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THE OCEANOGRAPHY OF THE CELTIC SEA

I. WIND DRIFT

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(With Text-fig 1)

In the Celtic Sea, an extensive shallow area bordering the eastern North North Atlantic in 50° N. lat., we need to know the pattern of the currents, what drives them and what they carry. Our climate is evidence that much warm water is brought to our shores, so that we are concerned with an embayment of what is loosely called the Gulf Stream.

Dr J. N. Carruthers has for long stressed the importance of wind in all studies of marine productivity and has initiated and maintained, with the help of many colleagues, current measurements at light vessels, to be correlated with wind. In the southern North Sea these light vessels are spread over the whole area, but in the Celtic Sea there are relatively few and these are placed where they cannot reflect the current system even a few miles away. We have seen that when the measurements at the Seven Stones Light Vessel were generalized for the whole of Land's End passage they were misleading, although hidden within them was the basis of understanding to be extracted (Cooper, Lawford & Veley 1960). Again, currents at the Coningbeg Light Vessel will in large measure reflect the shape of the Saltees rather than events in the Celtic Sea. Consequently the circulation of the central Celtic Sea cannot be studied by current measurements at light-vessels as in the central North Sea.

Though the circulation of the whole of the North Atlantic is wind driven there is very strong intensification of currents on the western side where they persist without regard to local winds. The part played by the earth's rotation in bringing about this western intensification is becoming better understood, largely due to work by Stommel and by Munk (Stommel, 1958). On theoretical grounds Munk has been able to devise a system of gyrals which closely represent events. There is a boundary between two gyrals in about 50° N. lat., so that if we had no local winds hereabouts and our local circulation was mainly due to ocean-wide causes we should have only trifling currents.

There is, however, a North Atlantic drift in a generally north-easterly or easterly direction towards the British Isles and Faroe–Shetland Channel. Within the Celtic Sea most current charts show arrows pointing east towards the English Channel, or with a clockwise curl parallel with the Biscayan coasts of France and then of Spain. Though this is the predominating current system resulting from the prevailing winds, at any moment currents created within the Celtic Sea by variable winds may be found flowing in any direction (*Irish Pilot*, Hydrographic Department, Admiralty, 1954). Over the year as a whole, and in most months, winds from south-west and west are more frequent than from any other direction, the most frequent directions after south-west and west being south and northwest. From March to May, by contrast, north-easterly winds become frequent while northerly winds are common in April. However, preceding our cruise in April 1950 (Cooper, 1961), northerly or north-easterly winds did not occur until we were actually running along the south coast of Ireland. Informative wind roses for the Western English Channel and the Irish Sea have been published by Dietrich *et al.* (1952).

Prevailing winds must create prevailing drift currents. In winter our prevailing south-westerly and westerly winds should produce a surface drift of about 45° to the right (Ekman, 1905). Our prevailing surface currents should therefore set towards east or south-east in winter and will be reflected by the drift of ships and surface-dwelling animals.

The empirical direction given in the *Irish Pilot* is 30° to the right of the wind. This is probably a mean statement derived from the drift of ships in all 12 months and from observations from survey ships, mostly made in summer.

The transfer of energy from the surface downwards takes time, so that transient changes in direction of surface drift should be smoothed out. The movement of deeper water, though much less in velocity, should be more constant in direction. It is this deeper drift that we have some hope of recognizing when we attempt to derive residual water movements from the distribution of properties such as temperature and salinity.

Mass transport in winter will tend to be 90° to the right of the prevailing winds in the Western Celtic Sea, i.e. towards south-east and south. As the Celtic Sea shoals towards the east, mass transport in winter will come more nearly in line with the surface drift, i.e. towards Ushant and the south-western English Channel.

In summer, when a strong thermocline builds up, wind drift will become confined to the warm surface layer and will approach more nearly to the direction of the wind.

These three paragraphs, written at the very end of the investigation, epitomize the empirical findings and agree with the requirements of the Ekman spiral.

They mean that wind records from the well-exposed Meteorological Station at Scilly, in conjunction with the Ekman spiral, may be used to give a rough and ready assessment of wind drift in the Celtic Sea well away from land at the time of a specific biological investigation. A further advantage of concentration of effort at Scilly is that there have already been a number of meteorological and current studies there (*inter alia*, Sheppard, Charnock & Francis, 1952; Carruthers, Lawford & Veley, 1951*b*).

They also mean that, if there is no change in the direction of the prevailing wind, the North Atlantic wind drift both over the deep ocean and within the Celtic Sea should take a more northerly direction in summer than in winter. Again the warmer the surface water, the more northerly the summer deviation will be.

The strandings of exotic animals on our coasts, such as Kemp's loggerhead turtles (Deraniyagala, 1939), *Physalia* (Wilson, 1947) and *Ianthina* (Wilson & Wilson, 1956) provide evidence about the north-easterly drift in the North Atlantic, but do not clarify our understanding of circulation within the Celtic Sea.

This account does not apply near coasts so that we have to search for restricted regions of the Celtic Sea where a more persistent and predictable system of currents may flow (Cooper, 1960 *a*, *b c*). Since the word 'current' has come to acquire a wide and diffuse range of meanings, we will first define what it is to mean here. Physicists commonly have precise meanings in mind, made clearer by suitable adjectives and use of the notion of streamlines (cf. Lamb 1924, p. 18, and Milne-Thompson, 1938, p. 273). The streamlines set out in an earlier paper on water flow west of Ushant in summer (Cooper, 1960 *b*) conformed with these limitations. The currents associated with such streamlines involve little turbulent mixing with enveloping waters and the chemical properties of water along the length of such currents will change little due to physical causes. The chemical properties may change due to photosynthesis and metabolic processes of organisms living in the water.

When measurements are made at a fixed position, such as a light vessel, the word 'current' has a different meaning. Each measurement singly is a measurement of current, but over a period of time very different water masses from very different sources may pass by. The sum of all the measurements does not make up a current in the sense first considered. This argument applies whether or not we first 'extract the tide'. With Carruthers *et al.* (1951 *b*) it is better here to speak of 'residual water movement'.

The eddy 'current' of the north-eastern Celtic Sea, to be discussed, is something different again. Though such a system of water movements does not conform with a physical picture based on streamlines, nevertheless, it must involve considerable conservation of energy and momentum. It is subject to exchange of heat with the atmosphere and of turbulent mixing with neighbouring waters. There is great variation in chemical and biological properties around the eddy so that it may be termed a current only in a diffuse sense. Separate sectors of the eddy will be described as the Land's End corner current, the South Wales coastal current, the Carnsore corner current and the Nymphe Bank current.

Movement of surface water by variable winds must necessarily lead to much exchange of water between water masses and to much turbulent mixing. Though in a somewhat statistical sense a residual current results, it is utterly different in character from a streamlined affair such as has been described for the intermediate and bottom water west of Ushant in summer (Cooper, 1960*b*). That had nothing to do with the local winds.

I prefer therefore not to use the precise word 'current' for the phenomenon observed in the western Celtic Sea in early spring but to describe it by the vaguer word 'drift'.

Evidence is slowly accumulating (cf. p. 263) that the movement of water in such a drift may be intensified over the break of slope between the shelf and the continental slope of the Celtic Sea. Application of the term 'current' to this feature, if indeed it persists over a distance, may be misleading since it might suggest the power of long-distance transport of animals. It seems more likely that such water, with the animals it carries, would frequently be slung to one side and replaced by new water with another population of animals. Unless and until streamline flow is established in currents above the continental edge it would be wise to assume its absence. There may be continuity of movement but not of matter.

In quantum theory it is impossible to regulate or measure the co-ordinates and momenta of a system more accurately than to require that they lie somewhere within a given cell. Although for different reasons, there is a similar limitation upon biological applications of non-streamlined water movements. One may say that, when studying transport of chemical constituents or biological organisms by a non-streamlined system of water movement, it is not practical to measure the co-ordinates and momenta of the system more accurately than to require that those lie somewhat within a given parcel of water of fairly large size.

ON COMPUTING WIND DRIFT FROM WIND STRESS

The wind stress at the surface τ is usually related to the wind velocity W by an equation due to Ekman (1905) and much studied by Thorade (1914)

$$\tau = \gamma^2 \rho' W^2, \tag{1}$$

where ρ' is the density of the air; γ^2 is a dimensionless constant but dependent upon the height at which the wind is measured, upon the nature of the stability of the moving air and upon the surface of the sea being hydrodynamically rough with a roughness length of 0·6 cm (Rossby, 1935; Rossby & Montgomery, 1935)

This means that equation (1) may hold for winds exceeding 5 m/sec (12 knots, or force 4 Beaufort and over). Winds of Beaufort force 3 and less would seem to have little power to produce wind stress sufficient to initiate much water movement. A number of investigations (Sverdrup, Johnson & Fleming, 1942, pp. 489–91) have agreed that γ^2 has a value close to 0·0026 and today there is no more assurance about this value (Fofonoff, 1960).

Associated with equation (1) and subject to the same limitations is a simple equation for calculating wind drift v from wind velocity W.

$$v = \frac{kW}{\sqrt{\sin\phi}}, \tag{2}$$

where ϕ is the latitude.

In view of the doubt that still remains today as to the value of k it is remarkable that the presently accepted value 0·0126 differs so little from that first proposed by Ekman (1905), 0·0127. In our waters it has been found to fit observations at a number of light vessels (Carruthers, Lawford & Veley, 1950*a*, *b*,; 1951*a*, *b*; Carruthers & Lawford, 1950).

Nevertheless, in a careful study, spanning 7 days in January, 1951 at Scilly (Sheppard *et al.* 1952), the conditions of air flow required for equations (1) and (2) to hold were not found.

Unfortunately, though Munk (1947) has agreed with Ekman (1905) and Thorade (1914) as to the validity of the two equations, others have proposed that the wind stress may be proportional to $W^{\frac{3}{2}}$ (Neumann, 1948) or W^3 (Francis, 1951). Evidently the conditions of stability or turbulence of air flow has a large effect on the relations between wind drift, wind stress and wind velocity.

For practical application, it would seem that we must accept equation (2) as a semi-empirical means of assessing wind drift from meteorological records.

MUGGIAEA AS A BIOLOGICAL INDICATOR OF WIND DRIFT IN THE CELTIC SEA

The siphonophore *Muggiaea atlantica* was first identified in Plymouth waters, and used as a drift indicator by Gough (1905). Russell (1934; 1935*a*, *b*) considers it to be an indicator of 'south-western' water. It may rapidly reproduce asexually, and, since it seems to favour the upper layers, it is an indicator of wind drift.

Extensive records of its distribution in the Celtic Sea were made during the mackerel investigations in 1937–9. In 1938 between 7 and 18 April and 31 May and 5 June (Corbin, 1947, p. 67, fig. 1; p. 107, fig. 13D and E), from the neighbourhood of Land's End it appeared to spread to the south-west. This direction of movement was not what would have been anticipated from our picture of the 'prevailing' drift current in the mouth of the English Channel (Matthews, 1914).

Consequently in 1947 I estimated the probable wind-drift current at the time of Corbin's investigations from the recorded winds at Scilly. Though recorded continuously with an anemometer at 10 m, these results were reported in the Daily Weather Report as Beaufort numbers.

The records have been reconverted by the standard formula (Meteorological Office, 1952)

$$W \text{ (in cm/sec)} = 83{\cdot}6\sqrt{B^3}. \quad (3)$$

In 49° N. lat, combining equation (2) and (3)

$$v = 1{\cdot}32\sqrt{B^3}. \quad (4)$$

Assuming that the wind blows steadily with force B Beaufort for 3 h before and 3 h after the time of the reading, the distance travelled by the surface drift in 49° N. would be $0{\cdot}285\,B^{\frac{3}{2}}$ km.

The wind does not blow for long with unchanged strength, neither does it continue precisely in one direction; none the less there are periods when it blows from one general direction for some time so that the time spent in initiating the drift is small compared with the time spent in maintaining it. When this happens, as in April and May 1938, it is possible to break down the wind records into consecutive groups. Within each group the computed wind drifts have been added vectorially (Table 1), but equating winds of force 0–3 to zero drift.

TABLE 1. WIND DRIFT AND DISTRIBUTION OF *MUGGIAEA*

Wind drift computed between two cruises on which the distribution of *Muggiaea atlantica* was charted, 1938.

Period	11 April (21.00 h) to 8 May (03.00 h)	8 May (03.00 h) to 15 May (15.00 h)	15 May (15.00 h) to 1 June (21.00 h)
Total number of records	105	30	69
Records of light breezes, force 0–3	34	14	25
Records of force 4–8	71	16	44
Days elapsing	$26\frac{1}{4}$	$7\frac{1}{2}$	$17\frac{1}{4}$
Vector mean direction of winds force 4–8, from	52°	187°	278°
Assumed deviation of wind drift from direction of wind	+40°	+35°	+30°
Direction of wind drift, towards	272°	52°	128°
Vector wind drift (km)	166	44	104
Scalar wind drift (km)	189	47	139
Efficiency factor	0·88	0·93	0·75
Depth of frictional influence (m)	65	74	72

If the wind blows steadily in a given direction the maximum proportion of the wind energy will be employed in moving the water in a straight line. If the direction and strength vary somewhat, the drift will change in direction so that the distance made good in a straight line will be less than the actual zig-zag course followed, i.e. the vector distance will be less than the scalar distance. Moreover, some of the available energy of the wind will be spent in overcoming inertia when changing the direction of the drift and not for urging this forward; about 24 h will be required to develop a new steady drift after a change of wind (Ekman 1905, p. 16). The ratio of the vector to the scalar distance therefore provides a measure of the efficiency of the winds in setting up a drift. A prolonged steady wind would have an efficiency factor of unity, whilst winds completely random in direction and strength would have an efficiency factor approaching zero. In Table 1 assessments of this factor are included and it is suggested that greater trust can be put in the final drift calculation if the factor exceeds 0·9 than if it had been only, say, 0·5.

An exact assessment of the angle of deviation of the mean vector drift from the mean vector wind is not possible. About 11 April the water had just ceased to be vertically homogeneous so that the surface skin of water would

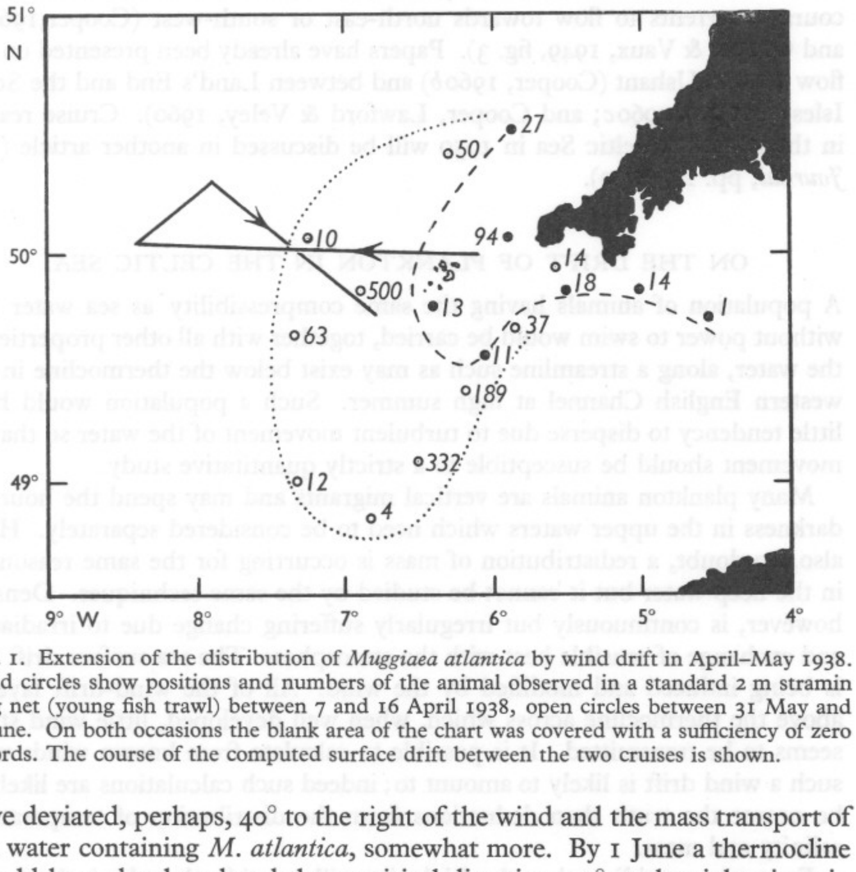

Fig. 1. Extension of the distribution of *Muggiaea atlantica* by wind drift in April–May 1938. Solid circles show positions and numbers of the animal observed in a standard 2 m stramin ring net (young fish trawl) between 7 and 16 April 1938, open circles between 31 May and 6 June. On both occasions the blank area of the chart was covered with a sufficiency of zero records. The course of the computed surface drift between the two cruises is shown.

have deviated, perhaps, 40° to the right of the wind and the mass transport of the water containing *M. atlantica*, somewhat more. By 1 June a thermocline should have developed and the empirical direction, 30° to the right given in the *Irish Pilot*, more likely applies.

In evaluating the wind drift of the water carrying *M. atlantica*, the deviations given in Table 1 have been assessed for the three periods. It will be seen that the dispersion of the population of the siphonophore south-west from Land's End agrees with this calculated wind drift (Fig. 1). The two methods check each other.

Thus (*a*) the semi-empirical equation (2) provides a means of computing the magnitude of the wind drift from wind records; (*b*) the assessed deviations of the wind drift cannot be very far wrong; (*c*) within their own catches marine ecologists may find the means of assessing wind drift.

Working in 1948 it had been deduced somewhat intuitively, that the prevailing south-westerly winds over the Celtic Sea were likely to initiate a current setting south or south-west from the neighbourhood of Carnsore Point and Waterford Harbour. Also it was thought that the bottom topography in the south-western and central parts of the Celtic Sea was such as to encourage currents to flow towards north-east or south-west (Cooper, 1960*a*; and Cooper & Vaux, 1949, fig. 3). Papers have already been presented on the flow west of Ushant (Cooper, 1960*b*) and between Land's End and the Scilly Isles (Cooper, 1960*c*; and Cooper, Lawford & Veley, 1960). Cruise results in the northern Celtic Sea in 1950 will be discussed in another article (this *Journal*, pp. 235–270).

ON THE DRIFT OF PLANKTON IN THE CELTIC SEA

A population of animals having the same compressibility as sea water and without power to swim would be carried, together with all other properties of the water, along a streamline such as may exist below the thermocline in the western English Channel at high summer. Such a population would have little tendency to disperse due to turbulent movement of the water so that its movement should be susceptible to a strictly quantitative study.

Many plankton animals are vertical migrants and may spend the hours of darkness in the upper waters which need to be considered separately. Here, also, no doubt, a redistribution of mass is occurring for the same reasons as in the deep water but it cannot be studied by the same techniques. Density, however, is continuously but irregularly suffering change due to irradiation and exchange of sensible heat with the atmosphere. The sea surface drift also is being induced and modified by the wind. All of the wind-drift layer is above the thermocline across which, when well developed, little wind stress seems to be transmitted. It is possible to calculate from known winds what such a wind drift is likely to amount to; indeed such calculations are likely to be nearer the truth than deductions from the distribution of temperature, salinity and mass.

Even so, providing that the biologist will provide the physical oceanographer with a detailed life history, particularly as to probable vertical distribution, of each animal of interest, it should be possible to make a reasonably probable estimate of its movements. In strong contrast in a drift, such as that of the north-western Celtic Sea in early spring, driven by variable winds, there is a large degree of randomness in all that happens. The forces which tend towards dispersion are large compared with those that tend towards streamline motion. Studies of the distribution of properties or, for that matter, information from current meters, can only measure a statistical trend.

The value of statistical assessment of drift may be improved if it can be combined with a very full knowledge of the habits and life history of an organism. Thus, if we know that an animal spends its whole life in the uppermost 10 m of water, then its future travel may be best assessed by computing vectorially the wind drift from the observed winds. Deductions from temperature and salinity are likely to be misleading. If, however, we know that the animal spends its whole life over the shelf in water deeper than, say, 50 m, the best the physical oceanographer can do is to assess the residual wind-induced deep drift on the basis of temperature, salinity or any more direct means available. Direct measurements of current are likely to be of value only if there are many of them from an appropriate depth.

SUMMARY

The dependence of prevailing wind drift in the Celtic sea upon prevailing winds is discussed and a proposal made to use wind records for the Scilly Meteorological Observatory for assessing drift currents for use in biological investigations.

If there is no seasonal change in the direction of the prevailing winds, nevertheless, the wind drift in summer will be more northerly than in winter.

The terms 'current', 'residual water movement' and 'drift', as used in this series of papers, are defined. The Ekman–Thorade equation for computing wind drift from wind is discussed and applied to the drift of the biological indicator *Muggiaea atlantica* in 1938. The two approaches agree to suggest that either method may be applied in biological distribution studies.

Some effects of drift, due to variable winds, on plankton distribution are outlined.

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