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HEAT EXCHANGE PROCESSES AT THE WATER SURFACE IN THE EASTERN IRISH SEA

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In the Eastern Irish Sea the increase in heat content of the water column was calculated from mid February (considered to be time of temperature minimum) to the time of the summer cruise, from the temperature profiles of the STD stations. It is found that the increase in heat content was predominantly due to the heat balance between Ocean and atmosphere. The values of approximately $3.5 \times 10^4 \text{ cal cm}^{-2}$ for the deeper water in the south-west of the area in 1975 are similar to the values given by Pingree (1975) for the heat stored in the water column from mid March to mid September in the Celtic Sea and in the western approaches to the English Channel. The higher values of $4.5 \times 10^4 \text{ cal cm}^{-2}$ shown between the North-East corner of the Isle of Man and the mouth of Solway Firth is comparable with Pingree's value of $5.0 \times 10^4 \text{ cal cm}^{-2}$ found in the Hurd deep area of the English Channel.

INTRODUCTION

The sea absorbs solar radiation and gives off energy in the form of back radiation, evaporation and conduction to the atmosphere. During the summer half of the year the incident solar radiation is higher than the combined effects of back radiation, evaporation and conduction, and the temperature of the water column is expected to rise during this period. The amount of heat used in changing the temperature of the water column can be calculated for a specific region and given time interval from a heat balance equation given by:

$$Q_t = Q_s - Q_b - Q_e - Q_h - Q_w$$

Where Q_t = heat used for changing the water temperature

Q_s = short wave radiant energy absorbed by sea

Q_b = back radiation from the sea surface

Q_e = loss of heat due to evaporation

Q_h = loss or gain due to conduction

Q_w = heat exchange by local currents or by mixing processes

It might be reasonable to assume that the bulk of monthly changes are produced locally and that advective and horizontal diffusive processes do not contribute significantly to the monthly changes. Then the equation reduces to:

$$Q_t = Q_s - Q_b - Q_e - Q_h \quad (1)$$

As a test of the hypothesis that the main source of heating of the water was the net heat flux through the surface, the increase in heat content of the water column at each station in the Eastern Irish Sea (Fig. 1), from mid February, the time of temperature minimum, to the time of summer cruise was estimated. The increase in heat content was then compared with an estimate of the net heat through the surface.

Absorption of Radiant Energy, Q_s . As a result of the nuclear reactions that occur in the sun the temperature of its surface is approximately 6000 K, which causes the radiation of a considerable amount of energy by the sun. The radiation coming from the sun in the only form of incoming radiant energy that determines the heat balance because the energy incident upon the earth from other celestial bodies is so small that it does not influence the processes of heat exchange. The solar radiation reaching the earth's surface is more easily measured than computed.

Some of the radiation that reaches the sea surface is reflected back into the atmosphere. The reflectance r increases with the angle of incidence as given below [5]:

First hour after sunrise $r = 0.33$.

Second hour after sunrise $r = 0.10$.

Other hours $r = 0.06$.

2nd last hours before sunset $r = 0.10$.

Last hour before sunset $r = 0.33$.

If Q is the amount of radiation recorded (the insolation) then the absorbed radiation at the sea surface Q_s is

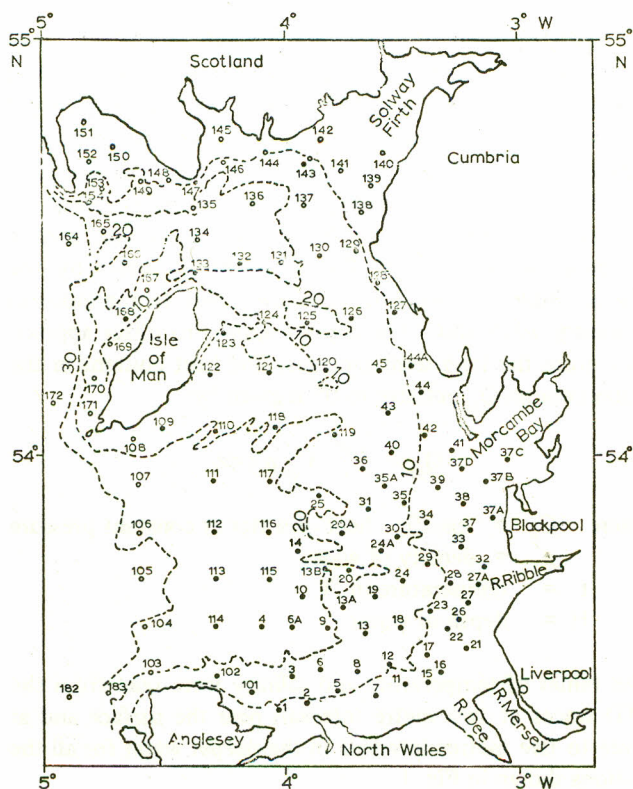


Fig. 1 Chart of the eastern Irish sea showing STD stations.

$$Q_s = Q(1-r)$$

The mean value of the solar radiation recorded at Aberporth ($52^{\circ} 8' N$, $4^{\circ} 34' W$) Aldergrove ($54^{\circ} 39' N$, $6^{\circ} 13' W$) and Fairfield ($53^{\circ} 48' N$, $2^{\circ} 43' W$) was considered to give a reasonable estimate for the incident solar radiation on the Eastern Irish Sea. As the recorded solar radiation, during the first 2 hr after sunrise and the last 2 hr before sunset were comparatively much less than at other times of the day, a fixed value for the reflection coefficient $r = 0.06$ was taken to simplify the computation. The resulting Q_s values in cal/cm^2 of sea surface (integrated over 15 days period) are shown in Tables 1 and 2 for 1975 and 1976 respectively.

Back Radiation Q_b . The value of the net long wave radiation depends on the air temperature, humidity, cloudiness and the vertical gradient of temperature and moisture in the atmosphere. As a result of investigations various formulae were found that relate the net long wave radiation under cloudless sky to the temperature and humidity of the air. The empirical formula by Brunt [2] is widely used. It has the form:

$$Q_b = \epsilon \sigma T_o^4 (a - b \sqrt{e_a})$$

where ϵ is the coefficient of emissivity with an average

value of 0.985 [4]

$$\sigma = \text{Stefan-Boltzman constant} = 82 \times 10^{-12} \text{ cal/min/cm}^2/\text{deg}^4.$$

T_o = absolute sea surface temperature.

e_a = vapour pressure in air a few meters above the surface.

a and b are constants.

This expression is favoured by Budyko [3] who used it with values

$$a = 0.39 \text{ and } b = 0.077 \text{ m b}^{1/2}.$$

The cloudiness reduces the effective outgoing radiation by a factor $(1 - cn^2)$ where

n = fraction of cloudiness

c = a factor which depends on latitude, given by Budyko [3].

Taking these values into account the expression for Q_b becomes

$$Q_b = 0.985 \sigma T_o^4 (0.39 - 0.077 \sqrt{e_a}) (1 - 0.74 n^2) \text{ cal/cm}^2/\text{min}$$

T_o was taken as the 9.00 am water temperature at Port Erin break water and n the cloudiness at Ronaldsway. The computed values of Q_b (integrated over 15 days), for 1975 and 1976 are shown in Tables 1 and 2 respectively.

Conduction, Q_h and Evaporation, Q_e . Heat can enter or leave water by conduction if the air temperature is greater than or less than the water temperature and the rate is proportional to the temperature difference between the two media.

$$Q_h = \rho_a C_p C_{10} (t_o - t_a) W \text{ cal/cm}^2/\text{sec} [4]$$

where ρ_a = density of air, $1.242 \times 10^{-3} \text{ g/cm}^3$ at 11° (mean temperature during the period).

C_{10} = drag coefficient for wind speed measured at 10 m height and is 1.3×10^{-3} .

C_p = specific heat of air at constant pressure, 0.2403 cal/g at 11° and normal atmospheric pressure.

t_o, t_a = temperature of sea surface and air respectively.

W = wind speed.

If the wind speed is in metres/sec and the temperature in

degrees centigrade then

$$Q_h = 0.140 (t_o - t_a) W \text{ cal/cm}^2/\text{hr}$$

The heat abstracted by evaporation per unit area of the sea surface in unit time is

$$Q_e = LE \text{ where } L = \text{latent heat of evaporation} \\ = 598.3 \text{ cal/g at } 11^\circ \text{ and } E \text{ is the rate of} \\ \text{evaporation in grams of water vapour/cm}^2 \\ \text{per unit time.}$$

There are many methods for estimating evaporation. Most of them are empirical. An equation for E, given by Kraus [4] is

$$E = \rho_a C_{10} (q_o - q_a) W$$

where q_o = saturated specific humidity at sea temperature,

$$q_o = 0.622 e_o / P,$$

q_a = specific humidity in air at temperature

$$q_a = 0.622 e_a / P,$$

e_o = saturated vapour pressure at temperature

$$t_o,$$

e_a = vapour pressure at temperature t_a ,

P = atmospheric pressure = 1013 mb for a standard atmosphere

If W is in metres/sec the formula becomes.

$$Q_e = 0.209 (e_o - e_w) W \text{ cal/cm}^2/\text{hr}$$

where e_w is the saturated vapour pressure at the wet bulb temperature.

Daily values of the sea surface temperature measured at 9.0 a.m. at Port Erin break water were used with dry and wet bulb air temperature and mean daily wind speeds at Ronaldsway airport, about 8 km away.

The calculated values of Q_h and Q_e (integrated over 15 days) are shown in Tables 1 and 2 for the years 1975 and 1976 respectively.

Heat Used in Raising the Temperature of Water Q_t .

The values of Q_t were calculated from the equation (1) using the values of the other terms as calculated above. The values were calculated from 15 February to the time of the summer cruise i.e.

- (a) 15 February – 31st July 1975
- (b) 15 February – 5th July 1976

The higher values of Q_t for 1975 are due entirely to the later end point of the calculation. Up to 30th June the values of Q_t in 1975 and 1976 are 2.49 and 2.62×10^4 cal/cm² respectively.

Heat Content of the Water Column. Since there was no cruise data for February in either year, it was assumed that at that time the water in the area was vertically mixed [1] and had the same temperature as the mean surface temperature for February, given in a chart published by Bowden [1]. An examination of charts of 5 days mean sea isotherms, provided by the Meteorological Office, and of temperature recorded at Port Erin break water by the Marine Biological Station, confirmed that temperature in February 1975 and 1976 did not appear to differ appreciably from the long term averages. The heat content in the water column Q_H relative to 0° is given by:

$$Q_H = \int_0^H C_p \rho t dz$$

where C_p = specific heat of water at constant pressure

ρ = density of water

t = temperature in $^\circ\text{C}$

H = depth of water

The values of temperature and salinity were read from the STD traces at two metre intervals near the surface and at three to five metres intervals in the deeper water for all the stations shown in Fig. 1.

These intervals were chosen because of the greater gradient near the surface and the smaller change of temperature in deeper water. The density ρ and specific heat C_p were calculated at each of these intervals.

The specified heat of pure water at temperature t is given by

$$C_p (t^\circ\text{C})/C_p (15^\circ\text{C}) = 0.996185 + 0.0002874$$

$$\frac{(t' + 100)^{5.26}}{100} + 0.011160 \times 10^{-0.036 t'} \text{ and}$$

$$C_p (15^\circ) = 4.185 \text{ Joules/g}$$

The density ρ was calculated from the temperature and salinity at the same intervals for all the stations.

For each depth interval the amount of heat is given by

$$\rho_i C_{pi} t_i dz_i \quad i = 1, 2, \dots, n$$

where $\rho_i = \rho(t_i, s_i)$
 $C_{pi} = C_p(t_i, s_i)$

the total heat content of the water column is given by

$$\sum_{i=1}^n \rho_i C_{pi} t_i dz_i$$

Table 1. Computed values of the solar radiation (Q_s), back radiation (Q_b), conduction (Q_n) evaporation (Q_e) and Q_t from 15th Feb. to 31st July. units = Cal cm² 1974.

Period	Solar Radiation Q_s				Back radiation	Conduction	evaporation	Q_t
	Aberporth	Aledrgrove	Fairfield	Mean				
15-28 Feb	2017.3	1585.4	1751.7	1784.8	966.0	502.6	1020.3	-704.1
1-15 March	2165.7	2861.0	2394.9	2473.9	1206.3	436.1	1085.5	-254.0
16-31 March	4139.7	3661.2	3959.2	3920.0	1617.0	717.5	1678.8	-93.3
1-15 April	4165.2	4170.6	3716.0	4017.3	1301.6	202.1	1353.6	1160.0
16-30 April	5296.9	4713.3	4663.8	4891.3	1009.6	-219.0	406.1	3694.6
1-15 May	5485.6	5098.3	5225.3	5269.7	1173.1	-65.5	1002.0	3160.1
16-31 May	8533.1	7849.2	8379.0	8253.8	1624.1	-414.7	1210.8	5833.6
1-15 June	8312.7	7674.0	7541.9	7842.9	1105.7	-355.6	864.3	6228.5
16-30 June	7195.6	8023.2	7378.7	7532.5	1102.0	-215.8	845.8	5800.5
1-15 July	6152.8	6288.5	6144.8	6195.4	736.4	-415.3	427.2	5447.1
16-31 July	6846.0	5744.4	5501.7	6030.7	672.8	-108.2	849.9	4616.2
Total				58212.3	12514.6	64.2	10744.3	34889.2

Table 2. Computed values of solar radiation (Q_s), back radiation (Q_b), conduction (Q_n) evaporation (Q_e) and Q_t from 15th Feb. to 5th July 1976. Units :- Cal cm²

Period	Solar Radiatio Q_s				Back radiation	Conduction	evaporation	Q_t
	Aberporth	Aledrgrove	Fairfield	Mean				
15-29 Feb.	1912.9	1347.6	1508.5	1589.7	783.0	346.0	659.2	-198.5
1-15 March	2946.6	2078.1	2132.3	2385.7	1158.4	836.8	1434.6	-1044.1
16-31 March	3642.1	2972.7	2951.6	3188.8	1056.0	282.5	1033.2	817.1
1-15 April	4040.2	4377.3	3501.1	3972.8	1109.8	-65.6	776.4	2143.2
16-30 April	6154.9	5015.0	5310.2	5493.4	1231.4	-221.2	573.3	3909.9
1-15 May	5888.3	5238.3	5247.2	5433.9	1003.5	-189.5	563.7	4080.3
16-31 May	5873.5	4562.9	5445.9	5284.1	794.5	-366.4	269.0	4597.0
1-15 June	7035.8	5759.8	6380.0	6391.8	815.2	-340.0	342.8	5573.8
16-30 June	6979.3	6685.7	6876.9	6847.3	711.2	-290.3	96.0	6330.4
1-5 July	2723.5	2516.8	2577.5	2605.9	317.2	-403.4	19.0	2673.1
Total				43227.4	8980.1	-402.1	5767.2	28882.2

The values of Q_H (heat content of the water column) were calculated for all the STD stations. The heat content for mid February, the time of the temperature minimum, assuming that the water column is vertically mixed, is given by

$$Q_F = \rho C_p t_s H$$

where t_s = temperature in February.

Values of ρ and C_p for all the stations were calculated from temperature and salinity read for a particular station from the chart published by Bowden [1].

The gain in heat content from mid February to the time of summer cruise (31st July 1975 and 5th July, 1976) is given by.

$$\Delta Q = Q_H - Q_F$$

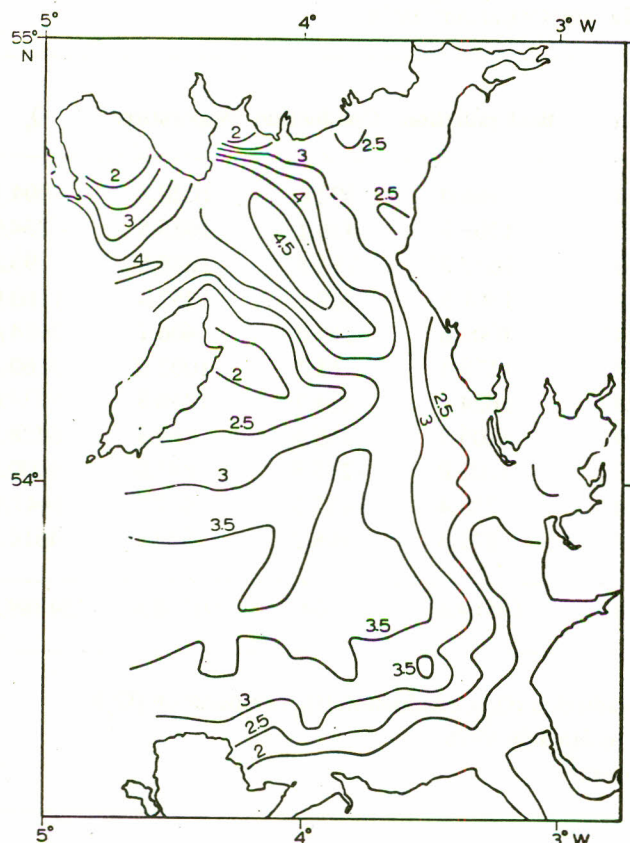


Fig. 2 Gain in heat content of a column of water, in 10^4 cal/cm² (from 15th Feb. to 31st July 1975).

contours of the heat gain ΔQ , expressed in calories in a column of water 1 cm^2 cross-sectional area, are given in Fig. 2 and Fig. 3 for 1975 and 1976 respectively.

The values are fairly uniform over the deeper part of the region and decrease in the shallower water towards the coast. The generally higher values shown in 1975 are due, no doubt, to the survey having been made about a month later in that year than in 1976.

DISCUSSION OF RESULTS

The values of ΔQ shown in Figs. 2 and 3 may be compared with the values of Q_t integrated upto the time of the summer cruise, calculated on the basis of the heat balance equation (1) and given in Tables 1 and 2 for 1975 and 1976 respectively. The calculated values agree reasonably well with those shown in the figures for the deeper water in the south-west of the area, confirming the hypothesis that in this area the predominant source of heating is through the sea surface.

The probable reason for the lower values of heat content observed near the coast is that in shallow waters the same gain in heat would be expected to cause a greater

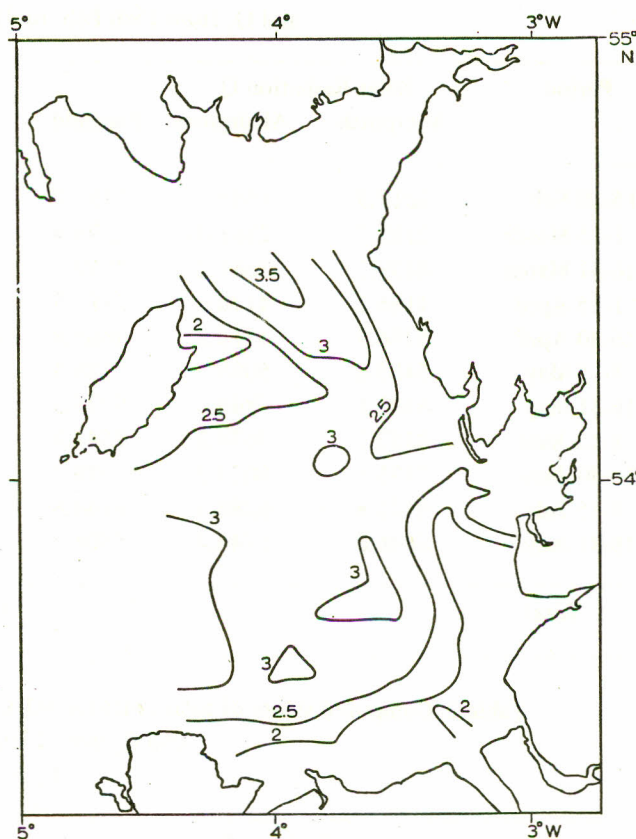


Fig. 3 Gain in heat content of a column of water, in 10^4 cal/cm² (from 15th Feb. to 5th July 1976).

increase in temperature of the water column than in deep water. However, this increase would probably be offset partly by increased heat loss to the atmosphere and partly by advection or eddy diffusion to the adjacent deeper water.

The higher values (greater than 4.5×10^4 cal/cm²) between the mouth of the Solway Firth and the north-east corner of the Isle of Man are about 30 % higher than would be expected from heating through the surface alone. This discrepancy is probably due to the horizontal transport of heat, by advection or diffusive processes, from the shallower areas to the north-east and south-west. The values of approximately 3.5×10^4 cal/cm² for the deeper water in the south-west of the area in 1975 are similar to the values given by Pingree [6] for the heat stored in the water column from mid March to mid September in the Celtic Sea and in the western approaches to the English Channel. The higher values of 4.5×10^4 cal/cm² shown between the north-east corner of the Isle of Man and the mouth of the Solway Firth is comparable with Pingree's value of 5.0×10^4 cal/cm² found in the Hurd deep area of the English Channel.

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