TIDAL CURRENT EFFECTS ON TEMPERATURE IN DIFFUSE HYDROTHERMAL FLOW: GUAYMAS BASIN

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Abstract. A twelve day record of temperature collected from the diffuse flow area of a Guaymas Basin hydrothermal site exhibits variations, from a minimum of 3.05°C to a maximum of 4.87°C, whose periodicity is correlated with tides measured at the nearby town of Guaymas. A simple model, based on the hypothesis that temperature variations result as changes in tidal bottom currents induce changes in the height of the thermal boundary layer, is in good quantitative agreement with observed temperatures for most of the record. The success of this model illustrates that the effects of tidal currents can be strong enough to dominate the time variability of a temperature signal at a fixed point in hydrothermal flow. Therefore, tidal currents must be taken into account when using temperature measurements to estimate time varying heat fluxes from hydrothermal diffuse flow regions.

Introduction

The high heat flow, high permeability and low sedimentation of the world’s Mid-Ocean Ridge system support the process of hydrothermal circulation which transfers heat and material from the lithosphere into the oceans, influencing oceanic composition as well as creating massive ore deposits on the seafloor. The significance and global impact of this process are determined by the heat and mass flux from individual sites, the number of hydrothermal sites, and the variation of these fluxes over time.

Quantifying even the instantaneous heat and mass flux from individual sites is difficult due to the complexity of flow systems typically encountered in hydrothermal fields. In a single field the flow can range in character from warm, 10°C water slowly seeping through large masses of tube worms and bacterial mats, to hot, 350°C water jetting from narrow sulfide chimneys only 0.05 m in diameter. Measurements of temporal changes in hydrothermal activities require some means of obtaining time-series data within the difficult constraints of deployment, recovery, power consumption, data storage, and instrument reliability (Johnson and Tunnicliffe, 1985).

The most straightforward flux measurements to make are those of well-defined plumes emanating from single chimneys (Converse et al., 1984; Macdonald et al., 1980; Littke et al., 1987). Much more difficult to quantify is the diffuse flow emanating from cracks, fissures and biological masses at velocities of less than about 0.1 m/s because the velocity and temperature signals are low and unevenly distributed over a large area. Velocity is particularly difficult to obtain because the flow is heterogeneous over scales as small as a few centimeters and the flow velocity is low and on the same order of magnitude as ocean currents (0.05-0.10 m/s) which can mask hydrothermal related flow. When making long-term temperature measurements in a hydrothermal environment, care must be taken to separate out the effects of changes in hydrothermal flow and temperature from changes in ambient currents. In this article we examine a time-series of temperature data collected near a diffuse flow area at a Guaymas Basin hydrothermal site. We will show that the effects of tidal currents can be strong enough to dominate the time variability of a temperature signal at a fixed point in hydrothermal flow, and are a plausible explanation for the variations seen in the Guaymas Basin temperature data. This study points out the necessity to measure currents whenever temperature measurements made in hydrothermal vent fields are used to examine time variability of venting.

Measurements and results

The experiment site was a hydrothermally active area located in the Southern Trough of Guaymas Basin in the Gulf of California at 27°00’N, 111°24’W where vents flow through a thick layer of pelagic sediment before breaking out onto the seafloor. In an effort to characterize temporal variability of diffuse hydrothermal flow, a temperature probe was placed 0.03 m above the sediment surface in an approximately 5x5 m zone characterized by bacterial mat, whitish mineral deposition and patches of shimmering water (Lonsdale and Becker, 1985).

The thermistor was deployed with a submersible and left in place for 12.5 days from July 17, 1985 to July 28, 1985, during which time temperatures were recorded every 5 min-
that of temperature, we have presented the frequency spectra with the tidal period axis divided by two (Figure 2). The tidal spectrum was calculated after cubic spline interpolation of unequally spaced tide data (see Figure 1). The temperature spectrum was produced by first dividing the data set into fourteen, 256 point segments by sub-sampling the full set every fourteen points. The new segments, with points separated by 70 min., were used to produce an averaged spectrum with a minimum resolvable period of 2.33 hours. The power levels are not normalized so comparison only can be made of the peak period locations, not amplitudes. There are striking similarities between the two spectra, especially at the 12 and 6 hour periods but also at the shorter periods such as 4 and 3 hours, indicating that tidal current speed, which peaks twice as often as tidal height, may be influencing temperature.

Fig. 1. Upper - Temperature data recorded by $T_1$, 3 cm above diffuse flow, samples every 5 minutes, showing semi-diurnal variations. Lower - Tidal maxima and minima above mean low water, recorded at the town of Guaymas (stars). A cubic spline interpolation between data points (dotted line) is then fitted with tidal harmonics to approximate a functional form for the tide.

utes for a total of 3790 points. The ambient temperature in this area as measured during descent of the instrument package was 2.85°C. The maximum recorded temperature was 20°C, which occurred during deployment probably as the probe touched or came very close to the sediment surface. We will use this value for sediment surface temperature in calculations that follow.

Tidal high and low water surface elevations were obtained from the town of Guaymas, Mexico, approximately 100 km away, for the same time period. Tidal currents measured at 10 m above bottom in the troughs of Guaymas Basin have reversing northwest-southeast flow with velocities of up to 0.12 m/s (Lonsdale and Becker, 1985). Current speed was not recorded at the vent site and will be derived from the tidal heights recorded at the town of Guaymas.

The most prominent feature of the raw temperature data (Figure 1) is the strong semi-diurnal oscillation, which exhibits a temperature range from a minimum of 3.05°C to a maximum of 4.87°C. The concurrent tide data (also Figure 1) show that the dominant tide in this region is diurnal. Closer examination reveals that the temperature reaches a peak when the tide is at a minimum or maximum, and reaches a low when the tide is at an inflection-point.

Discussion

From the above observations follows the hypothesis that temperature is influenced by tidal current speed, a process which can have a 90° phase lag to tidal height and which peaks twice as often as tidal elevation. To test this hypothesis we compared the frequency spectra of temperature and tide to determine whether correlations at frequencies higher than diurnal exist. The positive correlations which were found led to the use of a simple thermal boundary layer model which, when used with current speed estimated from tidal height, yielded predicted temperature variations to compare with measured temperature data.

To facilitate the examination of temperature and tidal frequencies under the supposition that tidal periods are twice

Fig. 2. Frequency spectra from temperature data (solid line) and cubic spline fit to tides (dotted line). The frequency axis for the tidal spectrum has been divided by two to show good comparison of estimated tidal current spectrum with temperature spectrum.

A simple boundary layer flow model was formulated to examine the effects of current speed on temperature at a fixed point above a heated surface (Figure 3). When a current passes over a heated surface, a thermal boundary layer is produced whose thickness increases with distance downstream from the leading edge of the surface. There are two ways that a current can influence temperature at a point inside a thermal boundary layer. First, if the sensor is not located at the center of the surface, then rotating the direction of the current vector while maintaining a constant current magnitude will change the effective distance between the sensor and leading edge of the surface. As boundary layer thickness is a function of this distance, a current rotation will result in a change of boundary layer thickness and hence the recorded temperature. Such temperature variations would have frequencies correlated with the tides. However, it would be pure chance if the phases of variation coincided - there would be no reason to expect a temperature low at a tidal inflection point since the timing of the variation would depend only on sensor position within the diffuse region.

The second mode of current influence on temperature depends on the fact that the temperature at a fixed point above the surface depends on the thermal boundary layer thickness, which is a function of current magnitude. We suggest that this mode is operating and temperature variations observed
Fig. 3. Schematic of model defining various parameters: $U(L)$ is the maximum velocity recorded at 10 m above the bottom, $U(z(p))$ is velocity at sensor, $z$ is the distance between the sensor and the leading edge of the heated surface, $\delta$ is boundary layer thickness, $T_s$ is ambient temperature, $T_h$ is heated surface temperature, $z$ is vertical distance from surface, $T(z)$ is temperature profile within the boundary layer.

at this site are due to the fact that the thermistor is in an area where a thickening and thinning of the boundary layer is caused by changes in current magnitude.

To examine how temperature relates to flow we first assume a general form for the dependence of the boundary layer thickness, $\delta$, on flow velocity, $U$:

$$\delta = C U^{-1/2}$$  \hspace{1cm} (1)

This functional relationship is consistent with a thermal boundary layer development in a flow with a uniform velocity and a constant diffusivity (Fischer et al., 1979). The constant $C$ will be determined by calibration with the temperature and velocity measurements, and will be limited in precision to an order of magnitude because surface temperature and bottom current speed are not well constrained. These approximations do not affect comparisons of temporal variability so much as comparisons of absolute temperatures.

To relate temperature to the position of a measurement point within the boundary layer we assume a parabolic form for the temperature profile:

$$T(z) = T_0 - (T_s - T_h) \left( \frac{2z}{\delta} - \frac{z^2}{2\delta^2} \right)$$  \hspace{1cm} (2)

Where $T_s$ is the surface temperature (20°C), $T_0$ is the ambient temperature (2.85°C), and $z$ is the distance from the surface (0.03 m). This profile reflects the general characteristics of the temperature variations within a thermal boundary layer (Slichting, 1968). A simple linear functionality was tried but yielded less satisfactory results.

The phase relation between tidal height and current varies depending on basin shape, but taking here the simplest case, the flow speed over the heated surface, $U$, was assumed to be proportional to the first derivative of tidal height ($A$) as measured at Guaymas. To obtain a functional form for $U$, the interpolated tide data was harmonically decomposed using a least squares sine fit such that:

$$h = K_o \sum_i A(i) \sin[\theta(i)t + \phi(i)]$$  \hspace{1cm} (3)

where $A(i)$, $\theta(i)$ and $\phi(i)$ are the amplitude, frequency, and phase of each component (see table 1). The flow speed $U$ was then modelled as being linearly dependent on the absolute value of the time derivative of equation 3:

$$U = K_o \sum_i A(i) \theta(i) \cos[\theta(i)t + \phi(i)] + K_1$$  \hspace{1cm} (4)

The constants $K_o$ and $K_1$ were determined to match estimated values of the maximum and minimum current speeds, $U_{max}$ and $U_{min}$, at the height of the sensor. $U_{max}$ is estimated from the maximum free stream velocity, $U(L)$, measured as 0.12 m/s at 10 m above bottom (Lonsdale and Becker, 1985) using a logarithmic velocity profile between height $z(L)$ and the sensor position $z(p)$:

$$\frac{U(z(p))}{U(L)} = \frac{\ln(z(p)) - \ln(z_o)}{\ln(z(L)) - \ln(z_o)}$$  \hspace{1cm} (5)

where $z_o = \text{roughness height}/25$ (Townsend, 1980). For a roughness height of 0.05 m we estimate $z_o$ to be 0.022 m. Using $z(p) = 0.03$ m, $z(L) = 10$ m, $U(L) = 0.12$ m/s in equation 5 results in an order of magnitude estimate for $U(z(p)) = U_{max} = 0.05$m/s.

This value of $U_{max}$ may be used directly in conjunction with the observed temperature minimum $T_{min} = 3.05$°C and equations 1 and 2 to calculate $C = 7.5 \times 10^{-3} \text{m}^2/\text{s}^{1/2}$. Using the same equations with this value of $C$ and $T = T_{max} = 4.85$°C yields an estimate of $U_{min} = 0.03$ m/s. Correspondingly, the values of $K_o = 9.27$ and $K_1 = 0.03$ m/s may be obtained. In addition, with the above values for $C$ and $U$, the boundary layer thickness varies between $\delta_{min} = 0.033$ m and $\delta_{max} = 0.043$ m.

The time series of velocities obtained from equation 4 may now be substituted into equation 1 and 2 to obtain an estimate of temperature at the sensor height (4a and 4b). A detailed examination shows extremely good correlation between predicted and actual temperatures between 0 and 150 hours. Following this, a notable difference arises where from 150-290 hours maximum temperature peaks decrease and the
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Fig. 4. a) Temperature (solid line) and temperature estimated from boundary layer flow model and tidal currents (dotted line). b) Temperature (solid line) and temperature estimated from boundary layer flow model and tidal currents (dotted line) from second half of data record.

variations get slightly out of phase. This is probably due to the fact that tides can have a rotational component which is not considered here, i.e., they are not exactly reversing and the minimum current increases during these periods rather than remaining constant as assumed in our simple model. In addition, there may be more complicated phase lags between current and tidal height.

It is of interest to see whether the value of \( C \) calculated by this procedure is consistent with theoretical estimates of the effective thermal diffusivity controlling vertical transport of heat. For a constant diffusivity \( K \), the thermal boundary layer thickness is given by \( \delta \approx (Kx/U^{1/2}) \) where \( x \) is the distance from the leading edge (Schlichting, 1968). This is equivalent to setting \( K \approx C^2/x \). From our estimated value of \( C \) and using \( x \approx 2 \text{ m} \) we obtain an empirical value of \( K \approx 10^{-5} \text{ m}^2/\text{s} \).

This value of diffusivity is about 100 times molecular, indicating that a turbulent transport process is operative. Using the observed current velocities and temperature differences, we estimate that the thermal boundary layer is influenced primarily by the upward buoyancy flux above the diffusive region and less so by the upward momentum flux. The theoretical diffusivity associated with this process (Ryan et al., 1974) is \( K = 10^{-5} \text{ m/s} \), (equivalent to a diffuse heat flux of 1000 W/m²) in agreement with the more empirical estimate above.

Conclusions

Temperature variability measured near a source of diffuse hydrothermal flow can be produced by tidal currents. A time series of temperature from a hydrothermal area in the Guaymas Basin can be explained in a large part, if not entirely, by invoking boundary layer theory and tidally driven cross currents. These results point out the importance of collecting simultaneous temperature and bottom current velocities to allow unambiguous interpretation of temperature data for the purpose of estimating heat flux and flux variability from hydrothermal vents.

Acknowledgements: This work was supported in part by NSF, grant number OCE83-11201, and in part by the WHOI/MIT Joint Program Education Office. WHOI contribution number 6807; CWR number ED-88-277.

References


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(Received May 27, 1988; accepted September 30, 1988.)