GEOPHYSICAL RESEARCH LETTERS, VOL. 12, NO. 12, PAGES 793-796, DECEMBER 1985

OBSERVATION AND INTERPRETATION OF THE SEAFLOOR VERTICAL ELECTRIC FIELD IN THE EASTERN NORTH PACIFIC

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Abstract. A 37 day long recording of the seafloor vertical electric field collected on the East Pacific Rise and south of the mouth of the Gulf of California is examined. The principal barotropic ocean tides are detected by regression analysis and display electric field values that yield typical open ocean water velocities of 1 cm/s or less. Spectral analysis and modeling indicate that internal wave-induced electric fields consistent with the Garrett-Munk kinematic description explain the data between the local inertial frequency of 0.033 cph and about 1 cph. At lower frequencies, a variance enhancement near 90 h period of unknown origin is also present. Low but significant coherence of the VEF with land magnetic observatory data is also demonstrated; this is probably due to motion of the electric field instrument in ambient water currents.

Introduction

Horizontal electric field (HEF) measurements are being made routinely in the deep ocean, usually in conjunction with geophysical experiments utilizing magnetotelluric sounding [e.g., Filloux, 1982]. Interpretation of the HEF in terms of water velocity is complicated by the necessity to separate the contemporaneous oceanic and external parts from the data on all time scales, and by the effects of inductive and galvanic interactions with the earth and the spatial averaging inherent in the HEF at low frequencies. Despite these difficulties, measurements of the HEF have been applied successfully to the study of oceanographic phenomena, especially transport monitoring in narrow boundary currents [Larsen and Sanford, 1985].

By use of the vertical electric field (VEF), many of the problems that occur with the HEF may be avoided. The insulating atmosphere prevents significant vertical electric currents from flowing into the ocean from the ionosphere and magnetosphere, so that the VEF is entirely of oceanic origin. Because of the large electrical conductivity contrast between sea water and rock, vertical electric current leakage into the seafloor is small, and to an excellent degree of approximation

$$E_z = -(\vec{u}_h \times \vec{F}_h)_z \qquad (1)$$

where $\vec{u}_h$ is the horizontal water velocity and $\vec{F}_h$ is the horizontal part of the geomagnetic field. This means that the VEF is a direct measure of the local geomagnetic east-west component of the water velocity on all temporal and spatial scales. Due to the nearly axially geocentric orientation of the earth's magnetic field, this corresponds closely to the zonal water velocity at all except high latitudes.

Previous work has established a technique for measuring the VEF in the deep ocean [Harvey, 1974] and demonstrated a qualitative similarity between VEF and conventional current meter measurements at long periods in equatorial waters [Harvey and Patzert, 1976]. This paper continues the development by a more quantitative examination of a single, 37 day long seafloor VEF record collected south of the Gulf of California. Spectral analysis and modeling show that ambient internal wave activity consistent with the Garrett-Munk description is dominant between the local inertial frequency (≈.033 cph) and about 1 cph. The barotropic ocean tides and a long period (≈90 h) disturbance of indeterminate origin are also prominent features of the data. A low but significant coherence of the VEF with land magnetic field observations indicates a slight coupling of the HEF into the vertical component, limiting the ultimate sensitivity of the VEF to water motion. Nevertheless, the VEF can detect moving seawater with mm/s or better precision.

Data

The VEF time series was acquired in Jan—Mar 1979 at 21°32.3'N, 109°56.1'W, near the crest of the East Pacific Rise and south of the mouth of the Gulf of California in water 3200 m deep. The data were collected as an ancillary part of ROSE (Rivera Ocean Seismic Experiment) and in conjunction with a program of seafloor magnetotelluric [Filloux, 1982] and pressure field [Filloux, 1983] measurements.

The VEF measuring package consisted of a self-buoyant, aluminum pressure case containing a digital cassette recorder and associated electronics and was anchored to the seafloor on a meter-long tether. An insulated cable was floated over the instrument and connected to silver-silver chloride electrodes at about 4 m and 161 m above the bottom. The potential difference between the electrodes was recorded $2^7 = 128$ times per hour with a least count sensitivity of 0.00488 μV/m; this corresponds to a geomagnetic east-west water velocity of 0.0162 cm/s averaged over the interelectrode spacing of 157 m.

Figure 1 shows a 5.5 day section (equivalent to ≈4 inertial periods) of the VEF data, along with simultaneous measurements of the north magnetic and east electric fields from a site less than 1 km distant. These

Paper number 5L6719
0094-8276/85/005L-6719$03.00

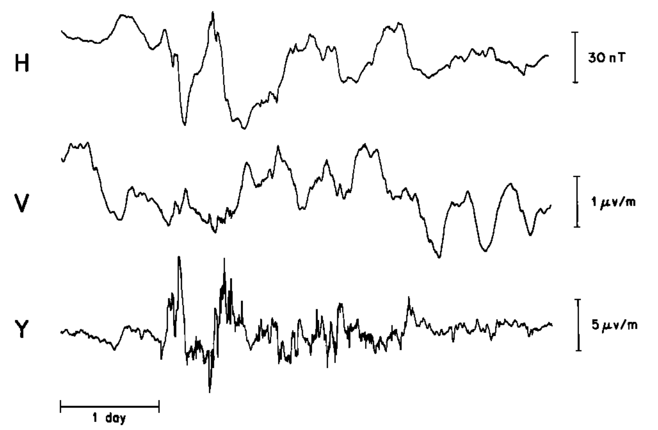

Fig. 1. A 5.5 day section (equivalent to 4 inertial periods) of the vertical electric field (V) starting at 0000 UT on 19 Feb 1979 compared to simultaneous sections of the north magnetic field (H) and east electric field (Y) collected at a nearby seafloor site. The scales are indicated by the tic marks.

components were chosen for comparison because they contain most of the variance in the horizontal fields. Geomagnetic activity was quite high during this time, but the impulsive signature of a magnetic storm is obvious only in the horizontal electromagnetic fields. By contrast, the VEF data are dominated by diurnal and semidiurnal tidal elements, inertial oscillations, and a lower amplitude, higher frequency constituent due to internal waves, as will be demonstrated.

In order to establish the oceanic origin of the periodic variations that characterize the VEF data, sinusoids with the known frequencies of the principal tides were fit to the time series. Since the sensitivity of conventional least squares regression to a small fraction of statistically inconsistent data (outliers) is well known, a robust regression procedure [Huber, 1981] utilizing iteratively reweighted least squares was employed. This automatically minimizes the influence of outliers and ensures that the regression residuals have zero mean and are uncorrelated, as is required by the Gauss-Markov theorem to yield an unbiased estimate of the line parameters. Due to the short length of the record, attempts to resolve closely spaced tidal components (e.g., P_1 and K_1, which differ by 1 cycle per sidereal year from 1 cycle per day) were not successful, and in those instances only the member with the larger contribution to the astronomical driving potential was retained. Table 1 lists the tide parameters by species, including the VEF amplitude, the phase referenced to 0000 UT 1 Jan 1979, single sided 95% confidence limits based on normal statistics, and the equivalent geomagnetic east-west (≈zonal) water velocity computed from (1). The largest component is the lunar semidiurnal (M_2) tide with a velocity of about 1 cm/s, typical of the open ocean barotropic tide, followed by substantial contributions from K_1, M_1, Q_1, and S_2. No coherent energy could be detected at the harmonics of the solar daily variation of ionospheric origin which dominates both the HEF and its magnetic counterparts. The tide removal procedure reduced the data variance from 0.394 $(\mu V/m)^2$ to 0.305 $(\mu V/m)^2$, a change of about 23%.

Spectral Analysis and Discussion

The regression residuals were decimated to 8 samples per hour for subsequent analysis. After prewhitening with a five term autoregressive filter, a power spectrum of the entire time series was computed using the multiple prolate expansion method proposed by Thomson [1982], and appears as Figure 2. The data series is windowed separately with members of a family of discrete prolate spheroidal sequences and Fourier transformed to yield raw spectral estimates, called eigenspectra. The orthogonality of the data windows ensures independence of the eigenspectra. Statistical consistency is achieved by data adaptive averaging of the individual spectra using a minimum broadband bias (spectral leakage) criterion. This results in correlations in the final spectrum over a region of $O(T^{-1})$ in width, where T is the length of the time series. This bandwidth is a free parameter, and the variance of the spectrum is reduced as it is increased at the obvious penalty of reduced frequency resolution, assuming that the bias does not also rise. The final spectrum is characterized by low bias due to the use of optimal data windows and adaptive smoothing, yet the statistical efficiency is quite high, in contrast to more conventional band averaged estimates. Further details may be found in Thomson [1982].

Table 1. Tidal Line Fit

Species	Period (hr)	Amplitude (μV/m)	% Error	Phase	Uncertainty	Zonal Velocity (cm/s)
Q_1	26.868356	0.0829	5.0	152.8	2.8	0.27
O_1	25.819341	0.0482	8.7	71.3	5.0	0.16
M_1	24.833248	0.0950	4.4	−67.7	2.5	0.31
K_1	23.934469	0.244	1.7	−127.3	1.0	0.81
J_1	23.098477	0.0554	7.4	−93.2	4.2	0.18
N_2	12.658348	0.0277	14.8	75.0	8.5	0.09
M_2	12.420601	0.305	1.4	−72.2	0.8	1.01
S_2	12.000000	0.0692	5.8	−49.5	3.3	0.23

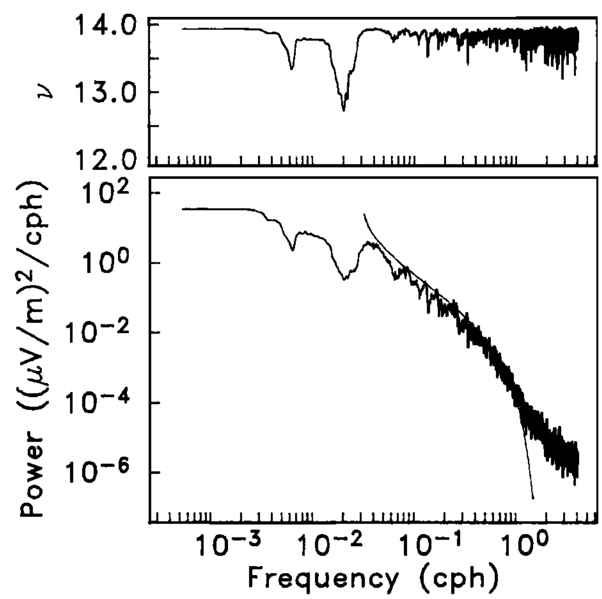

Fig. 2. The power spectral density (bottom) for the vertical electric field data after removal of the tidal contribution computed using the multiple prolate window method described in the text with a time-bandwidth product of 4 and 7 eigenspectra. The data were padded with zeroes to avoid circular convolutions during processing, so the lowest frequencies are not significant. The solid line is the model spectrum for internal waves consistent with the Garrett-Munk description. The top plot shows the equivalent degrees of freedom in the spectrum after data adaptive weights were applied.

The solid line in Figure 2 is a model spectrum for the VEF produced by ambient internal waves that is based on the Garrett-Munk kinematic description, as discussed in Chave [1984]. The model is constructed by combining a numerical vertical normal mode expansion of the internal wave field using the exponential Brunt-Väisälä profile suggested by Garrett and Munk [1972] with a set of Green functions for the electromagnetic field. Agreement of the predicted internal wave spectrum with the observations is excellent, except for a possible deficit in power near the inertial frequency. In particular, the computed spectrum of Figure 2 is approximately χ^2_{14} distributed, yielding an uncertainty of about a factor of 2 in power, while the parameters of the Garrett-Munk spectrum are only known with a similar accuracy, and the small differences between observation and model are not significant. This suggests that oceanic internal waves are the dominant source of VEF fluctuations between the inertial frequency and about 1 cph outside of the tidal bands.

It is more difficult to make quantitative assertions about the VEF spectrum at lower (sub-inertial) frequencies due to the short record length. The unknown effect of instrument drift limits the usefulness of the data at the longest periods; this will be eliminated in future experiments by the use of electrode chopping techniques [Filloux, 1974]. There is little evidence for residual variance enhancement in the semidiurnal band (≈0.07–0.09 cph) in Figure 2, suggesting limited tidal baroclinicity, although diurnal baroclinic tides could be present but indistinguishable from the broad inertial peak. A significant concentration of variance at about 0.01 cph is also apparent. The width of this feature is controlled by the correlation properties of the multiple window estimator, and it could in reality represent a fairly narrow band disturbance. Integrating the variance spectrum over the peak yields an equivalent water velocity of about 0.5 cm/s. In the absence of independent oceanographic data from the area, the origin of this low frequency spectral bump cannot be inferred unambiguously. It should be noted that Filloux [1983] observed intensification in the same frequency band in a single nearby seafloor pressure recording. No significant coherence could be obtained between the VEF and pressure field near 0.01 cph, but dynamical arguments suggest that correlation of the pressure gradient (which is not known) with the water current measured by the VEF would be expected. The spectral bump is clearly of oceanic origin; a similar feature is not observed in any of the nearby seafloor HEF or magnetic field data, nor is it present in the spectra of contemporaneous land magnetic observatory time series. Possible causes include topographically-trapped waves on the East Pacific Rise or along the North American coast and the basin-wide, barotropic oscillation of the Pacific observed at about the same period by Luther [1982].

At the highest frequencies, the spectrum of Figure 2 displays an abrupt decrease in slope. This cannot be attributed to internal waves, as the seafloor horizontal velocity from that source decreases rapidly as the

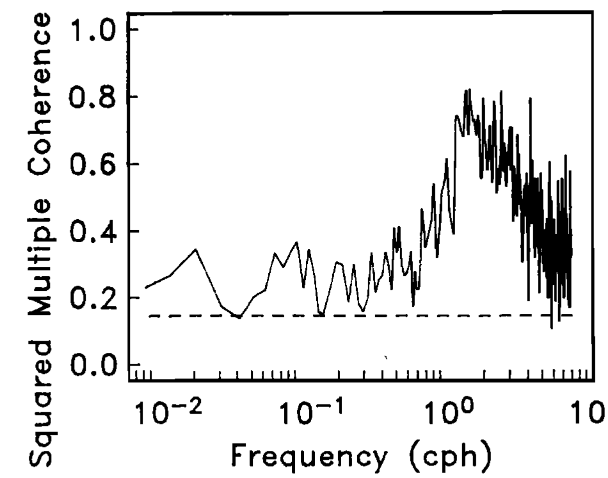

Fig. 3. The squared multiple coherence of the vertical electric field with all three magnetic field components at the standard observatories in Honolulu, HI and Tucson, AZ. The coherence has about 25 independent estimates at each point, and adjacent frequencies are partially correlated due to the data window used in the processing. The dashed line is the 95% significance level for zero true coherence.

Brunt-Väisäla frequency is approached. While benthic boundary layer processes are a possible explanation, the BBL is poorly developed in the eastern Pacific [Hayes, 1980], and an alternate cause is sought.

Standard three-component magnetograms with a time resolution of 1 cm/hr and synchronous with the seafloor VEF data were collected for the magnetic observatories at Tucson, AZ and Honolulu, HI. The paper records were digitized at approximately 1 mm intervals and interpolated to 8 samples per hour using a taut cubic spline. The squared multiple coherence of the VEF time series with all three magnetic field components at Tucson and Honolulu was computed and appears as Figure 3. The estimate was calculated using section averaging after windowing four day blocks of data with a prolate spheroidal taper of time-bandwidth product 4 and 70% overlap between pieces, yielding about 25 independent estimates at each frequency. The resulting coherence is fairly low (≈ 0.25) at frequencies below 0.6 cph, rises to a peak at about 1.5 cph, and falls off slowly toward the Nyquist frequency.

To assess the meaning of the coherence at the longer periods where it is small, it is important to attach a significance level to the estimate. While a number of empirical tests exist, it is not difficult to derive an exact test from the probability density function (pdf) for the squared coherence. The pdf for the sample coherence $\hat{\gamma}^2$ given that the true coherence γ^2 is zero is [Carter and Nuttall, 1971]

$$f(\hat{\gamma}^2|\gamma^2=0;\nu) = (\frac{\nu}{2}-1)(1-\hat{\gamma}^2)^{\frac{\nu}{2}-2} \quad (2)$$

where $\nu = 2(n-p)$ is the number of degrees of freedom given the number of spectral estimates n and the number of input time series p used in the analysis. The desired critical value C of the coherence satisfies

$$p[\hat{\gamma}^2 \leq C] = \alpha = \int_0^C dx f(x|\gamma^2=0;\nu) \quad (3)$$

at the 100α% confidence level. This yields

$$C = 1 - (1-\alpha)^{\frac{2}{\nu-2}} \quad (4)$$

and is shown as the dashed line in Figure 3 for $\alpha = .95$. It is obvious that there is a low but significant coherence of the VEF with the externally-induced electromagnetic field, as measured by the observatory data. The coherence rises above 1 cph because the masking effect of internal wave-induced electric fields vanishes. Since the spectrum of the HEF is 1–2 decades larger than that of the VEF above 0.1 cph and comparable in size below this, a slight instrument tilt out of the vertical by a few degrees would explain the correlation. This could be caused by motion of the moored VEF instrument in ambient water currents. The observed lack of coherent energy in the solar daily variation and its harmonics indicates that the package did not have a consistent orientation and moved in the horizontal plane.

Scaling the spectrum of Figure 2 by a factor of 11 converts it to geomagnetic east-west or (nearly) zonal water velocity in $(cm/s)^2$/cph. In spite of the contamination of the VEF by the HEF, this gives a noise level of about 10^{-4} $(cm/s)^2$/cph, substantially better than is obtained with mechanical current meters. The VEF is also free of the rotor stalls which plague current meters in the absence of a mean flow.

Acknowledgments. This work was supported by National Science Foundation Grant OCE83-08595.

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(Received October 2, 1985;
accepted October 14, 1985.)