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ESTIMATE OF STOKES' DRIFT FROM TIDAL CURRENT HARMONIC CONSTITUENTS

by

H.D. Dooley
Marine Laboratory, Aberdeen, Scotland.

Introduction

Currents in the North Sea, as in all shallow sea areas, vary considerably in space and time and, to a large extent, are controlled by wind. Superimposed on this near random motion is a theoretically predictable component of flow, the Stokes' drift, which is a consequence of the physical properties of a progressive tidal wave (Longuet-Higgins 1969). Its properties are such that it cannot be directly measured by moored current meters since the drift is a property only of the Lagrangian frame of reference. Its magnitude is extremely small relative to tidal currents but its persistence means that it can, over a long time interval, transport passive organisms and pollutants over large distances. Consequently a detailed knowledge of its distribution in the North Sea is extremely desirable.

This paper is an attempt to examine the limitations imposed on the measurement of Stokes' drift, and, with these limitations in mind, the appropriate computations are described using data from two current meter moorings located in the central northern North Sea.

Background

At least two attempts have been reported recently which describe field experiments designed to measure Stokes' drift. Dooley (1974) made estimates by comparing plots of parachute drogue trajectories with progressive vector diagrams obtained from current meter data. Ramster and Durance (1973) made use of the relation

$$U_s = \int^t u\,dt\,\frac{\partial u}{\partial x} \qquad (1)$$

(where U_s is Stokes' velocity
u is tidal current
x is a horizontal dimension and t is time)

to obtain estimates of Stokes' drift. This required the deployment of a triangular array of current meter moorings in order to assess the field gradients of the tidal current $(\frac{\partial u}{\partial x})$. Both these efforts failed in their objective however because of the disturbing effect of spatial variability of tidal current. This disturbing influence is obvious in areas of strong tidal streams and complex bottom topography, since here parachute drogue displacements are dominated by 'residual' flows that are a consequence of rectification in a 'noisy' tidal current. Consequently such data merely provide information on the mesoscale field of turbulence. Realistic estimates of Stokes' drift could only be obtained by comparing an ensemble average of a large number of drogue and current meter records over an area large than the dimensions of the turbulence. These mesoscale variations in tidal stream characteristics also invalidate the application of equation (1) since in such instances the time average of spatial gradients has no physical meaning. One facet of this effect can be demonstrated by varying the spatial distribution of tidal current amplitude. In Fig 1 a tidal current amplitude of 50 cm s^{-1} is considered from which a Stokes' drift of 0.45 cm s^{-1} towards the south is obtained when a wave number typical of the northern North Sea is chosen and the current amplitude is uniformly distributed. With increasing inhomogeneity the estimates rapidly become distorted, especially when the data are integrated over time intervals as long as one hour. Another complication arises if the tidal current ellipse varies its rotating sense as was evident in the data considered by Ramster and Durance (1973). Here clockwise and anti-clockwise rotating ellipses were obtained from adjacent corners of their triangle of moorings. This sort of inhomogeneity invalidates the application of equation (1) since the 180° phase difference in the east components of the tidal current is interpreted as a very slowly propagating wave towards the west which is of course not so. Consequently a very significant west going Stokes' drift results which completely dominates the true component of Stokes' drift.

Clearly, reliable estimation of Stokes' drift is dependent primarily on a homogeneous distribution of tidal current. This demands that current meter records must first be examined for the quality of their harmonic constituents and once the above condition has been verified, Stokes' drift can be reliably estimated. This paper describes how these calculations were carried out using data from two current meter moorings located in the central northern North Sea during the 40 day period 14 April - 28 May 1973. Each mooring consisted of two current meters located at approximately 30 m below the surface and above the bottom. One of the moorings (N) at 58°N 1°E was in water of 150 m depth; the other (S) at 57°30'N 1°E was in water of 100 m depth. Obviously it is possible to derive only the N-S component of Stokes' drift from such data but the loss of directional information should not be too great since the propagation of the tidal wave in this part of the northern North Sea is predominantly southerly.

Computation of Stokes' drift

The first stage in the analysis of Stokes' drift was to examine the characteristics of the tidal currents in the area under consideration. This involved computing harmonic constituents from the appropriate current meter records, the results of which are tabulated in Table 1 for the three principal constituents M_2, S_2 and O_1. All of the other constituents are insignificantly small because of the weak tidal streams present here and were ignored in subsequent analysis. The current ellipses produced partly from the information in Table 1 are displayed in Fig 2 for the M_2 constituent only. They are almost 'flat' with their major axes orientated within a few degrees of south. Consequently as previously noted the southerly component of Stokes' drift will give a fair indication of the total Stokes' drift in this area. Unfortunately tidal streams are not quite homogeneous since, near the surface at S, a rather broad counter-clockwise rotating ellipse of larger amplitude is present. This inhomogeneity is most probably due to the influence of the thermocline located near the depth of this current meter and for the reasons outlined above this record had to be omitted from the computations. The values of the tidal constituents chosen for this analysis are shown at the bottom of Table 1.

The magnitude of the southerly component of Stokes' drift averaged over a tidal period of 25 hours is, as expected, very small, (Fig 3). Values range from 0.08 cm s^{-1} at the time of neap tides to 0.18 cm s^{-1} at springs. In both cases the components are towards the south. The southerly displacement of a water particle due to this is 2.3 NM's over 40 days: the very low magnitude of this drift epitomises the difficulties of its identification from field measurements. The importance of its contribution to the circulation of the area is however dependent on the distribution and magnitude of the Eulerian residual currents produced by averaging current meter data over a tidal cycle and these are discussed in the next section.

Description of Eulerian residual currents

Residual currents in this area of the northern North Sea are typically large in comparison to other areas (Dooley (1974)) and these new data demonstrate this. Virtual water displacements of the order of 80NM's over the period of 40 days were observed on this occasion but there was considerable variability in space and time (Fig 4). The magnitude of the residual flow decreased with depth at N and somewhat unusually increased with depth at S. In general, the direction of residual drift was similar at each position and typically towards 030°T. Apart from these records other measurements were made in the area at this time but were not of sufficient length to make a satisfactory analysis of the tidal stream constituents. They are mentioned here however because they provide additional information on the rather complex distribution of residual current in this area. Fifteen days of current measurements at the beginning of the period under investigation mid-way between N and S (the site of BP's Forties field production platform) indicate a current of similar direction but of almost double the speed. Other measurements to the south of 57°30'N indicate lower residual velocities than those occurring near the surface at S. These characteristics of horizontal and vertical distribution of current indicate that locations N and S are straddling an area of generally eastward flow of water which apparently originates from Fair Isle (Dooley (in press)). The significant northward component of flow is possibly a consequence of the proximity of Ling Bank a few miles to the East.

The Eulerian residual flows are clearly much larger than Stokes' drift which contributes to less than 2% of the total flow near the bottom at N but as much as 10% near the surface at S. In spite of this, Stokes' drift may play an important part in the distribution of organisms in this area since it provides a mechanism for their transport into and out of the easterly going current. Similarly it may influence the dynamics of the flow since, in the frame of reference of the current, mass can be transported from one side to the other (i.e. from high to low density) within the time it takes to cross the North Sea. Consequently Stokes' drift can play as important a role in areas of strong residual currents and high spatial variability as in areas of very small (Eulerian) residual current where it is the dominant component of flow.

Discussion

Clearly the accurate computation of Stokes' drift from field measurements is fraught with difficulties. The distribution in the North Sea of the two parameters necessary for its computation, the current amplitude and phase velocity of the tidal wave, are however well documented in the literature (e.g. Defant (1961)) and are consistent with the harmonic constituents presented here If this agreement is valid for other areas of the North Sea it is possible to deduce Stokes' drift components, such as those of Fig. 5 which is the distribution of the southerly component of Stokes' drift between 1°E and the Scottish coast, based on predictions of the M_2 tidal wave. The increase in drift near the coast is a consequence of the increased tidal amplitude that has been partly offset by the higher phase velocity of the tidal wave. Even near the coast however it is probably expecting too much of field data to attempt to extract currents of only 0.5 cm s^{-1} from records consisting of 'noisy' tidal streams. If the available data are of short duration the problem is analogous to attempting to compute harmonic constants from short data runs.

According to calculations based on Fig 5 the southerly component of volume transport between 1°E and the coast is, 0.04×10^6 m^3 s^{-1}; it is similar in magnitude to the outflow from the Baltic and also to the inflow from the English Channel to the North Sea. In a year, displacements due to Stokes' drift range from 20 NM's in the central North Sea to over 100 NM's near the east coast of Scotland. This latter figure represents a large fraction of the linear dimension of the North Sea.

Even though these displacements are large over very long time scales the verification of their existence from short term experiments may prove to be difficult since their magnitude (maximum 0.3 NM's per day) appears to be too small to separate from small scale spatial variability which in itself need not necessarily contribute to residual water movements when extended to a larger space scale. Further difficulties arise from the fact that over short periods of time (~ 2 weeks) Stokes' drift can vary by as much as 100% due to spring-neap fluctuations and allowance must be made for this in any future verification. Even after taking all these factors into account direct measurement of Stokes' drift by local methods such as comparisons between parachute drogue trajectories and current meter virtual displacements is further complicated since the former measurements are made at a fixed distance below the sea surface whilst current meter measurements are usually made at a fixed distance above the sea bottom. It may be that the only satisfactory field verification of Stokes' drift will be by examining distributions of labelled tracers over long periods and comparing these distributions with current meter predictions, subject to the restrictions outlined here.

References

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Dooley H D	(in press)	Hypotheses concerning the circulation of the northern North Sea. J. Cons. perm. int. Explor. Mer 36 (1).
Ramster J W & Durance J A	1973	A comparison from the northern North Sea, of the drift of a parachute drogue with estimates of Lagrangian drift calculated from the data collected at a triangle of moored current meter stations. ICES C.M. 1973/C:4. Hydrography Committee. (mimeo)
Longuet-Higgins, M S	1969	On the transport of mass by time-varying ocean current. Deep Sea Res. 16 431-447.

TABLE 1

Harmonic Constants (Phase relative to 0000hr GMT 15 May 1973)

(NORTH COMPONENTS)

Position	Depth(m)	AMPLITUDE (Cm s^{-1})			PHASE (DEGREES)		
		M_2	S_2	O_1	M_2	S_2	O_1
N	36	19.03	3.95	2.38	348	165	205
N	109	18.54	3.51	1.95	348	163	196
S	30	25.91	5.19	2.88	29	208	219
S	90	19.78	3.48	2.23	21	209	229
N*	-	19.00	4.00	2.5	348	165	200
S*	-	19.00	4.00	2.5	25	209	224

*Figures used in Stokes' drift calculations.

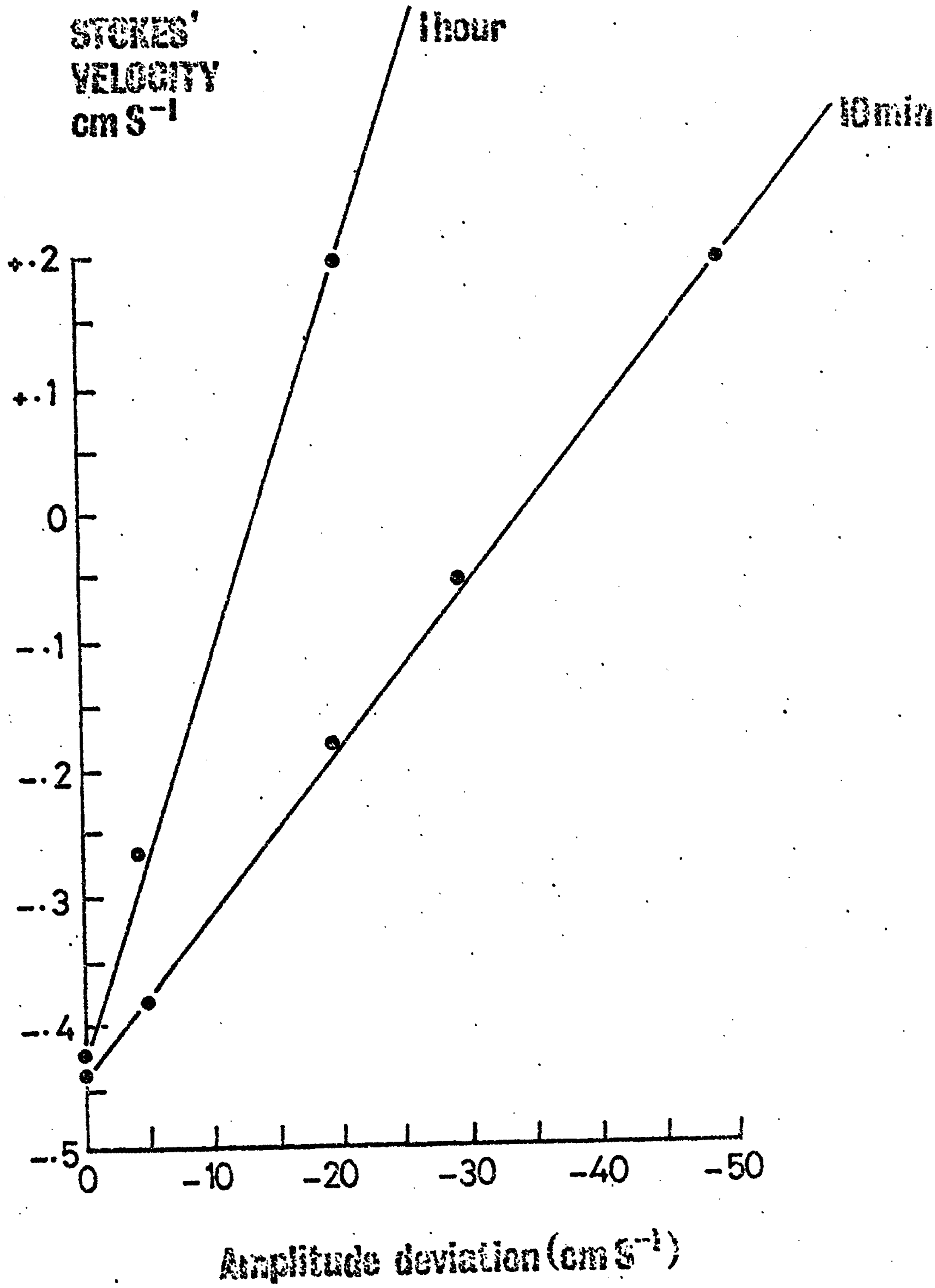

Fig. 1 Computational distortion of Stokes' velocity due to inhomogeneous tidal streams.

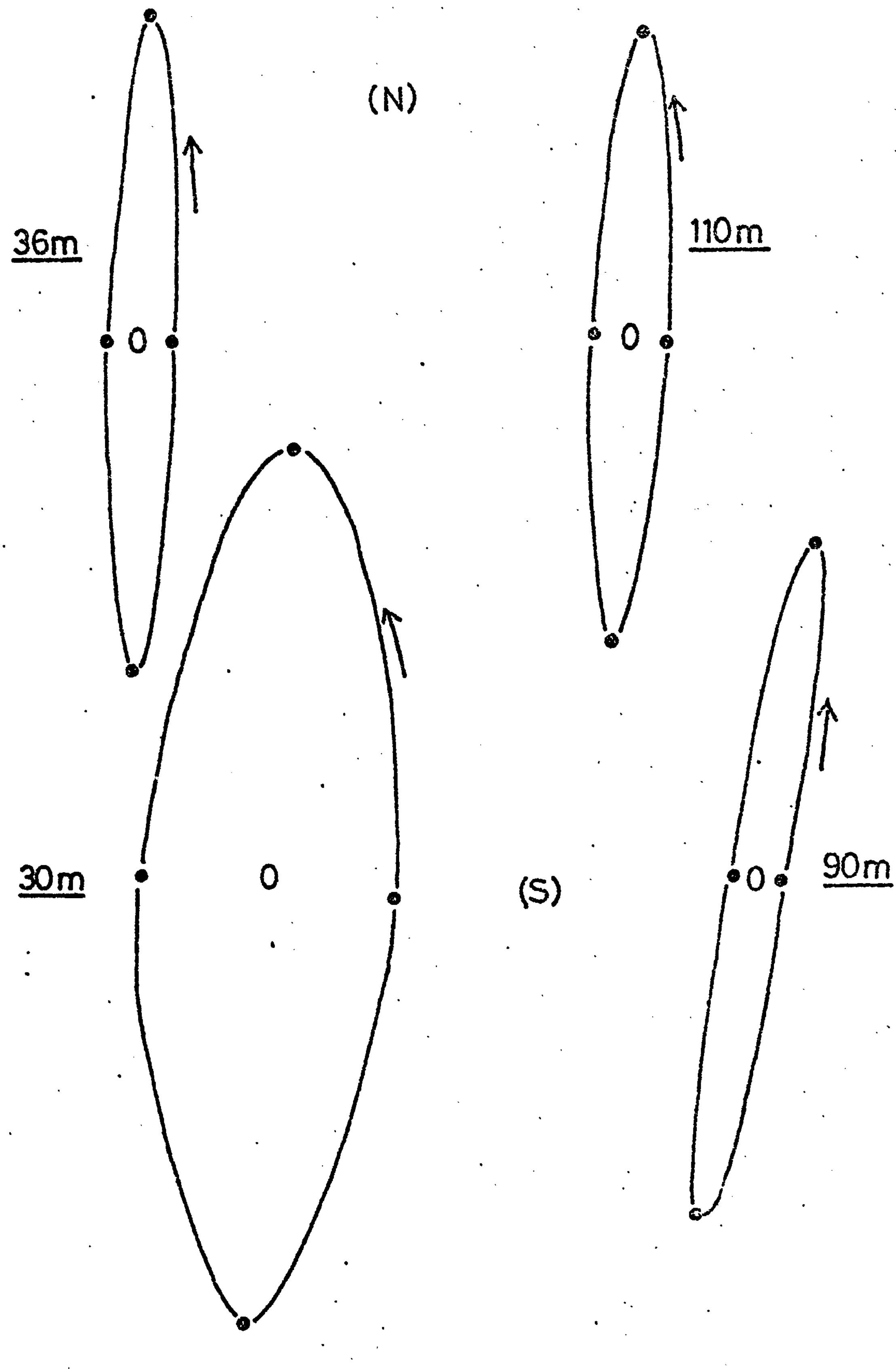

Fig. 2 Current ellipses for M_2 constituents at positions N and S.

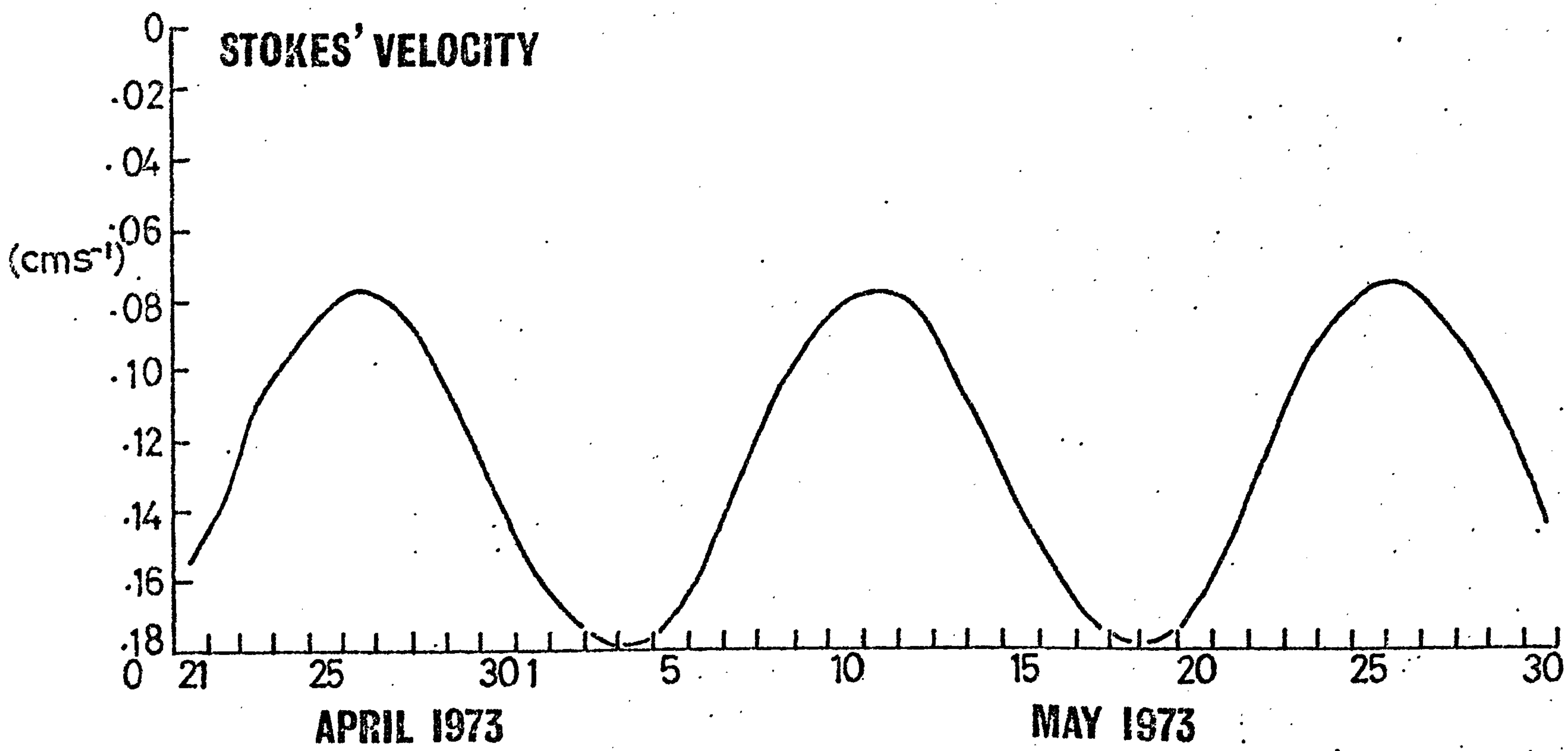

Fig. 3 Southerly component of Stokes velocity from 21 April - 30 May 1973.

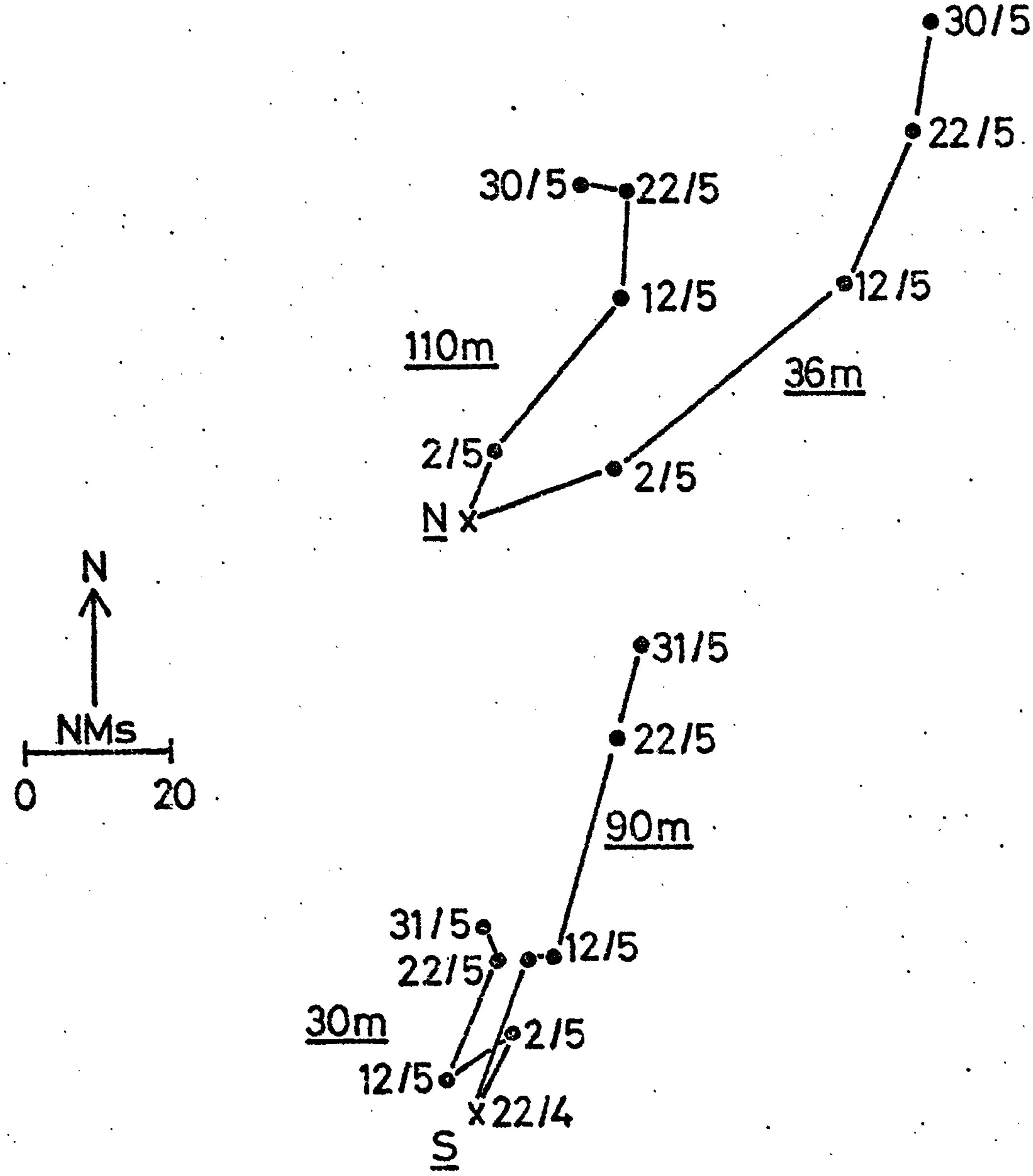

Fig. 4 Virtual displacement of currents over 10 day periods at positions N and S.

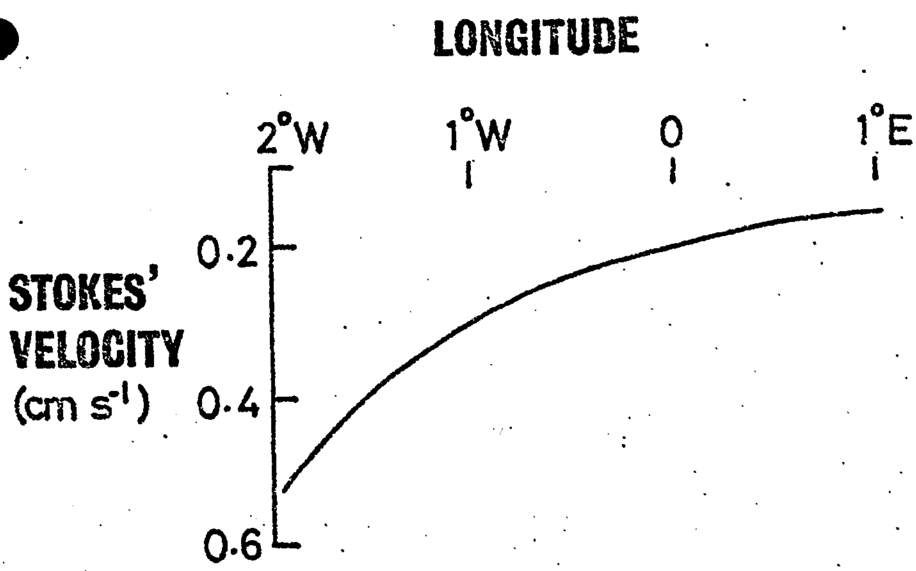

Fig. 5 Predicted distribution of Stokes velocity between 1°E and 2°W (Scottish coast).