Magnetic daily variations compared between the east and west coasts of Canada[1]

F. E. M. LILLEY[2]

Division of Geomagnetism, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Ont., Canada K1A 0Y3

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Magnetic observatory data from St. John's, on the Atlantic seaboard of Canada, and Victoria, near the Pacific seaboard, are analysed for coast effects at diurnal periods by comparison with similar records from inland observatories. The five international quiet days of August 1968 are studied. When resolved to geographic coordinates and adjusted to local solar time, the horizontal components of the daily variation are spatially uniform across the continent, but the vertical components vary greatly. Subtracting the vertical signal recorded at Ottawa (inland) from that recorded at St. John's demonstrates a long-period coast effect, with an anomalous vertical component leading the cross-shore horizontal component in phase by about an eighth of a cycle. Subtracting the vertical signal at Newport (inland) from that at Victoria demonstrates a similar but lesser effect. These results are consistent with the diurnal coast effect observed for two coasts of the Australian continent and for California. A Parkinson-type coast effect is interpreted to occur at the long periods of the daily variation, in addition to the substorm periods at which it has traditionally been observed.

Separate from the coast effect, there is a substantial difference in the daily-variation vertical component between the two inland stations of Ottawa and Newport. This difference may be caused by a change in typical source-current configuration from one station to the other or it may indicate a contrast in electrical conductivity between the two inland regions of the continent. In the latter case the indication would be of higher conductivity to the east and lower conductivity to the west, the reverse of many currently accepted models.

On analyse les données magnétiques des observatoires de St-Jean, Terre-Neuve, sur la côte Atlantique du Canada et de Victoria, près de la côte du Pacifique, pour évaluer les effets côtiers à des périodes diurnes par comparaison avec des données semblables provenant d'observatoires situés à l'intérieur du Canada. On a étudié les cinq journées tranquilles internationales d'août 1968. Lorsque corrigées pour les coordonnées géographiques et ajustées pour l'heure solaire locale, les composantes horizontales de la variation journalière sont spatialement uniformes à travers le continent mais les composantes verticales varient beaucoup. En soustrayant le signal vertical enregistré à Ottawa (intérieur) de celui de St-Jean, on peut démontrer l'existence d'un effet côtier de longue période avec une composante vertical anormale se résolvant en une composante horizontale perpendiculaire au rivage en phase par environ un huitième de cycle. La soustraction du signal vertical de Newport (intérieur) de celui de Victoria démontre l'existence d'un effet semblable mais moins marqué. Ces résultats sont compatibles avec l'effet côtier diurne observé sur les deux côtes du continent australien et pour la Californie. On interprète l'effet côtier du type Parkinson comme se produisant aux longues périodes de la variation journalière en plus des périodes d'orages magnétiques auxquelles il a traditionnellement été associé.

Se distinguant de l'effet de côte, il y a une différence substantielle dans la composante verticale de la variation journalière entre les deux stations intérieures de Newport et d'Ottawa. On peut attribuer cette différence à un changement dans la configuration typique de la source de courant d'une station à l'autre, on à un contraste de conductivité électrique entre les deux régions intérieures du continent. Dans le dernier cas, cela indiquerait une conductivité plus grande à l'est qu'à l'ouest, contrairement aux modèles couramment acceptés.

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Introduction

The coast effect in geomagnetic variations at substorm periods has been studied widely throughout the world since its description by Parkinson (1959, 1962). An important aspect of its interpretation has been whether the contrast in electrical conductivity between continent and sea water is by itself sufficient to account for the effect, or whether in addition a contrast in electrical conductivity is needed between continents and the material under the sea floor (see, for example, Schmucker 1964; Coode and Tozer 1965; Lambert and Caner 1965; Cox *et al.* 1970). An associated question is that of the particular physical mechanism dominant in

[1]Contribution from the Earth Physics Branch No. 739.

[2]Present address: Research School of Earth Sciences, The Australian National University, Canberra, A.C.T. 2600, Australia.

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causing the coast effect. If the cause is basically electromagnetic induction in the oceans alone, then induction must be considered on a global scale by all components of the magnetic variation source field, the vertical component of which may be the most effective (Bullard and Parker 1970). If, however, the cause is basically local induction at an ocean–continent electrical conductivity contrast, then the contrast may need to extend deeper than the sea water, and the causing mechanism will be induction by the cross-shore horizontal field.

At substorm periods of about 1 h, a discriminant between these two mechanisms appears to lie in the existence of the Parkinson vector itself, coupled with the observation that the coast effect occurs generally in the vertical component of the magnetic fluctuation field with little or no contribution to an anomalous horizontal component. Parkinson vectors typically point directly out to sea and in so doing indicate a linear relationship between the local vertical fluctuation field component and the local cross-shore horizontal field component. Because the vertical fluctuations are typically anomalous and the horizontal fluctuations typically not anomalous but regional, there is the clear indication that the latter have caused the former: especially when, as in the coastal array study of Lilley and Bennett (1972), the Parkinson vectors follow around a sharp corner in a coastline while the horizontal magnetic fluctuations are observed to be effectively uniform over the whole area.

Information at longer periods may be critical to resolving the two questions of geologic origin and physical mechanism of the coast effect because, for the first, the longer period disturbances penetrate deeper and so are more affected by material under the ocean floor; for the second, it appears that it is for long periods that the oceanic induction problem is first likely to be solved (Bullard and Parker 1970; Hobbs 1975; Hobbs and Brignall 1976), allowing reliable comparison of theory with observation.

A Parkinson-vector approach at daily variation periods is made difficult, however, by the repetitive nature of the source field and by the common presence at coastal stations of a substantial regional or nonanomalous vertical-field component. Bennett and Lilley (1973) subtracted an inland field from a coastal array to observe a coast effect for east Australia and showed it was related in amplitude and phase consistently to the cross-shore horizontal field but not to any other component. A similar relationship was demonstrated also for Schmucker's (1970) data for California and subsequently by Lilley and Parker (1976) for west Australia.

This present paper now applies the technique to examine data for the coasts of Canada. Observatory data are taken to ensure freedom from contamination by diurnal temperature variation. In particular, St. John's, Newfoundland, is taken as a station on the Atlantic Canadian coast, with Ottawa, Ontario, as its inland control station; Agincourt, Ontario, is taken as a check on the regional nature of the Ottawa records. Victoria, British Columbia, is taken as a station near the Pacific coast, with Newport, Washington State, U.S.A., as its inland control station; the pattern of daily variation in the Newport region is known quite well from array studies. The positions of these observatories are shown in Fig. 1 and their geographic coordinates are listed in Table 1.

Previous Work on the Coast Effect in Canada

A great deal of previous work on the coast effect at periods of less than 12 h exists for Canada. Results for the Pacific coast have been published in a series of papers by Lambert and Caner (1965), Caner *et al.* (1967), Cochrane and Hyndman (1970), Caner (1971), Caner *et al.* (1971), and Dragert (1973); extensive model studies were reviewed by Dosso (1973) and have continued since that time (e.g., Nienaber *et al.* 1978). Studies of the Atlantic coast have been published by Srivastava and White (1971), Hyndman and Cochrane (1971), Bailey *et al.* (1974), Cochrane and Hyndman (1974), Srivastava and Folinsbee (1975), Kurtz and Garland (1976), and Cochrane and Wright (1977); see also Edwards and Greenhouse (1975). Observations at coasts in the Canadian Arctic are described by Niblett *et al.* (1974) and DeLaurier *et al.* (1974): the

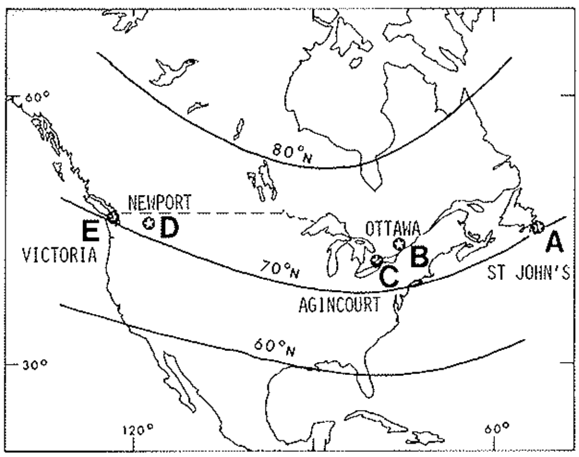

FIG. 1. Positions of magnetic observatories referred to in this paper. Contours of equal magnetic inclination are shown for North America as 60°N, 70°N, and 80°N.

TABLE 1. Magnetic observatories

	Location	Latitude	Longitude	Geomagnetic latitude	Magnetic declination
(A)	St John's	47°36′N	52°41′W	58.7°N	27°W
(B)	Ottawa	45°24′N	75°33′W	57.0°N	14°W
(C)	Agincourt	43°47′N	79°16′W	55.0°N	7½°W
(D)	Newport	48°16′N	116°59′W	55.2°N	21½°E
(E)	Victoria	48°31′N	123°25′W	54.3°N	22½°E

description of a profile across the western Arctic coast and out to sea is at present in preparation by R. D. Kurtz.

The papers referred to concentrate mainly on phenomena at substorm periods, with occasional references to daily variation phenomena. Srivastava (1971) describes total-field daily variation measurements at the Atlantic seaboard, noting unusual amplitude values for Sable Island and questioning the occurrence of a coast effect there. Caner and Auld (1968) discuss tidal effects on telluric signals at Victoria, and Cochrane and Srivastava (1974) deal specifically with magnetic variations at diurnal and tidal frequencies at the Atlantic coast. It is concluded generally that although tidal effects on telluric signals may be strong at coastal stations, tidal effects on magnetic signals are weak against the background of the regular solar daily variation.

Data

If coast effects occur in the magnetic daily variations at St. John's and Victoria, they should be present in virtually all records from the two observatories. Of the many data therefore available for analysis, a period was chosen when both Ottawa and Agincourt observatories were in operation,[3] so that the latter could be used as a check on the former as representing the inland variation field for eastern Canada. In particular, August 1968 was chosen as a summer month when the diurnal magnetic variation might be expected to be enhanced relative to its annual mean (Matsushita 1967).

For the interest of comparing across continent, the same period was also taken for the western stations, Victoria and Newport. Mean hourly values for the three geomagnetic elements, each meaned again over the international five quiet days of August 1, 2, 28, 29, and 30, were taken as basic data for all stations (Brown 1971; Hruska 1974; Darker and McKeown 1970; Auld and Fetterley 1970). Because a diurnal effect was sought, universal time was adjusted to local solar time for each station according to its geographic longitude; and because the range in magnetic declination across Canada is from 27°W at St. John's to 22½°E at Victoria, the horizontal magnetic variation components H and D were resolved into geographic north (X) and east (Y) variation components. The data thus reduced are presented in Fig. 2. The horizontal component Y', introduced in Fig. 5, is the cross-shore field obtained by resolving X and Y perpendicular to a coastline, and taking the onshore direction as positive.

A preliminary inspection of the plots in Fig. 2 shows the horizontal components X and Y to be quite uniform across the continent, whereas the

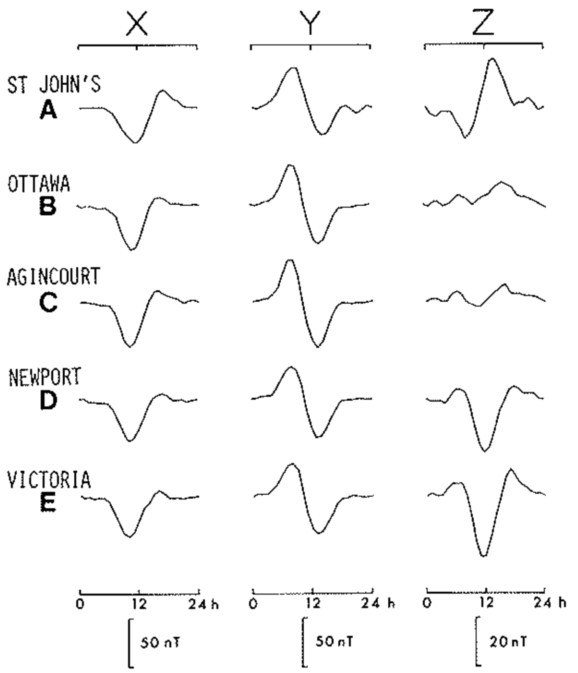

FIG. 2. Mean hourly values of the geomagnetic variation components recorded at the observatories in Fig. 1 averaged over the five international magnetic quiet days of August 1968, resolved to geographic coordinates (X, north; Y, east; Z, vertically down), and plotted relative to local solar time.

[3]The Ottawa observatory was set up to replace Agincourt and simultaneous recording occurred for nine months after the former was opened in 1968 and before the latter was closed in 1969.

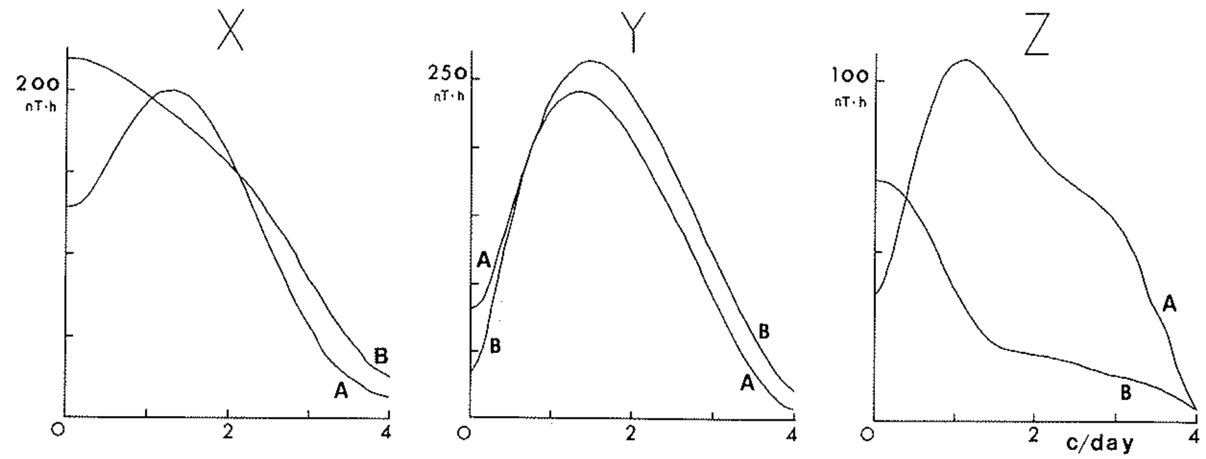

FIG. 3. Fourier transform amplitude spectra of the data in Fig. 2 for the two easterly stations of St. John's (A) and Ottawa (B).

vertical component Z varies greatly. Note also that the Agincourt records are consistent with the Ottawa records.

Spectral Analysis

The data have been analysed by computing Fourier transforms of the signals shown in Fig. 2 according to

$$g(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t}\, dt$$

where $g(\omega)$ is the Fourier transform of a signal $f(t)$ at angular frequency ω. The approach of Lilley (1975) has been followed in the sense of regarding a distinct quiet day as an isolated event, so that the data of Fig. 2 represent estimates of the components of a mean quiet-day signal for each station, and the Fourier transform for each component can be computed by assuming zero signal before and after that shown. Fourier transforms are then computed directly and the amplitude spectra for St. John's and Ottawa are compared in Fig. 3. It would be more traditional to carry out a harmonic analysis of the data of Fig. 2 by fitting Fourier series to the signals shown, but the author is of the view that the transform spectra are more informative and appropriate; in fact the two approaches are compatible and the subsequent analysis will use values corresponding to the 24 and 12 h harmonic components of the data, related to the transform values by the equations given by Lilley (1975, p. 6).

The harmonic values thus obtained for all stations are presented diagrammatically in Fig. 4. Phase leads are used, defined such that a more positive phase lead corresponds to a signal having occurred at an earlier real time.

Interpretation

Basic Principles

The technique applied to the data is that of Bennett and Lilley (1973), in which an inland variation field is subtracted from a coastal variation field to give a residual which is interpreted as a coast effect, all signals being taken relative to their own local solar times. This procedure is based on the premise that the daily variation source currents remain stationary in position on the daytime side of the earth, so that the same primary-field signal, relative to local solar time, will be observed at all points at the same geographic latitude. This simple model is perturbed by the partial dependence of the daily variation source currents on geomagnetic coordinates; however, choosing an easterly inland station for St. John's and a westerly inland station for Victoria should reduce the effect of possible source-field changes across the continent.

Taking the mean of five quiet days should further reduce the effects of incidental changes in the daily variation source currents as they move from above a coastal station to above an inland station (or vice versa). An east coast effect and a west coast effect can thus be sought individually.

Coast Effect at St. John's

Applying the technique described to the data of Fig. 4, an estimate of anomalous vertical field for St. John's is obtained by vectorially subtracting the Ottawa arrow from the St. John's arrow. Two such subtractions, for 24 and 12 h periods, are shown in the polar plots of Fig. 5. Also shown in each polar plot is an arrow representing the amplitude and phase of the cross-shore horizontal field component. For St. John's a cross-shore direction is not

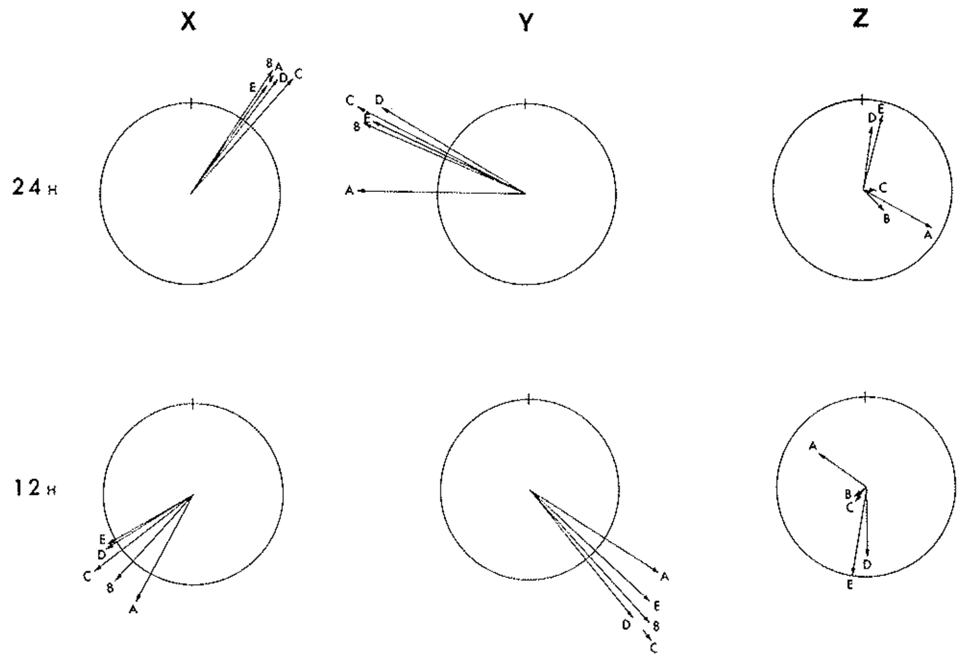

FIG. 4. Polar plots of the Fourier coefficients (converted from their Fourier transform equivalents) for the data of Fig. 2 at periods of 24 and 12 h. Phase leads increase clockwise from zero for local solar midnight at the top of each diagram. The scale of each circle radius is 10 nT. Letters mark the values for the different stations as shown in Fig. 1.

immediately obvious, as the coast does not approximate a two-dimensional structure. Therefore, the direction N60°W given by the in-phase substorm response arrow at period 1 h of Hyndman and Cochrane (1971) has been taken, as also confirmed by Bailey *et al.* (1974).

Coast Effect at Victoria

Similarly in Fig. 5, vector subtractions are made for the west coast, taking Victoria minus Newport at both 24 and 12 h periods. The cross-shore horizontal component is drawn upon the basis of an estimate that the Pacific deep ocean edge off Victoria strikes at a representative geographic direction of N25°W.

Discussion

The subtractions can be seen to determine residual anomalous vertical fields at the coastal stations. These anomalous vertical fields bear a consistent relationship in phase to the regional cross-shore horizontal component Y' at both 24 and 12 h periods, leading this latter by about one eighth of a cycle for St. John's and one quarter of a cycle for Victoria. The amplitude ratios of anomalous vertical to cross-shore horizontal are 0.3 at 24 h and 0.4 at 12 h for St. John's, and 0.1 at 24 h and 0.15 at 12 h for Victoria.

These results are consistent with those found for other coasts as summarized by Lilley and Parker (1976). Particularly, the phase leads of anomalous vertical to cross-shore horizontal given above are consistent with the lead of about one eighth of a cycle found generally for the other coasts, even though the geographic direction of the cross-shore horizontal component varies from coast to coast. A simple interpretation of the phenomenon is thus supported: that it is the familiar substorm coast effect occurring at long periods.

The amplitude ratios obtained in this paper are weaker than those given by Lilley and Parker (1976): 0.8 for west Australia (Gnangara), 0.5 for east Australia (Moruya), and 0.6 for California (Cambria). For Victoria, a contributing factor to the weak value of 0.1 may be the distance of the observatory (some 90 km) from the Pacific coastline.

Comparison of Inland Stations

A further note of interpretation can be made about the data of Figs. 2 and 4. The coast effects have been estimated individually, for reasons explained, but as the data are simultaneous a comparison is also allowed between the variations recorded at the inland stations.

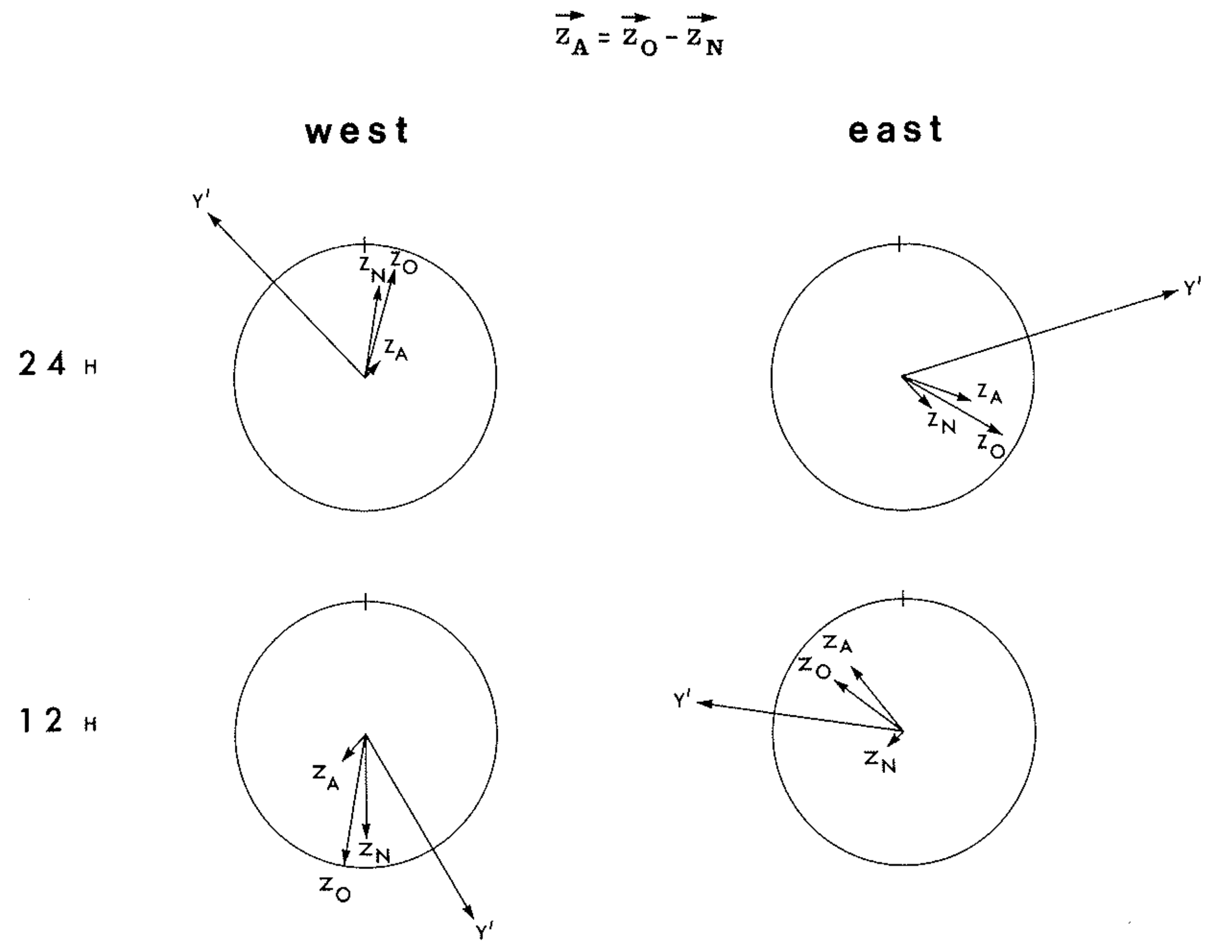

FIG. 5. Vector subtraction of the regional or 'normal' vertical fluctuation components, denoted Z_N, from the coastal observed vertical fluctuation components, denoted Z_O, to give the anomalous vertical fluctuation components, Z_A. The appropriate cross-shore horizontal fluctuation component, Y', is also shown in each case. The St. John's minus Ottawa diagrams are marked 'east' and the Victoria minus Newport diagrams are marked 'west'. Note that Z_A leads Y' in phase by about one eighth of a cycle for St. John's and one quarter of a cycle for Victoria. The scale of each radius and the phase convention are as for Fig. 4.

There is, in fact, a considerable difference in the vertical component between the two inland stations Ottawa and Newport, the cause of which must be either external or internal to the earth. In principle the external is the easier to invoke, appealing to the different positions of Ottawa and Newport relative to the geomagnetic pole, and hypothesizing that the daily-variation source currents change with geomagnetic longitude. There are minor changes in the horizontal components X and Y, and the changes in the spatial gradients $\partial X/\partial x$ and $\partial Y/\partial y$ could be greater; even so, the enhancement of Newport relative to Ottawa is sufficiently strong that the alternative possibility, of some induction effect in the earth, should not be ignored.

Neither station appears to be in a region where the daily variations are affected by local two-dimensional or three-dimensional conductivity anomalies. The similarity of the Agincourt and Ottawa records supports this claim for the east. For the west, the station Newport lies within the area of the magnetometer array of Camfield and Gough (1975), which confirmed the earlier results of Caner (1971) that vertical field fluctuations at the long periods of the daily variation show no spatial variation across the Rocky Mountain Trench. Further, Newport appears to be typical of the regional daily variations observed in a more easterly array study over the Prairies (private communication from P. A. Camfield based on the array study described by Alabi *et al.* (1975)).

For one-dimensional conductivity structure in the earth, the magnetic fluctuation components will be related by a frequency-dependent complex parameter c (Schmucker 1970, p. 68), given by

$$c = Z/(\partial X/\partial x + \partial Y/\partial y)$$

where x and y are horizontal spatial coordinates, north and east. For a continent, at a typical daily variation period of say 12 h, the real and imaginary parts of c might be expected to be of the order of several hundreds of kilometres and minus several tens of kilometres respectively (Lilley and Sloane 1976). Disregarding the possibility of significant changes in $\partial X/\partial x$ and $\partial Y/\partial y$, the increase in amplitude by a factor of two in the vertical component would imply a doubling of c and a corresponding contrast in conductivity structure between the two stations. For a simple two-layer earth, the real part of c gives an estimate to the depth of the induced currents flowing in the lower (better conducting) layer: such a 'substitute good conductor' would thus be substantially less deep beneath Ottawa than Newport.

Many interpretations to date have stated or implied that the electrical conductivity beneath western Canada should be higher than beneath eastern Canada. Such models have been at least partly guided by the relationship of electrical conductivity to temperature, and have thus placed the lesser conductivity under the shield of eastern Canada, where the heat flow is low. The suggestion of the present paper is contrary to such conventional wisdom, but may have some correlation with the seismic low-velocity layer found under this part of eastern Canada by Jordan and Frazer (1975), and the evidence gradually accumulating for a highly-conducting lower crust in eastern North America, such as that of Edwards and Greenhouse (1975) and Nekut *et al.* (1977).

Conclusions

The horizontal daily variation is smooth across southern Canada but the vertical component changes greatly from coast to coast. In the first instance this change is interpreted as a regular coast effect at each continent–ocean interface, the inducing mechanism being the local cross-shore horizontal variation field. Modelling this coast-effect phenomenon at the long periods of the daily variation should extend the information on the requirement that the electrical conductivity contrast at a coast be in excess of that provided by the deep ocean to continent change alone.

There is also a regional difference inland in the amplitude of the vertical component from east to west. If this difference is of internal origin, and not due to external causes such as changing source-field pattern with changing magnetic declination, it may represent a contrast in the deep electrical conductivity structure across the continent, with the higher conductivity on the eastern side.

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