JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. C9, PAGES 20,495–20,507, SEPTEMBER 15, 1999

Dimensions and dynamics of megaplumes

Andrew W. Woods
Centre for Environmental and Geophysical Flows, School of Mathematics, University of Bristol, England

John W. M. Bush
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Abstract. We investigate the generation of megaplumes by the release of buoyant hydrothermal fluid from the seafloor. We show that megaplumes may be generated from various modes of venting, including both the instantaneous and continuous release of hydrothermal effluent from either a point or line source. The hydrothermal effluent forms a buoyant plume, which rises through the water column to its neutral buoyancy height and then intrudes laterally to form a neutral cloud. Owing to the influence of the Earth's rotation f, whose magnitude is $\Omega = f/2$, the neutral cloud eventually becomes unstable, giving rise to geostrophic vortices that propagate away from the source. By combining the scaling laws governing turbulent plumes and geostrophic vortices, we establish new relationships between the megaplume geometry and the source conditions. We find that megaplumes whose radius greatly exceeds their height of rise are formed from sources that persist for at least several days, since, in the deep ocean, the radii of eddies produced by short-lived releases of buoyant fluid are comparable to their rise height. Our model predicts the total buoyancy B of the hydrothermal effluent released in forming such megaplume structures. We also calculate the total megaplume heat content in terms of the total buoyancy release and the thermal anomaly of the megaplume, by considering the effects of the ambient stratification in both temperature and salinity on plume properties. Finally, we apply the model to data from three historic megaplume events at the Juan de Fuca ridge.

1. Introduction

Megaplumes are lenticular clouds of hydrothermal effluent, which have been discovered during hydrographic surveys of the deep ocean in the vicinity of active mid-ocean ridge spreading centers [*Baker et al.*, 1989]. Megaplumes, identifiable on the basis of their thermal and chemical signatures, are as large as 10 km in radius, 700 m thick, and located 800-1000 m above the seafloor. They are manifestations of the most vigorous style of hydrothermal venting, and the volume flux of hydrothermal effluent involved is typically several orders of magnitude larger than that associated with the more ubiquitous black smoker plumes whose ascent height is typically 200-300 m [*Speer and Rona*, 1989]. While the origin of megaplumes is still the source of speculation, they are thought to be manifestations of the episodic discharge of hydrothermal effluent associated with heightened tectonic activity near spreading centres, which may lead to either lava-flow eruptions on the seafloor or the exposure of a sub surface fracture system [*Cann and Strens*, 1989; *Baker*, 1995]. Although there have been very few observations of megaplumes [*Baker*, 1995], such observations have raised important questions concerning the temporal and structural behaviour of the sub surface hydrothermal circulation.

Several workers have made estimates of the heat budget of megaplumes by applying the classical theory of turbulent, non rotating buoyant plumes [*Morton et al.*, 1956], which makes it possible to relate the plume rise height to the source heat flux. In order to do so, assumptions concerning the plume source conditions are required. *Cann and Strens*, [1989] assumed that the megaplumes originated from a continuous release of hydrothermal fluid at a point source and so inferred extremely large source mass fluxes of $\sim 15,000 kg^{-1} s$. *Baker et al.*, [1989] assumed that a megaplume was produced from a continuous line source of buoyancy and calculated the source buoyancy flux per unit length to be $3.5 \times 10^8\ J\ m^{-1}/s^{-1}$. By using measurements of the average temperature anomaly in the plume and combining these with the observed plume volume, *Baker et al.*, [1989] estimated the heat content of the megaplume to

Paper number 1999JC900063.
0148-0227/99/1999JC900063$09.00

be $10^{16} - 10^{17}$ J. Coupling this result with the buoyancy flux led to an estimate of $t_s L = 2 - 4 \times 10^8$ ms where t_s is the time of discharge and L is the source length. From the distribution of hydrothermal crystals within the megaplume, they concluded that the megaplume was emplaced in a time 2 days $< t_s <$ 20 days, which suggests a source length in the range 200 m $< L <$ 2 km.

The purpose of this contribution is to use the results of new laboratory experiments to identify the constraints on the megaplume geometry imposed by the dynamical influence of the Earth's rotation. These experiments identify that if a megaplume remains in the water for times in excess of a few days, then the Earth's rotation can have a dominant influence on the motion of the neutral cloud above the buoyant plume. We use our laboratory results and dimensional analysis to relate the time of discharge and the total megaplume buoyancy to its radius and rise height for instantaneous and continuous releases from point and line sources. Furthermore, we demonstrate that by considering the effects of the ambient stratification in both temperature and salinity, one may combine these new results with measurements of the thermal anomaly of the megaplume in order to make new estimates for the total megaplume heat content. As well as developing new constraints on the buoyancy and heat budget of megaplumes, improved understanding of the effects of the Earth's rotation on hydrothermal effluent is important for developing a more complete picture of mid-ocean ridge processes.

In section 2, we describe experimental evidence that megaplume-type structures may emerge from point or line sources and that multiple megaplumes may emerge from sufficiently long sources. In section 3, we present quantitative estimates of the total buoyancy associated with megaplumes for these various possible source conditions. We demonstrate that the total buoyancy of a megaplume located at a given height above the sea floor varies according to its origins; in particular, whether it originated from a point or line source, and the duration of the source. In section 4, we calculate the heat content associated with such megaplumes by considering the combined influence of ambient stratification in temperature and salinity and apply our model to make inferences concerning a number of known megaplume events.

2. Dynamics of Plumes in Rotating Stratified Environments

While the details of the plume dynamics depend explicitly on whether the plume fluid emerges from a point or a line source, one may present a generic physical picture that describes the motion of turbulent buoyant plumes in rotating stratified fluids. The classic work on turbulent plumes in stratified, non rotating fluids is that of *Morton et al.*, [1956]. They demonstrated that as the buoyant plume fluid rises, it is diluted by entrainment of ambient fluid, so that the mean density of the plume decreases with height above the source. Therefore, if the ambient fluid is stably stratified and characterized by a constant Brunt-Väisala frequency N, then the plume fluid eventually reaches a level of neutral buoyancy at which it intrudes laterally to form a neutral cloud.

In rotating stratified environments, the importance of rotation on the plume dynamics is prescribed by the relative magnitudes of N and f. We here focus on the parameter regime relevant for the deep oceans, in which $N \gg f$, where f is Earth's rotation. In this case, the ascent phase of the plume motion is not affected by the system rotation. However, rotation does influence the spreading of the neutral cloud as well as the radial inflow forced by entrainment into the plume. As gravity forces the neutral cloud to spread laterally, the rotation begins to influence the motion on a timescale of order of a day. The rotation acts to generate a net circulation in the spreading cloud, as the current adjusts to the so-called geostrophic balance, in which the outward gravitational force is balanced by the inward Coriolis acceleration. The evolution of the neutral cloud depends explicitly on whether the plume source is a localized 'point' source, in which case the neutral cloud is axisymmetric, or a line source.

We begin in section 2.1 by reviewing the key results presented by *Helfrich and Battisti* [1991] and *Helfrich and Speer* [1995] in their studies of turbulent point source plumes in rotating stratified fluids. We proceed in section 2.2 by extending the physical description of point source plumes in order to describe the release of hydrothermal effluent from line sources. This discussion draws on a companion study in which we present a detailed account of an experimental study of line plumes in rotating stratified fluids [*Bush and Woods*, 1999]. For the interested reader, further details of the experiments may be found in this companion study.

2.1. Point Source Release

The dynamics of hydrothermal plumes rising from a point source on the sea-floor have been described by several workers, and a recent review is provided by *Helfrich and Speer* [1995]. In this case, the neutral cloud remains axisymmetric as it adjusts to geostrophic balance over a time of order $10/f$. When it does so, the geostrophic balance requires that

$$f v_s R \sim N^2 h^2 \quad (1)$$

where v_s is the azimuthal or swirl velocity within the cloud and h and R denote the half height and radius, respectively, of the neutral cloud. The conservation of angular momentum within the spreading neutral cloud requires that $v_s \sim fR$; consequently, the aspect ratio h/R of the geostrophically balanced neutral cloud is proportional to f/N, and the neutral cloud is characterized by a Prandtl ratio, also known as the Burger number:

$$P = \frac{Nh}{fR} \tag{2}$$

which is typically an order one quantity varying between 0.3 and 0.8 [*Helfrich and Battisti,* 1991, *Bush and Woods,* 1999].

Experiments and numerical calculations have identified that if the source supplies fluid for a time t_s shorter than $100N/f^2 (\gg 1/f)$, then the cloud assumes the form of an anticyclonic lenticular vortex, with an underlying cyclonic vortex in the ambient fluid below. In laboratory experiments, such baroclinic dipolar vortices are very stable and decay slowly through viscous influence on a spin-down timescale $\tau_s \sim h/(\nu\Omega)^{1/2} \sim 10^8 - 10^9 s$ [*Hedstrom and Armi,* 1988]. If the source is maintained, the cloud grows and deepens until it becomes unstable after a time $\tau \sim 100N/f^2$ [*Helfrich and Speer,* 1995]. The nature of the instability depends on the relative magnitudes of N and f: for $N/f > 2$, the neutral cloud simply drifts off the source, and together with the underlying ambient, fluid it forms a single, dipolar, baroclinic vortex. For $N/f < 2$, the neutral cloud, together with the underlying ambient fluid, breaks into a pair of baroclinic dipolar eddies [*Helfrich and Battisti,* 1991; *Speer and Marshall,* 1995].

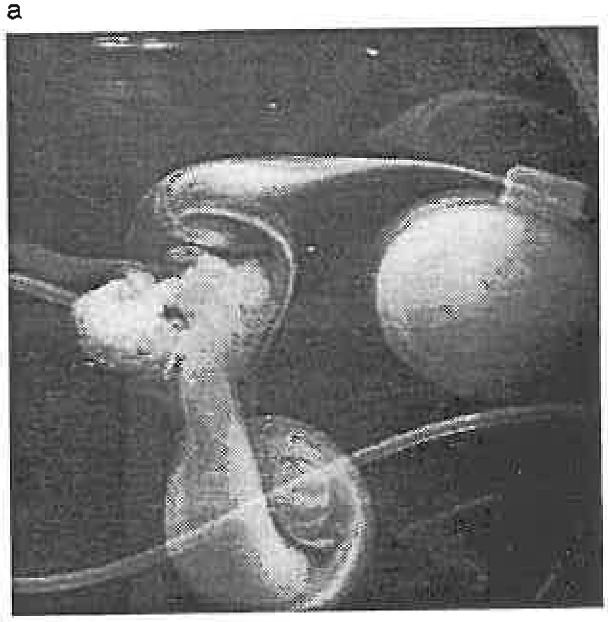
In both cases, the instability is baroclinic and the size of the eddies formed from a continuous release of buoyancy is limited by the influence of rotation. The successive generation of dipolar baroclinic vortex pairs from the instability of the neutral cloud above a point source in the case $N/f = 1.4$ is shown in Figure 1 [cf. *Helfrich and Battisti,* 1991].

2.2. Line Source Release

Tectonic fracturing or a sea floor fissure eruption may lead to venting from a line source (Figure 2) [*Baker et al.,* 1989]. The development of the neutral cloud under the influence of the Earth's rotation depends critically on the length of the source compared to the critical radius at which the neutral cloud becomes unstable. We consider, in turn, two distinct cases, that in which the line source is longer and shorter, respectively, than the critical radius of the neutral cloud. In the former case, the neutral cloud is no longer axisymmetric; consequently, its dynamics are much more complex and our discussion is based on the experimental results of *Bush and Woods,* [1999]. In the latter case, the neutral cloud adjusts to an axisymmetric form, and its subsequent dynamics are analogous to that above a point source, as discussed above (Figure 2).

2.2.1. Long-Line source. The line plume which rises above a long line source supplies a correspondingly long neutral cloud that spreads in a direction perpendicular to the source (see Figure 3). The neutral cloud evolves toward a geostrophic state after a time of order 1 day; counterflowing currents develop on either side of the neutral cloud (see Figure 3a). The Coriolis force associated with these horizontal motions matches the outward force due to gravity. Entrainment into the line plume is influenced by the system rotation, giving rise to a flow beneath the neutral cloud consisting of currents aligned with the plume but directed opposite to the overlying currents in the neutral cloud. Under the combined influence of the horizontal and vertical shear across it, the neutral cloud eventually breaks into a series of axisymmetric, lenticular eddies (Figures 3b-3d). By conservation of mass, the radius of each eddy scales

a



b

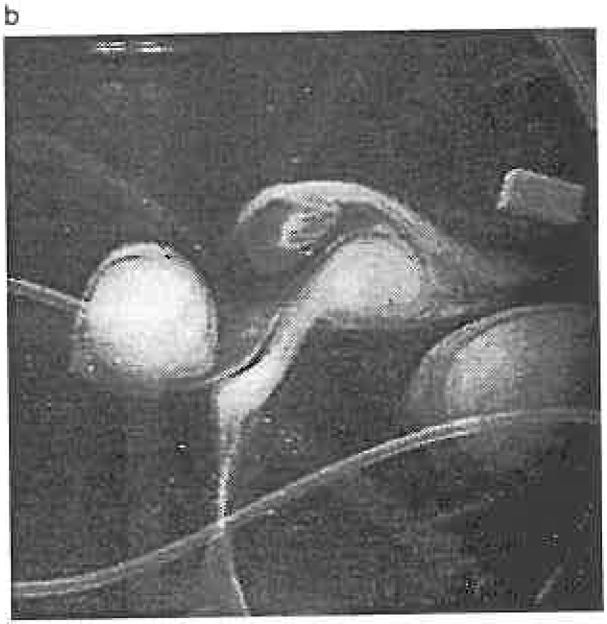


Figure 1. The shedding of dipolar vortices from a point plume discharging into a rotating stratified fluid. (a) $t = 7.3/f$, where $\pm$ is time and f is Earth's rotation, where the first two dipoles propagate away from the source, above which a third develops, (b) $t = 13.6/f$: the third dipole propagates away from the source, above which the neutral cloud is re-established.

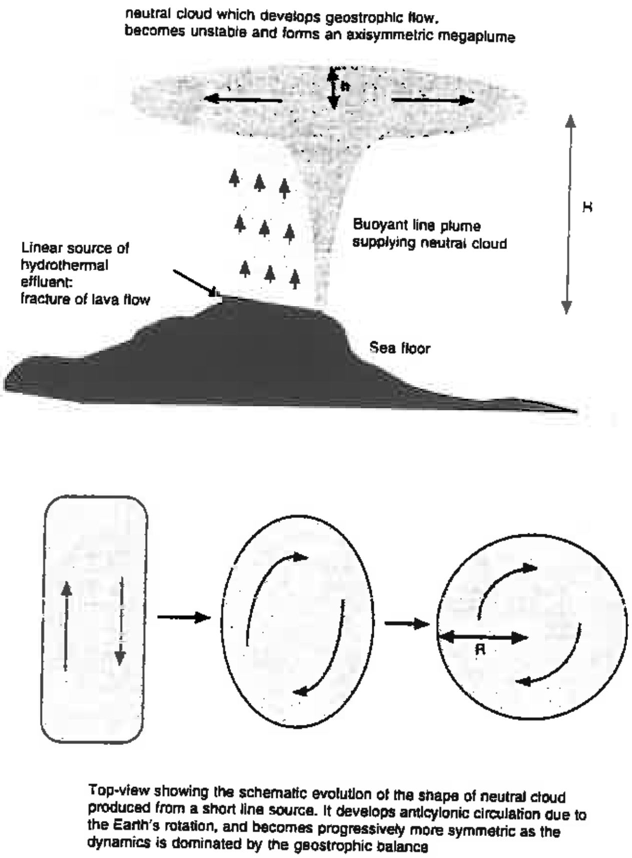


Figure 2. Schematic of the neutral cloud above the vertical buoyant plume produced from a short-line source. This neutral cloud eventually develops anticyclonic circulation, as shown in the schematic top view, and adjusts to an axisymmetric, geostrophically balanced eddy typical of megaplumes observed in the field.

with the width of the current at the onset of instability, which was observed to occur after approximately 10 rotation periods. While this instability is reminiscent of the break-up of a linear gravity current in a rotating stratified fluid [*Griffiths et al.*, 1982], the relative importance of the vertical and horizontal shears across the neutral cloud in driving the instability is not yet understood [*Bush and Woods*, 1999].

It is important to note that a long, linear neutral cloud, in contrast to that above a point source plume, will always break up into a series of axisymmetric eddies, regardless of whether the source is maintained for a time which is short ($t_s < 100/f$) or long ($t_s > 100/f$) relative to the timescale of the instability. For a long linear source, of length L, the volume of the eddies that develop is comparable to R^2h where $R(\leq L)$ and h are the width and depth of the neutral cloud, respectively, after a time of order $100/f$. It is interesting to note that the size of the resulting eddies will thus increase with the time of discharge. The dependence of eddy size on source properties will be clarified in section 3.

2.2.2. Short-Line source. An interesting hybrid situation arises if the source length L is larger than the rise height of the line plume H_l but smaller than the width R of the two-dimensional neutral cloud after it has become strongly influenced by rotation. In this case, the plume ascent will be governed by the dynamics of a line plume [cf. *Sparks et al.*, 1997; *Baker et al.*, 1989]. However, as the neutral cloud spreads outwards to distances greater than the length of the source, it becomes progressively more circular. After several rotation periods, the neutral cloud becomes axisymmetric and appears to originate from a point source. The subsequent dynamics and instability of the neutral cloud are analogous to that produced by a point source axisymmetric plume, even though the plume assumes a linear form.

Owing to the combined influence of stratification and rotation, there is a complex family of source conditions, which may lead to the formation of one or more isolated, lenticular vortex structures above mid-ocean ridges. These different regimes are summarized in Table 1. The dynamics of the geostrophically adjusted neutral clouds that may be generated in each case are similar. Thus, without detailed information about the origin of the megaplume, it may be difficult to infer the origin of an isolated neutral cloud above an active mid-ocean ridge spreading center. However, the fluid mechanical principles governing the formation of these coherent vortical structures provide a new means of estimating their buoyancy and heat content. In the next section, we describe how the total buoyancy associated with an eddy at a given height in the water column may be related to the megaplume dimensions for each of the regimes described in Table 1.

3. Inferences of Total Megaplume Buoyancy

We proceed by demonstrating how estimates for the total buoyancy of a megaplume may be made in terms of the megaplume geometry (specifically, its rise height H, radius R, and half thickness h) as well as the magnitude of the ambient stratification N and the Earth's rotation f. Results are derived and compared for each of the idealised source conditions described in Table 1. In section 4, we describe how these estimates of the total buoyancy may be converted to estimates of the total heat content of the megaplume, given that source fluid may be of different temperature and salinity than the ambient water and that the ambient water column is stratified both in temperature and salinity [*Turner and Campbell*, 1987; *Speer and Rona*, 1989; *McDougall*, 1990]. In section 5, we include a summary table, Table 2, for readers who wish to access the results directly. The calculations of subsection 3.1, 3.2, and 3.3 follow a similar pattern. We therefore include a relatively detailed discussion for secton 3.1, followed by a more concise description in subsection 3.2 and 3.3.

3.1. Localized Source of Buoyancy

As a lenticular, neutral cloud spreads radially through a stratified environment, it attains a geostrophic bal-

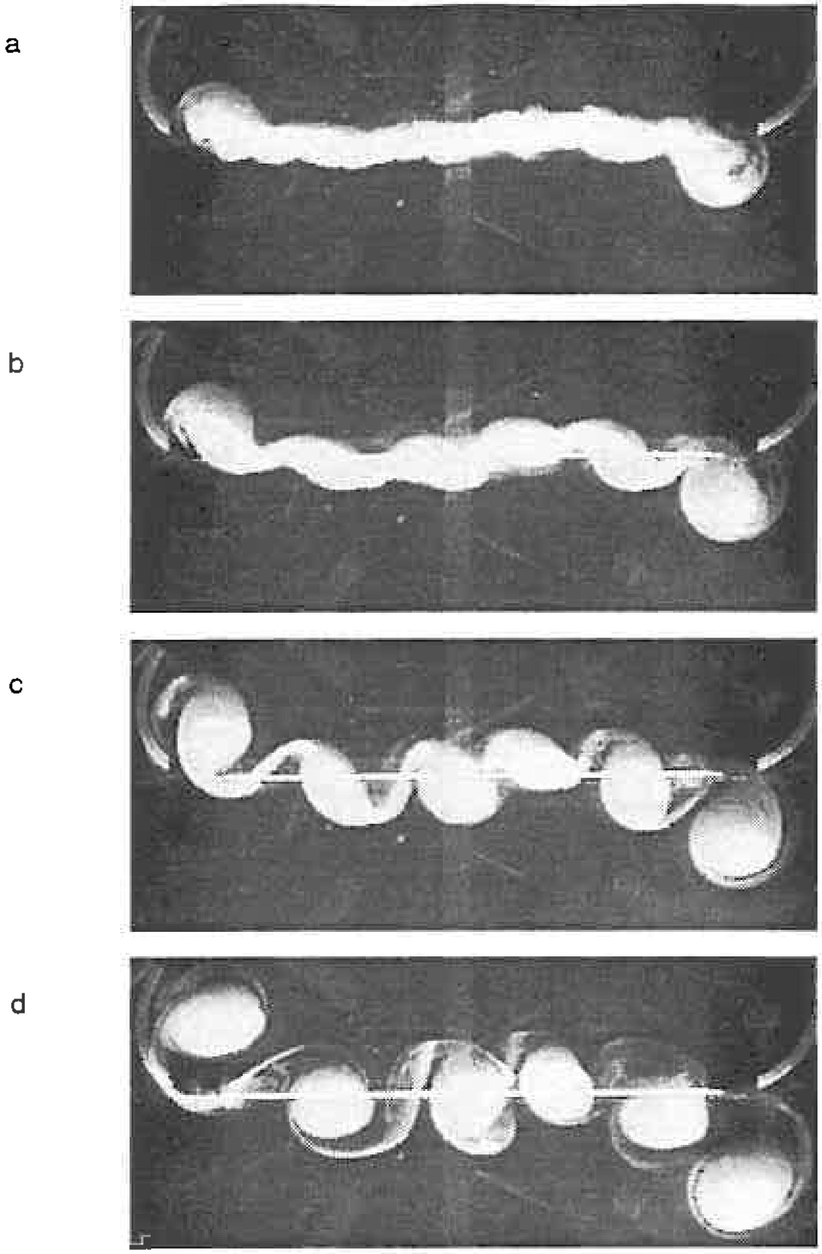


Figure 3. The development of coherent vortices from the discharge of a line plumes in a rotating stratified fluid as viewed from above. (a) The plume fluid shown spreads at its level of neutral buoyancy. The Coriolis force generates a strong shear across the neutral cloud. (b) The neutral cloud begins to go unstable. The plume source is turned off. (c) The neutral cloud wraps into size distinct anticyclonic vortices. (d) the persistence of six coherent vortical structures of comparable size.

ance and its Prandtl ratio assumes a constant value. Denoting the volume of the cloud by

$$V = \beta R^2 h \tag{3}$$

and eliminating h from (2), it follows that the radius of the geostrophic eddy is

$$R = \left(\frac{NV}{\beta P f}\right)^{1/3} \tag{4}$$

where β is a shape factor for a geostrophically adjusted eddy. In section 3.2.2, we determine the value of β by comparison with the experimental results of *Bush and Woods* (1999). Given this scaling and the classical relationships between the source buoyancy or buoyancy flux and (1) the height of rise and (2) the volume flux supplied to the top of a buoyant plume [*Morton et al.*, 1956; *Sparks et al.*, 1997, chapter 2], we can now estimate the total buoyancy associated with megaplumes formed from a localized source of buoyancy for the three special cases of interest: an instantaneous thermal release, a finite plume release, and a continuous plume release.

3.1.1. Instantaneous release, $t_s < 1/N$. For an instantaneous point release of buoyancy B (a release

Table 1. Dimensions and Dynamics of Megaplumes

Time	Point or Short-Line Source	Long-Line Source
$t_s \ll 1/N$	single monopole	chain of monopoles
$1/N < t_s < t_i$	single monopole	chain of monopoles
$t_s \gg t_i$	periodic shedding of dipole pairs	continuous shedding of dipole pairs

Variables are defined as follows: t_s, time of discharge; N, Brunt Väisäla frequency; and t_i, timescale of instability.

over a time $t_s \ll 1/N$) into a stratified environment, the buoyant fluid may be described as a thermal that grows through entrainment as it rises. This mode of discharge has been considered by *Scorer* [1957] and *Helfrich* [1994]. The thermal ascends to a height

$$H = 2.66\ B^{1/4} N^{-1/2} \tag{5}$$

before spreading laterally to form a neutral cloud with volume

$$V = 3.0\ B^{3/4} N^{-3/2} \tag{6}$$

The numerical constants in (5) and (6) are calculated from the bulk entrainment parameter $\epsilon = 0.33$ reported in the experimental study of *Scorer* [1957]. The total buoyancy released at the source B may be deduced from (5) in terms of the neutral height H and the Brunt-Väisäla frequency as

$$B = 0.02\ H^4 N^2 \tag{7}$$

and so does not depend explicitly on the plume dimensions. The radius of the resulting neutral cloud may be deduced by substituting (6) into (4), which yields

$$\frac{R}{H} = 0.54 \left(\frac{N}{fP\beta}\right)^{1/3} \tag{8}$$

These relations may be used in a straightforward manner to estimate the buoyancy flux of the neutral cloud produced from a point source plume, if the ratio of the radius to the height of the cloud satisfies (8). For example, a neutral cloud of hydrothermal fluid at height 500 m in a stratified environment with $N = 10^{-4}$ s^{-1} could be produced from a short-lived release of buoyant fluid $B = 12.5$ m^4 s^{-3} if the ratio of the radius to the height of the cloud satisfies (8), $R \approx H$. However, if the radius of the cloud was much larger than the value H, then much more fluid would be needed to produce the neutral cloud. This could not be acheived by releasing a much larger mass of buoyant fluid over the same rel-

Table 2. Estimates of Buoyancy B and Radial Dimension of Megaplumes Produced by the Discharge of Buoyant Fluid From a Point or Line Source in Terms of the Megaplume Dimensions and Neutral Height

	$t_s \ll 1/N$	$1/N < t_s < t_i$	$t_s \gg t_i$
Point Source, Section 3.1	$B = 0.02H^4N^2$	$B = 0.54N^2R^2hH$	$B = 0.54H^4PN^4/f^2$
$L \ll H$	$R = 0.39\dfrac{HN^{1/3}}{f^{1/3}P^{1/3}}$	$R = 0.22\dfrac{Ht_s^{1/3}N^{2/3}}{P^{1/3}f^{1/3}}$	$R \sim NH/f$
	$R = H$	$R = 0.06Ht_s^{1/3}$	$R = 10H$
Short-Line Source, Section 3.3	$B = 0.31H^3LN^2$	$B = 0.81N^2R^2hH$	$B = 0.81H^4N^4P/f^2$
$R > L > H$	$R = 0.79\dfrac{H^{2/3}L^{1/3}N^{1/3}}{P^{1/3}f^{1/3}}$	$R = 0.32\dfrac{H^{2/3}L^{1/3}N^{2/3}t_s^{1/3}}{P^{1/3}f^{1/3}}$	$R \sim NH/f$
	$R = 2.2H^{2/3}L^{1/3}$	$R = 0.08H^{2/3}L^{1/3}t_s^{1/3}$	$R = 10H$
Long-Line Source, Section 3.2	$B = 0.46\dfrac{H^4N^{5/2}}{P^{1/2}f^{1/2}}$	$B = 0.81N^2R^2hH$	$B = 0.8H^4N^4P/f^2$
$L \gg R$	$R = \dfrac{HN^{1/2}}{f^{1/2}P^{1/2}}$	$R = 0.24\dfrac{HNt_s^{1/2}}{P^{1/2}f^{1/2}}$	$R \sim NH/f$
	$R = 4.7H$	$R = 0.04Ht_s^{1/2}$	$R = 10H$

The timescale of instability t_i is comparable to $100N/f^2$, $100HN/Lf^2$, and $100/f$ for the point source, short line source, and long line source, respectively, where N is Brunt-Väisäla frequency; f is Earth's rotation; L is source length. The third line in each section of this table corresponds to a specific calculation appropriate for the deep ocean in which $N \sim 10f$.

atively short time, since the neutral cloud would then ascend higher into the water column. Instead, the fluid would need to be released over a longer time, as if issuing from a continuous source. We consider this different situation below.

3.1.2. Short-lived continuous release. For a continuous release of buoyancy flux F from a point source for a time t_s such that $1/N \ll t_s \ll 100N/f^2$, the rising fluid may be modeled as a steady state plume. The neutral cloud adjusts to geostrophic balance, and the final volume of the cloud may then be determined in terms of the timescale of the source t_s.

The rise height of the plume is given by

$$H = 3.76\, F^{1/4} N^{-3/4} \quad . \tag{9}$$

The total volume of the neutral cloud is given by the product of the volume flux in the plume $Q(H) = 1.27\, F^{3/4} N^{-5/4}$ and the source time:

$$V \ = \ Q(H)\, t_s \ = \ 1.27\, F^{3/4} N^{-5/4} t_s \quad , \tag{10}$$

where the entrainment coefficient was estimated from experimental results compiled by *List* [1979], $\epsilon = 0.13$. Using (3) and (10), we may express t_s in terms of the cloud radius R and depth h, giving the result that $t_s = \beta R^2 h/(1.27 F^{3/4} N^{-5/4})$. Combining this result with (9), the total buoyancy released at the source, $B = F t_s$, may then be expressed simply in terms of the megaplume dimensions:

$$B = 0.2\, N^2 R^2 h H \beta \tag{11}$$

This relation is different from (7) owing to the different rates of entrainment into rising plumes and thermals. Finally, substituting (10) into (4) yields an expression for the radius of the neutral cloud in terms of the source conditions:

$$R = \ 1.1\, \frac{F^{1/4} t_s^{1/3}}{P^{1/3} f^{1/3} N^{1/12} \beta^{1/3}} \tag{12}$$

Eliminating F via (9) yields the relationship between the megaplume radius and neutral height for this particular mode of venting:

$$\frac{R}{H} \ = \ 0.3\, \frac{t_s^{1/3} N^{2/3}}{P^{1/3} f^{1/3} \beta^{1/3}} \tag{13}$$

If the ratio of the radius to the height of a neutral cloud satisfies (13) and the neutral cloud is known to have been produced from a point source, then we may use (11) to calculate the total buoyancy associated with the neutral cloud.

3.1.3. Long-lived continuous release. For a long-lived continuous release of buoyancy, the neutral cloud grows and eventually becomes unstable. By combining (3), (10), and (12), we can express h as a function of N, F and t_s, $h = F^{11/12} N^{-13/12} t_s^{1/3} P^{2/3} \beta^{-2/3}$. Comparing this expression for h with (9) for H, it may be seen that the depth of the neutral cloud h becomes comparable to the height of rise of the plume H as the source time approaches $\tau_i \sim 100N/f^2$. The cloud then becomes unstable to a baroclinic instability and drifts off the source as a dipolar vortex [*Helfrich and Battisti*, 1991]. Substituting the critical radius at which the plume becomes unstable, $R \sim NH/f$, into (11), we find that the maximum buoyancy that can be contained within a single megaplume generated from a point source is given by

$$B = 0.2\, h H^3 N^4 \beta / f^2 \tag{14}$$

In Figure 4, we illustrate how the ratio of the radius to height of the cloud varies as a function of the source time, for eddies at the same height in the water column. For short-lived releases, the ratio has constant value of about 2, and this corresponds to the result of section 3.1.1. As the source time increases, the plume becomes continuous and the ratio R/H increases to values as large as 20-30. Eventually, for long-lived sources, baroclinic instability develops after times $\sim 100N/f^2$ and eddies are shed from the neutral cloud. This diagram illustrates an important result, namely, that, given the geometry of the source, the timescale of the source may be estimated purely in terms of the aspect ratio of the geostrophic eddies formed from the neutral cloud. Similar results hold for line sources, as outlined below.

3.2. Long-Line Source

For a line source of buoyancy, the possibility of multiple lenticular vortical eddies arises. In order to calculate the size of the eddies that form following the breakup of the neutral cloud, we note that the eddies are in geostrophic balance so that the force balance (1) again applies. This suggests that the number of eddies that-

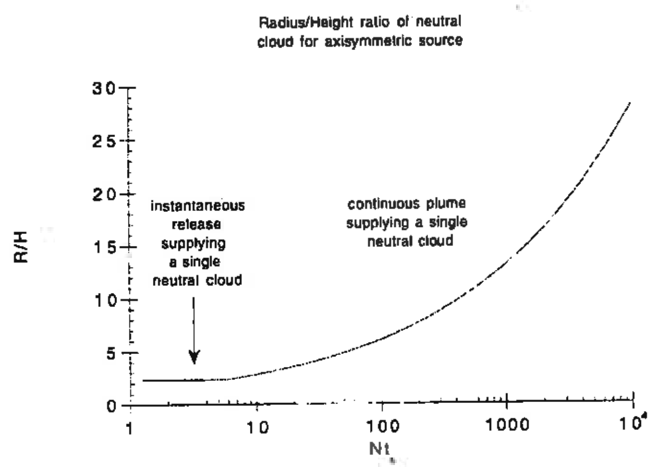


Figure 4. Variation of the aspect ratio of the eddies produced from the neutral cloud above an axisymmetric turbulent plume (section 3.1), R/H, as a function of the dimensionless timescale of the source Nt_s. Here we take $N/f = 100$.

form from a line source of length L should scale as L/R unless $R > L$, in which case a single eddy forms.

When the line source has broken up into segments of length $2R$, where R is the half width of the neutral cloud prior to the onset of instability, then the volume of each eddy, $\beta R^2 h$, may be related to the volume per unit length of the neutral cloud V_L according to

$$\beta R^2 h = 2RV_L \qquad (15)$$

Combining (15) with (4) leads to

$$R = \left(\frac{2NV_L}{\beta f P}\right)^{1/2} \qquad (16)$$

We now examine how the radius and size of the eddy change as the discharge time varies.

3.2.1. Instantaneous release. For an instantaneous release of buoyancy per unit length B_L, the dynamics of the buoyant fluid corresponds to that of a line thermal. The height of rise of a line thermal in a stratified fluid is given by

$$H = 1.6\, B_L^{1/3} N^{-2/3} \quad , \qquad (17)$$

while the volume per unit length of the neutral cloud is

$$V_L = 3.7\, B_L^{2/3} N^{-4/3} \quad , \qquad (18)$$

where the entrainment coefficient, $\epsilon = 0.66$, was estimated from the experimental data of *Noh et al.*, [1992] and by assuming that the ascent height is much larger than the original depth scale of the thermal. Combining (16) and (18) to eliminate V_L, we find that the radius of the geostrophically adjusted flow is given by

$$R = 3.4\, \frac{B_L^{1/3}}{N^{1/6} f^{1/2} P^{1/2} \beta^{1/2}} \qquad (19)$$

By expressing the buoyancy released per unit length B_L in terms of H and N using (17) and combining this with (19), one may express the total buoyancy contained within each eddy as

$$B = 2B_L R = 0.75\, \frac{H^4 N^{5/2}}{P^{1/2} f^{1/2} \beta^{1/2}} \quad . \qquad (20)$$

The megaplume radius may then be expressed in terms of its neutral height by eliminating B_L from (19) using (17), which yields the result

$$\frac{R}{H} = 1.64\, \left(\frac{N}{fP\beta}\right)^{1/2} \qquad (21)$$

As in section 3.1, if a neutral cloud is known to originate from a long line source and the ratio of the radius to the height of the cloud satisfies (21), then (20) may be used to estimate the total buoyancy associated with the neutral cloud. For neutral clouds with larger radius-height ratios, the following models for the continuous release of buoyant fluid from a line source are more appropriate.

3.2.2. Continuous short-lived release. For a continuous line source of buoyancy F per unit length, the rising fluid may be described in terms of a steady line plume. The rise height of a line plume in a stratified ambient is

$$H = 3.41\, F^{1/3} N^{-1} \quad . \qquad (22)$$

The volume flux per unit length supplied to the neutral cloud is given by $Q(H) = 0.98\, F^{2/3} N^{-1}$, so that the final volume of the neutral cloud is

$$V_L \;=\; Q(H)\, t_s \;=\; 0.98\, F^{2/3} N^{-1} t_s \quad , \qquad (23)$$

where, once again, the entrainment coefficient was taken from data compiled by *List* [1979], $\epsilon = 0.11$. For a discharge persisting for a time $t_s < 100/f$, this expression, (23), for the total volume per unit length in the neutral cloud may be combined with (22) and (16) in order to deduce the length scale of the geostrophically adjusted flow:

$$R = 1.4\, \frac{F^{1/3} t_s^{1/2}}{P^{1/2} f^{1/2} \beta^{1/2}} \quad , \qquad (24)$$

Bush and Woods [1999] performed an experimental study of the formation of eddies above a long line source of buoyancy. A number of eddies of radius R formed above the source and the average radius R of the eddies was measured (Figure 5). Analysis of the data shows that the individual eddies were characterized by Prandtl ratios $P = 0.45 \pm 0.1$ and by radii $R = (0.8 \pm .12)(Ft_s/f)^{1/3}$. Comparison with (24) suggests that the shape factor β thus has a value of $\beta = 2.7 \pm 0.7$.

The total buoyancy of each eddy that develops from the instability of the neutral cloud is given by $B = 2FRt_s$. Using (22) and (24) for F and t_s leads to the estimate for the total buoyancy

$$B = \; 0.3\, HR^3 N f P \beta \qquad (25)$$

Apart from the different numerical coefficient, this result is identical to the scaling for a megaplume produced from a point source of buoyancy (equation (11)). However, in this case, there would be a series of such megaplumes above the fissure, with the total number of megaplumes being $n = L/(2R)$.

Finally, eliminating F from (24) using (22) yields a relationship between R and H for this venting style:

$$\frac{R}{H} \;=\; 0.4 \frac{N t_s^{1/2}}{P^{1/2} f^{1/2} \beta^{1/2}} \qquad (26)$$

3.2.3. Continuous long-lived release. For a maintained source of buoyancy, the experiments suggest that the current again becomes strongly influenced by rotation after a time of order $10/f$. The neutral cloud continues to expand until a time $\sim 100/f$, after which it breaks into a series of eddies [*Bush and Woods*, 1999]. The eddies thus formed from a continuous release represent the most voluminous megaplumes consistent with a long-line source of buoyancy. The flow breaks up into this train of eddies after about 10 rotation periods,

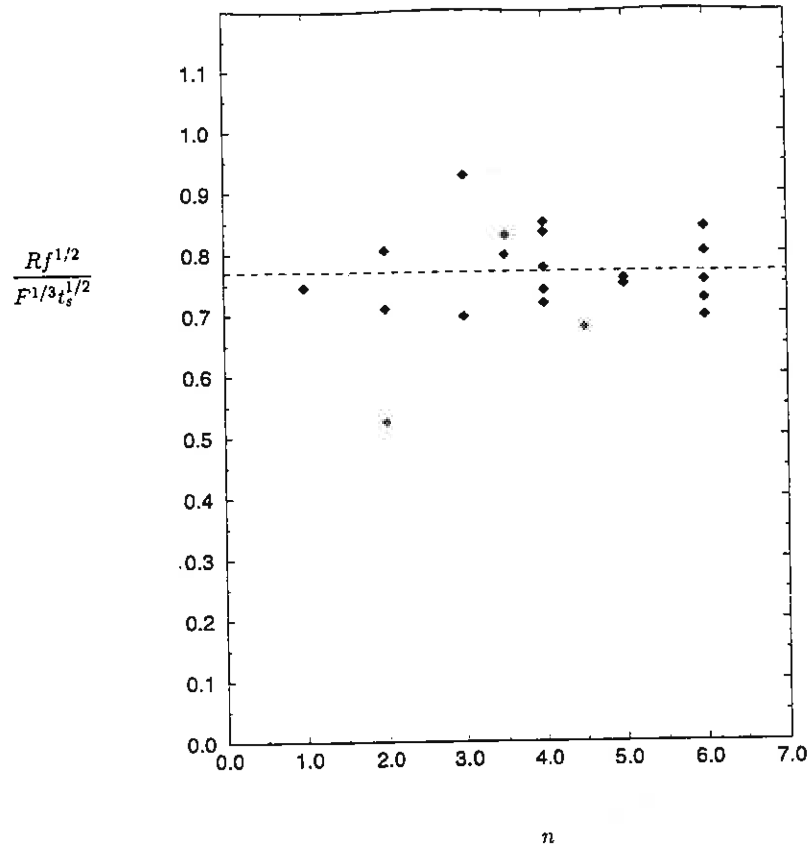


Figure 5. Average size of the eddy formed during a series of experiments in which the neutral cloud above a line source of buoyancy became unstable and broke up into eddies (figure 3). The data were gathered from a series of experiments in which one to six eddies were produced through variation of the source strength, the rotation rate and the stratification of the ambient fluid. The dashed line represents $R = 0.77\ F^{1/3}t_s^{1/2}\ /\ f^{1/2}$. Further details of the experiments are given by *Bush and Woods*, [1997]. A characteristic error bar is shown.

$\sim 100/f$, at which point the depth of the neutral cloud, $h = PfR/N$ is comparable to the height of the plume. Using the result (25), it follows that the total buoyancy associated with each of these eddies is comparable to

$$B = 0.3\ H^4N^4P\beta/f^2 \tag{27}$$

in accord with experimental results of [*Bush and Woods*, 1999]. Once again, this result is identical, apart from a numerical coefficient, with the prediction for a continuous point source of buoyancy above a point source (equation (14)).

3.3. Short-Line Source $L < R$

Finally, we consider the case in which the length of the line source L is shorter than the length scale over which the neutral cloud attains the geostrophic balance, R, but is greater than the height of rise of the plume, H. In this case, the plume behaves as if issuing from a line source, while the dynamics of the neutral cloud are analogous to that associated with an axisymmetric point source plume.

3.3.1. Instantaneous release. Using the above results for the rise height and volume of the neutral cloud (17) and (18) of a line thermal and for the radius (4) of the neutral cloud produced from an instantaneous localised release, it follows that

$$R = 1.1\ \frac{H^{2/3}L^{1/3}N^{1/3}}{P^{1/3}f^{1/3}\beta^{1/3}} \tag{28}$$

while the total buoyancy is

$$B = \ 0.23PHNR^3f\beta. \tag{29}$$

3.3.2. Continuous short-lived release. For a constant buoyancy flux F per unit length, released for a time $t_s < t_i$ shorter than the time for instability of the neutral cloud t_i (see section 3.3.3), (22) and (23), together with (4), imply that the radius of geostrophic eddy is given by

$$R = 0.44\ \frac{H^{2/3}L^{1/3}N^{2/3}t_s^{1/3}}{P^{1/3}f^{1/3}\beta^{1/3}} \tag{30}$$

Note that in this case the radius of the plume is related to both the length and discharge time of the source. The total buoyancy of the eddy is given in terms of the cloud dimensions by (see (22) and (25))

$$B = FLt_s = 0.3\ N^2 hHR^2\beta \quad . \qquad (31)$$

3.3.3. Continuous long-lived release. If a maintained line source of buoyancy continues to supply fluid beyond the timescale of instability of the neutral cloud, $t_s > t_i$, then when the depth of the neutral cloud scales with the rise height H, the flow becomes unstable. Therefore for a geostrophically adjusted neutral cloud, the radius of the cloud following instability scales as $R \sim HN/L$ and the total buoyancy of the cloud follows from (31) as

$$B = 0.3H^4N^4P\beta/f^2 \quad . \qquad (32)$$

Note, however, that for $H/L < f/N$, the neutral cloud becomes unstable before it has grown sufficiently to assume the form of an axisymmetric point source, and the analysis of section 3.2.3 applies. When $H/L \gg 1$, the source begins to resemble a point rather than line source and the relevant physical picture is that described in section 3.1.3.

4. Heat Release Associated With a Megaplume

The above estimates of the buoyancy release associated with a megaplume may be converted to an estimate of the heat release if the mean temperature anomaly of the megaplume is also known. We now derive a simple relation for this heat flux building on the work of *Speer and Rona,* [1989] and *McDougall,* [1990], who considered the effect of the thermal and solutal stratification of the water column on the properties of the neutral cloud. Note that since the ocean is stratified in both temperature and salinity, all calculations in the above model should be made in terms of the net buoyancy frequency,

$$N^2 = N_T^2 + N_s^2 \qquad (33)$$

[cf. *Sparks et al.*, 1997; *McDougall,* 1990], where N_T and N_s represent buoyancy frequencies associated with gradients in temperature and salinity, respectively.

Thermal and solutal stratification introduces some complications in estimating the total heat content of the megaplume. Indeed, the source fluid may be hot but either saline or fresh relative to the ambient water. In the former case, given the megaplume dimensions and height in the water column, the heat content will exceed that associated with a pure source of heat. while in the latter case, it will be smaller. It is this effect that we consider in detail below. A second complication is that the thermal expansion coefficient of water becomes very large at high temperatures and so the total buoyancy of hydrothermal effluent as it vents at high temperature is not conserved as it mixes with sea water and cools [*Turner and Campbell,* 1987]. However, the heat flux associated with the hydrothermal effluent is conserved as it mixes; therefore, in order to use the simple plume models in which the thermal expansion coefficient is fixed and the buoyancy is modeled as a conserved quantity *Speer and Rona,* 1989], one should work with an equivalent low temperature plume, of the same heat and salt flux, but which is only a small amount hotter, 1°C say, than the ambient fluid at the source [cf. *Turner and Campbell,* 1987]. It has been shown that predictions of this equivalent plume model, which ignore the non-Boussinesq effects near the source, provide a very good approximation to those of the full plume model [*Woods,* 1997].

We proceed by showing that, although the hydrothermal fluid may be of different salinity and temperature then the ambient water, it is possible to estimate the total heat release using the above model together with a measurement of either the potential temperature anomaly or the salinity anomaly in the megaplume.

The salinity flux $Q_S(z)$ and heat flux $Q_T(z)$ within the plume are defined in terms of the mean salinity, $S(z)$, temperature $T(z)$, and volume flux $Q(z)$ of the plume through

$$Q_s(z) = [S(z) - S_a(0)]Q(z) \qquad (34)$$

$$Q_T(z) = \rho C_p[T(z) - T_a(0)]Q(z) \qquad (35)$$

where $S_a(z)$ and $T_a(z)$ represent ambient conditions at the sourceand C_p is the specific list. Assuming that, to leading order, the ambient salinity $S_a(z)$ and potential temperature $T_a(z)$ vary linearly above the source [cf. *Speer and Rona,* 1989], then conservation of salt and heat, respectively require that

$$Q_s(z) = Q_s(0) + \frac{dS_a}{dz}\int_0^z \frac{dQ}{dz} z\,dz \qquad (36)$$

$$Q_T(z) = Q_T(0) + \rho C_p \frac{dT_a}{dz}\int_0^z \frac{dQ}{dz} z\,dz \qquad (37)$$

The total buoyancy flux of the plume F follows from the relation [*McDougall,* 1990]

$$\frac{dF}{dz} = -N^2 Q \qquad (38)$$

Integrating (38) by parts indicates that

$$\int_0^z \frac{dQ}{dz} z\,dz = Q(z)z + \frac{F(z) - F(0)}{N^2} \qquad (39)$$

Evaluating this expression at $z = z_n$, where $F = 0$, and eliminating the integral with (35) and (37) yields an expression for the heat flux at the origin,

$$Q_T(0) = \rho C_p \left\{ \frac{dT_a}{dz}\frac{F(0)}{N^2} + Q(z)[T(z_n) - T_a(z_n)] \right\} \qquad (40)$$

Integrating (39) over the time of emplacement of the megaplume, we deduce that the total heat released at the source in generating the megaplume is

$$Q_{\rm TOT} = \rho C_p \left\{ \frac{dT_a}{dz}\frac{B_T}{N^2} + V[T(z_n) - T_a(z_n)] \right\} \quad (41)$$

where $V = \beta H R^2$ is the total volume of the megaplume and B_T is the total buoyancy release at the source. The final term in(41) accounts for the difference in potential temperature between the ambient fluid and the megaplume, while the former term represents the heat flux that would be predicted if the total buoyancy of the eddy was assumed to be due to the temperature anomaly at the vent. Both terms may be important depending on the thermal anomaly in the eddy and the ratio of the thermal stratification to the total stratification, which has a value of order 0.5 on the Juan de Fuca ridge and about 4.3 on the mid-Atlantic ridge, where the salinity field is actually destabilizing [*Helfrich and Speer*, 1995].

Combining (41) with the scaling for the buoyancy and volume of the megaplume that may be generated from a long-lived (short linear) source (Table 2), we deduce that the heat flux associated with the megaplume,

$$Q_T = \rho C_p R^2 h \left[0.8H\frac{dT_a}{dz} + 2.7(T - T_a) \right]. \quad (42)$$

Such a megaplume would have a maximum radius of order $NH/f \sim 10H$, and with this value, (42) provides an estimate for the maximum possible heat flux associated with a megaplume at height H above the seafloor:

$$Q_{\rm TOT} \sim \rho C_p \frac{N^2 H^3}{f^2} \left\{ 0.4H\frac{dT_a}{dz} + 1.4[T(z_n) - T_a(z_n)] \right\} \quad (43)$$

5. Discussion

Table 2 summarizes the principal results of this study, namely, predictions for the buoyancy and radial dimension of the lenticular vortices that may be produced from a variety of sources of hydrothermal fluid on the sea floor. In the absence of strong currents, the discharge of effluent from the seafloor may produce either isolated eddies (from a point or short line source; Figure 1 and 2) or a train of eddies (from a long-line source; Figure 3). In table 2, we include the eddy radii for the special case of $N/f = 10$ (as is typical in the deep ocean) and $P = 0.45$, the value of the Prandtl ratio (equation (2)) determined experimentally by *Bush and Woods*, [1999].

We note that in deriving the estimates of the radius to height ratio of the neutral clouds, we have adopted published experimental values for the entrainment efficiency. Owing to the limitations of scale of laboratory experiments, these values are subject to some error; consequently, caution should be applied in using the quantitative predictions. Although the coefficients reported in Table 2 serve only as a guide, it is clear that for a given height in the water column H, the radius R of the emerging eddies increases with the source discharge time. Indeed, as may be seen in Figure 4, the radii of the vortices emerging increases from H for short lived releases ($t_s < 1000$ s), to $10H$ for long-lived releases ($t_s > 10^5$ s). If the source geometry is known, information about the aspect ratio of the eddy may be used to constrain the time of discharge, as well as the buoyancy flux at the source.

We note that a similar range of R/H ratios arises for each of the different source geometries considered; consequently, it would be difficult to distinguish between source geometries on the basis of this ratio. Indeed, considerable ambiguity arises concerning the origins of single megaplumes from shorter-lived releases for which $R/H < N/f$. However, Table 2 does indicate that only the longer lived hydrothermal discharges (persisting for times $t_s \geq 10^5$ s) are capable of generating megaplume vortices with radii comparable to those reported in the literature [*Baker*, 1995]. This provides a new constraint on the timescale of the discharge events responsible for producing megaplumes.

Megaplumes ascend 3-4 times higher into the water column than the more common black smoker plumes [*Baker et al.*, 1989]. The scalings for the height of rise of the plume as a function of the source buoyancy flux (equations (9) and (17)) therefore suggest that the associated rate of venting is nearly 30-300 times greater, depending on whether the source is a line or a point. Since the new prediction that the timescale of venting required to produce megaplumes with the observed radii of order 5-10 km [*Baker*, 1995] is typically in excess of 10^5 s, we deduce that the volume of hydrothermal fluid released in producing a megaplume is comparable to the annual budget of hydrothermal fluid released by a steadily venting black smoker. This is in accord with the independent calculations of [*Baker*, (1995)] based on measurements of megaplume sizes. This calculation emphasizes the potential importance of megaplume events in exchanging heat at mid-ocean ridges and illustrates the value of our fluid dynamical constraints in developing estimates for the properties of megaplumes purely in terms of their observed height and radius.

In the remaining discussion we focus on maintained sources, which we predict are responsible for the observed megaplumes. For long-lived sources, Table 2 identifes that the total buoyancy released in producing a megaplume of radius R and height H is given by

$$B \sim HR^3Nf \quad , \quad (44)$$

where the numerical scaling coefficient varies from about 0.5-0.8 according to whether the source is a line or a point. The difference in the coefficient arises from the different entrainment efficiency in axisymmetric and line plumes. Expression (44) is particularly useful in practice since it allows one to make an estimate of the megaplume buoyancy on the basis of the megaplume dimensions (which may measured in the field), without knowledge of the manner of discharge (which is typically unknown).

The experimental results [*Helfrich and Battisti*, 1991; *Bush and Woods*, 1999] identify that, for a given height of rise, the radius of the megaplume, in geostrophic balance, satisfies the constraint

$$R < HN/f \qquad (45)$$

As seen in Table 2, this limit provides an upper bound on the total buoyancy associated with a single megaplume at a given height in the water column,

$$B = H^4N^4/f^2 \quad . \qquad (46)$$

Such a megaplume can only be produced if the flux supplying the plume persists for a time in excess of the instability time of the cloud, $\sim 10^5$ s; if the source continues to discharge hydrothermal fluid beyond this time, a second megaplume or second line of megaplumes will develop. Equation (46) is also useful, since if the only accurate field measurement of a megaplume was the height of the plume in the water column, then (46) would provide an upper bound on the total buoyancy associated with the eddy.

We proceed by applying our model to estimate the heat flux of several recorded megaplumes. For the megaplume EP86 described by *Baker et al.*, [1989], for which the source was thought to be linear, the heat content was estimated to be of order $10^{15} - 10^{17}$ J, based on measurements of the temperature anomaly, $\sim 0.24^\circ$ C, and volume of the eddy. The present model can provide a new estimate for this heat content based on the fluid dynamical constraints of mixing and eddy formation, and also, our model accounts for the uncertainty in the initial salinity and temperature of the hydrothermal effluent forming the megaplume (section 4). Published field data indicated that the eddy had radius of order 7-9 km and a height of about 800 m. We deduce from Table 2 that the source was long-lived, and using (44), we deduce a heat content of about $3.5 - 7 \times 10^{16}$ J, in accord with the earlier estimates.

For the later event plumes EP93A and EP93B, the radii of the plumes were about 2-3 km, and the heights were about 600 and 800 m, respectively with temperature anomalies of about 0.14° and 0.2°C, respectively [*Baker*, 1995]. Again, given their radii and heights, and assuming that these megaplumes were produced from relatively short ($\sim 1 - 2$ km) linear sources, we infer that the sources persisted for a time of order 10^5 s and that the total heat release associated with the megaplumes was 6×10^{14} and 2×10^{15}, respectively.

This work has identified that a long, linear source may lead to formation of several eddy structures from a single discharge; consequently, lenticular eddies may be a ubiquitous feature of vent fields. Since black smoker plumes often arise in collinear arrangements along the mid-ocean ridge, the merging of neutral clouds associated with individual smokers may give rise to a single extended compound neutral cloud, which may become unstable in a fashion similar to that above a line source, generating a chain of anticyclonic vortices. Moreover, we note that in the presence of a strong ambient current, the discharge from a point source resembles that above a line thermal [*Helfrich and Speer*, 1995]; in this case, the evolution of the hydrothermal effluent at the level of neutral buoyancy may be analogous to that of a neutral cloud produced above a line source.

5.1. Limits of Applicability of the Model

It is important to qualify the above results. First, the modeling has focused on highly idealized source conditions of a point and a line source; although these provide a useful insight into the importance of source geometry on the flow, actual source conditions for megaplumes may involve fully two-dimensional areal sources, which have different plume entrainment laws and will therefore affect the quantitative details of the model. However, the general principles concerning the impact of background rotation on a convective plume are still applicable. Second, we expect that the presence of ambient currents would alter the physical picture described herein and not simply through influencing the rate of entrainment into the plume. In the presence of a steady, horizontal, ambient current of 1-10 cm/s, the megaplume structure would drift 1-10 km over a period of 10^5 s; consequently, one expects that stronger time-dependent currents may disperse the hydrothermal effluent to such an extent as to entirely preclude the formation of coherent vortical structures. Third, the shape of lenticular eddies in rotating stratified fluids is a function of time. In particular, we expect the Prandtl ratio characterizing an eddy to decrease in a similar fashion to that of meddies [cf. *Hedstrom and Armi*, 1988; *Bormans*, 1992] over a timescale of 1 year. Consequently, inferences made for the origin and heat content of megaplumes older than a few months will be subject to error.

5.2. Future Work

The estimates of the timescale for instability of the neutral cloud (Table 2) have been drawn from experiments and numerical modelling [*Helfrich and Speer*, 1995; *Bush and Woods*, 1999] to be approximately $100N/f^2$ for an axisymmetric cloud and $100/f$ for a linear cloud. It would be of considerable interest to derive a more complete theoretical estimate for this time of instability. While a theoretical description of the instability of the point plume system has been treated in detail by *Helfrich and Send* [1988], an analogous study of the line plume has yet to be undertaken. Specifically, it would be valuable to assess the relative importance of the vertical and horizontal shear in the instability of the neutral cloud above a line plume.

Acknowledgments. This work is supported by a bridge grant from NERC. A.W.W. thanks W. and S. for their encouragement, and C.P.C. for assistance with the preparation of the manuscript.

References

Baker, E.T., Characteristics of hydrothermal discharge following a magmatic intrusion, in *Hydrothermal Vents and Processes, Geol. Soc. Spec. Publ., 87*, 65-76, 1995.

Baker, E.T., J.W. Lavelle, R.A. Feely, G.J. Massoth, and S.L. Walker, Episodic venting of hydrothermal fluids from the Juan de Fuca Ridge, *J. Geophys. Res., 94*, 9237-9250, 1989.

Baker, E.T., R.A. Feely, R.W. Embley, R.E. Thomson and B.J. Burd, Hydrothermal event plumes from the CoAxial seafloor eruption site, Juan de Fuca Ridge, *Geophys. Res. Lett., 22*, 141-150, 1995

Bormans, M., An experimental study on the formation and survival of stratified subsurface eddies, *J. Geophys. Res., 97*, 20,155-20, 167, 1992.

Bush, J.W.M., and A.W. Woods, The generation of coherent vortices by line plumes in a rotating stratified fluid, *J. Fluid Mech.*, in press, 1999.

Caan, J., and M.R. Strens, Modeling periodic megaplume emission by black smoker systems, *J. Geophys. Res., 94*, 12,227-12,237, 1989.

Griffiths, R.W., and P. F. Linden, The stability of vortices in a rotating, stratified fluid, *J. Fluid Mech., 105*, 283-316, 1981.

Griffiths, R.W., P. Killworth, M. Stern, Ageostrophic instability of ocean currents, *J. Fluid Mech., 117*, 343-377 1982.

Hedstrom, K., and L. Armi, An experimental study of homogeneous lenses in a stratified rotating fluid, *J. Fluid Mech., 191*, 535-556, 1988.

Helfrich, K., Thermals with background rotation and stratification, *J. Fluid Mech., 259*, 265-280, 1994.

Helfrich, K., and Battisti, Experiments on baroclinic vortex shedding from hydrothermal plumes, *J. Geophys. Res., 96*, 12,511-12,518, 1991.

Helfrich K., and K. Speer, Oceanic hydrothermal circulation: mesoscale and basin scale flow, in *Seafloor Hydrothermal Systems, Physical, Chemical, Biological and Geological Interactions, Geophys. Monogr. Ser., vol. 91*, edited by S.E. Humphris et al., pp347-356, AGU, Washington D.C., 1995.

List, E.J., Turbulent jets and plumes, in *Mixing in Inland Coastal Waters*, edited H.B. Fischer, chap. 9, pp. 315-389, Academic, San Diego, Calif., 1979.

McDougall, T.J., Bulk properties of 'hot smoker' plumes, *Earth Planet Sci Lett., 99*, 185-194, 1990.

Morton, B., G.I. Taylor and J.S. Turner, Turbulent gravitational convection from maintained and instantaneous sources, *Proc. R. Soc. London, Ser. A, 234*, 1-23, 1956.

Noh, Y., J.S. Fernando and C.Y. Ching, Flows induced by the impingement of a two-dimensional thermal on a density interface, *J. Phys. Oceanogr., 22*, 1207-1220, 1992.

Scorer, R., Experiments on convection of isolated masses of buoyant fluid, *J Fluid Mech., 2*, 583-594, 1957.

Sparks, R.S.J., M.I. Bursik, S. Carey, J. Gilbert, L. Glaze, H. Sigurdsson, and A.W. Woods, *Volcanic Plumes*, 574pp., John Wiley, New York, 1997.

Speer, K.G., and K.R. Helfrich, Hydrothermal plumes, a review of flow and fluxes, in *Hydrothermal Vents and Processes*, edited by L.M. Parson et al., *Geol Soc. Spec. Publ., 87*, 373-385, 1995.

Speer, K.G., and J. Marshall, The growth of convective plumes at seafloor hot springs, *J. Mar. Res., 53*, 1,025-1,057, 1995.

Speer, K.G., and P. Rona, A model of an Atlantic and a Pacific hydrothermal plume, *J. Geophys. Res., 94*, 6,213-6,220, 1989.

Turner, J.S., and Campbell, I., Temperature, density and buoyancy fluxes in black smoker plumes and the criterion for buoyancy reversal, *Earth Planet. Sci. Lett., 86*, 85-92, 1987.

Turner, J.S., and L.B. Gustafson, The flow of hot saline solution from vents on the seafloor - Some implications for exhalative massive sulfide and other deposits, *Econ. Geol., 73*, 1082-1100, 1978.

Woods, A.W., A note on non-Boussinesq plumes in an incompressible stratified environment, *J. Fluid Mech., 345*, 347-356, 1997.

J. W. M. Bush, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, CB3 9EW, England, U. K.

A. W. Woods, Centre for Environmental and Geophysical Flows, School of Mathematics, University of Bristol, University Walk, Bristol BS8 1TW, England, U. K. (e-mail: a.w.woods@bris.ac.uk)

(Received March 10, 1998; revised November 12, 1998; accepted January 12, 1999.)