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A simulation modeling approach to hydrothermal plumes and its comparison to analytical models

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ABSTRACT

We study the dynamics of hydrothermal plumes with the 3D time-dependent, Eulerian, adaptive mesh refinement code GERRIS, which solves the equations of viscous, incompressible hydrodynamics. We have implemented a new module into Gerris that treats buoyancy-driven turbulence by means of a subgrid mode. Our model is validated in numerical experiment and applied to the dynamics of a rising plume. First we simulate hydrothermal plumes in a static environment and compare our results to the widely used integral models (MTT or Briggs' model). The entrainment coefficient that we deduce from simulations falls into the range of the experimentally determined values. We also investigate the ratio between the level of the neutral-buoyancy layer and the maximum plume height. This ratio is frequently used to estimate plume heat flux via the measured level of neutral buoyancy. Although the ratio is only moderately (less than 10%) higher than the one predicted by the integral model, heat flux estimations can be substantially different. Finally, we explore the importance of background currents. We find that the simulated trajectories agree with integral models in the rising stage but the subsequent oscillations around the neutral-buoyancy layer are damped much more quickly and the level of the neutral buoyancy is also higher, same as the calm environment cases. By simulating the oscillation of a plume with suppressed transported turbulence and find a stronger oscillation than the original simulation, we suggest that a significant fraction of the difference between our model and the integral model can be explained by the absence of the turbulent transport of the latter.

1. Introduction

Hydrothermal fluids form when seawater exchanges heat and chemical components with the earth's crust along sea floor spreading axis and is subsequently re-injected into the ocean. This fluid is highly enriched with minerals from the crust (German and Von Damm, 2006) and often has a dark appearance because of the sulfide precipitates, which is why such flows are colloquially called "black smokers". Due to buoyancy caused by the low density, hydrothermal fluids start to rise after injection and form plumes. The plume fluids loose this buoyancy during their ascent by mixing with cooler sea water, finally becoming neutrally buoyant and reaching an equilibrium layer at a height determined by the plume heat flux and sea water stratification (Speer, 1989; McDuff, 1995; Woods, 2010).

Hydrothermal systems play an important role in exchanging both thermal energy and chemical components between the ocean and the earth crust. It is estimated that 11 TW out of the 43 TW global heat flux from the earth is emitted via the sea floor hydrothermal system and for several chemical elements hydrothermal system flux is comparable to riverine input (German and Von Damm, 2006). The knowledge of global heat and material flux output from hydrothermal plumes could be significantly improved if individual fields and plumes were better understood. This would require both improved in situ data acquisition and more physically complete modeling approaches.

Hydrothermal systems exist in various configurations and are influenced by many environmental factors. Rising from the sea floor to up to a few hundreds meters, some hydrothermal fields are dominated by one single vent or several vents with large enough separation so that they may be treated individually [e.g. Nibelungen field (Melchert et al., 2008)], while some other systems include clustering vents which are close enough to interact with each other [e.g. Clam Acres field (Bemis et al., 2002)]. In many cases, hydrothermal fields host diffusive fields which release comparably low temperature fluids but with a greater overall heat flux (e.g. ASHES field [Rona, 1992)]. While some hydrothermal fields are stable over years, there are fields in which fluid properties such as temperature vary over a time scale that is comparable to its

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plume rising time (Chevaldonn et al., 1991). All these vent settings and tectonic structures, together with the multi-phase flow (solid particles and gas bubbles) and background current and temporal variability make hydrothermal systems differ from the standard simple plume model, and often require case by case investigations. Nevertheless, the fundamental physics of hydrothermal plumes is described by the buoyant flow, which is intensively studied in atmospheric physics, astrophysics and many other fields. So in this paper we will focus on the model of single-phase buoyant plumes.

Over the past decades many efforts have been made to develop models of buoyancy-driven plumes to answer various questions. One of the earliest plume models was proposed by Morton et al. (1956) in 1956 and is referred to as the **MTT model** for short. They considered a single plume from a point source and closed the one-dimensional vertical mass, momentum, and heat conservation equations by making fluid entrainment into the rising plume at each level proportional to the vertical velocity via an entrainment coefficient α_e. The resulting set of ordinary differential equations can be readily solved to obtain the maximum rising height Z_m,

$$Z_m = C_e \left(\frac{B_0}{N^3} \right)^{1/4}, \tag{1}$$

where C_e depends on α_e and was considered as a universal constant in the **MTT model**, $B_0 = g \times \frac{\Delta\rho}{\rho} \times Q$ is the overall buoyancy flux of the point source, in which Q is volume flux and g is gravity, $N = \sqrt{-\frac{g}{\rho_0} \frac{\partial \rho(z)}{\partial z}}$ is the buoyancy frequency. The point source approximation is not valid for plumes originated from multiple sources or a source with a large area, in which case the overall buoyancy flux B_0 as well as the source diameter and buoyancy frequency N determine the rising height (Whitehead et al., 1996). In this paper, we will focus on point source plumes. After half a century, the MTT model is still widely applied to hydrothermal plumes due to its simplicity and good agreement with laboratory experiments and field measurements concerning the scaling law described in Eq. (1) (i.e. Rudnicki and Elderfield, 1992; Melchert et al., 2008). Despite its great popularity, the MTT model suffers from several short-comings. For example, the hypothesis that entrainment only depends on vertical velocity with a constant entrainment coefficient is not fully supported by experiments (Carazzo et al., 2008). Several authors have proposed to apply variable coefficients instead to cure this problem. In Wang and Law (2002) the author considered buoyant jets, which have both buoyancy as plumes and momentum as with jets and determined the local entrainment coefficients by fitting their integral model to the experiments. In this work, the local entrainment coefficients depend on the local Richardson number along the stream line of the jet. Despite the buoyant jets are different from the plumes by having initial momentum at the outlet, we believe that the physics behind the varying entrainment coefficients also applies to plumes in stratified environments. The mixing is dominated by turbulence which is energized by both shear stress and buoyancy. The relative strength of the two mechanisms determine that the over all entrainment coefficient is close to that of a pure plume or a pure jet. Even in a pure plume, these two mechanisms coexist as in a buoyant jet because during the rise of a pure plume it gains momentum and becomes a buoyant jet to some extend, at least locally. At the level where the density of the plume is equal to the ambient environment, the local Richardson number is actually 0, which by definition means it is a pure jet at that level and consequently, the local entrainment coefficient should be jet-like instead of an averaged constant of a plume. Carazzo et al. (2006, 2008)proposed a more general function of the entrainment coefficient which can be used in plumes in stratified environment. The authors compared the maximum heights of the plumes produced by the model with laboratory results and show good agreement. Besides ambient sea water stratification, at high latitude, Coriolis force could also play an important role by inducing circulation of the plume. Although the time scale of the rising plume (around one hour) is much shorter than the time scale of the Coriolis force, the time scales of the lateral spreading of hydrothermal plumes could be long enough to be comparable to the Coriolis scale and cannot be neglected if this part of the plume is of interest. This effect was studied in Speer (1989), Whitehead et al. (1996), Lavelle and Baker (1994) and Lavelle and Smith (1996). Crossflows bend over the plumes and thus alter the mixing and the rising heights and were addressed in integral models later in Briggs (1965), Hoult et al. (1969), Fay et al. (1970), Hoult and Weil (1967), Middleton (1986) and Wang and Law (2002).

Further two-dimensional or three-dimensional, time-independent models including various additional effects have been developed to address more complicated plume configurations. The so called Very Large Eddy Simulation (VLES) was applied to hydrothermal plumes, first to an episodic hydrothermal discharges (Lavelle and Baker, 1994), and then a line segment source (Lavelle, 1995) and extended to include rotation (Lavelle and Smith, 1996) and crossflows (Lavelle, 1997). VLES implies that the resolution of the model is not high enough to resolve turbulence to a scale where the remaining turbulence dissipation can be fully resolved by a subgrid model. Beside the low resolution, there is another draw back of this model, in which turbulent properties are calculated locally and are not transported. For example turbulence created in the lower part of the plume cannot be transported to the top. We will discuss this effect in detail in the latter sections of this paper. The model also heavily relies on parameterizations, for example the subgrid turbulent viscosity is taken as a sum of a conventional turbulent viscosity of LES and a background value which is not fixed physically, despite that such a background value influences the plume rising height significantly (Lavelle, 1997). Princeton Ocean Model (Blumberg and Mellor, 1987) was also used to study the hydrothermal activities (Thomson et al., 2005, 2009). As initially developed to meet the need of coastal systems, the POM model has its own limit for plume modeling. In the works using POM model cited above, the resolution is too low (10 m) to resolve the near field plume and the simulations were more fitted for qualitative study of the far field of hydrothermal plumes. In Devenish et al. (2010), Large Eddy Simulation (LES) was used to study the entrainment rate for plumes in a crossflow. They proposed an integral model with modified entrainment assumption in which the horizontal and vertical velocity contribute to the entrainment additively with different weight and compared their LES simulations with such a model and found good agreement. This work was motivated to use LES simulation to test the proposed integral models rather than aimed for quantitative real life plume simulation.

As introduced above, until recently, most quantitative studies of hydrothermal plumes were made by integral models which have their limits when the system cannot be fully described by their assumptions or approximations. 3D models, though have great potential, were mainly used for qualitative studies of the dynamic of the plumes, varies environmental impacts or to test proposed integral models. There is a huge demand for 3D models which can analysis the field data and provide quantitative information of the plume in case studies. In recent years, technology progresses such as high resolution in situ sampling and stationary real time sensors enable field researchers to study hydrothermal plumes in great details that was unimaginable before. On the other hand, ever growing power of super computers as well as the latest numerical methods make it possible for the modelers to simulate the plume with such a high resolution and precision that the models can quantitatively cooperate with the latest field researches. The purpose of our work is to develop a 3D time-dependent numerical