Hydrothermal Plume Near-Field Dynamics from LES and Observations

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Key Points:

- Hydrothermal plumes exhibit strong mixing reflected by significant vertical and temporal variability in entrainment rate in the near-field
- Plume theory cannot be applied directly since forced and lazy plumes are in a transitional state at the scale of hydrothermal edifices
- Short exposure times to high temperatures suggest that biological materials can be transported through the plume without lethal effects

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Abstract

Hydrothermal plumes play a crucial role in vent fields by injecting significant buoyancy flux from centimeter-scale vents and rising hundreds of meters, yet their near-field dynamics remain poorly understood. Using a Large-Eddy Simulation approach with adaptive mesh refinement, we study these plumes at centimeter-scale resolution within a 6 m domain above the vent. We first study a typical black smoker in the forced plume regime to quantify the mean flow and spatial variability, investigating the link between turbulent structures and the entrainment rate α of surrounding water. Significant vertical and temporal variability in α is observed, with an overall value of $\alpha = 0.19$. The results are compared with in-situ data and plume theory. Next, we investigate the sensitivity of the flow field to source parameters, characterizing the transition between forced or lazy plume regimes and the pure plume regime. In the far-field, plumes achieve self-similarity and the flow field is consistent with theoretical plume scalings, showing a dependence on source buoyancy flux for predictions in this region. The extent of the transition region where plume self-similarity breaks down is defined, and its importance in the context of in-situ observations is highlighted. Finally, we show that extreme temperatures above 100°C occur in the first two meters of the column, but exposure times for a proxy tracer are short, suggesting that hydrothermal plumes could serve as viable transport vectors for biological materials.

Plain Language Summary

Hydrothermal vent fields on the ocean floor release hot, mineral-rich water that forms rising plumes, known as black smokers. These plumes are critical to the unique ecosystems around vents (the source points) and influence how heat and materials spread through the ocean. However, the details of plume behavior near the seafloor, where they are most energetic, remain poorly understood. Using advanced computer simulations, we studied these plumes at high resolution, focusing on the region close to the vent. We examined how the plumes mix with the surrounding water and found that the mixing rate changes significantly with height and time. The results were compared with in-situ data and plume theory. Vent temperatures reach 300°C, but anything transported by the plumes would only experience these extreme conditions for very short times. This suggests that hydrothermal plumes may carry biological material, such as larvae, without causing harm. We also studied how vent conditions affect plume behavior, focusing on its transition from the source-dominated region to the turbulent region farther away, where it aligns with the established theory. The transition zone shows behaviors crucial for interpreting seafloor observations. Our findings provide new insights into how hydrothermal plumes behave and interact with deep-sea environments.

1 Introduction

Unlike most of the abyssal plain, hydrothermal fields are oases of life and sites of complex chemistry (Van Dover, 2002; Cotte et al., 2020), where hot fluids are discharged through vents from chimney structures as black smokers, i.e., buoyant plumes. While the total Earth's surface heat flux is typically $\mathcal{O}(0.1 \text{ W m}^{-2})$ (Sclater et al., 1980; Davies & Davies, 2010), hydrothermal plumes can generate heat fluxes of up to $\mathcal{O}(1 \text{ GW m}^{-2})$ (Mittelstaedt et al., 2012). They play a significant role in the heat flux balance of hydrothermal fields (Barreyre et al., 2012; Mittelstaedt et al., 2012), influence faunal assemblages several meters away from fluid discharge points (Girard et al., 2020), and contribute to the injection of dissolved iron and rare earth elements into the ocean (Chavagnac et al., 2018).

Hydrothermal plumes typically rise several hundred meters (Lavelle et al., 2013; Adams & Di Iorio, 2021) in the weakly stratified deep ocean, while vent radii are on the order of centimeters. The discharged fluids reach temperatures of $\sim$ 400 °C and fluid velocities of up to ~ 1 m s^{-1}, e.g., Koschinsky et al. (2008); Sarrazin et al. (2009), making hydrothermal plumes an exotic phenomenon in contrast to typical ocean conditions. Vent characteristics give rise to a wide range of plume behaviors, from jet-like plumes (forced plumes) to highly buoyant plumes (lazy plumes). The great depths involved make in-situ observations challenging, with data collection generally limited to the first few meters above the source to attribute measurements to a specific vent cluster. Only recent developments in acoustic imaging have efficiently captured hydrothermal system properties (Xu et al., 2013; Bemis et al., 2015).

Despite the importance of buoyant plumes in hydrothermal fields, few numerical studies achieve resolutions that capture the physical processes at the scale of individual vents. Most studies investigate plumes at much larger scales, assuming that the hot fluid has already mixed with the environment and approximating the merging of vent fields (Lavelle et al., 2013; Tao et al., 2013; Gao et al., 2019; Adams & Di Iorio, 2021). This is largely due to the computational cost of achieving vent-scale resolution. Jiang and Breier (2014), however, approached this level of detail using Reynolds-Averaged Navier-Stokes (RANS) simulations, and showed that near-vent dynamics involve complex mixing processes.

Morton et al. (1956) established a simplified theoretical model of plume dynamics that successfully describes convective plumes in many situations (Kaye, 2008; Woods, 2010). The model parameterizes turbulence with the assumption that the entrainment of surrounding fluid in the plume is proportional to its axial velocity. Dimensionless studies outside the hydrothermal regime, using Direct Numerical Simulation (DNS) by Plourde et al. (2008); Taub et al. (2015); Marjanovic et al. (2017) and Large Eddy Simulation (LES) by Devenish et al. (2010), have demonstrated that the classical assumptions of the theoretical model do not hold in the near-field. In particular, forced or lazy plumes with initial buoyancy transition to a purely buoyant – pure plume – regime (Van Reeuwijk & Craske, 2015). The adjustment between the near-field and far-field hinders the application of theoretical models (Ciriello & Hunt, 2020) and has been poorly characterized for plumes, with even less attention given to the hydrothermal regime.

The aim of this paper is therefore to work within a realistic framework, specifically in the hydrothermal regime. We focus on the near-vent region, which represents the window for in-situ operations and where black smokers interact with biochemical processes. This makes the results directly applicable to the scale of hydrothermal fields.

In particular, due to their proximity to benthic communities, hydrothermal plumes may serve as a mechanism for the vertical transport of larvae (Kim et al., 1994; Mullineaux & France, 1995), influencing larval dispersal within the regional circulation (Xu et al., 2018; Vic et al., 2018). However, no studies have focused on the near-vent region at high resolution, particularly with regard to the influence of potentially lethal high temperatures on biotracers. This work aims to quantify the exposure time to high temperatures in black smokers for a proxy tracer.

To address the near-vent physics of buoyant plumes with adequate resolution, we use a Large Eddy Simulation (LES) approach with adaptive mesh refinement, which allows centimeter-scale resolution within a 6 m domain above the vent. Specifically, we extensively study conditions encountered at the Lucky Strike hydrothermal vent field (northern Mid-Atlantic Ridge), providing a realistic case study. This approach allows us to gain new insights into the near-field hydrothermal regime, establish links with theoretical models, and explore the link between hydrothermal plumes and near-vent benthic communities.

The paper is organized as follows. Section 2 presents the governing equations and details of the numerical experimental setup. Section 3 investigates the turbulent field of a typical black smoker through its flow structure and compares it with the theoretical model of Morton et al. (1956) and in-situ measurements. Section 4 extends the results to a wide range of source parameters to examine the flow field from forced to lazy plume. Section 5 discusses the impact of the transition regime on in-situ observations and the effect of temperature fluctuations on biotracer proxies. A summary of the results is given in section 6.

2 Model and Numerics

2.1 Plume Theory

The theory established by Morton et al. (1956) describes an axisymmetric Boussinesq plume with a radius r in a stratified fluid, with the assumption that the radial profiles of vertical velocity w and buoyancy b are similar at all heights. This model is hereafter referred to as the MTT model. This approach relies on a parameterization of mixing, the entrainment rate α, which relates w at each height to the radial velocity e of the entrained water in the plume, such that $\alpha = e/w$.

The conservation of volume, momentum, and buoyancy flux, under these assumptions, yields the following equations:

$$\frac{d}{dz}(r^2 w) = 2\alpha r w \,, \tag{1a}$$

$$\frac{d}{dz}(r^2 w^2) = 2r^2 b \,, \tag{1b}$$

$$\frac{d}{dz}(r^2 w b) = 2r^2 w \frac{g}{\rho_r}\frac{\partial \rho_a}{\partial z} \,, \tag{1c}$$

where ρ_a represents the ambient fluid density, ρ_r is a reference density, and g is the gravitational acceleration.

From the solutions of equations 1, the neutral buoyancy level H_{nbl} and the maximum height due to momentum overshoot H_{top} can be estimated as follows (Devenish et al., 2010):

$$H_{nbl} = 1.04\,\alpha^{-1/2} B_0^{1/4} N^{-3/4} \,, \tag{2a}$$

$$H_{top} = 1.36\,\alpha^{-1/2} B_0^{1/4} N^{-3/4} \,, \tag{2b}$$

where N is the buoyancy frequency, and $B_0 = \pi r_0^2 w_0 b_0$ is the buoyancy flux at the source, with $z = 0$ denoted by the subscript 0. The momentum flux and vertical volume flow are defined as $M_0 = \pi r_0^2 w_0^2$ and $Q_0 = \pi r_0^2 w_0$, respectively.

In most cases, hydrothermal plumes carry momentum from the source, induced by subseafloor pressure. Morton and Middleton (1973) introduced two dimensionless parameters to characterize the balance of forces, expressed as

$$\Gamma(z) = \frac{r(z) b(z)}{\alpha w(z)^2} \,, \tag{3a}$$

$$\Gamma(z)' = \frac{\alpha b(z)}{r(z) N^2} \,. \tag{3b}$$

At $z = 0$, Γ_0 and Γ_0' represent the plume source parameters. For $\Gamma_0 < 1$ the plumes are forced (relative excess of momentum), and for $\Gamma_0 > 1$ the plumes are lazy (relative excess of buoyancy). When $\Gamma_0' \ll 1$, the plume is rapidly balanced by the ambient stratification. The a priori choice of α affects the Γ_0 level and plume classification near $\Gamma_0 = 1$. Taub et al. (2015) noted that this dependence can cause inconsistencies between theory and observations.

The value of α remains a subject of debate. The generally accepted values are 0.12 for buoyant plumes and 0.076 for pure jets (Woods, 2010; Kaye, 2008; Van Reeuwijk &

Craske, 2015; Richardson & Hunt, 2022). However, recent studies show that α can vary greatly in the near-field (Van Reeuwijk et al., 2016; Marjanovic et al., 2017). We assume a fixed value of $\alpha = 0.12$ for application to equations 1, 2, and 3.

2.2 Basilisk

Basilisk (Popinet, 2013) is an Adaptive Mesh Refinement (AMR) code that uses an octree structure to discretize the computational domain. This approach provides refined resolution in regions with small-scale features, while coarsening the grid in quiescent areas. The dynamic refinement adapts the mesh on the fly, efficiently focusing computational effort on turbulent regions, making it well suited for plume studies. We set the resolution so that the maximum resolution is $d_{max} = 2.49$ cm to spatially resolve the vent outlet, while the minimum resolution is set to $d_{min} = 20$ cm. The code uses a LES approach with a second-order accurate finite-volume solver for the Navier-Stokes equations (Popinet, 2003, 2009, 2015). The equations are solved using the Boussinesq and incompressibility assumptions, expressed as

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = \frac{1}{\rho_r} \left(-\nabla p + \nabla \cdot \mathbf{T} \right) + b \nabla z \,, \tag{4a}$$

$$\nabla \cdot \mathbf{u} = 0 \,, \tag{4b}$$

where $\mathbf{u}$ is the filtered velocity and z is the height above the source. The buoyancy is defined as $b = -g(\rho(x,t) - \rho_r)/\rho_r$, where $\rho(x,t)$ is the density at position x and time t. The model pressure p, representing the deviation from the hydrostatic reference pressure P, is computed using a multigrid Poisson solver. Temperature T is integrated as a conservative tracer using the robust upwind advection scheme of Bell et al. (1989). Density is computed by an extension of the Equation Of State (EOS) beyond the oceanic funnel, namely for $T > 40$ °C (see below). The stress tensor $\mathbf{T}$ accounts for unresolved small-scale turbulence. The Vreman (2004) sub-grid scale model is used to compute the local eddy viscosity. This model requires a coefficient c, set to 3.6×10^{-2}, to allow a fair chance for turbulent shear flow. The turbulent Prandtl number is set to unity, which implies equal heat diffusivity and viscosity.

The Boussinesq approximation may seem questionable due to the large temperature anomalies at the vent, where the source temperature in this study is typically around $T_0 = 300$ °C ($\rho_0 = 782$ kg m^{-3}) and the ambient temperature is $T_a = 4.6$ °C ($\rho_a = 1035$ kg m^{-3}). However, the plume mixes rapidly as it exits (see section 3). At 25 cm above the source, the average temperature drops to $T = 50$ °C ($\rho = 1021\,\mathrm{kg\,m^{-3}}$), corresponding to an average density fluctuation of 1.4 % with respect to the reference density. At $z = 1$ m, the mean temperature is close to $T = 10$ °C, corresponding to a fluctuation of 1 %, and temperatures of $T > 40$ °C ($\rho < 1025\,\mathrm{kg\,m^{-3}}$) make up only 40 % of the distribution (Figure 2-e). Furthermore, the buoyancy flux is preserved in this approximation. Thus, the introduced error is not expected to have a significant effect on our results.

2.3 Equation Of State

An accurate EOS is needed for the 4–300 °C temperature range, at the hydrostatic pressure of our target site, which is $P \sim 1700$ dbar. TEOS-10 (IOC et al., 2010) is the standard for computing seawater thermodynamics but is only valid in the oceanic funnel, i.e. $T < 40$ °C at 2000 m (McDougall et al., 2003). We need to extend the EOS for temperatures above this range. Previous work by Sun et al. (2008) established a set of fitted polynomial equations in the 4–300 °C range by combining freshwater and seawater data. A more recent study by Safarov et al. (2009), based on in-situ measurements at $S_A = 35.17\,\mathrm{g\,kg^{-1}}$, covers the entire 0–195 °C range up to 1400 dbar with improved accuracy. Bischoff and Rosenbauer (1985) determined the EOS for $S_A = 32.16\,\mathrm{g\,kg^{-1}}$ for the 200–350 °C range and up to 1000 dbar. To simplify the model, and due to a lack of sufficient data, we neglect the specific chemistry of black smokers and assume a uniform absolute salinity of $S_A = 35.2\,\mathrm{g\,kg^{-1}}$. To develop a smooth EOS that closely matches these published results, we developed a non-linear parametric fit covering the temperature and pressure range 0–350 °C and 1500–1700 dbar, typical of the conditions at Lucky Strike (Figure A1). To balance the salinity differences, the data from Sun et al. (2008) and Bischoff and Rosenbauer (1985) are adjusted based on TEOS-10 at $S_A = 35.2\,\mathrm{g\,kg^{-1}}$. The corresponding correlation is given in Appendix A by equation A1.

2.4 Outlet Turbulence Parameterization

The discrete sources observed at Lucky Strike systematically exhibit turbulence at the vent, which is expected due to the complex and irregular subsurface circulation that hot fluids undergo before reaching the seafloor (Fontaine et al., 2014). However, without numerical adjustments, the plume initially develops as a transitional laminar flow (Figure 1-a) until it destabilizes into a turbulent plume. This is an unrealistic feature that is corrected using the method of Plourde et al. (2008). To trigger turbulence in the plume, a uniform discrete white noise is added to the vertical velocity at all outlet nodes (Figure 1-b, experiment 1 in Table 1), such that $w = w_0(1+AW(t))$, where $W(t)$ is a white noise signal, and A is the noise amplitude. This parameterization represents the turbulence pre-existing in the flow prior to injection into the water column and fully accounts for the turbulent state at the outlet. The calculations show that for disturbance magnitudes $A = [0–2]$, the level of turbulence can be increased while keeping the plume numerically stable. However, a burst of viscous dissipation ε_k in the first nodes above the outlet limits the maximum energy that can be injected at the source. Therefore, we choose the optimal value of $A = 0.5$, which allows turbulence to develop quickly after the outlet while minimizing the burst in ε_k.

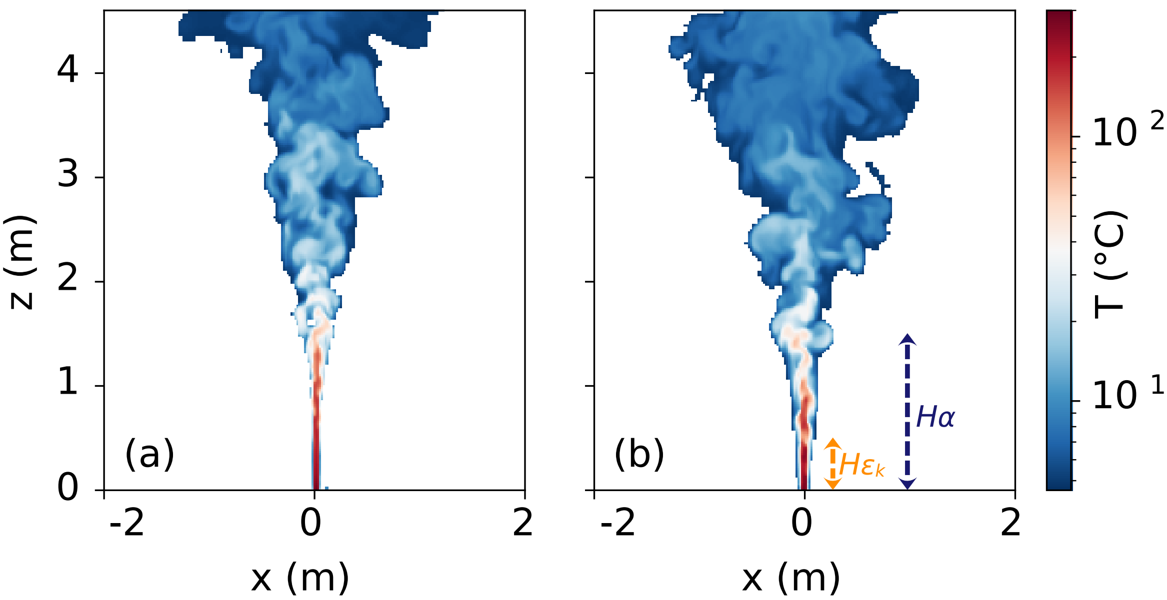

Figure 1. Cross-section of the instantaneous temperature field for (a) the scenario without noise perturbation at the outlet ($A = 0$), and (b) with turbulence triggered by noise immediately after the outlet ($A = 0.5$). The two reported heights correspond to the transition region to a pure plume regime (see section 4).

2.5 Experiment Setup and Modeling Case

The Tour Eiffel vent field (-1690 m) located at the Lucky Strike hydrothermal site (37°17'N 32°16'W) is selected as the baseline modeling case. It features a prominent 15 m high chimney with approximately 10 vents (Mittelstaedt et al., 2012) and is considered a biological hotspot (Van Audenhaege et al., 2022). We define a hydrothermal edifice as the collection of chimneys and complex topography resulting from hydrothermal activity. Usual structures are smaller than Tour Eiffel, typically $\sim$ 1–2 m in height (Barreyre et al., 2014).

Hydrothermal fluid exits the seafloor through two types of sources: diffuse low temperature sources ($T < 10$ °C), which are a mixture of hydrothermal fluid and ambient water, and discrete high temperature sources, typically black smokers (Barreyre et al., 2014). We focus on the plumes emitted by the latter. The EMSO-Açores (European Multidisciplinary Subsea Observatory) long-term observatory, maintained through the MoMARSAT campaign series, provides the framework for in-situ measurements.

The model domain is a cubic box of width $L = 6.375$ m with open boundary conditions on all sides, except for a solid flat bottom. To avoid boundary effects, results are presented excluding regions near the boundaries. The plume is forced by imposing a temperature T_0 and vertical velocity w_0 at the vent, modeled as an outlet with radius r_0. A solid pipe was tested as a small chimney model to raise the outlet 1 meter above the seafloor to allow more effective entrainment of the surrounding fluid. Simulation results showed no significant differences, so for simplicity the outlet is kept at the bottom boundary. The ambient stratification is linear in the vertical, with $N = 1.63 \times 10^{-3}$ s^{-1}, determined from observations at Lucky Strike. The ambient temperature at the outlet is $T_a = 4.6$ °C.

The diversity of source conditions is large, ranging from highly forced plumes to highly lazy plumes. To capture this variability, the study examines a number of key parameters: r_0 (1.4–2.8 cm), w_0 (0.02–1.4 m s^{-1}), and T_0 (40–340 °C). The selected range for these parameters is based on field data collected by Mittelstaedt et al. (2012) at Tour Eiffel. The experimental parameters are summarized in Table 1.

Table 1. Summary of simulations. The experiments are grouped based on common varying factors. The numerical domain size is $L_0 = 6.375$ m. The maximum resolution is the same across all simulations ($d_{max} = 2.49$ cm).

Experiment	Symbol	$w_0\,(m\,s^{-1})$	$r_0\,(cm)$	T_0 (°C)	$B_0\,(m^4\,s^{-3})$	Γ_0
1, 2, 3	■, ⬟, ♦	0.7	2.8	[300, 100, 200]	[4.15e-3, 7.12e-4, 2.14e-3]	[1.1, 0.2, 0.6]
4, 5, 6	✚, ✖, |	[1.4, 0.7, 0.4]	[1.4, 2.0, 2.8]	300	2.08e-3	[0.1, 0.8, 4.6]
7, 8	×, ▶	[1.4, 0.1]	2.8	300	[8.30e-3, 2.97e-4]	[0.3, 224]
9, 10, 11	★, ⬢, ◀	0.5	[1.4, 2.0, 2.8]	300	[7.41e-4, 1.48e-3, 2.97e-3]	[1.1, 1.6, 2.2]
12, 13	◆, ●	[0.05, 0.2]	1.4	300	[7.41e-5, 2.97e-4]	[112, 7.0]
14, 15	▲, ⬣	[0.05, 1.4]	2.8	40	[1.13e-5, 3.16e-4]	[8.5, 0.01]
16, 17	_, ✸	[0.05, 1.12]	[1.4, 2.8]	200	[3.82e-5, 3.42e-3]	[58, 0.23]
18	▼	0.02	2.8	340	1.61e-4	1897

2.6 Averaged Diagnostics

To synthesize the LES results, diagnostic quantities are averaged both in time and horizontally to provide vertical profiles. Horizontal averaging is performed within the plume, which requires the definition of the plume boundary relative to the ambient. This definition is not straightforward and there is no generally accepted approach in the literature. Few attempts have been made to provide a precise definition (Pham et al., 2005; Plourde et al., 2008).

In this study, we define the plume boundary based on w: the plume interior is where $|w| > \sigma$. The typical value used is $\sigma = 10^{-2}$ m s^{-1}, determined by sensitivity tests, with any deviations specified. This criterion filters velocities between 1% and 10% of the axial values and is consistent with Morton et al. (1956)'s definition of the theoretical plume radius. We have verified that this criterion accurately captures the plume boundary for all source parameters in this study.

We define $r(z,t)$ as the equivalent radius of the area $S(z,t)$, where $S(z,t)$ is the plume cross-sectional area used for horizontal averaging. On average, $S(z,t)$ corresponds to a disc, but this is not true for snapshot times, as turbulence causes the plume boundary to become convoluted. The profiles are time-averaged over the integration time ($\sim$10 min plume time) with an output every 1.5 s.

The entrainment rate is a key quantity from the LES and is obtained by $\alpha(z,t) = e(z,t)/w(z,t)$, where $e(z,t)$ is the lateral flux entering the plume and $w(z,t)$ is the mean vertical velocity. It is computed using

$$e(z,t) = \frac{1}{2\pi r(z,t)} \frac{d}{dz}(wS)\,, \tag{5a}$$

$$w(z,t) = \frac{1}{S(z,t)} \int_{S(z,t)} w\, dS\,. \tag{5b}$$

3 Model Result for a Black Smoker

The aim of this section is to describe the near-field plume dynamics, to investigate the flow structure as a function of the entrainment rate, and to compare these results with those predicted by the MTT theoretical model and in-situ data.

3.1 Mean Field

The experiment presented here represents a typical source at the Lucky Strike field (experiment 1 of Table 1). The regime is weakly lazy ($\Gamma_0 = 1.14$), and as noted in section 2.1, the choice of α affects the value of Γ_0. Its turbulent flow is more similar to a forced plume regime (see section 3.3), and the term forced plume is used for Experiment 1. We present the mean quantities averaged with $\sigma = 1$ cm s^{-1} in Figure 2, together with the 95th percentile mean to highlight the upper range of the data distribution. Positive and negative spatial standard deviations are shown separately.

The high value of $\Gamma'_0 = 4{\times}10^6$ reflects the strong injection of B_0 into a weak stratification. The plume exits with an extremely high temperature anomaly ($T{-}T_a \approx 300$ °C) and intense momentum forcing ($w_0^2 = 0.5$ m^2 s^{-2}), significantly different from typical ocean conditions. It results in $H_{nbl} \approx 3400\, r_0$ according to the MTT model (see below), underscoring the focus on near-field behavior within this study ($L_0 \approx 230\, r_0$). However, the plume quickly converges to a more tempered state within the numerical domain, typical of the scale of hydrothermal edifices.

The mean temperature drops sharply from $T_0 = 300$ °C at the vent to less than $T = 6.5$ °C at $z = 4$ m, and then follows a slower decay rate (Figure 2-b). Within the first meter, the temperature drops below $T = 15$ °C. Despite this rapid decrease, the region near the vent retains significantly high mean temperatures. The mean vertical velocity goes from $w_0 = 70$ cm s^{-1} to $w = 7$ cm s^{-1} within the first meter (Figure 2-c). w remains almost constant above this, with only a 10% variation between $z = 1$ m and

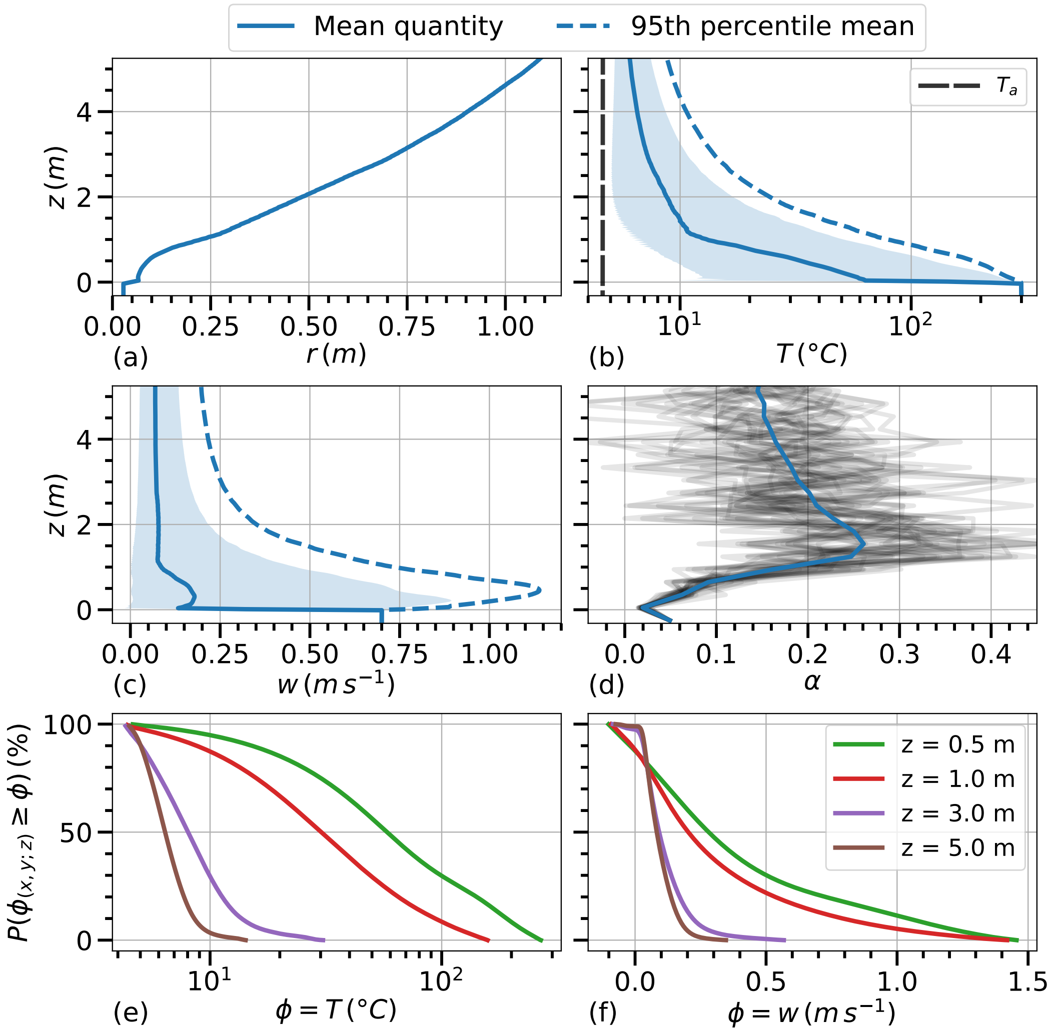

Figure 2. Vertical profiles for the time averaged (a) radius, (b) temperature, and (c) vertical velocity. (b) T_a is the ambient temperature (4.6 °C). The dashed line represents the 95th percentile mean (core plume), and the shaded region indicates the asymmetric spatial standard deviation. (d) Evolution of the entrainment rate $\alpha(z)$ and its temporal variability. Complementary cumulative density function for (e) temperature and (f) vertical velocity at different heights above the source.

$z = 5$ m. The first meter is characterized by fluid acceleration, with the plume core reaching a peak velocity of $w = 1.14$ m s^{-1} at $z = 0.5$ m, as discussed further below. The radius increases linearly, indicating a constant spreading rate, reaching $r = 1.05$ m at $z = 5$ m. The area of averaging includes the boundary of the plume where most of the mixing occurs. The averages are therefore sensitive to these regions of very low values, which contribute to the sharp decreases in key variables and the rapid expansion observed immediately after the outlet in Figure 2-a.

The plume dynamics observed in Figure 2, notably the stabilization of T and w profiles to nearly constant values, represent the adjustment between the near-field and far-field regions. The entrainment of ambient water is necessary to dissipate the large values of T_0 and w_0 through mixing. This is reflected in the rapid increase in radius, which grows by a factor of 37 between the vent and a height of $z = 5$ m. This can be considered the dilution factor of the hydrothermal fluid (Figure 2-a). Coupled with the vertical velocity, this results in a significant volume flow of $Q = 0.25\,\mathrm{m}^3\,\mathrm{s}^{-1}$ at $z = 5$ m. Thus, Q grows by a factor of 145 over a height of $z \approx 200\,r_0$, highlighting the efficiency of buoyancy-driven entrainment.

The weak stratification has no significant effect in the near-field. It was included in the LES setup to make the simulation more realistic and to avoid unnecessary assumptions about the surrounding fluid. However, LES runs under the same conditions as Experiment 1, but with a uniform ambient, give identical results for the vertical profiles of the mean quantities. Nevertheless, the parameter N is crucial for explaining the plume equilibrium level and cannot be ignored in larger numerical domains. According to the MTT model, the neutral buoyancy level and maximum height are predicted to be $H_{nbl} =$ 94 m and $H_{top} = 123$ m, respectively (equations 2-a, b). The solution of the MTT equations in uniform versus stratified environments begins to diverge at $z \approx 0.4 H_{nbl}$. Here, the numerical domain represents $0.07 H_{nbl}$, which seems to be a reasonable limit for assuming a uniform environment, without accumulating significant errors.

3.2 Spatial Fluctuations

The rapid drop in mean temperature does not mean that the hot water is immediately and completely mixed. Mixing takes some time. The 95th percentile distribution is assumed to represent the core of the plume. In this region, the temperature is significantly higher than at the plume's edge (Figure 2-b), where ambient cold water is drawn in and subsequently mixed.

To understand the mixing process, we present the Complementary Cumulative Density Function (CCDF) for temperature at different heights above the source (Figure 2-e). The CCDF shows the probability of finding a parcel at height z with a temperature greater than T. For example, at $z = 1$ m, 50 % of the parcels have temperatures above 30 °C, and 10 % exceed 100 °C, while the mean temperature is only 10 °C. This provides information beyond the predictions of the MTT model and is valuable for understanding chemical processes and larval dispersal. Implications for biological particles are discussed in section 5.2. At $z = 3\,\mathrm{m}$, the maximum observed temperature is 30 °C.

We apply the same diagnostic to the vertical velocity (Figure 2-f). Two points stand out. First, local velocities can reach up to twice the exit velocity (up to $1.5\,\mathrm{m\,s^{-1}}$) below $z = 1$ m. Second, downward velocities occur within the plume, although with low probability. The latter is directly related to the twisting vortical structures and their associated circulations (Figure 3). The first property shows that the core of the plume is being accelerated. This acceleration is driven by buoyancy, with the available potential energy carried by the hot water acting as a source of kinetic energy (Winters et al., 1995; Wykes et al., 2015). Figure 2-c clearly shows that the vent buoyancy provides a local acceleration of the core plume, strong enough to influence the mean value. The fluid acceleration means that any in-situ measurement must take this effect into account, as estimating the vent volume flow just centimeters above the source could lead to significant errors.

The distribution of large anomalies in T and w remains significant within the first meter. Due to the high temperature of the core being mixed, a specific extension of the TEOS-10 EOS is still required 1 m above the vent. This highlights that the assumption of a homogenized fluid based on mean quantities, with low w and T values for $z < 3$ m, is incorrect. However, mixing drastically changes the balance of forces, subsequently slowing the vertical motion and reducing the variance in the plume quantities w and T. Beyond this region ($z > 3$ m) the distributions of T and w show reduced spatial variation, which explains the slower decrease of their profiles and their convergence to nearly constant values. At $z = 5$ m, the absolute spread of T and w decreases to 10 °C and 0.34 m s^{-1}, with a lower probability of extreme values, compared to an absolute spread of 155 °C and 1.4 m s^{-1} at $z = 1$ m.

A key result is that the flow structure must be carefully considered in experiments that initiate simulations at a dilute point above the vent, as many hydrothermal plume simulations rely on this approach (Lavelle et al., 2013; Gao et al., 2019; Adams & Di Iorio, 2021). Approximating a uniform source below $z = 5$ m fails to capture the dynamics of the near-vent flow structure. In particular, the velocity fluctuations indicate that turbulence is fully developed, and the plume cannot be assumed to be laminar in the near-field.

3.3 Entrainment and Flow Structure

The entrainment rate, $\alpha(z, t)$, shows strong vertical and temporal variability, associated with intense mixing and the plume dilution. The overall value in the domain is $\alpha = 0.19$, but it shows a vertical dependence with three distinct zones, consistent with previous results obtained using DNS by Van Reeuwijk et al. (2016). For $z < 0.7$ m, the forced plume is driven by the source condition. The entrainment rate is similar to that of a jet-like plume, $\alpha = 0.07$. This region corresponds to most in-situ observation capabilities. Between 1 m $< z <$ 2 m, the entrainment rate reaches its maximum ($\alpha = 0.26$), which is twice the commonly accepted value for buoyant plumes. This entrainment rate reflects intense mixing with cold fluid, contributing to the plume spreading, as well as the dilution and homogenization of the temperature anomaly distribution. Buoyancy driving the flow weakens, resulting in deceleration. For $z > 3$ m, the entrainment rate converges to a more conventional value ($\alpha = 0.15$) for a pure plume (Van Reeuwijk & Craske, 2015; Richardson & Hunt, 2022). This suggests that the plume reaches a self-similar state, marking the end of the near-field transition regime (discussed in more detail in section 4). This transition, as previously noted, is associated with an abrupt change in the key variables T and w for $z > 2$ m, with both converging to a weaker vertical decay rate (Figure 2-b, c). The dilution process is responsible for the dissipation of the large buoyancy flux B_0 at the source.

The $\alpha(z)$ profile is closely related to the turbulence field, which consists of different scales of coherent structures. These structures can be observed using the λ_2 technique (Jeong & Hussain, 1995), as shown in Figure 3. A real-time sequence of the turbulent field observed with this technique is provided by the authors (Lemaréchal et al., 2024a). The jet-like entrainment rate close to the source ($z < 0.7$ m) is associated with an unstable shear layer that forms ring vortices along the plume axis, typical of jet-like flow. As the entrainment rate increases with height ($z < 1.5$ m), the flow field becomes turbulent. The vortices destabilize and break down into a helical mode, as described by Fiedler (1988). The large, well-organized vortex structures between 1 m and 2 m, predominantly aligned in the horizontal plane, entrain more fluid than the smaller, less organized vortices that appear further downstream. This explains the maximum value of $\alpha(z)$ observed at this height. This marks the transition region, where both the kinetic

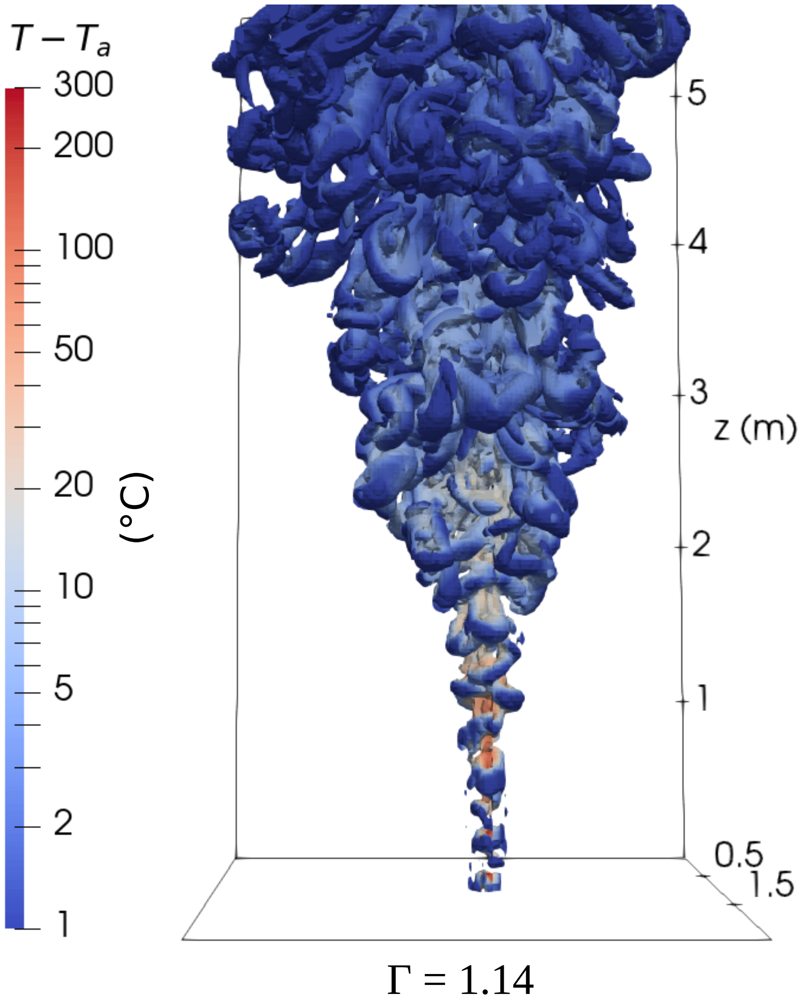

Figure 3. Three-dimensional coherent structures are visualized using the λ_2 method (Jeong & Hussain, 1995) for iso-surfaces at $\lambda_2 = -0.1$ for a plume near the forced plume regime (experiment 1). The colormap represents the temperature anomaly, with $T_a = 4.6$ °C.

energy dissipation and the entrainment rate reach their peak. Beyond $z = 1.5$ m, the entrainment rate decreases as the flow enters a fully 3D convective turbulent state (pure plume). The plume structure directly influences the entrainment rate and the energy dissipation dynamics.

The instantaneous entrainment rate profiles (Figure 2-d – black lines) show significant temporal variability. $\alpha(z, t)$ reaches a value of 0.5 at $z = 1.6$ m, representing a 90% deviation from the mean. This observation adds to the evidence for strong mixing in the vicinity of the vent. Similar behavior has been observed in experimental studies (Matulka et al., 2014) and DNS studies (Plourde et al., 2008; Marjanovic et al., 2017). We observe the same pattern in the hydrothermal regime. The temporal variability results from large-scale vortical structures driving the turbulent flow, as highlighted by Plourde et al. (2008). Most of the entrainment occurs at the plume's edge, while the core remains less sensitive to mixing. Negative entrainment, up to $\alpha = -0.06$, is associated with detrainment processes reflected in the local downward velocities. This is associated with the expulsion of fluid from the plume due to coherent turbulent structures. The influence of this mechanism on the mean field becomes noticeable only after $z = 3$ m. Plourde

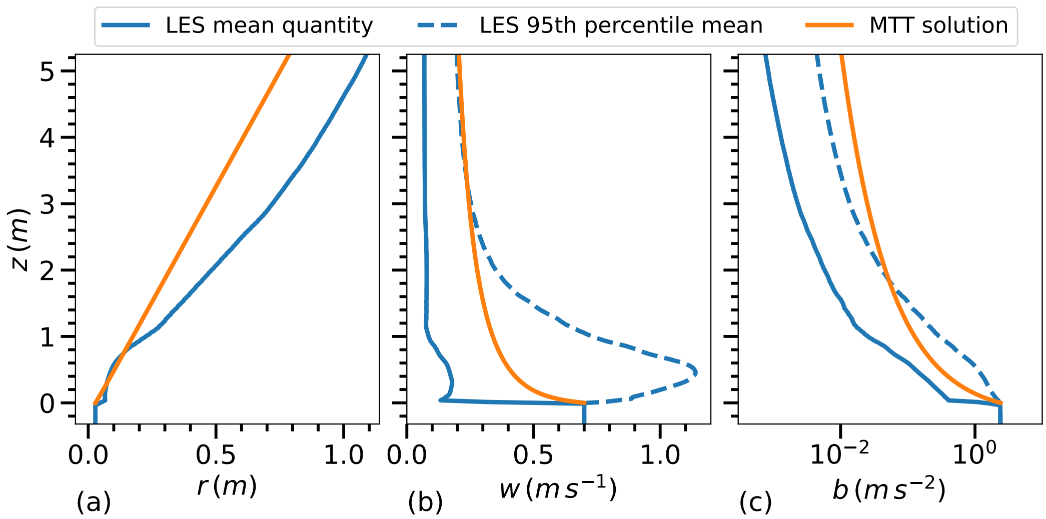

Figure 4. Vertical profiles of the flow field compared to the results obtained with the MTT model (1956) for its governing parameters: (a) radius, (b) vertical velocity, and (c) buoyancy. The dashed line represents the 95th percentile mean of the LES results (core plume).

et al. (2008), using higher resolution DNS, identified it as an expulsion and contraction mechanism of local coherent structures driving the dominant entrainment process.

3.4 Comparison with the MTT Model

LES mean quantities can be compared with predictions from integral models. Figure 4 compares LES data with the MTT model predictions, the most widely used theoretical model. It shows that the self-similar conservation equations derived by Morton et al. (1956) do not hold in the near-field. The MTT equations in Figure 4-a, b, c capture the general trend of the flow field but do not agree well with the mean profiles. This discrepancy cannot be attributed to horizontal averaging choices, as the MTT model best represents the core plume evolution for $z > 2$ m. At $z = 5$ m, the radius predicted by the MTT model is 30 % smaller, and the difference in the velocity profiles results in $Q = 0.37$ m^3 s^{-1}, which is 30 % higher than the LES flow field.

In particular, the fluid acceleration contradicts the self-similarity assumption in the MTT model, which predicts a monotonic decrease in vertical flow velocity (Figure 4-b). This was shown by Marjanovic et al. (2017) for lazy plumes. Here, we show that the buoyancy flux injected by black smokers in a forced plume regime is sufficient to induce the same effect.

A virtual origin correction can be applied to the source to account for the point source assumption of the MTT model (Hunt & Kaye, 2001). However, the length $L_q = 5Q_0/(6\alpha M_0^{1/2})$, which represents the distance from the actual source to the virtual source of a pure plume (Hunt & Kaye, 2005), has little effect on the results ($L_q = 29$ cm) and is therefore not applied.

The adjustment between the vent conditions and an ordered far-field flow, corresponding to a pure plume regime, is responsible for the breakdown of the self-similarity assumption. This prevents the direct application of the theoretical model. This is in agreement with recent findings by Matulka et al. (2014); Van Reeuwijk et al. (2016); Marjanovic et al. (2017); Ciriello and Hunt (2020) and highlights the need for analytical solutions adapted to this region. This adjustment to the far-field occurs through mixing, which is reflected in the strong variability of the $\alpha(z,t)$ profile. Thus, our work confirms the main limitation of the MTT model: the entrainment rate cannot be assumed constant in the transition region between the near-field and far-field. It shows that although theoretical models are often used to calibrate measurement techniques (Crone et al., 2008; Mittelstaedt et al., 2012), near-field hydrothermal plume predictions cannot rely solely on these models.

Another approach to measuring the entrainment rate is to derive α from the spreading rate, represented by the local derivative $\partial z/\partial r$ and expressed as the angle $\hat{\beta}$ between the plume boundary and the horizontal. Plumes do not always maintain a constant spreading rate, particularly in cases of necking in lazy plumes (Marjanovic et al., 2017). Here, however, the radius shows a steady increase, corresponding to a nearly constant angle $\hat{\beta} = 84°$. The spreading rate is linked to the MTT assumptions through α. Applying $\hat{\beta}$ to the conservation of volume in the MTT model gives a theoretical value of $\alpha = 0.10$.

Two key points can be made. First, the spreading rate remains nearly constant in the near-field for hydrothermal plumes. This is consistent with the assumption of the model developed by Priestley and Ball (1955), which is related to the MTT model (Fox, 1970). Secondly, the derived value of $\alpha = 0.10$ is close to the classical one (Richardson & Hunt, 2022), while the mean value $\alpha = 0.19$, obtained through direct computation, is almost twice as high due to the turbulent field in the near-vent region. This shows that while black smokers can be captured to some extent by integral models, these models fail to reproduce the detailed dynamics observed near the vent.

3.5 Comparison to In-Situ Observations

Here, we assess how accurate our model is compared to direct measurements. Reproducing black smokers in laboratory experiments is technically challenging (Shabbir & George, 1994; Crone et al., 2008), while accessing hydrothermal fields at depth presents its own set of challenges. Our LES results are compared with in-situ data from the MoMARSAT2023 cruise using Remotely Operated Vehicle (ROV) operations.

The in-situ experimental setup is shown in Figure 5. Sampling was performed at a typical source in the Tour Eiffel field. The vertical observation window, H_{obs}, is limited to 60 cm above the vent. The key parameters to be retrieved are the plume radius and the temperature profile. The optical width, i.e., the visible gradient density anomalies, provides a measure of the apparent radius of the plume, although this measure is subject to perspective distortion. Radius measurements are based on video recordings with a reference scale, consisting of 300 frames and a step size of $dz_{obs} \approx 5\%\, H_{obs}$. The temperature profile is measured with a probe positioned along the plume centerline above the vent, with $dz_{obs} \approx 10\%\, H_{obs}$ and a sampling rate of 1 Hz. Horizontal currents were negligible during the experiment.

The in-situ data are compared with the LES equivalent in Figure 6 (experiment 9 of Table 1). The values of $r_0 = 1.4$ cm and $T_0 = 300$ °C for the LES experiment are chosen based on the in-situ measurements at $z = 0$ m. The Root Mean Squared (RMS) value is used to represent the temporal dispersion of the in-situ data.

The vertical velocity at the source is a complicated parameter to measure accurately using only video data (Crone et al., 2008; Mittelstaedt et al., 2012). First, σ is set to 10 cm s^{-1}, which captures the plume contour effectively measurable in videos. For any given set of source parameters tested, a smaller σ value includes density gradients too weak to be detected visually in the video, as well as colder parcels. This causes an incoherent sharp increase and decrease in r and T, respectively, immediately after the exit (Figure 6-a, b). Then, w_0 is estimated based on LES experiments. Several experiments are run with the same r_0 and T_0 values as above, to determine the w_0 value that gives a ra-

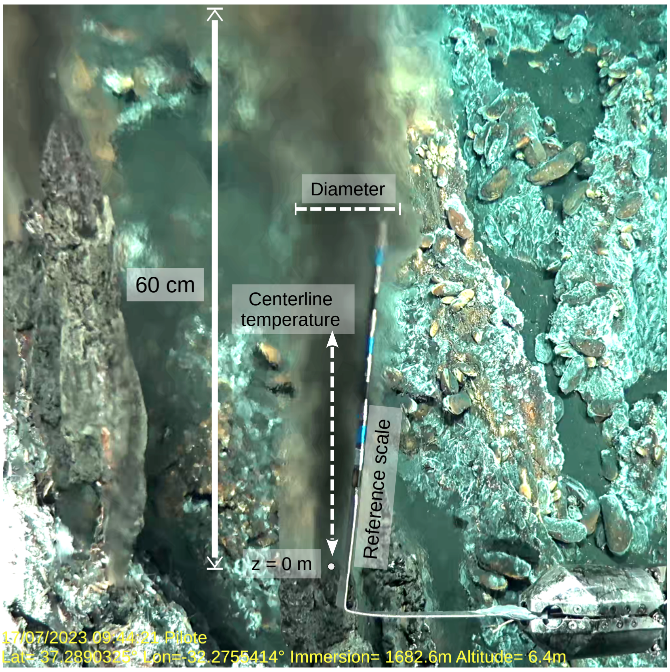

Figure 5. Photograph of the plume and schematic of the parameters used to measure the temperature and diameter of the plume. The reference scale gives the pixel-to-real distance ratio. Height above the source is measured from the reference point at $z = 0$ m. Diameter is measured by identifying the visible outer edges of the plume relative to the surroundings. Temperature is measured along the centerline of the plume.

dius and temperature profile that best matches the in-situ data. It is found to be $w_0 = 0.5$ m s^{-1}.

The LES radius and temperature profiles are in good agreement with the experimental data. The variability of the in-situ radius at z_0 reflects the temporal evolution of the effective equivalent surface through which the flow passes. In fact, the vent geometry does not resemble a well-defined pipe, but consists of closely spaced sources, each less than a centimeter wide, which together form a single plume exit. The RMS of the in-situ data increases with height as the plume moves and bends away from its axis, introducing a bias from the 2D view of the apparent radius, which is not captured by the LES method of calculating r.

The LES plume is slightly colder at the source, but this does not significantly affect the profiles. The LES experiment accurately reproduces the rapid decrease from 220 °C at $z = 5$ cm to 85 °C at $z = 30$ cm. The blue dots in Figure 6-b represent the profile expected from LES for a thermal sensor placed on the axis. Due to the stirring effect of turbulent structures, the mean profile along the axis is interchangeable with the temperature averaged over a slice bounded by $\sigma = 50$ cm s^{-1}. This indicates that w measurements on the axis are expected to be larger than this σ value.

The in-situ profile deviates from the LES profile for two reasons. In practice, the sensor is not perfectly centered, resulting in a colder in-situ profile. The in-situ profiles correspond better to the mean LES profile for the area bounded by $\sigma = 10$ cm s^{-1}. Second, the thermal inertia of the instrument misses the parcels with the highest fluid temperatures, such as rapidly ascending turbulent structures, as shown by the small RMS of the field data compared to the LES spatial variability.

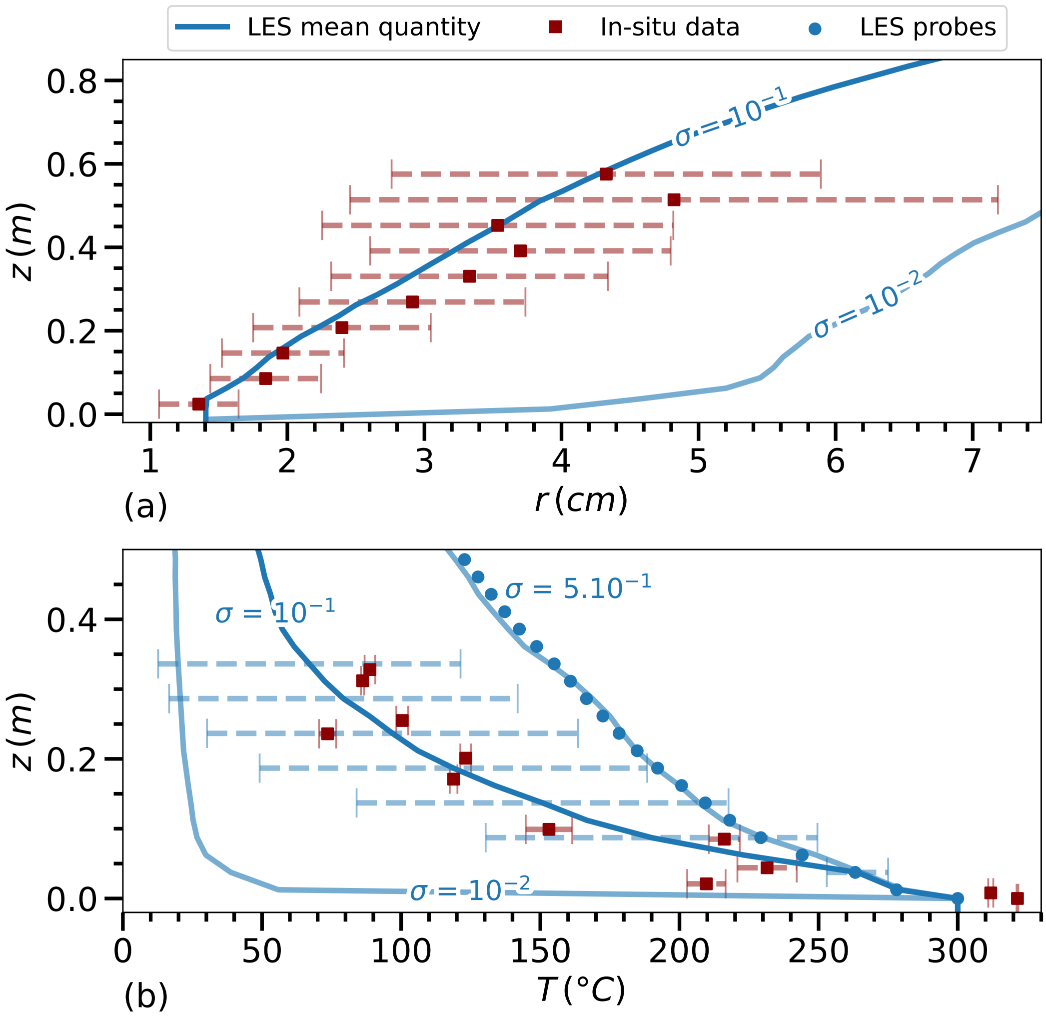

Figure 6. Profiles of (a) the plume radius and (b) temperature for the in-situ data and the LES mean quantities for different values of σ (in m s^{-1}). The blue dots represent numerical probes indicating the time-averaged temperature at the plume axis. The error bars represent the spatial RMS for the LES data and the temporal RMS for the in-situ data.

The consistency of the LES and in-situ radius and temperature profiles for $H_{obs} =$ 60 cm gives us confidence in the reliability of the LES model in the near-vent region, in contrast to the MTT model. In addition, the good agreement close to the source validates the parameterization of the vent turbulence.

4 Sensitivity to Source Parameters

Hydrothermal plumes can exist under a wide range of conditions, from forced to lazy plume regimes. In this section, we extend the results to a large set of vent source parameters. We provide a detailed description of the transition region from the near-vent to the pure plume regime. The resulting flow field adjustments are analyzed on the basis of plume theory. We use experiments 1 to 18 (Table 1), for which the set of conditions is summarized in Figure 7-a, covering most of the parameter space of hydrothermal vents.

4.1 Transition Region

As the plume mixes with the ambient fluid, the potential energy of the density anomaly decreases, and a fraction of it is converted into momentum through the buoyancy flux (Wykes et al., 2015). Therefore, assessing the transition height H_t based on the ratio of forces using the $\Gamma(z)$ parameter becomes complicated because the momentum combines with the kinetic energy resulting from buoyancy. Indeed, several studies have shown that $\Gamma(z)$ exhibits complex behavior before converging to 1 (Hargreaves et al., 2012; Taub et al., 2015; Marjanovic et al., 2017), and its dependence on α further complicates the task.

To address this issue, we frame the transition region using two indicative heights. The first height, H_{ε_k}, corresponds to the location of maximum viscous dissipation, excluding the peak associated with noise injection. A consistent pattern in the vertical profile of viscous dissipation is observed across all results, showing an increase that culminates in a peak within the first meter. This point indicates the establishment of a balance between the shear generated by the injection of momentum and the buoyancy force. The second height, H_α, marks the location where the maximum entrainment of ambient water occurs, indicating the complete destabilization of the plume column into 3D turbulence. As noted by Taub et al. (2015); Marjanovic et al. (2017), $\alpha(z)$ converges to a constant in the self-similar state. These heights are illustrated in Figure 1-b.

Figure 7-b shows the rapid horizontal expansion in the transition region for a highly lazy plume (S1 - experiment 12), a plume in balance (S2 - experiment 9), and a forced plume (S3 - experiment 7). H_{ε_k} and H_α effectively capture the transition from vertical streamlines to a turbulent field (Figure 3) and frame the maximum of the derivative $d\log(r^2/r_*^2)/dz$, where r_* is a reference radius. In Figure 7-c, the heights H_{ε_k} and H_α are plotted against the parameter Γ_0. Two key points emerge.

Despite a 6 order of magnitude variation in Γ_0, the transition region exhibits relatively small amplitude changes ($\Delta H_{\varepsilon_k} = 0.5$ m and $\Delta H_\alpha = 0.95$ m). This shows that the transition region remains almost invariant to the set of parameters r_0, w_0 and b_0 encountered at the hydrothermal site. H_α ranges from 1.20 m to 2.15 m, and H_{ε_k} ranges from 0.25 m to 0.75 m, with S1 and S3 differing by a factor of only 1.7. However, a similar trend emerges for both heights H_{ε_k} and H_α. The transition region extends further away from the source as Γ_0 increases. This is consistent with the results of Taub et al. (2015), whose analysis of entrainment rate profiles suggests that lazy plumes reach self-similarity further away from the source than forced plumes.

Forced plumes – up to $\Gamma_0 = 1$ – driven by momentum flux are unstable, characterized by intense shear leading to rapid destabilization of the column ($H_{\varepsilon_k} \approx 0.3$ m for $\Gamma_0 < 1$). When the source buoyancy flux balances the input momentum, it slows

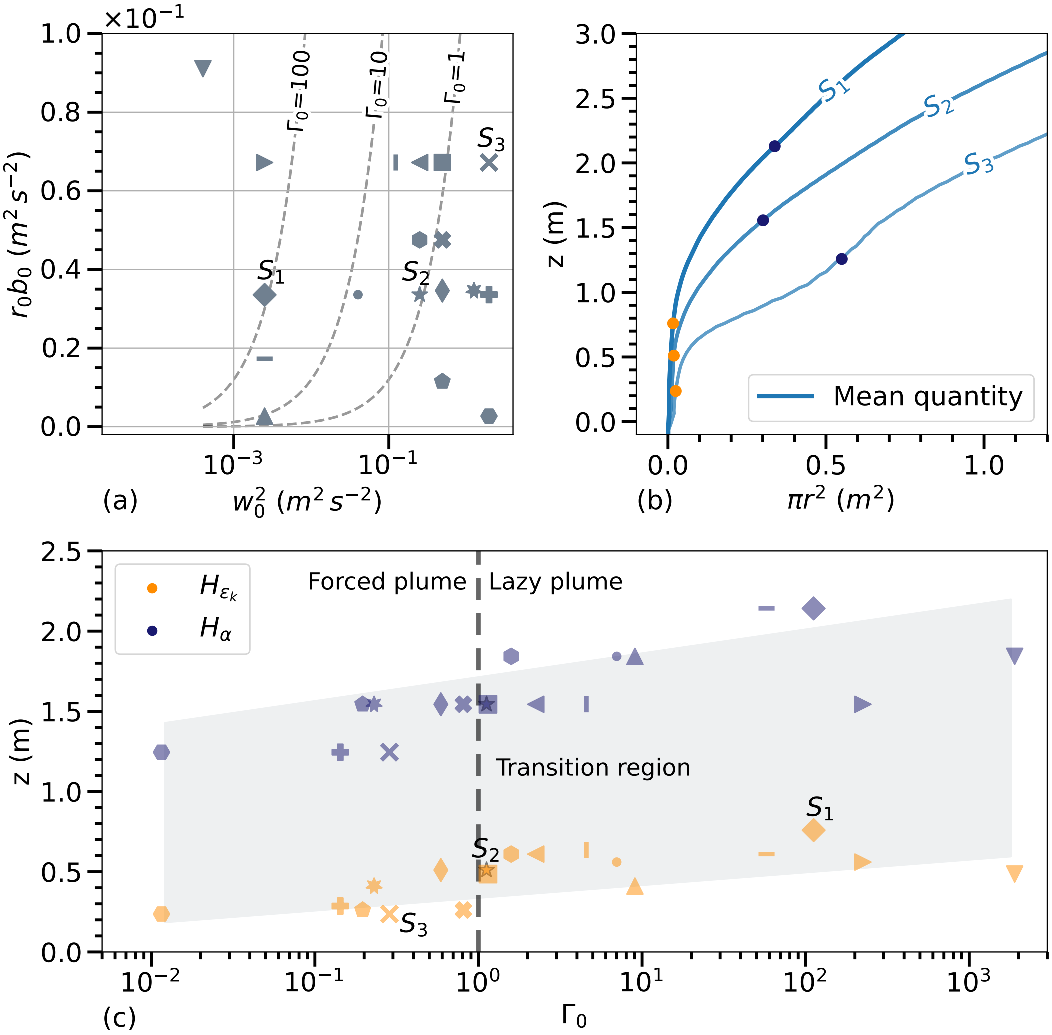

Figure 7. (a) Ratio of input buoyancy-radius product to momentum for experiments 1 to 18. (b) The surface of horizontal expansion for three different source conditions, with their transition heights defined by H_{ε_k} (in orange) and H_α (in blue). (c) Transition heights as a function of Γ_0, the plume source parameter. The dashed line separates the forced and lazy plume regimes, while the grey area encompasses the plume's transitional state.

the development of convective turbulence compared to jet-like plumes ($H_{\varepsilon_k} \approx 0.5$ m for $\Gamma_0 = 1$). In all cases, the flow requires a minimum height of $H_\alpha \approx 1.2$ m to fully develop convective turbulence, even under a highly forced plume regime. It is worth noting that the noise injected at the source accelerates the onset of turbulence.

The second consequence is that the transition region is not sharply delineated, as it extends between H_{ε_k} and H_α. The characteristic length scale, $L_m = M_0^{3/4} B_0^{-1/2}$, has been proposed for forced plumes as the separation between jet-like and plume-like regions by Morton (1959). A similar length scale for lazy plumes, marking the transition to pure plume behavior, is $L_a = Q_0^{3/5} B_0^{-1/5}$ (Hunt & Kaye, 2005). Recent studies by Taub et al. (2015) and Wang and Law (2002) report $z > 5\,L_m$ or $z > 6\,L_m$ as the transition limit between jet-like and plume-like regions. However, these lengths do not accurately represent the hydrothermal plume flow field. For $\Gamma_0 < 1$, $L_m \approx 18$ cm, and the transition to the plume-like region occurs for $z > 8\,L_m$, which is slightly higher but still within reasonable agreement with the literature. In contrast, L_m increases for highly forced plumes, which is not consistent with the trend observed for the LES. For $\Gamma_0 > 1$, $L_a \approx 4$ cm, but convergence to self-similarity clearly occurs at $z > 40\,L_a$.

The high buoyancy flux involved may explain the limited relevance of both L_m and L_a. Our results support the definition of a relatively broad transition region, bounded by H_{ε_k} and H_α, above which the plume reaches a pure plume regime and below which the source conditions dominate. This region is highlighted in grey in Figure 7-c, spanning from 0.25 m to 2.15 m, and is characteristic of hydrothermal vent conditions. For simplicity, this region is referred to as H_t hereafter. The transition region corresponds to the scale of hydrothermal edifices and falls within the range accessible by in-situ observational techniques, indicating that hydrothermal plumes observed near the seafloor are typically in a transitional state.

Finally, the minimal effect of b_0 and w_0 on H_t suggests that other factors play a more significant role. H_t is closely related to the vertical extent of the plume, with results showing $H_t \approx H_{nbl}/100$. While variations in r_0 were limited due to small vent sizes and could influence H_t, the parameter N, which was kept constant and is weak enough to assume uniform ambient conditions, has a dominant effect on H_{nbl} due to its larger scaling exponent in equation 2a. With realistic stratification, H_t remains less than 5% of H_{nbl}, even for the experiment with the lowest B_0 (experiment 14, where $H_{nbl} = 21$ m from equation 2a). Thus, it is very likely that achieving a significant change in H_t would require unrealistically high N values to reduce H_{nbl} to a scale comparable to the observed H_t for hydrothermal plumes.

4.2 Organization of the Flow Field

We focus on the relationships between the key flow variables in this transition region. Figure 8 presents the link between r and w, and b and w below ($z = 0.29$ m) and above ($z = 5.0$ m) the transition height. Each experiment is related to its B_0 value. Consistent relationships indicate that the flow primarily depends on B_0. To limit spatial averaging effects of cold fluid at the plume boundary, we restrict σ to $10\,\mathrm{cm\,s^{-1}}$, which filters out experiments 12, 14, and 16 in Figure 8-b, d.

The organization is chaotic in the near-vent region, dominated by vent conditions (Figure 8-a, c). In contrast, a clear organizational pattern emerges after reaching the pure plume regime (Figure 8-b, d). The relationships between r and w, as well as b and w, both collapse to single power-law curves. Wang and Law (2002) showed that the mean axial velocity and turbulent concentration fluctuations similarly collapse into Gaussian curves for both forced and lazy plumes in pure plume regime.

In Figures 8-b and 8-d, B_0 governs the overall organization of the flow, setting the levels reached for each key variable above the transition region, where pure plume behavior is observed. The pattern does not depend on the excess force at the source. Consequently, there are no scenarios where one quantity, such as w, becomes disproportionately large while others, such as r or b, remain small. Instead, the system organizes itself to maintain consistency in the overall energy and momentum balance, with all variables adjusting together to reflect the level of B_0 injected.

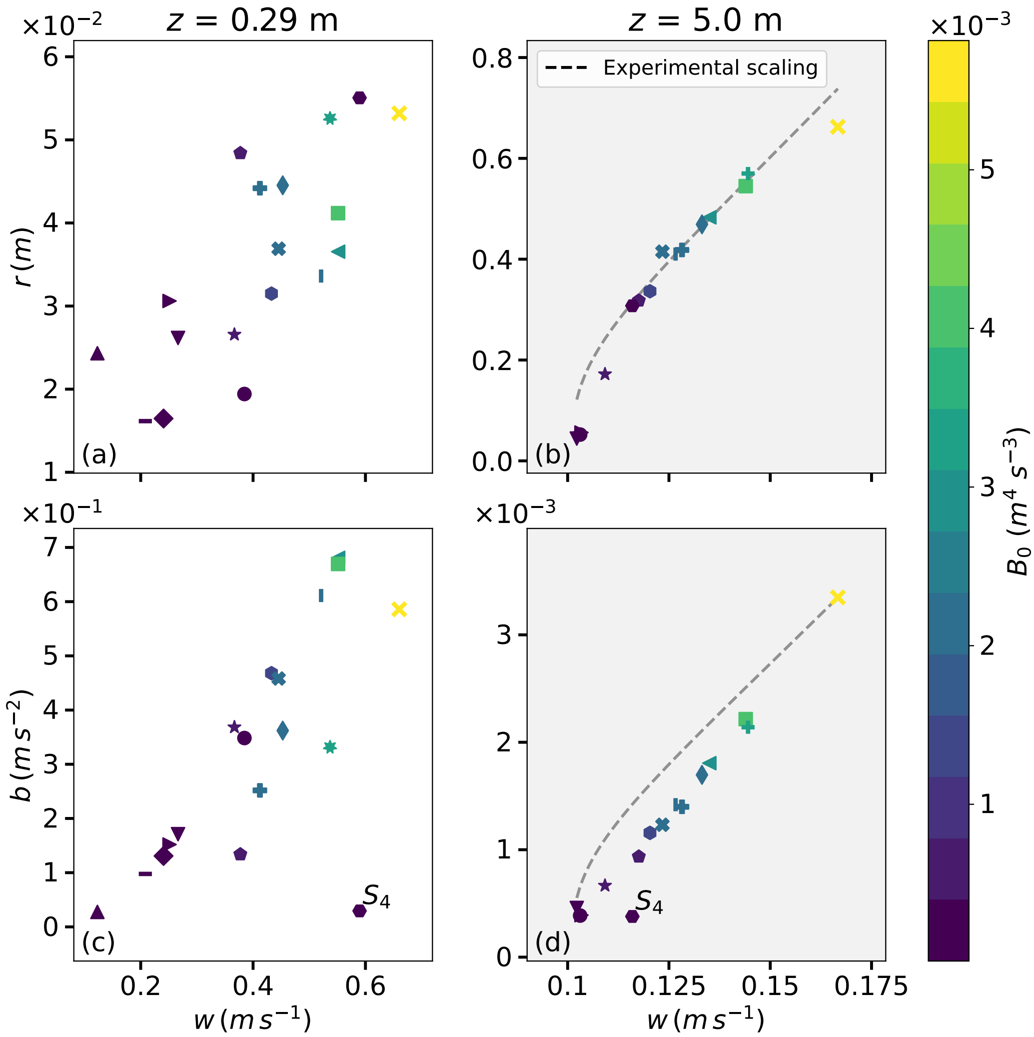

Figure 8. (a, b) Plume radius and (c, d) horizontal mean of buoyancy as a function of vertical velocity for $\sigma = 10$ cm s^{-1}. Each experiment is shown (a, c) below and (b, d) above the transition region identified in section 4.1. The symbols are colored according to the source buoyancy flux. Experimental scalings are plotted from (b) equation 8 and (d) equation 7b.

This is consistent with the buoyancy flux conservation approach in the MTT equations. The derivation of the theoretical model predicts an equilibrium level based solely on B_0 and the ambient stratification (equations 2). The scaling laws obtained from the LES experiments reflect this behavior.

In a uniform environment, which is a valid assumption here (see section 3.1), the right-hand term in equation 1-c vanishes, simplifying the MTT model to the analytical solutions

$$r \propto z\,, \tag{6a}$$
$$b \propto B_0^{2/3} z^{-5/3}\,, \tag{6b}$$
$$w \propto B_0^{1/3} z^{-1/3}\,. \tag{6c}$$

These equations imply that the buoyancy flux is conserved at all heights. By combining them, the relationships between the key plume variables are derived

$$r \propto B_0^{-1/3} z^{4/3} w\,, \tag{7a}$$
$$b \propto B_0^{1/3} z^{-4/3} w\,. \tag{7b}$$

A custom factor $C_1(z) = 2.81\, z^{-0.74}$ is applied to equation 7b to account for empirical deviations observed in the flow field data, resulting in the scaling shown in Figure 8-d. It agrees within 20% with the factor predicted by Morton et al. (1956).

The agreement with the scaling laws improves with height as the distance from the transition region increases, indicating a breakdown of self-similarity in this region. Typically, for plumes with $\Gamma_0 \ll 0$, such as solution S4 ($\Gamma_0 = 0.01$ - experiment 15), equation 7b incorrectly predicts high values of b for high values of w. Only when the highly forced plume dissipates its input momentum does it converge to the solution predicted by the scaling (Figure 8-c, d). However, even at $z = 5$ m, the relationship between b and w has not fully collapsed to the self-similarity solution. Taub et al. (2015) suggests that buoyancy fluctuations are influenced by source conditions over a longer range than velocity fluctuations.

Equation 6a shows the limitations of the analytical solution based on the assumption of a uniform environment. In this case, the plume radius is predicted to be independent of B_0, leading to an inconsistent relationship between r, w, and B_0 in equation 7a. In particular, increasing values of B_0 result in decreasing plume radius for the analytical solution, which is not consistent with the LES flow field. This discrepancy with the MTT model is due to its assumption of a constant spreading rate between plumes. The deviation observed in our results indicates a difference in the spreading rates, which is consistent with the experimental results of Kitamura and Sumita (2011). They observe that pure jets have a slightly higher spreading rate than plumes; however, this difference is generally considered to be small (Kotsovinos & List, 1977; Van Reeuwijk et al., 2016).

To align the scaling in equation 7a with the LES flow field, the dependence on B_0 is adjusted, and an empirical correction factor $C_2(z)$ is introduced. This modified scaling is expressed as

$$r = C_2(z) B_0^{1/3} z^{4/3} w\,, \tag{8}$$

where $C_2(z) = -0.27z + 3.9$. This adjustment results in the scaling shown in Figure 8-b.

The overall agreement between the scaling and the LES experiments shows that, despite the strong influence of the near-vent region on the flow, the turbulent field can be simplified by scaling laws as plume quantities converge toward self-similarity. This indicates that in the far-field the MTT model captures the underlying physics based on the B_0 value. The LES results highlight that B_0 is the main controlling parameter, even in the exotic hydrothermal regime where high buoyancy flux is injected into weak stratification.

5 Discussion

5.1 Transition Region Observation

The transition region between vent conditions and the pure plume region is identified in an in-situ recording of a black smoker at the Tour Eiffel site. The video described below was captured by a ROV and is provided by the authors (Lemaréchal & Matabos, 2023). The comparison is summarized in Figure 9. The source observed here is the same as that used for the in-situ measurements in section 3.5, and experiment 9 is presented as the numerical counterpart.

We focus first on observations near the seafloor (between 15:10 and 15:44 in the video). The visible plume length is about 60 cm (Figure 9-b), while for this source, $H_{\varepsilon_k} = 0.51$ m and $H_\alpha = 1.53$ m. Compared to its numerical equivalent, this limits the analysis to region (1) in Figure 9-a, which is dominated by vent conditions. As the ROV ascends (between 16:15 and 18:54), the camera transitions from focusing on the near-vent region through the transition region (gray region labeled 2). At $z \approx 2$ m, the camera reaches the fully buoyant region of the plume (gray region labeled 3 – around 17:30), where larger convective structures and fully three-dimensional turbulence dominate (according to LES data we get $r \approx 0.4$ m, $w \approx 5$ cm s^{-1}). At this height, the mean temperature ($T \approx 7$ °C) and the density gradient anomalies associated with the refractive index gradient decrease drastically. The light reflection from plume particles becomes insufficient to distinguish the plume clearly from its surroundings (e.g., at 17:50). In addition, the plume merges with those from neighboring sources, making numerical comparisons or in-situ studies of single source plumes extremely challenging.

Region (1) to (2) is the primary source of data for in-situ experiments, but this limitation introduces a bias in our understanding of the plume dynamics. By restricting observations to this specific region, we capture a view of the plume that is limited to its near-vent structure, which is strongly influenced by the transition from vent condition to pure plume behavior, where scaling laws fail.

5.2 Impact of Temperature Fluctuations on Tracer Proxies

Temperatures above 40°C have been documented as lethal to various organisms (Fisher, 1998; Bates et al., 2010; Lee et al., 2015). Given the high temperatures typical of black smokers, biotracer survival during transport through the plume might be expected to be unlikely. Consequently, studies often focus on stable environments that exclude such high-temperature conditions, e.g., Lee et al. (2015). However, LES results suggest that hydrothermal plumes could serve as a viable vector for biological material transport, as prolonged exposure to high temperatures is unlikely.

Below, we estimate how long particles transported within the first three meters of the rising plume are exposed to high and potentially lethal temperatures. To establish a high-temperature threshold of interest, we use the 40 °C criterion, which represents a reasonable estimate of the thermal tolerance limit for hydrothermal fauna. We distinguish between the plume's inner core and its outer envelope, numerically defined as the closest cells to the plume boundary. The LES experiment is chosen to reflect the source conditions identified in section 3.5 (experiment 9 in Table 1). It provides an actual example of a source in close proximity to a dense faunal community (Van Audenhaege et al., 2022).

Due to computational limitations, an Eulerian approach was chosen over the ideal Lagrangian method. Fixed probes serve as proxies for the trajectory of a particle entrained in the plume. These probes are placed vertically at intervals corresponding to the mesh resolution, either along the plume axis or at its boundary. The envelope probes are positioned at the intersection of the horizontal plane with the contour of the plume vol-

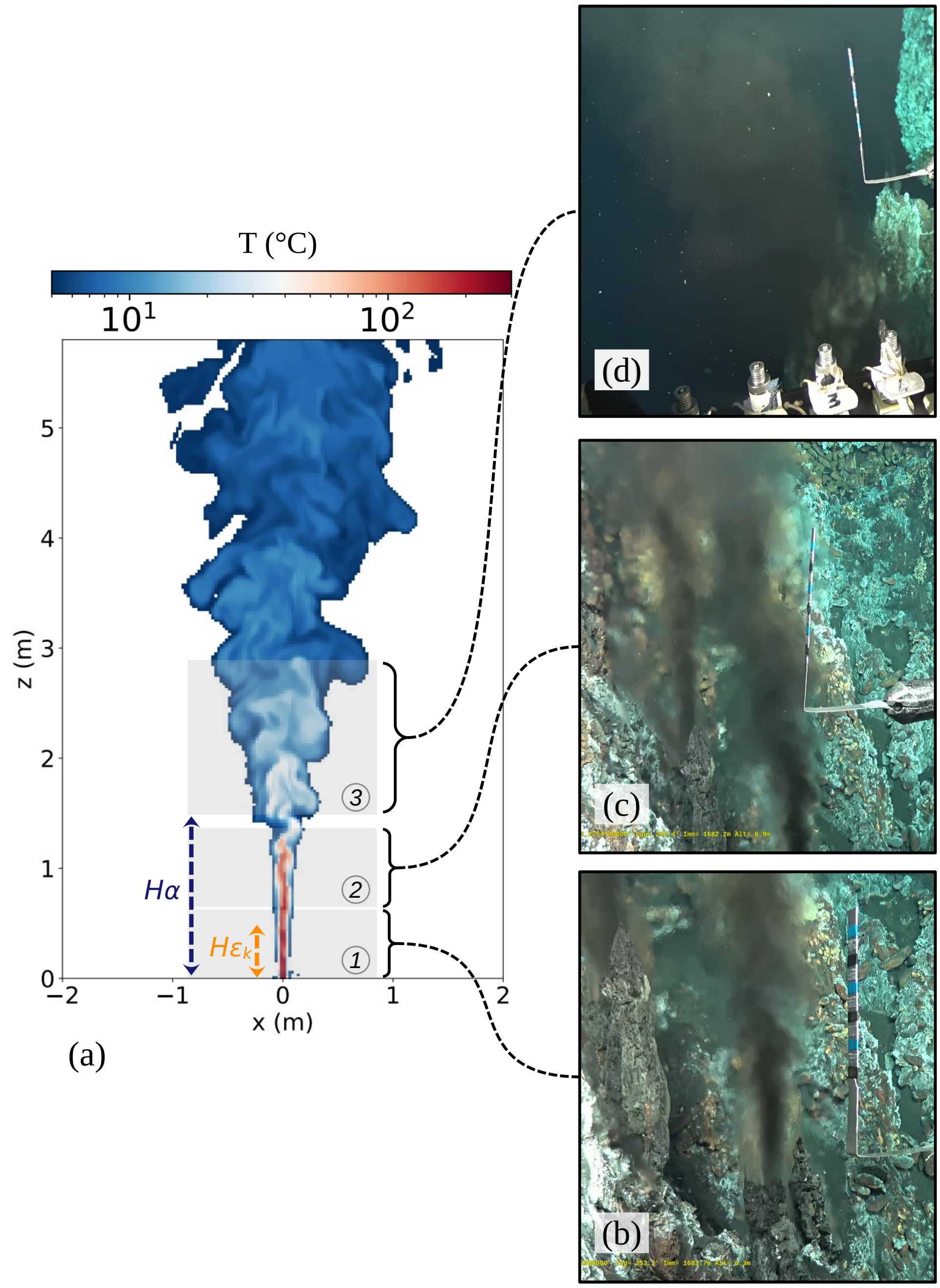

Figure 9. (a) Cross-sectional view of the instantaneous temperature field from a LES experiment (exp. 9), illustrating three types of regions corresponding to their respective in-situ observation windows as viewed during a video-recorded ROV exploration at Tour Eiffel. (b) The view corresponding to the height H_{ε_k}, (c) the view corresponding to H_α, and (d) the region where the plume reached its fully convective turbulent state.

ume that satisfies the criterion $\sigma = 0.1$ m s^{-1} on time average. This criterion is consistent with that used to match the in-situ data, and selects a plume region with sufficient vertical velocity to effectively advect materials. The bias introduced by sampling the plume with a 1D line of probes is mitigated by the large number of measurements taken over time: we use a sampling rate of 0.4 seconds over a duration of 14 minutes.

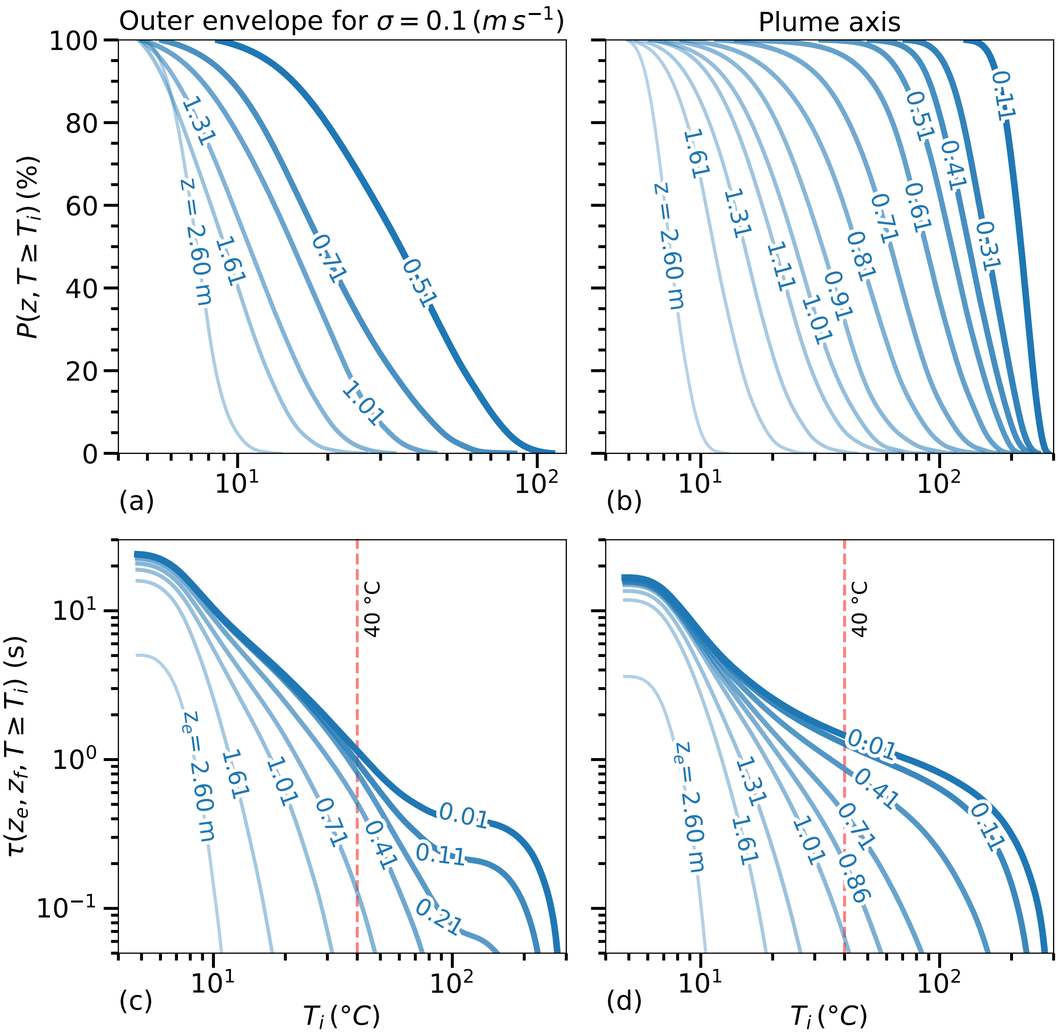

Figure 10. Complementary Cumulative Distribution Function (CCDF) of temperature at different heights z above the vent, for (a) the plume envelope selected by the criterion $\sigma = 0.1$ m s^{-1} and (b) the plume axis. (c, d) The cumulative time τ spent above each temperature T_i encountered in the hydrothermal fluid for trajectories along the vertical is shown in the same regions. Integration is performed for different starting entry heights z_e inside the plume up to $z_f = 3$ m. (c, d) Plots are truncated below 5×10^{-2} s.

Figure 10-a,b shows the CCDF, $P(z, T \geq T_i)$, derived from the time series of temperature at each fixed probe location. At $z = 80$ cm, the plume axis shows $T > 40$ °C events representing 60 % of the time distribution, with a maximum temperature of 150 °C at this height (Figure 10-b). These high temperatures disappear from the core

after 1.30 m. Within the envelope, it takes 1 m to eliminate temperatures above 40 °C. At 70 cm, such temperatures occur 12 % of the time, peaking at 80 °C.

The probability distribution alone suggests that a tracer would encounter lethal temperatures in both the core and the envelope of the plume within the first meter above the vent. To investigate this further, we compute the cumulative time τ (s). It is the time taken by a parcel entering the plume at height z_e to reach height z_f, following the trajectory traced by the 1D probe lines, with a temperature exceeding T_i. This computation is performed in the envelope (Figure 10-c) and along the plume axis (Figure 10-d). The results are integrated from different starting entry heights z_e in the plume up to $z_f =$ 3 m, where the temperature has decreased significantly, according to

$$\tau(z_e, z_f, T \geq T_i) = \int_{z_e}^{z_f} \frac{P(z, T \geq T_i)}{w_p(z)} dz \,, \tag{9}$$

where $w_p(z)$ is the vertical speed at the probe location. The maximum τ for each curve indicates the transit time between z_e and z_f.

The rationale for considering different starting heights z_e is that hydrothermal plumes are often associated with complex local topography, where the fluid comes into contact, providing different entry points for a tracer above the plume source. Below 30 cm, the envelope and core become indistinguishable, resulting in a characteristic bump in the envelope curve, as the cumulative time reflects the core values (Figure 10-c), and w_p exceeds the value chosen for σ in this region.

In the envelope, below $z_e = 40\,\text{cm}$, exposure to temperatures above 40 °C lasts for around 1 s, with significant exposure to higher temperatures, e.g., more than 0.3 s above 70 °C for $z_e = 11$ cm. For a particle entering at 41 cm, exposure to temperatures above 40 °C lasts for 0.5 s, with only 5×10^{-2} s above 75 °C. Exposure to high temperatures decreases significantly above 70 cm. A trajectory along the axis experiences 0.9 s above 40 °C for $z_e = 41\,\text{cm}$, with a significant duration above very high temperatures compared to the envelope, e.g., 0.25 s above 100 °C. High temperature exposure along the plume axis becomes negligible only after 1 m. While particle paths are simplified for practical purposes by considering 1D lines, it is important to note that particles could be advected through both regions discussed, and it is essential to assess the viability of tracers as a percentage of success. Nevertheless, both the core and the envelope of the plume show minimal exposure to high temperatures for a particle entrained 1 m above the vent. The envelope is a more favorable region for sustained transport for an entry closer to the vent ($z_e = 40\,\text{cm}$), considering the temperature levels and time exposure ratio, compared to the plume centerline.

These results support the findings of Kim et al. (1994), who demonstrated through dye experiments and the MTT model that a single black smoker can enable substantial vertical transport of larvae, opening pathways to habitats typically inaccessible to near-bottom larvae.

6 Conclusions

Hydrothermal plumes inject a high buoyancy flux into weak stratification, rising from centimeter-scale vents to heights of several hundred meters (Lavelle et al., 2013). They play a key role in vent fields but have been poorly characterized in the near-vent region. To study these plumes, we used a LES approach with adaptive mesh refinement to achieve centimeter-scale resolution within a 6 m domain above the vent. Several key points can be highlighted.

First, a typical black smoker (forced plume) is studied to quantify the mean flow and spatial fluctuations, which are difficult to measure in deep-sea vent fields. The mean temperature decreases sharply from $T_0 = 300$ °C to $T - T_a = 1.5$ °C at $z = 5$ m, and the velocity decreases from $w_0 = 70$ cm s^{-1} to $w = 7$ cm s^{-1}. This results in a substantial volume flow of $Q = 0.25\,\mathrm{m^3\,s^{-1}}$ at $z = 5$ m. The plume expands at a nearly constant spreading rate. The results compare well with in-situ measurements. While lazy plumes initially accelerate (Marjanovic et al., 2017), we show that forced plumes in the hydrothermal regime also accelerate due to significant buoyancy, reaching $w = 1.14$ m s^{-1}. Numerical approaches to hydrothermal plumes often model a diluted point source above the vent, e.g., Adams and Di Iorio (2021); however, approximating a uniform source below $z = 5$ m fails to capture the flow dynamics, especially since turbulence is fully developed at this height.

Secondly, we show that the entrainment rate exhibits strong vertical and temporal variability, associated with the intense mixing required to dissipate the high source buoyancy flux. The overall value in the near-field is $\alpha = 0.19$, which is significantly higher than the classical value of $\alpha = 0.12$ for a pure plume (Van Reeuwijk & Craske, 2015; Richardson & Hunt, 2022). However, the values vary significantly in the vertical, from $\alpha = 0.07$ in the jet-like plume region to $\alpha = 0.15$ in the pure plume region, with much larger values in between. The large variations in $\alpha(z,t)$ are linked to the coherent structures of the turbulent field. Variations reaching up to 90% above the mean profile dilute and homogenize the temperature anomaly distribution, contributing to the flow deceleration. It highlights the main limitation of the MTT model (Morton et al., 1956): α cannot be assumed constant in the near-field. A more appropriate approach would incorporate the work of Wang and Law (2002), who developed a second-order integral model to account for entrainment rate variations, where $\alpha(z)$ is treated as a function of the local Richardson number.

Extreme temperatures ($T > 100$ °C) occur for $z < 2$ m, coinciding with the ability of the plume to entrain biotracers from the seafloor. While the limited biological tolerance to high temperatures suggests that particle survival during transport through the plume is unlikely, our study offers a different perspective. For a proxy tracer, exposure times at $T > 40$ °C can be as short as 0.5 s in the plume envelope, depending on the height of entrainment, decreasing to 5×10^{-2} s above $T = 75$ °C. This challenges the concept of lethal temperatures in dynamic flows. Hydrothermal plumes could thus act as viable vectors for the transport of biological material from the seafloor, supporting the findings of Kim et al. (1994), provided more is known about the ability of the fauna to withstand such conditions for very short periods.

Finally, the sensitivity to source parameters is investigated for the forced and lazy plume regimes. We show that the adjustment from the near-vent region, dominated by source conditions, to the far-field, pure plume regime, leads to the breakdown of self-similar plume behavior in this transition region. This prevents the application of the theoretical model of Morton et al. (1956) in the transition region, which extends from $z = 0.25$ m to $z = 2.15$ m. The transition height shows little sensitivity to the plume regime and would require unrealistic changes in stratification to be significantly affected. Plumes observed at the scale of hydrothermal edifices are typically in a transition state, which may introduce bias into experimental studies at this depth. In the far-field, plumes converge to self-similarity and can be described by scalings 7b and 8 derived from plume theory. While the mean quantities do not agree well with the MTT model predictions, the flow field in the pure plume region agrees with the MTT model approach and is primarily organized according to the source buoyancy flux.

Data Availability Statement

The real-time sequence of the turbulent field observed with the λ_2 technique is available on Zenodo at `https://doi.org/10.5281/zenodo.13829868` (Lemaréchal et al., 2024a). The in-situ recording of a black smoker can be accessed online in 720p resolution at `https://video.ifremer.fr/video?id=52548` and downloaded in 4K resolution on SEANOE at `https://doi.org/10.17882/103869` (Lemaréchal & Matabos, 2023). A code to compute the parametric EOS is available on Zenodo at `https://doi.org/10.5281/zenodo.14332032` (Lemaréchal et al., 2024b).

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Appendix A Parametric EOS

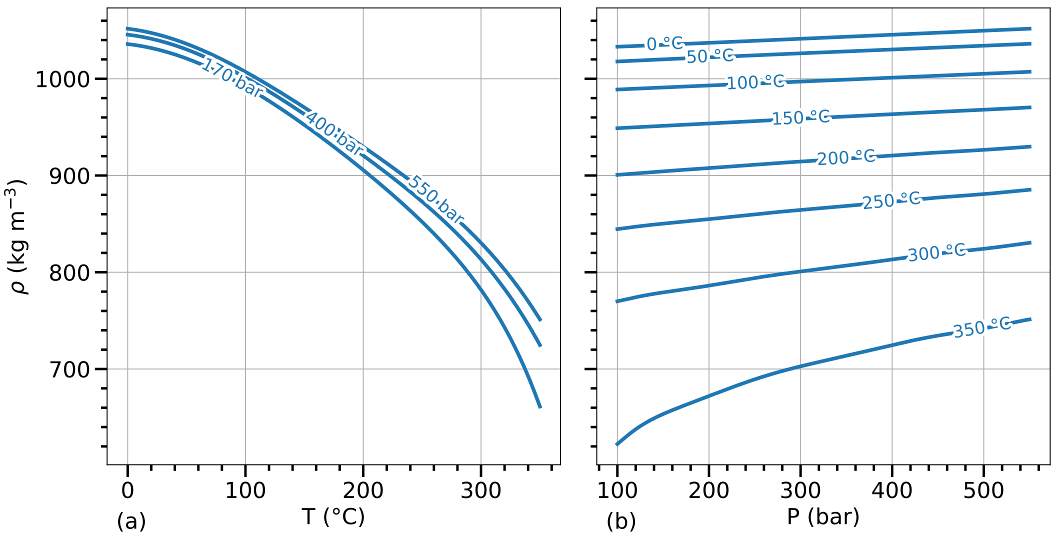

Figure A1. (a) Density of seawater vs. temperature calculated by equation A1 for different levels of pressure. (b) Density vs pressure for different levels of temperature.

This section presents the Equation Of State (EOS) developed for hydrothermal fluids. The EOS is valid in the range of 100–550 bar and 0–350 °C at $S_A = 35.2\,\mathrm{g\ kg^{-1}}$. A plot of density for different pressure and temperature ranges is shown in Figure A1.

The density ρ (kg m^{-3}) as a function of absolute temperature T (°C) and absolute pressure P (bar) is given by

$$\rho(T,P) = A(P)\exp\left(-B(P)T\right) + C(P) + D(P)\exp\left(-\frac{(T-E(P))^2}{2F(P)^2}\right), \tag{A1}$$

where $A(P)$ ... $F(P)$ are polynomials in P of the form

$$X(P) = \sum_{i=0}^{8} c_i P^{8-i}, \tag{A2}$$

with c_i being the polynomial coefficients given in Table A1 for each parameter. A code sample to compute this equation is provided by the authors (Lemaréchal et al., 2024b). To spare computing resources during calculations, we recommend generating an EOS table with a fixed step for efficient data interpolation through array indexing.

Table A1. Polynomial coefficients of equation A2

	0	1	2	3	4	5	6	7	8
A	-7.01307390e-21	1.95660070e-17	-2.23352820e-14	1.30848310e-11	-3.97395990e-09	5.53535930e-07	-3.96405330e-05	1.37810860e-03	-1.62833820e-02
B	-2.04801770e-22	5.85654850e-19	-7.17814260e-16	4.93110400e-13	-2.08500570e-10	5.61590670e-08	-9.67436850e-06	1.04954760e-03	-7.55052580e-02
C	-9.08091870e-18	2.56711040e-14	-3.09991740e-11	2.08730680e-08	-8.57874330e-06	2.21278690e-03	-3.54404280e-01	3.36599270e+01	-7.59305030e+02
D	9.14772610e-18	-2.58613080e-14	3.12300980e-11	-2.10288630e-08	8.64259430e-06	-2.22918380e-03	3.57047310e-01	-3.38666710e+01	1.79999190e+03
E	-2.57551460e-19	7.36404340e-16	-9.02945380e-13	6.20751900e-10	-2.62358970e-07	7.01422040e-05	-1.17048000e-02	1.14665420e+00	-7.20442180e+01
F	2.80580730e-18	-7.95146740e-15	9.63263680e-12	-6.51411210e-09	2.69367930e-06	-7.01266430e-04	1.14048660e-01	-1.11301910e+01	7.25953200e+02

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