Observations of Strong Mid-Pacific Internal Tides above Horizon Guyot

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ABSTRACT

Large semidiurnal current and isotherm oscillations were observed by one current meter continuously for 9 months in the waters above Horizon Guyot, a seamount located in the central Pacific. The M2 tides dominated the current-meter record. The M2 current ellipse was oriented along 142°; the semi-major amplitude was 7.6 cm s⁻¹ and the currents rotated in a clockwise direction. The M2 isotherm deflection amplitude was 20 m. The M2 currents observed above the guyot were two to three times larger than M2 currents either observed in or predicted for this region of the mid-Pacific. Evidence suggests that the semidiurnal tide was predominantly an internal tide that was generated at the guyot. The observed internal tide had a narrow bandwidth and a constant amplitude and phase for 9 months, and had characteristics similar to a vertically propagating, rather than a vertically standing, internal wave.

1. Introduction

Mid-ocean internal tides are often observed in regions that are far from their generation sites (Barnett and Bernstein 1975; Earle 1975; Hendry 1977; Simpson and Paulson 1979; Weisberg et al. 1987). The generation sites are usually continental slopes (Regal and Wunsch 1973; Hendry 1977) or shallow banks near continental margins (DeWitt et al. 1986). Although theoretical models suggest that many other topographic shapes can serve as generation sites (Baines 1974, 1982), sites in the central ocean are rarely identified. In particular, there is no evidence that internal tides are generated over seamounts and guyots located in the central oceans.

In November 1983, a VACM current-meter mooring was deployed for 9 months in the eastern mid-Pacific, on the cap of Horizon Guyot (Fig. 1). The current meter was placed 213 m above the guyot at a depth of 1427 m. Two CTD profiles, one over the guyot and one to the side of the guyot, were obtained when the current-meter mooring was deployed (Fig. 1). These measurements were part of a set of geological and geo-technical studies that are reported elsewhere (Schwab et al. 1987; Cacchione et al. 1987).

The semidiurnal tide dominated the current and temperature records (Figs. 2 and 3). Tidal current amplitudes often exceeded 15 cm s⁻¹; and temperature oscillations were often larger than 0.1°. These strong tidal currents were unexpected, since previous measurements in the Pacific have shown that semidiurnal tidal current speeds are 2–3 cm s⁻¹ (Fig. 4). The strong semidiurnal oscillations in the current and temperature fields suggest that at least a portion of the tidal current was baroclinic. In the following discussion, we will show that strong internal tides are indeed present over Horizon Guyot and that these tides are likely to have been generated at the guyot.

2. Data analysis

The raw periodogram for the Horizon Guyot current and temperature records showed that the diurnal and semidiurnal tides were strongest at the O1, K1, M2 and S2 frequencies. The variances in the nearby P1 and K2 spectral bands were much weaker. Hence, the tidal parameters discussed below were calculated at the O1, K1, M2 and S2 tidal frequencies (0.03873, 0.04175, 0.08052 and 0.08333 cph).

The amplitude of an isotherm oscillation at a tidal frequency was not directly measured, but was calculated by dividing the temperature by the amplitude of the temperature gradient at 1400 m measured by the CTD (0.0019 deg m⁻¹, Table 1). The isotherm deflections were phase-shifted 180° from the temperature oscillations. Hence, the isotherm deflection record is simply a rescaled, phase-shifted temperature record.

An objective of this study was to describe the tides near Horizon Guyot. The barotropic tide cannot usually be separated from the baroclinic when one has a
single current-meter record. But one can calculate the amplitude and phase of that portion of the current and temperature signals that has a constant phase over time. In long records, these phase-stable currents are usually associated with the barotropic tide because baroclinic tides often have phases that change more randomly (Hendershott 1981). One can also use the observed phase relations between the current and temperature signals to distinguish barotropic from baroclinic tides.

The phase-stable amplitudes for the current and temperature fields at the four tidal frequencies were calculated from the amplitude of the frequency-response function between a unit amplitude signal at a specified frequency and the current or temperature record. The frequency-response method for calculating the tidal parameters is similar to the response method of Munk and Cartwright (1966), given that the amplitude of the tidal potential is unity at all frequencies, that the phase of the potential is independent of the phases of the sun and moon, and that only the most energetic tidal frequencies are used to model the tidal potential. Both methods assume that the phase of the tidal potential is constant. For the principal tidal constituents, the tidal constants calculated using the frequency-response method are indistinguishable from tidal constants calculated using a standard least-squares analysis, such as the one described by Boon and Kiley (1978) (see Noble et al. 1987).

The strongest phase-stable tidal currents were observed at the $M_2$ frequency (Table 1). The current am-

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FIG. 1. Location of the current-meter mooring and the CTD stations around Horizon Guyot. Depth contours are in meters.

FIG. 2. Hour-averaged current and temperature records from the Horizon Guyot mooring. The records have been high-pass filtered to remove frequencies shorter than 0.5 cpd. The major axis is parallel to 142°.
amplitudes were 7.6 and 3.1 cm s\(^{-1}\) for the semi-major and semi-minor current components respectively. The ratio of the minor-to-major axis currents, 0.41, is consistent with the ratio predicted by linear wave theory, \(f/\sigma = 0.35\). The phase-stable currents rotated in the clockwise sense, and the current ellipse was aligned parallel to 142\(^\circ\).

Twenty meter phase-stable isotherm deflections also occurred at the M\(_2\) frequency (Table 1). These isotherm deflections are larger than the approximately 2 m deflections that would be associated with a 7.6 cm s\(^{-1}\) barotropic tide. The observed deflections were not due to mooring motion. A calculation of the tilt of the mooring for a current as strong as the maximum current observed during the deployment period showed that the current meter would only be displaced 3 m downward. If mooring motion had significantly contaminated the isotherm deflection (or temperature) record, then a significant spectral peak would have occurred at the 6-h period as the mooring tipped in response to the strong semidiurnal tidal speeds. No strong spectral peak was observed at this period (Fig. 3).

The phase-stable M\(_2\) currents accounted for over 89% and the phase-stable isotherm oscillations accounted for 72% of the variance contained in their respective frequency bands for the 9-month record (Table 1). The phase-stable amplitudes were also constant over shorter periods of time. The phase-stable M\(_2\) current amplitude, estimated for successive blocks of record 75 days long, varied by less than 1 cm s\(^{-1}\) for both

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**Table 1.** Characteristics of the phase-stable diurnal and semidiurnal tides calculated from the frequency response method with a bandwidth of 1/720 cph. The ellipse orientation is clockwise from north. The rotation sense is C for clockwise, A for anticlockwise. The isotherm deflection amplitude is the temperature amplitude divided by the temperature gradient at 1400 m (0.0019 deg m\(^{-1}\)). The value for the temperature gradient is an average of the temperature gradient measured by the CTD for depths between 1300 and 1500 m. The standard deviation of the temperature gradient over this interval is 0.0006 deg m\(^{-1}\). The coherence squared (\(\gamma^2\)) denotes the percentage of energy in each constituent that is phase-stable over the 9 months of current record.

<table>
<thead>
<tr>
<th>Tidal component</th>
<th>Semi-major axis current amplitude</th>
<th>Semi-minor axis current amplitude</th>
<th>Ellipse orientation</th>
<th>Rotation sense</th>
<th>Isotherm deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm s(^{-1})</td>
<td>cm s(^{-1})</td>
<td>deg</td>
<td>m</td>
<td>(\gamma^2)</td>
</tr>
<tr>
<td>O(_1)</td>
<td>1.7</td>
<td>0.5</td>
<td>122(^\circ)</td>
<td>C</td>
<td>4.0</td>
</tr>
<tr>
<td>K(_1)</td>
<td>1.1</td>
<td>0.4</td>
<td>43(^\circ)</td>
<td>C</td>
<td>4.37</td>
</tr>
<tr>
<td>M(_2)</td>
<td>7.6</td>
<td>3.1</td>
<td>142(^\circ)</td>
<td>C</td>
<td>20.72</td>
</tr>
<tr>
<td>S(_2)</td>
<td>2.3</td>
<td>1.0</td>
<td>148(^\circ)</td>
<td>C</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Fig. 5. Temporal variation of the $M_2$ semi-major current (5a), semi-minor current (5b), and isotherm oscillation (5c) amplitudes and phases. Each component is calculated using the frequency-response function on blocks of record 75 days long, with a bandwidth of 1/360 cph. The dashed lines denote the amplitude of the phase-stable component for the entire record. Error bars are at the 95% level. All coherence levels are significant at the 95% confidence level. The coherence-squared denotes the percentage of energy in the $M_2$ band that is phase stable over 75 days.
current components (Figs. 5a and 5b). Individually, the phase-stable major and minor axis currents accounted for more than 90% and 75% of the variance in the frequency band at each time interval. The phase-stable M₂ isotherm deflection amplitude was more variable (Fig. 5c). In April and May, the phase-stable oscillations were 7 m larger than average. In July, the phase-stable oscillations were 5 m smaller than average. However, none of the phase-stable M₂ tidal parameters had a time-varying amplitude that was significantly different from the amplitudes estimated over the full record.

The semidiurnal S₂ tidal currents were weaker than, but had characteristics similar to, the M₂ currents. The S₂ current ellipse rotated in the clockwise sense and was aligned nearly parallel to the M₂ current ellipse (Table 1). The isotherm oscillations in the S₂ band were about half the amplitude of the M₂ isotherm oscillation. The S₂ current and isotherm deflection fields showed only small variations in the estimated amplitude over time.

The currents in the semidiurnal bands were highly coherent with the large isotherm oscillations in the individual frequency bands (Table 2). The coherence between the major-axis current components and temperature was larger than 0.90 for both semidiurnal frequencies. The currents led the temperature by 53° to 76°. The minor-axis currents were also highly coherent with temperature; coherence amplitudes were greater than 0.80 and led the temperature by 147° and 163°.

The phase-stable diurnal currents were weak; current amplitudes were less than 2 cm s⁻¹ (Table 1). The phase-stable diurnal currents rotated in a clockwise sense, but the current ellipses were not aligned. The axis of the O₁ ellipse was parallel to 122°. The K₁ ellipse axis was aligned along 43°.

In the diurnal frequency bands, the dominate portions of the current and temperature signals had phases that changed rapidly over the 9 month observation period. The only phase-stable diurnal tidal parameter that could account for more than 50% of the variance in a frequency band was the current components oriented parallel to the major axis of the individual current ellipses (Table 1). The diurnal currents were usually not coherent with the small diurnal temperature oscillations (Table 2).

3. Discussion

Previous observations have shown that the semidiurnal tidal currents in the central Pacific have amplitudes of 2–3 cm s⁻¹ (Fig. 4) (Earle 1975; Halpern 1979; Hayes 1979; Irish et al. 1971; Noble et al. 1987; Weisberg et al. 1987). The isotherm deflection associated with a barotropic current of this magnitude is small, less than 1 m. The numerical model of Accad and Pekers (1978) also predicts that the barotropic M₂ tide is small in the region around Horizon Gouyt. The predicted current and isotherm deflection amplitudes are less than 2 cm s⁻¹ and 0.3 m respectively. Because the barotropic deflection amplitude is too small to be reliably separated from a generally energetic isotherm deflection field in this region of the central Pacific, the barotropic tidal currents are not expected to be coherent with the isotherm deflections.

The diurnal and semidiurnal tidal currents over Horizon Gouyt can be a combination of surface and internal tide, since the inertial period is 36 h. The diurnal currents near Horizon Gouyt can be consistently classified as dominantly barotropic. The diurnal currents have small amplitudes and stable phases, and are generally incoherent with the diurnal isotherm oscillations. A portion of the diurnal current may be associated with an internal tide, since 4 m diurnal isotherm oscillations are observed in the current-meter record.

The semidiurnal tides over Horizon Gouyt are predominantly baroclinic. The large isotherm deflections cannot be generated by a surface tide, nor can the sur-

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**Table 2.** The phase relationships for the diurnal and semidiurnal tides among currents oriented along the major and minor axis of the individual current ellipses and temperature. A positive phase indicates that the first component leads the second. The phase of the temperature is shifted 180° from the phase of the isotherm deflection. Error bars are calculated for the 95% confidence level. Coherence amplitudes less than the 95% zero significance level are not listed. The phase relationships between the current and temperature fields for a single vertically-propagating wave and for the surface tide are calculated from mathematical formulas by Gill (1982) and by Hendershott (1981), respectively. The phase relationships for a single-mode internal tide are the same as the surface tide relationships, except for a possible 180° shift of the current-temperature phase.

<table>
<thead>
<tr>
<th>Tidal component</th>
<th>Major-axis current—minor axis current</th>
<th>Major-axis current—temperature</th>
<th>Minor-axis current—temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coherence  Phase</td>
<td>Coherence  Phase</td>
<td>Coherence  Phase</td>
</tr>
<tr>
<td>O₁</td>
<td>0.80  -85° ± 23°</td>
<td>0.67  -151° ± 36°</td>
<td>0.84  147° ± 20°</td>
</tr>
<tr>
<td>K₁</td>
<td>0.73  -99° ± 29°</td>
<td>0.93  53° ± 12°</td>
<td>0.89  163° ± 16°</td>
</tr>
<tr>
<td>M₂</td>
<td>0.95  -91° ± 10°</td>
<td>0.95  76° ± 10°</td>
<td>90°</td>
</tr>
<tr>
<td>S₂</td>
<td>0.93  -88° ± 12°</td>
<td>180°</td>
<td></td>
</tr>
<tr>
<td>Vertically propagating internal wave</td>
<td>-90°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface tide</td>
<td>-90°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Table 3. The amplitudes of the $M_2$ currents and isotherm deflections as a function of bandwidth. The error bars are calculated at the 95% confidence level.

<table>
<thead>
<tr>
<th>Bandwidth (cph)</th>
<th>Phase-stable amplitude (cm s$^{-1}$)</th>
<th>$\gamma^2$</th>
<th>Phase-stable amplitude (cm s$^{-1}$)</th>
<th>$\gamma^2$</th>
<th>Phase-stable amplitude (m)</th>
<th>$\gamma^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/360</td>
<td>7.6 $\pm$ 1.3</td>
<td>0.87</td>
<td>3.1 $\pm$ 0.8</td>
<td>0.76</td>
<td>19.9 $\pm$ 6.6</td>
<td>0.64</td>
</tr>
<tr>
<td>1/720</td>
<td>7.6 $\pm$ 1.6</td>
<td>0.90</td>
<td>3.1 $\pm$ 1.0</td>
<td>0.81</td>
<td>19.9 $\pm$ 8.3</td>
<td>0.72</td>
</tr>
<tr>
<td>1/1080</td>
<td>7.6 $\pm$ 1.8</td>
<td>0.94</td>
<td>3.1 $\pm$ 1.2</td>
<td>0.85</td>
<td>19.9 $\pm$ 8.8</td>
<td>0.81</td>
</tr>
<tr>
<td>1/1440</td>
<td>7.5 $\pm$ 2.8</td>
<td>0.92</td>
<td>2.9 $\pm$ 1.5</td>
<td>0.86</td>
<td>21.2 $\pm$ 12.1</td>
<td>0.85</td>
</tr>
<tr>
<td>1/6534</td>
<td>7.4</td>
<td>1.00</td>
<td>3.0</td>
<td>1.00</td>
<td>18.7</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Face tide generate the large current amplitudes observed over the guyot. The measured $M_2$ current amplitude is two to three times greater than the $M_2$ current amplitudes previously measured in or predicted for the mid-Pacific (Fig. 4). The current-temperature phase relationships are much closer to the relationships predicted for a vertically propagating internal wave than for a surface tide (Table 2).

The baroclinic semidiurnal tidal parameters are phase-stable for the 9 months of current-meter record. This stable phase indicates that in the Horizon Guyot region, the internal tide is a narrow-banded signal. Indeed, the observations show that the $M_2$ current and isotherm deflection amplitudes are independent of bandwidth for bandwidths from 1/360 to 1/6534 cph (Table 3). The $S_2$ internal tide has a similar narrow bandwidth. The two semidiurnal frequencies are distinct enough so that a 15 day$^{-1}$ beat frequency is apparent in both the temperature and the current records (Fig. 2).

The semidiurnal internal tides are generated close to the measurement site, since the observed tidal characteristics do not correspond to those of an internal tide observed far from a generation region. In the far field, nonlinear interactions between the internal tide and the lower-frequency oceanic currents tend to broaden the internal tidal bandwidth. Observations have shown that far-field internal tides have bandwidths on the order of several cycles per month, which gives them a decorrelation time scale on the order of a month (Hendershott 1981; DeWitt et al. 1986). Temporal variability in the oceanic velocity and density fields shifts beams of internal wave energy so that an observation site in the far field usually does not remain in a stationary position relative to the beam’s energy. Dissipative processes, which damp out small spatial scales, and wave reflections from the ocean surface and bottom encourage a low-modal, rather than a vertically propagating far-field structure.

The obvious generation site for an internal tide is the guyot itself. We cannot specify an exact location, but a likely one is the abrupt change in slope at 2000 m, where the steep guyot flanks join the fairly flat guyot cap. Internal tides may be generated at this abrupt change in topography. There is evidence for enhanced currents at 2000 m; eroded terraces are found along the northwest guyot rim (Lonsdale et al. 1972) (Fig. 1). We do not expect that internal tides are generated by barotropic currents flowing over the surface of the guyot. The slope of the guyot cap is shallower, and the slope of the flanks is steeper, than the slope of the semidiurnal tidal characteristic (4°).

Strong internal diurnal tides were not observed at the measurement site. It may be that diurnal internal tides were present over the guyot but that the current meter was not near a diurnal characteristic. It is also possible that Horizon Guyot’s shape favored the generation of a semidiurnal internal wave. The Brunt–Väisälä frequency for the Horizon Guyot region is 1 cph. If one assumes that the vertical wavelength for the internal tidal current is at least double the water depth over the guyot, about 3 km, then the horizontal wavelength is 35 km, approximately equivalent to the guyot width.

4. Conclusions

These limited results suggest that large midoceanic topographic features such as seamounts and guyots can be generation sites for internal tides. Indeed, the semidiurnal internal tides generated at Horizon Guyot are larger than the barotropic tides. The stable phase and constant amplitude of the internal tidal parameters over time suggest that the internal tides are generated at a continuous, rather than an intermittent rate.

Unfortunately, the dataset is too limited for us to be able to specify parameters for the generation process. However, several features suggested by this dataset warrant further study of currents around guyots. For example, does the guyot shape favor the generation of a specific internal tidal frequency? Typically, how far does an internal tide propagate before the stable phase observed at a generation site disappears? How broad does the beam of internal tidal energy become farther away from a guyot? Since previous observations show that tidal currents in the mid-Pacific are less than 3 cm
s^{-1}, the energy in internal tides could remain tightly focused and hence be unlikely to pass through an observation site, or the energy could spread and weaken far from a guyot.

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