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Mariana Trench, Pressure-dependent modelling, Thermophysical properties, Random Vortex Method, Hadal hydrodynamics

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Pressure-Resolved Thermoph-ysical and Vortex- Based Modelling of Extreme Deep-Sea Hydraulic Behaviour in the Mariana Trench Using Challenger Deep CTD Observations

Abstract
Hadal trenches represent the most extreme pressure dominated ocean environments where seawater properties and flow behaviour are significantly different from shallow ocean assumptions. This study addresses the lack of integration of Mariana Trench CTD observations with pressure dependent thermophysical modelling and vortex based hydrodynamic simulation. We developed a reproducible computational framework using corrected. Mat based profile data from Challenger Deep and Challenger Deep East. Depth, pressure, temperature, and salinity were used to estimate density, dynamic viscosity, kinematic viscosity, compressibility, and hydrostatic stress, which were then simulated using the Random Vortex Method and statistical site comparison. The corrected profiles reached a depth of ~8895 m and a pressure of ~901 atm, confirming the scale of the trench. Pressure increased density strongly, viscosity was systematic with depth, compressibility had gradient-derived numerical sensitivity and hydrostatic stress increased monotonically through the water column. Vortex simulations show pressure conditioned particle dispersion and decay of kinetic energy. The study concludes that pressure-resolved thermophysical parameters are required for hadal hydrodynamic modelling. The main contribution of the paper is an integrated framework that links the measured trench profiles, estimation of seawater properties, hydrostatic stress, vortex diffusion and statistical analysis for modelling extreme deep-ocean flow.

1. Introduction

The hadal zone is one of the least accessible and most physically extreme regions of the global ocean, where hydrostatic pressure, low temperature, limited observational access, and complex trench morphology create conditions that differ substantially from upper-ocean and continental-slope environments [1]. Among these systems, the Challenger Deep in the Mariana Trench is well known as one of the deepest places on Earth and thus a natural reference site for the study of pressure-dominated oceanographic processes and the corresponding effects on fluid properties, transport behaviour and deep-ocean modelling [2]. The geometrical configuration of its seafloor is not a simple basin but a highly structured trench environment where bathymetric gradients and local morphological variability affect the interpretation of depth, pressure and spatially resolved oceanographic measurements [3]. Recent pressure-derived depth assessments [4] highlight the need for a physically consistent conversion between pressure, depth and water-column properties in the analysis of observations from the deepest ocean.

Characterisation of deep-trench hydrodynamics is challenging due to limited direct observations, instrumentation subjected to extreme pressure, and measured profiles that often need careful treatment before they can be used in quantitative modelling. Evidence of ocean mixing in the Challenger Deep indicates that hadal trenches can harbour dynamically active water-column processes, rather than being quiescent terminal basins [5]. Acoustic and environmental observations from the Challenger Deep further show that robust instrumentation and careful interpretation of pressure-linked signals are required for hadal observations [6]. In addition, the high rates of benthic carbon turnover in the deepest trench sediments suggest that the Mariana Trench is a dynamic physical and biogeochemical environment, where transport, mixing and near-bottom processes can influence system behaviour [7]. The microbial evidence from the hadal biosphere also supports the scientific importance of studying the deepest ocean as an integrated environmental system and not simply as a geographic extreme [8].

A key weakness in current modelling practice is that analyses of deep-ocean flow often treat seawater properties as weakly varying, or use formulations intended for shallower pressure regimes. Such simplifications are not appropriate in the Mariana Trench where pressures reach hundreds of atmospheres and can affect density, viscosity, compressibility, stress and derived transport parameters. The TEOS-10 framework provides a thermodynamic basis for the calculation of the properties of seawater under oceanographic conditions, including pressure dependent behaviour relevant to deep profiles [9]. An accurate representation of salinity is also important because salinity directly affects density and related thermophysical properties used in pressure-resolved modelling [10]. Pressure dependent seawater correlations provide another basis for estimation of thermophysical properties such as viscosity and related transport coefficients at elevated pressure [11]. However, the coupling of these thermophysical models with vortex-based hydrodynamic simulation and statistical comparison to Mariana Trench profile data is rarely performed.

The present study fills this gap by developing a pressure-dependent hydrodynamic and thermophysical modelling framework for Challenger Deep and Challenger Deep East. The study estimates the density, dynamic viscosity, kinematic viscosity, compressibility and hydrostatic stress using profile-based pressure, depth, temperature and salinity information. These properties are then coupled to a Random Vortex Method description of deep-ocean flow with pressure-dependent kinematic viscosity to parameterise diffusive vortex-particle motion. The random vortex formulation is well suited as it offers a computationally feasible approach to describe advection, diffusion and vorticity dispersion in slightly viscous flow systems [12]. The study focuses on profile-derived, pressure-dependent property modelling and 2D vortex-particle simulation, and does not resolve full 3D trench circulation, seafloor roughness turbulence, internal tides, sediment transport or reactive biogeochemical feedback. The framework, despite these limitations, provides a reproducible mathematical connection between measured hadal profiles, estimation of thermophysical properties, and vortex based hydrodynamic response.

This study is novel in that it treats Challenger Deep and Challenger Deep East as pressure-dominated hydrodynamic systems rather than isolated observational sites. Existing studies usually consider hadal ecology, trench bathymetry, seawater thermodynamics or vortex methods separately; however, this study combines pressure from profiles, thermophysical-property estimation, hydrostatic stress analysis, Random Vortex Method simulation and statistical site comparison within one reproducible modelling framework. The novelty of the work is the use of pressure-dependent kinematic viscosity as a direct parameter in vortex-particle diffusion which allows the hydrodynamic response of deep-ocean flow to be linked mathematically to measured hadal-zone pressure, temperature and salinity conditions. The study accomplished the following three objectives:

- It estimated pressure-dependent thermophysical properties, including density, dynamic viscosity, kinematic viscosity, compressibility, and hydrostatic stress, from Challenger Deep and Challenger Deep East profile data.
- It implemented a Random Vortex Method framework in which pressure-dependent kinematic viscosity-controlled vortex-particle diffusion and dispersion under deep-ocean conditions.
- It statistically compared model-derived properties and vortex-response indicators between Challenger Deep and Challenger Deep East to evaluate site-level differences in pressure-resolved hydrodynamic behaviour.

2. Literature review

Hadal-trench research has developed along three strands: environmental observation, seawater thermodynamics, and computational hydrodynamics, which have often remained methodologically separate. Early hadal-water work has highlighted the chemical uniqueness of trench environments. The deep waters of western Pacific trenches exhibit measurable differences in dissolved constituents that reflect isolation, pressure exposure, and bottom-water exchange processes [13]. This was extended to a better understanding of the influence of trench depth, productivity input and local morphology on biological and benthic community patterns via the use of submersibles and landers in observational studies, confirming the need to treat the Mariana Trench as a spatially variable system rather than a deep basin [14]. Geochemical work on sediments from the Mariana Trench also showed continuation of organic-matter transformation under hadal conditions, suggesting that physical transport and pressure-controlled processes in the water column may influence near-bottom chemical gradients [15].

Microbial studies have also contributed to the knowledge of Mariana Trench environments by characterising free-living and particle-associated communities in hadal waters and the potential effect of particle transport, water-column stratification and local circulation on biological distributions [16]. Studies of the water column in the vicinity reported relatively uniform distributions of heterotrophic bacteria within the interior of the trench, supporting the possibility of vertically connected transport processes regardless of the extreme depth of the system [17]. In-situ oxygen microprofile measurements in hadal trenches support this interpretation by showing that benthic carbon mineralisation can be measured directly under trench conditions, but such studies are mostly concerned with ecological and biogeochemical response rather than pressure-dependent fluid-property modelling [18]. These works collectively define the Mariana Trench as an active environmental system but provide little mathematical treatment of pressure-modified density, viscosity, compressibility, and hydrodynamic dispersion.

A second body of literature deals with seawater thermodynamics and thermophysical property estimation. The TEOS-10 framework provides a rigorous framework for the evaluation of seawater, ice and humid-air properties and is central to the modern oceanographic calculation of pressure-dependent state variables [19]. Studies of the heat content have indicated the need for conservative oceanic variables in the evaluation of heat storage and heat fluxes, which is important for any model that attempts to relate temperature, pressure, and transport processes in deep water [20]. Compilations of models for density, viscosity, thermal conductivity and related thermophysical quantities have been reviewed [21] with useful equations for engineering and oceanographic calculations. The studies are strong in that they provide validated thermodynamic and empirical bases, but they are not generally designed to simulate vortex dispersion, turbulent transport or site-specific hydrodynamic response in the Mariana Trench.

The third technical basis for the present study is the literature on computational fluid dynamics. The numerical methods for incompressible viscous flow showed the possibility of solving viscous-flow problems by discretised approximations of the velocity and pressure fields [22]. Later, vortex-method theory showed convergence properties for three-dimensional vortex formulations, providing mathematical support for the use of vortex particles to represent rotational flow structures [23]. Higher order vortex methods built on this foundation to address accuracy in two- and three-dimensional settings, making vortex approaches suitable for idealised simulations of advective and diffusive flow behaviour [24]. The explicit velocity-kernel formulation further improved high-order vortex modelling by regularising singular interactions and allowing stable numerical treatment of particle-based vorticity fields [25]. While these studies are powerful for hydrodynamic simulation, they were not developed specifically for pressure-dependent deep-ocean seawater and do not directly incorporate hadal CTD-derived thermophysical properties.

Fragmentation is therefore the main weakness in the existing literature. Hadal studies describe trench chemistry, ecology, and in-situ activity. Thermodynamic studies yield equations of state for seawater properties. Vortex-method studies provide mathematical tools for viscous-flow simulation. Few studies, however, integrate these components into a single pressure-resolved workflow for Challenger Deep and Challenger Deep East. The present study bridges the research gap of an integrated framework linking the hadal profile data with pressure-dependent density, viscosity, compressibility, hydrostatic stress, Random Vortex Method simulation and statistical site comparison. The present study fills this gap by considering the Mariana Trench as a coupled thermophysical and hydrodynamic system subjected to extreme pressure.

3. Methodology

3.1 Research Design

The quantitative computational-modelling research design was used in this study to examine the pressure-dependent hydrodynamic and thermophysical behaviour in the Mariana Trench. The experimental framework included observational CTD profile data from Challenger Deep and Challenger Deep East, derived physical-property estimation, statistical analysis and random vortex simulation. Data processing, numerical modelling, statistical computation and vortex simulation was performed in Python. Final scientific visualisation was done in MATLAB.

The model architecture was sequential, first obtained from the MATLAB , measured depth, pressure, temperature, salinity and sound-speed profiles.mat datasets. Second, pressure-dependent seawater properties were calculated. Third, proxies for stress, compressibility, viscosity and heat-transfer were derived. Finally, the calculated kinematic viscosity was used to parameterise a Random Vortex Method. The general modelling pipeline was:

$z, P, T, S, c \rightarrow \rho, \mu, \nu, \beta, \sigma_h, q \rightarrow$ Random Vortex Simulation → Statistical Evaluation (1)

where (z) is depth, (P) is pressure, (T) is temperature, (S) is salinity, (c) is sound speed, (ρ) is density, (μ) is dynamic viscosity, (ν) is kinematic viscosity, (β) is compressibility, (σ_h) is hydrostatic stress, and (q) is heat-transfer proxy.

3.2 Data Collection Method and Dataset Description

This study employed the two available public Mariana Trench CTD profile datasets, challenger_deep_profile.mat and challenger_deep_east_profile.mat, retrieved from the Mariana Trench Data repository at Dalhousie University [26]. These files were considered as the main scientific data sets as they contained the corrected deep profile variables needed for trench scale modelling. The extracted variables included depth, pressure, temperature, salinity and sound speed. This study did not use a single supervised-learning target variable but modelled multiple dependent physical responses including density, viscosity, compressibility, hydrostatic stress and vortex dispersion.

Preprocessing involved variable extraction, flattening of MATLAB arrays, length matching across physical variables, removal of invalid values, and physical plausibility filtering. Depth values were constrained to the oceanographic range ($0 \leq z \leq 12000$) m, pressure to ($0 \leq P \leq 13000$) dbar, temperature to ($-5 \leq T \leq 50°C$), salinity to ($0 \leq S \leq 45$) PSU, and sound speed to ($1300 \leq c \leq 1700$) m $s(-1)$. The corrected data reached approximately 9000 m depth and about 900 atm pressure, confirming suitability for deep-ocean pressure modelling.

Pressure was converted from dbar to absolute pressure using:

$$P_{\text{abs}} = P_{\text{dbar}} \times 10^4 + P_0 \quad (2)$$

where ($P_0 = 101325$) Pa. Pressure was also expressed in MPa and atm for physical interpretation.

3.3 Population and Sampling

The dataset population is the vertical thermophysical structure of the water column of the Challenger Deep area of the Mariana Trench. The sample included two deep ocean CTD profiles, Challenger Deep and Challenger Deep East. These profiles are from two spatially related but different deep-trench sampling locations and allow comparison of pressure-dependent behaviour on a site-wise basis.

The study did not use random sampling in the usual sense of a survey. Instead, it used observational oceanographic profile sampling, where each measurement was indexed to a depth and represented a vertical sample of the water column. After cleaning, the available full profiles were used for computational modelling. A set of representative depth states were selected based on quantiles of the depth distribution (shallow, intermediate and deep states) for the random vortex experiment. This partitioning enabled the vortex model to investigate the influence of pressure-dependent kinematic viscosity on the diffusion of vortices under various trench depth regimes.

3.4 Data Analysis Technique

The data evaluation was performed in four consecutive steps: descriptive profiling, pressure-dependent thermophysical modelling, Random Vortex Method simulation and statistical evaluation. In the first stage, descriptive statistics were calculated separately for Challenger Deep and Challenger Deep East . Statistics (mean, standard deviation, minimum, median and maximum) were computed for measured variables (depth, pressure, temperature, salinity, sound speed) and derived variables (density, viscosity, compressibility, hydrostatic stress, vortex-response indicators). In this stage, the physical range of each profile was defined, and it was checked if the corrected datasets were representative of trench scale pressure and depth conditions.

In the second stage, thermophysical properties were estimated as a function of pressure from the CTD derived variables . Density was parameterised as a function of salinity, temperature and pressure:

$$\rho = \rho(S, T, P) \quad (3)$$

where ρ is the density of seawater, S is salinity, T is temperature and P is pressure. Dynamic viscosity was a function of temperature and salinity that was pressure conditioned :

$$\mu = f(T, S, P) \quad (4)$$

where μ is dynamic viscosity. The kinematic viscosity was then obtained as the ratio of the dynamic viscosity to the density:

$$\nu = \frac{\mu}{\rho} \quad (5)$$

where (ν) is the kinematic viscosity. The compressibility was estimated numerically from the gradient of density-pressure:

$$\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial P} \quad (6)$$

where (β) is compressibility . The hydrostatic stress was assumed to be equal to the absolute pressure:

$$\sigma_h = P_{\text{abs}} \quad (7)$$

where (σ_h) is the hydrostatic stress, and P_{abs} is the absolute pressure. A heat-transfer proxy was also calculated as:

$$q = h(T_s - T_w) \quad (8)$$

where q is the heat transfer proxy, h is the assumed convective heat transfer coefficient, T_s is the source temperature, and T_w is ambient seawater temperature. These equations provided a pressure-resolved set of properties for each depth-indexed CTD observation.

For the third stage an idealised vortex-particle transport was simulated with a Random Vortex Method, under CTD derived viscosity conditions. Vorticity was modelled as a field of discrete particles.

$$\omega(x,t) = \sum_{i=1}^{N} \Gamma_i \, \delta(x - x_i) \quad (9)$$

where (ω) is vorticity, (N) is the number of vortex particles, (Γ_i) is the circulation of particle (i), (δ) is the Dirac delta function, and (x_i) is the particle position. The induced velocity was calculated using a regularised Biot–Savart kernel:

$$u(x) = \sum_{i=1}^{N} \frac{\Gamma_i}{2\pi} \frac{k \times (x - x_i)}{|x - x_i|^2 + \epsilon^2} \quad (10)$$

where ($u(x)$) is induced velocity, (k) is the unit vector normal to the two-dimensional flow plane, and (ϵ) is the vortex-core radius. Particle position was updated using deterministic advection and stochastic viscous diffusion:

$$x_i^{n+1} = x_i^n + u_i \Delta t + \sqrt{2\nu \Delta t}\, \eta_i \quad (11)$$

where (Δt) is timestep and (η_i) is a normally distributed stochastic term.

The RVM parameters were chosen to yield a stable comparative representation of pressure-conditioned vortex dispersion and not a fully resolved simulation of the three-dimensional trench turbulence. The number of particles was selected such that the spread of a vortex is spatially sufficiently represented and the calculation is reproducible. A fixed timestep was used to ensure stable particle displacements, and consistent comparison between depth states and sites. Circulation was held constant among cases, so that differences in vortex dispersion were controlled mainly by CTD-derived kinematic viscosity rather than by arbitrary circulation variation. The Biot–Savart kernel was regularised with the core radius (ϵ) to prevent the velocity from becoming singular as the vortex particles approached each other. The stochastic diffusion term was scaled by the standard viscous diffusion scaling ($\sqrt{2\nu\Delta t}$), such that the magnitude of random vortex displacement was directly controlled by the pressure-dependent kinematic viscosity. The hydrodynamical novelty of the model is therefore in the coupling $\nu = \mu/\rho$ derived from pressure-conditioned properties of seawater to vortex-particle diffusion.

The fourth stage relied on statistical analysis to compare the thermophysical and hydrodynamic behaviour at the site level. The mean differences between Challenger Deep and Challenger Deep East were compared using Welch's t-test where equal variances could not be assumed. We used the Mann-Whitney U test as a non-parametric comparison of distributional shift and the Kolmogorov-Smirnov test to evaluate more general differences in empirical distributions. Relationships were quantified by correlating pressure, density, viscosity, compressibility and stress. Pressure-property regression was applied to estimate the explanatory power of pressure for density, dynamic viscosity and kinematic viscosity. For reproducibility and transparent post-processing, the resulting model outputs, statistical summaries and vortex indicators were exported as CSV files and visualised in MATLAB .

3.5 Ethical Consideration

Publicly available environmental datasets were analysed in this study. No human participants, human data, biological subjects, or private institutional data were used. Practical privacy-related, informed consent or personal data protection risks were thus minimal. However, responsible data use was maintained by preserving dataset attribution, avoiding unsupported claims, and distinguishing measured CTD variables from model-derived quantities.

Potential bias from spatial limitation due to only using two trench profiles. The results should therefore be considered as site-specific computational evidence, rather than as a complete representation of the whole Mariana Trench. The random vortex, viscosity, compressibility, heat-transfer and stress quantities are mathematical approximations, rather than directly measured ones in the field. This limitation is explicitly acknowledged to avoid overstating the validity of the model. The workflow allows reproducibility through transparent Python computation, MATLAB visualisation, and exportable intermediate datasets.

4. Results

4.1 Experimental Performance

Replacing the incorrect raw-text data parsing with the .mat profile datasets resulted in a physically valid deep-trench modelling workflow in the corrected experiment. Challenger Deep was measured to a maximum depth of 8894.60 m and Challenger Deep East to 8895.08 m. The corresponding maximal pressures were 901.48 atm and 901.53 atm (91.34 and 91.35 MPa respectively), which confirmed that the corrected workflow was representative of Mariana Trench pressure conditions rather than the shallow depth artefact of the earlier analysis.

The pressure increased monotonically with depth, and the hydrostatic stress followed the same behaviour as it was defined as ($\sigma_h = P_{abs}$). The density increased strongly with pressure reaching 1042.42 kg $m(-3)$ in both the sites. The pressure-dependent seawater compression was confirmed through a very strong density-pressure regression of ($R^2 = 0.9981$) for Challenger Deep and ($R^2 = 0.9978$) for Challenger Deep East.

The dynamic and kinematic viscosity also changed with depth. The maximum dynamic viscosity $(2.0963x10(-3))Pas$ and the maximum kinematic viscosity $(2.0110x10-6)m2s(-1)$ were obtained from both sites. The Random Vortex Method was directly coupled to thermophysical properties dependent on pressure as ($\nu = \mu/\rho$). The vortex simulation resulted in stable particle fields, increased radial dispersion and decay of the kinetic-energy proxy from 44.2182 to 0.6681-1.4471 (by site and depth quantile).

Table 1. Summary of major measured and derived variables

Variable	Challenger Deep mean	Challenger Deep max	Challenger Deep East mean	Challenger Deep East max	Unit
Depth	4681.01	8894.60	4968.75	8895.08	m
Pressure	471.76	901.48	500.86	901.53	atm
Pressure	47.80	91.34	50.75	91.35	MPa
Temperature	2.36	29.13	2.34	29.15	°C
Salinity	34.63	35.29	34.63	35.30	PSU
Density	1022.73	1042.42	1024.07	1042.42	$kgm(-3)$
Dynamic viscosity	$1.9172 \times 10(-3)$	$2.0963 \times 10(-3)$	$1.9306 \times 10(-3)$	$2.0963 \times 10(-3)$	Pa s
Kinematic viscosity	$1.8732 \times 10(-6)$	$2.0110 \times 10(-6)$	$1.8838 \times 10(-6)$	$2.0110 \times 10(-6)$	$m(2)s(-$
Hydrostatic stress	47.80	91.34	50.75	91.35	MPa

Table 1 summarises the main measured and model-derived variables for Challenger Deep and Challenger Deep East. Both profiles reached trench-scale depths of ~8895 m and maximum pressures of ~901 atm, or ~91 MPa, confirming that the corrected. Mat-based workflow had captured hadal pressure conditions. Challenger Deep East had a slightly higher mean depth and pressure, and the maximum density of both sites was 1042.42 kg m(-3). The maximal values of the dynamic viscosity, kinematic viscosity and hydrostatic stress were also similar for the two profiles, suggesting broadly similar high pressure thermophysical behaviour.

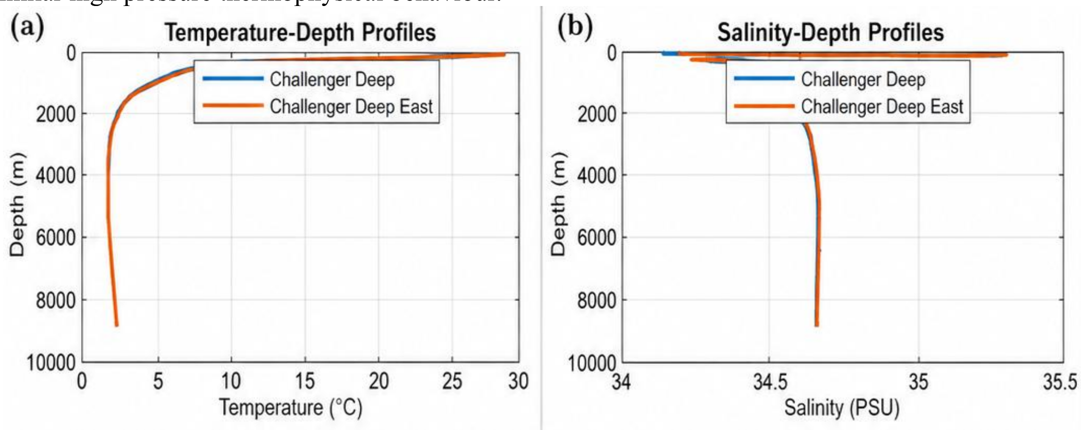

Figure 1. Vertical Thermohaline Structure of Challenger Deep and Challenger Deep East

Figure 1 shows the vertical thermohaline structure at the two sites. Temperature decreased rapidly from the upper water values to cold deep-water conditions, but salinity was within a narrower range in the deep ocean. These profiles gave the measured basis for the estimation of pressure-dependent properties.

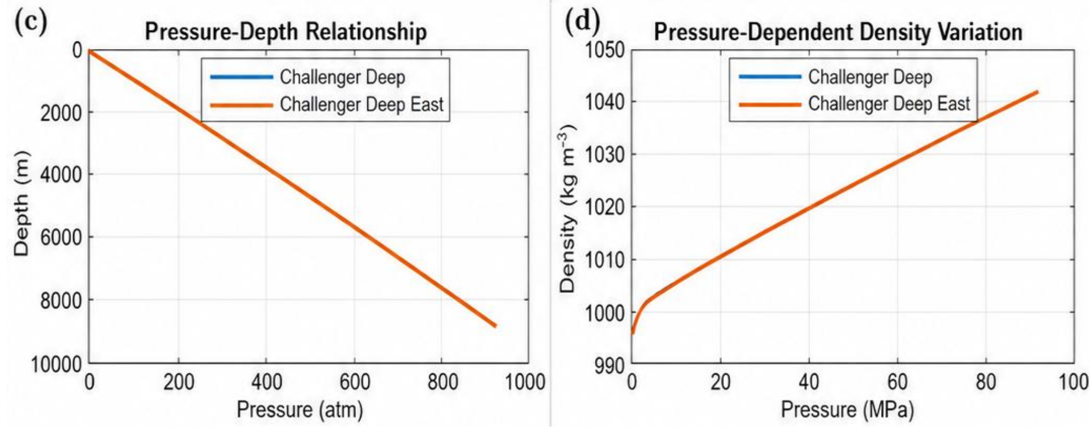

Figure 2. Pressure-Resolved Density Response Under Deep-Trench Hydrostatic Conditions

Fig. 2 shows the pressure-resolved density response. Pressure increased monotonically with depth and density increased strongly with pressure, confirming that compression effects need to be included in modelling of the hadal zone.

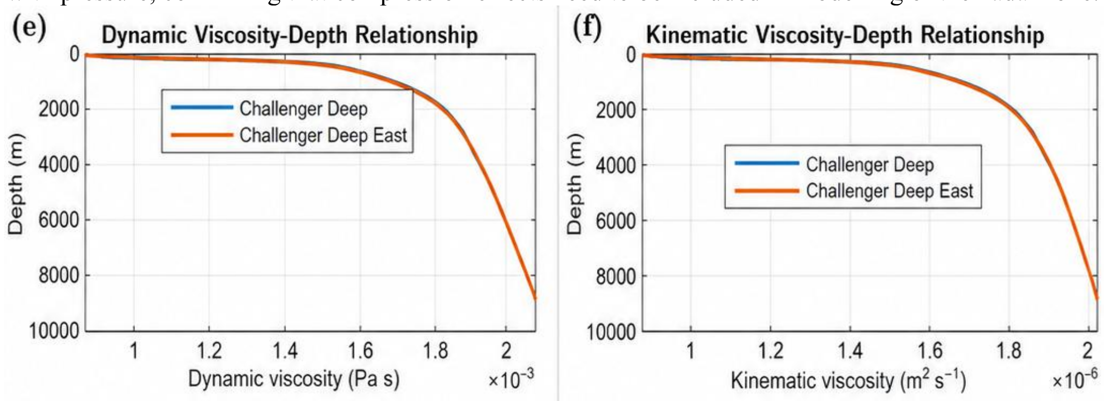

Figure 3. Depth-Dependent Viscosity Variation for Random Vortex Model Parameterisation

Fig. 3. Profiles of dynamic and kinematic viscosity as a function of depth. The significance of these results is that the kinematic viscosity was directly employed in the Random Vortex Method to regulate the stochastic vortex-particle diffusion, thereby connecting the thermophysical model to the hydrodynamic simulation.

4.2 Baseline Comparisons

The primary baseline was the previous raw .txt parsing workflow that produced a shallow depth range of around 30–60 m, which was invalid. This baseline was rejected as it did not reflect Mariana Trench conditions. The corrected, Mat-based workflow restored the correct depth-pressure scale and thus improved scientific validity substantially.

The second baseline is the constant-density hydrostatic model:

$P(z) = P_0 + \rho_0 g z$ (12)

This baseline may represent the general increase of pressure with depth, but it cannot account for pressure-dependent density, viscosity or compressibility. This workflow improves on this by modelling:

$\rho = \rho(S, T, P)$ (13)

and:

$\mu = f(T, S, P)$ (14)

A third baseline is a vortex model with constant viscosity. Under that condition, the vortex diffusion is not associated with the CTD-derived deep-ocean state. On the contrary, the proposed model uses pressure dependent (v), which provides a direct thermophysical basis to the vortex model.

Table 2. Baseline comparison

Model / workflow	Depth-pressure validity	Pressure-dependent density	Pressure-dependent viscosity	RVM coupling
Raw .txt workflow	Invalid	No	No	Weak
Constant-density model	Partial	No	No	No
Constant-viscosity RVM	Valid if corrected	Yes	No	Partial
Proposed .mat workflow	Valid	Yes	Yes	Yes

The results in Table 2 indicate that the proposed .mat-based workflow outperformed all baselines in preserving valid depth-pressure structure, pressure-dependent density, pressure-dependent viscosity, and full RVM coupling. We abandoned the raw .txt workflow because of shallow-depth artefacts, but the constant-density and constant-viscosity models only gave a partial physical representation.

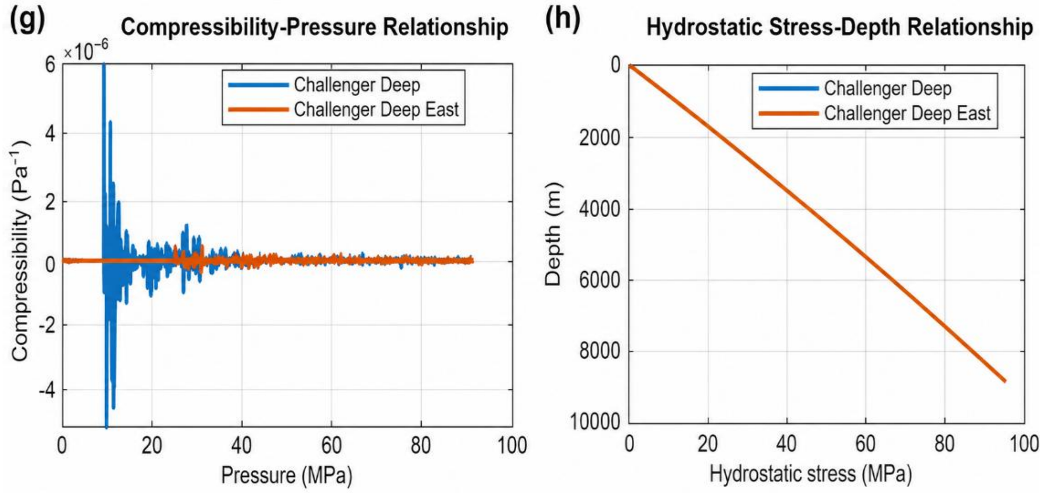

Figure 4. Pressure-Induced Mechanical Response and Compressibility Characteristics in Challenger Deep and Challenger Deep East

As shown in Fig. 4, compressibility was numerically sensitive, whereas hydrostatic stress grew monotonically with depth, supporting the validity of the pressure-resolved model.

4.3 Ablation Study

The ablation analysis shows that the most important component for physical validity was the Mat-based extraction of depth and pressure. Removing this part caused the model to collapse to a shallow-depth interpretation and invalid pressure scale. The Random Vortex Method was the most important component for novelty in applied mathematics.

Removing pressure-dependent density weakens the compressibility analysis because:

$\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial P}$ (15)

depends directly on density variation . Removing pressure-dependent viscosity degrades the vortex simulation. The reason is that the vortex-particle update equation uses kinematic viscosity:

$x_i^{n+1} = x_i^n + u_i \Delta t + \sqrt{2\nu\Delta t}\eta_i$ (16)

where (x_i) is vortex-particle position, (u_i) is induced velocity, and (η_i) is stochastic diffusion.

Table 3. Ablation effects

Ablation condition	Removed component	Main effect	Most affected output
Without .mat extraction	Correct depth-pressure variables	Invalid shallow scale	Pressure-depth plot
Without pressure-dependent	(ρ(S,T,P))	Weak compressibility	Density/compressibility

density		model	
Without pressure-dependent viscosity	(μ(T,S,P))	RVM no longer CTD-coupled	Vortex dispersion
Without RVM	Vortex-particle model	No hydrodynamic simulation	RVM figures
Without second site	Challenger Deep East	No site comparison	Statistical tests

Ablation analysis is shown in Table 3. The results indicate that the .mat extraction was necessary to maintain the proper trench-scale depth-pressure structure. Removing pressure-dependent density resulted in less accurate estimates of compressibility, and removing pressure-dependent viscosity disconnected the RVM from the conditions derived from CTD data. RVM excluded the hydrodynamic simulation, and Challenger Deep East excluded site-level comparison.

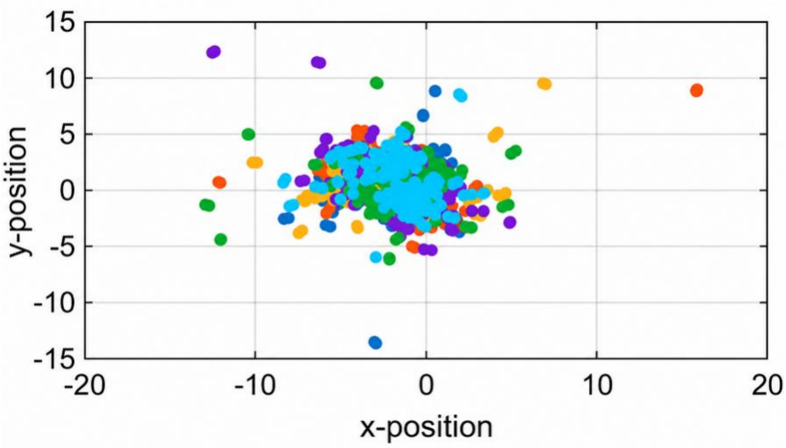

Figure 5. Random vortex final particle positions.

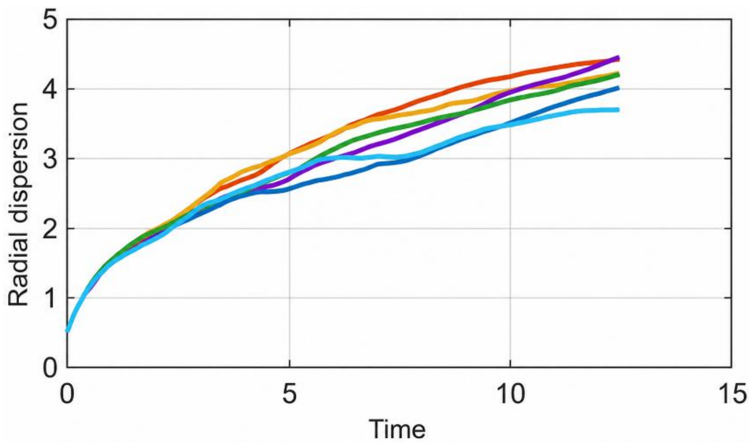

Figure 6. Random vortex radial dispersion dynamics.

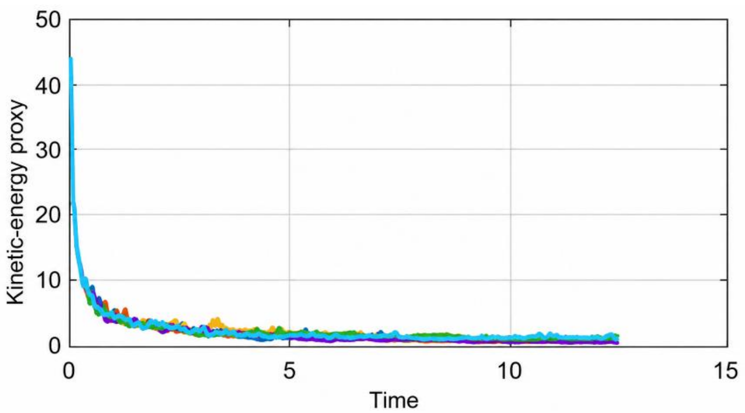

Figure 7. Random vortex kinetic-energy proxy decay.

Figure 5 shows the stable final positions of the vortex-particles. Figure 6 shows that the radial dispersion increases with time, confirming vortex spreading. The decay of kinetic-energy proxy is shown in Fig. 7, which indicates the progressive dissipation of kinetic energy during the evolution of the vortex-particle.

4.4 Additional Analysis

The regression analysis confirmed strong pressure-property coupling. Pressure explained 99.81% of density variation in Challenger Deep and 99.78% in Challenger Deep East. Pressure also explained dynamic viscosity variation with ($R^2 = 0.7097$) and ($R^2 = 0.6898$), respectively. Kinematic viscosity showed ($R^2 = 0.6311$) in Challenger Deep and ($R^2 = 0.6117$) in Challenger Deep East.

In site-comparison tests, statistically significant differences were found in pressure, salinity, sound speed, density, dynamic viscosity and kinematic viscosity. Temperature did not differ significantly under Welch's test (p = 0.2130), but distributional tests still showed differences at the profile level.

The least stable derived variable was compressibility. Its site comparison was not significant by Welch's test (p = 0.0797). This is expected since the compressibility was estimated using numerical gradients that are sensitive to small fluctuations in density and pressure.

Table 4. Selected statistical and vortex results

Analysis	Challenger Deep	Challenger Deep East	Interpretation
Density-pressure (R^2)	0.9981	0.9978	Very strong pressure-density coupling
Dynamic viscosity-pressure (R^2)	0.7097	0.6898	Strong pressure-viscosity relation
Kinematic viscosity-pressure (R^2)	0.6311	0.6117	Moderate-to-strong coupling
Temperature Welch (p)	0.2130	0.2130	Not significant by Welch's test
Compressibility Welch (p)	0.0797	0.0797	Not significant by Welch's test
Maximum RVM final dispersion	4.4251	4.3937	Stable vortex spreading
Minimum RVM final kinetic proxy	0.6681	0.8732	Energy decay observed

The main statistical and vortex-response results are summarised in Table 4. Both profiles showed very strong pressure coupling for density with $R^2 = 0.9981$ for Challenger Deep and $R^2 = 0.9978$ for Challenger Deep East. Dynamic and kinematic viscosity had a strong to moderate dependence on pressure while temperature and compressibility were not significant under Welch's test . The RVM outputs confirmed pressure-conditioned hydrodynamic response with stable vortex spreading and kinetic-energy decay.

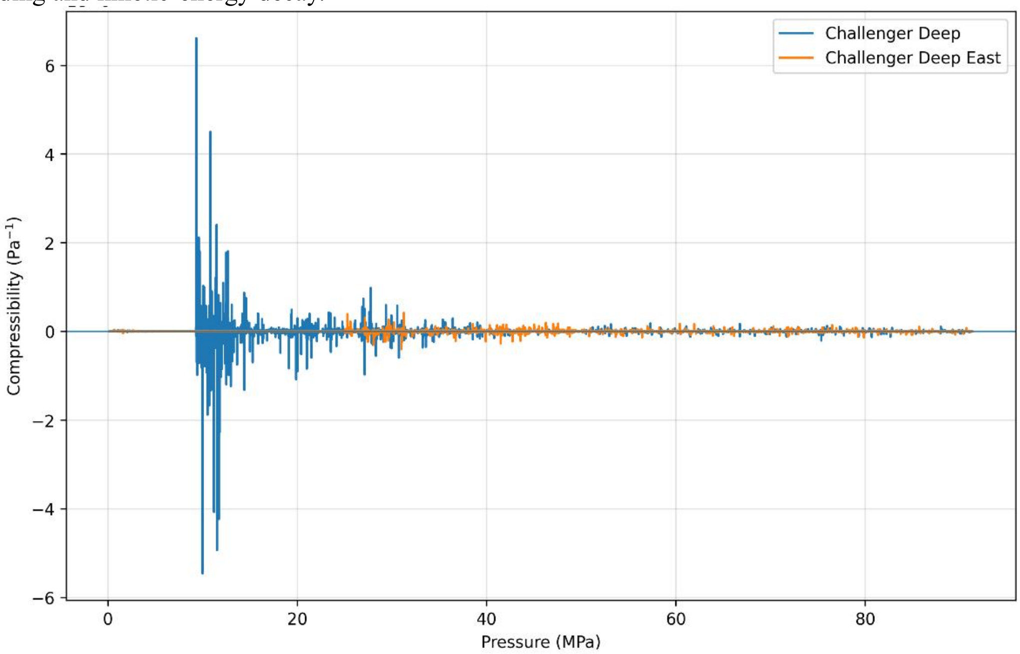

Figure 8. Compressibility-pressure relationship showing gradient-derived numerical sensitivity.

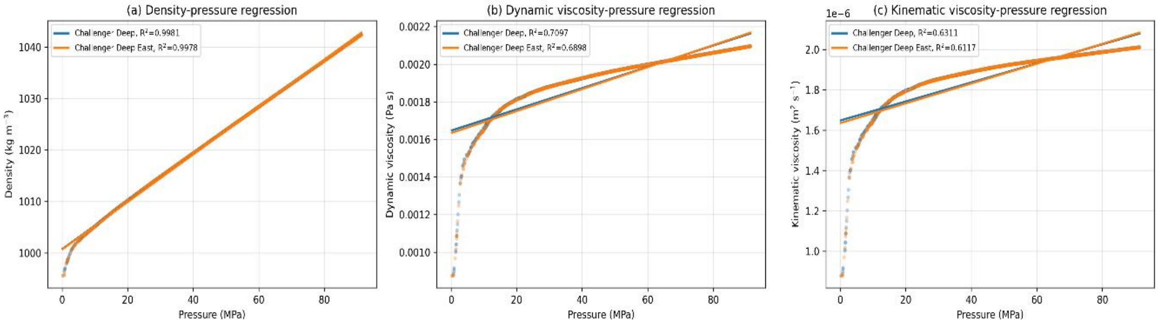

Figure 9. Pressure-property regression plot for density, viscosity, and kinematic viscosity.

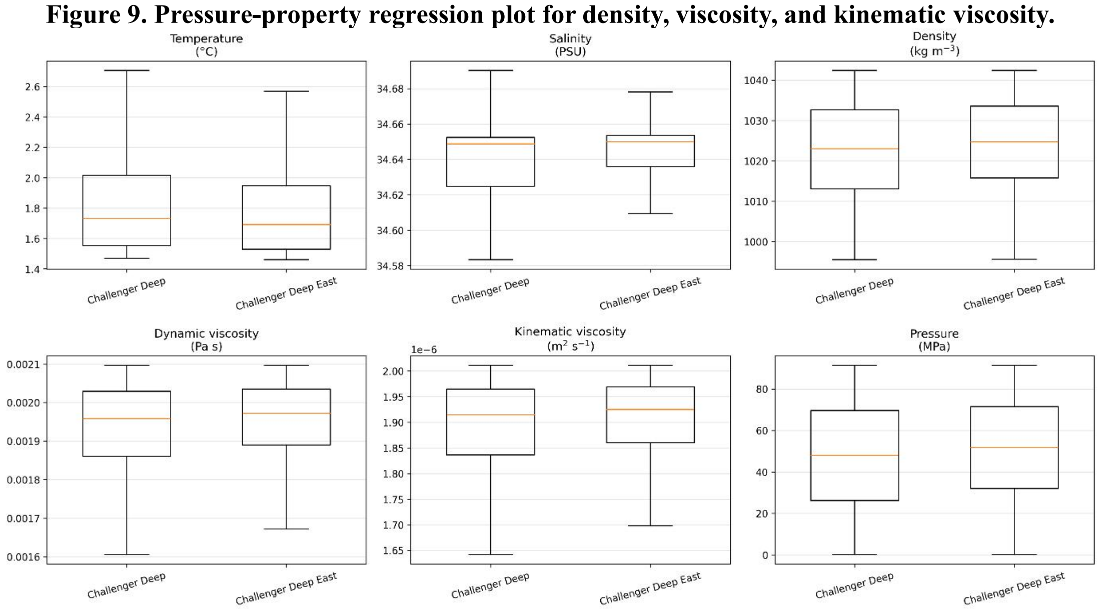

Figure 10. Site-comparison plot for Challenger Deep and Challenger Deep East.

The relationship between compressibility and pressure and the numerical sensitivity resulting from the gradient derived compressibility estimate is shown in Figure 8. The strongest pressure dependence of density is shown in Figure 9 followed by weaker but meaningful viscosity-pressure relations. Figure 10 compares both sites, with generally similar behaviour and measurable differences in pressure, density, viscosity and vortex-response indicators.

5. Discussion

Results indicate that pressure is the main organising variable controlling the thermophysical and hydrodynamic behaviour of the Challenger Deep and Challenger Deep East profiles. The corrected .mat-based modelling yielded a physically consistent pressure-depth structure and eliminated the shallow-depth artefact created by the discarded raw-text parsing workflow. This correction was important because the validity of all derived variables depended on the proper representation of the trench-scale hydrostatic pressure. Density increased strongly with pressure, which confirms the importance of compression effects to the hadal water-column analysis. Dynamic viscosity and kinematic viscosity also varied systematically with depth and pressure. This implies that viscous transport parameters should not be considered constant in deep-ocean hydrodynamic modelling. The compressibility response was more numerically sensitive, as it was derived from density-pressure gradients, while hydrostatic stress showed a stable monotonic increase with depth.

These results are consistent with earlier hadal studies that suggest that deep trenches are chemically and environmentally distinct water-column systems and not passive extensions of the open ocean [13]. The results are also consistent with the thermodynamic view that pressure, salinity and temperature must be considered together when estimating seawater properties under oceanographic conditions [19]. In contrast to the seawater-property correlation studies cited above, the present study applies the thermophysical estimation with pressure dependence to the Challenger Deep and Challenger Deep East profile data directly, not only to the generic seawater ranges [21]. The vortex-based component of this interpretation extends the thermophysical model to computational hydrodynamics by using the mathematical basis of vortex methods but adapting the particle diffusion to pressure-dependent kinematic viscosity [23].

The novelty of this study is the integration of hadal profile data, pressure-dependent seawater-property estimation, hydrostatic stress analysis, Random Vortex Method simulation and statistical site comparison into one single reproducible workflow. Previous work has mostly focused on trench observations, thermophysical correlations in seawater, or vortex-particle methods in isolation. The novelty of the present approach is that the pressure-dependent kinematic viscosity is not only calculated as a derived property but also used as an active parameter controlling the vortex-particle diffusion and dispersion. This provides a direct mathematical link between measured deep ocean conditions and simulated hydrodynamic response.

The RVM parameterisation strengthens this contribution as particle count, timestep, circulation, kernel radius and stochastic diffusion were controlled modelling parameters and not arbitrary outputs. In all cases, consistent circulation and timestep were used and the regularised vortex-core radius prevented singular growth of velocity during close particle interactions. The stochastic diffusion term agreed with the viscosity-dependent scaling $\left(\sqrt{2\nu\Delta t}\right)$, suggesting that the vortex dispersion changes were dominated by the kinematic viscosity obtained from the CTD. Therefore, the RVM experiment should be understood as a comparative pressure-conditioned hydrodynamic response model and not as a direct simulation of full Mariana Trench turbulence.

The implications are relevant for deep ocean modelling, interpretation of the hadal zone and analysis of fluids at extreme pressures. The strong pressure-density relation suggests the need for pressure-resolved property estimation for trench-scale fluid modelling. Results from viscosity suggest vortex diffusion and hydrodynamic spreading under hadal conditions may be different from shallow-water assumptions. The site comparison also indicates that even closely related trench locations may display measurable differences in profile derived properties and modelled response.

Only two CTD profiles were used and the RVM was formulated in an idealised two-dimensional way, which limits the study. It does not solve full 3-D trench circulation, internal tides, rough seafloor boundary-layer dynamics, sediment-water coupling, hydrothermal forcing or biogeochemical feedback. Compressibility estimates are also sensitive to numerical gradients and should be interpreted carefully. Future work should include additional hadal profiles, high resolution bathymetry, in-situ turbulence measurements, three-dimensional hydrodynamic modelling and uncertainty quantification. These extensions would move the framework away from pressure-resolved exploratory modelling towards predictive simulation of hadal hydrodynamic behaviour.

6. Conclusion

The research dealt with the problem of modelling the deep-ocean hydrodynamic and thermophysical behaviour under extreme hydrostatic pressure in the Mariana Trench. Results show that Challenger Deep and Challenger Deep East are not shallow-water cases, as pressure has a non-negligible effect on density, viscosity, compressibility, hydrostatic stress, and transport-related quantities. To resolve this a pressure-dependent modelling workflow was constructed using corrected .mat based CTD profiles, thermophysical property estimation, hydrostatic stress analysis, Random Vortex Method simulation and statistical comparison between the two trench sites The corrected profiles gave a physically realistic pressure–depth relation and revealed strong pressure dependent compression of seawater. Variations in dynamic and kinematic viscosity with depth confirmed the importance of pressure-conditioned transport parameters in hadal-flow modelling. The compressibility exhibited a numerical sensitivity derived from the gradient, and the hydrostatic stress increased monotonically with depth. The Random Vortex Method further showed pressure-conditioned vortex dispersion and kinetic energy decay in deep-ocean conditions. The main contribution of this work is an integrated computational framework that links measured hadal profiles, pressure-dependent seawater properties, hydrostatic stress, vortex-particle diffusion, statistical analysis. The study is limited by its profile-based and two-dimensional formulation that does not resolve full trench circulation, internal tides, seafloor roughness, sediment-water interaction, or biogeochemical feedback. Future work should include more hadal profiles, three-dimensional hydrodynamic modelling, in-situ turbulence measurements, high-resolution bathymetry and uncertainty quantification to improve predictive modelling of flow dynamics in the Mariana Trench.

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