

# Electromagnetic induction by ocean currents: BEMPEX

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The theory of electromagnetic induction by ocean water currents is reviewed using a modal formulation, with an emphasis on interactions of the induced fields with the conducting Earth and on their association with distinct, dynamically significant parts of the water velocity field. It is shown that the dominant electromagnetic mode at low frequencies ( $< 1 \text{ cycle d}^{-1}$ ) is the toroidal magnetic type, in which the electric currents flow in planes containing the vertical. This means that the electrical conductivity structure of the oceanic lithosphere can profoundly influence low-frequency motional electromagnetic fields, and subsequent oceanographic interpretations of them. Such effects are minimized if the upper oceanic lithosphere contains a resistive layer; there is increasing evidence for a low-conductivity zone under the deep ocean basins.

A recent, major experiment to study the low-frequency variability of the ocean using electromagnetic induction principles is described. Denoted by the acronym BEMPEX for Barotropic ElectroMagnetic and Pressure EXperiment, this effort involves 41 seafloor magnetometers, horizontal and vertical electrometers, and pressure recorders covering an area 1100 km east–west by 1000 km north–south in the North Pacific for 11 months. The major oceanographic objectives of BEMPEX are multifold, and include a description of the wind-forced barotropic variability of the deep ocean, studies of the frequency–wavenumber characteristics of certain oscillations of basin-wide scale, and tests of predictions from existing models of wind-forcing.

## 1. Introduction

Electromagnetic fields are induced in the conducting oceans and Earth by external, ionospheric and magnetospheric, electric current systems flowing  $10^2$ – $10^5$  km above the surface and by the dynamo action of moving seawater cutting across the Earth's stationary magnetic field. The gross spatial and temporal morphology of the former is reasonably well understood, and the fluctuating electromagnetic fields that external currents pro-

duce at the Earth's surface can be characterized and classified. Magnetospheric fields have been used for studies of the Earth's conductivity structure by either the geomagnetic depth sounding or the magnetotelluric method for many decades, and these techniques have recently been extended to the seafloor environment.

By contrast, motionally induced electromagnetic fields are less well understood, primarily owing to the complexity of the oceanic velocity field and to a paucity of observations covering the long (days–months) periods where most of the ocean's variability is concentrated. Studies of motional electromagnetic induction in the oceans have

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largely been confined to short-period phenomena, especially the barotropic tides, surface gravity waves, and internal waves (e.g., Larsen, 1968; Chave, 1984). However, recent work has demonstrated that electric field measurements using seafloor cables that span intense, localized streams such as the Florida Current can be interpreted in terms of transport to yield unique time sequences of low-frequency oceanic variability (Sanford, 1982; Larsen and Sanford, 1985). Electric field data contain information about the barotropic (depth-independent) motions of the ocean that is difficult to obtain using conventional oceanographic tools. As a result, there is increasing interest in applying electromagnetic methods to large-scale, low-frequency oceanographic studies (Sanford, 1986), and results are now beginning to appear (Lilley et al., 1986).

In this paper, the theory of motional electromagnetic induction is reviewed, with the emphasis on interaction of the induced fields with the conducting Earth and on their association with distinct, dynamically significant parts of the water velocity field. The theory is used to motivate the application of electromagnetic induction techniques to oceanographic problems. The paper concludes with a description of the experimental and scientific goals of a major, ongoing experiment to study low-frequency barotropic variability of the ocean, as well as the conductivity of the lithosphere, that is based in part on electromagnetic principles. This study, called BEMPEX for Barotropic ElectroMagnetic and Pressure EXperiment, involves a large horizontal array of 41 seafloor instruments that has been deployed in the North Pacific for 1 yr beginning in the summer of 1986.

## 2. Motional electromagnetic induction

The governing equations for motional electromagnetic induction are those of Maxwell in the quasi-static limit, in which the magnetic effects of displacement currents are neglected

$$\nabla \cdot \mathbf{B} = 0 \quad (1)$$

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0 \quad (2)$$

$$\nabla \times \mathbf{B} - \mu_0 \sigma \mathbf{E} = \mu_0 \mathbf{J}^0 \quad (3)$$

The symbols have their usual meaning, the magnetic permeability is assumed constant, and the source electric current is

$$\mathbf{J}^0 = \sigma(\mathbf{v} \times \mathbf{F}) \quad (4)$$

where  $\mathbf{v}$  is the water velocity which is allowed to vary in all three spatial dimensions and  $\mathbf{F}$  is the static, sourceless geomagnetic field. If (4) is used in (3), then  $\mathbf{E}$  is the electric field in a reference frame fixed to the Earth.

Solutions of (1)–(4) can be found using a Mie representation for the magnetic field (Chave, 1984)

$$\mathbf{B} = -\nabla_h^2 \Psi \hat{z} + \nabla_h \partial_z \Psi + \nabla \times (\Pi \hat{z}) \quad (5)$$

where  $\Psi$  and  $\Pi$  are scalar functions which represent poloidal magnetic (PM) and toroidal magnetic (TM) modes respectively. The source current is also written in terms of scalar functions

$$\mathbf{J}^0 = \Xi \hat{z} + \nabla_h T + \nabla \times (\Gamma \hat{z}) \quad (6)$$

where  $T$  and  $\Gamma$  satisfy the Poisson equations

$$\nabla_h^2 T = \nabla_h \cdot \mathbf{J}^0 \quad (7)$$

$$\nabla_h^2 \Gamma = -(\nabla_h \times \mathbf{J}^0) \cdot \hat{z} \quad (8)$$

If the electrical conductivity is assumed to vary only with the vertical co-ordinate, then uncoupled differential equations for  $\Psi$  and  $\Pi$  can be obtained

$$\nabla^2 \Psi - \mu_0 \sigma \partial_t \Psi = -\mu_0 \Gamma \quad (9)$$

$$\begin{aligned} \nabla_h^2 \Pi + \sigma \partial_z (\partial_z \Pi / \sigma) - \mu_0 \sigma \partial_t \Pi \\ = -\mu_0 \Xi + \mu_0 \sigma \partial_z (T / \sigma) \end{aligned} \quad (10)$$

where the electric field is given by

$$\begin{aligned} \mathbf{E} = -\frac{1}{\sigma} (\nabla_h^2 \Pi / \mu_0 + \Xi) \hat{z} + \frac{1}{\sigma} \nabla_h (\partial_z \Pi / \mu_0 - T) \\ - \nabla \times (\partial_t \Psi \hat{z}) \end{aligned} \quad (11)$$

There are conditions on the scalar functions in (5) and (6) given by Backus (1986) for a spherical geometry; these are readily extended to the planar situation used here. Independence of the PM and TM modes is assured because the boundary conditions from (5) and (11) are uncoupled.

The concept of PM and TM modes is important both because of the very different ways in which they interact with conducting media and because of their intimate association with distinct

parts of the water velocity field. The PM mode involves no vertical electric component, and its associated electric current systems are everywhere parallel to the Earth's surface, as seen in (6) and (11). Coupling of oceanic PM mode fields with the conducting Earth occurs purely by induction, and the fields vanish in the limit of zero frequency. The TM mode includes no vertical magnetic component, and its associated electric current systems flow in planes containing the vertical. Coupling of oceanic TM mode fields with the underlying Earth occurs both conductively and inductively, and the effects do not disappear at low frequencies. The TM mode is quite sensitive to the presence of low conductivity zones within the Earth, especially near its surface, whereas PM mode currents couple inductively across such regions.

The different behavior of the two modes in the presence of resistive upper mantle structure may be important if the recent controlled source measurements of Cox et al. (1986) prove to be typical of mature oceanic lithosphere away from tectonic complications such as mid-ocean ridges or transform faults. As will be shown, the TM mode is dominant at sub-inertial frequencies (roughly,  $\leq 1$  cycle  $d^{-1}$ ). If the upper oceanic lithosphere is resistive ( $< 10^{-4}$  S  $m^{-1}$ ) over horizontal distances of order the scale length of the oceanic disturbances that generate  $\mathbf{v} \times \mathbf{F}$  electric currents, then the TM mode cannot leak appreciably from the ocean, and in situ measurements do not need large corrections for nonlocal conductive effects. The typical scale of low-frequency barotropic flow is  $\sim 1000$  km, and little is known about lateral variations of conductivity in the upper oceanic lithosphere on this scale. However, if the upper lithosphere were resistive over distances  $\gg 1000$  km, then the electrostatic fields of boundary electric charges on the continent-ocean contact would be appreciable everywhere in the ocean basins, and this effect is not prominent in existing magnetotelluric data (Chave and Cox, 1983). This suggests that high-conductivity pathways exist within the oceanic lithosphere, probably at the mid-ocean ridges where hot rock is very close to the seafloor or at the continental margins where high-conductivity pore fluids are present. The influence of mutual induction and conduction on motional

electromagnetic fields depends critically on the scales of the water flow and that of lateral heterogeneity of conductivity. Because details of the conductivity structure of the oceanic mantle are not well established, the importance of interactions of oceanic electromagnetic fields with the Earth is also poorly understood, although a few measurements suggest only a small ( $\approx 10\%$ ) effect on the electric field (Sanford, 1986). This underscores the importance of carrying out geophysical experiments to determine the conductivity of the mantle in conjunction with electromagnetic experiments to measure the water velocity field.

From (6), (9) and (10), the PM mode is driven by the non-divergent part of the source electric currents which flow in closed horizontal loops, while the TM mode is driven by vertical electric currents and the horizontally divergent part of the source. The decomposition (6)–(8) can be expanded for motional induction problems by using simple vector identities and (4). If the ocean conductivity is assumed to be constant ( $\sigma_0$ ), then  $\Xi$  and (7) and (8) reduce to

$$\Xi = \sigma_0(\mathbf{v}_h \times \mathbf{F}_h) \quad (12)$$

$$\begin{aligned} \nabla_h^2 T = & \sigma_0(\nabla_h \times \mathbf{v}_h) \cdot F_z \hat{z} + \sigma_0(\nabla_h \times v_z \hat{z}) \cdot \mathbf{F}_h \\ & - \sigma_0[(\nabla_h \times \mathbf{F}_h) \cdot v_z \hat{z} + (\nabla_h \times F_z \hat{z}) \cdot \mathbf{v}_h] \end{aligned} \quad (13)$$

$$\begin{aligned} \nabla_h^2 \Gamma = & \sigma_0(\nabla_h \cdot \mathbf{v}_h) F_z - \sigma_0(\mathbf{F}_h \cdot \nabla_h) v_z \\ & + \sigma_0[(v_h \cdot \nabla_h) F_z - (\nabla_h \cdot \mathbf{F}_h) v_z] \end{aligned} \quad (14)$$

There are three types of terms on the right-hand sides of (13) and (14); one involves derivatives of the horizontal velocity field, the second contains derivatives of the vertical velocity field, and the last comprises spatial variations of the geomagnetic field. Considerable simplification results if two characteristics of the real ocean are noted: the vertical velocity of sub-inertial flow is small compared with the horizontal component, and the ratio of vertical to horizontal scale lengths is typically  $10^{-2}$  or less. The first of these conditions means that the second terms in (13) and (14) may be neglected relative to the first. The relative importance of the first and last terms in the equations may then be assessed by scale analysis using

an axial geocentric dipole approximation for  $\mathbf{F}$ ; this shows that the effect of geomagnetic spatial variations is small for hydrodynamic scales under a few thousand kilometers at mid-latitudes. Then, the PM mode is associated with the horizontally divergent part of the water velocity field, while the TM mode is connected with the vertical component of fluid relative vorticity and vertical source currents. However, vertical source currents have a scale comparable with the water depth, while those described by  $T$  have the horizontal scale of the ocean flow. Their ratio is comparable with the aspect ratio of the flow, hence vertical currents are unimportant. This means that the TM mode is intimately associated with Coriolis deflection of moving water on the rotating Earth, and will be important at periods where Coriolis effects on the ocean dynamics are dominant. In addition, low-frequency, large-scale ocean flows are nearly horizontally non-divergent (Gill, 1982), so the source for the PM mode is small at low frequencies and large spatial scales. These effects justify the assertion made earlier about the predominance of the TM mode at long periods. Note that only the local vertical component of the geomagnetic field enters the induction problem under these approximations. Figure 1 gives a conceptual picture of the source mechanisms for the two modes.

A complete view of motional electromagnetic induction can be obtained using the Green function solutions of (8) and (9) for a flat-bottomed ocean of infinite extent given in Chave (1984). These are complicated expressions involving a Fourier wavenumber expansion at each frequency and including conduction and induction effects through modal reflection coefficients. The solutions for (8) and (9) may be written

$$\hat{\Psi} = -\mu_0 \int_{-H}^0 dz' g_\psi(z, z') \hat{\Gamma}(z') \quad (15)$$

$$\hat{\Pi} = -\mu_0 \int_{-H}^0 dz' g_\pi(z, z') \hat{\Xi}(z') - \mu_0 \int_{-H}^0 dz' \partial_z g_\pi(z, z') \hat{T}(z') \quad (16)$$

where  $g_\psi$  and  $g_\pi$  are the Green functions, the circumflex accent denotes the spatial Fourier transform, and  $H$  is the water depth.

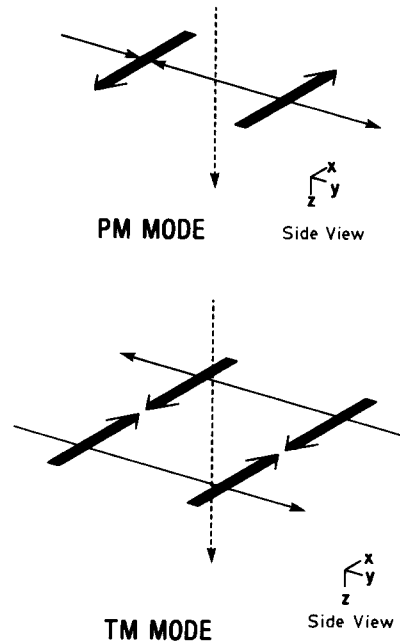


Fig. 1. Sketch showing the modal source mechanisms for low-frequency, large-scale oceanic flows. The dashed line shows the vertical component of the geomagnetic field, while the solid line denotes the water velocity, and the double line is the source E.M.F. The top part of the figure depicts a side view of a velocity field with horizontal divergence, such as occurs in gravity waves with displacement of the sea surface. The source currents flow in horizontal loops in alternate directions along peaks and troughs of the wave-like disturbance, closing at infinity. The bottom part of the figure shows a plan view of a velocity field with relative vorticity. The induced electric currents are horizontally divergent, cannot penetrate the sea surface, and so dive down into the Earth.

The electric field follows from (11), and consists of two terms: one involves the velocity field at the measurement point from (12)–(14) and the other involves non-local current leakage effects through (15) and (16). For the vertical electric field, the former completely dominate the latter, and vertical electric measurements give the local water flow; this is the magnetic east component of the water velocity, and corresponds closely to the zonal water velocity at mid-latitudes owing to the nearly axial nature of the geomagnetic field. Chave and Filloux (1985) and Bindoff et al. (1986) interpret vertical electric field measurements in terms of zonal water flow. The situation is more complicated for the low-frequency horizontal electric

field than is immediately apparent. By careful examination of the Green functions and (11), it can be shown that the seafloor horizontal electric field is a vertical integral of the horizontal water velocity plus an error term due to current leakage into the seafloor. Sanford (1971) has used a different approach to demonstrate that the horizontal electric field is actually a seawater conductivity-weighted, vertical integral of the water velocity plus a current leakage error term. In either case, the horizontal electric field gives a direct measurement of transport, a quantity which is difficult and expensive to determine using conventional oceanographic tools.

Actual measurements of low-frequency electromagnetic fields in the ocean will contain components due to motional induction and a part due to ionospheric sources. These can be separated by correlation techniques using remote electric and magnetic instruments if the ionospheric component is of broad spatial extent and does not

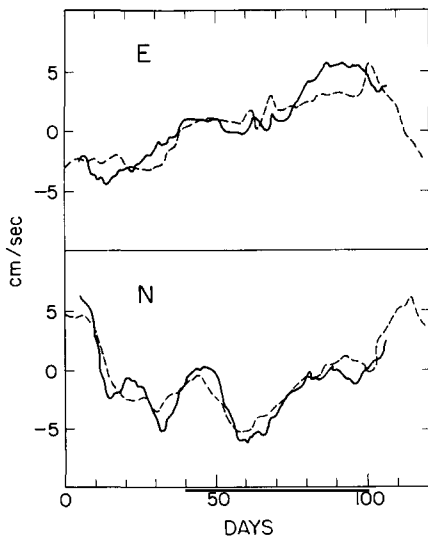


Fig. 2. Low-pass filtered seafloor measurements of the water velocity inferred from the horizontal electric field (solid line) obtained during the Mid-Ocean Dynamics Experiment (e.g., Richman et al., 1977) in the eastern North Atlantic in 1973. No correction has been applied for either ionospheric contamination of the data or current leakage into the seafloor, and the electric field  $\mathbf{E}$  is assumed to equal  $-\mathbf{v}_h \times F_z \hat{\mathbf{z}}$ . The dashed line is the local water current estimated by Freeland and Gould (1976) from SOFAR float data (after Cox et al., 1980).

dominate the oceanic part. Larsen and Sanford (1985) found the externally induced fraction of the Florida Current data to constitute less than half of the total variance at periods  $> 1$  day, and other measurements suggest that deep ocean electric field data are dominated by the oceanic part at long periods. This implies that seafloor electric field data can be used to measure ocean transport with minimal difficulty. Figure 2 compares the barotropic velocity inferred from horizontal electric field measurements with the directly measured water velocity in the western North Atlantic. The effect of external field contamination on the seafloor magnetic field is less clear, and a test of the utility of motional magnetic fields for oceanography is a goal of BEMPEX.

### 3. BEMPEX

At sub-inertial frequencies, much of the deep ocean's variability is believed to be due to barotropic (depth-independent) fluctuations, especially (but not exclusively) in regions devoid of intense mean currents such as the Gulf Stream and the mesoscale ( $\sim 100$  km) eddies that are common in the western half of most ocean basins. The atmosphere, through direct forcing by surface wind stress, is probably the dominant energy source for this barotropic field, but such an assertion has been difficult to prove experimentally. This is both because a multiplicity of free waves on many temporal and spatial scales can be generated throughout the ocean, reducing the apparent correlation between local oceanic and atmospheric fields, and because extensive conventional instrumentation is required to separate the barotropic from the background baroclinic (depth-dependent) field. However, at sub-inertial frequencies, bottom pressure is dominated by the barotropic field, and the horizontal electric field has been shown to be a vertical average of the horizontal water velocity, accentuating barotropic flow and averaging out (in a rough sense) the baroclinic component. These observations, together with the well-known utility of external-source electromagnetic data for inferring the electrical conductivity of the Earth, led to the design of a major experi-

ment with the dual purposes of estimating the properties of certain barotropic flows and probing the structure of the upper mantle. The acronym BEMPEX has been coined to describe this study.

Over the past three decades, oceanographic experiments designed to study sub-inertial motions in the deep ocean have emphasized measurements from locations with the most energetic fluctuating or mean currents (e.g., the Gulf Stream). The necessity of such an approach is undeniable in view of the prior lack of descriptive knowledge of the ocean's current regimes. However, this complicates subsequent discrimination of the dynamical processes in data sets because the fluid motion

is highly energetic and non-linear. In particular, a strong baroclinic field often dominates the much weaker barotropic field in energetic parts of the ocean. For this reason, BEMPEX involves the study of a region of the ocean where reasonable hypotheses of the dominant physical processes suggest a strong barotropic response to wind-forcing. The particular experimental region (Fig. 3) was chosen because it has weak eddy kinetic energy levels (Cheney et al., 1983), only a few sources for sub-inertial fluctuations, and linear, viscous dynamics should be predominant at sub-inertial frequencies. Since there is strong observational (Niiler and Kobalinsky, 1985) and theoretic-

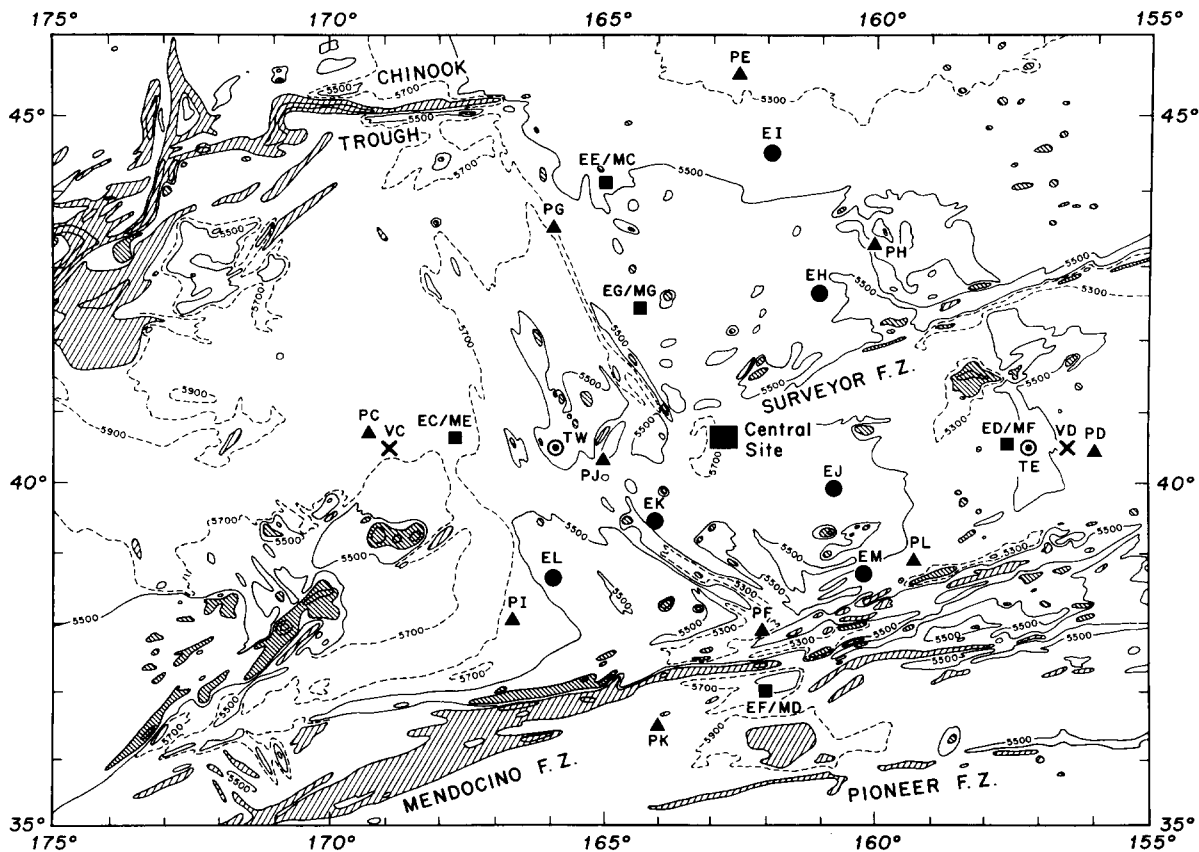


Fig. 3. Bathymetric map showing the BEMPEX array and selected contours from the Mammerickx and Smith (1984) chart of the North Pacific.  $\square$  = regions deeper than 6000 m, while  $\boxplus$  = regions shallower than 5000 m; the average depth in the area is  $\sim$  5500 m. The symbols indicate the locations of the electromagnetic and pressure instruments in the main part of the array, with  $\times$  denoting vertical electrometers,  $\bullet$  denoting horizontal electrometers,  $\blacktriangle$  denoting pressure recorders, and  $\blacksquare$  denoting horizontal electrometer–three-component magnetometer pairs.  $\odot$  shows the sites of acoustic tomography moorings, while the central site is detailed in Fig. 4.

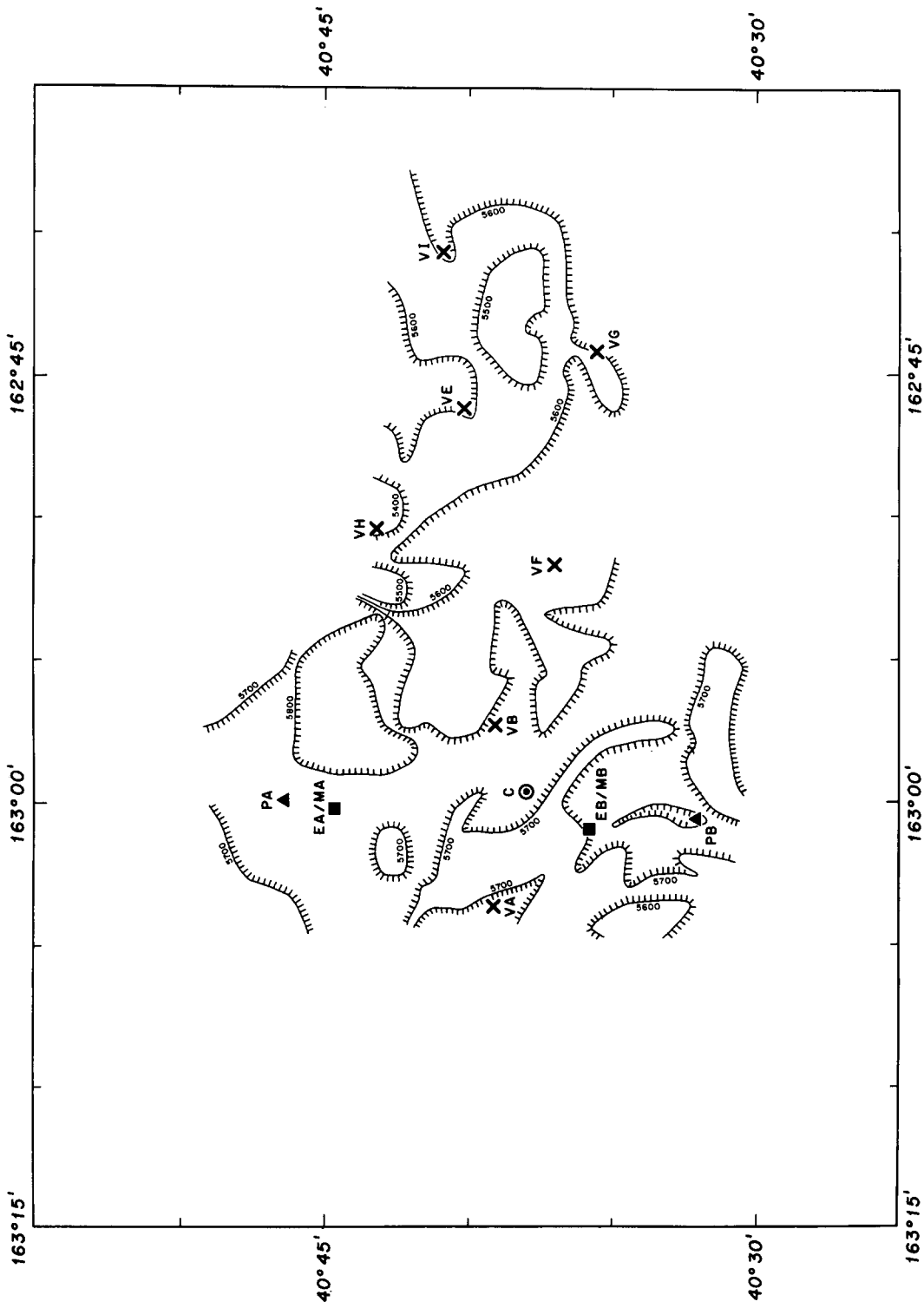


Fig. 4. Bathymetric map of the central site shown on Fig. 3 and the locations of the central cluster instruments. The symbols are as defined in Fig. 3, and C denotes a single oceanographic mooring containing six current meters and two temperature-pressure recorders. Depth contours are in uncorrected meters compiled from shipboard soundings.

cal (Frankignoul and Müller, 1979; Willebrand et al., 1980) evidence to suggest that direct atmospheric forcing will be the dominant source of energy at the spatial and frequency scales that can be resolved, the results of BEMPEX should have a wider range of applicability than simply regions of low eddy noise. It will also serve as a proving ground for electromagnetic techniques as an oceanographic tool.

The major oceanographic objectives of BEMPEX are multifold, and a complete description is contained in Luther et al. (1987). A summary would include

(1) the description of the variability of the pressure and oceanic part of the electromagnetic field that can be identified as being either locally or atmospherically forced or the result of disturbances propagating from distant sources;

(2) the determination of the amplitude and wavenumber characteristics of specific, known barotropic oscillations of basin-wide scale, including the long-period (14 and 28 days) tides and a 4–6 day planetary oscillation of the Pacific noted by Luther (1982);

(3) an investigation of the consequences of geostrophy and the testing of predictions from existing models of wind-forcing;

(4) the study of several high-frequency barotropic gravity wave phenomena, including basin-wide modes at periods near 1 cycle  $d^{-1}$ ;

(5) intercomparison with other oceanographic measurements in the area; and

(6) a detailed assessment of the role which electromagnetic data can play in oceanographic research.

The emphasis of BEMPEX is on obtaining high-quality estimates of the frequency–wavenumber structure of a variety of oceanic flows; this type of information is extremely difficult to obtain from more conventional experiments, yet is fundamental to the understanding of ocean dynamics. Because a large number of instruments can be deployed at relatively low cost, electromagnetic and pressure measurements are ideally suited to wavenumber studies.

While oceanic sources are expected to dominate at sub-inertial periods, at least for the electric field, considerable information about the electrical

structure of the BEMPEX region should be available from magnetotelluric and geomagnetic depth sounding analyses of the data at frequencies above 1 cycle  $d^{-1}$  and by comparing the amplitudes and phases of tidally generated electromagnetic fields with predictions from global ocean tide models. The former should provide especially high-quality information because of the size of the BEMPEX array and the availability of multiple remote reference sites. The tidal induction method is proving to be a new and viable way to get averages of the conductivity in the uppermost mantle over large horizontal areas; this is a region which is not generally accessible to external-source sounding methods in the ocean. The importance of the conductivity in this region to the interpretation of motional electromagnetic fields has already been emphasized.

Figure 3 shows the layout of the BEMPEX array superimposed on large-scale bathymetric contours. A total of 41 seafloor instruments were placed in an array  $\sim 1100$  km east–west by 1000 km north–south centered at  $40.5^\circ$  N,  $163^\circ$  W in the Pacific Ocean north of Hawaii. The breakdown of instrument types deployed is 12 pressure recorders, 13 horizontal electrometers, nine vertical electrometers, and seven three-component magnetometers. A second group of two magnetometers and a single horizontal electrometer was set near  $31^\circ$  N,  $159^\circ$  W as a remote reference site. Additional terrestrial remote reference data will be provided by a digital instrument emplaced in Eugene, Oregon, and by the standard geomagnetic observatories at Honolulu, Tucson, and Fresno. Figure 4 shows a detailed view of the central site, in which a dense cluster of instruments was placed for redundancy and a conventional oceanographic mooring with six vector measuring current meters and two temperature–pressure recorders was deployed for comparison purposes and monitoring of the ambient baroclinic field. All of the seafloor instruments, which are based on a proven design that has been used repeatedly for over a decade (Filloux, 1987), will record for 11 months (July 1986–June 1987) at sampling rates of 16–32 times per hour.

Choice of the experimental location was motivated by the oceanographic considerations sum-



marized above, and especially by observations of a barotropic response to wind-forcing during the winter (Niiler and Koblinsky, 1985). Historic weather data suggest that frequent, intense storms will occur throughout the area, maximizing the size of the barotropic signal in the data. High-amplitude, small-scale bathymetry can introduce new scales into the water current field, reducing inter-sensor coherence, while high-amplitude, large-scale bathymetry can dominate the barotropic dynamics. The region shown in Fig. 3 minimizes topographic problems, insofar as that is possible in the real ocean.

The actual location of the instruments was motivated by a number of oceanographic factors. The largest dimensions had to be adequate to observe the phase propagation of large-scale disturbances such as the long-period and short-period tides. Small instrument separations were used in the center of the array (Fig. 4) both for redundancy and to estimate noise levels. Dynamical considerations require that current-measuring devices (e.g., horizontal electrometers) be placed between pressure recorders. An overwhelming consideration was that each of the array elements be coherent with at least one nearby element at the frequencies of interest. This is a trivial requirement for the pressure recorders, based on the observed coherence lengths of 500 km or more in earlier experiments (e.g., Brown et al., 1975). For the water current fields measured by the electrometers, the coherence scale is less clear. In the presence of a strong baroclinic field, the coherence scale of single point measurements will be only a few tens of kilometers at mid-latitudes (Richman et al., 1977). The dense array of vertical electrometers seen in Fig. 4 was designed to study the extent of baroclinicity at the central site. However, theoretical studies suggest that wind-forced, barotropic, horizontal currents in the absence of topography will be coherent over distances of hundreds of km (Willebrand et al., 1980). For this reason, the horizontal electrometers were placed at a variety of spacings covering the range of 100–1000 km. The magnetometers were placed close to the horizontal electrometers to aid in the discrimination of external source field heterogeneity.

#### 4. Conclusions

The theory of electromagnetic induction by ocean currents has been reviewed with the intent of motivating the use of electromagnetic principles for oceanographic studies. It was shown that a modal formulation of the electromagnetic equations results in the isolation of the salient physics, especially with regard to the effect of mutual induction and conduction in the upper mantle and isolation of the dynamically important part of the water velocity field.

A major experiment to study the barotropic (depth-independent) wind-forced variability at very low frequencies of a mid-gyre region of the North Pacific based in part on electromagnetic techniques was reviewed. This project will serve as a testbed for the use of electromagnetic methods in oceanography.

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