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THE OCEANOGRAPHY OF THE CELTIC SEA

II. CONDITIONS IN THE SPRING OF 1950

By L. H. N. Cooper
The Plymouth Laboratory

(With Text-figures 1–18)

CONTENTS

In April 1950 a cruise was undertaken on R.V. 'Sabella', commanded by Lt.-Cdr. C. A. Hoodless, D.S.C., R.N.R., to learn more of the currents around Land's End, St David's Head and Carnsore Point and to test some of the hypotheses presented earlier (Cooper, 1960*a*).

Much evidence in that month (Cooper, 1960*c*) has shown that in the southern Celtic Sea south of the 50th parallel, the water was moving towards east or somewhat south of east. This is in exact agreement with the generalized surface current circulation illustrated in the regional Admiralty Pilots (Cooper, 1961). In spite of this (Cooper, Lawford & Veley, 1960) it was clear that earlier, probably during preceding periods of neap tides, there had been considerable transport from south to north of Cornwall by way of a narrow, strong, but intermittent current setting snugly around Land's End. In April and in June this movement of water was established by quite different

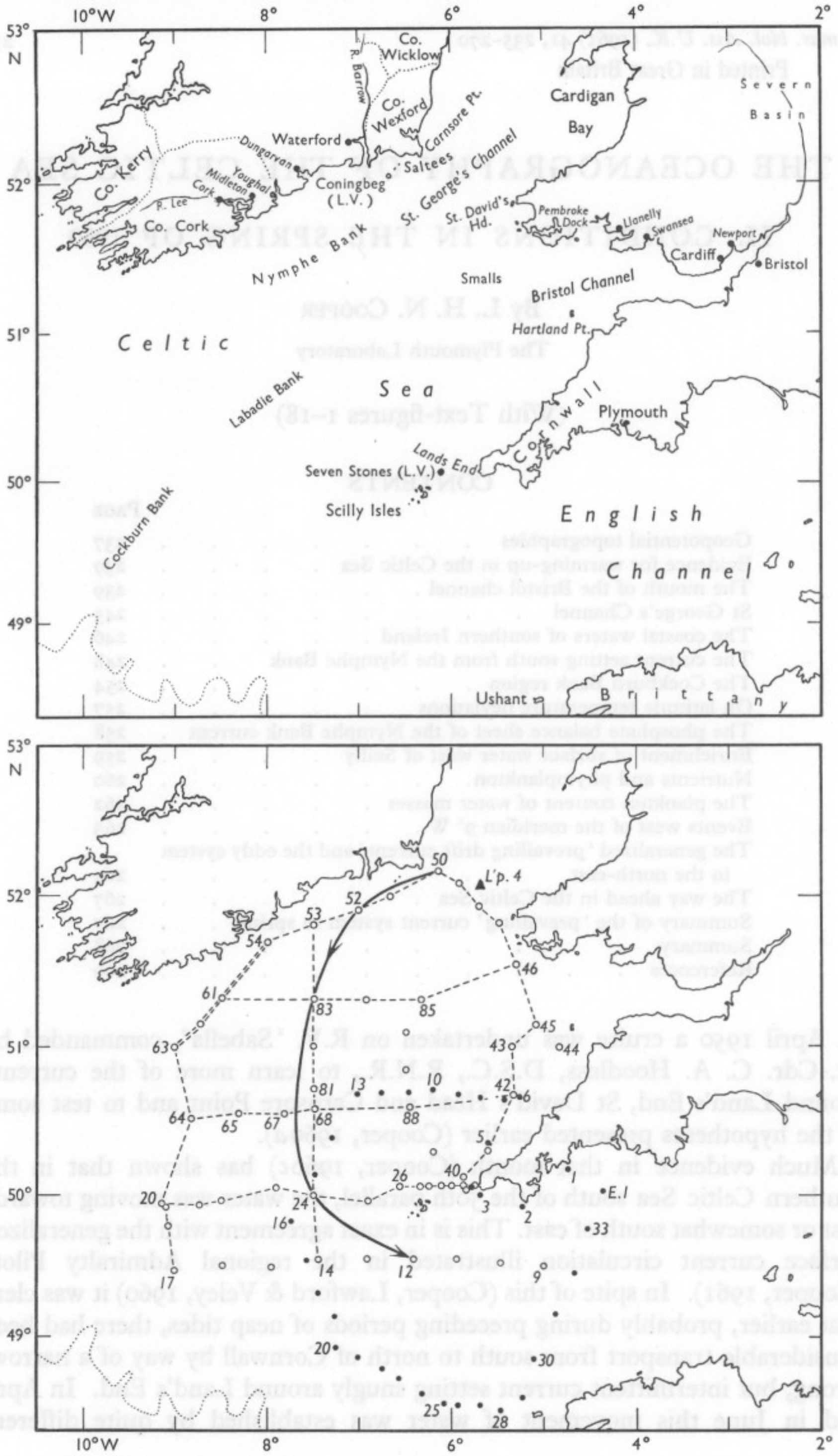

Fig. 1. Top: the Celtic Sea with place names used here. Bottom: open circles, stations 18–30 April 1950; solid circles, stations 12–16 June 1950; pecked lines, sections shown in Figs. 3, 5, 6, 8–12 (and also Cooper, 1960*c*, figs. 3 and 4); solid line, approximate course of the Nymphe Bank current in April. Sections for the June cruise have already been published (Cooper, 1960*b*, fig. 15; and 1960*c*, figs. 8, 9, and 10).

arguments (Cooper, 1960*a*, fig. 4; 1960*c*). This water north of Cornwall will here be called Land's End water.

The station positions are set out in Fig. 1. All fixes on R.V. 'Sabella' were astronomical, by land-marks or by dead reckoning. The observations have been published (Conseil International, 1954).

The pattern of winds over the Celtic Sea in the month preceding the cruise of April 1950 has already been published (Cooper, 1960*a*, table 1), together with the surface drift, likely to result from these winds (fig. 1, panel S.W). Again the further effect of the structure of the land mass of southern Ireland was there presented as fig. 3. The channeling effect on wind of the incised river valleys running west–east is likely there to initiate an offshore set towards south-east or south-south-east.

Nowhere in the observations presented was there evidence that in April 1950 there was any water heavy enough to have contributed to a cascading system (Cooper & Vaux, 1949).

GEOPOTENTIAL TOPOGRAPHIES

The geopotential topographies of Fig. 2 have to be interpreted with great care. There can nowhere be a surface of no motion and since the currents are wind-induced, a change of wind will at once start to change the current. Even when, as in April, 1950, the pattern of winds was predominantly westerly and south-westerly there were considerable variations in strength and direction. Consequently the wind drift can never become streamlined and fully equilibrated with the distribution of mass. None the less, when such topographies suggest a current required by a study of continuity of properties, the confirmation is valuable. When they suggest the opposite, they *may* indicate that transport was mostly in a subsurface current, or a change in the current system due to a change in wind.

Only around St David's Head do the topographies depict an equilibrium state, the South Wales coastal current in full flow. There is an indication of the Carnsore Point corner current. South of Ireland the topographies suggest the impossible, water running into the land mass of Ireland. Consequently we have to seek for compensation currents to get the water away again. Indeed, we shall produce evidence for strong up-welling off Waterford, but this had been created by northerly winds which only started to blow while the cruise was being run. The up-welled waters had not approached dynamic equilibrium and, since the cruise took 10 days, the chart is not strictly synoptic and does not show the effect. The chart gives a reasonably clear picture of the current from the Nymphe Bank as far as the parallel 50° 30′ N.

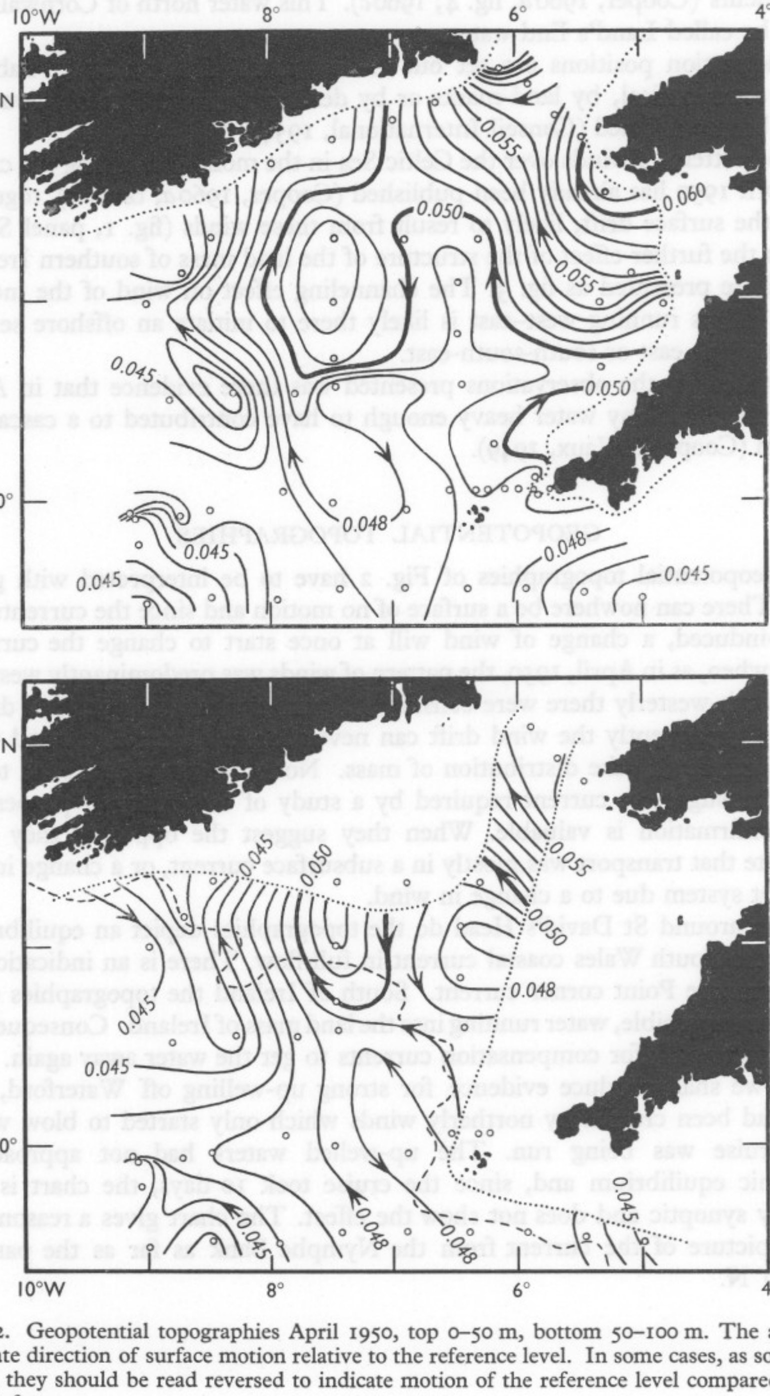

Fig. 2. Geopotential topographies April 1950, top 0–50 m, bottom 50–100 m. The arrows indicate direction of surface motion relative to the reference level. In some cases, as south of Cork, they should be read reversed to indicate motion of the reference level compared with the surface.

EVIDENCE FOR WARMING-UP IN THE CELTIC SEA

When comparing other years with 1950 one must consider the effect of short- and long-term climatic change. The Irish Fisheries vessel, S.S. 'Muirchu', under the direction of the late Mr G. P. Farran, made quarterly cruises to standard positions south of Ireland. Many of these cruises were made between 1920 and 1933 and they stopped in 1936. Bowden (1950, Appendix) has prepared tables of mean temperatures and salinities for nine of these stations. Three of these were incorporated in our cruises on 26–29 April and may be compared with Bowden's May averages for depths below the thermocline (Table 1).

TABLE 1. WARMING-UP SOUTH OF IRELAND

The year 1950 compared with a quarter of a century earlier.

Latitude	Longitude	Irish station	'Sabella' station	Rise in temperature (°C)
51° 40′ N.	8° 00′ W.	A	54	+0·50°
50° 40′ N.	8° 00′ W.	D	65/67	+0·20°
51° 00′ N.	9° 00′ W.	9B	63	+0·61°

Differences in salinity, being within ±0·02 %, call for no comment. The temperatures show that the deeper water was 0·2–0·6° warmer than 20 years earlier, in spite of our cruise being ahead of the month in which the Irish standard observations were made. This is consistent with the findings at the Seven Stones Light Vessel.

THE MOUTH OF THE BRISTOL CHANNEL

In the mouth of the Bristol Channel several types of water have been recognized (Fig. 3), which will be considered in turn.

Land's End water

The properties of the water north of Cornwall carried in early in April by the Land's End corner current have already been described (Cooper, 1960*c*, table 4, figs. 4 and 8, tables 6 and 7: positions U and V). Its properties in June (1960*c*, fig. 10) and the boundary with northern Celtic Sea Water will not be again discussed.

South Wales coastal water

This water, lighter than σ_t 26·9 less saline than 34·8 ‰, cooler than 9·5° C and turbid, was found off the coast of Pembrokeshire at stations 47 and 46 and covered much of the Smalls fishing ground. It was relatively rich in phosphate, total phosphorus and silicate (Table 2). Calculation suggested that the diluting fresh water brought in about 10 μg-atom phosphorus per litre, most of this being inorganic. Domestic and industrial sewage from

South Wales and leaching from the rich farmlands of the Severn Basin seem to be the source of this enrichment. The large catchment area of the Severn Basin draining to the Bristol Channel is depicted by Bowden (1950, fig. 1) and its run off is described by Lee (1960).

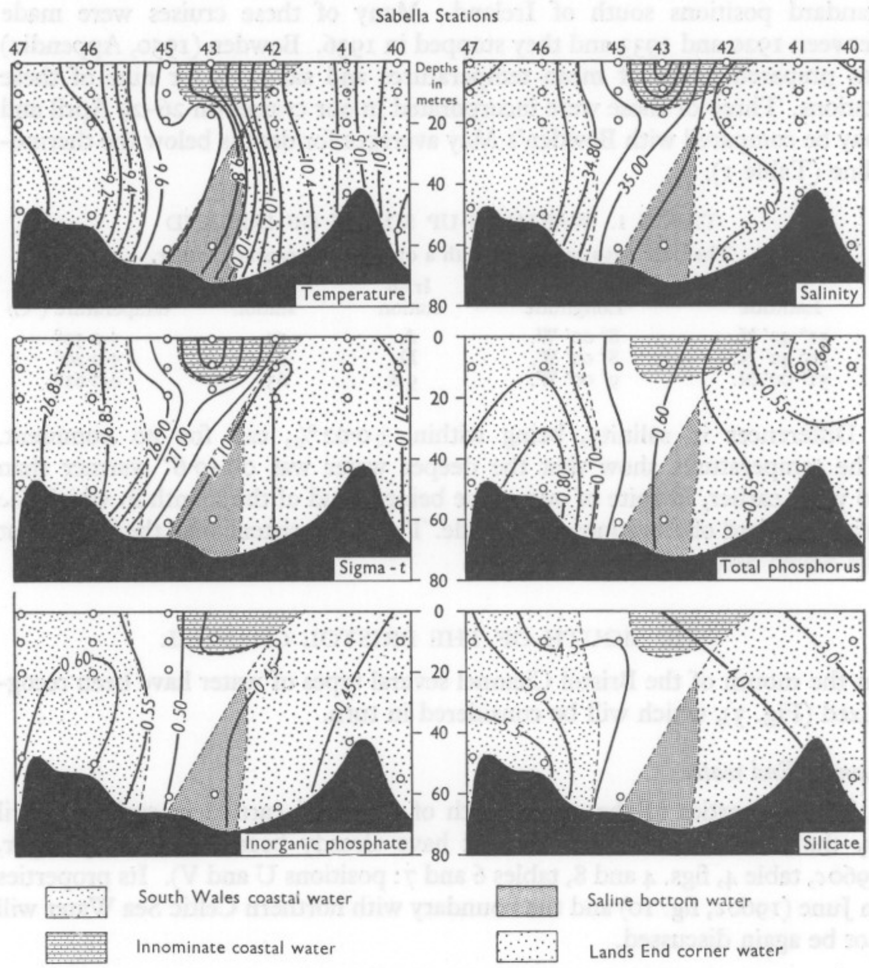

Fig. 3. A section from off St David's Head (station 47) to Land's End (station 40), 23–25 April 1950.

I had always assumed that nutrients discharged into the sea as sewage would be immediately available to plants and that a phytoplankton bloom would be followed in a few weeks by large populations of zooplankton which would then attract pelagic fish. The findings in the South Wales coastal water have seemed at variance with this postulate.

Only station 46 was sampled for plant pigments which, compared with the resources and the date, proved to be poor, 110 Harvey units/m³. The 2 m young fish trawls made with post-war stramin do not effectively sample the copepod herbivores. By station 48, a considerable population of carnivores was building up, but, since station 46 was 40 miles from Llanelly, the nearest considerable town and more than 80 miles from Bristol, Cardiff and Newport whence came much of the phosphate, there would seem to have been plenty of time for a large micro-plankton population to have built up. During the

TABLE 2. DISTRIBUTION OF NUTRIENTS IN SOUTH WALES COASTAL WATERS, 25 APRIL 1950

Station and sounding	Sample depth (m)	Phosphorus (μg-atom/l.) Total	Inorganic In unfiltered water	Inorganic In filtered water	Particulate	Organic	Silicon $-SiO_3$	Plant pigments Harvey units/m³
46	0·5	—	0·56	0·54	0·02	—	—	110
(58 m)	10	0·74	0·57	0·56	0·01	0·17	4·4	—
	20	—	0·62	0·56	0·06	—	—	—
	50	0·85	0·60	0·54	0·06	0·25	5·6	—
47	0·5	—	0·58	0·56	0·02	—	—	—
(90 m)	10	0·72	0·58	0·54	0·04	0·14	5·2	—
	20	—	0·59	0·54	0·05	—	—	—
	48	0·77	0·60	0·54	0·06	0·17	5·7	—
48	10	0·74	0·60	0·54	0·06	0·14	5·2	—
(110 m)	20	0·64	0·60	0·56	0·04	0·04	5·2	—
	48	—	0·57	—	—	—	—	—
	81	0·75	0·59	—	—	0·10	5·4	—

last 10 years I have repeatedly sought an understanding of these anomalous results and failed to find one. A remarkable parallel has now been published for the Hyperion sewage scheme of the City of Los Angeles by Stevenson & Grady (1956), whose results have been quoted by Emery (1960, p. 138). The content of phosphate in the effluent there is 1000 times its concentration in average surface sea water (p. 301). However, collections of plankton showed only a slight average increase of dinoflagellate populations, uncertain increases of diatoms, copepods, tunicates, tintinnids, and annelid larvae, and no increase of other forms. No blooms have there been related to sewage discharge. Abundant heavy metals discharged in sewage (as is likely from the Swansea area) had no identifiable effect on the sea water or its life. Since it is of much economic importance that the expensive nutrients discharged in sewage shall be recovered by the fisheries, this confirmation of failure quickly to do so by an investigation far fuller than ours is relevant.

The Los Angeles workers comment on the turbidity of sea water which has received sewage discharge. The turbidity of the samples drawn from the three stations in South Wales coastal water was notably great, so much so that for these stations and only for these, duplicate phosphate samples were filtered before analysis as shown in Table 2. Possibly it is this turbidity which so far reduces available light as greatly to slow down the rate of photosynthesis. If turbidity is not the cause, it may be necessary to search for an antibiotic in the effluent.

We have seen that along the coast of South Wales the drainage, largely urban, had introduced about 10 μg-atom inorganic phosphate per litre of fresh water and that we know nothing of the growth-affecting substances which may accompany this added phosphate. The littoral animals and plants of Pembrokeshire would then be bathed by water markedly different from that of North Cornwall. It would be of value to the hydrographer to know whether the flora and fauna of the coasts of Pembrokeshire differs in species and in total numbers from the coasts of North Cornwall under similar conditions of exposure and substratum.

The boundary between the warm saline water on the Cornish side of the Bristol Channel and the cold brackish water on the Welsh side sloped downward from south to north with a gradient of 0·2 % (cf. Uda, 1959) (Fig. 3). The gradient of the bevel dividing the two currents is likely to change with the state of the tide and the phase of the moon. For future development of this problem it will be necessary to know that on 23 April 1950, station 42 was worked 1 h before and station 43 $2\frac{1}{4}$ h after high water at Pembroke Dock.

Innominate coastal water

There was a detached surface bubble of brackish water in mid-Channel at station 43 (T, 9·85°; sal., 34·66–34·74‰). Its relatively low content of phosphorus compounds suggests either that it had been the site of a plant outburst or, more probably, that it had come from the English side of the Bristol Channel somewhere east of Hartland Point.

Saline bottom water

At station 43 (below 20 m), at the bottom at station 45 (Fig. 3), and at the extra station 44 off Hartland Point there was a wedge of heavy saline water. It was much too cold (mostly 9·65–9·75° C) to have come from south of Land's End in the immediately preceding weeks. Alternative possible origins are presented so that future work may be designed to choose between them. (*a*) The water had entered from the west along the 51st parallel of latitude from the seventh meridian to coalesce with the east-flowing Land's End water; this seems more probable (Table 3), but (*b*) it is not impossible that it had been formed during the coldest months of the winter from Land's End water which had invaded the shelf (mostly < 16 fm or 29 m) on the English side between Hartland Point and Watchet. On this shallow shelf it had been cooled to cascade into the deep channel where it became the southernmost and deepest part of the west-flowing South Wales current.

The nutrient contents are not truly diagnostic since there are bottom muds available to enrich waters from either source. In this position the distribution of mass based on too few observations and almost certainly subject to strong tidal displacement is considered a treacherous guide.

A definitive answer is much needed since if the bottom current is moving west, it is likely to be the carrier of the muds which build up the deposits around the 51st parallel still further west.

TABLE 3. PROPERTIES OF BRISTOL CHANNEL BOTTOM WATER

Station no.	86	87	43	Mean
Latitude (° N.)	51° 07′	50° 53′	51° 00′	—
Longitude (° W.)	6° 30′	6° 30′	5° 20′	—
Sounding, (m)	99	95	73	—
Depth sampled (m)	85	80	60	—
Temperature (°C)	9·57	9·77	9·75	9·7
Salinity (‰)	35·16	35·17	35·14	35·16
Density (σ_t)	27·16	27·14	27·13	27·14
Total phosphorus (μg-atom/l.)	0·63	0·60	0·59	0·61
Inorganic phosphate (μg-atom/l.)	0·44	0·44	0·46	0·45
Organic phosphorus (μg-atom/l.)	0·19	0·16	0·13	0·16

Other water

When these four water types have been recognized, there remained a body of water not stippled in Fig. 3. This was akin to the South Wales coastal water but was more saline, warmer and poorer in nutrients. However, it had little in common with the Land's End water. It evidently had spent some time within the Bristol Channel and was unquestionably moving west.

ST GEORGE'S CHANNEL

On the centre line is 'station 4', maintained by the Department of Oceanography in the University of Liverpool (Figs. 1, 4). Its most striking feature is the much greater variability of temperature and salinity than at the Seven Stones Light Vessel. The salinity was much lower in the summer than in the winter months. How the distribution of nutrients and plankton correlate with these variations is not known.

The water on 25–26 April in the St George's Channel, compared with the Celtic Sea, was cool and of low salinity (Fig. 5, stations 50–47). In the middle of the channel lay water with a salinity of about 34·66‰. This low salinity presents a problem. It is well established (Bowden, 1955) that the general movement of water in the Irish Sea is from south to north but if this water is recruited directly from the Celtic Sea its salinity would be expected to be much higher than it commonly is in summer. On a single occasion such a low salinity could be ascribed to a short-lived eddy, but it is difficult to explain the prolonged low-salinity water at 'station 4' between April and August 1950 (Fig. 4) in this way. It is easier to believe that the whole width of St George's Channel, except that occupied by the narrow Carnsore corner current, was filled during these months with water from the northern Bristol Channel and coast of South Wales, no water coming directly from the Celtic Sea.

In the first week of September conditions changed at 'station 4' where salinity increased rapidly and remained relatively high during the autumn. This change is in line with accepted principles. During the summer months the coastal waters of South Wales had become lighter than those of the Bristol Channel further from shore, due to the effects of dilution by run off and warming up in shallow waters, particularly in sandy bays. Dilution makes for

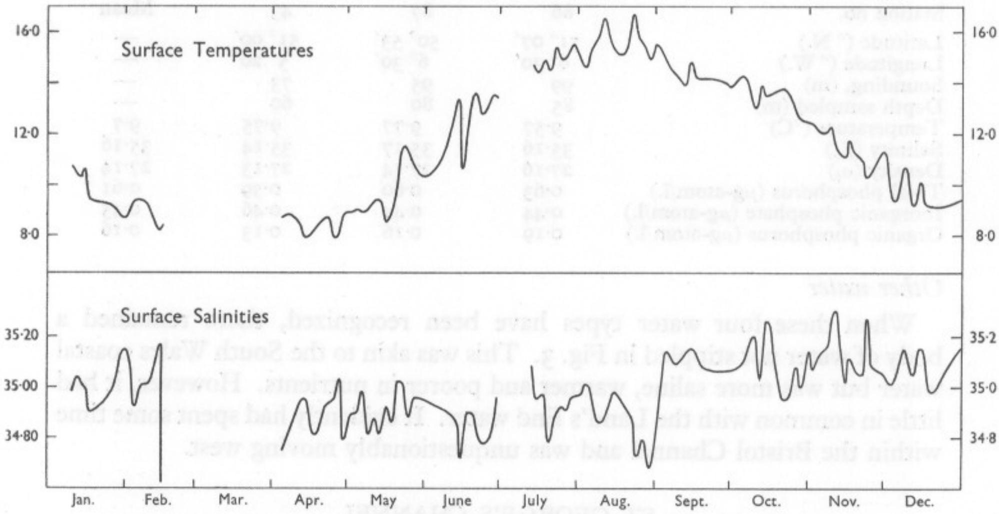

Fig. 4. Temperatures and salinities in 1950 at Liverpool University Station 4, 52° 04′ N, 5° 40′ W.

lighter water and a current running the whole year round with the coast on the right, but, as soon as autumn sets in, shallow coastal waters cool faster than deeper waters where the same heat loss is distributed through a greater quantity of water. When the increase in density due to cooling exactly offsets the decrease in density due to dilution no coastal density current should flow. Something of this kind seems to happen to the South Wales coastal current in autumn: as a result the position of 'station 4' may then become filled with more saline water more directly recruited from the Celtic Sea. Also during early September 'thermocline recruitment' into the Bristol Channel of the kind already described for the English Channel (Cooper, 1960*b*) may perhaps occur. If this account is correct, the consequences for the local climate and for the biological populations of West Wales may be notable (cf. Cooper, 1960*c* for the case of north Cornwall in summer).

The silicate content of the water on the South Wales side (station 47) was twice that on the Irish side (station 50). Though the two coastal streams had

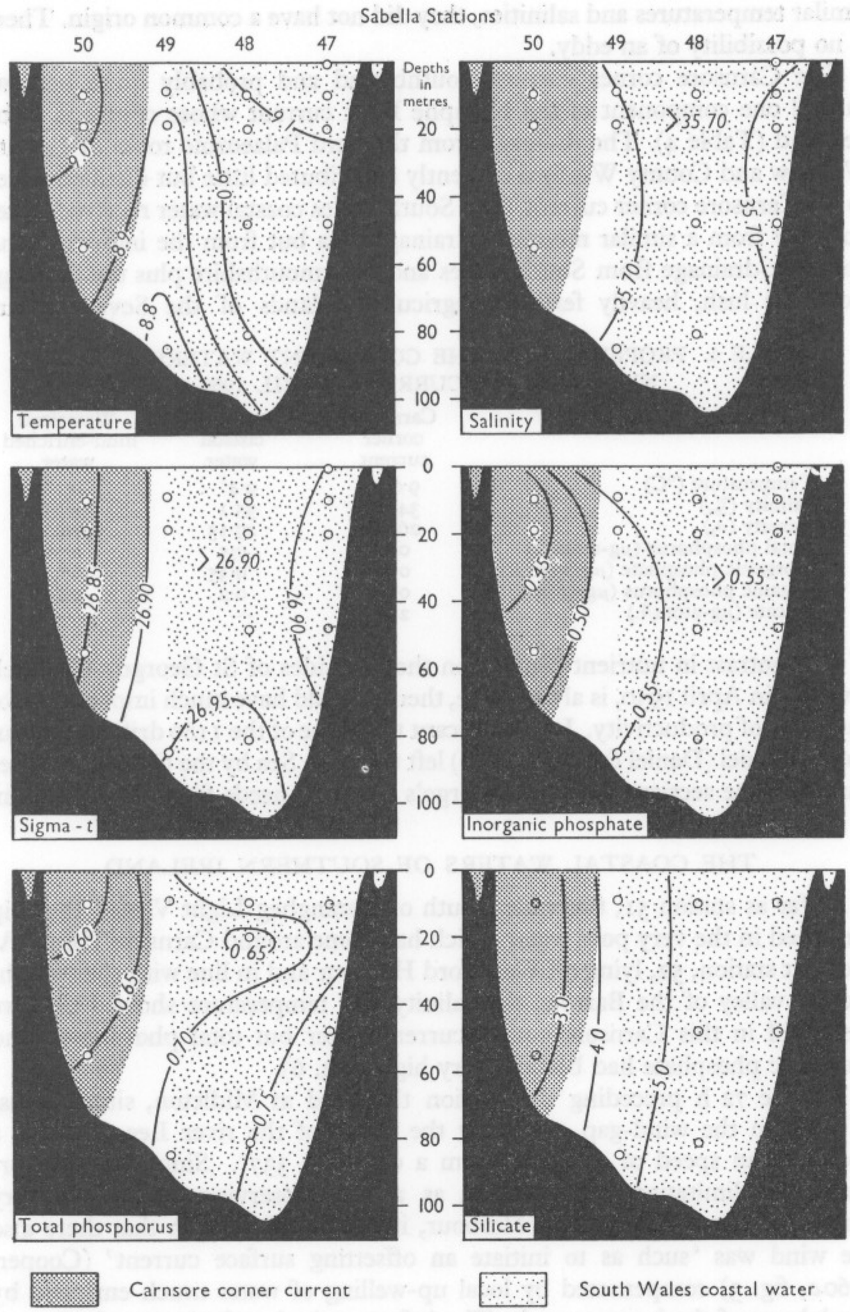

Fig. 5. Section from Carnsore Point to St David's Head, 25–26 April 1950. In the salinity diagram *for* '35.70' *read* '34.70'.

similar temperatures and salinities, they did not have a common origin. There is no possibility of an eddy.

The Carnsore corner current, southbound and probably quite narrow, carried one component of the Nymphe Bank current whose course is to be deduced (Table 4). The drainage from the hard Palaeozoic rocks of County Wicklow and County Wexford evidently contributed little but distilled water to the Carnsore corner current. The South Wales coastal water received water not only from a similar mountain drainage area but from the industrial and domestic drainage from South Wales and Monmouthshire plus the drainage from the lush, heavily fertilized agricultural lands of the Severn Basin.

TABLE 4. PROPERTIES OF THE COMPONENT WATERS OF THE NYMPHE BANK CURRENT, APRIL 1950

	Carnsore corner current	County Cork coastal water	Waterford mud-enriched water
Temperature (°C)	9·0°	9·4°	9·1°
Salinity (‰)	34·61	35·1	34·95
Density (σ_t)	26·83	27·15	27·08
Total phosphorus (μg-atom/l.)	0·61	0·5	0·71
Inorganic phosphate (μg-atom/l.)	0·45	0·35	0·61
Organic phosphorus (μg-atom/l.)	0·16	0·2	0·10
Silicate (μg-atom/l.)	2·4	—	—

If the contrast in nutrient content on the two sides of St George's Channel, revealed in April 1950, is always true, then it would have much importance for any study of productivity. It is significant that none of the 1180 drift bottles put out by Daniel (Daniel & Lewis, 1929) left the Irish Sea by the Carnsore corner current. The section across St George's Channel needs frequent repetition.

THE COASTAL WATERS OF SOUTHERN IRELAND

As far as station 51, two miles south of Coningbeg Light Vessel, the ship remained in the very poor water which had come around Carnsore Point. At the next station, 52, lying off Waterford Harbour and in line with the straight incised valley of the Barrow, the salinity and temperature showed that we were still in this Carnsore corner current water but total phosphorus and inorganic phosphate had become very high (Fig. 6).

For the 72 h preceding this station the wind at Midleton, situated east of Cork in the wind-gap extending the valley of the river Lee, attained a vector mean speed of 15 knots from a direction 337°. Since the geomorphological limitations of Midleton as a wind-observing station are very similar to those of Waterford Harbour, it is a fair deduction that there also the wind was 'such as to initiate an offsetting surface current' (Cooper, 1960*a*, fig. 3) compensated by local up-welling of water much enriched by breakdown of the bottom muds. The inference is that during northerly and north-westerly winds, a rich and productive water mass may be created from a poor one, leading ultimately to a temporary abundance of pelagic fish. This seems to be a key area for the nutrient oceanography of the Celtic Sea so that the process needs further study.

The more westerly stations 53 and 54 were occupied by County Cork coastal water, established on the basis of the geopotential topographies (Fig. 2,

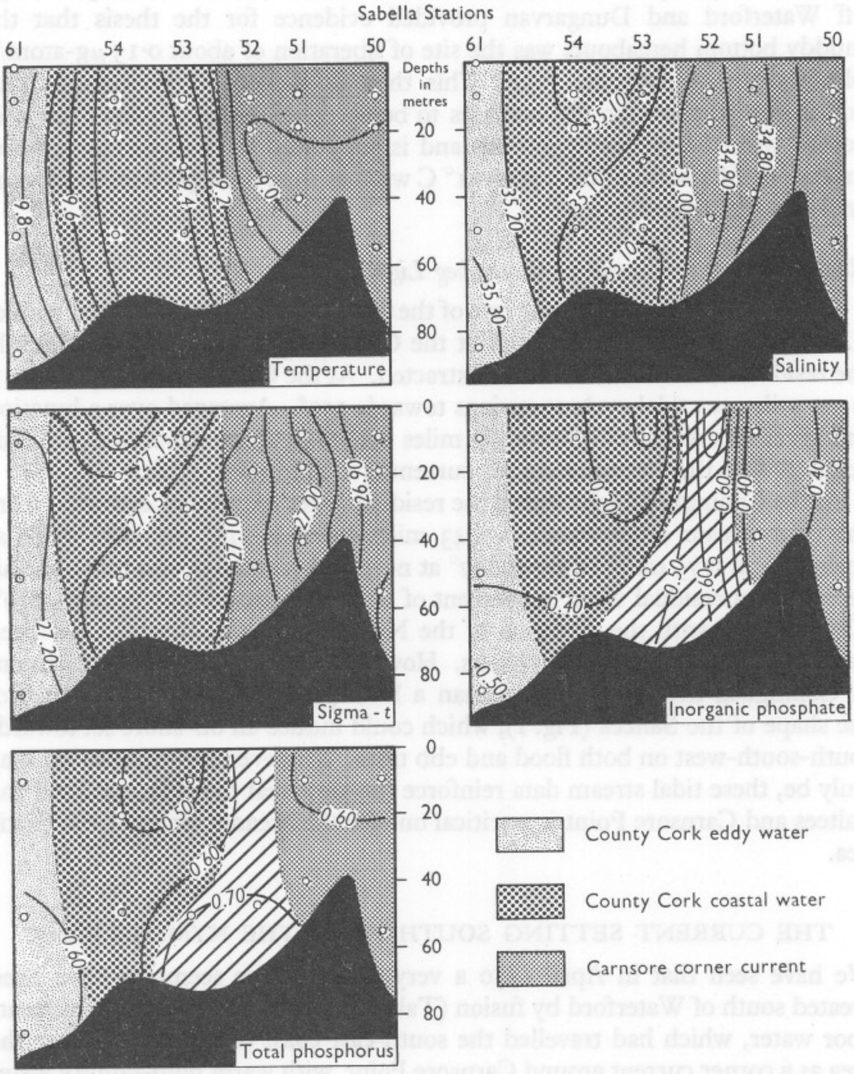

Fig. 6. Section along the south coast of Ireland, 26 and 28 April 1950. Stippled as shown. Cross-hatching in the panels for inorganic phosphate and total phosphorus indicates the area where northerly winds channelled by the valley of the Barrow caused up-welling of bottom water enriched with compounds of phosphorus from the bottom muds thereabouts.

p. 238) and the area distribution of properties. It was not established that this somewhat high salinity water bathed the cliffs. It was probably, as a wind drift, flowing east towards Youghal and Waterford, where it was forced to turn offshore by the pressure of the north eastern Celtic Sea cyclonic circulation (Cooper, 1960*a*, pp. 160–2).

The total phosphorus contents of the bottom water at stations 52 and 53 off Waterford and Dungarvan provided evidence for the thesis that the muddy bottom hereabouts was the site of liberation of about 0·15 μg-atom/l. phosphorus (cf. Cooper, 1951). This then up-welled off Waterford. This conclusion rests on too few analyses to be accepted without reserve but is in accord with the earlier hypothesis and is supported by a small temperature inversion. The bottom water was 0·1° C warmer than the top 20 m, suggesting an indraught from the south.

Residual water movement at Coningbeg Light Vessel

On admiralty Chart 2049 the rate of the tidal stream is given at a point 3 miles S.S.W. from Carnsore Point and at the Coningbeg Light Vessel. Evidently the residual current remains to be extracted. At the Carnsore Point position it is 3·1 miles per tidal cycle at springs towards 259°. Averaged over a lunation this gives an average current of 4·5 miles per sidereal day towards 259°. This suggests that the Carnsore corner current is a continuing affair.

At the Coningbeg Light Vessel the residual water movement extracted from the tidal stream observations is 1·43 miles towards 210° per tidal cycle at springs, and 0·75 miles towards 207° at neaps. Averaged over a lunation this represents a residual water movement of 2 miles a sidereal day towards 209°. This lines up with the direction of the Nymphe Bank drift which has been deduced from our own observations. However, the residual water movement at Coningbeg need be no more than a local physiographic consequence of the shape of the Saltees (Fig. 1), which could induce an off-shore set towards south-south-west on both flood and ebb tides. Whatever the explanation may truly be, these tidal stream data reinforce the view that the region around the Saltees and Carnsore Point is a critical one for the oceanography of the Celtic Sea.

THE CURRENT SETTING SOUTH FROM THE NYMPHE BANK

We have seen that in April 1950 a very mixed water seems to have been created south of Waterford by fusion (Table 4) of cold, low-salinity, nutrient-poor water, which had travelled the south-east coast of Ireland to enter the area as a corner current around Carnsore Point, with warm high-salinity water from the offing of County Cork. A core of water within this water mass, but not all of it, had been enriched by up-welling of water containing breakdown products from a veneer of bottom mud.

The chart of geopotential topography of the zero against 50 decibar surface has been presented in Fig. 2 (p. 238). A current around Carnsore Point sets on to the Nymphe Bank and then to the south for 100 miles. It had had two branches, one being controlled in some measure by the Labadie Bank.

Naturally the median course of the current does not set precisely through the positions of stations worked, but a section constructed on the basis of

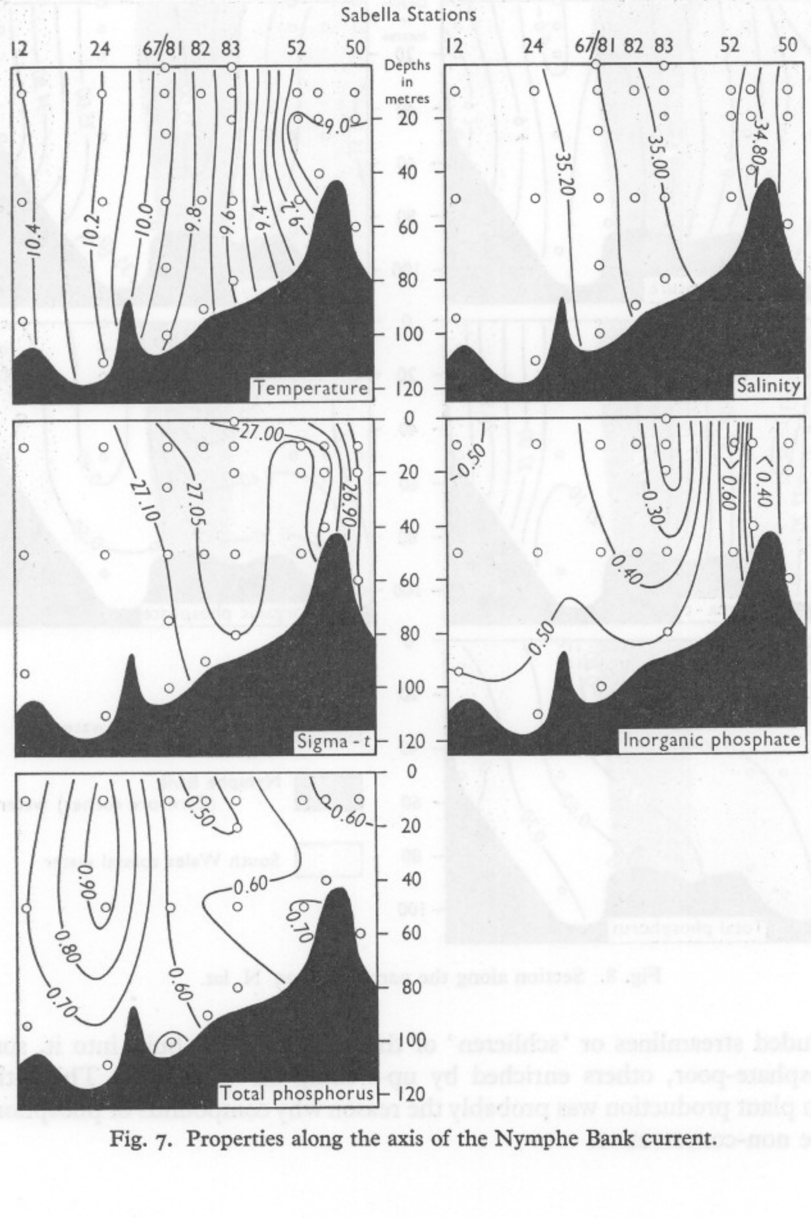

Fig. 7. Properties along the axis of the Nymphe Bank current.

minimum temperature and minimum salinity from the nearest stations to this course is presented in Fig. 7. Starting from a region with a depth of about 60 m, by the time it reached station 12 the water had warmed up by 1·4° C, due to irradiation and mixing. Salinity increased by 0·5‰. The current

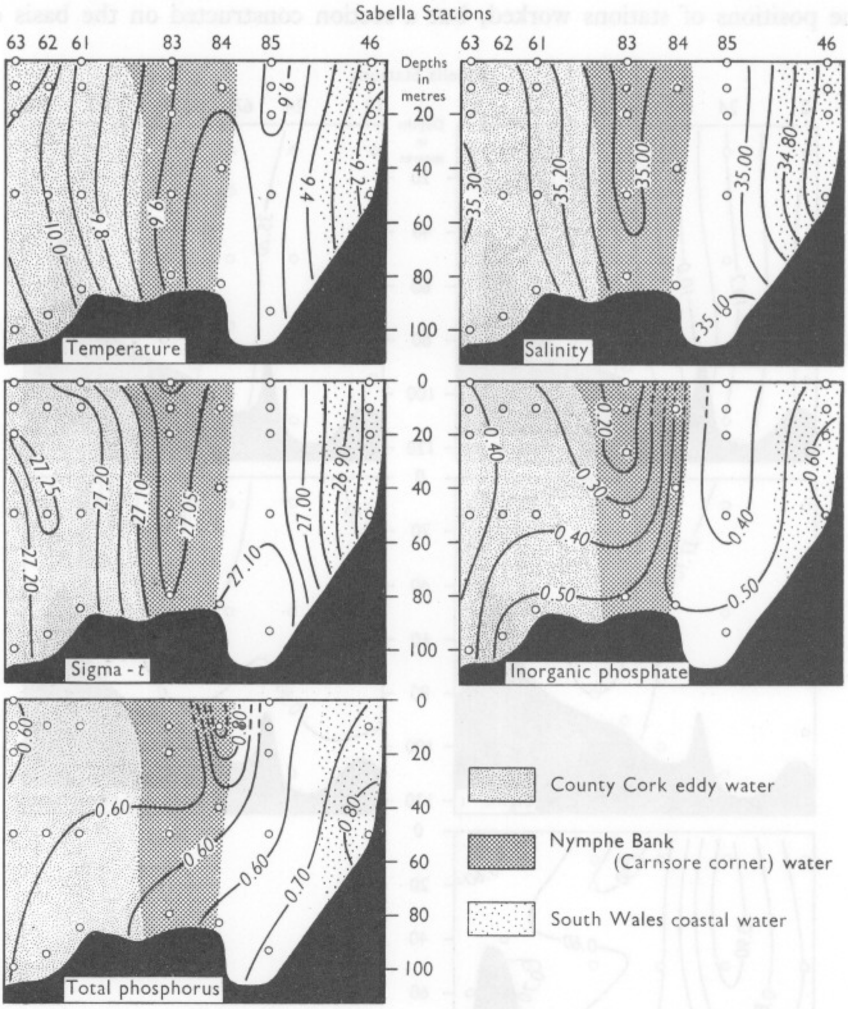

Fig. 8. Section along the parallel 51° 20′ N. lat.

included streamlines or 'schlieren' of the several waters built into it, some phosphate-poor, others enriched by up-welling off Waterford. This rather than plant production was probably the reason why compounds of phosphorus were non-conservative.

To deduce the course of the Nymphe Bank current in April 1950 sections along three parallels of latitude and two meridians have been selected (Figs. 8–12).

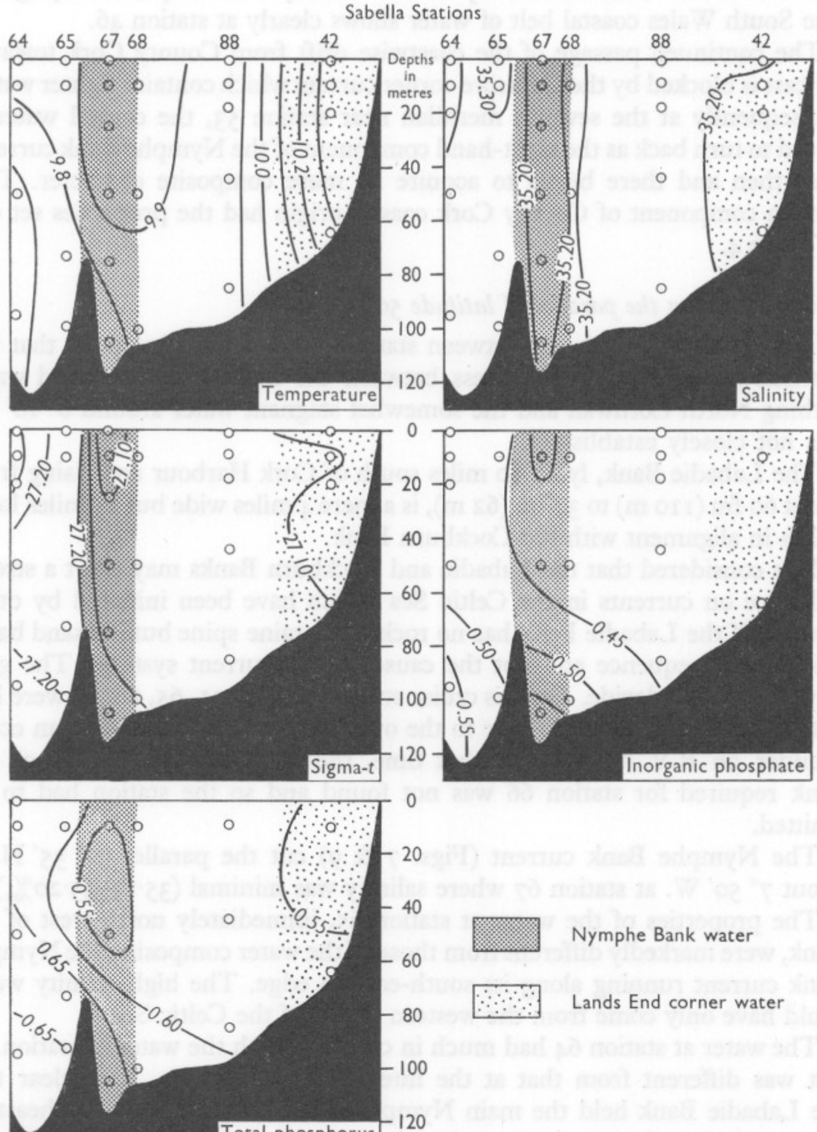

Fig. 9. Section along the parallel 50° 35′ N. lat. The Labadie Bank rises between stations 65 and 67.

The intercept on the parallel of latitude 51° 20′ *N*

The axis of the current crossed this parallel slightly to the east of station 83, where it is best characterized by its low salinity and temperature (Fig. 8). The South Wales coastal belt of water shows clearly at station 46.

The continued passage of the coastwise drift from County Cork towards the east is blocked by the Carnsore corner current which contains lighter water. Consequently at the seventh meridian near station 53, the coastal water is forced to turn back as the right-hand component of the Nymphe Bank current. This then and there began to acquire its more composite character. This bottom component of County Cork coastal origin had the properties set out in Table 4.

The intercept on the parallel of latitude 50° 35′ *N.*

There was a 45-mile gap between stations 42 and 88 (Fig. 9), so that the position and degree of sharpness between the mass of Land's End water bathing North Cornwall and the somewhat stagnant water around 6° 10′ W. was not closely established.

The Labadie Bank, lying 80 miles south of Cork Harbour and rising from about 60 fm (110 m) to 34 fm (62 m), is a mere 4 miles wide but 25 miles long. It lies in alignment with the Cockburn Bank.

It is considered that the Labadie and Cockburn Banks may exert a strong influence on currents in the Celtic Sea which have been initiated by other means. If the Labadie Bank has no rock or moraine spine but is a sand bank, it is the consequence and not the cause of this current system. The geophysicists could decide. On this cruise stations 19, 20, 21, 65, 66, 67 were laid out to test this hypothesis. Due to the overcast weather and lack of an echo-sounder on R.V. 'Sabella' at that time, the exact position on top of the bank required for station 66 was not found and so the station had to be omitted.

The Nymphe Bank current (Figs. 7 & 9) cut the parallel 50° 35′ N. at about 7° 50′ W. at station 67 where salinity was minimal (35·13–35·20‰).

The properties of the water at station 65, immediately north-west of the Bank, were markedly different from those of the water composing the Nymphe Bank current running along its south-eastern edge. The high-salinity water could have only come from the western sector of the Celtic Sea.

The water at station 64 had much in common with the water at station 67, but was different from that at the intervening station 65. It is clear that the Labadie Bank held the main Nymphe Bank current on its southeastern flank and that the water at station 65 had a western origin. The history of the water at station 64 will be discussed later (p. 258).

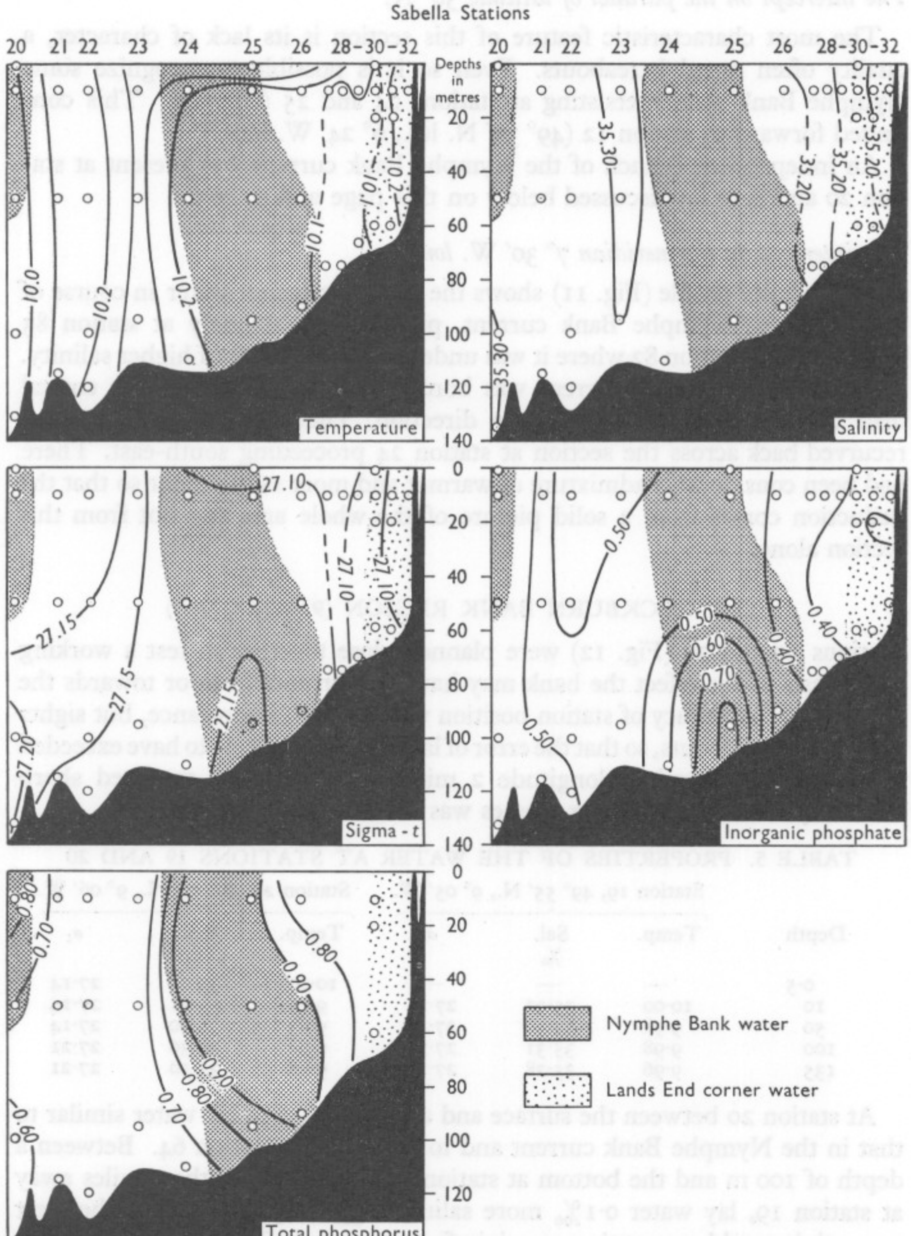

Fig. 10. Section along the parallel 50° N. lat. The Seven Stones Light Vessel lies between stations 29 and 30.

The intercept on the parallel of latitude 50° N.

The most characteristic feature of this section is its lack of character, a quality often noted hereabouts. Even so it is possible to recognize some Nymphe Bank water persisting at stations 24 and 25 (Fig. 10). This continued forward to station 12 (49° 33′ N. lat., 6° 24′ W. long.).

An independent branch of the Nymphe Bank current was present at station 20 and is to be discussed below on this page and p. 265.

The intercept on the meridian 7° 30′ W. long.

The salinity profile (Fig. 11) shows the Carnsore corner water in course of becoming the Nymphe Bank current, present very strongly at station 83 and present at station 82 where it was underpinned by water of higher salinity. To the northward, the current was bordered by the County Cork coastal drift there flowing in the opposite direction. The Nymphe Bank current recurved back across the section at station 24 proceeding south-east. There had been considerable admixture of warmer and more saline water so that the deduction comes from a solid picture of the whole area and not from this section alone.

THE COCKBURN BANK REGION (9° W. LONG.)

Stations 19 and 20 (Fig. 12) were planned close together to test a working hypothesis of the effect the bank may have on currents from or towards the south-west. Accuracy of station position was of much importance, but sights were good hereabouts, so that the error of latitude was unlikely to have exceeded 1 minute of arc and of longitude 2 minutes of arc. The expected sharp boundary between two water masses was found (Table 5).

TABLE 5. PROPERTIES OF THE WATER AT STATIONS 19 AND 20

	Station 19, 49° 55′ N., 9° 05′ W.			Station 20, 49° 57′ N., 9° 06′ W.		
Depth	Temp.	Sal. ‰	σ_t	Temp.	Sal. (‰)	σ_t
0·5	—	—	—	10·00	35·21	27·14
10	10·00	35·32	27·22	9·99	35·21	27·14
50	9·98	35·30	27·21	9·95	35·20	27·14
100	9·98	35·31	27·21	9·96	35·30	27·21
135	9·96	35·28	27·19	9·98	35·30	27·21

At station 20 between the surface and a depth of 50 m lay water similar to that in the Nymphe Bank current and to the water at station 64. Between a depth of 100 m and the bottom at station 20, and at all depths 2 miles away at station 19, lay water 0·1‰ more saline, suggesting water from the west or south but cold, suggesting an origin from the north. The combined indications therefore indicate that this water (at station 19) came from the north-west. A more direct origin from the continental edge west or south-west was also discounted by the low content of phosphate, 0·53 μg atom/l.

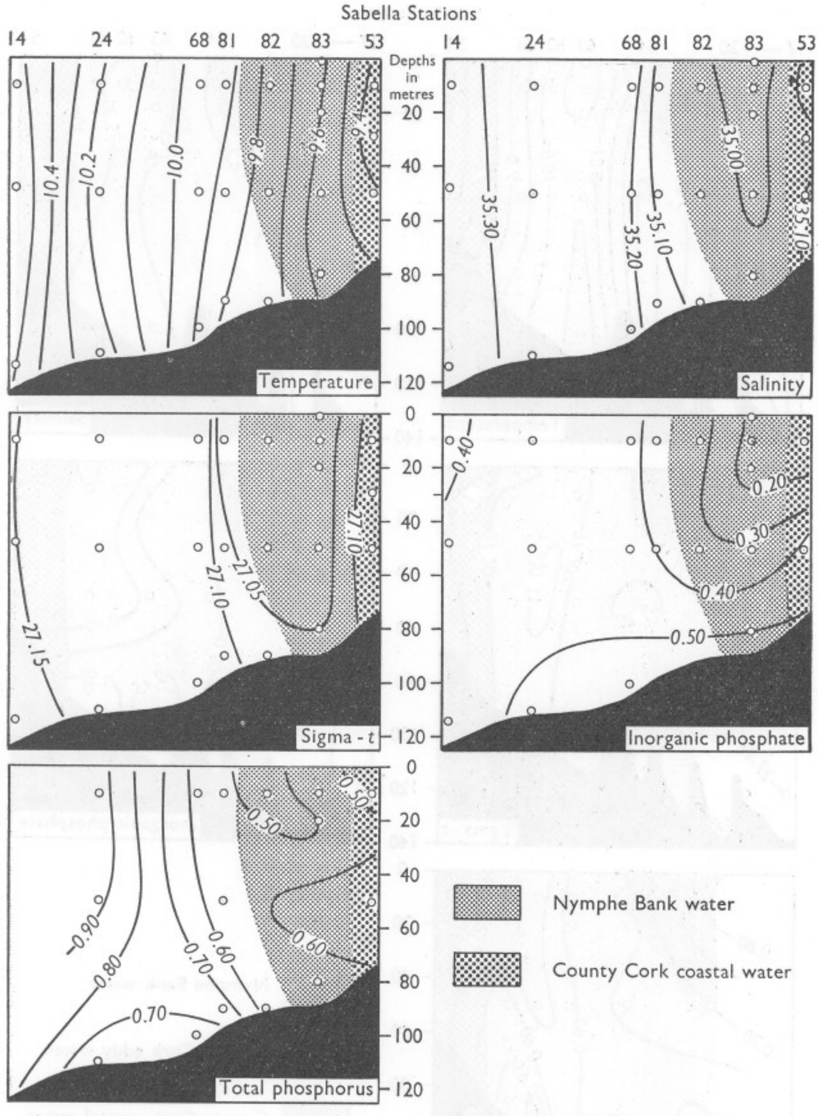

Fig. 11. Section along the meridian 7° 30′ W. long. The axis of the main Nymphe Bank current passed to the west of stations 68 and 81 and after admixture with warmer and more saline water re-cut this section at station 24 travelling south-east. This interpretation has been constructed from the complete solid model rather than from this section alone. Consequently the modified Nymphe Bank water at station 24 is not stippled.

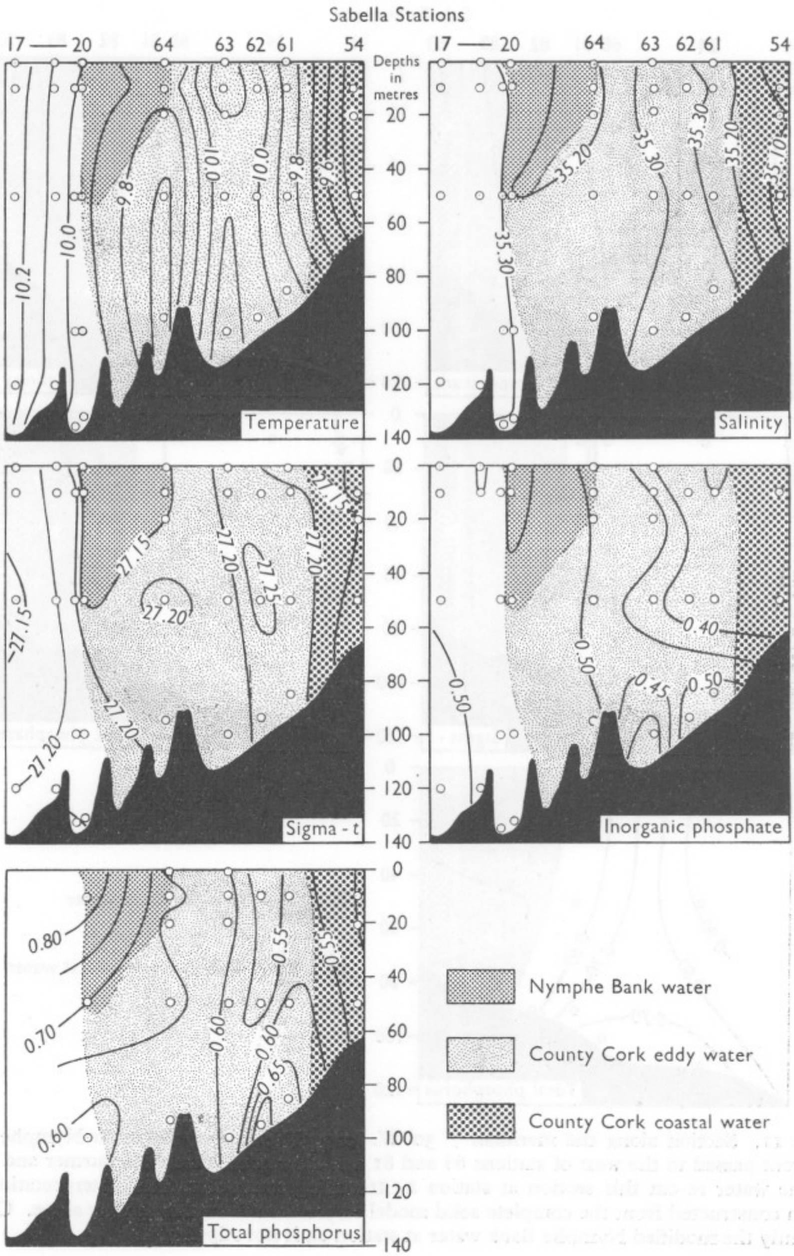

Fig. 12. Section along the meridian 9° W. long. Attention is drawn to the very sharp boundary between stations 19 and 20, 2 miles apart over the divide of the Cockburn Bank.

ON LATITUDE TEMPERATURE DEVIATIONS

Only very late in the investigation was it realized that the deviations from the latitude means of temperature already published (Cooper, 1960*a*, fig. 4 lower, reproduced here as Fig. 13) gave a clear understanding of what had happened. All the water in the central Celtic Sea had been concerned in a 'prevailing drift' from north-west to south-east, but between 24 and 29 March (Cooper, 1960*a*, Table 1) a change of wind had driven a layer of surface water rather more than 50 m thick from the eastern side of the drift towards the western and the break-out had been channelled by bottom topography such as that of the Cockburn Bank.

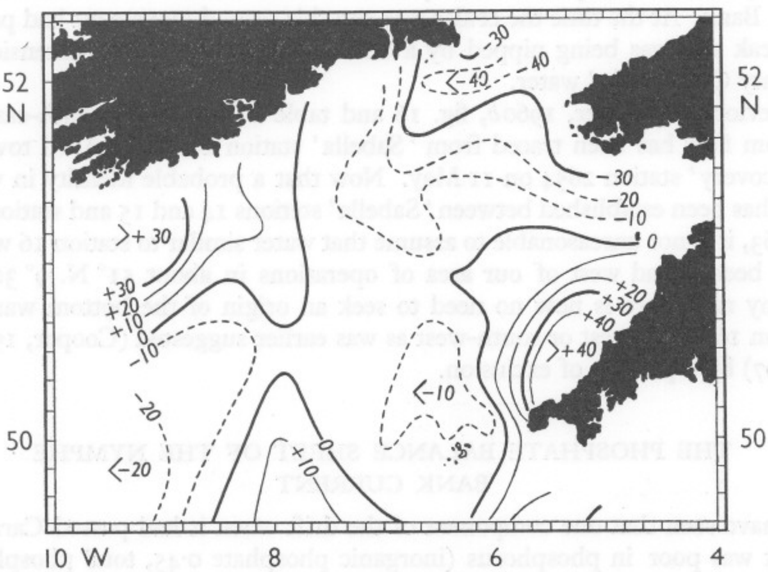

Fig. 13. Deviations of temperatures at 10 m depth from the latitude means (reprinted from Cooper, 1960*a*, fig. 4, lower half). Unit, 0·01° C.

The latitude temperature deviation revealed another component of the drift current which had been overlooked during the working up from the conventional diagrams, i.e. the remains of a warm saline current which had earlier set south from the coast of County Cork between Cape Clear and Kinsale. The northern part of this drift has already been recognized as the stagnating County Cork eddy. The possible correlation with the warm tongue centred on the position 49° 30′ N., 8° 00′ W. had been missed. The water had warmed up during southward transport through 95 minutes of arc by about 0·45°, instead of 0·67° computed from the coefficient established for the whole area.

The latitude temperature diagram provides strong evidence to suggest that these two separated water masses were indeed the same water mass which had been severed by a flow across it of water from the Nymphe Bank.

This would mean that the diagram (Fig. 13) portrays a level crossing in the sea at about 50° 30′ N., 8° W., with water movements taking turns as do trains and cars on a railway level crossing. First, there had been a south-south-easterly composite drift setting away from the Irish coast along its whole length from Cape Clear to Carnsore Point. The eastern component of this drift had consisted of cold Nymphe Bank water and the western of warmer and more saline water from between Cape Clear and Kinsale. Later a considerable arm of the Nymphe Bank component pushed out to the south-west cutting across the Cape Clear component to reach at least as far as the Cockburn Bank. At the time the cruise was run this second movement had passed its peak and was being nipped by a fresh south-south-easterly extension of County Cork 'eddy' water.

Previously (Cooper, 1960*b*, fig. 16 and table 2) a possible south-easterly bottom flow has been traced from 'Sabella' station 16 on 19 April towards 'Discovery' station 2654 on 11 May. Now that a probable identity in water type has been established between 'Sabella' stations 14 and 15 and stations 62 and 63, it is not unreasonable to assume that water similar to station 16 would have been found west of our area of operations in about 51° N. 9° 30′ W. At any rate there is now no need to seek an origin of the bottom water at station 16 to the west or south-west as was earlier suggested (Cooper, 1960*b*, p. 197) by a process of exclusion.

THE PHOSPHATE BALANCE SHEET OF THE NYMPHE BANK CURRENT

We have seen that one component of the drift when it had passed Carnsore Point was poor in phosphorus (inorganic phosphate 0·45, total phosphorus 0·61 μg-atom/l.). Over the muddy bottoms south of Ireland, this water was enriched by decomposition of organic material (Cooper, 1951). The rich water up-welled mostly off Waterford due to winds channelled by the land topography (Fig. 6, p. 247). The distribution of phosphate in the Nymphe Bank current therefore became streaky. Similar up-welling could contribute to an explanation of the high fisheries productivity observed hereabouts by the Lowestoft Laboratory in 1958–9.

In April 1950, by the time the current had reached station 83, 5000 Harvey units of plant pigments had been produced, inorganic phosphate had sunk to 0·17 μg-atom/l. while the organic phosphorus fraction rose to 0·36 μg-atom/l.

At other stations (e.g. station 81, cf. Cooper, 1960*c*, table 5) almost all the high total phosphorus content in bottom water was present in the inorganic form. In 1950 I attributed some of these results to errors of sampling or analysis. But now, in the light of the work of Strickland & Austin (1960) on the cycle of phosphorus in the North Pacific, I am inclined to accept and interpret them in terms of my experiments (Cooper, 1935) on the regeneration of phosphate from animal plankton. On this view, disturbance of the muddy veneer yielded to the water not only suspended matter containing organically bound phosphorus but also micro-organisms able to hydrolyse it. These organisms carried the process further by hydrolysing *dissolved* organic compounds which were elsewhere resistant to attack.

Much is implicit in this hypothesis since similar organisms may not only hydrolyse bound phosphorus but may chemically mature a water in subtler ways (Lucas, 1955). Combined with an effective means of up-welling, we would have a working hypothesis of great power. It is the more necessary, therefore, to provide it with a basis stronger than a few analyses which had first been dismissed as suspect.

ENRICHMENT OF SURFACE WATER WEST OF SCILLY

High contents of total phosphorus were found at 10 and 50 m depth at stations 20, 24, 25, 26 on April 20, 1950 (0·85–0·96 μg-atom/l.). The excess over the average for the cruise was due to organically bound phosphorus. The following possible explanations have been pursued and abandoned as untenable: (1) submarine eagres from canyons in the continental slope to the south and south-west; (2) vortex up-welling (Cooper, 1960*a*), i.e., up-welling along the lane followed by a cyclonic depression which passed over the Celtic Sea on 17 April[1]; (3) hydrodynamic up-welling.

No explanation for the high upper water content of organic phosphorus can be offered in terms of any of these. The four determinations, for inorganic and for total phosphorus at stations 25 and 26, when considered in pairs, are inconsistent. There remains the possibility that the high total phosphorus content originated from the muddy area 50 miles N.N.E. (Cooper, 1951) and after transport by the bottom current up-welled in the rising centre associated with the Scilly Isles (Cooper, 1960*a*). Though the basic data are scanty, we have had other rich catches near station 25. One such was diagnostic of the '*elegans*-type' water we sampled for Dr D. P. Wilson (Wilson, 1951, expts. 1 and 2). The possibility of rich water arriving as a bottom current from the north and being brought up in a rising centre deserves further study.

[1] The course of this depression was wrong by 50 miles and it was not strong enough to be effective. I am indebted to Dr R. C. Sutcliffe of the Meteorological Office for a critical discussion of the synoptic situation.

NUTRIENTS AND PHYTOPLANKTON

The nutrient contents of the several types of water which have been recognized are set out in Table 6. A primary objective of the cruise was to find where the rich water, present in the English Channel in the 1920's, came from. For this purpose the cruise was a complete failure since over the Celtic Sea as a whole, the phosphate content was too low.

TABLE 6. THE DISTRIBUTION OF NUTRIENTS IN APRIL 1950
(μg-atom/l.)

Water type	Total phosphorus	Inorganic phosphate	Silicate
English Channel south of Cornwall	0·66	0·44	—
Land's End corner current	0·57	0·47	3·3
North Cornwall (English Channel origin)	0·57	0·44	—
South Wales coastal	0·78	0·60	5·2
Carnsore corner current	0·61	0·31–0·45	2·4
Waterford up-welling	0·69	0·61	—
County Cork coastal	0·57	0·36	—
Nymphe Bank current	Very variable		—
Bristol Channel bottom water	0·61	0·45	—
Cockburn Bank area	0·71	0·45	—
Bottom water over mud	0·71	0·55	—
West Scillies enriched water	0·84	0·50	—

In 1950 we were examining the possibility that total phosphorus might be more nearly conservative than inorganic phosphate. This has proved not to be so. During the spring outburst of phytoplankton and the cycle of animal growth which develops from it, the total phosphorus content commonly decreases much as phosphate. The loss has gone into material which escapes the water-bottle. Again, much of the total phosphorus becomes particulate, and its distribution therefore tends to resemble that of iron (Cooper, 1948; but see Armstrong 1957). The analyst may correctly return a high figure for his sample but this may not truly represent the water from which it was drawn. If total phosphorus determinations are to be dependable they need to be replicated. Again, in April 1950 one set of bottles used for storage of total phosphorus samples gave off phosphate and the spurious results with them had to be rejected.

The results for bottom samples which seem analytically sound are presented here (Fig. 14), (*a*) as first drawn, and (*b*) adjusted to accord with the probable movements of the bottom water in the Celtic Sea. This adjustment has involved constructing a course for water containing over 0·7 μg-atom/l. total phosphorus from north to south along the meridian 6° 45′ W. between the grid stations. This is by no means impossible and is in line with the bolus concept in course of development for bottom water movements (Cooper, 1960*b*). Good reasons were found for rejecting alternative explanations.

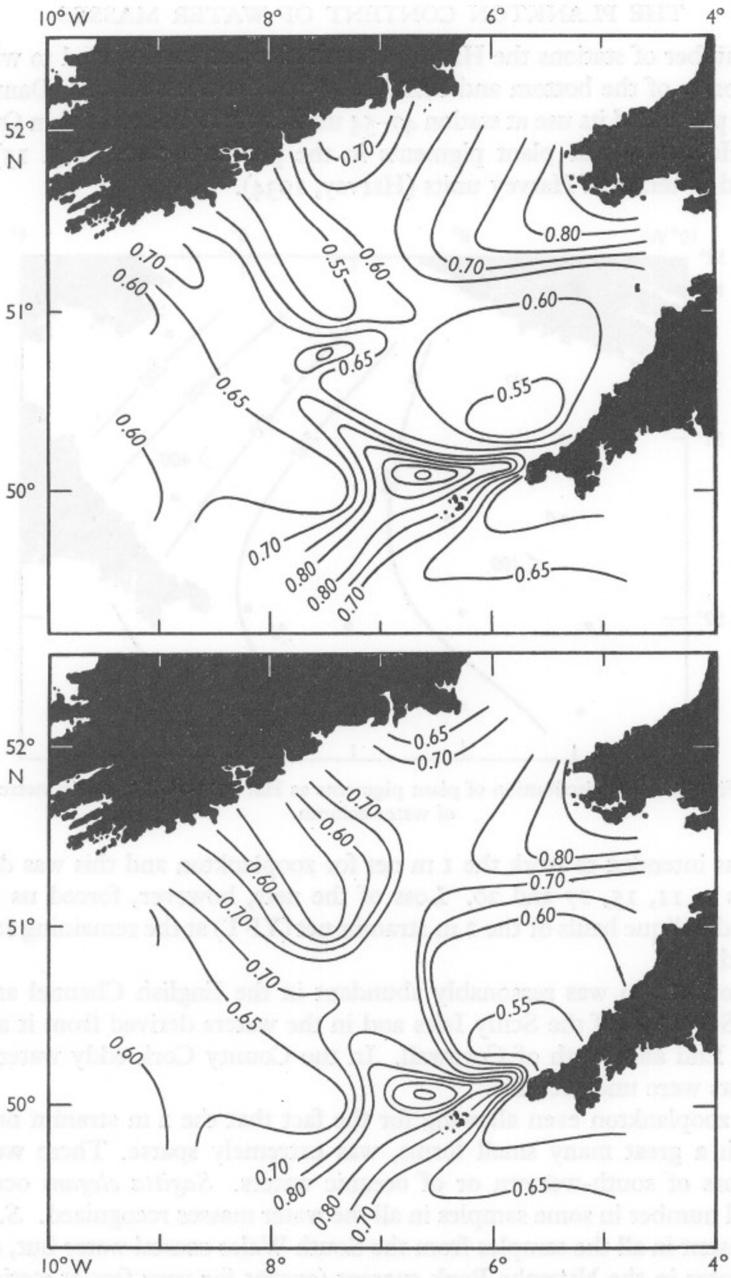

Fig. 14. Content of total phosphorus (μg-atom/l.) in bottom water as first contoured (upper) and adjusted to accord with the probable movements of bottom waters in March–April 1950. For station positions see Fig. 1, except that no reliable observations are available at stations 14–19.

THE PLANKTON CONTENT OF WATER MASSES

At a number of stations the Harvey quantitative net was lowered to within a metre or so of the bottom and then drawn back to the surface. (Damage to the net prevented its use at station 47–54 until it could be repaired in Queenstown Harbour.) The plant pigments in the plankton catch (Fig. 15) were assessed in terms of Harvey units (Harvey, 1934).

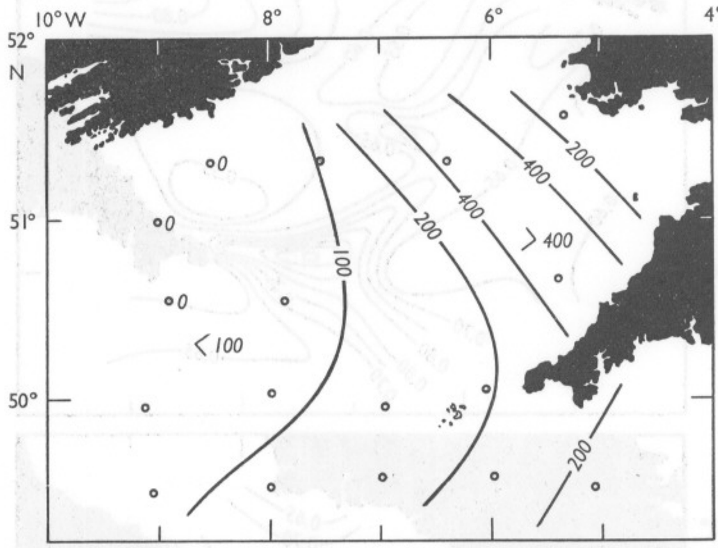

Fig. 15. The distribution of plant pigments as Harvey units per cubic metre of water column.

It was intended to work the 1 m net for zooplankton and this was done at stations 9, 11, 15, 17 and 20. Loss of the nets, however, forced us to use standard oblique hauls of the 2 m stramin net (YFT) at the remaining stations sampled.

Phytoplankton was reasonably abundant in the English Channel and the Celtic Sea south of the Scilly Isles and in the waters derived from it around Land's End and north of Cornwall. In the County Cork eddy water plant pigments were undetectable.

The zooplankton even allowing for the fact that the 2 m stramin net fails to catch a great many small forms, was extremely sparse. There were no indicators of south-western or of oceanic waters. *Sagitta elegans* occurred in small number in some samples in all the water masses recognized. *S. setosa* was present in all the samples from the South Wales coastal water but, absent from water in the Nymphe Bank current (except for very few at station 85) and the County Cork eddy water. *Tomopteris* was found only in the South Wales coastal water and off Land's End. *Saggita serratodentata*, an indicator of water from the continental slope, occurred in all the waters recognized as County Cork eddy water and only there.

Pilchard eggs were abundant only in the Land's End corner current and a few were found at stations 42, 67 and 88.

EVENTS WEST OF THE MERIDIAN 9° W.

The conclusions as to the drift current flowing in the northern Celtic Sea between 7° and 9° west prompt the question as to what may have been happening still farther west. On 19 March 1955 R.V. 'Sarsia' worked a section 40 miles long up the continental slope along the parallel 50° 34′ N. between 11° 28′ W. and 10° 20′ W. (Fig. 16). The iso-lines of all properties except salinity sloped steeply upwards towards the slope. The isopycnals showed that

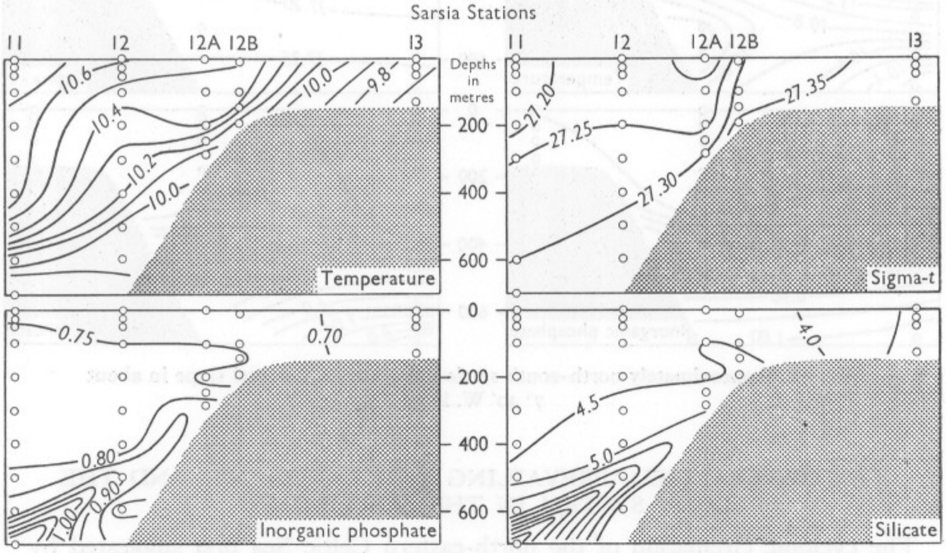

Fig. 16. East–west section over the continental slope on 19 March 1955 along the parallel 50° 34′ N. Salinity was almost uniform (35·42–35·47‰) except at station 12B (35·53‰). Silicate and phosphate are reported as μg-atom/l.

a current was running south above the break of the slope and extended down the slope to a depth of 600 m or more. The nutrients betrayed a similar slope indicating moderate up-welling.

We now have strong evidence for a south-going current in 7° W. and in 10° 50′ W. in March–April and an inference that it may run intermittently in 9° W. It is not unreasonable to conclude that everywhere between 50° and 51° N. lat. and between 7° and 11° W. long. there is in these months a general drift of water from north to south or south-east.

Also on 18 March 1955 there was a less strongly developed current setting south-east over the slope south of the Celtic Sea in about 7° 40′ W. (Fig. 17). This weak current is in line with evidence that has already been presented for that area (Cooper, 1960*b*). i.e. the broad current after it has lost the component which turns east into the English Channel, weakens and turns into alignment with the slope of the southern Celtic Sea.

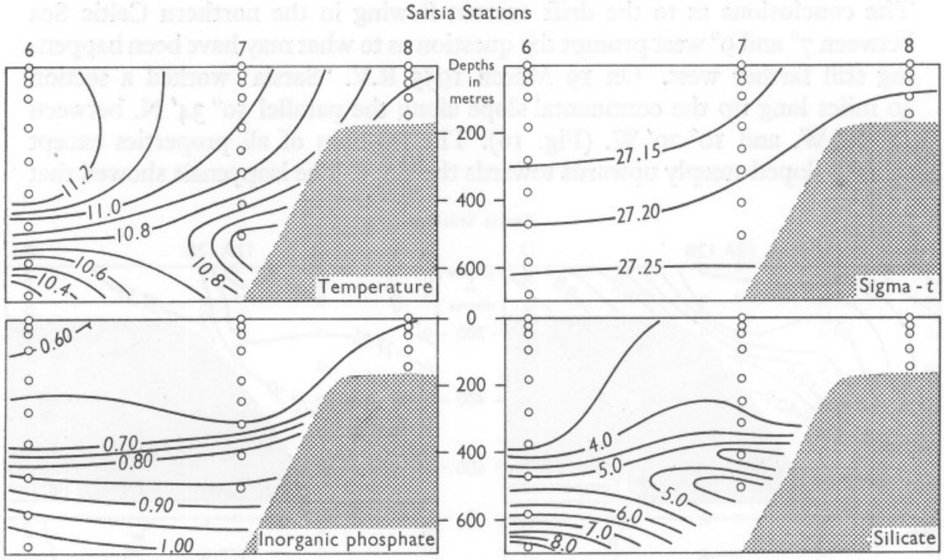

Fig. 17. Approximately north–south section over the continental slope in about 7° 40′ W. long.

THE GENERALIZED 'PREVAILING DRIFT CURRENT' AND THE EDDY SYSTEM IN THE NORTH-EAST

The cyclonic circulation of the north-eastern Celtic Sea first suggested by Matthews (1914) has been established for the early spring of 1950 (Fig. 18). The entry of warm, saline water intermittently in the Land's End corner current to the waters north of Cornwall may be said to initiate the circulation. In the shallow Bristol Channel this water is strongly cooled and diluted by run-off to give the cold but light South Wales coastal current flowing west. This current becomes enriched in phosphate from sewage but it has not been shown that this enrichment was followed by extensive production of plants and animals.

In St George's Channel there was a component of movement from east to west, but if there was any direct transfer of water it was through an area centred on 51° 45′ N., 6° 15′ W. which we did not sample. The South Wales water rich in phosphate and silicate turned St David's Head into Cardigan

Bay and was replaced mainly by a nutrient-poor water with similar temperature, salinity and density flowing south along the coast of County Wexford around Carnsore Point. The component of movement from east to west was therefore at best a resolvent from a diffuse cyclonic movement which involved much of the Irish Sea.

The Nymphe Bank is an extensive area with a depth of about 70 m lying south of County Waterford and County Wexford. Though this depth is considerable, even so the rate of fall of temperature over it in cold weather will be greater than in the vertically homogenous deeper water to the south. The Nymphe Bank is therefore an area where in winter cold water may become relatively colder still. The loop in the iso-lines in Fig. 13 (p. 257) centred on 51° 30′ N. 6° 30′ W. is the result of this property of the Nymphe Bank in winter.

This cold water escaped to the southward to provide a large statistically stagnant water mass centred on a position about 51 °N., 6° 45′ W. Probably its most usual movement is as a wind drift constrained by the topography of the land masses towards the Scilly Islands. The course in early April 1950 may have been as in the section shown in Fig. 7. (p. 249) and in Fig. 18. The cold pocket with a latitude deviation less than -10 (i.e. a temperature 0·1° C colder than the latitude mean) lying north of Scilly, may provide the water which Carruthers, Lawford & Veley (1951) so frequently find moving past the Seven Stones Light Vessel in a direction between east and south-east.

An alternative movement towards the south-west had also taken place not long before the April cruise. Channelled in direction by the Cockburn Bank, it was still running as a current with a sharp boundary between stations 19 and 20.

Piecing together all the arguments presented for March, April and May 1950 and in March 1955 in these several papers, we have a picture of a broad current in March–April setting south-east or south-south-east from the south coast of Ireland across the Celtic Sea towards the mouth of the English Channel and Brittany (Fig. 18).

This was recruited in some measure from water coming down the east coast of Ireland and probably by a large body of saline water recruited from the ocean south-west of County Kerry. A rather qualitative assessment would suggest, in spite of what has been written of St George's Channel, that a considerable volume of cold water of intermediate salinity (say 35·1‰) must be supplied from the east through the position 51° 45′ N., 6° 15′ W. where we had no observations.

During April and May water was drawn off in an easterly direction or somewhat south of east into the English Channel. On this view the cyclonic eddy of the north-eastern Celtic Sea in early spring is a secondary consequence of this extensive wide wind drift and not a primary event.

Some time before the April cruise there had been a break-out of Nymphe Bank water flowing on the eastern side of the stream across to the western side, cutting in two the more saline and warmer water mass composing it.

Current charts (e.g. Admiralty Hydrographic Department, 1954, p. 7) show a drift between east and south-east. Such charts, derived from the drift of ships, represent only the top 4 m or so of the sea. The present study in April 1950 has indicated in the Northern Celtic Sea a drift about 45° to the right of this direction, a deviation to be expected when one studies movement of the whole water column rather than the top 4 m.

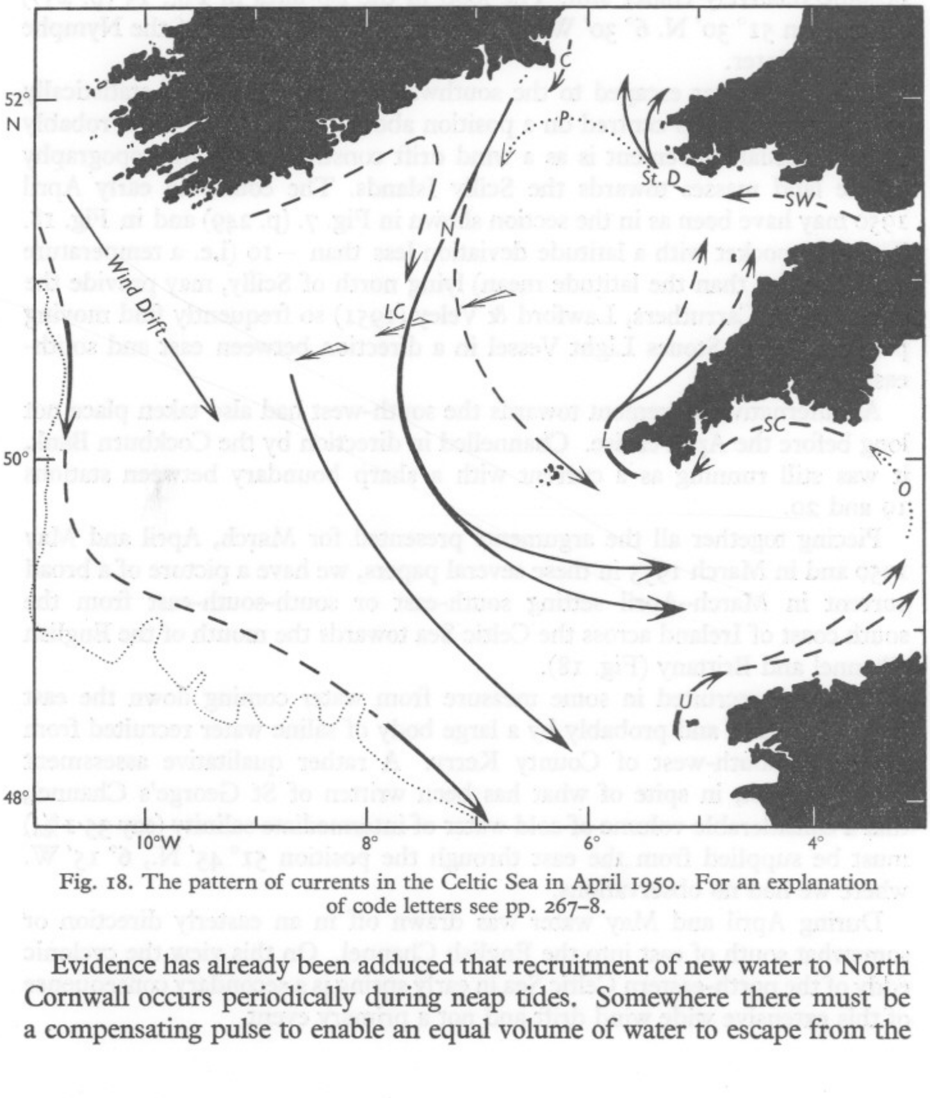

Fig. 18. The pattern of currents in the Celtic Sea in April 1950. For an explanation of code letters see pp. 267–8.

Evidence has already been adduced that recruitment of new water to North Cornwall occurs periodically during neap tides. Somewhere there must be a compensating pulse to enable an equal volume of water to escape from the north-eastern eddy. It is tempting to believe that the cold water observed on the ninth meridian between 50° and 50° 35′ N. may have been a consequence of this compensation pulse.

Acknowledgement of the generous help received was made earlier (Cooper, 1960c, p. 657). Further, I am much indebted to Mr P. G. Corbin for the zooplankton distribution pp. 262–3 and to Mr F. A. J. Armstrong for the analyses of compounds of phosphorus and silicon.

THE WAY AHEAD IN THE CELTIC SEA

The preparation of the papers on the Celtic Sea in this and the two previous issues of this *Journal* has involved much work spread over 10 years. For the years in question much valuable factual information about the area has been produced and some suggestions for further work have emerged. But it must be admitted that the main conclusions are no more than (*a*) that prevailing winds produce prevailing currents—an axiom, and (*b*) that the conclusions on circulation drawn by Matthews (1914) and by Russell (1935*a*, *b*) using biological indicators are confirmed. Such an inadequate return from so much effort gives cause to pause to consider the way ahead. The model of our 1950 programme is not the one to follow. The most fertile lines of work, to my mind, are (*a*) punctilious investigations in crucial regions such as major headlands and experimental sites such as station E1, (*b*) global studies such as those attempting to relate fishery success with global events like fluctuations in polar climates, and (*c*) studies of the chemical factors which control the success or failure of indicator species and commercial fish.

SUMMARY OF THE 'PREVAILING' CURRENT SYSTEM IN SPRING

The pattern of currents deduced largely on the basis of work in 1950 and described in this and the preceding papers is summarized in Fig. 18 (p. 266). Features of special interest are lettered:

U Ushant corner current. Favoured by very wet weather over western France and by very mild weather over the sea. May be completely suppressed during dry or cold weather.

O Occasional drift, consequent on very strong development of the Ushant corner current or upon more water being pressed into the western English Channel than the Straits of Dover can pass to the North Sea.

SC South Cornwall coastal current, which may be a compensation current to get rid of excess water from the western English Channel. It may be assisted by heavy rainfall or very mild weather over south-western England.

L Land's End corner current, running most strongly at neap tides and favoured by very wet weather over south Devon and Cornwall and by mild weather, May be suppressed at spring tides and/or during cold and dry weather.

SW South Wales coastal current, dependent on the amount of drainage from the Severn and other considerable rivers draining into the Bristol Channel. Deductions based very largely on inference, more observations needed.

St D St David's corner current, likely to share the characters of the Land's End Corner current.

C Carnsore corner current probably intermittent and small compared with the corner currents around Ushant, Land's End and St David's Head.

N The Nymphe Bank current.

LC 'Level crossing', see p. 258.

P Possible drift in an area where there were no stations.

This pattern of currents in spring is likely to flow when winds prevail from the west or south-west. Prolonged winds from other quarters may distort it, indeed prolonged easterly winds may destroy it completely.

Again, the pattern of currents in Fig. 18 has no application in the months June–September.

SUMMARY

The circulation of the northern and north-eastern Celtic Sea, has been studied, using especially observations made in April 1950.

The Celtic Sea in that month was 0·5° C warmer than the average temperature 20 years earlier.

The following distinctive water masses have been recognized (i) Land's End water; (ii) South Wales coastal water; (iii) Carnsore corner current water; (iv) Nymphe Bank water, including a component enriched by up-welling off Waterford; (v) County Cork eddy water.

The South Wales coastal water, though rich in nutrients presumably derived from sewage effluents, was not very productive. A parallel is drawn with the Hyperion sewage scheme of the City of Los Angeles.

The low-salinity water present in the centre of St George's Channel in summer is attributed to flow from the coast of South Wales. In the autumn water is recruited more directly from the Celtic Sea.

The silicate content of the Carnsore corner current was half that in South Wales coastal water on the opposite side of the Channel.

Up-welling of water enriched by breakdown of bottom muds occurred off Waterford.

The drift system in the central Celtic Sea is dominated by the prevailing winds. The drift in April 1950 was a composite affair and it has been possible to dissect some of the components and to show how they interplay.

In about 7° W. long., a mixed water mass sets south from the Nymphe Bank and was identified for more than 100 miles.

A tentative explanation is offered for the distribution of compounds of phosphorus in terms of regeneration from bottom deposits. The distribution of plant pigments and of some animals was related to the history of the water masses.

In March 1955 sections over the continental slope west and south of the Celtic Sea enable a pattern of wind-drift currents to be established (Fig. 18, p. 265). The drift of plankton is discussed.

Appendix added in proof

Since the paper was written Southward (1961) has published an article on the distribution of plankton animals in the English Channel and Western Approaches in 1955 and 1957. His conclusions are in close accord with those presented here. Though there are differences in detail, as might be expected when comparing different years, the broad agreement is striking. My contention that biologists may derive a sufficient understanding of water movements by study of their catches only is strongly reinforced.

I agree with his conclusions, at least in spring, that Russell's 'Western' water may be better described as 'North Western' water. As spring gives way to summer, experience may show that the term 'Western' remains more appropriate.

It is improbable that the high phosphate observed at Station E 1 early in 1955 was connected with the high phosphate bathing the upper continental slope south-west of Ireland. Though not yet examined in detail it is more probable that, as in 1950, the high phosphate content at E 1 had been earlier created by gales disturbing the muddy deposits in Lyme Bay (Cooper, 1958), followed by a coastwise drift to the west.

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