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Supporting Information for

Observations and Modeling of a Hydrothermal Plume in Yellowstone Lake

Robert A. Sohn[1], Karen Luttrell[2], Emily Shroyer[3], Christian Stranne[4], Robert N. Harris[3], and Julia E. Favorito[3]

[1]Woods Hole Oceanographic Institution, Woods Hole, MA, 02543.

[2]Louisiana State University, Baton Rouge, LA.

[3]Oregon State University, Corvallis, OR.

[4]Stockholm University, Sweden

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Introduction

This supporting information provides additional details regarding the Acoustic-Doppler-Current-Profiler data (Text S1) and a description of sensitivity tests conducted to assess the impact of our modeling assumptions on our results (Text S2).

Text S1.

Acoustic-Doppler-Current-Profiler (ADCP) surveys

The ADCP data were collected using a downward-looking 300 kHz *RDI Navigator* system mounted on a pole rigidly affixed to *R/V Annie II*. The data were acquired when the research vessel was stationary or moving very slowly (< 4 knots) over the Deep Hole hydrothermal site. The transducer was mounted roughly 2 m beneath the surface, allowing for resolution of currents from ~ 6 m beneath the surface to within ~15 m of the bottom. The maximum measured range between the transducer and the bottom was 95 m; current measurements in the lower 15% of the range were removed to avoid side-lobe contamination. Currents were sampled in 4 m vertical bins averaged into 2-minute

ensembles. Flagging of data (correlation threshold of 64) and conversion from beam to earth coordinates was done internally by the ADCP prior to ensemble averaging. The ADCP maintained bottom-tracking throughout the deployment, so that removal of ship motion to retrieve water column velocity was straightforward. Time ensembles were mapped to GPS latitude and longitude through a linear interpolation of GPS time onto ADCP time.

ADCP data were acquired during two discrete survey periods: a 4-hour window on 13 August and a 5-hour window on 14 August. The two surveys were separated from one another by roughly 12 hours. The entire survey on 13 August was opportunistic - i.e., data were acquired while the research vessel was conducting other research - and the survey pattern was therefore not optimized for plume measurements. The survey on 14 August was conducted in two parts. For the first ~3 hours, data was collected in a similar, opportunistic way, but for the final ~2 hours the survey pattern was expressly designed to systematically measure currents in the water column above the Deep Hole hydrothermal field (radiator survey grid pattern shown in Figure 1b).

The systematic survey on 14 August provides an opportunity to assess the spatial structure of the water column plume above the hydrothermal field. The vertical velocity field is described in the main body of the manuscript. The horizontal velocity field is more complex than the vertical velocity field, with significant spatio-temporal variability, and with current direction varying as a function of depth (Figure S1). Unfortunately, the sampling was too slow (2-minute ensemble averages) to resolve motions at the local buoyancy period of the thermocline (~2.5 min), and likely aliased large-scale motions associated with seiching (78 min fundamental mode compared to ~2 hour survey duration). The background current field into which the plume fluids rise is not adequately constrained by our data. Streamline plots (Figure S2) provide a sense of the complex interaction between the buoyant plume and the ambient current field.

The processed ADCP data are available for download as *Matlab* files from Sohn et al., (2019a), doi: 10.1594/IEDA/324712.

Text S2

Numerical model sensitivity tests

Our model makes assumptions about the nature of hydrothermal discharge at the lake floor that may affect our results. We conducted sensitivity tests to assess the impact of these assumptions on our analyses, and report those results here (Figure S3).

First, we consider the assumption that hydrothermal discharge occurs through a single feature at the bottom boundary (i.e., the lake floor), of a fixed size. By contrast, visual observations from ROV dives have established that discharge at the Deep Hole site occurs through numerous small features that are distributed over a wider area. Our baseline model assumes that discharge occurs evenly over an area of 54,000 m^2, which spans the entire pockmark field at the Deep Hole site. To understand how this assumption affects our results we ran the model with initial discharge areas at the bottom boundary ranging from 54 to 54,000 m^2. The results demonstrate that variations

in the source area have a weak and essentially negligible effect on all model parameters except for boundary velocity (Figure S3b). Variations in source area are almost exactly balanced by variations in the boundary velocity such that the total mass, heat and buoyancy fluxes of the best-fitting model parameters do not change.

Second, we consider the source depth assumption. The model assumes that fluid discharge occurs at a single depth, whereas the various discrete venting sites in the pockmark field sampled during HD-YLAKE fieldwork have depths that vary by ~8 m (109-117 m). Although this depth variation is not large, it nevertheless has a significant impact on the flux estimates for the best-fitting model (Figure S3d). This high degree of sensitivity is expected because changing the source depth changes the neutral buoyancy height estimate by an equal amount, and the plume fluxes in the best-fitting model are primarily constrained by the height of the neutral buoyancy horizon about the source. Changing the source depth boundary condition by ± 5 m changes the best-fitting plume heat flux by ± 7 MW.

We did not use the fluid temperature anomaly at the plume neutral height to constrain the model, but our simulations were able to reproduce the anomaly to within ~0.01°C (Figure S3c). The initial plume fluid temperature at the lake floor boundary for all of our best-fitting simulations is within a relatively narrow range (~9.1-9.7 °C), regardless of the assumed source depth and area (Figure S3a).

We did not use the vertical velocities observed during the ADCP surveys to formally constrain the modeling results, but we can nevertheless compare the vertical velocity profile from the model output to the observed profiles to assess the model accuracy (Figure S4). As described in the main text body, the positive vertical velocities observed in the upper part of the water column above the thermocline on 13 August (see main text Figure 3a) are not explained by our model and are likely due to other hydrodynamic processes. Below the thermocline, however, our model matches the observed 1D vertical velocity profile observed over the Deep Hole site fairly well.

In summary, our model is primarily sensitive to assumptions regarding the source depth through its impact on the plume's neutral height (since the depth horizon of the neutral layer is fixed by observations, variations in source depth translate directly into variations in neutral height). The assumed source area at the bottom boundary has a negligible impact on the results because the model adjusts the fluid velocity at the bottom boundary so that the total flux required to match the neutral height observed is preserved. Although the observed temperature anomaly at the plume neutral height and the vertical velocity profiles were not used to constrain the model, the model results nevertheless reproduce these parameters satisfactorily.

The sensitivity of the model to the plume neutral height estimate is expected given the relationship between buoyancy flux and neutral height in Equation 1 of the text, which is scaled by the buoyancy frequency of the ambient medium. Our estimate buoyancy

frequency depends on the interval over which it is calculated because of the strong density gradient in the thermocline (Figure S5). We find that the buoyancy flux from our baseline numerical model is reproduced in Equation 1 if the buoyancy frequency is calculated over the interval from the source depth at 115 m to 25 m.

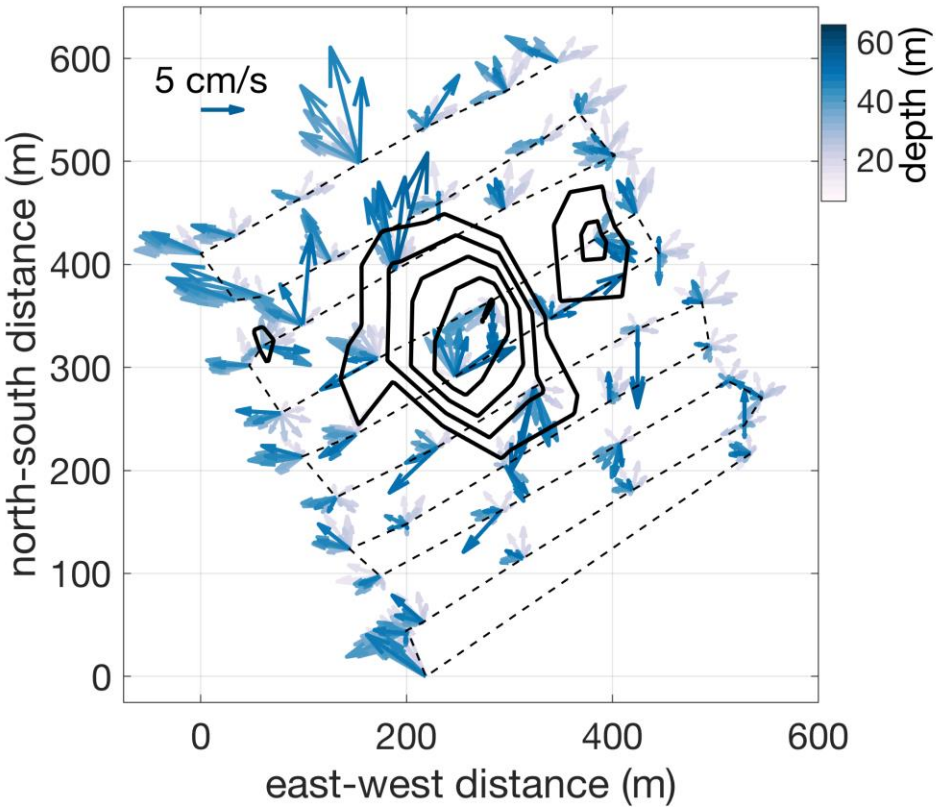


Figure S1. Horizontal velocity as a function of depth measured during the radiator survey on 14 August, 2018. Vectors are shown for each two-minute ensemble average. The duration of the radiator survey was roughly the length of the dominant seiche period. The measured flow field is complex. A general tendency for flow away from the region of upwelling is evident, as is significant vertical shear. Contours show the depth mean vertical velocity at 1 cm s^{-1} intervals in regions of upwelling.

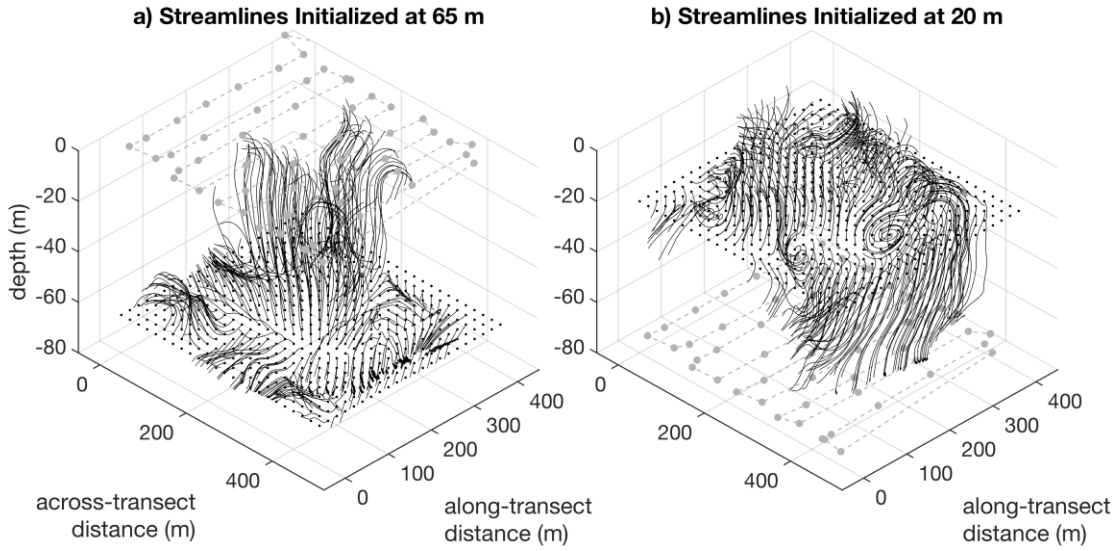
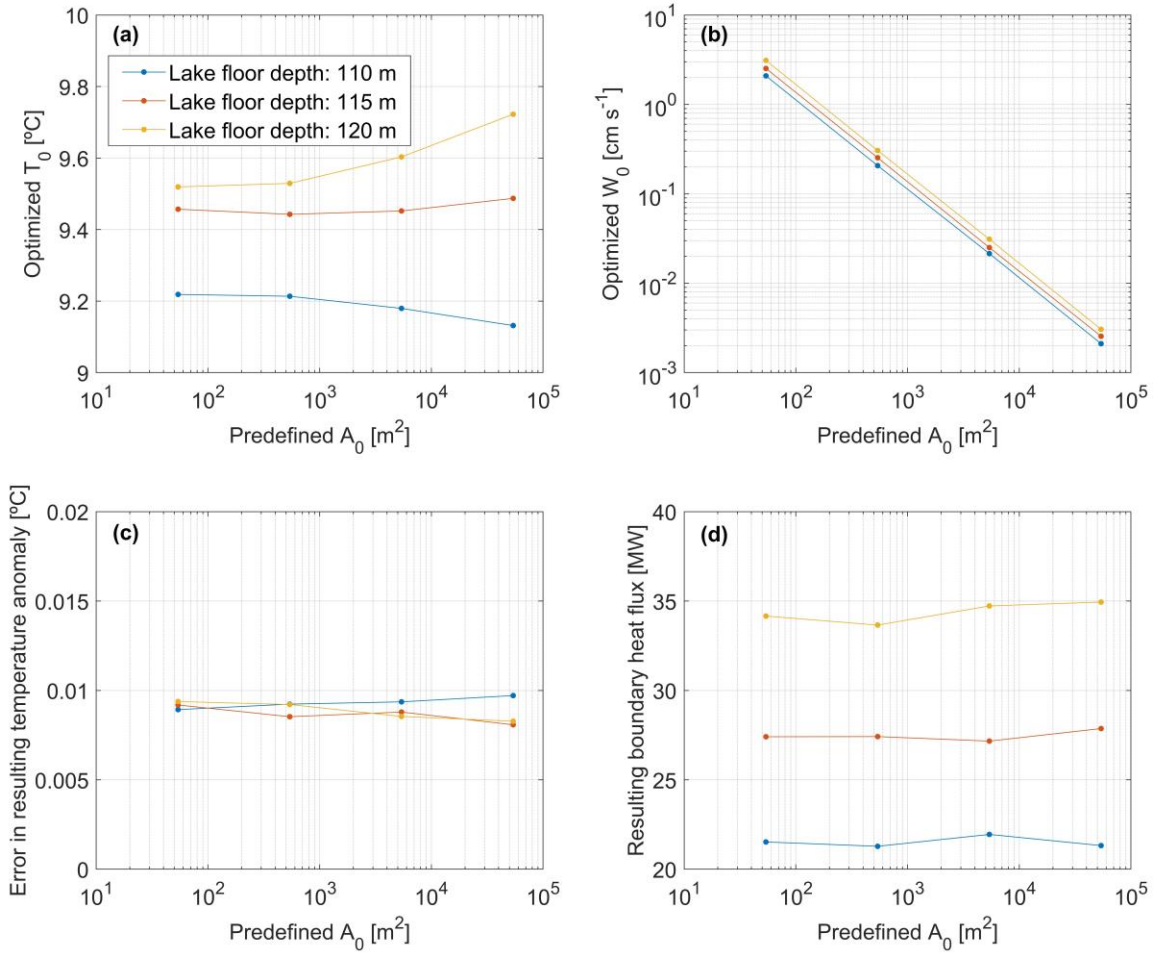


Figure S2. Streamlines calculated from 4-m gridded radiator survey data. Streamlines are initialized at 65 m (left) and 20 m (right) depth at 20-m intervals in the horizontal. The ship track and ADCP ensembles are shown in grey. The integration step is taken over 1 m and continued for 100 intervals. Streamlines highlight the tendency for upward (downward) motions near (away from) the plume centerline, as well as the similarity in the magnitude of horizontal and vertical velocity.



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140 **Figure S3.** Sensitivity tests for boundary source area and depth. Optimized boundary
141 temperature (a) and vertical velocity (b) for different predefined boundary areas and
142 lake floor depths. c) Error in resulting temperature anomaly (compared to CTD data) and
143 (d) resulting heat flux for different predefined boundary areas and lake floor depths.

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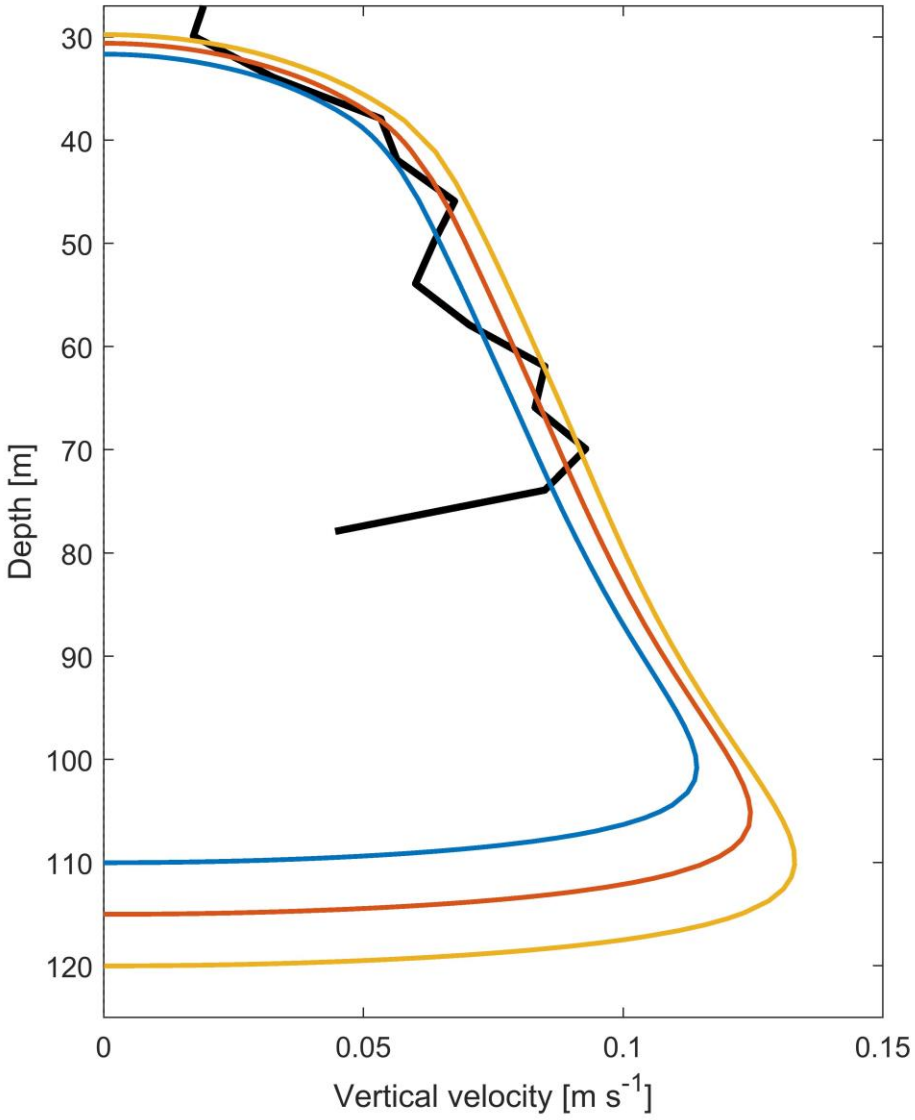

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148 **Figure S4**. Comparison of 1D average vertical velocity profile from Deep Hole site (black)
149 with resulting vertical velocity profiles from best-fitting numerical models for three
150 different source depths (blue: 110 m, red: 115 m and yellow: 120 m). The modeled
151 profiles represent values averaged over the radius of the buoyant plume as it rises
152 through the water column. The 1D average profile from the ADCP surveys only extends
153 to a depth of ~80 m because deeper intervals were truncated to avoid side-lobe
154 contamination due to beam spreading. In both the observed and modeled profiles
155 positive vertical velocities extend slightly above the plume's neutral depth (45 m),
156 reflecting the overshoot expected for these features. Over the depth interval with robust
157 estimates for the average vertical velocity (~30-80 m) the model output agrees fairly well

with the observations regardless of the source depth estimate, but the baseline estimate of 115 m matches the observed profile best.

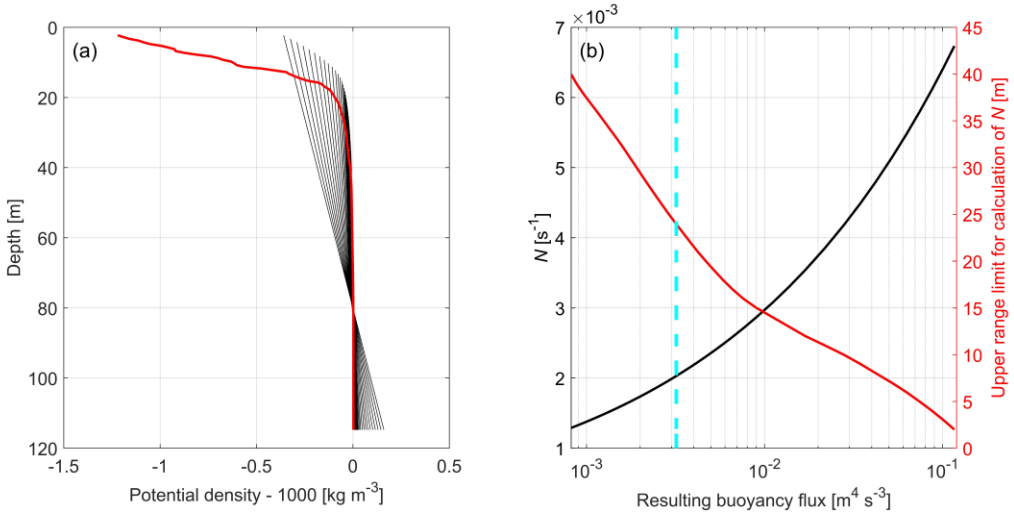

Figure S5. a) Observed background potential density (red line, reproduced from Fig. 2c in the main text) and linear regressions between the lake floor at 120 m depth and an upper limit ranging between 2 to 40 m below the lake surface (black lines). b) Resulting buoyancy flux (x-axis) as a function of the Brunt-Vaisalla (buoyancy) frequency (black) and the corresponding range over which the Brunt-Vaisalla frequency is calculated (red). The buoyancy flux from the best-fitting numerical plume model (3.2 x 10^{-3} m^4 s^{-3}) is marked with a cyan line.