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A REVIEW OF ANALOGUE MODEL STUDIES OF THE COAST EFFECT

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This work reviews electromagnetic analogue model studies of the coast effect, dealing particularly with a vertical interface model, a thin conducting sheet model, a wedge model, and a wedge underlain by a conducting block simulating an upwelling in a conducting zone beneath the coast. The vertical interface model results and the infinitely conducting thin sheet model results show good agreement with calculated values. It is concluded that a sloping sea–land interface alone cannot account for the experimentally observed coast effect, but that a sloping sea–land interface underlain by a conducting step could produce the observed coast effect.

1. Introduction

Through the years much effort has gone into attempting to obtain analytical solutions and numerical results for realistic mathematical models of laterally non-uniform conductors. Some of the early theoretical work was carried out by Price (1949), Ashour (1950), and Rikitake (1950). The problem of the "coast effect" (the anomalous increase of the vertical/horizontal magnetic field ratio as the coast is approached from the landward side) due to a lateral conductivity contrast, has received much attention but only a few greatly simplified two- or three-dimensional models have yielded to mathematical solution (Weaver, 1963; Roden, 1964; Ashour, 1965; Parker, 1968; Hermance, 1968; Weidelt, 1971; Weaver and Thomson 1972). A finite-difference method used by Jones and Price (1970), lends itself to studying the coast effect as well as other two-dimensional problems (Jones and Price, 1971a, b; Jones, 1971a, b, c; Jones and Pascoe, 1971; Pascoe and Jones, 1972). Numerical results obtained using the method of Jones and Price (1970) for a vertical sea–land interface model will be compared with analogue model results in a later section of this present work. In an analytical treatment of a vertical sea–land interface model, Weaver (1963) assumed, as an approximation, the horizontal magnetic field to be constant across the interface. This approximation led to a larger "coast effect" than expected. In a more recent work Weaver and Thomson (1972) extended Weaver's (1963) solution by obtaining a correction to the horizontal magnetic field. In a later section of this present work, their analytical approximation will be compared with both analogue model results and with values obtained using the Jones and Price (1970) numerical method. Roden (1964) using a numerical technique, carried out theoretical calculations for the simplified case of an ocean approximated by an infinitely long rectangular conducting sheet, the land approximated by a perfect insulator, and the mantle by a perfect conductor. His results indicated that the enhancement of the vertical field near the edge of the ocean should be observable for the case of magnetic variations of period as great as 24 hours. He carried out a laboratory analogue model study using a copper sheet shaped and scaled to represent the irregular coast of Japan and concluded that the coast effect should contribute strongly to the experimentally observed Japan anomaly. Both the mathematical model and the analogue model treated the ocean as having a sharp vertical boundary rather than a sloping one, and considered the land to have infinite resistivity. These simplifications would have considerable effect on the results. Parker (1968), employing an analytic technique, studied the electromagnetic induction in a thin conducting strip. He concluded the solutions should have validity several ocean depths away from the coast. Hermance (1968), using a conformal transformation technique, obtained the solution to the problem of an infinitely conducting half-sheet, representing an ocean, for an overhead ionospheric line current source. Using a hole in a copper sheet to simulate Iceland he carried out analogue model studies for an overhead Gaussian distribution current source. With the aid of his model results he was able to make "coast effect" corrections to measurements made for deep conductivity studies of Iceland. Schmucker (1964, 1970) used a type of transfer function analysis to determine the laterally non-uniform induction and was able to fit experimental data to models consisting of a finitely conducting sea, a non-conducting intermediate region, and an infinitely conducting substratum at the appropriate depth and of the appropriate contour. The finite-element method used by Coggon (1971) and by I.K. Reddy and D. Rankin (private communication, 1972) should also lend itself to studying the "coast effect" theoretically. Analogue model studies of the influence of the ocean and the "coast effect" reported include the work of Nagata et al. (1955), Parkinson (1964), Roden (1964), Dosso (1966b), Dosso and Jacobs (1968), Hermance (1968), Béthery et al. (1970), Launay (1970) and Thomson et al. (1972). Considerable reference to some of these will be made in a later section of this present work.

Analogue modelling has proved to be a useful method of studying problems which do not yield readily to mathematical solution. This method is not restricted to greatly simplified two-dimensional problems, but can readily be used to study rather complex two- and three-dimensional problems. Frequently, some of the idealizations required to permit mathematical solution, are not required in analogue modelling, and thus the analogue model solutions may at times be the more realistic. One of the idealizations commonly made to render certain electromagnetic induction problems mathematically tractable, is to assume zero conductivity for the host earth. With the aid of the principle of similitude, the poorly conducting host earth can readily be included in scaled-model studies of laterally non-uniform conductors.

2. Analogue model description

The theory of electromagnetic scale models has been treated in considerable detail by Sinclair (1948), Gaur (1964), Strangway (1966), Ward (1967), Negi and Gupta (1968) and Frischknecht (1971), and hence will not be covered in detail here.

It is readily shown that the necessary and sufficient conditions for invariance under a change in scale are:

$$(f/f')\,(L/L') = k\,, \quad (\sigma/\sigma')\,(L/L') = 1/k \tag{1}$$

where (f/f'), (L/L'), (σ/σ'), and $k = (E_x/H_y)\,(E_x'/H_y')^{-1}$ are the scaling factors for frequency, length, conductivity, and impedance respectively. The primed quantities refer to the geophysical problem, the others refer to the model. If magnetic fields only are to be studied, and the impedance scaling factor k is not of interest, the scaling conditions can be expressed as:

$$(\sigma/\sigma')\,(f/f')\,(L/L')^2 = 1 \tag{2}$$

It is readily shown that the scaling for apparent resistivity can be expressed as:

$$\rho_a/\rho_a' = (f'/f)\,k^2 = \sigma'/\sigma \tag{3}$$

A variety of analogue model configurations and field measuring equipment has been described in the literature. For the present purpose, a model that readily permits the use of a variety of source fields and has been used by the author, will be described briefly.

A schematic diagram of the experimental arrangement and the coordinate system used is shown in Fig. 1. The model consists of an overhead oscillating field source, modelling an ionospheric field source, and a large tank (244 cm by 168 cm and 76 cm deep) containing concentrated salt solution (64 cm deep) of conductivity $\sigma_1 = 2.1 \cdot 10^{-10}$ e.m.u. (21 mho/m)

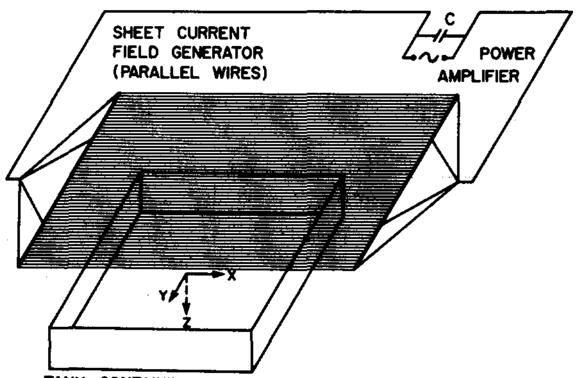

Fig. 1. Analogue model.

simulating a uniform upper layer of a poorly conducting earth. To minimize the effects of the concrete floor, the bottom of the tank was lined with a 5 cm thick graphite layer of conductivity $\sigma_2 = 1.2 \cdot 10^{-6}$ e.m.u. ($1.2 \cdot 10^5$ mho/m). This layer of graphite acts as a shield for any remaining field at the bottom of the tank. The source shown, consisting of alternating current flowing in the overhead grid of parallel wires, was designed to provide a field that approximated a uniform inducing field over a sizeable area of the model tank. The model is readily adapted to permit the use of a line current, or vertical or horizontal magnetic dipole sources.

The field detectors used for carrying out measurements at the surface of the salt solution have been described in detail previously (Dosso, 1966a). The vertical and horizontal magnetic field detectors each consisted of twin coils 0.67 cm long and 0.57 cm outer diameter. The electric field detector had a 1.48 cm probe separation. The instrumentation used was suitable for recording both amplitude and phase simultaneously for traverses across the tank. Two sets of scaling factors satisfying eq. 1 appropriate for the model are:

$$\sigma/\sigma' = 10^5, f/f' = 10^5, L/L' = 10^{-5}, k = 1$$

$$\sigma/\sigma' = 10^5, f/f' = 25 \cdot 10^5, L/L' = 10^{-5}/5, \ k = 5$$

The validity of the model has been tested for an oscillating sheet current (Dosso, 1966a), for an oscillating line current (Dosso and Jacobs, 1968), and for horizontal and vertical magnetic dipole sources (Thomson et al., 1972) for model frequencies $3 \cdot 10^4$, 10^4, $3 \cdot 10^3$, and 10^3 Hz.

3. Analogue model studies of the coast effect

The numerical method of Jones and Price (1970), and the analytical approach of Weaver and Thomson (1972), permits comparisons of theoretical and laboratory analogue model results for a vertical interface sea–land electromagnetic induction problem. For the theoretical calculations the conductivities of sea and land were taken to be $0.8 \cdot 10^{-11}$ e.m.u. and $2.1 \cdot 10^{-15}$ e.m.u., respectively. The frequency of the uniform inducing field was 0.3 Hz. For the analogue model studies the scaling factors for this problem had

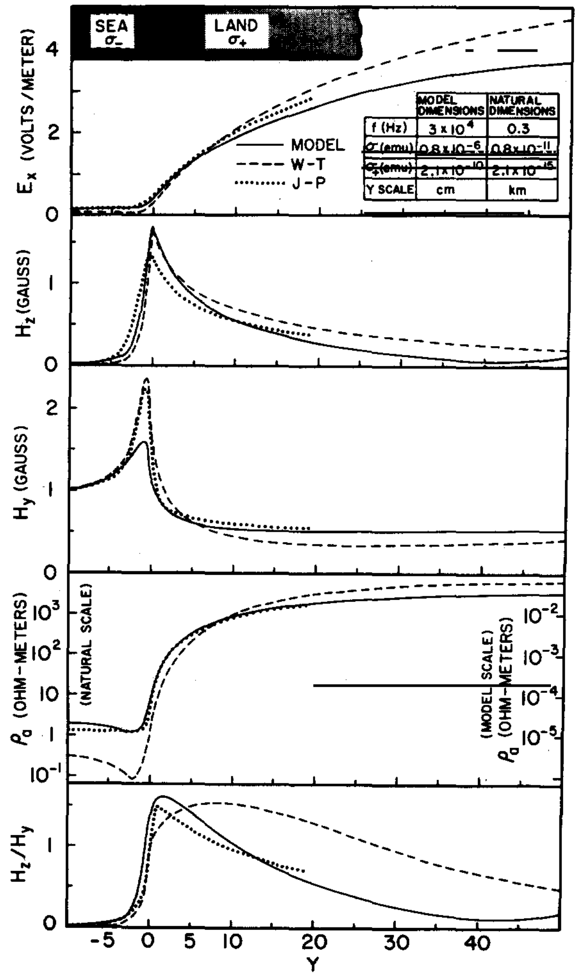

Fig. 2. Analogue model and theoretical results for a vertical sea–land interface, the W-T results from D.J. Thomson (private communication, 1972), the J-P results from F.W. Jones (private communication, 1972).

the values $\sigma/\sigma' = f/f' = 10^5$, $L/L' = 10^{-5}$, $k = 1$, and the apparent resistivity scaling was $\rho_a/\rho_a' = 10^{-5}$. Graphite of conductivity $0.8 \cdot 10^{-6}$ e.m.u. simulated the ocean, while salt solution of conductivity $2.1 \cdot 10^{-10}$ e.m.u. simulated the land. The inducing field of frequency 30 kHz, simulating a frequency of 0.3 Hz, was provided by the oscillating current sheet described earlier (Fig. 1).

The model results shown in Fig. 2 were obtained by the author, the W-T results (Weaver and Thomson (1972) method) were provided by D.J. Thomson (private communication, 1972) and the J-P results (Jones and Price (1970) method) were provided by F.W.

Jones (private communication, 1972). The three sets of results were normalized by equating the values of H_y at $y = -10$ cm. The agreement of the three sets of results is in general good for E_x and H_z in the region near the interface with the W-T electric field over the conducting sea somewhat smaller than the J-P and model results, and the J-P H_z maximum somewhat smaller than those of the W-T and model results. The maximum values of H_z for the three curves occur exactly at the interface. The H_z model values, for points well removed from the interface, are affected by the fact that the inducing field of the current sheet has a vertical component, though small, whereas the theoretical models employ a vertically incident uniform source field. The maxima of the three H_y curves occur over the highly conducting side very near the interface, with the J-P curve maximum occurring slightly further offshore. The low maximum of the model curve can be attributed, at least partially, to smoothing effects that take place, due to the finite size of the horizontal field detector, in regions where the field is changing rapidly. Calculations of H_y for this model carried out by U. Schmucker (private communication, 1972) using a finite-difference technique agree closely with the W-T and J-P results. Knowledge of the limits of accuracy of the mathematical results in the neighborhood of the interface might assist further in explaining the discrepancy. As can be seen from Fig. 2, the agreement between the model and the J-P apparent resistivities is remarkable, both yielding approximately the expected value (1.2 Ω–m) for graphite (sea) at $y = -10$ cm. The model apparent resistivity value in the neighborhood of $y = 50$ cm agrees almost exactly with the value for the salt water. The W-T apparent resistivity at $y = -10$ cm is approximately a factor of 10 lower than the model and J-P values, and has a value somewhat higher than that expected for points approaching $y = 50$ cm. The J-P and the model H_z/H_y curves are quite different at the interface. The maxima for the two curves occur on the landward side near the interface with the J-P curves having the sharper maximum. The W-T curve does not show a sharp maximum.

To assist in the analysis of deep conductivity studies in Iceland, Hermance (1968) carried out model studies of the effect of the ocean. In one phase of his work, in order to perform a check on his analogue model, he studied the idealized problem of the ocean a perfect conductor, and land a perfect insulator. The

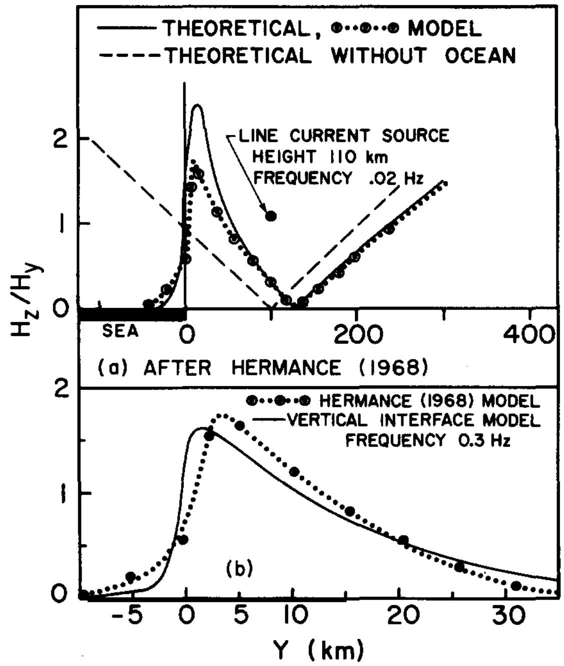

Fig. 3. The coast effect. (a) Analogue model and theoretical results adapted from Hermance (1968). (b) A comparison of the Hermance (1968) model and the vertical interface model of Fig. 2.

inducing field was taken to be an ionospheric line current. Using a conformal transformation technique, he was able to calculate the fields perpendicular to the coastline for a line current parallel to the coastline. The theoretical results, both with and without the ocean, as well as the analogue model results with the simulated perfectly conducting ocean, are shown in Fig. 3a. There is, in general, good agreement between the theoretical and model results except at the maxima near the coast. Hermance (1968) attributes the sharp peak in the model being suppressed as due to the finite size of the detecting coils, and to the fact that in the analogue model the ocean is not infinitely thin, nor infinitely conducting as required in the mathematical model. His calculations were made for a small height above the plane of the perfectly conducting ocean to correspond to the height at which the model measurements were made. Hermance (1968) also carried out calculations for the line current situated over the ocean 100 km offshore. For this case the peak shifted nearer the coastline and was diminished by approximately a factor of 2, indicating strong dependence on the source field.

To permit a comparison of the coast effect (H_z/H_y ratios) in Fig. 3a and Fig. 2, it is appropriate to change Hermance's (1968) scaling. Upon changing the frequency scaling by a factor of 15 (to convert the frequency to 0.3 Hz) and the length scaling by $\sqrt{15}$, while holding the conductivity scaling constant, the model curve shown in Fig. 3b results. The H_z/H_y vertical interface analogue model results of Fig. 2 are included for comparison. It is interesting to note that the maxima are approximately equal, with the maximum for the Hermance (1968) model curve occurring at approximately 4 km from the coast, as compared with 2 km for the vertical interface analogue model. The fall-off both over land and over sea differs little for the two models. It is rather surprising that these two radically different physical models (i.e., source fields, form of the ocean, and conducting contrasts between the ocean and the land) yield almost identical results. The close similarity of the results is somewhat fortuitous, since a different line current position (e.g., situated over the ocean), could result in a significantly different response curve. As mentioned earlier, Hermance's (1968) calculations for the line current situated over the ocean 100 km offshore, indicated a much reduced maximum H_z/H_y value as compared with the results for the line current over the land 100 km from the coast.

Launay (1970) employed an analogue model, based on electromagnetic image theory, to study the coast effect. The model employed two copper sheets which, with the aid of image theory, represented an ocean underlain by an infinitely conducting mantle at depth h, with a perfectly insulating region between the ocean and mantle. The model source field, provided by an alternating current in a large solenoid, approximated a uniform inducing field in the geophysical problem. The cases studied, for various depths h of the conducting mantle, had applications to the models of Schmucker (1964) and Everett and Hyndman (1967) for the California coast and Australian experimental field measurements. The analogue model results shown in Fig. 4a though based on a rather idealized model, agree with the general form of the experimental results for the California coast and Australia. Schmucker (1970), taking into account deep-sea measurements by Filloux (1967), proposed a high conductivity at much shallower depth under the sea than under the continent. An analogue model of this situation could be represented by a step at the coast in the infinitely conducting mantle. Launay's (1970) model does not include this aspect, but considers the underlying conductor to be at uniform depth. The length scale factor ($L/L' = 10^{-7}$) and the material used by Launay (1970) to represent the ocean (copper sheet) did not permit taking into account the sloping ocean–continent interface. This aspect of the model could be particularly important for regions near the interface.

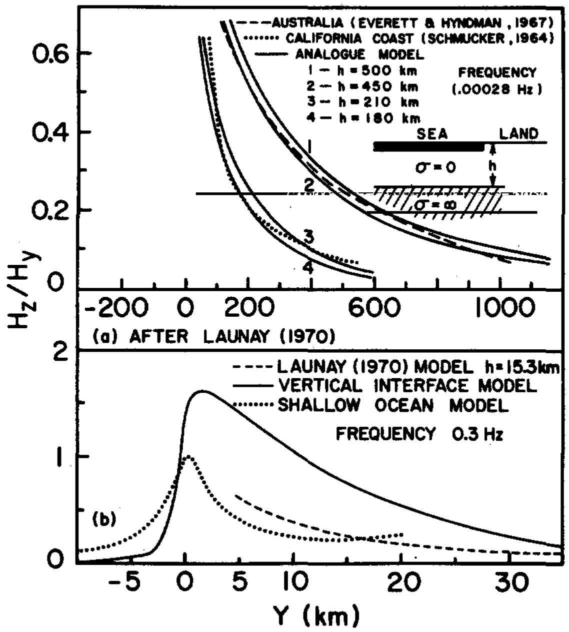

Fig. 4. The coast effect. (a) Australia and California coast measurements compared with analogue model results, adapted from Launay (1970). (b) A comparison of the Launay (1970) model, the vertical interface model of Fig. 2, and a shallow sea model (0.1 km deep).

To permit a comparison of Launay's (1970) model results with the vertical interface analogue model results of Fig. 2, it is again appropriate to change the scaling factors. Upon changing the frequency scaling by a factor of 1071 (to convert the frequency to 0.3 Hz) and the length scaling by $\sqrt{1071}$, with the conductivity scaling remaining unchanged, the model curve shown in Fig. 4b results. It is noted that for the curve shown in Fig. 4b the infinitely conducting mantle depth (h = 500 km) and the ocean depth (4 km) in this new scaling becomes 15.3 km and 0.12 km, respectively. The H_z/H_y vertical interface model results of Fig. 2 as well as analogue model results for a shallow ocean (graphite sheet 0.1 cm thick representing an ocean 0.1 km deep) are included in Fig. 4b for comparison. Although the general form of the fall-off over land with distance from the coast is quite similar for the three models, the vertical interface model values on the landward side near the coast are approximately a factor of 2 greater than those of the other two models. It should be expected that the very shallow ocean (0.12 km) together with the conducting mantle at the shallow depth of 15.3 km would lead to a much reduced coast effect as compared with the vertical interface model. The fall-off over the sea is much more rapid for the vertical interface model than for the shallow sea model as expected, since the shallow sea is only a fraction of a skin depth deep while the quarter-space ocean of the vertical interface model is effectively infinitely deep. The purpose in comparing the results for the three physically different models of Fig. 4b as well as those of Fig. 3b is to demonstrate the general similarity of the model coast effect as well as indicate some specific differences that can be attributed to certain aspects of the individual models.

In other studies of the coastline problem Dosso (1966b) and Dosso and Jacobs (1968) presented analogue model results for various shelving sea–land interface models for overhead sheet and line current sources. Fig. 5 shows results for traverses over a graphite wedge for the overhead sheet current source. Since the line current results were very similar to those of

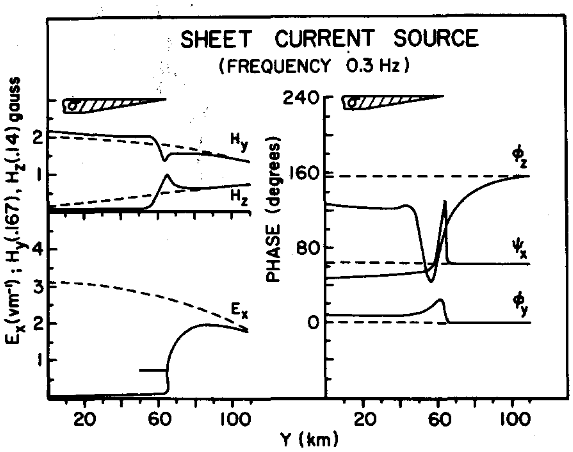

Fig. 5. Analogue model results of measurements over an inverted truncated graphite cone and a graphite wedge, adapted from Dosso (1966b).

the sheet current, they are not shown. Using the scale factors $L/L' = 10^{-5}$, $\sigma/\sigma' = f/f' = 10^5$, the frequency 30 kHz corresponded to 0.3 Hz in the natural scale. The wedge sloping from 0.1 cm to 2.5 cm in a distance of 50 cm, and with a constant thickness beyond, represented a shelving ocean with the sloping part of the wedge representing a 50 km continental slope, and an ocean of 2.5 km depth beyond. This wedge was a model of the ocean on the west coast of Vancouver Island (Tofino area), the continental slope begins approximately 25 km from the coastline. The maximum enhancement of H_z occurs exactly at the interface, while the maximum H_y occurs over the graphite corresponding to off-shore location in the geophysical case. The results of Fig. 5 indicate that a coast effect should be apparent near the coast for a frequency of 0.3 Hz. Model measurements at lower frequencies carried out by Dosso (1966b) indicated that the response was highly frequency-dependent, and that at the lower frequency of 0.01 Hz there was no enhancement at the interface. Lambert and Caner (1965) observed enhanced H_z/H_y ratios at Tofino (approximately 25 km from the continental slope) for frequencies of 0.01 Hz and lower, whereas the model results for this frequency showed negligible enhancement for all regions near the wedge. It can be concluded from the model results that, in this case, the earth–sea interface alone cannot account for the experimentally observed coast effect.

Various workers (e.g., Rikitake and Whitham, 1964; Schmucker, 1964, 1970; Lambert and Caner, 1965; Cox et al., 1970; Hyndman and Cochrane, 1971; and Srivastava and White, 1971) have proposed an upwelling in a highly conducting zone in the substratum below the ocean. Analogue model results for such a model are shown in Fig. 6. The upwelling below the ocean was modelled using large graphite blocks at a suitable depth below the surface of the salt solution. In order for the field to penetrate the wedge to the blocks below, a thin wedge was used. The wedge sloped to a thickness of 0.5 cm in a distance of 10 cm and had constant thickness beyond. The graphite blocks simulating an upwelling conducting zone, were 3 cm below the surface of the salt solution. For the scaling factor $L/L' = 10^{-5}$ this model simulates a shallow sea sloping to a depth of 0.5 km in a distance of 10 km and underlain by a highly con-

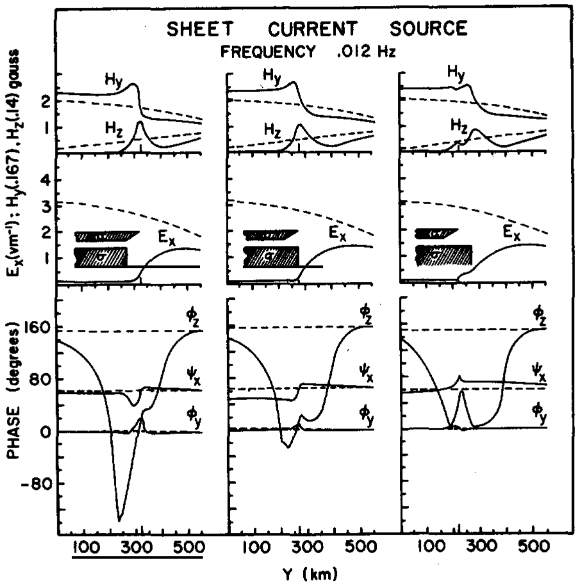

Fig. 6. Analogue model results for coastline models of a shelving ocean over a highly conducting step, adapted from Dosso (1966b).

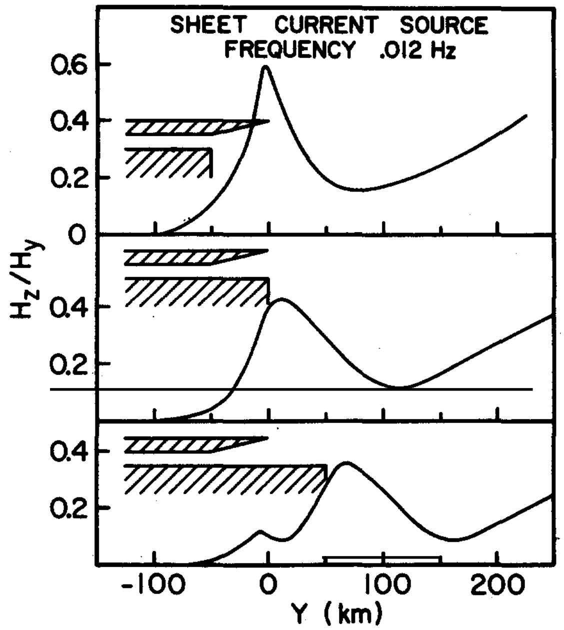

Fig. 7. Analogue model H_z/H_y values (based on the results in Fig. 6) for coastline models of a shelving ocean over a highly conducting step, adapted from Dosso (1966b).

ducting zone 3 km below the surface of the sea. If the scaling factors $L/L' = 10^{-5}/5$, $\sigma/\sigma' = 10^5$, are chosen, the scaling for f/f' and k are $25 \cdot 10^5$ and 5, respectively. The model then represents a sea sloping to a depth of 2.5 km in a distance of 50 km and underlain by a highly conducting step 15 km below the surface of the sea. The model frequency of 30 kHz simulates a frequency of 0.012 Hz.

Fig. 6 shows analogue model results for the amplitudes and phases for three wedge positions relative to the conducting block below. The inducing field is provided by the overhead sheet current source. As is to be expected, the position of the maxima in the H_z and H_y curves shifts relative to the tip of the wedge (coastline) depending on the position of the graphite block. In the geophysical problem, the coast effect should be observable at a much greater distance (as great as 150 km) from the coast for the case of the conducting step 50 km inland as compared with the case of the step 50 km seaward. For the case of the conducting step 50 km inland, H_z actually decreases as the coastline is approached for points beyond the maximum due to the conducting step and then increases again to a second maximum right over the coastline. The phase of the vertical component (ϕ_z) is seen to depend strongly on the conducting step.

To bring out more clearly the effect of an underlying conducting step, the H_z/H_y ratios, corresponding to the amplitudes in Fig. 6, are shown in Fig. 7. Moving the conducting step landward has the effect of producing a coast effect at greater distances from the coastline. For the case of the step extending 50 km inland, the H_z/H_y ratio begins to increase at 150 km from the coast, reaches a maximum at approximately 75 km from the coast, and then decreases as the coast is approached further. The increasing of H_z/H_y, moving to the right in Fig. 7 far from the wedge-block model, is due to the presence of the vertical magnetic field component of the sheet current source. For a truly uniform horizontal inducing field, H_z/H_y would continue to decrease and approach zero for increasing distance from the coast. It can be concluded from Fig. 6 and 7 that an underlying highly conducting step in coastal regions could play an important role in the coast effect. In particular the analogue model results indicate that an upwelling conducting zone would be an important factor in accounting for the coast effect observations of, for example, Lambert and Caner (1965) and Schmucker (1964).

The coastline problem of a highly conducting step below the sea was recently studied further by

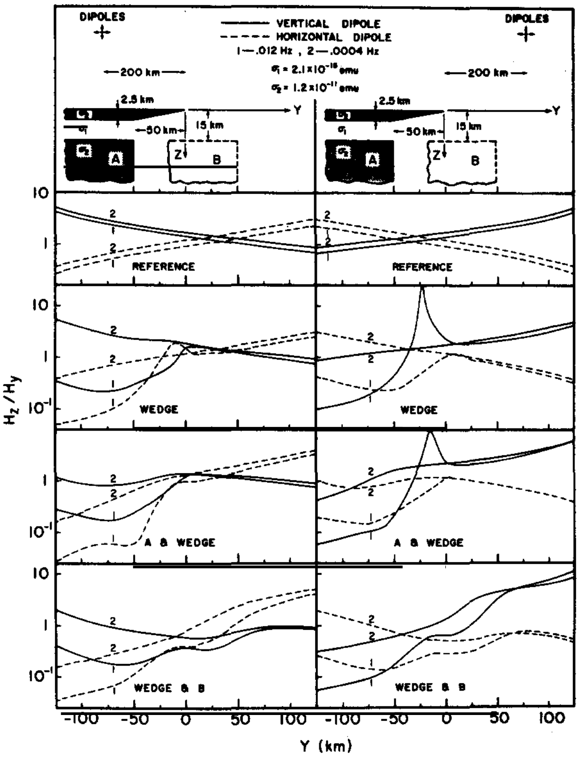

Fig. 8. Analogue model results for coastline models of a shelving ocean over a highly conducting step for overhead dipole sources, adapted from Thomson et al. (1972).

Thomson et al. (1972) for overhead vertical and horizontal dipole sources. The model, including the wedge and graphite block, was the same as the one used by Dosso (1966b). The H_z/H_y ratios for the two dipoles located −40 cm offshore and 40 cm onshore for the wedge alone, and for the seaward (*A*) and landward (*B*) graphite block position, as well as reference curves (wedge and block removed) are shown in Fig. 8. For the scaling factor $L/L' = 10^{-5}/5$, the distance of 40 cm on the model scale represents 200 km on the geophysical scale. The labels *A* or *B* in the lower figures identify the position of the block relative to the wedge for the particular set of results.

For the offshore locations of the dipoles given in Fig. 8 (left column), a comparison of the results for the wedge alone with the results for the seaward (*A*) and landward (*B*) block positions shows that the overall effect of the conducting step is to further suppress the H_z/H_y ratio over the ocean. In particular, the high frequency (0.012 Hz) enhancement over the wedge for the horizontal dipole in the presence of the wedge alone is damped out for both block positions. For points over land, the fields are essentially unaffected when the step is on the seaward (*A*) side, but moving the step to the landward (*B*) side causes the low frequency (0.0004 Hz) fields to increase for the horizontal source and to decrease for the vertical source for points inland. This behaviour is reversed when the dipoles are situated over land (right hand side of Fig. 8), the ratios for the vertical dipole are enhanced while the ratios for the horizontal dipole are reduced. In further comparing the results for the two dipole positions, the maximum that appears at 0.012 Hz for the onshore location of the vertical dipole in the presence of the wedge alone is much larger than it was for the horizontal dipole in the offshore position, and is still significant for position *A* of the underlying block. The H_z/H_y ratio for the onshore vertical dipole shows considerable enhancement near the step for the landward position of the block. In the overall comparison of the results for the onshore and offshore dipole positions, the similarity in the behaviour of the H_z/H_y ratios for the onshore (offshore) horizontal dipole and the offshore (onshore) vertical dipole is most apparent.

It can be concluded from the results of Fig. 8 that for onshore and offshore locations of dipole sources, the conducting ocean alone has little effect on the fields on the landward side of the coastline, but it does affect the fields over the ocean. The presence of a conducting step in the substratum is also seen to have little effect on the fields for points over land when the step is on the seaward side, but does have an effect when located on the landward side. The presence of the coastline is evident for all cases in the behaviour of the fields offshore. This indicates that, when interpreting the coast effect, the fields over the sea should also be taken into consideration.

4. Concluding remarks

Compared with the large effort that has gone into theoretical studies of mathematical models through the years, relatively little effort has gone into analogue model studies. Nevertheless, analogue model studies have provided considerable information, particularly on two-dimensional electromagnetic problems. With the many two-dimensional problems yielding to theoretical solution, interest in three-dimensional problems is increasing, and in this area too, analogue model studies should be of continuing interest.

Acknowledgments

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