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Investigations with drift cards to determine the influence of the wind on surface currents

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ABSTRACT

The relation between the wind velocity at 10 m above the sea and the velocity of the respective drift current was checked by means of experiments. Postcards watertightly wrapped into 1–2 mm thick plastic envelopes were used as drift bodies. On the assumption that no difference exists between wind and drift direction, a statistic evaluation of 42 experimental series with 948 drift bodies showed that the velocity of the surface layer amounts to 4.2 per cent of the wind velocity.

1. Introduction

One reason for the surface currents in the oceans is the stress effected by the wind on the surface of the sea. It is this stress that maintains a current system in the area of lower and middle latitudes where constant winds are prevailing. The great equatorial currents and the current systems of the Gulf Stream and the Kuroshio are the eminent features of this system. But even in higher and middle latitudes with winds changing in direction and force, drift currents can be met. But they are as inconstant as the winds themselves. Though they are therefore without importance for the whole circulation of the oceans, they might, nevertheless, be felt strongly in some localities. They play e. g. a decisive part in the transport of oil residues released into the sea from ships, from tankers in particular. For years the German coasts have been suffering from considerable oil pollution, as such oil residues have been driven to the coasts by the wind. For this reason the German Hydrographic Institute has conducted experiments with drift bodies which should elucidate the drift velocity of the surface layer. When scrutinizing the respective literature on drift experiments, it turned out that there exists a variety of different results. The velocity of drift currents varies between 1.0 and 3.3 per cent of the velocity of the wind above the sea. Our own observations conducted during the average of a tanker in the mouth of the river Elbe had even given a value of 4.3 per cent, as can be seen from Fig. 1. The 8,000 t of crude oil pumped into the sea from the damaged tanker *"Gerd Maersk"* were for 12 days followed and fixed by bearings from aeroplanes and ships. Fig. 1 represents the southern boundary-line of the oil patch from 19th to 29th January 1955 and the positions which will result when 4.3 per cent of the wind velocity observed in the southern North Sea are used to determine the drift route.

An analysis of the drift data varying between 1.0 and 4.3 per cent suggests that the thickness of the layer represented by the drift bodies has a decisive influence on the result (compare Table 3). It was for that reason that drift bodies were used in the experiments carried out in 1961/62 nearly corresponding to the thickness of the layer of oil patches (1–2 mm) before spreading over the water as thin oil film. The drift bodies consisted of post cards (Fig. 2) wrapped into double plastic envelopes to protect them from water and birds and flatly drifting on the water. They cor-

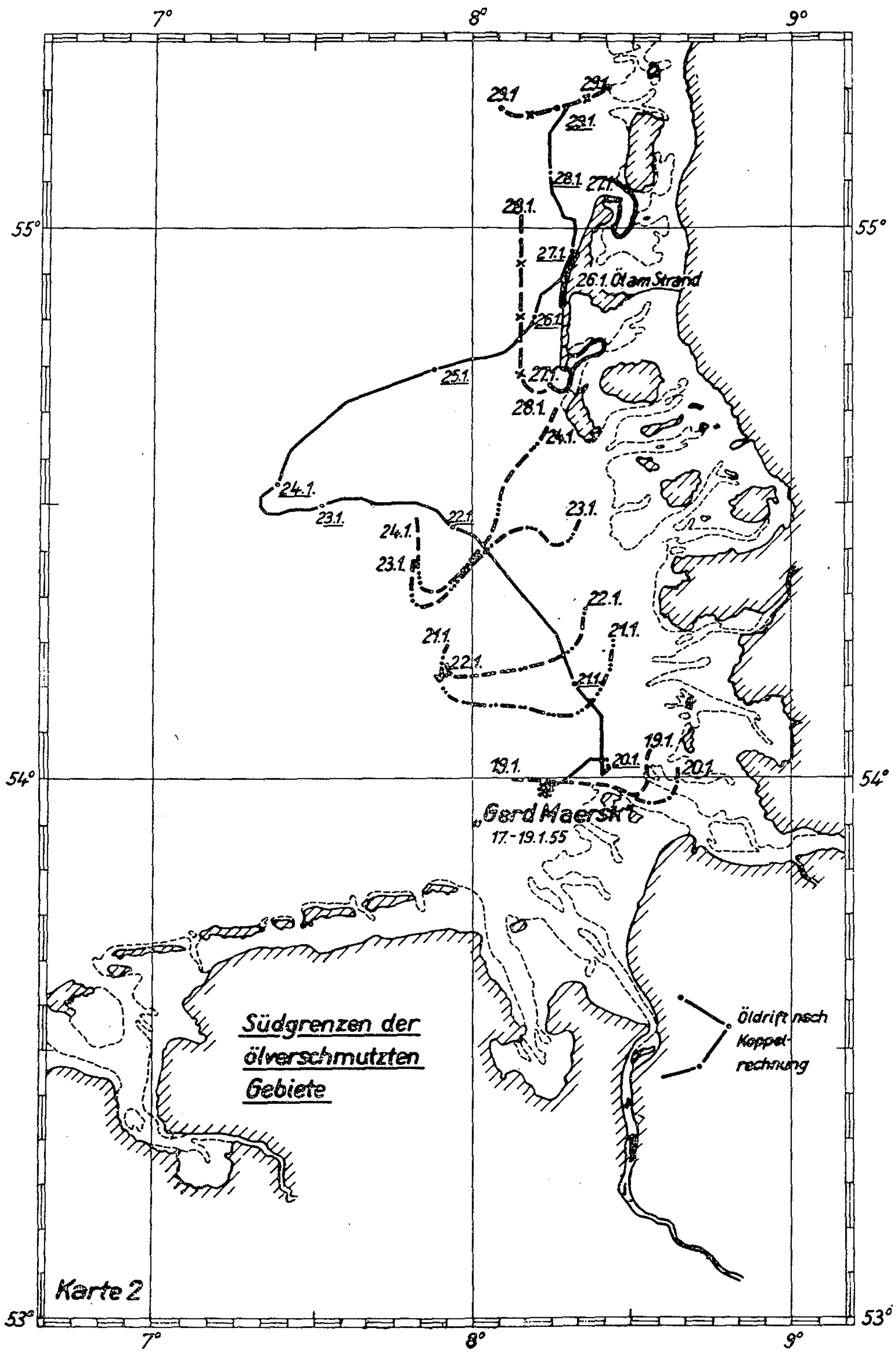
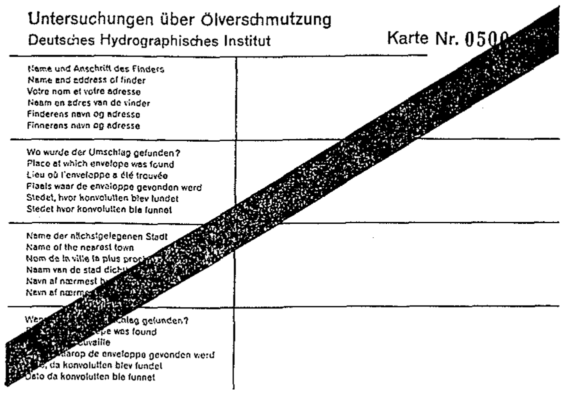


Fig. 1. Drift route of an oil patch of 8,000 t crude oil.
-·-·- = Southern boundary-line of the oil polluted area.
—— = Drift route computed with $k=4.3$ per cent.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Karte Nr.

Name und Anschrift des Finders
Name and address of finder
Votre nom et votre adresse
Naam en adres van de vinder
Finderens navn og adresse
Finnerens navn og adresse

Wo wurde der Umschlag gefunden?
Place at which envelope was found
Lieu où l'enveloppe a été trouvée
Plaats waar de envaloppe gevonden werd
Stedet, hvor konvolutten blev fundet
Stedet hvor konvolutten ble funnet

Name der nächstgelegenen Stadt
Name of the nearest town

Fig. 2. A drift card used by the German Hydrographic Institute as drift body.

responded to the envelopes formerly used by the National Institute of Oceanography in Wormley, England, for similar experiments in the Atlantic Ocean (Lawford, 1956; Hughes, 1956).

2. Observations

The experiments were conducted in the North Sea. Within 15 months 4,122 drift bodies were liberated in the sea; in one position generally 20–30 pieces at the same time. These positions are spread all over the North Sea between 53.5° and 60°N latitude as well as 1.5°W and 7.5°E longitude. 68 per cent of the cards were retrieved and returned. They were recovered at the coasts of all states bordering the North Sea: 16 per cent of the cards were returned from Norway, where the remotest place of discovery off to the North lay east of the North Cape (70.5°N; 28.8°E); 10 per cent from Sweden, mainly along the coast to the North of Göteborg; 30 per cent from Denmark; 11 per cent from Germany; and 1 per cent from both Great Britain and the Netherlands. The duration of the drift varied between 2 and 566 days.

4 months after the release of 2,000 cards when 48 per cent of them were returned, an intermediate computation was carried out to get a first impression of the results. This computation will be the subject of this report. Cards were released from 42 places. 948 cards returned from 133 places of retrieval could be evaluated. Out of the cards originating from the same place of release and discovered in a coastal strip of 10 nm length only one place of retrieval was taken into consideration. The date of the firstly discovered card was in such cases assumed as date of retrieval. The drift duration of the 948 cards considered in the intermediate computation varied between 10 and 92 days.

The wind values were derived from weather maps. They were fixed for the hours 0, 6, 12, and 18 for 11 fields into which the North Sea had been divided. These fields had a side length of $3\frac{1}{3}°$ latitude and 5° longitude. It was not the gradient wind that was used but the wind at 10 m height above the sea. The wind velocity determined by the isobars of the weather maps was reduced to this height and checked by the ship's reports of the respective fields; the wind direction was taken direct from the weather maps. The value ascertained for a field was accepted to be valid for the whole field and for a period of 6 hours. It was thus assumed that a drift card located e. g. at 0 o'clock in a distinct field was subjected for 6 hours to the influence of a wind constant in direction and force, i. e. to the mean value derived for this field from the weather maps.

3. Computation method

It results from the theory of the drift currents set up by V. W. Ekman (1905) and developed among others by J. E. Fjeldstad (1929) that between the velocity of the wind above the sea W and the surface current u exists the linear relation $u=k \cdot W$. The factor k called "wind factor" represents a percentage rate, in case u is given in cm/sec and W in m/sec as is the custom. According to this theory, a deviation angle α exists between the direction of the wind and that of the drift current, pointing to the right of the wind direction in the Northern Hemisphere. After Ekman $\alpha=45°$ results for a stationary current in an unstratified and unlimited ocean with infinite depth. This value was not often confirmed by drift ob-

Table 1. Wind factor k according to a rough evaluation of the observations.

Time of drift t=time between release and retrieval	Length of drift l =distance between place of release and place of retrieval	Minimum drift velocity $u_0=l/t$	k presuming a mean wind force of		
			3 Bft	5 Bft	7 Bft
10.5 days	152.7 nm	14.5 nm/day	6.7	3.4	2.0
25.75	145.0	5.6	2.6	1.3	0.8
74.0	522.4	7.1	3.3	1.7	1.0
90.25	679.0	7.5	3.5	1.8	1.0

servations. In stratified seas, limited as to area and depth, as, for example, in the North and Baltic Seas, the observations indicate considerably smaller angles of deviation (WITTING, 1909). In case of a thin surface layer of 1–2 mm and changing conditions—wind direction and force frequently changing—$\alpha=0°$ can be assumed as experimental basis.

a) Rough calculation

It should be ascertained by a rough calculation which of the k values should be considered in the final computation. It was assumed that the drift route of the cards (l) from the place of release to the place of retrieval was a straight line. The firstly discovered card of each experimental series served to determine the drift time (t). As drift velocity results a minimum value $u_0=l/t$. Table 1 gives the results of several experimental series with a drift duration between 10 and 90 days and a drift route of 145–679 nm. The drift velocity u_0 amounted therefore to 5.6–14.5 nm/day.

The last columns of the table demonstrate which k values will result if a mean wind force of 3, 5 or 7 Beaufort (=wind velocity 4.5, 9, or 15 m/sec) is assumed for the whole drift time. It is further assumed that high drift velocities were connected with high mean wind velocities and insignificant drift velocities with moderate winds; the underlined k values may be taken as probable. The average of all experimental series produced a k value of 2.9. It has, however, to be considered that the u_0 values of the Table are too small, as the actual drift route does not consist of the shortest distance between the place of release and place of retrieval. It is more likely to have taken a zigzag course corresponding to the changing directions of the wind during the drift time. It must also be considered that too high a value of t was assumed in the Table because the card may have been lying for some time on the beach before being discovered. The rough calculation therefore suggested $k>2.9$. Thus $k=3.5$ was assumed as central value in the following computation and the computation for $1.5<k<5.5$ was carried out.

b) Final Computation

The wind factor valid for the surface drift was statistically ascertained in a second process of work. Therefore, 16 drift routes were computed for each experimental series, i.e. for each of the 42 places of release, assuming 16 different k values between 1.5 and 5.5. In all cases $\alpha=0°$ was fixed. The drift routes were composed of sections which corresponded to the influence of the wind in a period of 6 hours, as the observed winds were known from 6 to 6 hours. Each computation of a drift route was dropped as soon as the drift reached a coast. When no coasts were reached on the computed drift route, that position was considered to be the computed place of retrieval which was reached by the drift card at the time of retrieval. The distance was determined between the computed and the observed places of retrieval of each experimental series. If this distance was not greater than a fixed r, the so-called "radius of the area of hit", a hit was booked for that k value used for the respective drift route.

The computation was carried out by means of an electronic computer IBM 1620. Dr. MUNKELT of the German Hydrographic Institute prepared the programming. The geographic coordinates φ_1, λ_1, were derived from six to six hours from the position φ_0, λ_0 through the relations:

$$\varphi_1 = \varphi_0 - a \cdot \cos \alpha$$
$$\lambda_1 = \lambda_0 - a \cdot \sin \alpha \cdot \sec \bar{\varphi}$$

where

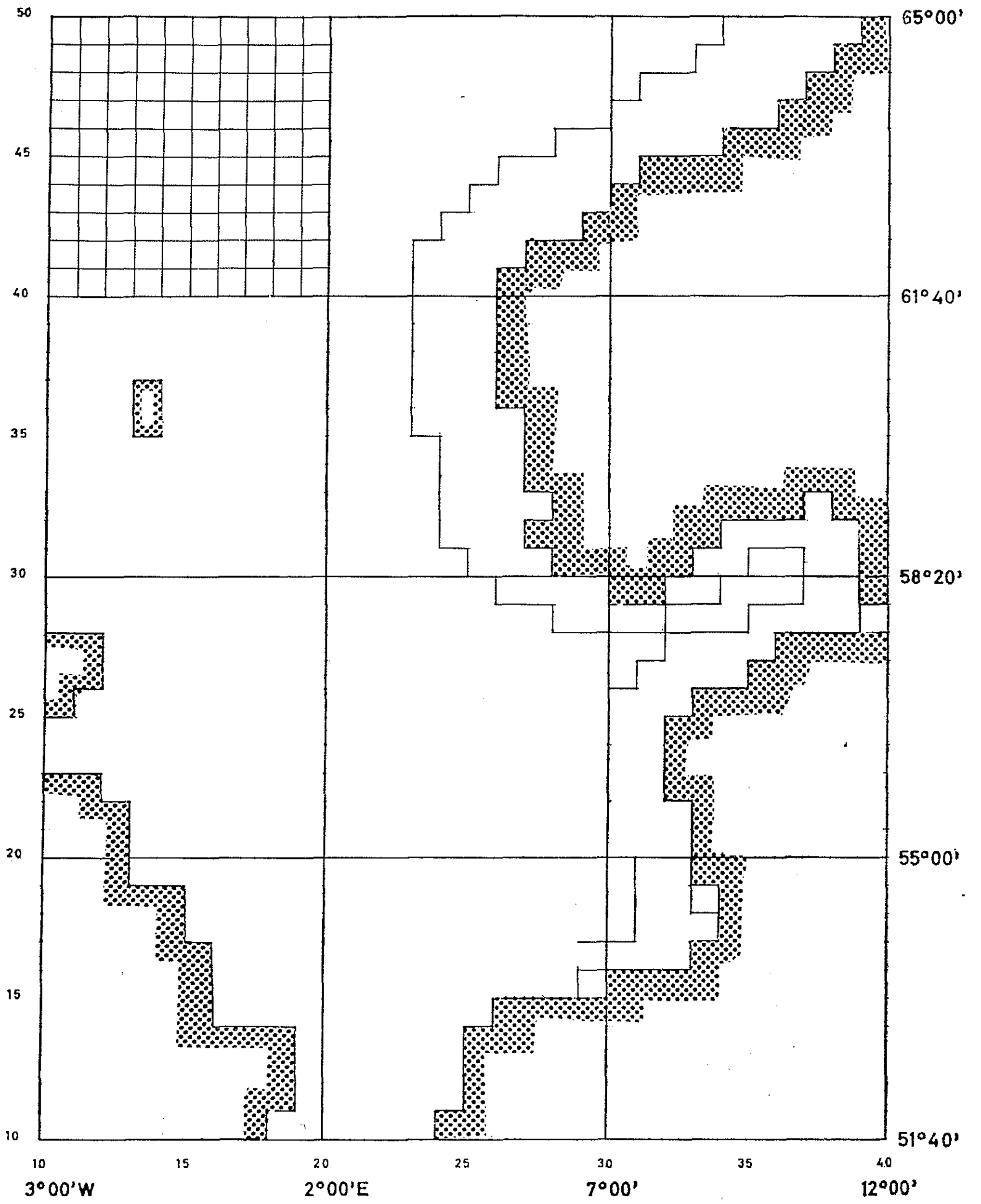

Fig. 3. The area of the North Sea considered in the drift investigations (schematic representation of the trend of the coast for computational reasons; sea area sub-divided into 11 parts, for which equal meteorological conditions were assumed).

a=drift route in 6 hours=loxodromic distance between the positions at the times T and $(T+6)$ hours$=6\delta \cdot d$
δ=proportional factor=0.01 k
d=run of the wind per hour
α=angle to the North direction
$\bar{\varphi}=\frac{1}{2}(\varphi_0+\varphi_1)$

The computation was facilitated by a transformation of coordinates where the zero point was so placed that all positions in the North Sea, latitude as well as longitude, could be expressed by a figure between 0 and 4 with three decimal places (Fig. 3). Thus the position of the drift cards could be determined within an area of investigation of 40×40 m. Areas of 100 times the side length (comp. Fig. 3, left top) served to distinguish between land and sea which was automatically done by a suitable programming of the computer. The trend of the coast could therefore be represented in the dimensions of these areas, as the hatching of Fig. 3 will show. The thinner line off the coasts of Norway, Sweden, Denmark, and Germany represents a coastal zone where the computed wind drift was superposed by

Table 2. Number of hits for different values of r (region of hit) and k (wind factor).

r \ k	1.5	2.0	2.5	3.0	3.5	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	5.0	5.5
20 nm	6	32	32	49	42	36	38	35	27	36	50	58	56	52	38	30
40 〃	17	51	50	99	102	69	72	69	87	93	93	84	102	94	105	65
60 〃	28	74	89	130	147				141					148	126	123
80 〃	54	105	152	199	178				176					171	158	154
100 〃	111	174	204	234	193				200					190	162	158

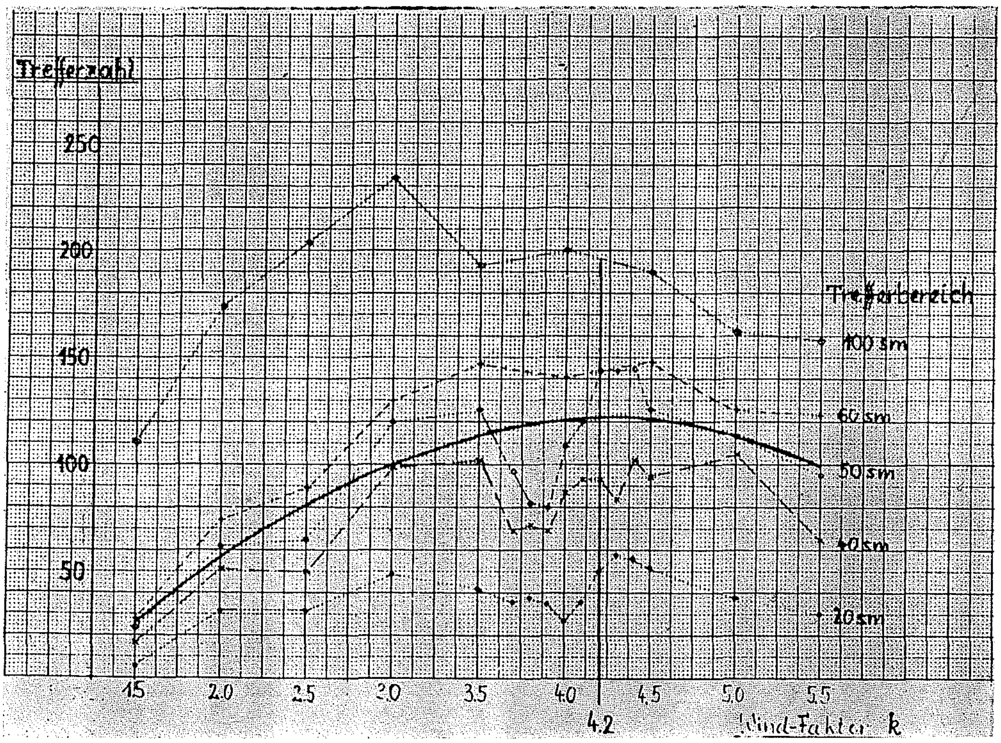

Fig. 4. Frequency of hits in different regions of hit (20, 40, 50, 60, and 100 nm). (Ordinate: number of the hits; Abscissa: wind factor k).

a constant current parallel to the coast, the force of which was assumed to lie between 0.4 and 0.8 nm/h. Off the British coast where no cards were discovered in the period of elaboration, it was unnecessary to assume an additional current close to the shore.

Table 2 represents as result of the computation the number of hits for the wind factors used lying between $k=1.5$ and $k=5.5$ for different areas of hit expressed by r. With an increased r the number of hits for each k value will rise too, as was expected. If the area of hits is getting too large ($r \geqq$ 80 nm), the number of hits for different k values will no longer differ considerably. If the results of the area of hits between 40 and 60 nm are taken as a basis, it will turn out that the number of hits depends on k, whereby the most favourable value is $k=4.2$. In Fig. 4 where the values of Table 2 are mapped out this can be seen from the compensation curve for $r=50$ nm.

4. A comparison of the results of different authors

The evaluation of the drift of nearly 1,000 cards by an intermediate computation produced the wind factor $k=4.2$, when the angle of deflection between the direction of the wind and that of the current amounts to $\alpha=0°$. This value nearly corresponds to that obtained when tracing a large oil patch ($k=4.3$). It will thus be possible to compute the drift route of the 42 experimental series in satisfying agreement with the places of retrieval of the cards. Figs. 5 and 6 demonstrate some examples. The plotted drift routes with different release places and times differ according to the changing wind conditions during the drift. The representation marks the distance covered by the drift cards in one day by various symbols. The same symbols indicate the places of retrieval of the various routes. The date of the beginning and end of the drift way as well as the times of retrieval are plotted.

Fig. 5 demonstrates with the route No. 1 to what high extent the surface drift depends on the changing wind conditions. The computed place of retrieval is in good agreement with the observed place. But one card of this experimental series retrieved near Skagen shows on the other hand what dispersion can be achieved with such experiments. Route No. 2 describes a long drift along the Norwegian coast with a good distribution of the places of retrieval. Route No. 3 justifies the high wind factor to a special extent. After an initial zigzag course the drift of the cards from November 29 on proceeds in a straight line towards the German and Danish coasts where it ends on December 7, midday. The mean wind velocity amounted in these days to 27 m/sec, i. e. wind force 6–7 Beaufort. The comparison of the times of retrieval with the computed times of the arrival at the coasts is of importance in this example: the cards have arrived up to 30 hours before the time. This suggests that under very high wind velocities the wind factor will probably be greater than 4.2. But perhaps it is also possible that an additional transport of the cards has taken place direct through the wind. It was observed during the release of the cards under storm conditions (wind force 9 Bft.) that the cards were sometimes seized by the wind when they were in the breaking crest of a wave. It was, however, never observed that the cards completely rose from the water; they only turned sometimes but then adapted themselves again to the surface layer. It can thus be assumed that the drift is not essentially falsified by this effect. And perhaps this phenomenon which could be observed only under rough sea conditions is limited to the first hours after the release when the plastic envelopes are still too stiff.

In Fig. 6 route No. 1 demonstrates another uninterrupted wind drift along the Danish coast to places of retrieval between Göteborg and Lysekil (Sweden). Even in this case a considerable mean wind velocity prevailed. It amounted in the last week of the drift to 26 m/sec. But here the cards did not precede the route computed with $k=4.2$. The cards were retrieved 3 days after the time computed for the arrival at the shore. On an average the difference in time between the retrieval of the first card and the computed time of the drift route near the place of the retrieval amounted to more than 10 days. This has to be considered if the attempt shall be made to compute the wind factor on a provisional basis as was done in

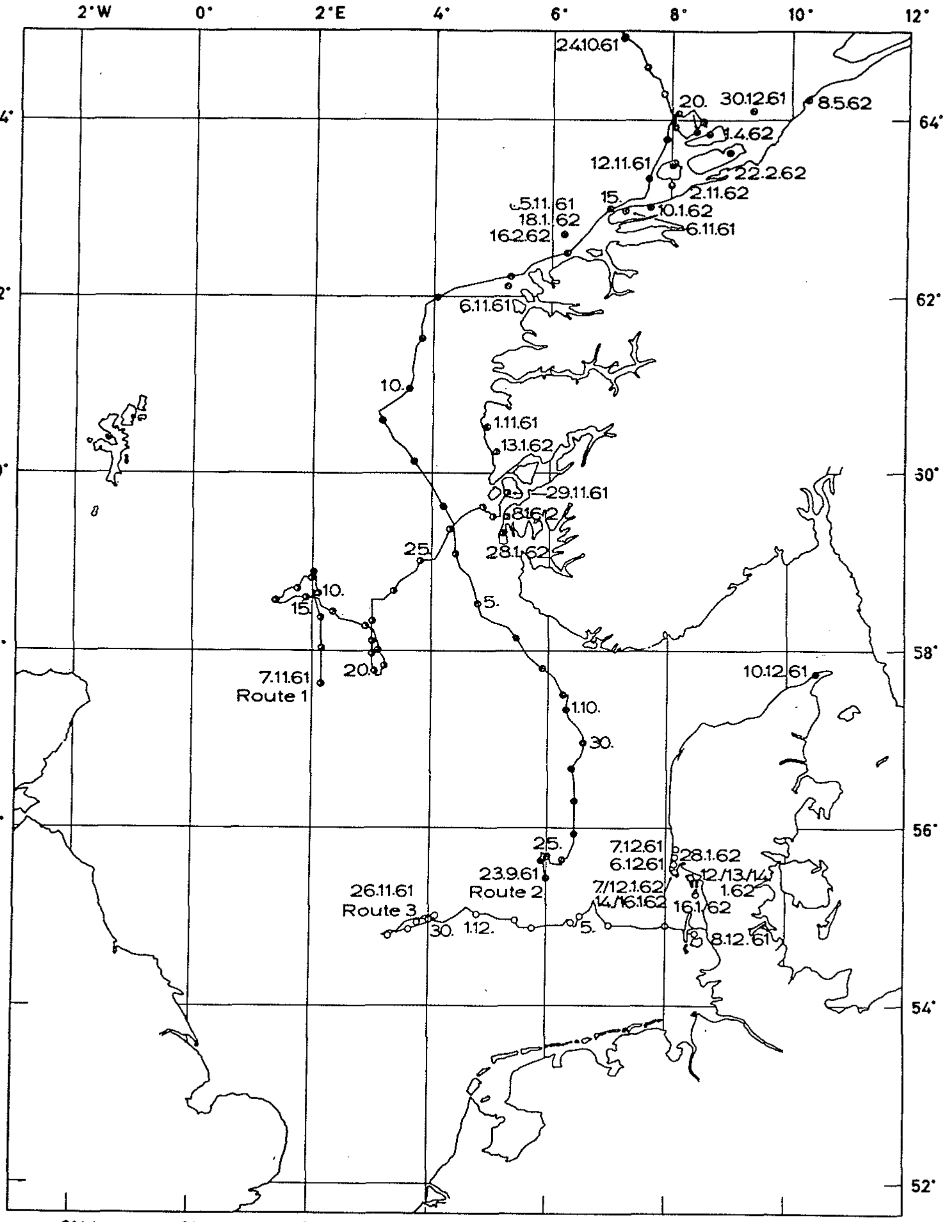

Fig. 5. Drift routes computed with a wind factor $k=4.2$ per cent.
Route 1: November 7–29, 1961;
Route 2: September 23–October 24, 1961;
Route 3: November 26–December 8, 1961.

part 3a (rough calculation). Route No. 2 demonstrates the influence of the current close to the Norwegian coast. The wind data referring to a field of 100,000 km^2 are no longer valid under the mountainous coast when the wind is blowing towards the coast. Some cards reach the computed place, but others are carried on to the North by the

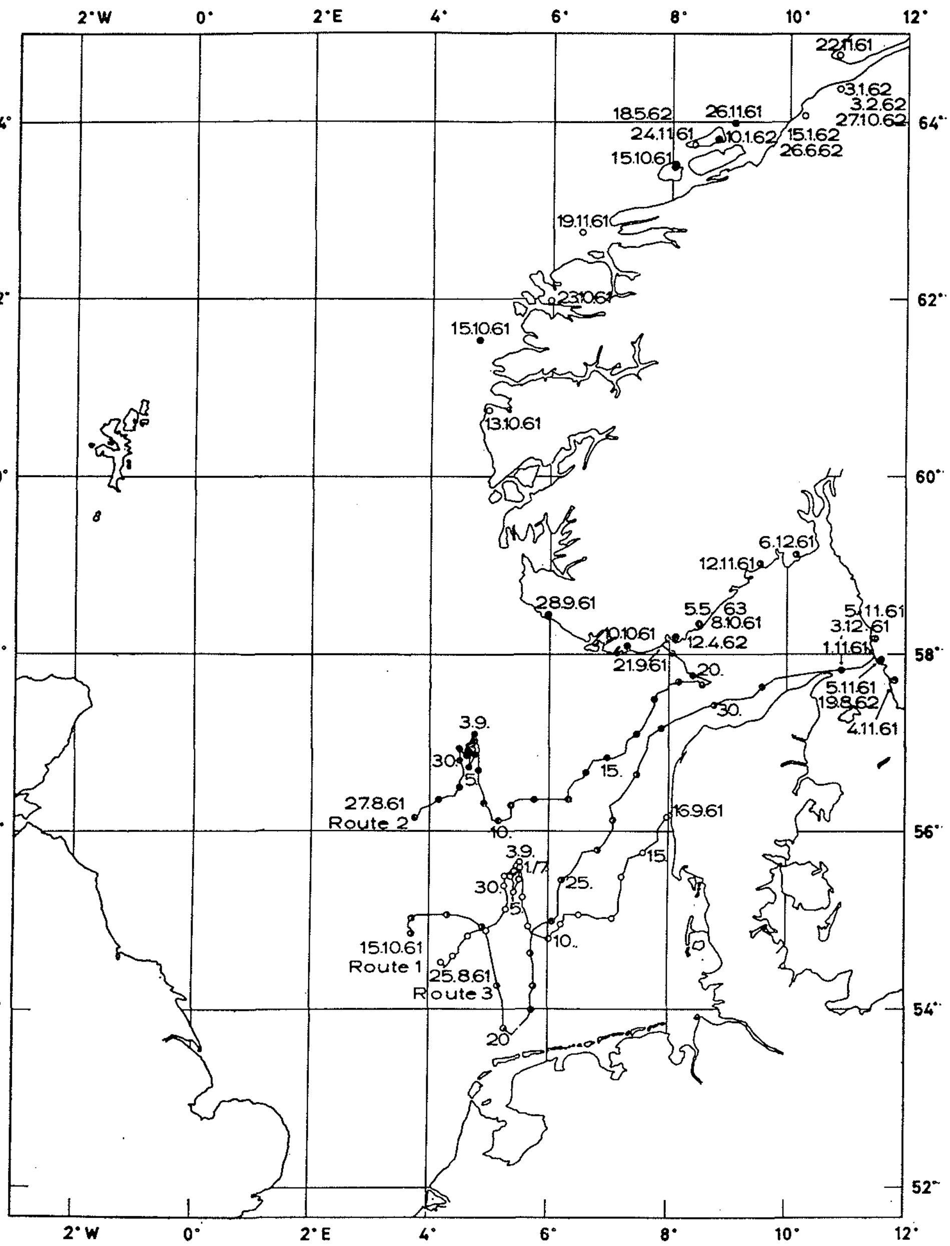

Fig. 6. Drift routes computed with a wind factor k=4.2 per cent.
Route 1: October 15–November 2, 1961;
Route 2: August 27–September 22, 1961;
Route 3: August 25–September 16, 1961.

current close to the Norwegian coast, and even at 64°N was one card of this series of experiments retrieved. The last example (route No. 3) shall demonstrate finally that in some cases considerable differences existed between the computed and the observed places of retrieval. It may be assumed that the North component was stronger during the last days of the drift than could be derived from the mean wind conditions. The cards will then have drifted along the Danish coast to the North where they were seized by the current close to the shore and distributed on a longer line of the coast.

In the following Table 3 a final compilation of the results of various authors is given.

From the way in which k was obtained in this compilation can clearly be gathered what was said in the beginning as to the perusal of the respective literature: the value computed for the wind factor k will increase with a decrease in the water layer from which the observations were obtained. The relation $k=1.26/\sqrt{\sin\varphi}$ (φ=geographic latitude) quoted by THORADE (1914) for which $\varphi=57°$ was taken in this Table, was derived from drifts of ships under high wind velocities. The thickness of the layer covered by it will amount to more than 5 m. The EKMAN value (1953) is based on current measurements conducted from anchored ships ("*Armauer Hansen*") at 5 m depth. ROSSBY and MONTGOMERY (1935) derived their value, which was again referred to the middle latitude of the North Sea, from experimental fluid dynamics. This value was considered

Table 3. Wind factor k determined by several authors.

Author	k	Method of determination	Valid for
THORADE	1.44	drift of ships	thick water layer wind; velocity 4m/sec
EKMAN	1.85	current measurements at 5 m depth	surface up to 5 m depth
ROSSBY/ MONTGOMERY	2.53	theory of hydrodynamics	"surface layer"
STOMMEL	2.9	drifting buoys	surface up to about 1 m
HUGHES	3.3	drift cards	thin surface layer
VAN DORN	3.6	experiments in basins	thin surface layer (extrapolated)
German Hydr.	4.2	drift cards	thin surface layer
Institute	4.3	drifting oil patch	thin surface layer

to be valid for the immediate surface layer. It is, however, open how this layer was defined. STOMMEL (1954) computed his value by means of drift observations from deep-going buoys; VAN DORN (1953) by means of model investigations in large artificial basins. His value corresponds to the critical value resulting for deep water. There remain in Table 3 those 3 values which were obtained direct on the basis of an observed oil patch drift or by means of the drift card method for a thin surface layer of some millimetres. The values of the German Hydrographic Institute agree with each other, while the value of HUGHES (1956) originating from drift observations in the Atlantic seems to be too small. His value (k=3.3) corresponds to the wind factor of gradient wind reduced to a wind at 10 m height above the sea used in our computations but also generally used. The computation method of HUGHES is not based on the exact drift route but corresponds to a similar consideration given in part 3a (rough calculation) yet improved in some items. It can be taken for sure that HUGHES would have obtained a higher value if he had considered the complete drift route and a more exact drift time (comp. the difference between our values $k>2.9$ in part 3a and $k=4.2$ in part 3b). $k=4.2$ to 4.3 will therefore be the critical value for a minimum surface layer drift in the sea. A further evaluation of the observations of 5,000 drift cards shall prove whether the assumption of $\alpha=0°$ is correct. It shall, moreover, demonstrate whether the relation between wind and current velocities assumed to be a linear one covers the whole range of wind velocities—from light breeze to heavy storm—or whether it is actually true that a higher wind factor results under higher wind velocities, as route No. 3 in Fig. 5 implies.

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