and advanced geospatial technologies to analyze the physical and human geographical characteristics of the region. Conducted under the General Authority for Marine Sciences and Aquatic Research, the research aims to support the Yemeni General Secretariat of the Aden and Arab Seas (YGSSA) in developing a cohesive national maritime policy and modern strategic vision. A mixed geographical methodology is employed, integrating GIS and remote sensing, marine geopolitics, regional geography, and marine spatial planning. These tools enable the collection, analysis, and management of advanced spatial databases. The study draws on applied experiences from the European Union, the Indian Ocean Rim Association (IORA), and collaborative data-sharing frameworks involving TUOAA, YGS, and AGS. The research is structured across three analytical levels: first, the role of GIS in strategic data management; second, the significance of regional and international maritime partnerships, including Arab-Chinese cooperation; and third, the analysis of maritime conflicts and challenges. The anticipated outcomes include the unification of Yemen,Äôs maritime policy, the formulation of a modern maritime strategy, and the advancement of regional marine spatial planning. These efforts aim to strengthen maritime security, enhance regional cooperation, and promote sustainable marine development across the Red Sea and Indian Ocean.

Oral D4 Cross-Sector Applications & Solutions

Chair: Matthew Palmer, Haruka Nishikawa

From Digital Ocean Twin Concepts to Ocean Decade Capability: Competence Development Lessons from SEADOTs

*Harald Hasler-Sheetal[1] (1. International Council for the Exploration of the Sea (ICES) (Denmark))

Abstract: Digital Twins of the Ocean are central to the ambition of the UN Ocean Decade to make ocean knowledge more accessible, usable, and actionable for sustainable development. As the Ocean Decade-endorsed

DITTO programme moves Digital Ocean Twins from concept to capability, an important question is how these systems can become trusted resources for real-world decision-making, not only advanced technical infrastructures.

This contribution uses SEADOTs as a practical example of how competence development can support this transition. SEADOTs develops social-ecological ocean management applications by combining ocean data, ecosystem information, socio-economic data, social-ecological indicators, and scenario-based decision support. The project applies this approach in three demonstrator areas: the Norwegian North Sea, the Southern North Sea, and the Baltic Sea. These cases address challenges with wider international relevance, including offshore energy expansion, fisheries interactions, low-trophic aquaculture, climate pressures, marine spatial planning, and coastal community impacts.

From an Ocean Decade and impact perspective, the demonstrators are not only technical pilots. They are learning environments for testing how users engage with Digital Ocean Twin outputs, where interpretation becomes difficult, and what forms of training, guidance, visualisation, and policy translation are needed for uptake. The contribution highlights three competence areas: conceptual competence, social-ecological competence, and uptake competence.

The main argument is that Digital Ocean Twins become operationally useful when technical development is combined with user competence, institutional uptake pathways, and transparent communication of uncertainty and trade-offs. SEADOTs offers lessons for designing user-driven Digital Ocean Twins that support the Ocean Decade ambition of transformative ocean science for sustainable ocean governance at local, regional, and international scales.

Evidence, Impact, and Investment: Scientometric Insights to Guide Digital Twin Priorities in Offshore Wind Development

**Madhulika Bhati*[1] (1. Dalhousie University (Canada))

Abstract: Offshore wind development is expanding rapidly worldwide, offering substantial benefits in clean energy and climate mitigation. However, its growth introduces environmental and operational challenges that require strategic attention. Research from multiple jurisdictions has documented impacts such as chemical releases, electromagnetic fields (EMF), underwater noise, and disturbances to benthic habitats and species. Recognizing which impacts are significant helps decision-makers prioritize areas for digital twin solutions, especially when some effects may be temporary or localized.

Digital twin technology is increasingly recognized as a promising tool for addressing environmental challenges like underwater noise and habitat disturbance by enabling real-time monitoring, predictive modeling, and scenario testing. However, digital twins remain capital-intensive, requiring significant investment in data infrastructure, sensors, modeling capabilities, and long-term maintenance. Identifying which environmental or operational challenges-such as noise pollution or habitat loss-should be prioritized for digital-twin-based solutions is essential, especially in early pilot deployments.

This study provides a high-level yet comprehensive overview of the evidence on environmental stressors associated with offshore wind farms. As one of the first studies to integrate both academic and grey literature such as PhD theses, industry reports, and policy documents, it maps the global research landscape by identifying leading countries, institutions, and authors in this field. Through thematic analysis, it offers concrete insights into how offshore wind development affects the marine environment. By synthesizing global findings, the study examines whether reported environmental effects are supported by evidence. This distinction is crucial: if certain impacts are shown to be minimal or short-term, digital twin development may not need to prioritize those areas. Conversely, if strong causal relationships or persistent effects are identified, they become strong candidates for digital-twin-enabled monitoring and mitigation. Clarifying which environmental risks are well supported and which remain uncertain helps build trust and guides strategic, evidence-based decisions for industry, researchers, and policymakers.

How can we make usable and useful DTOs for local communities facing large offshore developments? Tailoring DTO applications to the needs of a small island community

**Lara Veylit*[1] (1. SINTEF Ocean (Norway))

Abstract: Digital twins of the ocean (DTOs) are increasingly proposed to support sustainable management of marine and coastal systems by offering users digital representations of ocean systems. Thus far, the DTO community has largely focused on challenges related to technological implementation rather than on the usability of tools by end users. Here, we discuss how in a demonstration use case we tailored the development of a regional DTO by co-designing solutions with end users. Our use case focuses on developing digital tools for stakeholders living near or at Norway's smallest municipality, Utsira. This small island community faces the development of the world's largest floating offshore wind park in its local waters. In meetings and discussions with stakeholders, they voiced concerns about how the development will contribute to visual and sound pollution. In addition,

stakeholders voiced interest in the development of a digital tool that can help them understand what potential social, economic, and ecological impacts the offshore wind park will have on the community. To meet these needs, we are co-designing a decision support dashboard in which local stakeholders can simulate social, ecological, and economic impacts of different wind development decisions using relevant “what-if” scenarios. These scenarios are modelling using a novel fuzzy cognitive mapping approach in which key stakeholders define model variables and assign values to links, which are re-parameterized over time through a democratized, app-based approach. As part of this dashboard, we have developed an immersive Virtual Reality (VR) experience to simulate different proposed configurations of the wind park from an iconic, high point of the island. In our presentation, we would like to demonstrate our DTO and our stakeholder needs-first approach.

SOCIB MeDITTO: User-Centred Regional Digital Twin Ecosystem for Cross-Sector Coastal and Ocean Decision-Making

**Camilo Melo Aguilar* (1. SOCIB (Spain))

The Mediterranean Sea provides a unique "miniature laboratory" for Digital Twins of the Ocean (DTOs), where climate change, extreme events, and human pressures intersect with vulnerable ecosystems and socioeconomically vital activities, challenging marine protection, coastal resilience and a sustainable Blue Economy. Addressing these challenges requires transforming observations and models into user-centred solutions that turn complex science into actionable knowledge for real-world decisions. DTOs offer this potential, yet translating technological capabilities into fit-for-purpose, sustained regional services remains challenging.

Within the SOCIB2030 strategic framework, the Balearic Islands Coastal Observing and Forecasting System (SOCIB) is developing MeDITTO (Mediterranean Digital Twins of the Ocean), a regional prototype DTO ecosystem integrating multi-platform observations, numerical models, what-if-scenarios (WiS), artificial intelligence and environmental indicators. Working backwards from user needs through co-design, MeDITTO is designed to translate shared capabilities into cross-sector decision-support services. A conversational interface is being developed to provide natural-language access to scientific evidence, data, models and scenarios, complemented by interactive maps and visualisations tailored to user expertise.

We present three complementary prototypes progressing from situational awareness ("What now?") to prediction ("What next?") and scenario exploration ("What if?"). MeDITTO-PROTECT integrates near-real-time and historical observations, models and indicators to support monitoring and adaptive management of marine protected areas, demonstrated in Cabrera National Park. MeDITTO-ALERT combines real-time met-ocean

observations and numerical modelling for meteotsunami forecasting and early warning in Ciutadella Harbour. Finally, MeDITTO-ADAPT integrates observations, climate projections and predefined WiS to assess coastal flooding and erosion and explore adaptation strategies at Cala Millor.

Together, they illustrate the framework through which MeDITTO aims to serve diverse users, sectors and decision timescales within a shared regional DTO ecosystem. MeDITTO explores a transferable pathway from co-designed prototypes towards sustained operational services, with interoperability and continuous user validation guiding their progressive development and future integration into European and global DTO initiatives.

ATALAYA: A national-scale digital twin for climate-resilient coastal management in Spain

**Moises Alvarez* (1. University of Cantabria (Spain))

Abstract:

Towards a Digital Twin for Search and Rescue Operations to Enhance Shipping Safety in the Canadian Arctic

**Floris Goerlandt*[1] (1. Dalhousie University (Canada))

Abstract: Digital Twins of the Ocean (DTOs) increasingly provide integrated representations of oceanographic, sea-ice, and atmospheric conditions to support monitoring, forecasting, and decision-making. While these platforms offer detailed environmental intelligence, they currently provide only limited insight into the operational implications of those conditions for maritime safety and emergency response. This presentation outlines a vision and modeling progress for extending Digital Twin Ocean capabilities towards a Digital Twin for Search and Rescue (SAR) operations in the Canadian Arctic.

The proposed framework couples environmental information from ocean, sea-ice, and weather models with operational simulation models that estimate SAR system performance. Building on recent work towards understanding Maximum Expected Time to Rescue (METR) in the Canadian Arctic, the framework integrates probabilistic models of maritime and helicopter response operations that account for vessel availability, ice conditions, weather, asset capabilities, and operational constraints. These models estimate spatially and temporally varying response times across the Canadian Arctic, providing a dynamic representation of SAR capability rather than environmental conditions alone.

Within a Digital Twin architecture, these models form an operational layer that continuously interprets evolving environmental conditions in terms of expected emergency response performance. Such a system would support strategic preparedness, risk-informed voyage planning. Beyond monitoring current conditions, the framework enables predictive analyses that translate environmental forecasts into actionable estimates of rescue capability.

The presentation discusses the proposed Digital Twin architecture, the underlying modelling components, and the research challenges associated with integrating heterogeneous environmental and operational models into an adaptive decision-support capability for improving shipping safety in the Canadian Arctic.

Oral A5 Ocean Digital Twins, Data Architectures and AI-Enabled Approaches

Chair: Philipp S. Sommer, Tomoki Tozuka

Second Cooperative Study of the Kuroshio and its Adjacent Region (CSK-2)

**Akira Nagano[1]* (1. JAMSTEC (Japan))

Abstract: Our knowledge of the Kuroshio is mostly based on data obtained in the international Kuroshio observation programme during 1965-1977, the Cooperative Study of the Kuroshio and Adjacent Regions (CSK). Most of ongoing long-term observations in the western North Pacific have been initiated since the CSK era. In addition, the activity of the CSK led to the establishment of WESTPAC as a branch of UNESCO/IOC. To take our current understanding of the Kuroshio to the next level such that it can benefit society, we have initiated the successor of the CSK, the CSK-2, since 2022 as a UN Decade Action project of UN Decade of Ocean Science for Sustainable Development (UNDOS). The CSK-2 contributes to UNDOS with two objectives: to elucidate the relationship between the Kuroshio Current and climate and weather, and its impact on marine ecosystems. As of now, 14 projects from 6 countries participate the CSK-2. To achieve the goals, we share information on progresses, discuss future cooperation and direction, and solicit new proposals. Stimulating research activities across the themes due to data sharing and gaining a deeper understanding of the Kuroshio and surrounding current systems due to data assimilation are future tasks and are working on them. In addition, we are eager to enhance

collaborative research with numerical modeling and prediction communities. In this presentation, we introduce the present efforts of the CSK-2 for further collaboration with ocean modeling and prediction communities.

Federated Data Architectures for Environmental Evidence: Observations from Offshore Energy Programmes and the DAFNI Fellowship

*Thomas Mansfield[1] (1. Plymouth Marine Laboratory (UK))

Abstract: The increasing scale and complexity of environmental evidence generated through offshore energy programmes presents significant challenges for data interoperability, discoverability, and reuse. While FAIR (Findable, Accessible, Interoperable and Reusable) data principles are widely recognised, their implementation across distributed projects, organisations, and disciplines remains inconsistent. This fragmentation can limit the integration of environmental datasets into digital research infrastructures and reduce their value for digital twins, decision-making and policy development.

This paper presents findings from a DAFNI (Data & Analytics Facility for National Infrastructure) Fellowship investigating how federated data architectures can support improved environmental data management across UK offshore energy programmes. Drawing on experiences from the EQUIFy, VALMAS and AtlantiS projects, the research examines technical, organisational and workflow-related barriers to interoperability, with a particular focus on metadata practices, data onboarding, and cross-community collaboration.

The study adopts an iterative co-design approach involving stakeholders from academia, industry, government and environmental data centres. Evidence is collected through a series of workshops, structured observations and engagement activities embedded within existing project and community events. These insights are synthesised to identify recurring challenges and emerging good practices for enabling federated approaches that allow communities to maintain local ownership of data while supporting system-wide integration and reuse.

The work demonstrates how federated FAIR workflows can enhance the readiness of environmental datasets for integration with platforms such as DAFNI, improving reproducibility and supporting national-scale digital infrastructure initiatives. It also explores the role of digital research environments in bridging the gap between technical standards and operational practice.

These interim findings provide practical recommendations for digital twin communities seeking to improve the interoperability and long-term value of environmental evidence. More broadly, the work highlights how federated

architectures can strengthen the digital foundations needed to support resilient, evidence-driven decision making in the transition to sustainable offshore energy systems.

Understanding and Predicting Ocean–Climate Variability through Dynamical Models and Data-Driven Approaches

*Tomoki Tozuka (1. The University of Tokyo (Japan))

Abstract: Ocean–climate variability arises from complex interactions across a wide range of spatial and temporal scales, posing fundamental challenges for both physical understanding and prediction. In this presentation, I will highlight our recent efforts to address these challenges using complementary dynamical and data-driven approaches. First, long-term, high-resolution climate model simulations provide "virtual oceans" in which ocean–atmosphere interactions and rare events can be investigated beyond the limitations of the observational record. Examples include interactions between the Kuroshio Extension, the atmosphere, and the tropical Pacific, as well as the dynamics of rare Kuroshio large-meander events. Second, reduced-order data-driven models provide an efficient framework for exploring climate variability and its underlying interactions. Using a cyclostationary linear inverse model of the Indo-Pacific climate system, we examine how changes in interbasin coupling alter the characteristics of El Niño–Southern Oscillation, illustrating how data-driven models can be used not only for prediction but also for hypothesis testing through virtual experiments. Finally, neural-network-based prediction of winter temperature variability around Japan demonstrates how artificial intelligence can help identify important predictors and motivate subsequent investigation of the underlying physical mechanisms. Together, these studies illustrate the complementary strengths of dynamical models, reduced-order models, and artificial intelligence. Integrating these approaches with observations may provide a pathway toward ocean digital twins that not only reproduce and predict ocean states, but also facilitate exploration and understanding of the processes governing ocean–climate variability.

OceanDataStore: Cloud-Native Ocean Data for Research, Collaboration and Scalable Science.

*Jon Blower[1], Oliver Tooth[1] (1. National Oceanography Centre (UK))

Abstract: The growth of high-resolution ocean models, sustained observing systems and machine learning applications is transforming marine science, but also bringing new challenges in how large datasets are stored, maintained and distributed. OceanDataStore is an open-source library developed to streamline writing, updating and accessing ocean model and observational datasets by leveraging cloud object storage, enabling more scalable and accessible ocean science throughout the research community.

Developed by the National Oceanography Centre (NOC), OceanDataStore has evolved into a production-ready platform serving both data producers and data consumers. For ocean modellers, the library provides command-line and scripting interfaces to transform archival datasets (e.g., netCDF) into Analysis-Ready Cloud Optimised (ARCO) formats, including version-controlled data cubes. For users of ocean data, the accompanying OceanDataCatalog enables dataset discovery and access using Spatio-Temporal Asset Catalog (STAC), allowing researchers, students and stakeholders to access public ocean datasets seamlessly across local and high-performance computing environments.

Developed through the AtlantiS National Capability programme and now integrated into NOC's global ocean modelling pipelines, OceanDataStore has transformed how we distribute ocean model outputs, including through the Earthmover Data Marketplace. This work provides a foundation for future digital services that prioritise data accessibility, accelerate multidisciplinary research, and broaden access to strategic ocean datasets across the wider NERC community.

JAXA's Earth Observation Data Infrastructure for Digital Twins

*Kei Oyoshi[1] (1. Japan Aerospace Exploration Agency (JAXA) (Japan))

Abstract: Earth observation satellite data provide a fundamental data infrastructure for digital twins by archiving the state of the Earth from the past to the present and supporting change detection, understanding current situation, and future prediction. JAXA develops and operates a wide range of Earth observation satellites and has continuously advanced the observation, calibration/validation, archiving, and distribution of satellite data.

To facilitate the development of digital twins and AI-driven applications, JAXA has been exploring scalable data management and dissemination approaches, including cloud-native architectures and API-based access services. These efforts are expected to promote wider adoption of Earth observation data, expanding the user community beyond traditional Earth science researchers to include private-sector stakeholders developing operational solutions and value-added services.

Recent advances in cloud computing enable large-scale analysis of archived satellite data in combination with numerical models and AI technologies, supporting both research and service development. Furthermore, the integration of satellite observations with measurements from ground-based sensor networks is accelerating the creation of practical decision-support services.

This presentation highlights JAXA's recent activities, technological advancements, and emerging applications in satellite data infrastructure, generative AI, foundation models for Earth observation data analysis, and integrated Earth observation systems designed to contribute to digital twin ecosystems.

Developing an Observation-Constrained Ocean Digital Twin: EnOI Data Assimilation for the GEPSv3 Coupled Prediction System

**Lalu Mantigi Wana Paksi* (1. Academia Sinica X National Taiwan University and BMKG (Taiwan))

Abstract: Accurate ocean state estimation is crucial for developing operational Digital Twins of the Ocean and coupled climate prediction. We've created an Ensemble Optimal Interpolation (EnOI) system for the Taiwan Multi-scale Community Ocean Model (TIMCOM), which is the ocean component of Taiwan's Global Ensemble Prediction System version 3 (GEPSv3). This system operates in a cycling, weakly coupled configuration and provides ocean initial conditions for subsequent coupled forecasts. It assimilates diverse observations, including Argo temperature and salinity profiles, World Ocean Database in situ profiles from moorings, XBTs, CTDs and OSDs, and NOAA OISST sea-surface temperatures. A 100-member NMC-method ensemble is used for surface assimilation, followed by a demeaned 250-member year-to-year ensemble for in situ assimilation.

We evaluated the system using an observing system experiment with four configurations: full assimilation, assimilation without Argo, SST-only assimilation, and a no-assimilation control. An independent 20% subset of Argo profiles from the SynObs ArRef dataset was withheld from all experiments for verification. Full assimilation significantly reduced the temperature RMSE by 7.8% at depths of 100–300 metres and 4.4% at 300–750 metres, with no statistically significant degradation at any depth. This improvement is particularly notable in the upper thermocline. However, below 300 metres, attributing the improvement to individual observing systems remains uncertain due to sparse independent profile coverage.

Following the SynObs Flagship protocol, TIMCOM achieved a 0.710 °C RMSE over the 0–50 metre depth range, comparable to MOVE-G3F, FOAM, GIOPS and ORAS6. These results demonstrate the effectiveness of the observation-assimilation component in a global coupled prediction system and support further development towards an operational, observation-constrained ocean digital twin.

Oral B5 Coastal and Marine Ecosystems, Blue Carbon and Regional Ocean

Chair: Konobu Kimura, Fadli Syamsudin

Development of a digital twin for estimating blue carbon sequestration by macroalgal beds from the coastal areas of Hokkaido to the open ocean

*Hiromichi Igarashi[1] (1. Japan Agency for Marine-Earth Science and Technology (Japan))

Abstract: An accurate estimate of the potential distribution of blue carbon sequestration enables us not only to understand the processes of transport and its fate but also to evaluate the amount of stored carbon in the deep sea. We are now developing a digital twin framework for quantifying blue carbon sequestration by seagrass and macroalgal beds from the coastal waters around Japan by integrating field observation of seagrass and macroalgal production and export, oceanographic observation by research vessels, chemical analyses of sediment and water samples, decomposition experiments for tracing the fate of organic carbon derived from seagrasses and macroalgae, and ocean numerical model simulation. In this study, we developed a numerical simulation model for estimating blue carbon sink by macroalgal beds from the coastal area of Hokkaido Island to the open ocean. A 3-dimensional particle tracking technique was applied to transport of kelp (Saccharina longissima) from the coastal area to the open ocean, taking into account decomposition and size reduction processes, as well as the associated change of sinking velocity. As ocean environments, we used daily 3-dimensional (zonal, meridional and vertical) current velocity fields derived from an historical run of Future Ocean Regional Projection (FORP)-JPN02 (Ver.4) datasets produced by JAMSTEC and MRI-JMA. The horizontal resolution of FORP-JPN02 is 1/33*1/50 degree with 60 vertical levels, which can provide realistic fields of 3-dimensional ocean circulation and environmental structures around Japan coastal area to the open ocean. The result of our experiments suggests that a part of the kelp drifted from coastal area of Hokkaido is transported offshore and trapped within submarine canyon in several days and sinks rapidly to the deep sea. And not only DOC but also decomposed DIC rapidly transported into the deep-sea could contribute to long-term blue carbon sequestration.

Marine Excess and Stressor Occurrences: A Digital Twin Perspective for Ocean Health, Biodiversity and Coastal Stewardship

*Katja Breitenfelder[1] (1. Fraunhofer Institute for Building Physics IBP (Germany))

Abstract: Coastal and marine environments are increasingly shaped by substance-based occurrences linked to climatic change, extreme events and human activity. Episodic sediment surpluses, extensive macroalgal accumulations, polymers and mixed biogenic fractions alter ecosystem functioning, reduce biodiversity and intensify pressure on coastal communities and infrastructure. These developments expose a critical scientific need to determine when such occurrences act as ecological stressors, when they represent temporary excess, and when

they may be suitable for safe removal or circular utilisation. At present, no unified methodology exists to define, classify or evaluate such occurrences across their physical, ecological and governance dimensions.

Digital Twins of the Ocean (DTOs) provide the computational environment in which these elements can be integrated. Their capacity to combine multi-source observations with dynamic ocean modelling provides a foundation for multi-criteria assessment logic that reflects regional ecosystem characteristics. This contribution presents a conceptual framework that maps the required data integration, modelling pathways and decision criteria needed to embed excess and stressor occurrences within digital-twin architectures.

The framework synthesises existing European and international indicator catalogues, parameters and ecological typologies to structure the analytical workflow: from initial observation data and hydrodynamic transport modelling to assessing ecological carrying capacities and delivering transparent information for decision-makers and downstream material pathways. To enable multi-criteria decision support, it specifies how monitoring pipelines, predictive transport models and impact functions must be interlinked.

This work establishes the analytical foundations required for developing region-specific criteria, modelling components and governance protocols within evolving ocean-twin infrastructures, supporting a gradual shift towards science-based evaluation, informed decision-making and strengthened coastal stewardship.

Blue discovery 2.0: the development of Self-made AI-USV and Multispectral UAV to Investigate Seagrass Meadow and DO Monitoring in Penghu Archipelago, Taiwan

**Cheng-Hao Lu*[1] (1. National Penghu University of Science and Technology (Taiwan))

Abstract: Seagrass meadows serve as vital blue carbon ecosystems and critical coastal habitats, yet globally and locally, there remains a lack of an efficient, low-cost monitoring system capable of large-scale and repetitive surveys. Traditional seagrass assessments heavily rely on manual intertidal wading or boat-based scuba diving. These conventional methods suffer from severe operational bottlenecks: limited air tank capacity, strict diving safety constraints, and brief effective working windows. Consequently, surveying deep or expansive seagrass beds is exceptionally difficult, carrying escalating human risks and prohibitive costs as depth increases.

To overcome these constraints, this study introduces an innovative, cost-effective, and non-invasive integrated framework that pairs a multispectral Unmanned Aerial Vehicle (UAV) with a custom-built Unmanned Surface Vehicle (USV). The self-made USV represents a next-generation scientific research vessel equipped with multi-channel communication systems, high-precision RTK GNSS positioning, bathymetric mapping capabilities, and

multi-parameter water quality sensors for real-time dissolved oxygen (DO) and gas monitoring. Crucially, the USV features an onboard edge-computing AI model trained for high-accuracy, real-time seagrass identification.

Field deployments conducted across the Penghu archipelago demonstrate the successful synergy of airborne and surface automation. The multispectral UAV provides expansive spatial overviews, while the AI-USV performs close-range, high-resolution under-surface verification, bathymetric profiling, and localized water quality mapping. This integrated approach successfully generated precise spatial distribution maps of seagrass coverage alongside synchronized DO and environmental data. Supported by systematic, long-term robotic surveys, this framework delivers an empirical baseline for marine habitat management and ecological restoration strategies. While the initial development focuses on establishing foundational data for blue carbon accounting in Taiwan, the ultimate trajectory of this platform is to scale into a universal, high-efficiency tool for monitoring broader nearshore ecosystems.

Towards a Digital Twin Framework for Monitoring Marine Heatwaves and Ocean Variability in the Bay of Bengal

*Sourav Sil[1] (1. Indian Institute of Technology Bhubaneswar (India))

Abstract: The Bay of Bengal is one of the most dynamic regions of the Indian Ocean, where ocean circulation, marine heatwaves (MHWs), and tropical cyclones interact across a wide range of spatial and temporal scales. Continuous monitoring and improved prediction of these processes are essential for climate adaptation, disaster preparedness, and sustainable ocean management. The concept of a Digital Twin of the Ocean provides an opportunity to integrate diverse ocean observations and numerical models for a comprehensive representation of the evolving ocean state.

In this study, we present an integrated framework based on our recent research on marine heatwaves, ocean circulation, and cyclone–ocean interactions in the Bay of Bengal. Long-term analyses using satellite, in-situ observations and reanalysis (ORAS5 and JCOPE) show an increasing occurrence of marine heatwaves and highlight the role of upper-ocean thermal conditions in regulating their evolution. Evaluation of high-resolution sea surface temperature products demonstrates their improved capability to resolve coastal thermal variability, which is critical for monitoring marine heatwaves. Data-driven pattern recognition has also been used to identify the dominant modes of surface circulation and their seasonal and interannual variability, providing a simplified representation of the complex ocean dynamics. Furthermore, analyses of recent tropical cyclones indicate that anomalously warm upper-ocean conditions can create a favourable environment for cyclone intensification.

These studies demonstrate the importance of integrating observations, numerical modelling, and data-driven analysis to better understand coupled ocean–atmosphere processes. Such an integrated approach provides essential building blocks for developing regional Digital Twins of the Ocean, enabling improved ocean monitoring, forecasting, and decision support for climate resilience and coastal hazard management in the Bay of Bengal.

Dendê Platform - Coastal Ocean Observing platform for Community-Led Monitoring

**Emilio Heyser Ojeda*[1] (1. Oceanus Data Analytics (Mexico))

Abstract: Coastal communities worldwide face accelerating environmental change from climate change, pollution, and pressure on its marine ecosystems, however timely, locally relevant ocean observations remain insufficient. Existing traditional observing systems, which have significant scientific value, are often costly, technically complex, or limited in coastal coverage, leaving persistent gaps between scientific data, local knowledge, and effective coastal management. Dendê, an international volunteer-led initiative born from the All-Atlantic Intergenerational Hackathon 2026, addresses this gap by developing a cost-effective, community-deployable ocean observing platform. Rather than building a new standalone affordable sensor, Dendê integrates accessible technologies, open-source software, standardized monitoring protocols, and intuitive, multilingual data visualization tools, into a unified, interoperable platform designed for community-led implementation.

The project pilot sites in coastal communities are planned for Ghana and Brazil, with the expectation to deploy systems to monitor temperature, salinity, turbidity, and community-based environmental observations. Local participants will be trained to deploy, maintain, and interpret the data in the platform, with technical performance, data quality, and usability evaluated to refine a scalable, transferable model for community-led coastal observing. Data generated through Dendê is structured for integration with broader ocean data systems, increasing its value for researchers, communities, and decision-makers while expanding observing capacity in historically underrepresented regions.

Dendê is building a scalable framework of deployment workflows, training resources, quality assurance practices, and visualization tools adaptable across coastal regions globally. Supported by an interdisciplinary, early-career core team and advisors from around the world, Dendê demonstrates how accessible, standards-aligned observing platforms can strengthen the human and technical foundations of Ocean Digital Twins, turning distributed

community observations into interoperable, decision-ready data that complements existing networks and advances more inclusive, resilient ocean governance.

Growth, physical loss, and detrital-release timing in Saccharina longissima kelp beds of eastern Hokkaido, Japan, from long-term validation to future climate projection

*Ahmed Eladawy[1] (1. Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Japan))

Abstract: Kelp forests are highly productive, yet their contribution to coastal carbon cycling depends not only on standing crop but also on when biomass is detached and where it may be transported. We developed a process-based, station-scale model for the long-blade kelp Saccharina longissima across its confirmed range in eastern Hokkaido (Kushiro–Nemuro), Japan. The model extends a biomass–internal quota formulation with carbon-reserve bookkeeping and a current-driven erosion term used as a detrital-release proxy. It is driven by daily temperature, currents, nitrate, and surface shortwave irradiance from the high-resolution FORA-JPN60 reanalysis and the FORP-NP10 nutrient product over 1991–2020, then extended to RCP2.6 and RCP8.5 scenario forcing for 2006–2100. Validation used 963 Habomai blade wet-weight measurements collected at 52 monitoring sites over 14 years (May–June, 2001–2014), summarized as annual May and June medians. The model reproduces the annual median biomass signal more clearly in June (annual-median r = 0.48, RMSE ≈ 25 g DW) than in May (r = 0.39, RMSE ≈ 27 g DW). Regionally, group-median peak biomass was high in the late 1990s (~149–150 g DW), fell to ~55–72 g DW at the 2014 minimum, and recovered to ~123–133 g DW after 2016. These shifts tracked Jun15–Jun15 light and temperature anomalies, while current-driven loss mainly affected years when strong flow coincided with high standing biomass. In the future ensemble, late-century peak biomass remains high under RCP2.6 (about 145 g DW per thallus) but falls sharply

under RCP8.5, from roughly 47 g DW in the eastern group to 11 g DW in the western Kushiro group. Late-century standing biomass totals ~3.3×10^4 t DW under RCP2.6 against ~4.3×10^3 t DW under RCP8.5. We therefore provide the source strength, timing, and location of modeled detrital release needed to couple kelp production to transport-and-fate models that can test carbon export and sequestration.

Oral C5 A Federated Ocean-Earth Digital Twin Ecosystem: Connecting EDITO, Destination Earth and Open Standards

Chair: Bente Lilja Bye, Marco Oliveira

Intro: From project twins to an ecosystem of twins

*Bente Lilja Bye[1] (1. BLB (Spain))

Abstract: Digital Twins of the Ocean are moving from individual research demonstrators towards operational, distributed and increasingly interconnected infrastructures. The completion of the ILIAD Digital Twins of the Ocean project provides an opportunity to examine which components of local and thematic digital twins can persist, travel between infrastructures and contribute to a wider ecosystem of Digital Twins of the Earth.

ILIAD demonstrated a federated, standards-based approach encompassing local and thematic digital twins, interoperable data and services, semantic harmonisation, portable analytical workflows and links to the European Digital Twin Ocean infrastructure. The challenge now is to move from interoperability within individual initiatives towards interoperability between digital-twin ecosystems.

This session connects ILIAD results and their continuation with EDITO, the Destination Earth Digital Twin Engine, IEEE P3501 and related OGC standardisation, and emerging European initiatives including SEADOTs and EOSC-Marine. Short contributions will examine semantic interoperability, portable application workflows, infrastructure federation, cross-domain Digital Earth standards and pathways for onboarding local and regional twins into persistent infrastructures.

Rather than presenting individual projects, the session asks a common question: **what is the minimum interoperability contract that allows a local Digital Twin of the Ocean to become a reusable component of a European and ultimately global federation of Digital Twins?** The concluding discussion will identify

practical requirements and opportunities for collaboration between DITTO, European initiatives and international standards communities.

What Survives ILIAD? From 22 Local and Thematic Twins to Reusable Building Blocks

*Arne Jørgen Berre[1] (1. SINTEF (Norway))

Abstract: ILIAD developed and demonstrated 22 local and thematic Digital Twins of the Ocean across a wide range of marine applications. Beyond the individual pilots, one of the project's main legacies is the set of reusable architectural principles, data-space concepts and interoperability mechanisms that can support future digital-twin ecosystems.

This presentation will highlight what can be taken forward from ILIAD: its federated architecture, common Digital Twin pipeline, interoperable data and services, semantic approaches, portable analytical components and experience with distributed data ownership and access.

The focus is on the lessons learned from moving from individual pilots toward a more connected ecosystem of Digital Twins of the Ocean, and on which building blocks, modules and design principles can be reused in future regional, European and global DTO initiatives.

Making the analytics travel: Iliad application packages from local twins to EDITO

*Marco Oliveira[1] (1. INESC TEC (Portugal))

Abstract: Many ocean Digital Twin applications begin as standalone analytical models, research scripts or locally deployed workflows configured for a specific computing environment. These implementations produce valuable scientific results, although they are frequently difficult to discover, reproduce, transfer between infrastructures, integrate into operational systems, replicate, or deploy in other Digital Twin infrastructures

The ILIAD project addressed this challenge by extending the concept of the Application Package defined in the OGC Best Practice (BP) for Earth Observation Application Packages. That BP specifies how applications can be described, packaged with their dependencies, and deployed on exploitation platforms, using technologies such as the Common Workflow Language, containers, and the OGC API – Processes. Building on this foundation, ILIAD refined the packaging guidelines for ocean and Digital Twin workflows and developed a standards-based processing service layer supporting the full application lifecycle.

The resulting architecture combines portable workflow descriptions and containerised tools with registries and execution services. OGC API – Records supports the registration, discovery and retrieval of Application Packages,

while Processes API supports their deployment and execution as interoperable processing services. The same packaged workflow can therefore be prepared for execution across personal computers, cloud systems, clusters and HPC environments.

ILIAD also explored interoperability with broader European Digital Twin infrastructures. A translation tool was developed to transform suitable CWL-based packages, facilitating their deployment as processes on platforms such as EDITO. Several ILIAD workflows were translated and deployed using this approach, enabling the use of the European infrastructure as the computing backbone for Local DTs, while also revealing practical constraints related to workflow complexity, storage models, and infrastructure-specific requirements.

The main contribution is a practical transition pathway from research code to an operational, reusable service. The presentation will discuss architectural decisions, implementation experiences and remaining challenges related to portability, reproducibility, security, infrastructure heterogeneity and operational sustainability.

Acknowledgements: This work has received funding from the European Union's Horizon Europe Research and Innovation Programme under the Grant Agreement No. 101136903, through the project INESCTEC.OCEAN - Centre of Excellence in Ocean Research and Engineering (HORIZON-WIDERA-2023-ACCESS-01 - Teaming for Excellence) and National Funds from the Portuguese Republic.

Building Blocks for AI-Ready Ocean Data: An Interoperability Architecture for Digital Twins of the Ocean

**Robert Atkinson*[1] (1. OGC (Germany))

Abstract: A digital twin of the ocean is only as trustworthy as the data flowing through it. Ocean information arrives from many communities, from physics and biology to fisheries and socio-economics, in different structures, described with different metadata, and named with different vocabularies. Forcing all of it into one common schema fails, because it either loses what each community depends on or grows into a superset no one can validate. And as digital twins increasingly rely on automated and AI-driven analysis, a further problem appears: a machine arriving at a dataset cannot reliably tell what it means, how good it is, or how it was produced, so it guesses, and confident, plausible, unaccountable answers are exactly what a decision-support twin cannot afford.

This talk presents a practical answer developed openly within OGC and its community. Interoperability requires handling four things together: APIs, schemas, semantic models, and vocabularies, and above all a way to declare how they join up. Rather than another standard, the approach is an architecture of composable, independently

testable building blocks that bind structure, discovery, meaning, and provenance into machine-actionable artifacts. Meaning is declared and resolvable, provenance is assembled step by step, and correctness is checked automatically. The result is data that is interoperable, auditable, and AI-ready, whose lineage a person or an agent can trace back to the observation behind it.

Illustrated with marine worked examples, the talk introduces the Oceans Information Model, used as the basis for interoperability in the ILIAD Digital Twin of the Ocean. It shows how the same building blocks can make ocean data reusable across borders and platforms by reusing common standard models, and how declared meaning reduces the risk of AI hallucination. It is offered as a shared basis for discussion, consolidating recent pilots and testbeds rather than proposing a single mandate.

Digital Ocean Twins as an Emerging Tool for Advancing Ocean Literacy: Opportunities and Challenges

**Lara Veylit*[1] (1. SINTEF Ocean (Norway))

Abstract: Digital twins of the ocean (DTOs) have the potential to be an ideal digital tool to enhance ocean literacy due to their interactive capabilities and integration of data from multiple disciplines. However, DTOs are vulnerable to misuse and to be misinterpreted by users, which could hinder users' ability to act as responsible ocean stewards. In this work, we assess whether DTOs can be useful affective learning tools for advancing ocean literacy, considering the possible mismatch between the technological complexity of DTOs and the needs of non-technical end users. We particularly highlight the importance of co-designing DTOs for explicit user groups in collaboration with experts from a range of fields, including Human-Computer Interaction (HCI) researchers and information designers, to develop effective and accessible user interfaces. We cautiously conclude that DTOs can be useful affective learning tools for improving collective ocean literacy via attitudinal change and can facilitate reaching high-level policy objectives (per the goals of initiatives such as the EU DTO and the UN Ocean Decade) when user needs (such as those of decision makers) are prioritized.

If Odysseus had a DTO: From Iliad practices to digital twin Earth development standards

**Sigmund Kluckner*[1] (1. IEEE France / self (France))

Abstract: Digital Twins of the Ocean (DTOs) leverage advances in computing and data storage to improve ocean research and management through enhanced simulations, monitoring, and predictions. DTOs are an emerging field, with diverse approaches resulting in unique implementations. DTOs are currently developed for different localizations, time and geographic resolutions, and goals; their common denominator is the goal to support decision making through Digital Twin enabled simulations on 'what-if' scenarios.

Standardization and best practices enable interoperability and comparability across DTO systems, connecting data storage, models, simulation tools, and user interfaces from different domains. This enables the creation of a trusted ecosystem with consistency, accuracy, and reliability while still allowing proprietary innovation. Common data formats, protocols, metadata standards, and vocabularies reduce redundancy, minimize integration costs, and promote scalability. DTOs can then incorporate more variables or complex interactions without sacrificing quality, remain adaptable to new technologies, and support transparency and reproducibility.

Clear standards and practices prevent fragmented efforts and accelerate global DTO adoption, improving decision-making for environmental and societal resilience. They streamline processes and ensure interoperability across technical and human layers and can shorten implementation timelines and improve communication among engineers and stakeholders.

The EU-funded Iliad project aimed to integrate localized DTOs for sectors like aquaculture, oil spill, offshore wind, or citizen science. Each pilot combines domain-specific engineering with digital systems practices, which were documented in the “Iliad Compendium”. Newly developed practices and standards from DTO projects are encouraged to be documented and shared with the broader digital twin and ocean research communities, for example on the Ocean Best Practices System OBPS or in professional societies like IEEE Oceanic Engineering Society.

Standards and best practices are essential for DTO development, ensuring interoperability, scalability, and trust. Initiatives like IEEE P3501 exemplify efforts to align practices globally, accelerating innovation and supporting resilient ocean management.

NorDITO: Building Norway's digital twin of the ocean.

**Konstantinos Christakos*[1] (1. Norwegian University of Science and Technology (Norway))

Abstract: NorDITO is developing a national framework for a Norwegian Digital Twin of the Ocean by connecting heterogeneous ocean observations, Earth observation, operational models, analytical services and digital infrastructures through interoperable interfaces and reusable components. The initiative addresses the challenge of moving from distributed data and modelling capabilities towards a more integrated system-of-systems that can support operational and decision-oriented marine applications. Particular emphasis is placed on standards-based interoperability, metadata and semantics, APIs, reusable computational workflows and portability across infrastructures. NorDITO also explores how national capabilities can connect with the wider European Digital Twin of the Ocean ecosystem, including EDITO and related digital-twin initiatives, while

retaining the flexibility needed for national and regional applications. The presentation will outline the emerging architecture, key technical building blocks and priority use cases, and discuss how Norway's strong ocean-observing and modelling capabilities can contribute to a scalable and federated DTO ecosystem.

Discussion: What is the minimum interoperability contract for a federated Digital twin of the ocean

*Bente Lilja Bye[1] (1. BLB (Spain))

Oral D5 Corss-Sector Applications & Solutions

Chair: Klaas Deneudt, Michio Kawamiya

Integrating Social-Ecological Systems into a Digital Twin for Multi-Use Offshore Wind and Aquaculture in the German Bight

*Matthias Daniel Berg[1] (1. Helmholtz-Zentrum Hereon (Germany))

Abstract: The German Bight is undergoing a major transition towards a sustainable Blue Economy. A key part of it is the development of offshore wind farms (OWF) with the potential of multi-use with lower trophic aquaculture (LTA), which can enhance resource efficiency while contributing to food production, ecosystem services, and climate-neutral economic growth. However, the success of such multi-use concepts depends on complex interactions between environmental conditions, ecosystem dynamics, governance structures, and stakeholder decisions.

This study deploys the Social-Ecological Systems (SES) framework of Ostrom and McGinnis within a Digital Twin approach. The SES framework provides a structured representation of interactions among ecological resources, infrastructure, governance systems, and resource users, while the Digital Twin enables the integration of observations, numerical models, indicators, and scenario-based decision-support capabilities within a common operational environment.

A series of "what-if" scenarios are investigated using the SCHISM hydrodynamic model coupled with the ECOSMO biogeochemical model. The simulations provide information on environmental conditions, ecosystem productivity, mussel growth potential, and harvestable biomass under different environmental and management settings. These results are integrated into the Digital Twin to evaluate alternative development pathways, assess trade-offs and synergies between offshore wind and aquaculture activities, and support stakeholder-oriented decision-making. The approach builds upon advances achieved in research initiatives addressing marine spatial planning, offshore multi-use systems, Digital Twins of the Ocean, and sustainable Blue Economy development.

The Digital Twin provides a platform for exploring future development pathways, evaluating management options, and supporting evidence-based decision-making under changing conditions.

The work contributes to the development of next-generation Digital Twins of the Ocean by demonstrating how social-ecological frameworks, numerical modelling, and stakeholder-oriented scenario analysis can be combined within an operational decision-support environment. The proposed framework supports adaptive marine spatial planning and contributes to the sustainable and resilient management of marine environments in the German Bight and beyond.

The SURIMI Framework for Model Coupling

**Patrycja Antosz*[1] (1. NORCE Research AS (Norway))

Abstract: The presentation introduces the SURIMI model coupling framework, a generic solution to achieve multidimensional simulation model interoperability, and showcases the framework's demonstration in a real-world use case of the Northwestern Mediterranean fisheries sector.

The coupled simulation models are organized in three thematic layers:
The ecological layer consists of Ecopath with Ecosim (EwE) - a spatially explicit food web model representing the ecosystem through energy flows, taking into account oceanographic conditions;

The assessment layer consists of CMSY++ - a stock assessment model for quantitative predictions for fisheries management and specifically with respect to stock biomass and fishing pressure applied by the fleets;

The socio-economic layer consists of:

• POSEIDON - an agent-based model of fishing fleet behaviour dynamics such as fishing activity, catches as well as interactions with the environment and regulations,

• Market dynamics model – a newly developed system dynamics model to estimate fish prices at various local (port) markets, and

• The Value-Chain model - a high-level representation of distribution and processing of marine catches, producing final goods for sale and consumption.

The models are coupled to represent fisheries as a complex adaptive socio-ecological system. The local digital twin allows users to run what-if scenarios related to climate change and mitigation strategies, discovering trade-off between subsystems (e.g., short vs long term impacts on the economy and marine ecology).

From simulation to decision: a particle-based DTO application for dispersal and connectivity of marine tracers in present and future scenarios

*Sofia Bosi[1] (1. Insitute of Marine Sciences (ISMAR) of the National Research Council of it (CNR) (Italy))

Abstract: Marine plastic, oil spills, chemical pollutants, fish eggs and larvae all have something in common: their dispersal in the ocean can be simulated using Lagrangian particle-tracking algorithms. Understanding how these tracers propagate through marine environments is a common challenge that underpins a wide range of decision-making processes, from marine spatial planning to the assessment of anthropogenic pressures. Digital Twin of the Ocean applications constitute a promising avenue in this direction. However, existing modelling approaches often target technical users, failing to reach marine planners, decision-makers and other non-technical stakeholders.

PMAR (Particle-based modelling and analysis for MARine decision support), is a user-centred, portable, and interoperable digital-twin application nested in the CNR-ISMAR Tools4MSP portfolio. It provides spatially explicit indicators for decision support and an intuitive graphical user interface, making advanced marine modelling accessible to non-technical users. By translating human activities to spatial sources, PMAR simulates the transport and accumulation of tracers across marine regions using Lagrangian trajectories. The lightweight exploration of alternative future states and planning scenarios is enabled by capitalizing on connectivity matrices as Markov-chains, allowing users to evaluate the potential effects of climate-driven changes in ocean circulation combined with different management strategies.

Fully open source, containerized, and currently deployed within the EDITO DataLab ecosystem, the application provides direct access to core European marine data-lakes, using Copernicus Marine oceanographic and atmospheric products to drive particle transport and EMODnet datasets to characterize the spatial distribution of human activities and other source layers. PMAR exposes on-demand processing capabilities through API specifications compliant with OGC API – Processes, enabling access to analytical functionalities and allowing external applications and services to seamlessly invoke and integrate processing workflows.

As an interoperable, user-centred and open-source Digital Twin application, PMAR aims to translate model outputs into practical and accessible indicators, empowering stakeholders to make science-based decisions across sectors.

Bridging the Blue Gap: A Media-Based Decision-Support and Participation Model for Localizing Nature-Based Solutions in Thailand

*Jareerat Petsom[1] (1. Bangkok,Thailand (Thailand))

Abstract: Coastal communities are increasingly exposed to climate variability and disaster risks, yet global ocean models and frameworks such as Nature-based Solutions (NbS) or Nature Posotive often remain insufficiently translated into locally actionable practices. This creates a severe "Blue Gap" a communication barrier between complex scientific ocean data and local community engagement. This study addresses this challenge by developing a media-based participation and decision-support model to localize climate information and support disaster risk reduction (DRR) in Thong Tom Yai, Chumphon, Thailand. Utilizing a qualitative, participatory action research approach, the study integrates scientific ocean-climate data into science-based creative media prototypes. These media tools serve as localized cognitive platforms to simulate environmental changes, communicate ocean risks, and facilitate co-design processes for bottom-up community planning. Preliminary findings indicate that local ecological knowledge deeply aligns with NbS principles, especially in traditional mangrove conservation and resource management. When abstract scientific concepts are translated into culturally relevant visual formats, they effectively bypass complex data jargon. Local stakeholders transition from passive information recipients to active co-designers, enabling them to collectively map coastal risk zones and co-create ecosystem-based adaptation strategies. This research demonstrates that effective coastal resilience relies not only on high-level technical data, but on inclusive communication systems that foster community data ownership. The proposed framework offers a scalable, transferable approach to bridge the ocean science-to-society gap, transforming raw environmental insights into actionable, community-led management policies across climate-vulnerable coastal regions.

The Moment of Catch: Linking Resource Extraction to the Digital

*Eva-Kristin Varheim[1] (1. Transparency in the Moment of Catch (Norway))

Abstract: The sustainable management of living marine resources depends on knowing not only the state of a fish stock, but also what is actually removed from it. Resource extraction is a physical event: when fish are harvested, the stock and its relationship with the surrounding marine ecosystem are affected at that moment. Yet

the registration and documentation of this extraction are generally separate processes, occurring after or alongside the harvesting operation.

This paper explores a principle-based proposition: could resource extraction and validated resource registration become the same event? If reliable information about species, size, quantity and actual extraction could be generated at the moment of catch, such data could strengthen catch documentation, traceability and quota accounting; contribute higher-resolution information on removals to the scientific basis for stock assessment and ecosystem understanding; and, where available in real time, support operational harvesting decisions within predefined biological and management criteria. This proposition is particularly relevant in the context of Digital Twins of the Ocean. Digital representations of exploited marine ecosystems depend on reliable observations of the physical world. A closer connection between observation, selection, extraction and registration could create a new data interface between the physical act of harvesting and its digital representation, supporting a continuous cycle of observe - identify - select - extract - register - update - assess - adapt.

The paper introduces TIMOC - Transparency in the Moment of Catch as a conceptual contribution to how such an approach might be realised in practice. TIMOC explores whether emerging autonomous underwater technologies could enable a different approach to pelagic harvesting, in which fish are first located and gathered as a school and subsequently guided into a controlled flow through a harvesting and selection system. Rather than capturing an entire aggregation first and determining its composition afterwards, the concept seeks to move identification and selection into the harvesting process itself.

Within the proposed architecture, cooperating autonomous underwater systems would interact with and manage the school before fish are directed through an underwater selection system. As fish pass through this controlled flow, species, size and other relevant characteristics could be identified, allowing fish or fractions of the school to be retained or released before final extraction. The approach thereby explores whether selective harvesting, resource observation and documentation can become integrated parts of the same physical process.

TIMOC is presented neither as an existing technological solution nor as a Digital Twin of the Ocean, but as a possible physical interface between living marine resources, future selective harvesting systems and the data environments required for digital ocean representations.

The paper invites interdisciplinary discussion on a broader question: Can future harvesting systems help close the gap between observing, selecting, extracting and digitally representing living marine resources - and thereby enable more transparent, selective and knowledge-based fisheries management?

Least-CO_2 routing of bulk carriers on the Australia–Japan iron-ore green corridor using VISIR-2

**Mario Leonardo Salinas*[1] (1. CMCC (Euro-Mediterranean Center on Climate Change) (Italy))

Abstract: Iron-ore shipping between Western Australia and Japan is one of the world's largest dry-bulk trades. In particular, the maritime lane from the Pilbara region in Australia has been identified as a priority corridor, with the operation of clean-ammonia vessels targeted from 2028 [1]. However, total-cost-of-ownership analyses indicate that, without a proper incentivising framework, scalable zero-emission fuels will remain above conventional bunkers [2, 3]. Thus, measures that cut fuel burned per voyage carry growing economic as well as environmental value. Operational voyage optimisation is one such measure, complementary to fleet renewal, and immediately deployable on this route.

We apply the open-source VISIR-2 weather routing model [4], which powers an on-demand service within the EDITO-Model Lab digital twin of the ocean [5], to a bulk carrier on the Australia–Japan corridor. Using a vessel performance curve derived from onboard sensor measurements [6], VISIR-2 computes least-CO_2 routes by optimising spatial diversions forced by the Copernicus Marine global ocean waves and global ocean physics (surface currents) products [7]. Additionally, it can optimise the engine load profile to achieve just-in-time arrival [ref Mannarini et al. (2027), in preparation].

We simulate a full calendar year in both laden (northbound) and ballast (southbound) directions, running each case with and without ocean currents to isolate their contribution. We quantify CO_2 savings against the least-distance route, their seasonal variability, and the trade-off with voyage time. The study shows how a digital-twin routing service extends from container trades [8, 9] to dry-bulk operations, providing physically consistent decision support. By lowering both emissions and exposure to rising fuel and compliance costs [2, 3], this approach complements fleet renewal and alternative fuels in decarbonising the Australia–Japan iron-ore corridor, and advances the blue-economy goals of the UN Ocean Decade.

Demos A2

Chairs: Takehisa Yamakita, Ibrahim Hoteit

The SURIMI Model GUI

Timo Szczepanska (NORCE Research AS (Norway))

Abstract: The usability of socio-ecological simulation models by non-technical stakeholders remains a challenge in applied social simulation. Most scientific models either lack a dedicated user interface or rely on the interface provided by their host modelling software, which constrains their accessibility in policy and management contexts. This paper presents the SURIMI Model GUI, a graphical user interface developed to make coupled socio-ecological fisheries simulations explorable and comparable by non-expert users, and to support their integration into the European Digital Twin of the Ocean (EDITO).

The interface functions as a gateway to three use cases: the Western Mediterranean Sea, the Aegean Sea, and Anchovy Bay. Through a guided scenario-definition pathway, users specify simulation parameters, compare outputs across scenarios, and access metadata describing the behaviour of the four coupled models both individually and in combination. Scenarios span short-term (5-year) and long-term (up to 50-year) horizons, five IPCC climate pathways (SSP1-1.9 to SSP5-8.5), and top-down mitigation measures such as harvest control rules. Results are reported across socio-economic indicators (catches, discards, employment by fisheries segment) and ecological indicators (stock status, biomass over time, bycatch, food-web effects).

Interface requirements were derived through a series of multi-actor co-design workshops involving policymakers, advisory councils, NGOs, the fishing industry, and scientists. These identified priorities of high interactivity, navigation between aggregate and detailed views, ready access to metadata, and the transparent visualization of uncertainty. This demonstration presents the current work-in-progress version of the SURIMI model interface and its integration into the EU Digital Twin of the Ocean.

py-off-bgc: A Python-based offline simulator for ocean biogeochemistry

Hakase Hayashida (JAMSTEC (Japan))

Abstract: Accurate regional and seasonal prediction of marine ecosystems requires robust and flexible modelling tools. We introduce py-off-bgc, a Python-based modelling framework designed to simulate ocean biogeochemistry offline. By utilizing prescribed daily-mean 3D physical fields (temperature, salinity, and velocity) from established ocean reanalysis products (e.g., JCOPE, LORA, BRAN, CMEMS), py-off-bgc ensures realistic tracer transport without the computational overhead of coupled physics. This offline architecture allows us to focus on refining complex ecological processes and developing targeted data

assimilation methods. In this presentation, we showcase preliminary results from regional py-off-bgc simulations and discuss the framework's trajectory toward seasonal prediction.

An Open, Democratizing Ocean Intelligence (DOI) - Interoperable Digital Twin for the Ocean - (DTO)

Asif Kabani (SaveOcean.Net (Norway))

Abstract: 1. Rationale & Objectives

Operational marine data often remains locked in dense, low-accessibility formats, limiting its utility for coastal managers, port authorities, and local stakeholders. Moving beyond static reporting, this work presents an end-to-end Digital Twin of the Ocean (DTO) framework grounded in SaveOcean.Net's paradigm: Science you can see, Action you can measure. The framework integrates deep-tech software architecture with ocean IoT infrastructure to deliver real-time, transparent, and auditable decision dashboards accessible to all.

2. System Architecture & Methodology

Built upon Nordic open data space principles and FAIR data standards, the proposed DTO architecture connects physical ocean dynamics with decentralized observational networks:

Multi-Source Ingestion: Ingestion of satellite streams, in-situ IoT sensors, and opportunistic vessel data (via SaveOcean.Net's 10,000 Ships for the Ocean initiative).

AI Surrogates: Hydrodynamic models coupled with deep learning surrogates enable low-latency scenario modeling for thermal stress, acidification, and pollution tracking.

Interactive Decision Layer: An open decision-support interface replacing static reports with "What-If" simulation engines, converting oceanographic data into CSRD-compliant metrics and SDG 14 tracking tools.

3. Results & Case Validation

Validated through regional coastal operational deployments, the system demonstrated up to a 60% reduction in simulation latency while closing in-situ observational gaps using mobile vessel IoT streams. By bridging deep tech, AI surrogates, and community sensing networks, this open-access twin directly aligns with UN Decade of Ocean Science goals, turning ocean science into measurable everyday action.

react-earth: Open-Source 3D Globe Visualization for Ocean Data

Clara Ni (JAMSTEC, Seasonal Prediction Center for Shipping digital transformation (SPDX) (Japan))

Abstract: Developing effective digital twins of the ocean requires accessible web interfaces to explore complex marine data. For scientists without advanced frontend programming skills, translating their results into interactive visualizations for the general public and policymakers remains a challenge, since existing 3D GIS tools are often too heavy or complex for deploying simple, public-facing web interfaces.

To bridge this gap, we present react-earth, an open-source library developed at JAMSTEC. Heavily inspired by the famous open-source cambecc/earth project, it provides a ready-to-use React component designed to display an interactive 3D globe along with geospatial datasets.

Engineered for maximum modularity, react-earth is adaptable to diverse contexts. Its architecture supports side-by-side globe displays, making it effortless to compare different climate states or variables. Scientists and developers retain complete control over data inputs and color palettes, accommodating everything from physical fields to biological metrics. Powered by WebGL and built-in interpolation algorithms, the library guarantees smooth, high-performance rendering.

In this presentation, we demonstrate how react-earth lowers technical barriers, allowing scientists to easily transform raw climate datasets into engaging, interactive 3D visual stories, ultimately fostering collaborative ocean science and data-driven governance.

Posters 2

[Poster 2-01] Deep-Learning Nowcasting of HF-Radar Surface Currents in the Sunda Strait: From One-Step Prediction to Six-Hour Forecasts

Dhava Gautama (Badan Meteorologi Klimatologi dan Geofisika (Indonesia))

Abstract: Surface currents in the Sunda Strait, which links the Java Sea and the Indian Ocean, are dominated by strong semidiurnal (M2) tides modulated by the reversing monsoon, and can exceed 200 cm/s, a hazard to the dense shipping traffic that crosses it. Indonesia's operational ocean model, Ina-CAWO, provides regional current forecasts, but does not resolve the narrow strait and its extreme tidal currents at kilometre scale, nor does it ingest

the local HF radar. We test whether deep learning applied to high-frequency (HF) radar observations can provide skillful, kilometre-scale surface-current nowcasts that complement this model as a data-driven component of an ocean digital twin.

We use hourly current fields from a BMKG HF radar covering 291 sea cells on a ~1 km grid, from December 2022 to February 2026. The fields are quality-controlled with speed, temporal, and spatial outlier filters, and short gaps are filled by tidal harmonic analysis. Models are trained on December 2022–December 2024 and evaluated on an independent July 2025– February 2026 period. We first benchmark nine one-step predictors; a CNN-GRU model attains the lowest error (U/V RMSE 13.8/19.6 cm/s), improving on a moving-average baseline by 19%/12%. For six-hour nowcasting, a bidirectional ConvLSTM encoder-forecaster predicts all six lead times at once, reaching 18.8/22.6 cm/s U/V RMSE and reducing persistence error by up to 56%. Skill is highest when the input window spans a full semidiurnal cycle (12 h), indicating the network exploits the dominant tidal periodicity.

Forecast error concentrates near the strait boundaries, where current gradients are steepest, and shows a diurnal modulation likely linked to diurnal tides and wind forcing. These results show that HF-radar deep learning can provide a high-resolution, observation-driven nowcasting layer that complements Indonesia's operational ocean model in a Sunda Strait digital twin, with potential to extend to other tidally energetic, data-sparse coastal seas.

[Poster 2-02] Subsurface Structure and Drivers of Marine Heatwaves in the Andaman Sea Using Bio-Argo Data

Nibedita Behera (Berhampur University (India))

Abstract: A marine heatwave (MHW) is defined as a prolonged anomalous warming of ocean temperatures persisting for more than five consecutive days. Such events pose significant threats to regional marine ecosystems, particularly coral reefs, which are highly sensitive to thermal stress. Although widespread coral bleaching associated with MHWs has been reported, in situ observations remain limited, and the physical mechanisms governing the persistence of MHWs in specific regions are still poorly understood. This study focuses on the northern Andaman region, known for its rich coral diversity. A Bio-Argo float (ID: GL_PR_PF_2902158) is used to investigate the physical oceanographic conditions during MHW and non-MHW periods along its trajectory, with emphasis on their implications for coral bleaching. Since reef-building corals are primarily confined to shallow waters (upper ~200 m), Argo profiles were selected based on upper-ocean depth

coverage and the occurrence of MHW and non-MHW events. Results show that during the MHW event (28 November–3 December 2017), the barrier layer thickness increased to 30 m, accompanied by a deeper mixed layer depth (55 m). In contrast, during the non-MHW period (4 December 2017–5 March 2018), a thinner barrier layer (20 m) and a shallower mixed layer (40 m) were observed. Additionally, the MHW period was characterized by stronger surface winds and elevated sea surface temperatures (SST), indicating enhanced surface mixing. However, the presence of a thick barrier layer inhibited vertical heat exchange, trapping heat within the upper ocean and thereby sustaining the MHW conditions. This prolonged thermal stress likely contributed to coral bleaching in the northern Andaman region.

[Poster 2-03] Developing a LiDAR-Derived Digital Twin of Mangrove Ecosystems in Tobago

Deanesh Ramsewak (Centre for Maritime and Ocean Studies, The University of tt (Trinidad and Tobago))

Abstract: Mangrove forests are important coastal ecosystems that support biodiversity, shoreline protection and blue carbon storage. Despite conservation efforts, they continue to experience degradation and fragmentation due to climate change impacts and anthropogenic pressures. Monitoring and conservation frameworks can be enhanced by capturing and incorporating more detailed information on the structural nature and spatial dynamics of mangrove ecosystems. Light Detection and Ranging (LiDAR) technology can be used to produce highresolution, digital replicas of these forests for enhanced analysis and monitoring. In this study a handheld mobile terrestrial scanner (Simultaneous Localization and Mapping – SLAM) was used to capture LiDAR point cloud data of mangrove forest on the island of Tobago. Handheld mobile LiDAR systems offer increased portability and agility which are particularly advantageous in dense mangrove environments. The point cloud data was used to generate a detailed, spatially accurate digital twin of the mangrove forest area. Established field sampling plots were used to capture spatial extent and canopy structure of trees. The three-dimensional digital model produced was used to derive key structural parameters, including tree height and canopy complexity. This information along with other key thematic layers were integrated to provide a comprehensive depiction of the natural mangrove forest environment. This study produced an interactive digital twin of the mangrove forest from remotely sensed LiDAR data for mapping and monitoring of fine scale, gradual changes in the system. Handheld LiDAR systems have significant mobility advantages and are particularly useful in small island developing states (SIDs) where the mangrove systems are relatively small. The digital twin generated here can be used for improved monitoring and assessments to support informed planning and simulation of future environmental changes. It is also a powerful tool for strengthening blue carbon accounting and coastal resilience within the Caribbean region.

Keywords: Mangrove, LiDAR, Digital Twin, Blue Carbon, Coastal Resilience, Remote Sensing

[Poster 2-04] SURF: A deep learning-based satellite-driven underwater reconstruction framework with fine-tuning for global three-dimensional particulate organic carbon retrieval

Haneul Cho (Graduate School of Carbon Neutrality, Ulsan National Institute of Science and Technology (UNIST) (Korea))

Abstract: Particulate organic carbon (POC) in the ocean plays a central role in the biological pump, which transports carbon to the deep ocean for long-term storage. Accurately analyzing its spatiotemporal variability is therefore crucial for understanding the global carbon cycle. However, existing ocean-color-based POC estimation algorithms are limited by the complexity and regional specificity of bio-optical relationships, and they have the particular drawback of relying excessively on surface data, which leads to error amplification when estimating values below the surface. To properly assess ocean carbon stocks, it is necessary to go beyond simple surface estimates and understand subsurface carbon dynamics. To overcome these limitations, this study proposes SURF (Satellite-driven underwater reconstruction and fine-tuning framework), a foundation model-based framework that integrates satellite observations with multiple environmental proxies to reconstruct global 3D POC. The proposed model transforms data into 2D and 3D tensors to process data from various sources.

Furthermore, by combining a FiLM (Feature-wise Linear Modulation) network with multihead depth attention, it organically links surface-level environmental factors with depthdependent features to capture complex vertical POC structures. In the training process, the model undergoes pre-training using 3D chlorophyll-a data estimated in previous studies based on profile types and parameterization, followed by fine-tuning using sparse in-situ observational data.

This model was validated using extensive global in-situ observation data. Cross-domain experiments conducted existing baseline models in terms of root mean square error (RMSE), mean absolute error (MAE), and profile correlation (R^2). Qualitatively, it also realistically reconstructs the response of the biological carbon pump to environmental changes using 3D continuous data at a resolution of 0.25 degrees.

In conclusion, the SURF framework is a highly robust and innovative model that successfully integrates satellite observation data with physical and biogeochemical dynamics, enabling high-resolution reconstruction of three-dimensional POC distributions and carbon dynamics across the entire ocean depth range.

[Poster 2-05] Understanding the Earth System Oscillations through Phase Reduction

Ayumi Ozawa (JAMSTEC (Japan))

Abstract: The Earth system exhibits a wide variety of oceanic and atmospheric oscillations arising from interactions across multiple spatial and temporal scales. Although predictions of the Earth system have become increasingly accurate, informed decision-making and the improvement of the models both require understanding the dynamical mechanisms underlying the predicted behavior. Numerical simulations under diverse conditions are valuable for investigating such mechanisms, but their computational cost limits the number of scenarios that can be explored, particularly when high spatiotemporal resolution is required.

We introduce the phase reduction method as a tool that complements large-scale numerical simulations and AI-driven analyses. It transforms an oscillatory system into a lowdimensional phase equation that describes how its oscillation responds to external perturbations. The reduction also provides a phase sensitivity function, which identifies where perturbations most effectively influence the system dynamics. However, many mathematical models in ocean and Earth science fall outside the scope of conventional phase reduction theory. We are therefore extending the phase reduction method for such models.

In this presentation, we analyze the quasi-biennial oscillation (QBO), the approximately periodic reversal of equatorial stratospheric zonal winds. The developed method identifies the altitudes at which external forcing most effectively modifies the QBO period. It also clarifies how the influence of the annual cycle depends on the drivers of QBO. Finally, we discuss the potential application of this framework to Boundary Current Synchronization, the synchronized sea surface temperature variability observed between the Kuroshio and the Gulf Stream. Thus, the phase reduction may contribute to digital twins that provide not only accurate predictions but also elucidate the underlying mechanisms.

[Poster 2-06] Data-Driven Inference of ENSO Phase Dynamics under Annual Forcing

Takahiro Arai (Japan Agency for Marine-Earth Science and Technology (Japan))

Abstract: The El Niño–Southern Oscillation (ENSO) is a dominant mode of interannual climate variability. Although ENSO events recur irregularly with periods of approximately 2–7 years, their evolution exhibits a pronounced seasonal preference, with El Niño events often peaking in boreal winter. This seasonality suggests that the annual cycle influences the timing and progression of ENSO events. However, how the annual cycle modulates ENSO phase dynamics remains insufficiently quantified.

In this study, we infer the phase dynamics of ENSO directly from observational sea surface temperature data. Using a data-driven Koopman analysis, we extract the fundamental oscillatory mode of ENSO. Its temporal evolution is represented by a rectified phase that behaves approximately as a harmonic oscillator. From the resulting phase time series, we infer a phase equation for ENSO. The inferred phase equation describes how periodic forcing by the annual cycle modulates the phase velocity of ENSO. The inferred dynamics reveal partial 3:1 phase synchronization between ENSO and the annual cycle. These results demonstrate that data-driven phase dynamics provide a quantitative framework for investigating the seasonal modulation of ENSO evolution.

[Poster 2-07] An eDNA-based Functional Community Representation for Coastal Digital Twins: A Proof of Concept in Orido Bay

Aya Suzuki (Space Environment and Energy Laboratories, NTT, Inc. (Japan))

Abstract: Environmental DNA (eDNA) metabarcoding has become a powerful tool for biodiversity monitoring by enabling broad, non-invasive detection of taxa from environmental samples. While recent studies have explored functional trait or guild analyses within individual taxonomic groups (e.g., fish communities), few have addressed the integration of heterogeneous biodiversity observations derived from eDNA into a unified functional representation of ecosystem structure for ecosystem-level assessment and Digital Twin applications.

In this study, we propose an eDNA-based framework for generating functional community representations through ecological functional guilds. Instead of directly interpreting species detection results, detected taxa are assigned to ecological functional guilds and integrated to generate functional community structure profiles that describe the relative composition of ecological functional guilds. This approach bridges biodiversity observations and ecosystem-level assessment by integrating heterogeneous observations across different biological groups into a common functional community representation.

As a proof of concept, the proposed framework was applied to seasonal eDNA observations collected in Orido Bay, a coastal ecosystem in Japan. The resulting functional community profiles resolved seasonal differences in functional guild composition beyond what could be inferred from species inventories alone. The proof of concept demonstrates the feasibility of translating eDNA-based biodiversity observations into a functional community representation.

Finally, we discuss the potential of the proposed functional community representation as a candidate ecological observation variable for future Digital Twin of the Ocean (DTO) applications. Beyond ecosystem monitoring, the proposed framework provides a modelcompatible ecological representation that can be coupled with forecasting ecosystem models to project future changes in ecosystem balance under different environmental conditions and restoration scenarios. Such a capability could support quantitative biodiversity assessment, restoration planning, and adaptive management for nature-positive coastal ecosystems.

[Poster 2-08] Beyond Conventional Sampling: Coastal Biogeochemical Insights from an Autonomous Water Quality Nowcasting System in the Southeastern Arabian Sea

Sanjiba Kumar Baliarsingh (Indian National Centre for Ocean Information Services, Ministry of Earth Sciences, Government of India, Hyderabad-500090 (India))

Abstract: Coastal waters off Kochi, in the southeastern Arabian Sea, change biogeochemically over hours rather than weeks, yet these sub-daily signals rarely surface in routine monthly or fortnightly sampling. To examine what such sampling misses, we analysed three high-frequency observation windows from the moored buoy of the INCOIS Water Quality Nowcasting System (INCOIS-WQNS) off Kochi, representing August 2023, January 2024, and April 2024. The INCOIS-WQNS is an autonomous moored platform carrying a multiparameter suite of in-situ physical, chemical, and biological sensors; it samples the water column continuously and relays observations to shore by satellite telemetry, supporting near-realtime water-quality nowcasting. Each window spanned three continuous days at 30-minute intervals. Thirteen quality-controlled variables were examined, namely temperature, salinity, dissolved oxygen (DO), pH, water and air pCO2, chlorophyll-a, turbidity, CDOM, dissolved methane (CH4), hydrocarbons, and currents, using Kruskal–Wallis testing, diel composites, spectral analysis, principal component analysis (PCA), k-means clustering, and a Hydrographic Stability Index. Every variable except current direction differed significantly among periods.

Most striking was a near-anoxic event in the pre-dawn hours of August 2023, when DO fell to 0.09 mg L-1 and stayed there for close to five hours, with several readings below the 2 mg L-1 hypoxia threshold; August also showed the strongest diel swings in oxygen and pH. April differed, marked by the highest methane concentrations (2.11 ± 0.30 µM), the broadest pCO2 range, and the weakest hydrographic stability, all pointing to a more unstable biogeochemical state. PCA explained 83.5% of the total variance, and clustering cleanly resolved the three seasonal regimes. Low-frequency sampling would therefore overlook the transient hypoxia, understate the diel range of the carbonate system and oxygen, and miss the episodic methane enrichment. Resolving these dynamics and improving monitoring in the southeastern Arabian Sea depends on sustained, autonomous high-frequency observation.

[Poster 2-09] Impact of Marine Heatwaves on Ocean-Atmosphere CO2 Fluctuations

Pierre Simiganoschi (Tohoku University (Japan))

Abstract: Marine heatwaves (MHWs) are prolonged periods of extreme ocean warming that are increasing in frequency and intensity under global warming. They can alter the air–sea exchange of CO_2, yet their effect on the CO_2 flux (FCO_2) remains poorly constrained, particularly at sub-monthly timescales. Using a daily-resolution decomposition of FCO_2 anomalies (1982–2023, global 2° grid), we apply a first-order Taylor-series decomposition to separate the flux anomaly into wind, ΔpCO_2, thermal, and non-thermal components and composite them over MHW events. To compare events of different length, each event's duration is min–max normalized onto a common 0–1 life-cycle axis and divided into onset, mature, and decay phases. Wind speed is systematically reduced during MHWs, consistent with the atmospheric high-pressure conditions that often accompany them; weaker winds slow gas exchange and reduce CO_2 uptake in sink regions. This wind suppression dominates the flux response for short events (10–30 days), whereas for events longer than about one month the thermal component accumulates and becomes the leading driver. The wind contribution is also seasonal in the midlatitudes—strongest in spring and autumn and weakest in summer. The phase analysis shows the response is not steady: the total FCO_2 anomaly is largest at onset, where a negative wind-speed anomaly reduces uptake, and weakens toward decay, where the wind effect fades or reverses while thermal and nonthermal components grow in relative importance. MHW impacts thus behave as compound events, in which co-occurring high SST anomalies and reduced winds jointly modulate the flux. As MHWs continue to intensify and lengthen, resolving this duration- and phasedependent behavior will be essential for accurately quantifying their contribution to ocean carbon-sink variability.

[Poster 2-10] Interpretable Latent Dynamics of Deep-Ocean Variability from Three-Dimensional Temperature Fields Using Koopman Autoencoders

Min Su Song (Chungnam National University (Korea))

Abstract: Deep-ocean circulation is a key component of the climate system, governing large-scale heat transport, carbon storage, and long-term variability. Its dynamics emerge from nonlinear interactions among buoyancy forcing, stratification, and internal ocean processes, making them difficult to characterize with conventional linear frameworks alone. In particular, much of the interior ocean's memory of climate variability is embedded in three-dimensional thermal structure.

This study applies a Koopman Autoencoder framework to three-dimensional ocean temperature fields to investigate whether low-dimensional and interpretable latent dynamics can be learned from high-dimensional ocean interior variability. The approach combines nonlinear compression of temperature fields with approximately linear temporal evolution in latent space, offering a structured way to represent complex ocean dynamics while retaining dynamical interpretability.

Using long-term climate model output, we examine whether the learned latent variables capture dominant variability patterns and characteristic time scales associated with deep-ocean circulation. Their physical relevance is assessed through comparison with conventional circulation metrics, including overturning-related indices. This work explores the potential of Koopman-based representation learning as a new framework for physically interpretable analysis of nonlinear deep-ocean climate variability.

[Poster 2-11] Storm surges associated with cut-off low-pressure systems along the South African coastline

Ramontsheng Sakia Rapolaki (South African Weather Service (South Africa))

Abstract: Cut-off low (COL) pressure systems are among the most devastating natural phenomena, with severe impacts on infrastructure and substantial socio-economic damage in South Africa. Beyond their known impacts, including damaging winds and flooding, they can also trigger storm surges along coastal areas when they occur under favourable ocean-atmosphere conditions, such as spring tides. Here, using three COL events that occurred between January 2014 and April 2024, the ocean-atmospheric mechanisms behind storm surges associated with these events are investigated. The 0.25° (~ 25 km) gridded Global Tide and Surge Model v3.0 data are used to identify storm surge events, and 0.25° (~25 km) gridded ERA5 data are used to assess the atmospheric circulation associated with the COLs. The preliminary results indicate that 2 out of 3 COLs (January 2014 and April 2024

events) were associated with storm surges along the South African coast. The analysis reveals that the location of the COL and its interaction with regional atmospheric circulation patterns, including the tidal cycle, are key determinants of storm surge occurrence. These findings underscore the critical need for a coupled ocean-atmosphere approach to improve disaster preparedness, as COLs increasingly intensify under climate change, leading to more costly disasters.

[Poster 2-12] Ocean State Estimation for Climate Research: Overview and Recent Progress of ESTOC at JAMSTEC

Satoshi Osafune (JAMSTEC (Japan))

Abstract: progress in the ocean observing network enables us to obtain an unprecedented amount of observational data. However, because observations contain variability across a wide range of temporal and spatial scales, it remains challenging to quantitatively assess the global budgets of heat and freshwater on climate timescales solely from observations. Therefore, much effort has been devoted to ocean state estimation, a synthesis of observations through a data assimilation approach that brings an ocean general circulation model (OGCM) into consistency with the diverse observations. At JAMSTEC, we have been developing and operating an ocean state estimation system which we call “Estimate of global ocean for climate research (ESTOC)”. In this presentation, we provide an overview of our system, highlight recent technical developments, and discuss its application to climate research.

[Poster 2-13] Oceanographic Drivers of Bigeye Tuna (Thunnus obesus) Habitat Suitability in the Eastern Indian Ocean off Java

Mega Laksmini Syamsuddin (1. Faculty of Fisheries and Marine Sciences, Universitas Padjadjaran (Indonesia))

Abstract: The eastern Indian Ocean off Java (EIO) is recognized as one of the primary tuna fishing grounds, with bigeye tuna (Thunnus obesus) being a prominent target species of economic significance. This study utilized bigeye tuna occurrence records and satellite-derived oceanographic data from 2017 to 2024, applying the Maximum Entropy (MaxEnt) model to predict habitat suitability based on six oceanographic variables: sea surface temperature (SST), chlorophyll-a, sea surface height (SSH), salinity, wind speed, and current speed. An empirical orthogonal function (EOF) analysis was carried out to gain a better understanding of the region's spatio-temporal ocean variability. The results showed that the first EOF modes for SST, SSH, wind speed, chlorophyll-a, salinity, and current speed each accounted for 68.53%, 60.42%, 58.27%, 51.41%, 51.16%, and 18.09% of the

total variation, corresponding to the interannual signal. The model demonstrated strong predictive capability, achieving an area under the curve (AUC) of 0.837. SST was found to have the highest contribution (24.7%), followed by wind (23.5%) and current (20.1%), highlighting temperature as the primary environmental factor influencing bigeye tuna distribution, while chlorophyll-a contributed the least at 5%. Bigeye tuna thrives in optimal environmental conditions with SST between 27 and 28 °C, chlorophyll-a levels of 0.05 to 0.10 mg m^{-3}, salinity ranging from 33 to 34.5 psu, SSH between 0.65 and 0.70 m, wind speeds of 4 to 10 m s^{-1}, and current speeds of 0.01 to 0.2 m s^{-1}, according to response curve analysis. The southern waters off Java (8°-11° S, 105°-115° E) consistently had the greatest habitat suitability index (HSI) values, with September to November being the most favorable months. The MaxEnt model accurately described bigeye tuna environmental conditions, however it is a correlation model that is dependent on the environmental variables included in the research.

[Poster 2-14] Supporting Essential Ocean Variables integration for Digital Twins with machine readable specification sheets

Adam M. Leadbetter (Seascape Belgium and Intergovernmental Oceanographic Commission of UNESCO (Belgium))

Abstract: The value chain of ocean observing to data to application and services (including forecasting) has been well established at the heart of the digital ecosystem development for the UN Ocean Decade.

Working closely with the Global Ocean Observing System and taking on board feedback from Member States of the Intergovernmental Oceanographic Commission of UNESCO, the Essential Ocean Variable (EOV) framework has been identified as a key strategic driver for data interoperability and data exchange in the UN Ocean Decade's data discovery and access service.

An analysis of the potential for EOV identification in regional and global data systems was undertaken in November 2025 by the Decade Coordination Office for Ocean Data Sharing, the European Marine Observation and Data Network technical coordinator, and experts from the British Oceanographic Data Centre and Ireland’s Marine Institute. A key finding of was that machine readable EOV specification sheets would be a vital next step in establishing EOV data exchange, which can underpin EOV product generation on Digital Twins.

In summer 2026, work was commenced on a JSON Schema to formally describe the structure of an EOV specification sheet. This work revealed that the current PDF documents are not well harmonised in structure and that a JSON Schema allows consistency, cross-checking and validation of the original documents. Experiments

have also been conducted using Large Language Models to populate JSON documents with content from the EOV PDF specification sheets conforming to the JSON Schema, giving the first fully machine readable EOV specification sheets.

This presentation will highlight the findings of the EOV data identification analysis, the need for machine readable EOV specification sheets and the progress made in delivering this vital piece of the ocean data interoperability puzzle.

[Poster 2-15] Improving Temporal Homogeneity of Long-Term Sea Ice Concentration Records Through Spatial Distribution Transformation Using Flow Matching

Suwon Choi (Department of Earth, Environmental and Space Sciences, Chungnam National University (Korea))

Abstract: Sea ice concentration (SIC) is a key variable for understanding polar climate variability, ocean–atmosphere interactions, and long-term climate change. Long-term climate analysis requires not only an extended observational record but also consistency across changes in satellite sensors, retrieval algorithms, and production systems. Although passive microwave SIC products provide multi-decadal coverage, systematic differences in their spatial structure can introduce artificial discontinuities, particularly across product-transition periods.
This study addresses this issue by treating SIC homogenization as a spatial field transformation problem between historical and recent satellite products. We reconstruct a temporally more consistent Antarctic SIC record by learning a transformation from historical Bootstrap SIC fields to AMSR2-like SIC fields. Daily Bootstrap SIC is used as model input, while daily AMSR2 SIC serves as the target reference product during the overlap period after spatial grid harmonization and preprocessing. AMSR2 is not treated as absolute ground truth, but as the target observational product space for harmonization.

We employ a Flow Matching model with a U-Net-based vector-field estimator. Unlike direct one-step regression, the model learns a continuous transformation path from the Bootstrap SIC state to the AMSR2 SIC state through a time-dependent vector field. During inference, this vector field is numerically integrated to generate AMSR2-like SIC fields from Bootstrap inputs. Rather than smoothing the time series directly, the method improves temporal consistency by consistently applying a learned spatial transformation between product spaces.

A mask-aware learning strategy is applied to exclude land, ice shelves, and missing-value regions. Results show lower root mean square error, higher coefficient of determination, and reduced coastal artifacts relative to the

original Bootstrap fields. The learned transformation reduces product-dependent structural differences, improving continuity while preserving physically meaningful nonstationarity in Antarctic sea ice variability.

[Poster 2-16] From Basin to Coast: Assessing the Added Value of HighResolution Nested Wave Modeling for Future Coastal Hazards along the Alexandria Coast

Amani Ali (Egyptian meteorological Authority (Egypt))

Abstract: Future climate change is expected to influence coastal wave regimes through modifications in atmospheric circulation, storm characteristics, and air–sea interactions. Translating these large-scale climate signals into actionable information for coastal adaptation remains a major challenge, particularly in vulnerable urban regions of the Global South. Alexandria, Egypt, located along the southeastern Mediterranean coast, is highly exposed to coastal flooding, erosion, and wave-induced hazards, making it an ideal testbed for investigating the benefits of high-resolution coastal modeling.

This study employs a multiscale nested modeling framework based on the Simulating WAves Nearshore (SWAN) model to examine future wave conditions along the Alexandria coastline. The modeling system consists of a regional Eastern Mediterranean domain at 5 km resolution and a nested coastal domain at 500 m resolution designed to resolve local shoreline geometry and nearshore bathymetric controls. Future simulations are conducted using climate-driven atmospheric forcing under the SSP1-2.6 and SSP5-8.5 scenarios through the end of the twenty-first century.

The framework is designed to evaluate how increasing horizontal resolution affects the representation of coastal wave processes and extreme-event characteristics. Particular emphasis is placed on the ability of sub-kilometer simulations to capture wave transformation, refraction, shoaling, and localized wave-energy concentrations that may not be adequately represented in coarser regional configurations. The analysis further investigates whether future climate forcing may alter the frequency, intensity, or spatial distribution of extreme wave conditions along the Alexandria coast and how these changes vary across scales.

By directly comparing basin-scale and coastal-scale simulations, this study addresses a central question in next-generation Earth system modeling: what scientific value is gained through increasing model resolution? The

results will contribute to ongoing efforts to bridge climate projections and coastal impact assessments while providing a framework for evaluating future coastal hazards and adaptation needs across the Mediterranean region.

[Poster 2-17] Five-year molecular monitoring indicates range expansion of harmful benthic dinoflagellates in Korean coastal waters

Eun Young Yoon (Climate Change Research Laboratory, Advanced Institute of Convergence Technology (Korea))

Abstract: Long-term standardized biological observations are fundamental for developing Digital Twins capable of representing dynamic coastal ecosystems and supporting ecosystem-based management. However, quantitative molecular observations of harmful benthic dinoflagellates remain scarce despite their increasing ecological and public health importance. Once considered restricted to tropical and subtropical reefs, several harmful benthic dinoflagellate taxa are now reported from temperate coasts undergoing rapid warming. Here we present results from a five-year (2021–2025) nationwide monitoring program designed to establish a long-term biological observation dataset for Korean coastal waters.

Seasonal sampling was conducted at coastal monitoring stations throughout Korean coastal waters, including the West, South, and East Seas, between 2021 and 2025. Quantitative real-time PCR (qPCR) assays targeting species-specific rDNA regions were used to estimate the abundance of four major harmful benthic dinoflagellates: Amphidinium massartii, Ostreopsis cf. ovata, Gambierdiscus jejuensis, and Coolia malayensis. Concurrent environmental observations, including in situ water quality parameters measured using a YSI multiparameter sonde and chlorophyll-a concentrations, were collected to examine relationships between harmful benthic dinoflagellate occurrence and environmental conditions.

Results from five years of monitoring demonstrate substantial spatial and seasonal variability in the occurrence and abundance of harmful benthic dinoflagellates throughout Korean coastal waters. Species-specific distribution patterns varied among coastal regions and survey periods, reflecting the influence of water temperature and hydrographic conditions. Warm current transport along the southern and eastern coasts may be one contributing factor. The long-term observations further reveal an increasing frequency of occurrence and an expanding geographic range for several species consistent with warmingdriven range expansion along the Korean coast. This monitoring program establishes a valuable biological observation resource for Digital Twin development.

Integrating quantitative molecular observations with environmental monitoring provides a robust foundation for model calibration and forecasting of harmful benthic dinoflagellate dynamics in Korean coastal ecosystems.

[Poster 2-18] Advancing Shallow Coral Reef Monitoring for Ocean Digital Twins: A Physics-Based Nonlinear Spectral Unmixing Approach for Simultaneous Benthic Cover, Water Quality, and Bathymetry Retrieval

Palika Wannawilai (Institute of Science Tokyo (Japan))

Abstract: Coastal ecosystems can change rapidly in response to sediment plumes, freshwater discharge, and thermal stress. Coral reefs are particularly sensitive to these changes; however, conventional field surveys provide observations at only a limited number of locations and time points. Ocean digital twins can help address this limitation by integrating observations, data assimilation, and numerical or AI-based models to represent the current state of a coastal ecosystem and predict its future condition.

For coral reef applications, ocean digital twins require frequent spatial information on both the seafloor and water column. Benthic cover, water quality, and bathymetry are important variables because they influence reef condition, light availability, and ecosystem responses to environmental change. Satellite remote sensing can provide repeated observations over large reef areas; however, these variables are often estimated separately or using site-specific empirical models.

This study develops a physics-based nonlinear spectral unmixing method to simultaneously estimate benthic cover, water quality, and bathymetry from seven-band PlanetScope imagery. The method combines nonlinear spectral unmixing with radiative transfer theory to retrieve the fractional cover of seven bottom-cover classes: sand, coral, seagrass, brown algae, green algae, reef rock, and red soil. It also estimates total suspended solids (TSS), turbidity, chlorophyll-a, and water depth from a single satellite observation providing spatially consistent estimates of reef condition. The method was applied to a reef area near the Todoroki River mouth, Ishigaki Island, Japan, and evaluated using in-situ measurements collected in September 2024. Further parameter refinement is ongoing to improve retrieval accuracy. These multi-variable datasets can provide regularly updated inputs for ocean digital twins, supporting coral reef monitoring and management.

[Poster 2-19] Reconstructing food-web networks invisible in the real ocean by using the Superposition Method in the virtual ocean

Naoto F. Ishikawa (Biogeochemistry Research Center, JAMSTEC (Japan))

Abstract: Food webs are the fundamental engine of planet Earth, transferring energy and nutrients from one life to another. Since perfectly mapping the food-web networks is extremely difficult, stable isotope analysis has advanced in recent decades to estimate "trophic positions" (TPs) of organisms. For instance, a TP of 3.0 in a predator means that the predator primarily eats prey with TP = 2.0; however, a single TP value does not indicate which specific prey was eaten by the predator. No methods are currently available to reconstruct a plausible network in nature where a predator has too many potential prey options. To overcome this problem and reconstruct food-web networks using TP data, we developed the

"Superposition Method", which assumes that predators generally prefer to eat prey being positioned approximately one TP below them. Using Bayesian statistics, the method breaks the food web down into potential prey pairs, assigns high probabilities to prey that perfectly meets the assumption, and penalize unlikely predator-prey links (such as a top predator with TP = 5.0 eating microalgae with TP = 1.0). We validated this method by hiding the original predator-prey links in 158 fully documented food webs from the EcoBase database and reconstructing the original network using only the TPs. The reconstrcuted food-web network consistently achieved over 80% accuracy and produced estimation errors <5%. Furthermore, the method proved highly stable even when noisy or imperfect data was introduced. The Superposition Method provides a new approach to study large-scale ecosystems, with applications to the conservation of keystone species, fisheries resources management, and better understanding of energy transfer through living organisms. We plan to establish a platform where anyone can reconstruct food-web networks invisible in the real ocean by using the Superposition Method in the virtual ocean.

[Poster 2-20] JAMSTEC contributions for GOOS: Enhancing Observation Value through Data Integration

Shinya Kouketsu (JAMSTEC-RIGC-GOORC/WPI-AIMEC (Japan))

Abstract: JAMSTEC GOORC contributes sustained, high-quality observations to global networks such as GO-SHIP, Argo, and TPOS, and supports the Global Ocean Observing System (GOOS) by prioritizing rigorous

sensor calibration, quality assurance, and rapid public release to international repositories. Beyond delivering primary measurements, GOORC actively shares technical development for water-sample analysis, sensor testing, intercalibration, and data processing to promote reproducible and trustworthy datasets across the observing community. We regard the downstream production of scientific outputs and the creation and publication of secondary statistical datasets from these primary observations as core activities within the DITTO framework.
To increase the scientific and operational value of observations, GOORC operates an integrated data assimilation system that fuses numerical models with multi-platform measurements from satellites, buoys, and shipborne sensors. The system provides gap filling and consistent gridded analyses that complement sparse in-situ coverage and enhance the usability of observations. Representative applications demonstrate improvements in spatial coverage and reduced analysis error enabling higher-value products. Based on the dataset, we present quantitative evaluations of ocean and climate variability, including metrics for coverage enhancement that have supported deeper scientific understanding.

[Poster 2-21] A Trial of Underwater Acoustic Inverse Analysis Using Surrogate Models and Diffusion Models

Masami Abe (IDEA Consultants, Inc. (Japan))

Abstract: The advent of diffusion models has spurred a growing body of applied research on inverse analysis techniques that infer subsurface conditions consistent with observed data under physical constraints — a paradigm exemplified by Full Waveform Inversion (FWI) and broadly framed within the context of Physics-Informed Diffusion Models (PIDMs). Applying analogous techniques to underwater acoustic analysis, however, presents a distinct challenge: because acoustic waves propagate in a cylindrically spreading manner underwater, measurements recorded at greater distances from the source inherently reflect contributions from a wide spatial extent, incorporating complex multi-path scattering and reverberation. This physical reality makes it difficult to describe the forward problem in terms of a single, exact governing equation, thereby complicating the direct application of physics-informed frameworks.

To address this challenge, we introduce a surrogate model that approximates the forward acoustic propagation process and employ it as guidance within a diffusion model-based inversion framework. Rather than relying on an explicit physical equation, the surrogate model is trained to capture the statistical input-output relationship of

the acoustic system, enabling the diffusion model to be steered toward physically plausible solutions during the reverse diffusion process.

We present results evaluating the effectiveness of the proposed approach using synthetic wavefields generated by numerical wave propagation simulations designed to emulate underwater acoustic environments. Our findings suggest that surrogate-guided diffusion models offer a promising direction for underwater acoustic inverse analysis in scenarios where exact physical formulations are unavailable.

[Poster 2-22] Bridging Ocean Modeling and Ocean Engineering: Relocatable Regional Ocean Modeling for Offshore Floating Wind Turbines.

Tsubasa Kodaira (The University of Tokyo, Graduate School of Frontier Sciences (Japan))

Abstract: Ocean models have traditionally been developed primarily for understanding and predicting ocean circulation and variability. However, rapidly growing offshore activities, including floating offshore wind energy, increasingly require detailed and site-specific information on ocean currents and their variability for engineering design, operation, and risk assessment. This presentation discusses how regional ocean modeling can bridge physical oceanography and marine engineering, with particular emphasis on its potential applications to floating offshore wind turbines (FOWTs).

As an example, I introduce RGEM, a relocatable regional modeling framework based on MITgcm, using the global ocean reanalysis GLORYS, atmospheric forcing from ERA5, and tidal information from TPXO8 as boundary and forcing data. The framework is designed to enable regional ocean simulations to be deployed relatively easily in different areas of engineering interest.

Compared with wind and wave conditions, information on ocean currents remains relatively limited in many offshore regions. Nevertheless, current-induced loads can be important for FOWTs because of their submerged structures, mooring lines, and power cables. Reliable characterization of current magnitude, direction, vertical structure, and variability is therefore relevant to both design and operation. While operational wind and wave forecasting systems are already widely used in offshore engineering, accurate reproduction and prediction of ocean currents remain challenging.

On the other hand, at the same time, the expansion of offshore engineering may create new opportunities for ocean science. I will therefore discuss the potential for a two-way interaction: ocean science and modeling supporting marine engineering, while offshore engineering activities in turn provide new opportunities to advance ocean observation and modeling.