Pakistan J.Sci.Ind.Res., Vol.25, No.6, December 1982

CRITERION FOR THE FORMATION OF A THERMOCLINE IN THE EASTERN IRISH SEA

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(Received May 10, 1981)

Several workers have proposed criteria to determine whether complete vertical mixing should occur or a thermocline be developed as a result of summer heating. For waters around the British Isles Fearnhead (1975) found that the existence of fronts between well mixed and stratified waters corresponds to a value of $H/u_m^3 \approx 100$. where H is the depth of water and u_m is the amplitude of the tidal current. Considerable degree of stratification in temperature and salinity was observed over a large part of the area in the Eastern Irish Sea during the summers of 1975 and 1976. In view of the current interest in the occurrence of the fronts and their relation to mixing processes the conditions observed in these two summers are related to various criteria which have been proposed. Contours of the values $P=H/u_m^3$ show that the critical value of about 100 applied fairly well to the area in the Eastern Irish Sea. One would expect a thermocline to be formed earlier in summer where the values of the parameter p are the highest.

INTRODUCTION

The heat energy absorbed by the upper layer of the ocean causes variations in temperature. When surface heating is sufficient, more buoyancy is produced than can be dissipated by wind and tide. Owing to the influence of gravity there is tendency for dense parcels of water to sink and for less dense parcels to rise towards the surface of the oceans.

The usually gentle vertical gradient of temperature in the ocean may sometimes be steepened in zones delineated by isopleths that are closely spaced relative to the total depth. In these layers the vertical gradient of temperature may be sharply graded from the deep water regime to that of the surface layer. A steep vertical gradient of temperature in an otherwise gently graded sounding is called a thermocline. In a body of water a thermocline does not necessarily form simultaneously over the whole area, so that the water column may be mixed in one region and stratified in an adjacent region. In this situation there is commonly an increased horizontal temperature gradient in the surface water between the two adjacent regions, which is termed a front.

In sufficiently shalow waters, the formation of fronts depends on the bottom generated turbulance due to the tidal currents. If the tidal currents are strong, there will be enough bottom generated turbulence to prevent the formation of a seasonal thermocline and keep the water in a mixed state. On the other hand in a region of weak tidal currents, the water will become stratified.

In view of the current interest in the occurrence of fronts and their relation to mixing processes, the conditions observed in the Eastern Irish Sea are described and related to various criteria which have been proposed.

Presentation of Data. The data were obtained during the following two cruises in R.R.S. John Murray:

27th July – 13th August, 1975
29th June – 12th July, 1976

Profiles of temperature and salinity form 1 m below the surface to within about 3 m of the bottom were obtained with a Bissett-Berman STD Probe. A model 9006 instrument was used in 1975 and a model 9040 in 1976. In each case an expanded depth scale was used to give adequate resolution in shallow water. 85 stations in approximately the same position were worked in both years and these provide the basic data for the present study. In the 1975 cruise, 55 other stations were occupied further to the north and west of the area. A chart of the Eastern Irish Sea showing the depth contours and the position of the stations is given in Fig. 1.

The distribution of surface temperature in the two years is shown in Fig. 2, that of surface salinity in Fig. 3 and that of density by σ_t [$\sigma_t = 10^3 (\rho - 1)$] where ρ is density, in Fig. 4. This paper is concerned primarily

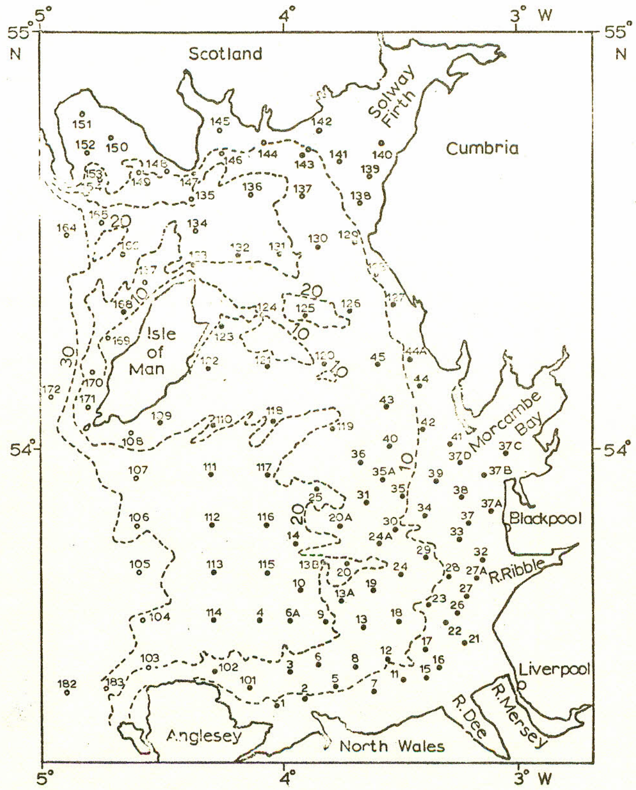

Fig. 1 Map of the Eastern Irish Sea with STD stations.

with the temperature distribution, but in view of the correlation between the temperature and salinity stratification it is reasonable to consider the two together. As expected the salinity decreased from the open sea towards the coast where the influence of river run-off is effective. In 1975 the decrease in salinity occurred fairly gradually, but in 1976 the decrease was concentrated into a narrow band in the Liverpool Bay area, as seen from the course of the 33.5 to 32.75 $^{o}/oo$ isohalines. The temperature increases from the open sea towards the coast, as expected in summer due to the greater rise in temperature of the shallow water. The surface distribution of σ_t may be compared with those taken by Heaps and Jones [3] as the basis of their calculations of density currents using a three dimensional numerical model. In 1975 the distribution was rather similar to that of September 17–October 6,1972 although the gradient of σ_t from the Isle of Man-Anglesey line towards the English Coast was somewhat greater. In 1976 the distribution was more similar to the second example taken by Heaps and Jones [3], for 6–20 September 1971 with sharp density gradients in the south-east of the area.

The difference between surface and bottom values of temperature, salinity and density in each of the two years are shown in Figs. 5,6 and 7 respectively. The areas with the largest differences in temperature and salinity correspond to one antother approximately, although the correspondence is by no means exact. The difference in density, being determined by the difference in temperature and salinity naturally follows a similar distribution. On the whole the temperature has the greater influence on the density difference. A temperature difference of 4^{o} between the surface and bottom corresponds to about 1.00 in σ_t, while a difference of 0.4 $^{o}/oo$ in salinity corresponds to 0.32 in σ_t. Comparing the two years, the area within which significant stratification occurred did not extend quite so far to the west in 1976, although the intensity of stratification, as indicated by the surface-bottom differences was somewhat greater at the beginning of July 1976 than it had been a month later in 1975.

Some representative examples of the STD traces at various stations are shown in Figs. 8 and 9. At some stations e.g. Fig. 8(a) there was a surface mixed layer several metres in thickness with sharp gradients of temperature and salinity immediately below it. At others, as in Fig. 8(b) the gradient appeared to start at the surface although, with the STD probe, measurements could not be made at a depth of less than 1 m. An some traces the temperature and salinity then decreased fairly uniformly to the bottom but in others, e.g. Fig. 9(b) a secondary mixed layer occurred at mid-depth. No systematic correlation could be found between the character of a traces and the area in which it occurred, considerable differences often appearing between traces at adjacent stations.

Criteria for the Formation of a Thermocline. Several workers have proposed criteria to determine whether complete vertical mixing should occur or a thermocline be developed as a result of summer heating. These involve a comparison of the energy required for mixing against a buoyancy flux with the turbulent energy generated by bottom friction. Simpson and Hunter [5] propsed the use of the parameter H/u_o^3 where H is the total depth of water and u_o the amplitude of the tidal current near the bottom. Denoting this parameter by P complete mixing should occur if

$$P = H/u_o^3 < P_{crit.}$$

where the critical value $P_{crit.}$ depends on various physical parameters and is inversely proportional to the rate of heat flux Q through the surface. If a single value of $P_{crit.}$ is to be used as a criterian for the occurrence of a summer thermocline, the value of Q may be taken as the maximum rate of heating in the summer months. Simpson and Hunter [5] found that the occurrence of a front separating well

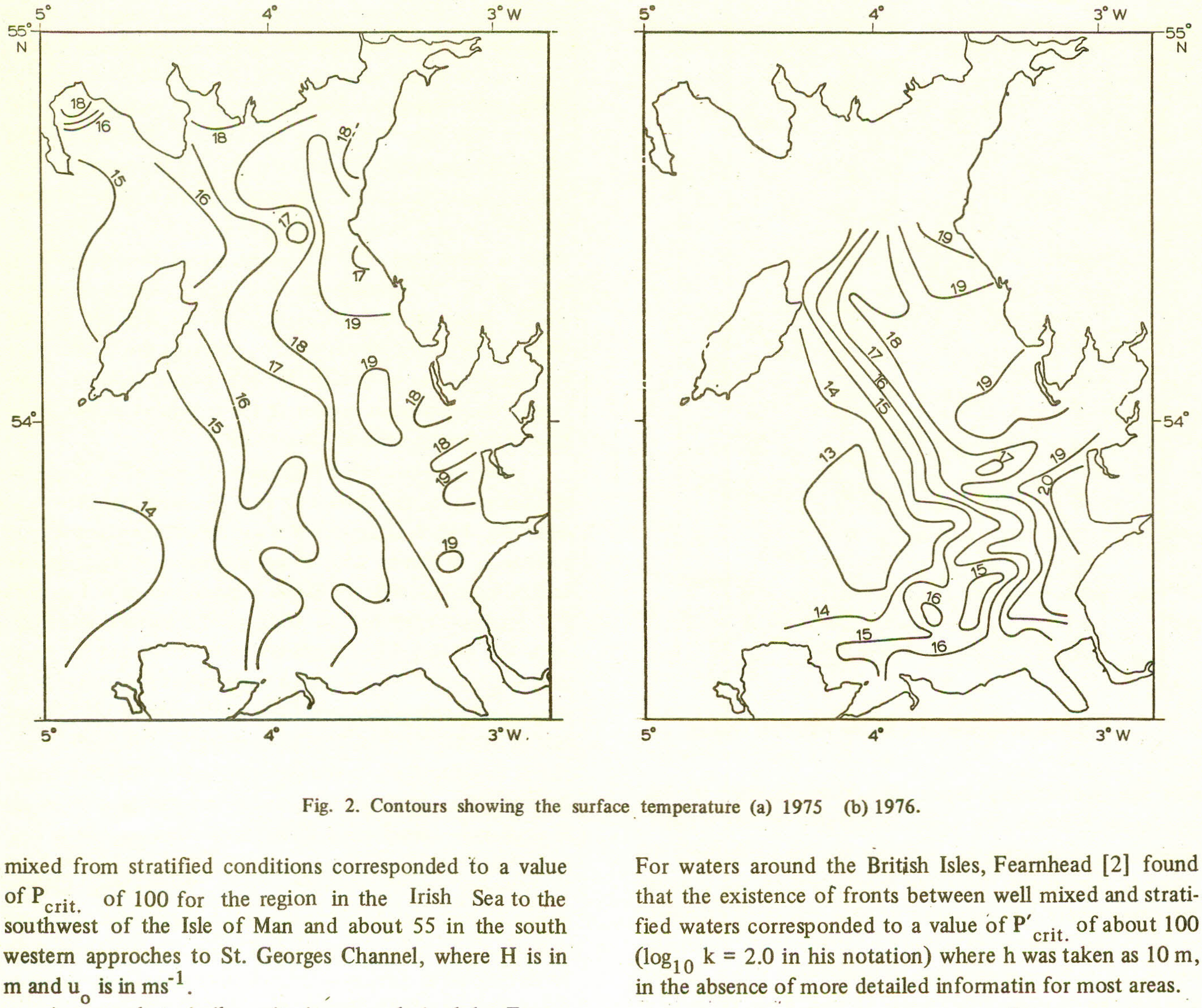

Fig. 2. Contours showing the surface temperature (a) 1975 (b) 1976.

mixed from stratified conditions corresponded to a value of $P_{crit.}$ of 100 for the region in the Irish Sea to the southwest of the Isle of Man and about 55 in the south western approches to St. Georges Channel, where H is in m and u_o is in ms^{-1}.

A somewhat similar criterian was derived by Fearnhead [2], but he allowed for wind mixing within a surface layer of depth h, whereas Simpson and Hunter [5] had assumed that the heat was absorbed in an infinitely thin surface layer and did not consider wind mixing explicitly. Thus the parameter introduced by Fearnhead [2] was $(H\text{-}h)/u_m^3$ where u_m is the amplitude of the average tidal current at springs. The conditions for complete vertical mixing may be expressed as

$$p' = \frac{H-h}{U_m^3} < p'_{crit.}$$

where $p'_{crit.}$ depends on similar physical parameters to P_{crit} and is inversely proportional to a buoyanc flux term. The two criteria are essentially the same if the buoyancy flux is assumed to be due entirely to the heat flux. For waters around the British Isles, Fearnhead [2] found that the existence of fronts between well mixed and stratified waters corresponded to a value of $P'_{crit.}$ of about 100 ($\log_{10} k = 2.0$ in his notation) where h was taken as 10 m, in the absence of more detailed informatin for most areas.

The values of the parameter H/u_m^3 for the stations in the Eastern Irish Sea were calculated and the contours are shown in fig. 10. u_m is the amplitude of the depth-mean tidal currents at springs, based on available measurements, supplemented by data provided by Dr. N. S. Heaps [3] from his two dimensional numerical model ofthe Irish Sea. It is seen that the critical value of about 100 applies fairly well to the area to the Eastern Irish Sea in which stratification was observed in the summers of 1975 and 1976.

In a study of thermocline formation in a frontal region at the south end of St. Georges Channel, James [4] found a minimum value of $\log_{10} P_{crit} = 2.5$ (i.e. $P_{crit} = 300$) to apply in August with somewhat larger values earlier and later in the year. Since P_{crit} is inversely proportional to the heat flux Q, a minimum value $(P_{crit})_{min}$ may be expected where Q attains its maximum

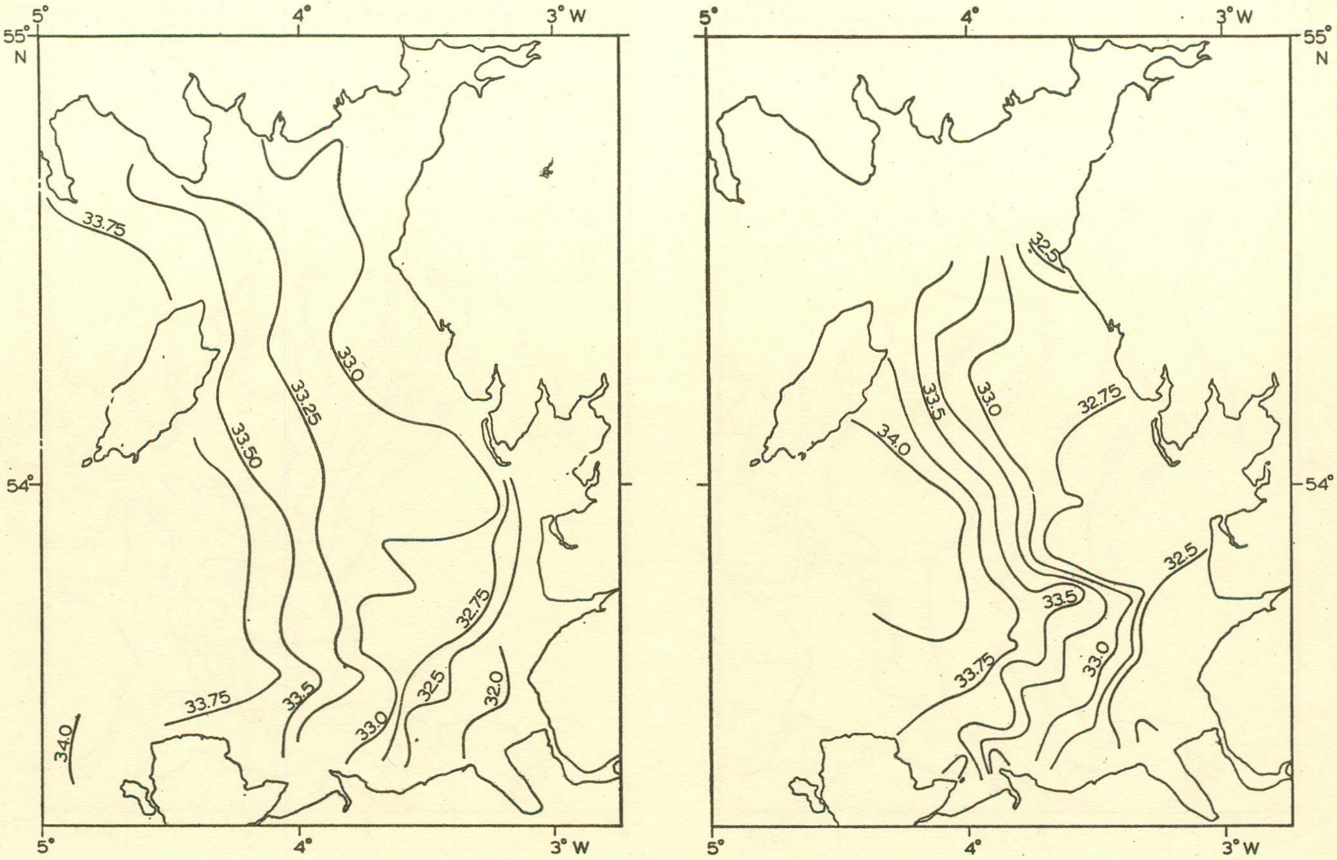

Fig. 3. Contour showing the surface salinity (a) 1975 (b) 1976.

value Q_{max}. In the heat budget estimate [1] Q, reached its maximum in June in both 1975 and 1976 with a value of approximately 400 Cal cm^{-2} day^{-1}.

$P_{crit.}$ would thus have its minimum value in June and its value in other months may be estimated from

$$P_{crit} = \frac{Q_{max.}}{Q} (P_{crit})_{min.}$$

Table I shows the monthly mean value of Q expressed as Cal cm^{-2} day^{-1} for each of the month in 1975 when Q was positive and the corresponding value of P_{crit}, where $(P_{crit})_{min}$ in June has been assigned the arbitrary value of 100. One would expect a thermocline to be formed earler in the summer where the values of the parameter P are highest. Thus in the Eastern Irish Sea a thermocline would be expected to form first in the band extending ENE from the Isle of Man to Cumbria, where $P > 300$ and then to spread northwards and southwards from this area. The parameter P applies to the initial formation of a thermocline. After a thermocline has been established, the stored buoyancy has to be removed before the water column can become mixed. A different parameter would be needed to predict the breakdown of the thermocline and the value of P_{crit} given in Table 1 for the months after June cannot be used for this purpose.

Effect of Fresh Water Flux. The buoyancy flux arising from a net excess of rainfall over evaporation at the sea surface may be incorporated by expressing the total buoyancy flux B as

$$B = g\left(\frac{\alpha Q}{C_p} + \beta s f\right) \quad [8]$$

Where f = excess of rainfall over evaporation
s = surface salinity
β = Coefficient of saline contraction.

Inserting typical values of Q and f for the Irish Sea in summer indicates that the freshwater flux term arising in this way is unlikely to exceed 5 % of the heat flux term. The appreciable salinity stratification observed at a number of station is more likely to be due to the spreading of river water cutward from the coast. To take this

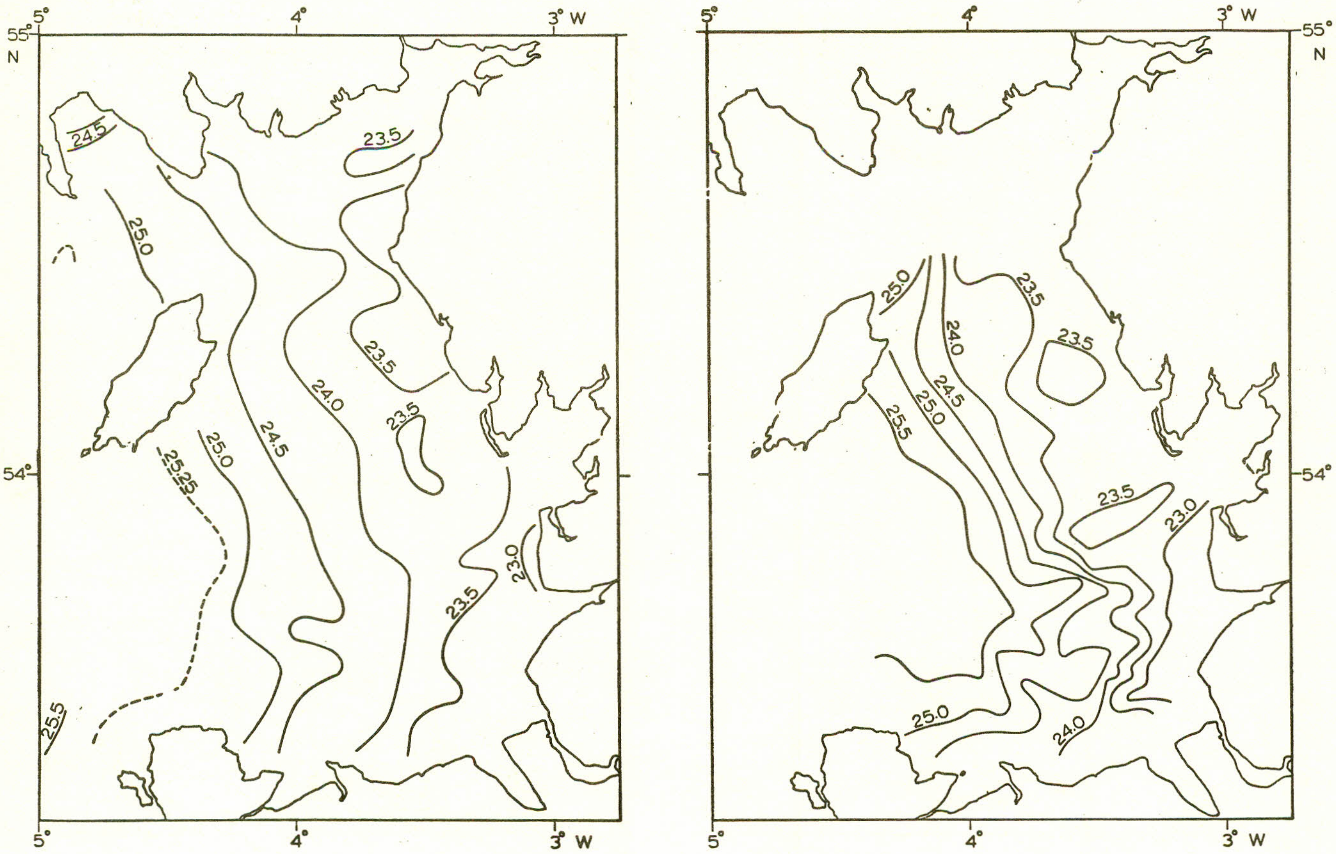

Fig. 4. Contours showing the surface density (a) 1975 (b) 1976.

into account requires a more complex model than the one-dimentional model considered in formulating the above criteria.

Comparison of Conditions in the Summers of 1975 and 1976 with Other Years. The summers of 1975 and 1976 were unusually sunny and warm in most parts of the British Isles and it may be asked whether the conditions in the waters of the Irish sea were also exceptional in these two years. Unfortunately, surveys of the type described here have not been carried out in other years and there is no direct evidence on the question. Some guidance may be obtained from the surface water temperature at Port Erin breakwater which has been measured daily for many years. The monthly mean temperature for the six months March – August in 1975 and 1976, expressed as deviations from the 10 years mean for the years 1962-71 are shown in Table 2. For all months except May 1975, the 1975 and 1976 temperatures were higher than the mean, but the difference exceeded 1° only in July and August, 1975. The deviations from the mean do not seem to be exceptionally large but Port Erin is on the Western edge of the area and the temperatures there may be influenced by the deeper water to the west of the Isle of Man rather than by those of the Eastern Irish Sea.

As an indication of the extent to which the meteorological conditions were abnormal, the solar radiation figures for Fairfield (about 10 km to the East of Blackpool) the nearest recording station to the area are shown tin Table 3. for the months March – August in 1975 and 1976, compared with the mean values based on 15 years data. In 1975 values 16–17 % above the mean were recorded in May, June and August, although July was slightly below average. In 1976 the value for May was below average, but those for the June, July and August were all higher. Taking the three months June, July and August together, the radiation received was about 10 % above average in both 1975 and 1976.

Another significant meteorological factor is the wind speed which has an important influence on the heat loss by evaporation. Table 4 shows wind speeds measured at three land stations around the Irish Sea. The monthly mean wind speeds measured at Squires Gate near Blackpool, during the periods March – August in 1975 and 1976 were consistently lower than the 10 years mean

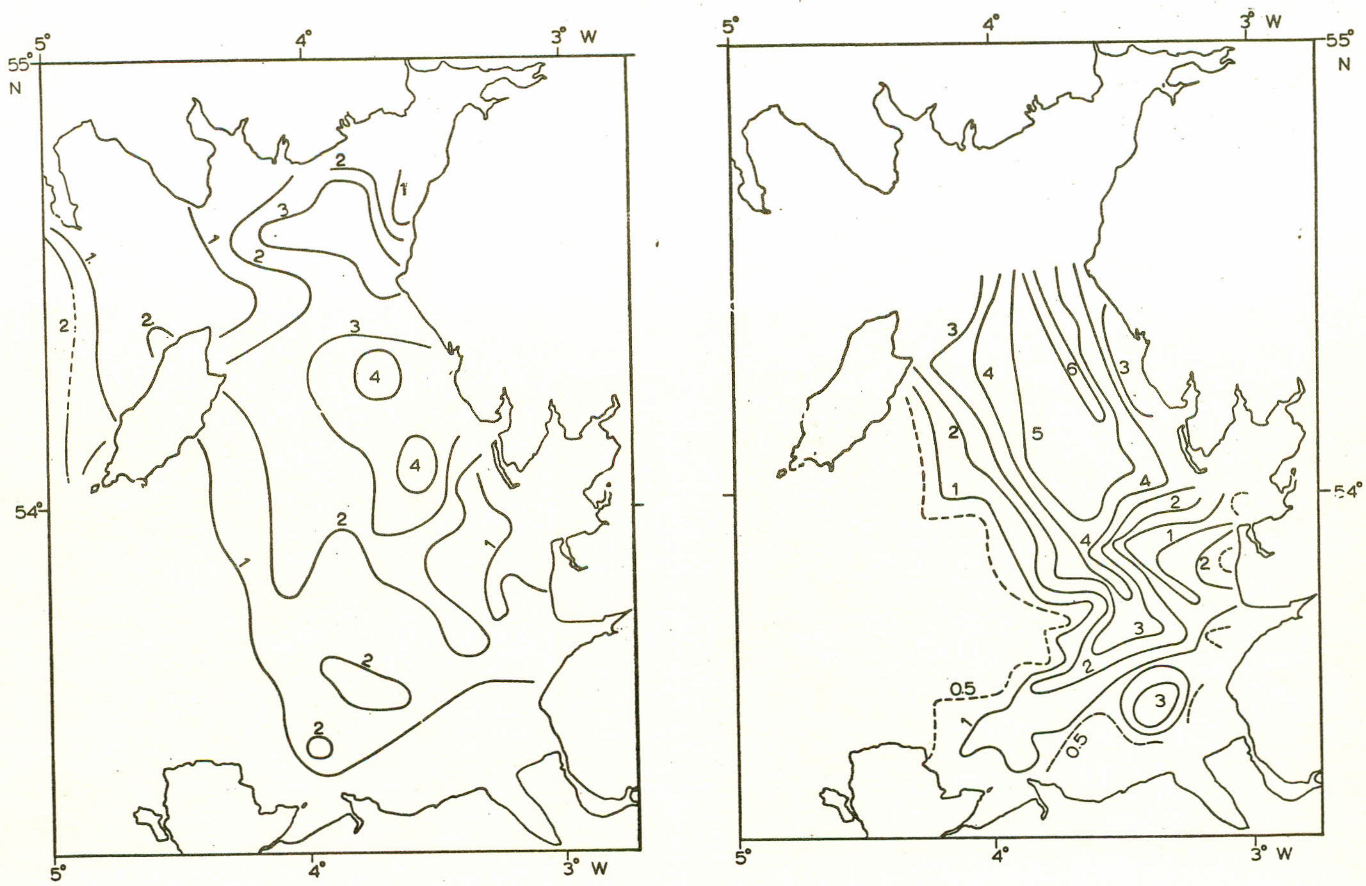

Fig. 5. Contours showing the temperature difference (surface temperature – bottom temperature) (a) 1975 (b) 1976.

Table 1. Monthly variation of heat flux Q (Cal. Cm^{-2} day^{-1}) and the parameter $P_{crit.}$ 1975.

	April	May	June	July	Aug.	Sept.
Q	162	290	401	235	268	11
$P_{crit.}$	248	138	100	123	150	3645

Table 2. Monthly mean sea surface temperature (^{o}C) at port Erin breakwater in 1975 and 1976 expressed as deviations from the 10 years average, 1962-1971.

	March	April	May	June	July	August
1962-71	6.62	7.48	9.25	11.40	12.99	13.92
Deviation 1975	0.76	0.43	0.00	0.30	1.17	1.11
Devaition 1976	0.47	0.24	0.12	0.44	0.78	0.30

Table 3. Monthly means of daily totals of solar radiation (Watt-hr m^{-2}) recorded at Fairefield expressed as percentages of the 15 years mean.

	March	April	May	June	July	August.
15 year mean	2183	3560	4660	5226	4734	3864
1975%	116.6	97.1	116.4	117.3	98.2	116.3
1976%	92.9	102.1	91.5	104.2	106.3	120.9

values for 1965–1974 by 8 to 28 %. Those at valley, Anglesey, were also consistently lower throughout the same period by a similar amount. The wind speeds measured at Ronaldsway did not show a pronounced deviation, being within $\pm$ 5 % of the mean in May, June and July of each year but lower in August by 25 % in 1975 and 15 % in 1976. On the whole it appears that wind speeds over the area were lower than average in the summers of 1975 and 1976, thus tending to reduce the heat loss by evaporation as well as to reduce mixing of the surface layer. The

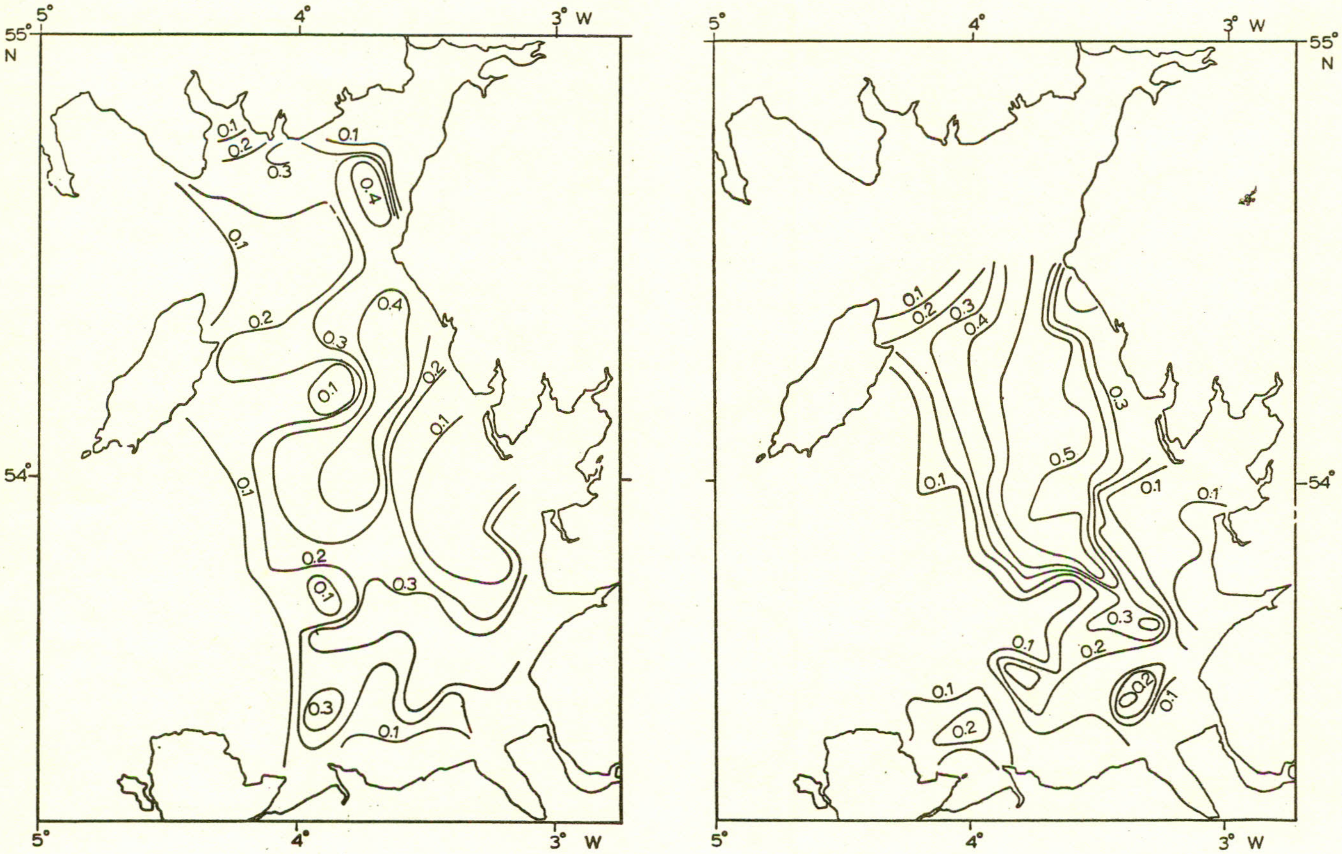

Fig.6. Contours showing the salinity difference (Bottom salinity) surface salinity) (a) 1975 (b) 1976.

Table 4. Comparison of wind speeds in knots measured at Squires Gate, Valley, Ronaldsway in 1975 and 1976 with monthly means of 1965-1974 period

	Squires Gate	Valley	Ronaldsway	Squires Gate	Valley	Ronaldsway
		March			April	
Mean 1965-74	13.2	14.7	13.6	11.9	13.4	12.1
1975 %	72.	80	84	86	96	93
1976 %	89	82	106	80	81	88
		May			June	
Mean 1965-74	11.6	12.9	10.3	11.2	12.5	9.0
1975 %	78	75	95	86	82	106
1976 %	91	98	106	78	94	94
		July			August	
Mean 1965-74	11.2	11.9	8.7	11.0	11.6	9.4
1975 %	85	99	103	79	78	74
1976 %	85	84	102	76	73	85

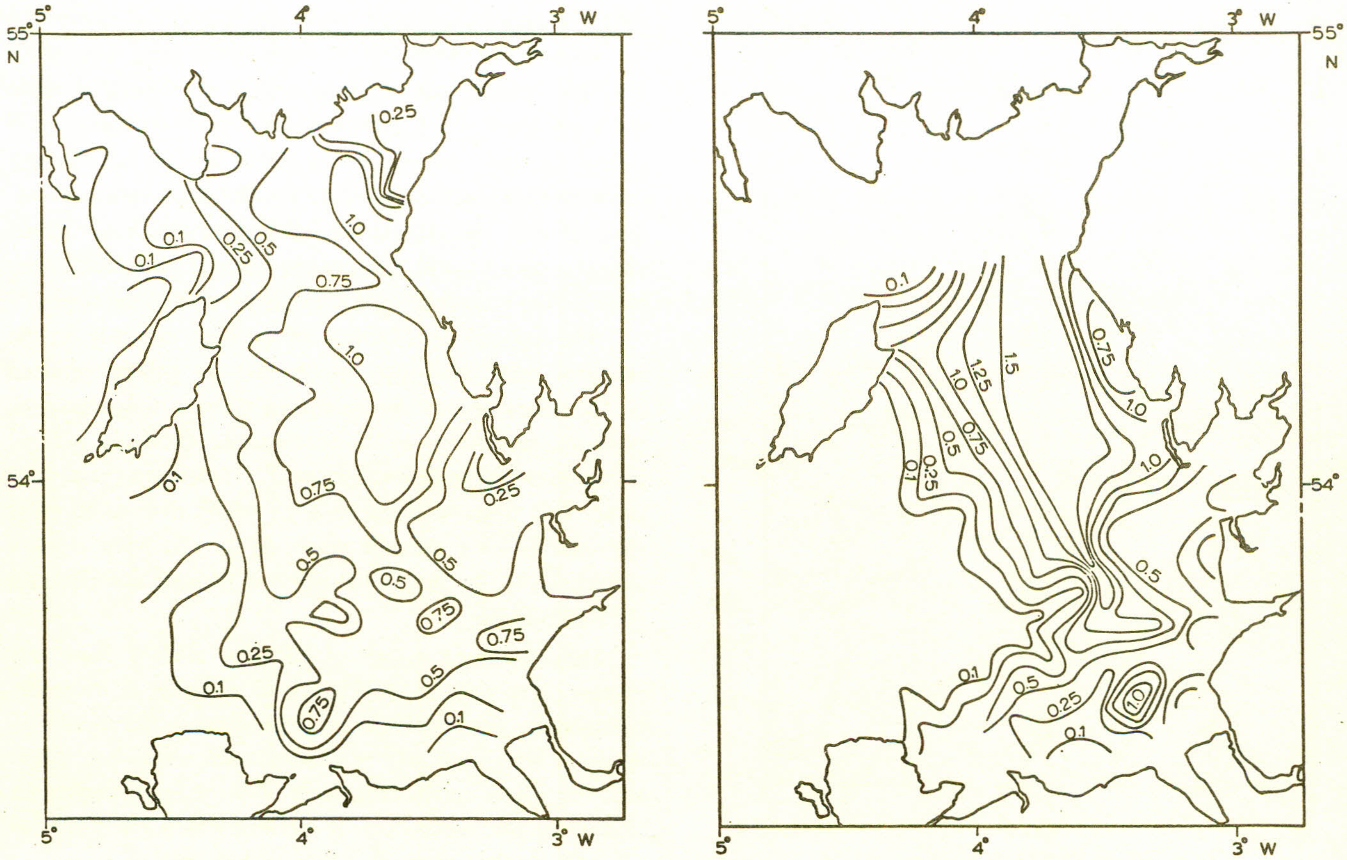

Fig. 7. Contours showing the density difference (Bottom density-surface density) (a) 1975 (b) 1976.

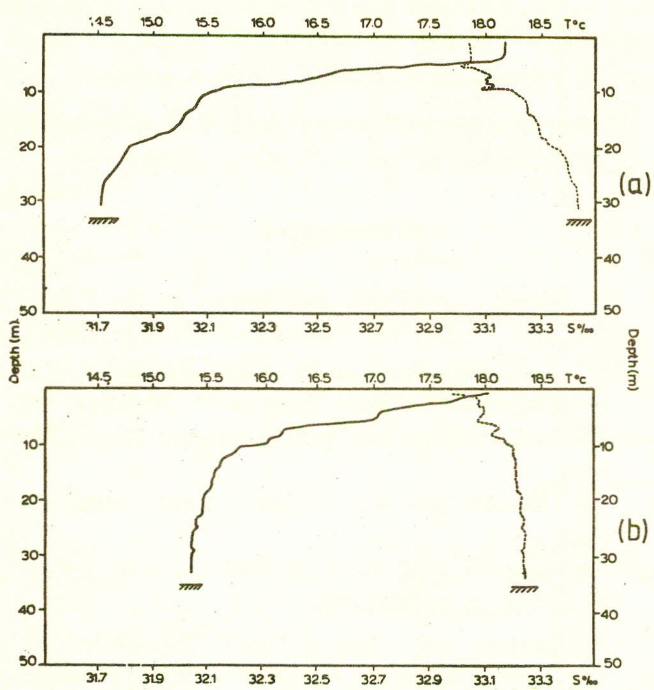

Fig. 8. Representative STD traces

——temperature (a) station 36, 3rd August, 1975
——salinity (b) station 31, 3rd August, 1975

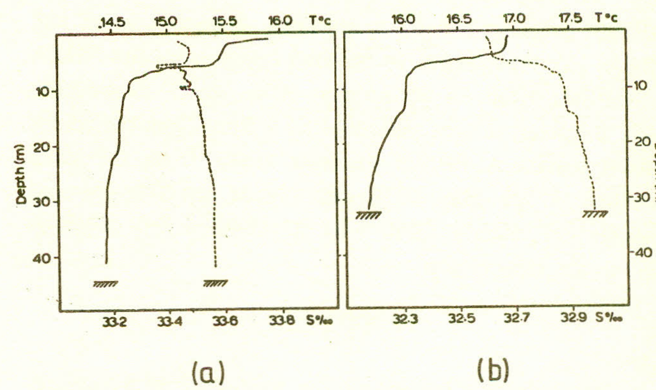

Fig. 9. Examples of STD traces with a secondary mixed layer

——temperature (a) station 115, 2nd August, 1975
——salinity (b) station 18, 31st July 1975

effects of increased solar radiation and reduced wind speeds taken together would tend to favour the formation of a summer thermocline in 1975 and 1976 more than in other years, but it is not possible to make a quantitative estimate of their significance.

It is interesting to note that the occurrence of a summer thermocline in the eastern Irish Sea, with the consequent increase in surface temperature relative to the water further

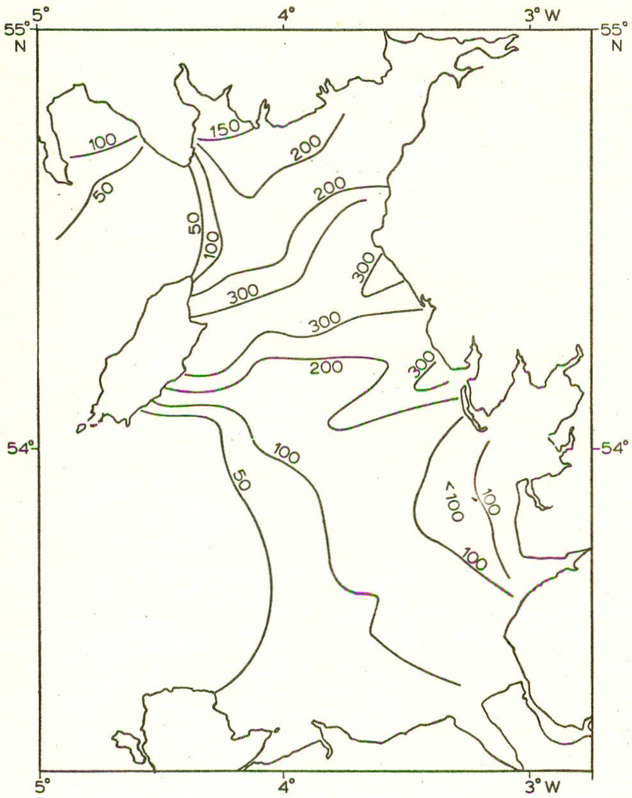

Fig. 10. Contours of H/u^3

west, as described in this paper, has also been shown by infrared photographs from satellites. Simpson, Allen and Morris [6] reproduced an infrared image from the NOAA 5 satellite, taken on 20 August, 1976, which showed the high temperature area separated by a front from the colder mixed water. A further example taken from the same satellite on 21 May 1978, reproduced by Simpson and Bowers [7], clearly showed an increased surface temperature in the same region.

DISCUSSION

The processes leading to the formation of a thermocline in coastal waters have an interest beyond that of the occurrence of the thermocline itself. One aspect is the dynamical effect which it can have on the density current flow generated by the offshore gradient of density. As shown by Heaps [9] in an analytical treatment the current vector rotates with depth, having an offshore component near the surface and an onshore component near the bottom. Subsequent work by Heapsand Jones [3], with a three dimensional numerical model of the Irish Sea, provided a more detailed picture of the circulation in the Eastern Irish Sea driven by a typical distribution of density. Comparing the density currents with the circulation produced by various distributions of wind stress, they concluded that the density current flow would be dominent when the wind speed was less than about 5 m s^{-1}. At higher wind speeds the wind driven current would become increasingly important and would dominate for the wind speeds exceeding 10 m s^{-1}. In general the wind speeds are lower in the summer months and the density current circulation may be expected to prevail for a high proportion of the time.

The vertical distribution of velocity depends on the effective eddy viscosity, which will be greatly reduced in the thermocline. An increased current shear may be expected to develop at the thermocline, probably with an increased offshore component of the velocity in the surface layer. This may be the process by which river water from the coastal zone spreads seawards as relatively shallow surface layer, so that a halocline is formed accompaying the thermocline.

The combined effect of offshore surface flow and onshore deep flow is to produce an apparent lateral eddy diffusion by the shear effect, thus assisting the mixing of coastal waters, and any pollutants associated with them, with the waters further off shore. The mixing zone may be limited by the occurrence of a front, which is a region in which distinctive patterns of flow may occur.

The occurrence of a summer thermocline accompanied over much of the area by a halocline, is thus of dynamical significance and may be of practical importance in its effect on the mixing of coastal and offshore waters.

Acknowledgement. I am grateful to Prof. K. F. Bowden for providing help and advice in carrying out this study.

REFERENCES

1. F. Ahmed, Circulation and Mixing in the Eastern Irish Sea, Ph. D. thesis University of Liverpool (1978).
2. P.G. Fearnhead, Deep sea. Res., 22, 311 (1975).
3. N.S. HeapsandJ.E. JonesJ. Geophys. Res. **30**,415 (1977).
4. I.D. James Coastal and Estuarine Marine Sci., **5**, 339 (1977).
5. J.H. Simpson and J.B. Hunter . Nature, **250**, 404 (1975).
6. J.H. Simpson, C.M. Allen, and N.C.G. Morris. J. Geo-Phys. Res. 83, 4607 (1978).
7. J.H Simpson and D. Bowers, Nature, **280**, 648 (1979).
8. J.S. Turner, *Buoyancy Effects in Fluids* (Cambridge University Press, 1973).
9. N.S. Heaps; Geophys. J.R. Astr. Soc., **30**, 415 (1972).