

Perspective from Unified Complex Systems Theory: Rethinking Ocean Science, Technology and Engineering for Earth's Sustainable Future

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Abstract

Against the backdrop of accelerating climate change, depleting marine resources, ecological degradation, and rising geopolitical risks, ocean science, technology, and engineering are indispensable to planetary health and long-term human sustainability. However, mainstream ocean research remains fragmented across disciplines, relying on reductionist methods, local optimization, and scenario simulations. While such approaches have yielded incremental technical progress, they fail to treat the ocean as an integrated, dynamically coupled complex system that spans physical, biological, geological, chemical, human, engineering, and even extraterrestrial influences. From the perspective of Unified Complex Systems Theory (UCST), this paper identifies seven critical flaws in contemporary ocean research: excessive Earth-centrism that neglects long-term cumulative solar system effects; incomplete non-inertial frame corrections in ocean dynamic modeling; the absence of a unified systemic ontology; insufficient cross-scale and cross-domain coupling mechanisms; structural disconnection between science, technology, engineering, and real-world deployment; underappreciation of warfare's irreversible harm to marine ecosystems; and the lack of a unified system-level objective function. By reconstructing ocean research within a unified complex-systems framework, this work reveals missing theoretical and observational dimensions, establishes a holistic multi-scale roadmap, and guides systematic, application-driven innovation to achieve genuine planetary sustainability.

Keywords: Unified Complex Systems Theory (UCST); Ocean Science; Ocean Technology; Ocean Engineering; Planetary Sustainability; Complex System Coupling

1 Introduction

The ocean covers more than 70% of Earth's surface, regulates global climate, supports the planet's largest biosphere, stores over 90% of anthropogenic excess heat, and serves as an irreplaceable reservoir of biological, mineral, and energy resources [1,2]. Conventionally, the ocean is studied as a geophysical fluid bounded by continental margins and seafloors, with dynamics driven primarily by solar radiation, atmospheric forcing, terrestrial runoff, and lunar tidal effects [3-6]. From the perspective of Unified Complex Systems Theory (UCST) [7], however, the ocean is far more than a passive collection of water masses, sediments, marine organisms, and submerged structures. It constitutes a self-organizing, multi-hierarchical, strongly nonlinear, coevolving complex adaptive system characterized by cross-temporal, cross-spatial, cross-domain, and even cross-cosmic coupling [8].

Ocean processes span multiple orders of magnitude in temporal scale, ranging from millisecond-scale turbulent mixing and microscale biological interactions to hourly tidal cycles, seasonal current variations, interdecadal climate oscillations (e.g., El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)), and million-year geological evolution involving plate tectonics, sea-level fluctuations, and biogeochemical sequestration. Spatially, the system extends from molecular biogeochemical reactions and microbial loop dynamics to mesoscale eddies, western boundary currents, global thermohaline circulation, and entire basin-scale interconnected systems. Domain coupling encompasses physical–geological–biological–chemical feedback loops, as well as intensive interactions between natural marine systems and human-engineered infrastructures such as offshore platforms, subsea pipelines, underwater communication networks, and deep-sea mining devices. More profoundly, the ocean is not dynamically isolated within the solar system: gravitational perturbations, solar irradiance variability, and subtle orbital dynamics of neighboring planets impose long-term, low-amplitude but cumulatively significant forcing on ocean circulation, tidal harmonics, and climate-relevant mass transport.

In recent decades, mainstream ocean science, technology, and engineering have achieved remarkable progress across frontier fields. Representative advances in ocean science include high-resolution satellite remote sensing for global sea-surface monitoring, autonomous underwater vehicle (AUV) observations for mesoscale and microscale process detection, global in-situ observation networks for real-time data acquisition, and high-resolution numerical simulations that reveal fine-scale ocean dynamic mechanisms. Ocean technology advances cover underwater wireless power transfer, intelligent sensing networks, and bionic detection systems that enhance observational precision and endurance. Ocean engineering breakthroughs include digital twin modeling for offshore structures and marine energy systems [9], machine learning-driven fluid–structure interaction analysis and fatigue assessment for marine facilities [10,11], blue energy harvesting and offshore wind farm optimization [12,13], tsunami early warning systems based on submarine landslide monitoring [14], physiological and metabolic studies of coral reef microbes under ocean warming and acidification [15-17], deep-sea

biodiversity surveys via robotic landers [18-20], and full-scale deep-sea exploration technology development [21].

These studies have advanced technical capabilities, improved prediction accuracy, and expanded understanding of local marine processes. Nevertheless, nearly all operate within disciplinary silos and reductionist frameworks, prioritizing component-level performance over system-level coherence. Many engineering designs optimize hydrodynamic efficiency or structural safety but neglect ecological cascading effects; ecological conservation studies identify degradation trends but lack scalable engineering interventions; climate adaptation projects focus on regional resilience without accounting for global teleconnections; and nearly all models exclude cosmic-scale external forcing, leading to structurally incomplete representations of ocean dynamics. A particularly concerning trend is the growing gap between publishable laboratory research and field-deployable, sustainable technologies, with many innovations remaining trapped in “paper-to-paper” cycles rather than contributing to real-world planetary stewardship.

Notably, several global holistic ocean modeling initiatives have emerged in recent years, including coupled Earth system models that integrate ocean–atmosphere–land processes [22], integrated ocean–climate–ecosystem models that link biogeochemical cycles with physical dynamics [23], and cross-domain digital twin projects that combine observational data with numerical simulations [24]. These initiatives represent important steps toward holistic ocean research, but they remain constrained by inherent limitations: most are still bounded by Earth-centrism and ignore solar system coupling [25], adopt incomplete non-inertial frame corrections [26], and fail to integrate cosmic and geopolitical factors into unified coupling mechanisms. These gaps highlight the urgency of adopting the UCST framework to advance beyond existing holistic attempts.

UCST provides a rigorous ontological foundation and mathematical framework to treat the ocean–human–engineering–cosmic system as a single, dynamically evolving complex system [7]. Unlike conventional interdisciplinary approaches that merely combine disciplinary methods, UCST establishes a unified ontology, consistent mathematical representation, and shared objective function for the entire coupled system. By integrating deep-sea engineering practices—such as the Rainbowfish Challenge to the Challenger Deep Project (Rainbowfish Project) [27], human-occupied deep-sea submersibles [28], intelligent bionic robotic fish [29], and bio-inspired marine environmental monitoring networks [30]—this perspective demonstrates how a systemic shift can redirect ocean science, technology, and engineering toward actionable, resilient, and truly sustainable development.

This paper makes three core innovative contributions to oceanography based on UCST: first, it breaks the traditional Earth-centric paradigm and incorporates solar system celestial coupling into ocean dynamic modeling; second, it corrects the incomplete non-inertial frame biases in classical ocean dynamics by deriving full non-inertial governing equations; third, it constructs a unified ontology, multi-scale coupling dynamics, and global planetary sustainability objective function for the ocean system, filling the theoretical gap of system-level ocean research.

2 Core Limitations in Current Ocean Science, Technology, and Engineering (UCST Perspective)

2.1 Excessive Earth-Centrism and Neglect of Solar System Celestial Influences

Nearly all modern ocean dynamic models are confined within the Earth system, restricting external forcing to solar radiation, atmospheric circulation, terrestrial inputs, and lunar gravitational effects. Standard ocean general circulation models (OGCMs) (e.g [31-34]) routinely include lunar and solar tidal forcing for coastal and basin-scale flow simulations, wind stress and heat flux at the air-sea interface, submarine geological activities as localized disturbances, and anthropogenic disturbances such as offshore construction, shipping, and pollution discharge [5]. From the UCST principle of system boundary completeness, a valid predictive model must encompass an environmental domain sufficiently larger than the target system to avoid truncating critical interactions.

The Earth's ocean is not dynamically closed: celestial mechanics studies have verified that gravitational perturbations from Venus, Mars, and Jupiter, as well as long-term solar variability and orbital Milankovitch cycles, exert low-amplitude but long-term cumulative effects on ocean mass redistribution, tidal potential, and large-scale circulation stability [35–40]. Existing literature on astronomical climate forcing can be split into two distinct research branches corresponding to these six core cited references. The first branch comprises studies focusing on indirect planetary forcing via Earth's orbital parameter modulation, represented by Refs. [35], [36], [38], and [39], which constitute the mainstream historical research on multi-million-year orbital astronomical forcing. Berger & Loutre [35] constructed a classic orbital numerical solution to compute long-term insolation fluctuations induced by planetary gravitational perturbations, quantifying how eccentricity, obliquity and precession reshape latitudinal and seasonal solar radiation distributions and modulate global paleoclimate patterns over the past 10 Myr. Laskar et al. [38] extended this orbital simulation framework to a 250 Myr timescale, optimizing planetary gravitational integration and tidal dissipation parameters to deliver a fundamental astronomical benchmark for calibrating paleoclimatic sediment archives. Müller et al. [39] systematically reviewed the cascading physical chain linking planetary orbital perturbations to reorganizations of ocean circulation, outlining how orbital eccentricity cycles regulate deep-water ventilation, water column stratification and basin-scale atmospheric circulation via insolation feedback loops. Building upon this orbital framework, Dutkiewicz et al. [36] uncovered a 2.4 Myr eccentricity grand cycle archived within deep-sea hiatus records, revealing that faint gravitational resonance between Earth and Mars subtly modulates Earth's orbital eccentricity, elevates global average insolation, and intensifies deep-ocean eddy activity to drive seafloor sediment erosion; critically, this entire mechanism operates through intermediate orbital adjustments rather than direct physical interference of other celestial bodies with Earth's oceanic and atmospheric fluid envelopes. Collectively, these four publications illustrate the prevailing indirect pathway through which extraterrestrial bodies shape

Earth's climate: interplanetary gravitational forces first alter Earth's orbital geometry, and resultant shifts in insolation then trigger dynamic rearrangements within the ocean and atmosphere.

The second branch encompasses publications that exclude interplanetary gravitational signals from planets other than the Moon and Sun, namely Refs. [37] and [40]. Gray et al. [37] synthesized worldwide investigations into solar variability and associated climatic responses, focusing exclusively on radiative and particle forcing originating from the Sun itself, with no consideration of gravitational perturbations exerted by other planets. Munk & Wunsch [40] quantified the mechanical energy budget sustaining abyssal turbulent ocean mixing, tracing mixing energy solely to surface wind forcing and lunar tidal dissipation; although lunar tidal effects are incorporated, this work does not address gravitational or radiative influences from other planets, nor any direct modulation of ocean–atmosphere dynamics by extraterrestrial bodies outside lunar tidal kinetic inputs.

Quantitative comparisons further demonstrate that the gravitational potentials of Venus, Mars, and Jupiter are vastly weaker than those of the Moon and Sun, such that their planetary signals evade detection in short-term tidal station observations; nevertheless, their long-term cumulative perturbations become geophysically meaningful for centennial to millennial ocean variability and climate projection research. At present, operational ocean circulation models only parameterize lunar and direct solar forcing, while contributions from other solar system planets are routinely discarded without rigorous quantitative evaluation. From the perspective of UCST, all celestial bodies act as intrinsic active sources that produce active forces distinct from conventional passive gravitational attraction [41]. It is these active forces that sustain the stable rotational motion of celestial bodies amid the real, dynamically variable gaseous medium with inherent damping effects. Passive gravitational attraction merely serves to constrain orbital trajectories. The decay rate governing these active interaction intensities may be far lower than that of Newtonian gravitational force, a characteristic analogous to the behaviour exhibited in quantum entanglement. Naturally, this conjecture requires further data analysis for validation. This theoretical framework furnishes additional physical rationale for incorporating auxiliary planetary signals of the solar system into quantitative investigations of long-timescale ocean dynamical processes.

This Earth-centric restriction creates fundamental flaws: long-term ocean circulation trends and low-frequency variability cannot be fully explained by terrestrial forcing alone; tidal amplitude anomalies and interannual current fluctuations are often misattributed to internal variability rather than cosmic perturbations; climate model projections over centennial and millennial scales suffer from unquantified systematic errors; and deep-sea and hadal zone dynamics, which are highly sensitive to weak long-period forcing, remain undercharacterized.

2.2 Incomplete Non-Inertial Frame Correction in Ocean Dynamics

A foundational issue in classical ocean dynamics is the incomplete treatment of non-inertial effects. Standard geophysical fluid dynamics models introduce the Coriolis force as an external correction to account for Earth's rotation in the Earth-fixed non-inertial frame [32, 33], but the fundamental

governing equations (e.g., Navier–Stokes equations) are still derived under ideal inertial frame assumptions. This leads to the omission of critical non-inertial components, including centrifugal acceleration, time-varying rotational perturbations induced by celestial interactions, and frame variations caused by solar system dynamics. Inertial frames are theoretical idealizations that do not exist in nature, and Earth-based observers cannot measure absolute platform motion; relying on partial inertial force corrections introduces unquantified bias into model predictions [42].

Contemporary ocean modeling practices exhibit problematic tendencies: direct application of inertial-frame-derived hydrodynamic equations to realistic ocean circulation simulations, inconsistent or incomplete incorporation of Coriolis effects as external corrections rather than inherent equation components, unjustified quasi-inertial approximation of the Earth-fixed frame for regional or mesoscale studies, lack of systematic error quantification between simulation results and field observations, and absence of theoretical descriptions for centrifugal energy compensation and adaptive mechanical responses in oceanic flows. These biases manifest in practical applications as inaccurate prediction of current shear and turbulence intensity, deviations in underwater vehicle dynamic positioning, misestimation of hydrodynamic loads on subsea structures, and reduced reliability of long-term ocean state forecasts.

2.3 Reductionist Dominance and Component-Level Isolation

Modern ocean research is dominated by reductionism, which decomposes the complex ocean system into isolated components for individual analysis. Typical reductionist studies include fluid–structure interaction analysis focused solely on offshore wind turbine blades or platform legs, control algorithm optimization for individual underwater robots without ecological context, laboratory studies of coral thermal stress decoupled from hydrodynamic and nutrient conditions, and isolated investigation of submarine landslide triggers without linking to basin-scale slope stability [10]. Reductionist methods inherently fail to capture emergent system behaviors arising from nonlinear interactions, such as ecological feedback loops triggered by localized engineering disturbances, collective dynamic responses across coastal–shelf–open-ocean–hadal domains, cascading failures in interconnected marine energy and communication infrastructures, and synergistic degradation from combined climate stress and anthropogenic disturbance. These emergent properties are critical to understanding and managing the ocean system but are completely overlooked in reductionist research.

2.4 Missing Cross-Scale and Cross-Domain Coupling Laws

A central failure of conventional ocean research is the absence of unified coupling rules across spatial, temporal, and domain boundaries. Current models rarely establish consistent mathematical relationships between hadal trench circulation and coastal flooding events, deep-sea biodiversity dynamics and marine carbon sequestration efficiency, offshore energy grid stability and coastal fishery sustainability, or celestial gravitational forcing and geopolitical conflict risks. Without such coupling laws, many “sustainable” ocean solutions merely redistribute environmental pressures rather than

eliminating them. For example, offshore renewable energy projects may reduce local carbon emissions but disrupt benthic ecosystems and migratory pathways, while coastal protection structures may mitigate erosion but alter sediment transport and degrade nearshore habitats. For the Rainbowfish Project, which aims to build a movable laboratory for hadal trenches composed of research vessels, landers, AUVs, and human-occupied submersibles [27], the lack of cross-scale coupling understanding hinders the design of a truly integrated observation system. In wind power utilization, the trade-off between greenhouse gas reduction and impaired atmospheric heat dissipation remains unquantified under traditional frameworks [43], a gap that UCST can address through system-level coupling analysis.

2.5 Structural Disconnection Between Science, Technology, Engineering, and Real-World Application

Advanced methodologies such as Bayesian optimization, digital twinning [9], and machine learning-based environmental monitoring are widely studied in academic literature [10,11], yet most remain confined to laboratory or simulated environments. Key deficiencies include lack of system-level validation under realistic, highly variable ocean conditions, incompatibility with coastal socio-ecological systems and industry practices, absence of life-cycle cost-benefit and resilience metrics under climate uncertainty and extreme events, and failure to account for long-term cosmic-scale variability in deep-sea infrastructure design. This science-technology-engineering-application gap is particularly evident in deep-sea technology: many prototype monitoring systems for hadal zones cannot withstand extreme pressure, are difficult to deploy and recover, or generate data incompatible with global ocean models [21]. The Rainbowfish Project was designed to overcome this gap by building a full-chain system from basic scientific exploration to engineering deployment and sustainable resource assessment [27], but without a unified systemic framework, even large-scale projects risk suboptimal integration and inefficient resource allocation.

2.6 Severe Underinvestment in Hot War Impacts on Marine Sustainability

Contemporary ocean sustainability research largely ignores the existential threat posed by ongoing and potential hot wars to marine ecosystems and human survival. Critical research gaps include quantitative assessment of marine ecosystem damage from naval combat, weapons testing, and coastal infrastructure destruction; long-term ecological impacts of warfare-related pollution such as oil spills, unexploded ordnance, chemical leakage, and radioactive contaminants; synergistic effects between wartime destruction, climate change, and ocean acidification; and frameworks for post-conflict marine environmental recovery and its relevance to planetary sustainability. Marine warfare causes irreversible harm: oil spills destroy pelagic and benthic habitats, underwater explosions cause mass marine organism mortality and cetacean hearing damage, sunken military vessels release heavy metals and toxic materials, and targeted coastal facilities release pollutants into estuarine and coastal waters. These impacts disrupt fisheries, threaten desalination-derived freshwater supplies, and undermine global food security, yet they are almost entirely absent from mainstream ocean sustainability models [1, 6]. From a UCST perspective, geopolitical conflicts represent extreme perturbations to the coupled human-ocean

system and must be integrated into systemic risk assessment.

2.7 Lack of a Unified System-Level Objective Function

Nearly all ocean research optimizes local performance metrics, such as power conversion efficiency of blue energy devices [12], structural load-bearing capacity [10,11], underwater robot tracking accuracy [29], or local flow field prediction precision [25]. Very few studies define a global objective function for the ocean system that simultaneously integrates ecological integrity and biodiversity conservation, long-term sustainability of marine resource exploitation, engineering safety and resilience, human well-being and climate change mitigation, and dynamic stability under cosmic-scale and geopolitical perturbations. This absence of a unified goal leads to fragmented innovation, where advances in one domain may inadvertently degrade another. A UCST-compatible objective function prioritizes planetary habitability and system-level resilience over narrow technical performance, providing a consistent benchmark for evaluating all ocean science, technology, and engineering endeavors.

3 A Unified Complex Systems Framework for Ocean Research

The UCST-based framework for ocean research is built on three foundational pillars, which together establish a consistent ontology, multi-level coupling dynamics, and global sustainability objective function for the ocean system.

3.1 Systemic Ontology: The Ocean as a Coevolving Complex Adaptive System

Under UCST, the ocean system is formally defined by four core elements that unify physical oceanography, marine biology, deep-sea engineering, and planetary science within a single conceptual framework. The entities of the system include physical water masses, geological structures, biological communities, engineered infrastructures, human activities, and solar system celestial bodies, all of which are interrelated components of the unified system. The interactions among these entities are nonlinear, multi-scale, and time-varying feedback loops, covering cosmic–terrestrial, physical–biological, engineering–ecological, and human–environmental couplings that drive system evolution. The system exhibits emergent properties that are irreducible to individual components, including climatic stability, carbon sink capacity, ecological resilience, and response to external perturbations, which are the core characteristics of complex adaptive systems. The system also possesses adaptive capabilities, with natural oceanic subsystems, human engineering systems, and celestial forcing coevolving across multiple spatial and temporal scales to maintain dynamic stability.

3.2 Multi-Level Hierarchical Coupling Dynamics

UCST emphasizes vertical and horizontal cross-scale coupling to eliminate artificial separations between deep and shallow, natural and artificial, local and global ocean components. Vertical coupling follows the cascade from solar system celestial dynamics to atmospheric dynamics, then to oceanic dynamics spanning hadal, deep-sea, continental shelf, and coastal zones, and finally to human social–

economic systems, forming a top-down dynamic linkage. Horizontal coupling includes inter-basin ocean connections, transboundary marine ecological networks, interconnected offshore energy systems, and multi-body celestial interactions, ensuring lateral system coherence. Cross-domain coupling integrates physics, biology, engineering, policy, cosmic science, and geopolitical security, breaking disciplinary barriers to form a fully integrated research paradigm. This hierarchical structure supports the development of scale-bridging mathematical models that capture the full complexity of the ocean system.

3.3 Unified System Objective: Global Planetary Sustainability

The UCST framework establishes a single system-level optimization goal to guide all ocean research and engineering activities: maximizing long-term planetary habitability and ocean system resilience under a set of non-negotiable constraints. These constraints include ecological integrity and biodiversity conservation to protect marine ecosystems, engineering robustness and long-term operational safety to ensure infrastructure reliability, renewable and sustainable marine resource utilization to avoid overexploitation, social equity and practical applicability to benefit coastal communities, and dynamic stability under cosmic-scale and geopolitical perturbations to ensure long-term system viability. This objective function replaces fragmented local optimization with unified system-level evaluation, aligning all research and engineering efforts with planetary sustainability.

3.4 Core Mathematical Formulations of the UCST Framework

To reduce theoretical abstraction, the framework incorporates four core mathematical formulations consistent with UCST. The unified cosmic–ocean coupling dynamic equation is expressed as:

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla) \vec{U} = -\frac{1}{\rho} \nabla P + \vec{F}_{geo} + \vec{F}_{bio} + \vec{F}_{cosmic} + \nabla \cdot \vec{\tau} \quad (1)$$

where $\vec{U}$ is the ocean velocity vector, $\frac{\partial \vec{U}}{\partial t}$ is the local temporal acceleration term, $(\vec{U} \cdot \nabla) \vec{U}$ is the convective inertial term, ρ is seawater density, P is pressure, ∇P is the pressure gradient force, $\vec{F}_{geo}$ is geological forcing, $\vec{F}_{bio}$ is biological feedback, $\vec{F}_{cosmic}$ is celestial gravitational forcing, and $\vec{\tau}$ is viscous stress tensor.

This is the extended Navier-Stokes momentum equation incorporating additional external forces including celestial passive gravitational pull, potential active forcing and biological effects, consistent with the dynamic unclosed characteristics of global ocean.

The revised non-inertial frame governing equation for ocean flows is:

$$\frac{D\vec{U}}{Dt} + 2\vec{\Omega} \times \vec{U} + \vec{\Omega} \times (\vec{\Omega} \times \vec{r}) = -\frac{1}{\rho} \nabla P + \vec{F}_{other} \quad (2)$$

Where $\frac{D\vec{U}}{Dt}$ is Material derivative of flow velocity, $\vec{\Omega}$ is Earth's angular velocity, $2\vec{\Omega} \times \vec{U}$ is Coriolis inertial force, $\vec{r}$ is position vector, $\vec{\Omega} \times (\vec{\Omega} \times \vec{r})$ is Centrifugal inertial force, and the left-hand terms include full Coriolis and centrifugal accelerations. $-\frac{1}{\rho}\nabla P$ is Pressure gradient force per unit mass, $\vec{F}_{other}$ is Other external resultant forces.

The cross-scale coupling scaling law follows:

$$\Pi = L^{\alpha} T^{\beta} M^{\gamma} \prod_{i=1}^n C_i^{\delta_i} \quad (3)$$

where Π is Dimensionless similarity criterion representing the coupling coefficient, L, T, M are spatial/temporal/mass scales, and C_i are Derived physical quantities representing domain coupling parameters. α, β, γ are Dimension exponents of fundamental physical quantities. δ_i are Corresponding exponential coefficients, $\prod_{i=1}^n(\cdot)$ are Product operation from $i=1$ to n .

The global planetary sustainability objective function is formalized as:

$$\text{Max } J = \int_0^T [\omega_1 E(t) + \omega_2 S(t) + \omega_3 R(t) + \omega_4 H(t)] dt \quad (4)$$

subject to $G(\vec{U}, t) \leq 0$, where $E(t)$, $S(t)$, $R(t)$, $H(t)$ are ecological, resource, resilience, and human well-being metrics, ω_i are weight coefficients, and G are constraint vector functions related to velocity field and time.

This section presents illustrative functions that demonstrate the fundamental application of the UCST method for analyzing various types of research problems. Since these illustrative cases serve only as methodological demonstrations rather than fixed standards, readers may flexibly adjust and adapt the UCST-based analytical approaches according to their specific research contexts and practical requirements.

4 Priority Research Directions Identified by UCST

4.1 Cosmic–Ocean Coupling Modeling

UCST-driven cosmic–ocean coupling modeling focuses on developing dynamic equations that integrate gravitational and energetic influences from the Sun, Moon, Venus, Mars, Jupiter, and other solar system bodies, moving beyond traditional Earth-centric forcing. This direction aims to quantify the amplitude, periodicity, and physical mechanisms of non-lunar celestial effects on tides, circulation, and mass transport, particularly their long-term cumulative impacts on centennial to millennial ocean dynamics. It also establishes statistical criteria to determine which cosmic influences are negligible for specific modeling scenarios, balancing model complexity and computational efficiency.

The schematic Fig. 1 presents a conceptual system model for investigating Earth's ocean dynamics under forcing beyond traditional Earth-centric drivers, framing the ocean as a dynamically open target system embedded within a broader environmental domain large enough to include cosmic perturbations. The diagram explicitly identifies key extraterrestrial forcing mechanisms—including gravitational perturbations (red arrows), solar variability (yellow arrows), and orbital Milankovitch cycles (blue arrows)—emanating from the Sun and other solar system bodies (Mercury, Venus, Mars, Jupiter, Saturn) and propagating into Earth's ocean system. This research addresses specifically four critical oceanographic problems that cannot be resolved under Earth-centric frameworks: unexplained long-term ocean circulation trends, tidal anomalies linked to multi-body gravitational perturbations, unquantified errors in long-term climate projections, and undercharacterized hadal zone dynamics sensitive to weak long-period forcing. Together, these elements visually articulate the rationale for developing UCST-based dynamic equations that integrate gravitational and energetic influences from the Sun, Moon, and other solar system bodies, quantifying the amplitude, periodicity, and physical mechanisms of non-lunar celestial effects on tides, circulation, and mass transport, and establishing statistical criteria to identify negligible cosmic influences for targeted modeling applications.

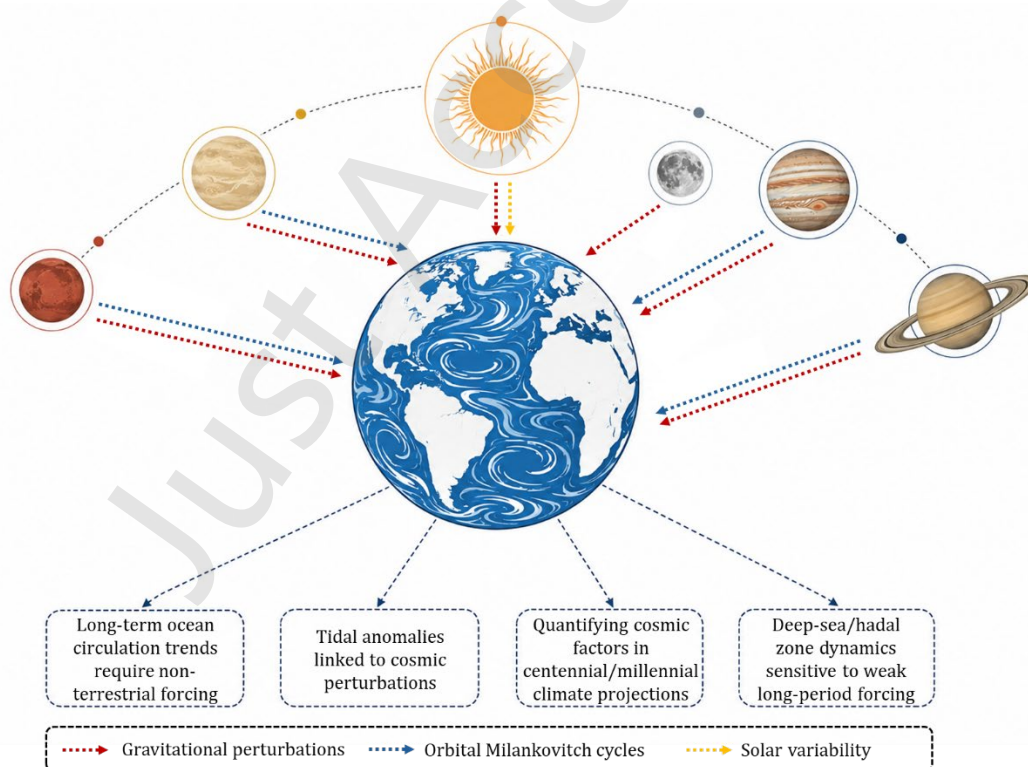


Fig.1 An illustrative system model for studying ocean dynamics beyond Earth-centric forcing

From the perspective of universal gravitation, quantitative comparison of gravitational forces exerted by solar system celestial bodies on any unit mass object on Earth verifies the rationality of the model's screening mechanism for negligible cosmic forcing. The Sun and the Moon constitute the two dominant

gravitational forcing sources that drive Earth's ocean tidal and large-scale dynamic responses. Adopting astronomically verified gravitational acceleration values acting on Earth's surface unit mass for standardized comparison: the solar gravitational acceleration is approximately $5.93 \times 10^{-3} \text{ m/s}^2$, and the lunar gravitational acceleration is approximately $3.31 \times 10^{-5} \text{ m/s}^2$. These two sources jointly dominate the periodic gravitational perturbation of Earth's ocean tides, thermohaline circulation, and large-scale mass transport. In contrast, the gravitational contributions of other major solar system planets are extremely marginal with precisely calibrated magnitudes. Venus, the closest terrestrial planet to Earth, imposes a gravitational acceleration of only $2.18 \times 10^{-8} \text{ m/s}^2$ on Earth's surface objects, accounting for merely **0.0037%** of solar gravitational forcing and **0.066%** of lunar gravitational forcing. Jupiter, the most massive gas giant in the solar system with the strongest planetary gravitational influence on Earth, generates a gravitational acceleration of approximately $3.08 \times 10^{-8} \text{ m/s}^2$, equivalent to **0.0052%** of solar forcing and **0.093%** of lunar forcing. The gravitational perturbations from Mars, Saturn, Mercury and other distant celestial bodies are further diminished, with their gravitational acceleration magnitudes all falling below $1.0 \times 10^{-9} \text{ m/s}^2$ and occupying less than 0.001% of the solar-lunar dominant gravitational forcing. Such ultra-weak instantaneous planetary gravitational perturbations are far below the sensitivity threshold of short-term ocean dynamic variation, demonstrating that **planetary gravitational forcing can be completely neglected in conventional short-term ocean modeling to reduce computational overhead.**

Nevertheless, UCST proposes a fundamental theoretical distinction that subverts the conventional understanding of celestial perturbation mechanisms: all stellar and planetary bodies should be regarded as living active entities analogous to microscopic active particles, rather than inert mass points governed merely by passive gravitational interaction [41]. Every celestial body continuously generates and outputs endogenous active forces, and the mutual coupling of active forces between two stars exhibits physical characteristics highly similar to quantum entanglement. Different from conventional planetary transient gravitational perturbations with rapid dissipation and no residual accumulation, the stellar active force interactions among the Sun, Moon, Earth, Venus, Mars, Jupiter, and other solar system bodies feature an extremely slow decay rate and long-duration superposition effect across centennial to millennial and even geological timescales. These stable, low-frequency, long-period active driving signals continuously modulate ocean stratification stability, long-term circulation drift, tidal resonance periodicity, and deep-sea dynamic equilibrium, ultimately forming detectable cumulative anomalous trends in long-term oceanic time-series datasets. Crucially, owing to the ultra-slow decay and long-range entanglement characteristics of interstellar active forces, the effective boundary of the system environment in UCST modeling must be defined far beyond the conventional gravitational action distance. Traditional ocean models only consider finite-range gravitational forcing and ignore long-term active force coupling effects, resulting in systematic omission of long-period celestial driving mechanisms. Therefore, while trivial instantaneous planetary gravitational effects can be reasonably excluded to optimize model computation, the long-term cumulative influence of slow-decay solar planet-earth active force entanglement interactions is indispensable in long-timescale cosmic-ocean

coupling simulations. While the existence of planetary intrinsic active forces is deduced via logical inferences accounting for sustained rotational motion within a dynamically varying gaseous damping medium [41], this line of inquiry undoubtedly merits rigorous scholarly investigation. This theoretical improvement effectively compensates for the core defect of Earth-centric models, which fail to capture long-term secular ocean dynamic variations driven by cross-scale celestial active interactions.

4.2 Non-Inertial Frame Correction for Ocean Dynamics

Non-inertial frame correction research quantifies the dimensionless relative errors (unit: %) induced by incomplete non-inertial corrections in circulation modeling, tide prediction, and underwater vehicle dynamics, with errors calculated as the residual ratio between simulated and observed values: $E_r = \frac{|X_{sim} - X_{obs}|}{|X_{obs}|} \times 100\%$. This direction derives revised governing equations for fully non-inertial Earth-fixed frames that incorporate complete Coriolis, centrifugal, and celestial-induced rotational effects, replacing the partial corrections in traditional models. It then implements these correction modules into OGCMs and other complex system models to eliminate structural bias, improving the accuracy of ocean state forecasts, underwater vehicle positioning, and subsea structure load prediction. The revised equations are clearly presented with standardized variable definitions to ensure reproducibility and clarity.

Figure 2 outlines a research framework addressing a critical flaw in conventional ocean dynamics modeling: the inertial frame assumption, which overlooks Earth's non-inertial motion and introduces potential errors. Specifically, the middle panel of Figure 2 displays the module of revised governing equations, in which the non-inertial additional force correction term serves as the dedicated correction item embedded into conventional governing equations established under the ideal inertial frame. This correction is theoretically rooted in non-inertial mechanics. The Earth is essentially a non-inertial reference frame subject to both rotational and revolutionary motions; nevertheless, conventional ocean dynamic models neglect the residual Coriolis force and orbital perturbation force induced by Earth's inherent non-inertial effects, and these omitted physical forces constitute the primary systematic error sources that necessitate targeted correction. It quantifies these inaccuracies across key applications—including circulation modeling (9.15), tide prediction (5.10), and underwater vehicle dynamics (5.50)—to highlight the magnitude of the problem. The core solution presented is a set of revised governing equations tailored for non-inertial Earth-fixed frames, designed to correct the flawed inertial approximation. The study may conclude with the implementation of these corrections into Ocean General Circulation Models (OGCMs), framing the task as a complex systems challenge to ensure the improved equations translate to more accurate, robust simulations of ocean behavior.

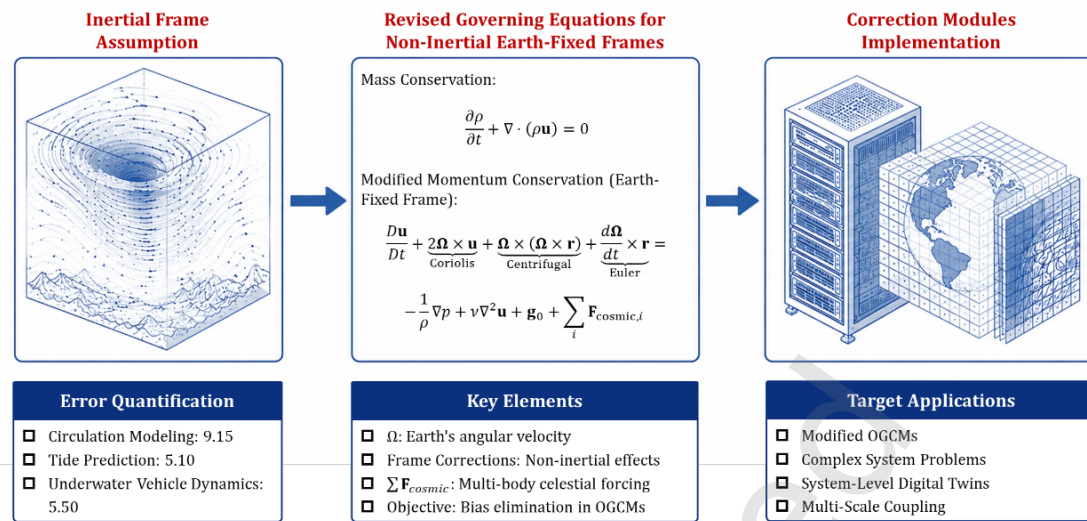


Fig.2 An illustration of using UCST to study Non-Inertial Frame Correction for Ocean Dynamics

The study carried by Huang and Cui [42] revealed that abandoning the inertial frame assumption—long taken for granted in classical lunar theories—leads to measurable discrepancies between predicted and observed lunar trajectories when Earth’s motion is perturbed. Unlike classical mechanics, which relies on inertial forces to interpret such deviations, the UCST provides a consistent explanation by modeling the Moon as a six-degree-of-freedom dynamic entity with active forces. A key discovery is that these active forces must be continuously adjusted to preserve the stability of the measured lunar trajectory, demonstrating that the inertial frame assumption introduces unaccounted systematic bias into lunar orbit calculations. These findings highlight the necessity of non-inertial frame corrections for precise lunar trajectory modeling, analogous to improvements seen in ocean dynamics and underwater vehicle systems when full non-inertial effects are incorporated.

4.3 Unified Mathematical Modeling of Coupled Ocean Subsystems

This direction constructs UCST-consistent dynamic equations for integrated cosmic–physical–biological–engineering systems, unifying previously isolated submodels into a single mathematical framework. It derives universal scaling laws that bridge hadal, abyssal, mesoscale, and coastal processes, establishing consistent mathematical relationships across spatial and temporal scales. It also establishes system-level stability criteria that go beyond traditional structural safety, incorporating ecological stability, dynamic resilience, and long-term sustainability to evaluate the overall performance of ocean systems. Demonstrations of the core mathematical formulas of the UCST framework are provided in Section 3.4. This modeling approach captures emergent behaviors and cross-scale feedbacks that reductionist models cannot reproduce, providing a theoretical basis for system-level ocean management.

4.4 System-Level Digital Twins for the Ocean

Next-generation ocean digital twins under UCST transcend structural engineering twins to integrate real-time hadal observation data from multiple platforms, including landers and human-occupied

submersibles, filling the data gap in deep-sea and hadal zones. These digital twins incorporate ecological, climatic, and cosmic perturbation data to form a full-dimensional virtual representation of the ocean system, supporting system-level “what-if” risk simulations that include warfare, extreme climate, and cosmic perturbation scenarios. They enable quantitative evaluation of system-level responses to external disturbances, providing decision support for marine disaster prevention, ecological protection, and sustainable engineering design.

4.5 Hadal Science as a Core Component of Global Ocean System

The hadal zone (>6,500 m) is a critical regulator of global biogeochemical cycles, and UCST prioritizes its integration into the global ocean system. This direction deploys integrated hadal observation networks as core investigative infrastructure, collecting long-term, multi-parameter data to reveal hadal zone dynamic mechanisms. It models hadal–abyssal–shelf teleconnections to establish cross-scale linkages between the deepest ocean and shallow coastal zones, clarifying the hadal zone’s role in global ocean circulation and carbon cycling. It also designs sustainable deep-sea engineering that preserves system-level functions, minimizing ecological disturbance while supporting scientific exploration and resource assessment.

4.6 Ecologically Embedded Ocean Engineering

UCST shifts ocean engineering design principles from structural safety to system-safe-by-design, prioritizing engineering solutions that enhance ocean resilience rather than merely avoiding harm. This direction develops coevolutionary design methods for bionic robots and marine ecosystems, creating submersibles and monitoring systems that mimic marine organisms to minimize ecological disturbance while enabling high-resolution environmental monitoring. It also designs low-negative-impact deep-sea infrastructure and blue energy facilities that align with ecological carrying capacity, balancing engineering performance with marine conservation. Intelligent bionic robotic fish [29] and BCI-controlled live-fish monitoring platforms [30] exemplify this paradigm, offering natural stealth, low disturbance, and high adaptability.

4.7 Systemic Assessment of Hot War Impacts on Marine Sustainability

This direction quantifies the ecological damage caused by naval conflicts, ordnance leakage, and targeted coastal infrastructure destruction, establishing quantitative metrics for warfare-induced marine pollution and biodiversity loss. It models the long-term recovery trajectories of polluted marine systems, predicting ecosystem restoration timelines and key intervention points. It integrates warfare risk into ocean sustainability and resilience indicators, incorporating geopolitical conflict scenarios into long-term ocean planning to address a previously overlooked existential threat. This research fills the gap in mainstream sustainability models and supports post-conflict marine environmental recovery.

4.8 Closed-Loop Translation: Science → Technology → Engineering → Application → Feedback

UCST promotes a closed-loop translation mechanism that connects basic science, technological development, engineering deployment, and real-world application with continuous feedback. This direction constructs field validation networks using comprehensive ocean observation platforms spanning the air–surface–subsea continuum, such as the Intelligent Swift Ocean Observing System (ISOOS) [44], to test and validate UCST models and technologies in real ocean environments. It develops techno-ecological-economic assessment frameworks to evaluate the comprehensive benefits of ocean innovations, balancing technical performance, ecological impact, and economic viability. It also creates governance decision tools directly derived from UCST ocean models, translating theoretical advances into practical policies for marine management and sustainable development.

5 Empirical Case Study: UCST Application to the Rainbowfish Hadal Trench Movable Laboratory Project

To demonstrate the practical value of the UCST framework, this section presents an empirical case study of its application to the Rainbowfish Project [27], a full-scale hadal trench movable laboratory composed of research vessels, landers, ARVs, and human-occupied submersibles.

5.1 Traditional Reductionist Design Limitations

Adopting conventional reductionist design thinking, the Rainbowfish movable laboratory conducts separate optimization for individual components including research vessels, deep-sea landers, autonomous underwater vehicles and human-occupied submersibles. Each unit is tuned to meet discrete performance targets, lacking holistic coordination across the entire system.

Such fragmented design fails to strike a reasonable balance between operational performance and economic expenditure. Component matching falls short of ideal status, restricting the overall functional output of the integrated observation system. Meanwhile, engineering deployment arrangements do not fully align with actual research requirements, lowering data utilization efficiency and creating obstacles to converting field observation results into valid inputs for global ocean models.

5.2 UCST-Guided Integrated Design

Redesigned under the guidance of UCST theories, the project is built upon three core supporting dimensions of the unified framework. It regards research vessels, deep-sea landers, underwater vehicles and other exploration facilities as correlated parts of an integral movable laboratory, and builds interactive response relations among all individual equipment units.

Hierarchical collaborative matching mechanisms are adopted to coordinate functional cooperation of each device, effectively connecting local deep-sea detection outcomes with global ocean research analysis. The overall design objective takes comprehensive operational efficiency and cost control into comprehensive consideration, making rational trade-offs instead of merely pursuing maximum

performance of single equipment.

Classic mathematical models are embedded into the whole observation and detection system. Revised dynamic formulas optimize operational stability of deep-sea devices, and revised kinematic equations enhance navigation and positioning precision of submersible equipment. Uniform computational criteria unify monitoring data collected by different functional units. The established full-scale digital twin system gathers real-time detection information and operational status data of all movable laboratory components, enabling predictive analysis on equipment operating conditions and overall mission execution effects.

Evidently, the original Rainbowfish Project [27] was carried out without UCST theoretical guidance. Its design and deployment adopted conventional reductionist approaches, and no benchmark parameters or comparative control schemes aligned with UCST integrated design were established throughout the whole process. Consequently, quantitative data and standard comparison tables between the original scheme and UCST-optimized design cannot be offered in this paper. The proposed improvements based on UCST analysis are retrospective methodological conclusions, which can only offer technical references for future analogous ocean engineering projects, rather than generating verifiable comparative results for the completed project.

6 Why a Systemic UCST Shift Is Essential for Real-World Impact

Without a unified complex-systems foundation, ocean engineering innovations risk unintended ecological harm, ecological protection lacks scalable engineering solutions, climate adaptation remains locally optimal but globally inefficient, cosmic and geopolitical risks are excluded leading to fragile long-term planning, and research accumulates without converging into a sustainable blue economy. Excessive wind energy development serves as a typical illustration: wind turbines draw kinetic energy from surface air and slow down wind flow, weakening vertical heat dispersion between the ground and upper air. Meanwhile, wind farm construction damages original vegetation and lowers surface albedo to absorb more solar heat, and blade rotation disturbs the atmospheric boundary layer to trap residual heat near the ground. Large-scale wind exploitation further disrupts natural global air circulation, eventually generating an overall planetary warming effect instead of lowering global temperature.

In contrast, the UCST framework transforms ocean research into a goal-directed endeavor focused on planetary sustainability, structurally embeds cross-disciplinary collaboration into the research paradigm, designs deep-sea technologies and comprehensive platforms for systemic utility rather than isolated performance, and ensures breakthroughs directly support evidence-based governance and real-world application. This systemic shift is the only path to unlock the full potential of ocean science, technology, and engineering for planetary sustainability.

7 Conclusion and Strategic Outlook

Ocean science, technology, and engineering have reached a historical inflection point. While disciplinary advances have been impressive, their full potential for planetary sustainability can only be unlocked through a paradigm shift to UCST. By moving beyond reductionism and Earth-centrism, embracing complete non-inertial frame physics, integrating cross-scale and cross-domain couplings, and accounting for cosmic and geopolitical risks, we can establish a truly holistic ocean research system.

The Rainbowfish Project [27], together with comprehensive platforms such as ISOOS [44], provides a tangible engineering framework for implementing UCST principles. By regarding the ocean as a single coevolving complex system spanning from solar system dynamics to human societies, we can responsibly explore and utilize marine resources, safeguard fragile ecosystems, and ensure a sustainable future for our planet.

Future efforts should focus on five strategic priorities: developing the first UCST-based global ocean circulation model with full cosmic forcing; deploying a full-scale comprehensive observation network from the atmosphere to hadal trenches to validate systemic models; establishing international standards for ecologically embedded deep-sea engineering; integrating warfare risk and geopolitical uncertainty into ocean sustainability assessment; and building global collaborative frameworks for unified complex systems ocean research. Only through systemic, unified, and mission-oriented ocean science can humanity achieve lasting harmony with the marine environment.

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