

MONITORING OF TEMPERATURE REGIMES TO WHICH THE PACIFIC OYSTER *Crassostrea gigas* IS SUBJECT TO IN COASTAL INLETS IN BRITAIN (THE FLEET LAGOON AND TEIGN AND DART ESTUARIES) IN RELATION TO THEIR REPRODUCTIVE SUCCESS

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MONITORING OF TEMPERATURE REGIMES TO WHICH THE PACIFIC OYSTER *Crassostrea gigas* IS SUBJECT IN COASTAL INLETS IN BRITAIN IN RELATION TO THEIR REPRODUCTIVE SUCCESS

Abstract

There has been a long-running debate over the ability of Pacific oysters *Crassostrea gigas* to reproduce successfully in British waters and become established in the wild. It is believed that temperature may be one of the major controlling factors to successful reproduction. In recent, warm summers, spatfall has been recorded in a number of marine inlets close to growing areas. In this study temperatures were monitored over the course of twelve months from March 1993 - March 1994 at sites on the south coast of Britain in the vicinity of Pacific oyster cultivation, where spatfall has been detected in recent years or where it was considered likely to occur on the basis of prevailing conditions. Records were taken every 96 minutes using continuous recording devices. Diurnal, tidal and seasonal variation in temperature were determined for the different sites and the patterns emerging are discussed. Oysters at two estuarine sites were exposed to the air at low water spring tides, whereas oysters at lagoonal sites were continuously submerged. This resulted in the exposure of oysters in the estuaries to more rapid fluctuations of temperature, which may be linked to their reproductive success. The available 'day degrees' are estimated for each site and compared with laboratory predictions of requirements for gametogenesis and larval development. Other environmental factors which may influence the development of larvae leading to eventual spatfall are considered.

1. Introduction

1.1 The introduction of non-native marine species

Species which are not native to British waters can be introduced through a variety of methods as follows:

- planned commercial introductions (including associated unintentional introductions pre 1960);
- transport on ship's hulls;
- transport in ballast water;
- escape or release from holding facilities eg. storage tanks, aquaria, fish farms; or
- rafting / floating or transport of larvae by wind-drift, tidal or oceanographic currents.

If an introduced species encounters favourable conditions it is likely to become established. Elevated temperatures relative to ambient have encouraged the establishment of species such as the hard-shelled clam, *Mercenaria mercenaria*, the barnacle *Balanus amphitrite*, and the serpulid polychaete worm *Ficopomatus enigmatica*. If the introduction of non-natives leads to their subsequent establishment and spread, there are a number of effects which can ensue, including:

- disease passed to native species
- disruption of the ecosystem through:
 - predation on native species,
 - competition with and displacement of native species,
 - alteration to habitat;
- hybridisation or genetic stock degradation;
- new food source for exploitation.

The most serious effects to nature conservation interests are disruption to the ecosystem, particularly if displacement of native species occurs or the nature conservation interest of a site is altered.

1.2 Pacific oyster spatfall monitoring

There has been a long-running debate over the ability of Pacific oysters *Crassostrea gigas* to reproduce successfully in British waters and become established in the wild. It is believed that temperature may be one of the major controlling factors to successful reproduction. On account of Pacific oysters being introduced for commercial purposes, they are of known distribution. These factors make them an interesting species for study. They were introduced to Britain in 1964. In 1985 Mitchell reported personal observation of naturally settled spat in 1970 in Poole Harbour and Loch Sween, although none were found in a survey carried out by the Nature Conservancy Council in 1991. Naturally settled spat of Pacific oysters have been recorded in Emsworth Harbour (Utting & Spencer 1992 based on personal record of two spat by Askew in 1971).

In 1992, monitoring for spatfall of Pacific oysters was carried out in the Fleet lagoon in Dorset as there was concern that the recent opening of an oyster farm might lead to the establishment of Pacific oysters in the wild. The most likely place for settlement of oyster spat to occur is on or around adult oysters. Consequently, the survey was directed mainly towards the sampling of oysters from bags. Oysters from the growing area (near the hut) which were continuously submerged on trestles below low water mark and oysters from the holding area on mid-Fleet banks, where they were briefly exposed at low water, were sampled. Approximately 50 oysters from each area were sampled on each of four occasions in 1992 (Seaward, 1992, 1993). There was an indication that spawning occurred, but no oyster spat were found in the Fleet in 1992 (Seaward 1993). Further searches in 1993 by Spencer *et al.* (1994) did not reveal any spat in the Fleet, despite finding a natural spatfall in the Dart, Teign and Exe estuaries. Spat were also found at the eastern end of the Menai Strait in the same year (Spencer 1993). It is interesting to note in this year that no spatfall was recorded east of Portland (at the mouth of the Fleet), or west of Start Point, despite the Fleet probably having a more favourable temperature regime and sites further west appearing no less favourable than the sites where spatfall did occur.

1.3 Temperature records

Spot temperature readings had been taken using a mercury thermometer in the Fleet during the period that Pacific oyster spatfall monitoring had been performed (Seaward 1992). Other temperature records for the Fleet were also available from the literature (Whittaker 1978) and from remote sensing imagery. These, however, did not describe the temperature regime to which oysters were subject, particularly in locations where spatfall has occurred.

2. Materials and methods

2.1 Temperature recorders

To assess the temperature regime in the vicinity of oysters, it was decided that a continuous temperature recording device should be used. 'Tinytalk' temperature recorders are powered by a lithium battery which lasts for up to four years, store up to 1,800 records made at intervals which can be varied from 0.5 seconds to 4.8 hours, and measurements are taken to the nearest 0.2°C. They can be housed in waterproof containers and the temperature probe connected to the outer surface. In practice, different models were used and interchanged following tests to determine their consistency. The temperature registered by recorders placed inside waterproof boxes with a surrounding air space quickly equilibrated with the temperature of the water. Although immediate changes in temperature could not be detected using this arrangement those occurring over the recording interval were detected. The advantage of these continuous temperature recorders,

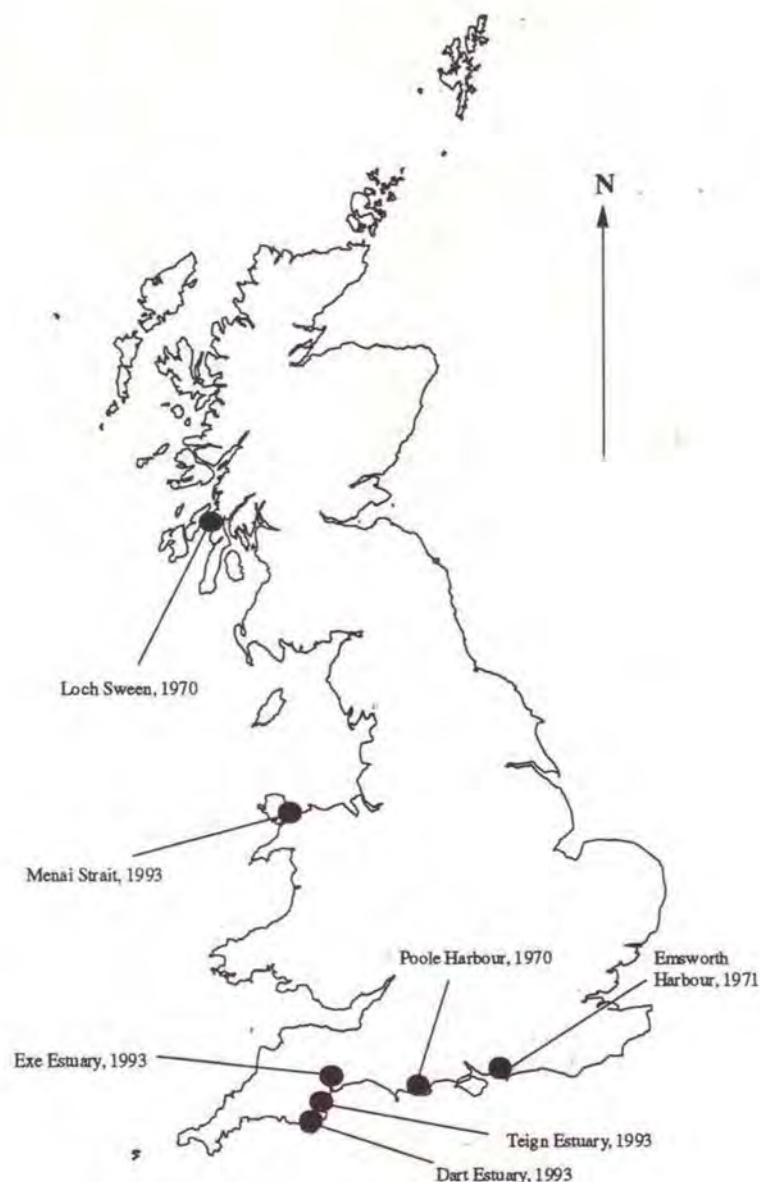


Figure 1 Sites where Pacific oyster spat have been recorded.

particularly for remote areas, over point source thermometers which indicate general seasonal variations, is that diurnal and tidal as well as seasonal variations can be monitored.

The recorders were activated and configured using a software operated on standard IBM personal computer. They were activated at particular times to ensure a sequence of continuous recording. Taking into account temperature variation and frequency of replacement, the recording interval was set at 96 minutes such that 15 measurements were made each day (the first instrument placed, in the Fleet, was set to record every 48 minutes). Temperature recorders were left in the field for a maximum of 120 days, after which they were removed and replaced. The times at which the exchange occurred was noted and the removed recorder was returned to the operational head quarters for data retrieval.

2.2 Site location for temperature recorders

The Fleet, a site of high nature conservation interest, with a recent introduction of non-native Pacific oysters was chosen for monitoring studies. As a consequence of its physiography it is

subject to localised warming. The Dart and Teign estuaries were selected for temperature monitoring for similar reasons to the Fleet and spatfall of Pacific oysters had occurred in 1989 and/or 1990 (Spencer *et al.* 1994).

Tinytalk temperature recorders were deployed at five locations (see Figures 2 & 3 below). OS grid references for these sites are: Fleet (Ferrybridge) SY 665 762, Fleet (Oyster Hut) SY 644 777, Fleet (Morkham's Lake) SY 590 823, River Dart (Waddeton boat house) SX 874 560 and River Teign SX 909 725. Temperature recorders were placed in bags with oysters so they were monitoring the temperature regime to which the oysters were subject, except at Ferrybridge and Morkham's Lake in the Fleet where they were attached to the jetties. Temperature was recorded at Ferrybridge and Morkham's lake for comparative purposes, to give an indication of how temperature varied in different parts of the Fleet lagoon over a set period.

At all the Fleet sites, the temperature recorders were placed about 0.5 metres below Low Water Springs (LWS). In the River Dart the position of the recorders on the shore was just below Low Water Neaps whereas in the River Teign they were placed between Mean Low Water and LWS.

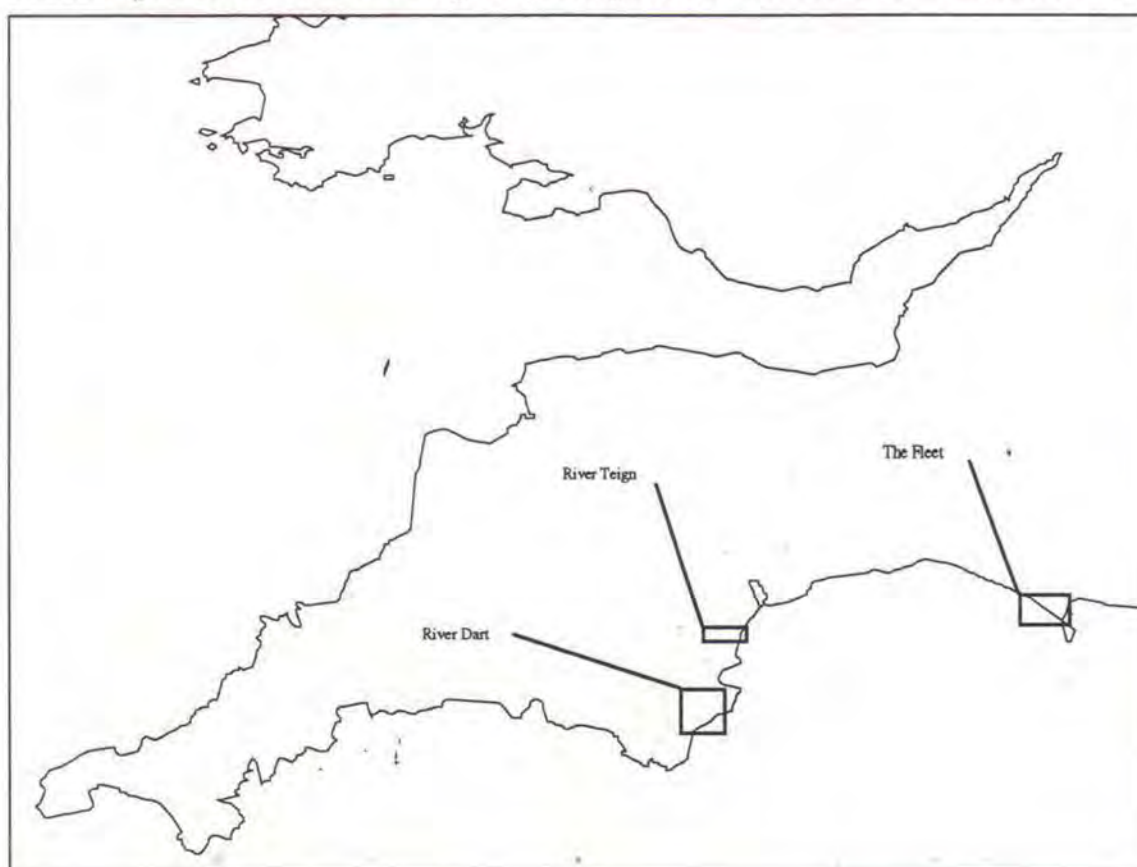


Figure 2. Locations of the Fleet, River Dart and River Teign.

Pacific oysters are cultivated in the lagoon near to the oyster hut in the Fleet as well as being held near Abbotsbury oyster farm; on the east bank opposite Flat Owners Mud on the Dart estuary; and on part of the south bank of the Teign estuary. Temperature was monitored at all these sites except near to Abbotsbury oyster farm. Additional temperature recorders were placed for short periods at other locations in the Fleet, namely at Morkham's lake, and at Ferrybridge at the mouth. This was done on the basis of available resources including helpers, as well as indications from spot readings and satellite imagery of high temperature variation throughout the Fleet.

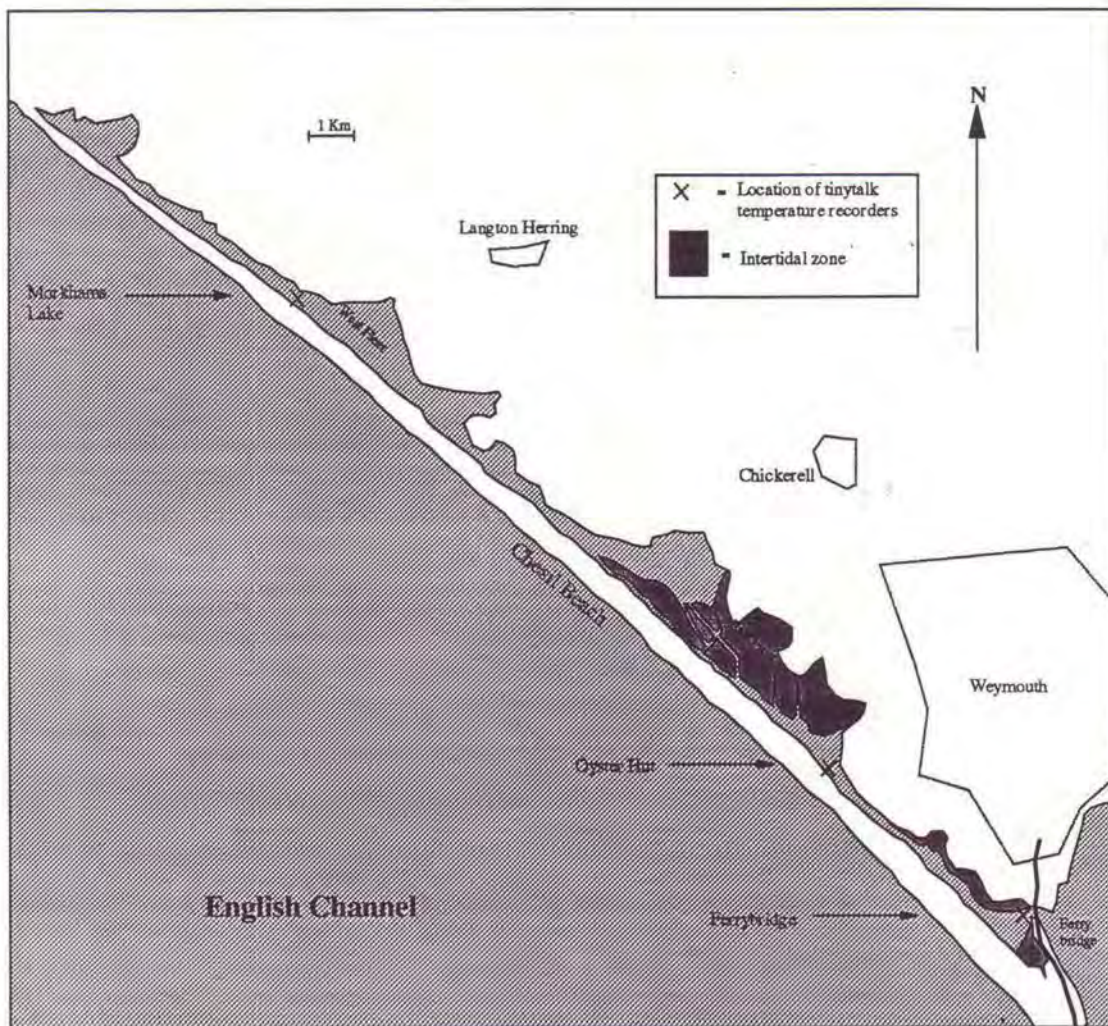


Figure 3 Location of Tinytalk temperature recorders in the Fleet.

2.3 Calculation of day degrees

Day degrees were calculated using the formula from Mann (1979);

$$D = d(t - t_0)$$

Where:

- D = number of day degrees required
- d = number of days to attain a ripe status
- t = temperature to which animals were exposed
- t_0 = temperature below which no evidence of gonad development is found.

Gametogenesis in Pacific oysters only occurs at temperatures of 10.55°C and above. The number of day degrees above 10.55°C for gametogenesis of Pacific oysters is 592 day degrees (Mann 1979). The critical temperature for spawning is 18°C and the minimum day degrees required for development of larvae prior to settlement is estimated as 350 - 400 day degrees at optimum hatchery conditions *ie.* plenty of food at 25°C (Utting pers comm.) no lower temperature limit for development is indicated so it is taken as the same as for gametogenesis.

3. Results

3.1 Dates of records

Table 1 Dates of temperature records collected from each location

Location	Dates	Gaps	Comments
Fleet lagoon			
Oyster hut	26 March 1993 - 24 June 1994		From 26 March - 23 April, the tinytalk was set to record every 48 minutes.
Ferrybridge	15 November 1993 - 28 February 1994		Temperature recorders were also placed at Ferrybridge from April - November 1993 but these leaked so no data was collected.
Morkham's lake	20 July - 10 August 1993		
Dart	20 April 1993 - 24 March 1994	24 - 27 November 1993	Battery ran out leading to gap of three days.
Teign	19 April 1993 - 17 March 1994		

The data in Table 1 shows the dates that records were collected from the locations indicated in Figure 1. A temperature recorder was submerged in the Fleet lagoon near to the oyster hut in the Fleet in March 1993 and set to record every 48 minutes. This trial led to the placement of recorders set to record at half that frequency.

3.2 Seasonal and tidal variations

The seasonal variation in temperature at the oyster hut site on the Fleet can be seen in Figure 4. The data from the Dart and Teign estuaries show similar seasonal patterns in average temperature. Average monthly temperature varied between about 6 and 18 °C in the Fleet at the oyster hut and between about 7 and 17°C in the Dart and Teign estuaries. Average temperature in the summer went highest (in mid July 1993) and also lowest (in late February 1994) in the winter, in the Fleet. During the summer it was apparent that average temperatures in the Teign did not rise to a peak as quickly as in the Dart and Fleet, and in all locations average temperatures dipped during late July / early August. Average daily temperatures for the English Channel show a similar seasonal pattern although the absolute temperatures are slightly lower than temperatures recorded in estuaries.

Temperature in relation to tidal cycle for the Dart in June 1993 (Figure 5) shows that the greatest extremes of temperature are recorded around spring tides in the estuaries; in winter this only relates to the minima. This pattern is not seen in records from the Fleet. At all sites, the average daily temperature does not appear to reflect the stage in the monthly tidal cycle, even though daily tides are reflected in the temperature records.

Seasonal Variation for Oyster Hut Site, Fleet Lagoon

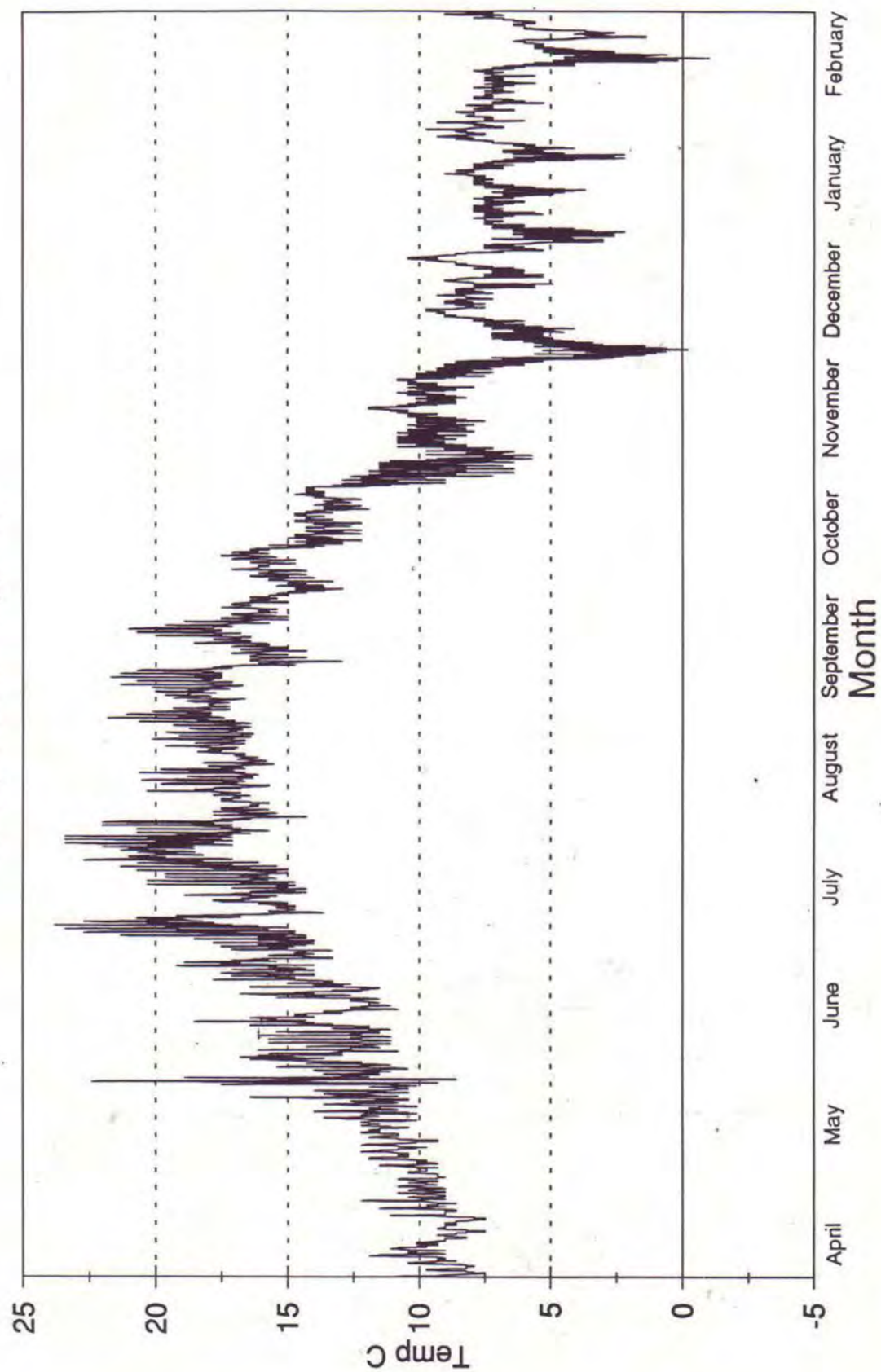


Figure 4 Seasonal variation from 25 March 1993 to 28 February for the Oyster Hut Site, Fleet lagoon

Temperature in Relation to Tidal Cycles for the Dart in June

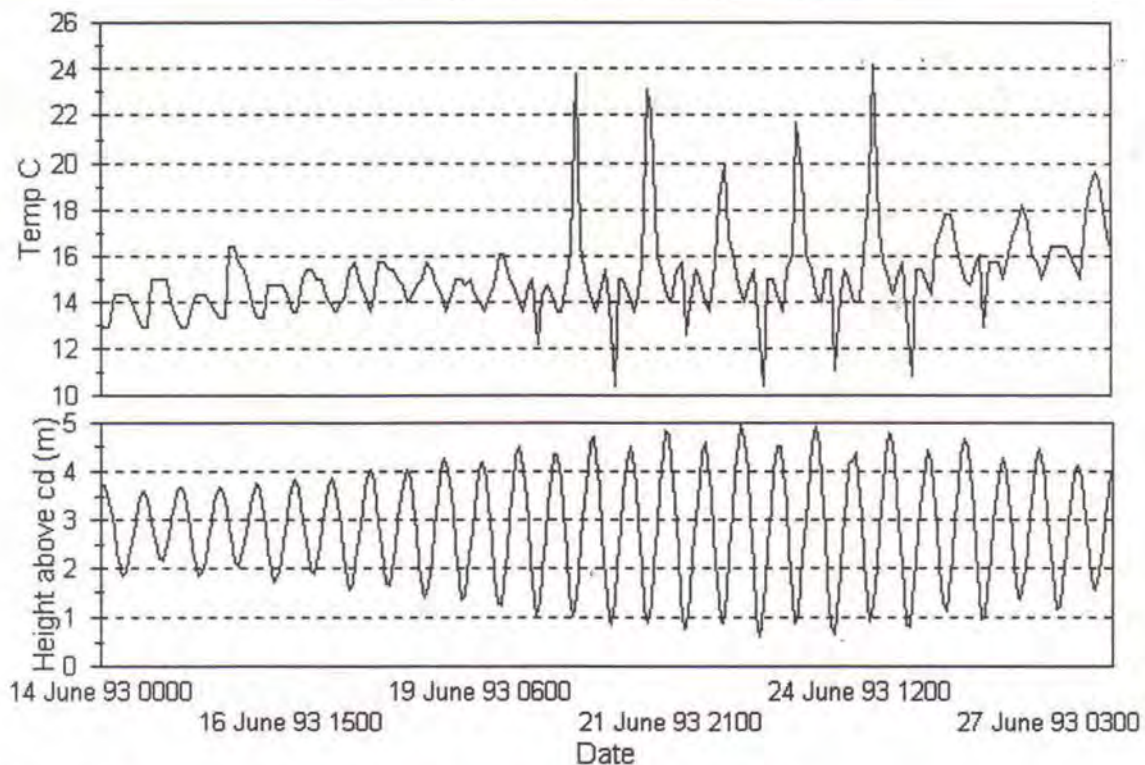


Figure 5 Temperature in relation to tidal cycle for the Dart in June 1993

3.3 Diurnal variations in temperature

The temperature records show an underlying twice daily cycle which appears to be correlated with the tidal cycle, (see Figure 6) although in the Fleet there appears to be a lag between temperature and tidal cycles, more so further from the mouth. [The time lag between these events at the oyster hut in the Fleet may be anything from 1.5 - 4 hours on the flood tide and from 2 - 7 hours on the ebb tide; a more detailed examination of this is made by Seaward (1994).] Records from the Dart and Teign estuaries were very similar. When the recorders were submerged in the summer, during the lowest neap tides in the Teign and for about half the tidal cycle in the Dart, and throughout the cycle in the Fleet, the pattern seen is that the troughs of the temperature cycles are recorded at or just after high water and the peaks in the temperatures cycles at or just after low water, regardless of the time of day or night as shown in Figure 6; in the winter, the pattern is reversed. The peaks were higher during the day although the troughs were similar day and night.

When the recorders were exposed to the air at low water, superimposed upon the twice-daily cycle, the temperature fell to a minimum during the night-time low water and rose to a maximum during the day-time low water; however, in the winter, day-time low waters often also resulted in a fall in temperature. In the summer (Figure 5 shows the situation in the Dart for June) the extremes of temperature were higher during the day in the Dart and lower during the night in the Teign.

On the whole, water temperature, and to a lesser extent, intertidal temperature underwent less extreme fluctuations than air temperature and was also more stable throughout the year.

Details of the extremes of temperature recorded at each site are shown in Table 2. Fluctuations in temperature were generally greatest in the Dart and Teign at low water spring tides; in the Fleet

the most rapid change of temperature recorded was a swing from 23.4°C to 15.0°C in 6.5 hours, occurring between 18:37 on 7 June and 01:01 on 8 June 1993. There were also periods of relatively little change in temperature, particularly in the Fleet in the winter months; for example at the oyster hut site from 3 February at 00:01 to 7 February 1994 at 22:25 the temperature only varied by 1.5°C.

Table 2 Extremes of temperature recorded at each location

Location	Maximum temperature (°C)	Date and time	Minimum temperature (°C)	Date and time
Fleet				
Oyster hut	23.8	20:13 on 8/6/93	-1.0	08:01 on 15/2/94
Ferrybridge	10.8	15:58 on 10/2/94 in winter months	1.8	03:10 on 15/2/94
Morkham's lake	23.3	16:50 on 7/8/93	14.5	05:38 on 7/8/93
Dart	25.6	15:36 on 7/6/93	-1.5	03:25 on 14/2/94
Teign	23.4	16:43 on 20/8/93	-2.3	04:32 on 16/2/94

3.4 Comparison between records from different parts of the Fleet

Temperature records from different locations in the Fleet indicate that the water at the oyster hut, half way up the lagoon is generally a few degrees Centigrade colder than the water at Ferrybridge in winter (15 November - 28 February, see Figure 7) and colder than the water at Morkham's lake in summer, other than in the early morning during neap tides. Temperature fluctuations at Ferrybridge parallel those at the oyster hut in winter months, despite there being several degrees Centigrade difference in actual values.

In the Fleet, the temperatures recorded at Ferrybridge in the winter closely parallel sea water temperature (on the basis of records from Portland Harbour) and at Morkham's lake in the summer closely parallel the air temperatures (Seaward 1994).

3.5 Comparison with air and sea temperatures

By comparison with sea temperatures measured in mid-(English) Channel, off Portland Bill and in Weymouth Harbour, it can be seen that in the winter (from mid September) water temperatures are highest at sea and lowest in the Fleet, the converse during the rest of the year (from March onwards). On the whole, the lagoon water temperatures nearer to the mouth are closer to open sea temperatures, particularly in winter, and closer to air temperatures further away from the mouth. The effect of air temperature is superimposed on the twice daily fluctuations associated with tidal variations. See Seaward (1994) for a more detailed analysis of sea and air temperatures in relation to water temperatures recorded in the Fleet. No air or sea temperatures were available from the vicinity of the Dart or Teign estuaries for comparison.

Temperature Fluctuation with Tides for the Oyster Hut Site, The Fleet

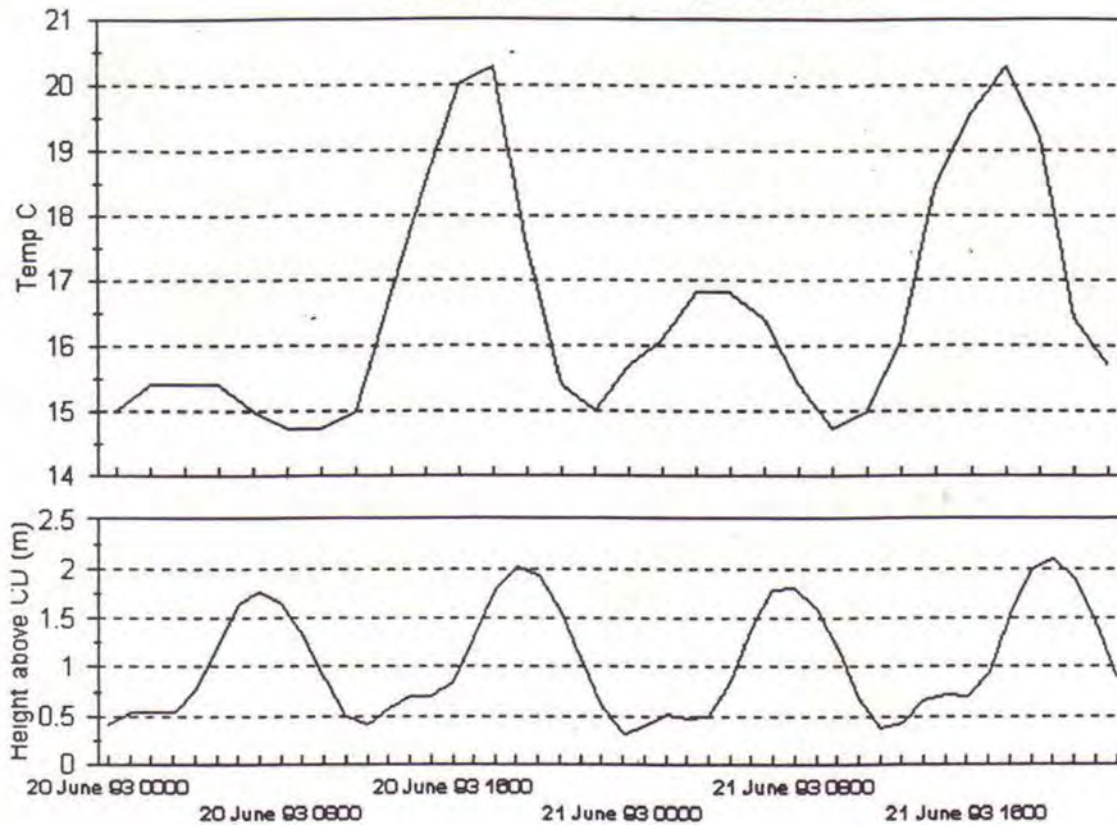


Figure 6a Diurnal temperature variation with tidal cycle for the Oyster Hut in June 1993

Temperature Fluctuation with Tides for the River Dart

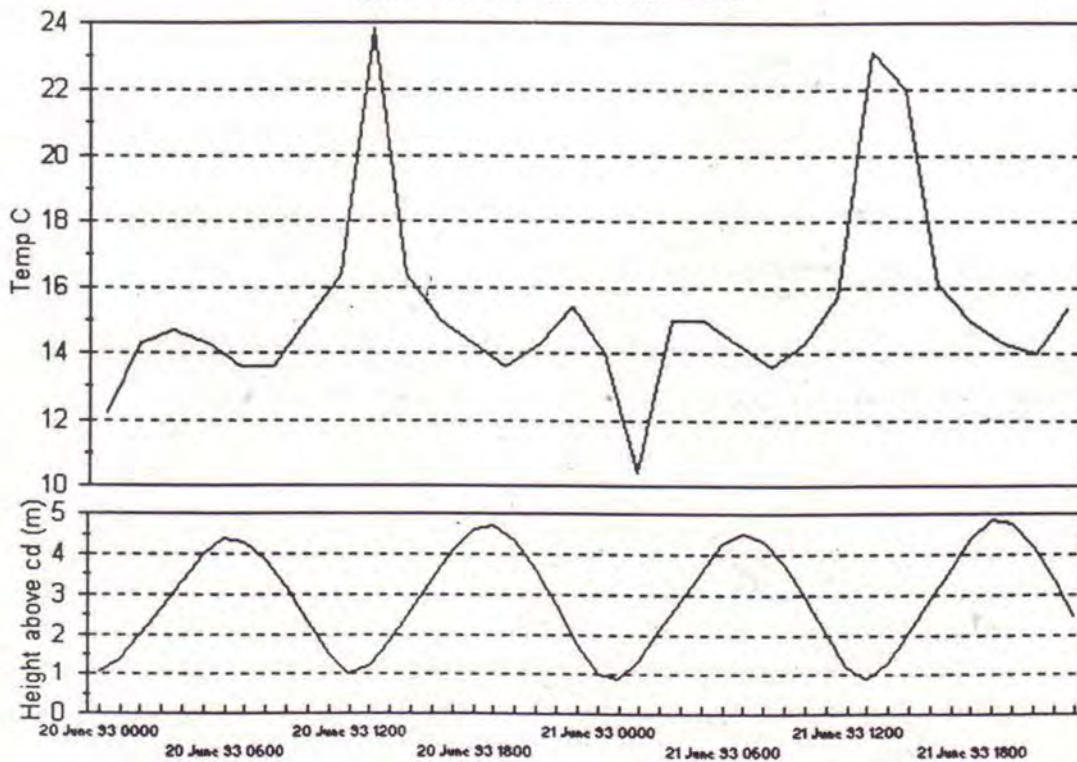


Figure 6b Diurnal temperature variation with tidal cycle for the River Dart in June 1993

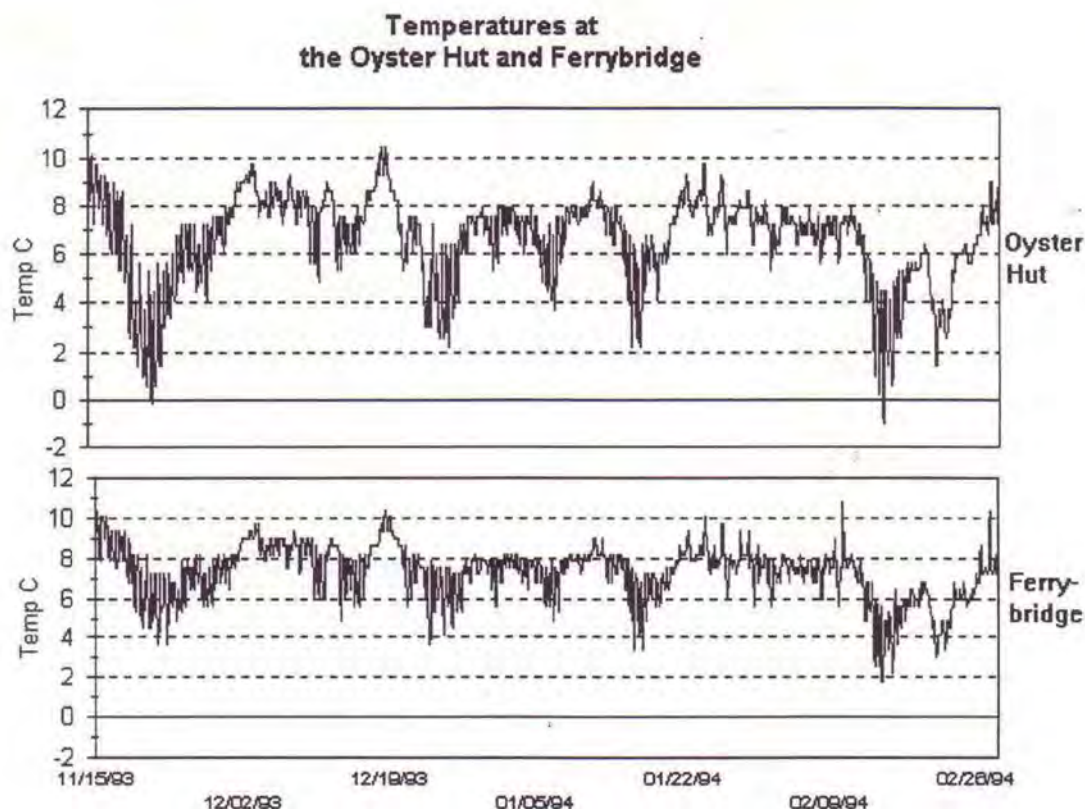


Figure 7 Comparison of temperatures for the Oyster Hut and Ferrybridge sites.

3.6 Day degrees

The data in Figure 7 show that the number of day degrees experienced in the Fleet lagoon was higher than in the estuaries between May and September and lower between October and March, there were incomplete data sets from April so data for this month can not be compared. In 1993 the number of day degrees measured in the Dart was consistently higher than in the Teign between May and November; over the winter months the temperature rarely rose above 10.55°C so very few day degrees were recorded, however there were marginally more at the site on the Teign than on the Dart.

The data in Table 3 and Figure 8 shows that the temperature regimes experienced by the oysters at all locations monitored favoured the production of spawn, according to Mann's findings (1979), as the number of day degrees exceeded 592. In the Fleet lagoon, near to the oyster hut, there were also sufficient day degrees for spatfall to occur. However, none was recorded.

4. Discussion

4.1 Temperature recording

No record of continuous intertidal or lagoonal temperature records for the UK has been found in the literature prior to this study, although daily, weekly, monthly or occasional records do exist for some areas; and these have generally been taken with hand-held mercury glass thermometers. This study concentrated on temperatures to which Pacific oysters were subject; however, the data could equally apply to intertidal or lagoonal species at similar positions relative to low water mark.

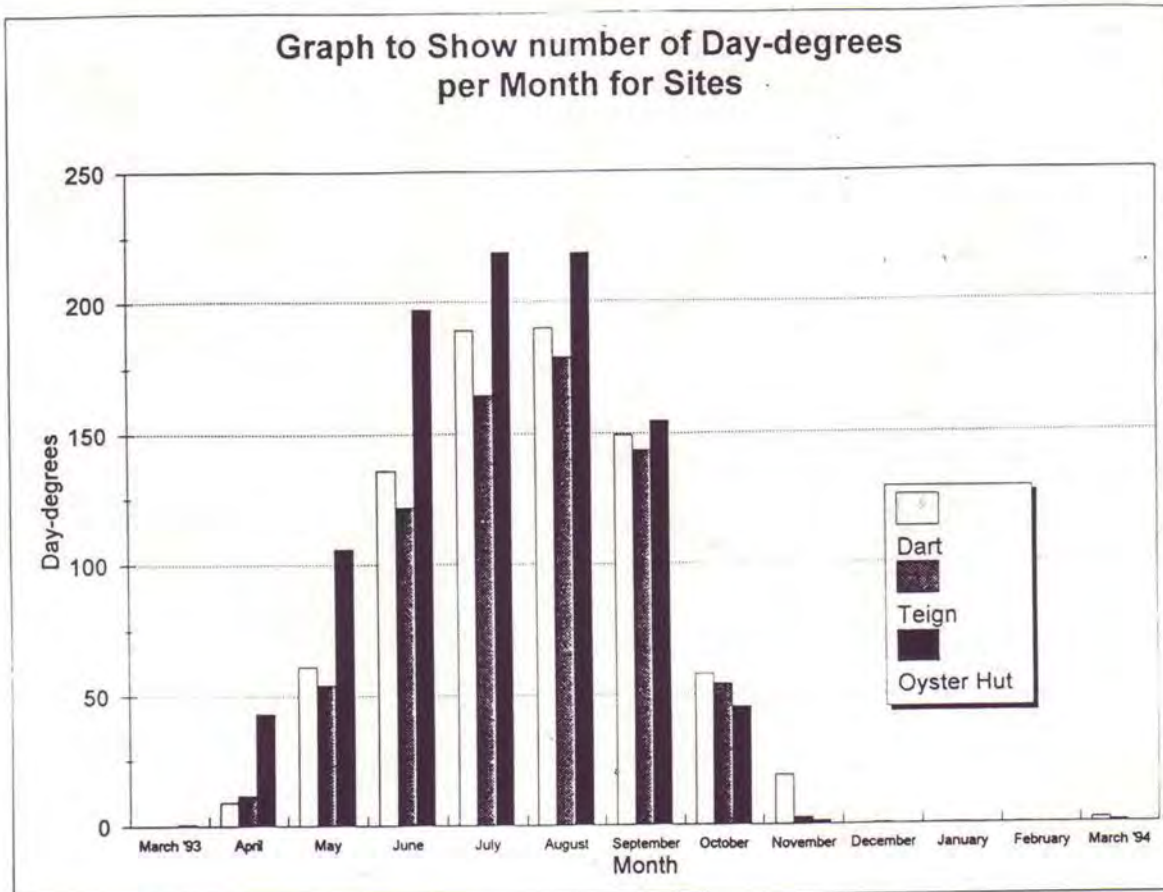


Figure 8 Comparison of numbers of day-degrees per month for the Oyster Hut, River Dart and the River Teign

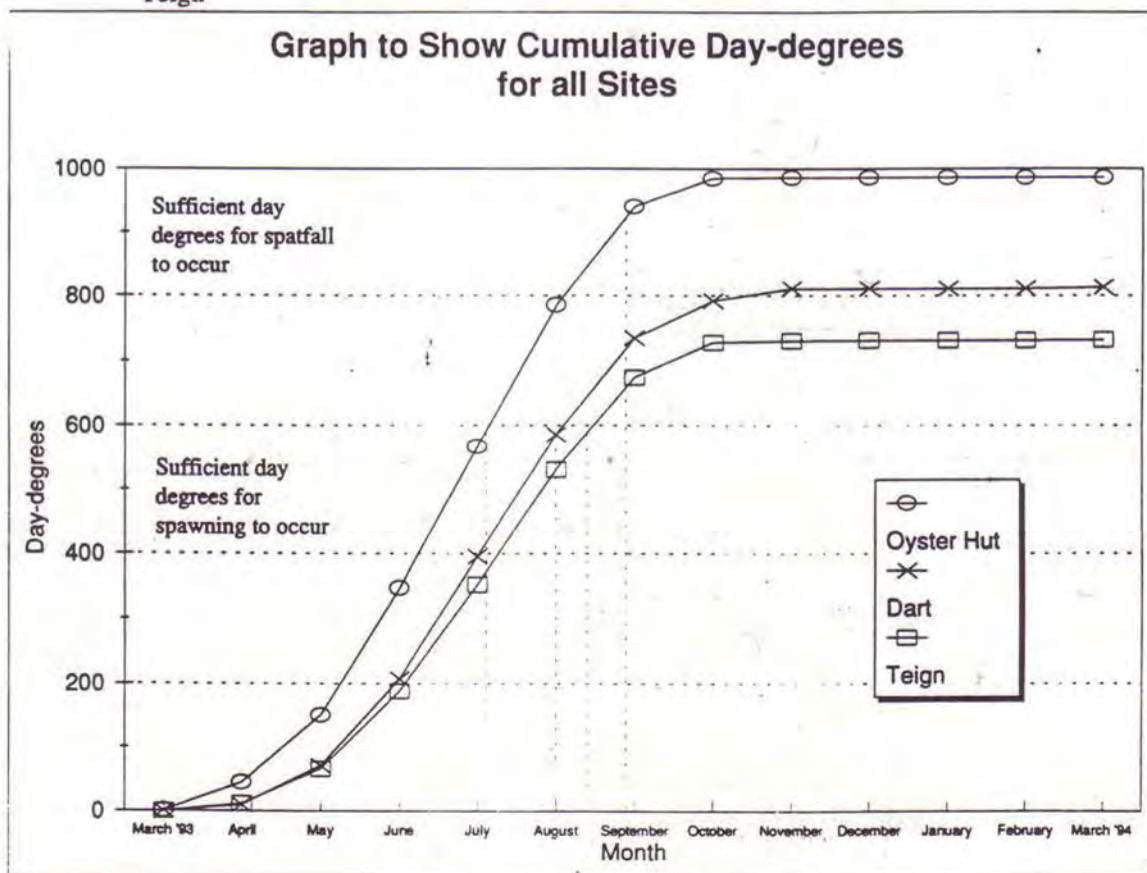


Figure 9 Cumulative day-degrees for the Oyster Hut, River Dart and the River Teign

Table 3. Results of day-degrees in relation to spawning and spatfall.

Location	Dates over which temperature was recorded	Total number of day-degrees over period	Date when 592 day degrees were exceeded (total number of days for gametogenesis)	Date when 18°C (required for spawning to occur) was exceeded	Date when a further 350 day degrees required for larval development were exceeded
Oyster hut, Fleet lagoon,	26 Mar 1993 - 28 Feb 1994	986.13	4 Aug 1993	4 Aug 1993	1 Oct 1993
River Dart	20 Apr 1993 - 24 Mar 1994	812.977	4 Sept 1993	4 Sept 1993	Did not occur
River Teign	19 Apr 1993 - 17 Mar 1994	732.127	16 Sept 1993	30 Sept 1993	Did not occur

The similarity in temperature patterns between the sites at Ferrybridge and the oyster hut on the Fleet (Figure 7) is a good indication of the consistency between recorders. On the whole, the recorders were reliable, however, some of the supposedly 'waterproof' recorders leaked. Those which were not waterproof were placed in plastic boxes, with the added precaution of suspending them above any possible ingress of water; this system is recommended in all cases to prevent potential loss of data. As stated earlier this means that there may be a short delay before rapid changes in temperature are detected, however, with a recording frequency of 96 minutes this is not crucial to the overall results. The lithium batteries supposedly last up to four years, however, one did run out after a year, so it would be a sensible precaution to replace them annually.

4.2 Factors affecting temperature readings

The major factors affecting temperatures recorded in the study were sea and air temperatures, exposure to the air, water depth, local topography, incidence of sunlight and the state of the tide. Other weather conditions, particularly barometric pressure, cloud cover, rain, and wind speed are also likely to have affected the readings.

Open sea temperature around the UK varies seasonally but is fairly constant on a daily basis, it is also generally cooler than daytime air temperatures in the summer and warmer than air temperatures in the winter. As a consequence of this, the incoming tide generally has a cooling influence in summer and a warming effect in winter. Conversely the exposed intertidal has the effect of warming / cooling the flood tide depending on the time / season. Within the Fleet, where temperature was recorded at different locations in the lagoon, the sea had a greater influence on locations nearer to the mouth. It takes time for the sea water incoming with the tide to reach different locations, this accounts for the regular peaks and troughs coinciding with the tidal cycles at the estuarine sites but there being a considerable lag at the Fleet sites, especially away from the mouth.

The effect of air temperature and incidence of the sun's rays has a pronounced effect. During a 24 hour period, the temperature rises to its highest point at low water during the daytime, as the water above the oysters became shallower, *ie.* as the tide is going out and the sun's rays have a more concentrated effect. In the Teign, the oysters were exposed to the air at low water on more days than they were exposed on the Dart, as a consequence of their position on the shore. It is

interesting to note that the maxima and minima temperatures recorded in the estuaries when the oysters were exposed during the tidal cycle occurred just after low water, presumably as the air temperature continued to fall or rise and influence the temperature recorded. [intertidal mud flats act as heat exchangers, producing warming as water runs over them in the summer and the reverse in winter.] During periods of low water exposure to the air, higher day-time temperatures were recorded in the Dart than the Teign, presumably on account of the recorders being in a more sunny position in the Dart. However, lower night-time temperatures were recorded in the Teign, as a consequence of the longer exposure to the air. These minor temperature variations between estuaries is probably of limited relevance to the likelihood of oysters to spawn.

Temperatures are also influenced by local topography. The site in the Dart is on a depositing shore on the outside of a bend in the river, where the water tends to be shallower and travel more slowly, in addition to which there is a vast sandbank adjacent to it. Shallow water flowing slowly over tidal banks tend to warm up considerably and have a warming influence, which is likely to have occurred in the Dart.

The Fleet is the largest saline lagoon in Britain, open at one end to Portland Harbour and thence to the English Channel, and at the western end there is fresh water input. During the tidal cycle water passes the oyster hut from near the mouth of the Fleet and sea on the flood tide, and from the upper or western Fleet on the ebb tide. The influence of the sea has already been mentioned, however, the influence of water from the upper Fleet is equally significant. The shallow water of the upper Fleet presents a large surface area to insolation, evaporation and influence by air temperature as well as other weather conditions. Consequently it would be expected for the water in the upper Fleet to experience greater seasonal extremes of temperature, certainly this is seen for the summer months for which records were collected at Morkham's lake. On the ebb tide, water from the upper Fleet, which is warmer in summer and cooler in winter than the oyster hut water has a moderating effect.

At all sites, the influence of the tidal cycle is evident twice daily in the temperature profiles. Even on neap tides at Morkham's Lake, there is usually some evidence of this, suggesting that the statement by Robinson *et al.* (1983) that 'the semidiurnal tide propagates into the West Fleet only weakly ... at spring tides, and not at all ... at neaps' may need qualification.

4.3 Effect of temperature on reproductive success of oysters

Owing to the shallow depth of water and reduced amount of mixing with water from outside the lagoon, temperatures around the oysters were warmer in the summer months and colder in the winter months in the Fleet compared with the estuaries. This is reflected by the number of day degrees for each month at the different locations. The number of day degrees recorded in the Dart is higher than for the Teign probably on account of the recorder in the Dart being in the sun and that in the Teign being in the shade.

This study represents the first time that day degrees have been estimated in the wild for Pacific oysters. This is significant, as day degrees in hatchery conditions are generally applied to shellfish maintained at constant temperatures, where, once they are ripe, spawning may be induced by temperature shocks (Utting & Spencer 1991).

In 1991, when spat of Pacific oysters were observed in the Dart, Teign and Exe estuaries suggesting a 1989/1990 spatfall (Spencer *et al.* 1994), none was recorded in the Fleet. Although the summer was generally warmer and therefore the required number of day degrees may have been achieved for spatfall to occur, the comparative temperatures between these estuaries and the Fleet would no doubt have been similar. In the Fleet lagoon, it appears that temperature is not a limiting factor to spawning and spatfall of Pacific oysters.

As the oysters (outside the oyster hut) in the Fleet are submerged throughout the tidal cycle they do not experience the large extremes of temperature, caused by exposure to the air, recorded in the Dart and Teign. It may be that rapid fluctuations in temperature experienced through exposure to the air might play a part in inducing spawning in Pacific oysters as applied in hatchery conditions.

Temperature records from outside the oyster hut in the Fleet for early summer 1994 indicate that June 1994 was cooler than June 1993, however, this situation is likely to have changed later in the summer as air temperatures in July 1994 were the highest recorded this century.

4.4 Environmental conditions

The temperature records from the Fleet lagoon indicate that it is a fairly variable environment, particularly further from the mouth. Indeed, the variables to which lagoons are exposed are similar to those within rockpools. These factors have an effect on the resident fauna and flora, which must be resilient to stressful conditions.

There may be other factors which account for the lack of spatfall in the Fleet in years when it has been recorded in nearby estuaries. These include the absence of larvae to settle, unfavourable conditions for settlement, the low availability of food for the larvae, the residence time of water, the presence and effect of pollutants such as the anti-fouling chemical tri butyl tin which is used at the naval base in Portland Harbour and combinations of any of these factors.

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