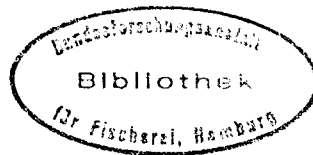


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THE INFLUENCE OF COOL WATER INCURSIONS ON PHYTOPLANKTON
POPULATIONS IN BANTRY BAY, SOUTH-WEST IRELAND.

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Introduction

A seven month time series of observations in Bantry Bay, south-west Ireland, demonstrated the location to be characterised between late spring and autumn of 1991 by a series of cool water incursion events. These events, which were wind-driven, resulted in the lateral transport of cooler water into the sub-surface layers of the Bay, with an accompanying offshore surface flow. Two water types were observed in the sub-surface layers during these events; Type I water was characterised by relatively high nutrient concentrations and temperatures $< 11\text{ }^{\circ}\text{C}$, while Type II water was defined by lower nutrient concentrations and temperatures in the range $13 - 14\text{ }^{\circ}\text{C}$. Type I water, which was observed in the deeper layers during the May, June and July incursion events, was associated with major developments of diatoms populations, whereas the Type II water observed during the August incursion events was associated with large numbers of dinoflagellates, especially *Gyrodinium aureolum*. Light did not appear to limit phytoplankton growth between late spring and the autumn, and it appears that the dominant factors controlling phytoplankton biomass and species succession in summer are incursions of offshore phytoplankton populations into the euphotic zone of the Bay together with the enhancement of nutrient concentrations during Type I incursions. The data indicated that the 1991 spring diatom bloom was terminated by potential nitrate limitation, and the summer dinoflagellate bloom either by potential phosphate limitation or by the disappearance of Type II water following autumn overturn.

Methods

The results presented in this paper were obtained during a survey which was undertaken between 11 April and 25 October 1991. Temperature and salinity profiles were taken twice weekly at 1 m intervals using a T-S Bridge at Station 1, adjacent to Whiddy Island, Bantry Bay (Fig. 1). Weather data were recorded on a daily basis at Station 1, and were supplemented by data from Valentia Weather

Station. Samples for nutrient and chlorophyll *a* determinations were collected from the surface, bottom and the 10 % light depth. The 10 % light depth was estimated using a LI-COR Type LI-193SA Quantum Sensor. Standard methods were used for the analysis of nutrient and chlorophyll *a* concentrations. Discrete water samples for phytoplankton taxonomic analysis and enumeration were preserved using a 1 % solution of acidified Lugol's Iodine and examined with a Wild M40 inverted microscope.

Results

The variations in temperature with depth at Station 1 over the survey period (Fig. 2) clearly reflected the cool water intrusion events. There were five such events observed in the summer and autumn of 1991, represented by a rise in the cool, bottom isotherms towards the surface of the water column during periods of cool water inflow, and a subduction of the warmer isotherms towards the bottom of the water column during the relaxation periods. The duration and intensity of these incursion events varied considerably; event V which occurred in late August only lasted for 1 - 2 days and had no visible effect on the temperature of the water column above approximately 8 m, whereas event II in late June lasted for 14 days with the cooler water (<12 C) penetrating almost to the surface of the water column before reversal of the cool water inflow. The cool, bottom layer incursion water with temperature <12 C did not penetrate to the surface of the water column between early May and the end of September, such that a surface-to-bottom temperature difference was apparent over the summer with a maximum difference of 6 °C observed in late August.

Bottom water temperatures were higher when strong ($> 4 \text{ m s}^{-1}$) west or south-westerly winds were observed in the Bay. However, it was following relaxation of the south-westerly winds or upon initiation of north-easterly winds that the bottom water temperatures decreased as a result of the sub-surface inflow of cooler water characterising the incursion events. In the present study, a significant correlation

was found between the wind vector prior to the incursion events and bottom silicate and phosphate concentrations in the Bay at the time of the events.

There was evidence for the influence of two different water bodies associated with the inflow into the deeper waters of the Bay during the incursion events. A water mass, arbitrarily labelled Type I water, was observed in the sub-surface layers during the first three incursion events which occurred between May and July, this being characterised by temperatures $< 11\text{ }^{\circ}\text{C}$ and increased nutrient concentrations. A second water mass, defined as Type II water, was observed in the deeper layers during the two August incursion events (IV and V), and was characterised by temperatures of $13 - 14\text{ }^{\circ}\text{C}$, relatively low nutrient concentrations and significantly increased dinoflagellate populations.

Fig. 3 shows the successive changes in temperature-depth profiles over a five day period during the May incursion event. On 20 May, the water column was essentially isothermal, with temperatures approximately $12\text{ }^{\circ}\text{C}$ throughout the water column. By the following day, a sub-surface intrusion of cooler water with temperature $< 12\text{ }^{\circ}\text{C}$ was apparent at depths $> 19\text{ m}$ whilst a slight warming had occurred in the upper layers of the water column. Cooling of the deeper water continued for the next three days, with the surface water becoming progressively warmer, such that by 24 May temperatures of $10\text{ }^{\circ}\text{C}$ were recorded below 21 m, and temperatures in the surface 2m were $> 14.0\text{ }^{\circ}\text{C}$. Over this five day period, and indeed for much of the survey, temperatures increased or decreased steadily from the surface downwards, with very little evidence of the formation of a clearly defined thermocline.

The effect of the incursion events on nutrient concentrations at the three sampling depths is shown in Fig. 4. Nitrate (NO_3) concentrations varied from undetectable to $8.1\text{ }\mu\text{g-at. NO}_3\text{-N l}^{-1}$ over the period of observations. The homogeneity in NO_3 concentrations observed at the start and end of the season was due to seasonal wind mixing of the water column. Between late spring and early autumn, large increases in sub-surface NO_3 concentrations were recorded associated with the inflow of

nutrient-rich deeper water. Fig. 4 clearly demonstrates that the incursed water did not reach the surface layers, with surface NO_3 concentrations remaining $< 1 \mu\text{g-at NO}_3\text{-N l}^{-1}$ over the entire summer season. Later in the season from mid-July until the end of September the incursed water did not penetrate to the intermediate depths with low nutrient concentrations being maintained at that stratum. The nitrate data also emphasise the variation in nutrient content of the inflowing water, with the largest observed increase being recorded during the late July incursion event III.

Phosphate (PO_4) concentrations varied from undetectable to $0.99 \mu\text{g-at PO}_4\text{-P l}^{-1}$, with maximum concentrations again being observed during incursion event III. As with NO_3 , surface PO_4 concentrations were highest at the start and end of the survey when the water column was essentially homogeneous, although during the upwelling season maxima were observed at the sub-surface depths. An anomalous peak in surface PO_4 concentrations was observed on 30 May during event I.

A feature of interest in the PO_4 data was the low concentrations recorded between 21 August and 25 September at all three sampling depths, with undetectable concentrations recorded on 10 September. The relatively low NO_3 and PO_4 concentrations observed during August, when incursion events supplied Type II water to the sub-surface layers, emphasize the distinctness of this water body from the Type I water in its nutrient characteristics.

Chlorophyll *a* concentrations showed two maxima with concentrations $> 11 \mu\text{g l}^{-1}$ being observed during the spring diatom bloom between 22 and 25 April and an autumn maximum of $> 9 \mu\text{g Chl } a \text{ l}^{-1}$ being observed between 21 August and 3 September. During the spring bloom period, chlorophyll *a* concentrations were essentially homogenous throughout the water column, whereas from mid-May until the end of September a sub-surface maximum persisted, indicative of possible surface nutrient limitation.

For the majority of the survey diatoms were present in much greater numbers than dinoflagellates, constituting on average 73.25 % of the phytoplankton population at the three depths surveyed in terms of total cell numbers. However,

again on a cell density basis, both diatoms and dinoflagellates exhibited sub-surface maxima with 55.81% of all dinoflagellates and 51.34% of diatoms being recorded at the intermediate depth over the survey period.

From 14 May until 7 June five diatom taxa co-existed at the three sampling depths and dominated the phytoplankton population: *Chaetoceros* spp., *Nitzschia seriata*, *N. closterium*, *Leptocylindrus danicus* and *L. minimus*. There was evidence for a change of dominance within the population following incursion event I from *N. seriata* to *L. minimus* following incursion event I, suggesting that the smaller diatoms were better able to tolerate the reduced nutrient supply encountered following the injection and utilisation of nutrients during the first incursion event. *Chaetoceros* spp. dominated the phytoplankton flora at the surface during incursion event II, although densities decreased rapidly with the onset of the relaxation period such that from mid-June until mid-August diatom numbers were low at Station 1, possibly due to the low surface nitrate concentrations.

Dinoflagellate numbers were low prior to 17 June, although there were two minor increases of *Scrippsiella* spp. during incursion events I and II in May and June at the intermediate and surface depths respectively. However, in the latter part of the summer between 8 August and 10 September a succession of dinoflagellate population increases were observed, especially at the intermediate depth, coincident with the appearance of Type II water in the sub-surface layers. In general, the water column was thermally stratified at this time, resulting from the combination of strong solar heating and the two incursions of cool bottom water which provide the stratified conditions suitable for dinoflagellate growth. Four main dinoflagellate groups were important during this period; *Prorocentrum micans* and *Katodinium rotundatum* were found in varying numbers throughout this latter part of the survey, while *Gymnodinium* spp. and *Gyrodinium aureolum* increased in numbers towards the end of August and in early September. Highest cell numbers were recorded for *G. aureolum*, which attained maximum numbers of 0.99×10^6 cells l^{-1} at the intermediate depth on 3 September. Numbers of *G. aureolum* declined rapidly as

PO₄ concentrations decreased to zero, coincident with the disappearance of Type II water from the surface layers and a rapid decrease in the column water temperature caused by the autumnal decrease in insolation and increased wind mixing.

From mid-August until the end of September the enhanced dinoflagellate population co-existed with large numbers of diatoms, cryptophytes, tintinnids and unidentified cysts. It seems likely therefore, especially considering also the low concentrations of dissolved nutrients, that rapid nutrient recycling was occurring at this time, possibly through the pathways associated with the components of the microbial loop.

From 10 September onwards diatoms again dominated the phytoplankton at Station 1. Three species previously present in only negligible numbers, *Skeletonema costatum*, *Thalassionema nitzschoides*, and a *Thalassionema* spp. became the dominant phytoplankton in the Bay.

Discussion

The results clearly indicated that the wind strength and direction had a fundamental control on the movement of water masses within Bantry Bay, and that the resultant initiation of the series of incursion and relaxation events controlled the succession of the phytoplankton communities and the concentrations of dissolved nutrients present at the sampling location. Evidence obtained from previous spatial surveys of the Bay suggests that the incursion events influenced the dynamics of the whole Bay.

It was evident that for up to ten days preceding the start of each incursion event the wind direction was generally from the west or south-west. During this time it is likely that the surface water within the Bay was driven towards the head of the Bay with an associated movement of sub-surface water towards the open ocean. During relaxation of the south-westerly winds or at times when north-easterly winds prevailed, it is possible that the surface water withdrew towards the mouth of the Bay, allowing the cooler sub-surface waters to intrude towards the head of the Bay.

The ultimate origin of the two water types observed in the deeper layers during incursion events is not known, but it is hypothesized that they originate from the shelf region. During early summer, when the pycnocline on the continental shelf was expected to be weak or non-existent, Type I water was observed characterised by temperatures < 11 °C, high nutrients, and a relatively low phytoplankton biomass. These characteristics may be typically expected of shelf waters in early summer. During late summer, however, the Type II incursion water was warmer, relatively low in nutrients, and contained a larger phytoplankton, especially dinoflagellate, biomass. The presence of this water was observed in late August when the surface-to-bottom temperature difference was maximal. The origin of the Type II water is not clear although it appears responsible for the import of a substantial seed dinoflagellate population into the Bay. The association of this water with a seed population of this type suggests that this water may originate from a dynamical interface region on the adjacent shelf, such as is often linked with major developments of dinoflagellate populations in summer. Bantry Bay is thus seen to be an open ecosystem, strongly influenced by external events and inputs.

The data recorded during the survey suggests that light is unlikely to be the dominant control of phytoplankton growth, with the 1% light depth generally being greater than the depth of the water column, and nutrient concentrations may hence expected to be the major controlling influence of this growth. Given this scenario, the incursions of cool, nutrient-rich Type I water recorded early in the season are likely to be of particular importance.

A reduction in bottom chlorophyll a concentrations was noted during incursion events I, II and III, followed by an enhancement during the subsequent relaxation periods. This increase in bottom chlorophyll a concentrations following the incursion events may reflect sedimentation of a population generated in the surface layer consequent on the incursion. The absence of substantive dinoflagellate growth in the early part of the survey may not only reflect the lack of a seed population but

may also reflect growth of this taxa being outcompeted by that of the diatoms under higher nutrient concentration conditions.

The sub-surface maxima observed from May onwards in both chlorophyll a concentrations and phytoplankton cell counts reflect the non-limiting nature of light for most of the survey and also the effect of surface nutrient limitation. It seems probable that nitrate limitation in the surface waters was the cause both of the termination of the spring diatom bloom, and possibly also of the low surface chlorophyll a concentrations recorded for much of the survey. The summer/autumn phytoplankton species, on the other hand, displayed a much greater tolerance for low nutrient concentrations, with evidence for very rapid nutrient recycling, probably through the medium of the microbial loop. The termination of the dinoflagellate-dominated growth period coincided with the occurrence of undetectable PO_4 concentrations throughout the water column, immediately prior to the Type II water being replaced by well-mixed, cooler conditions associated with the autumn overturn. This event signalled the return to domination of the phytoplankton by diatom taxa.

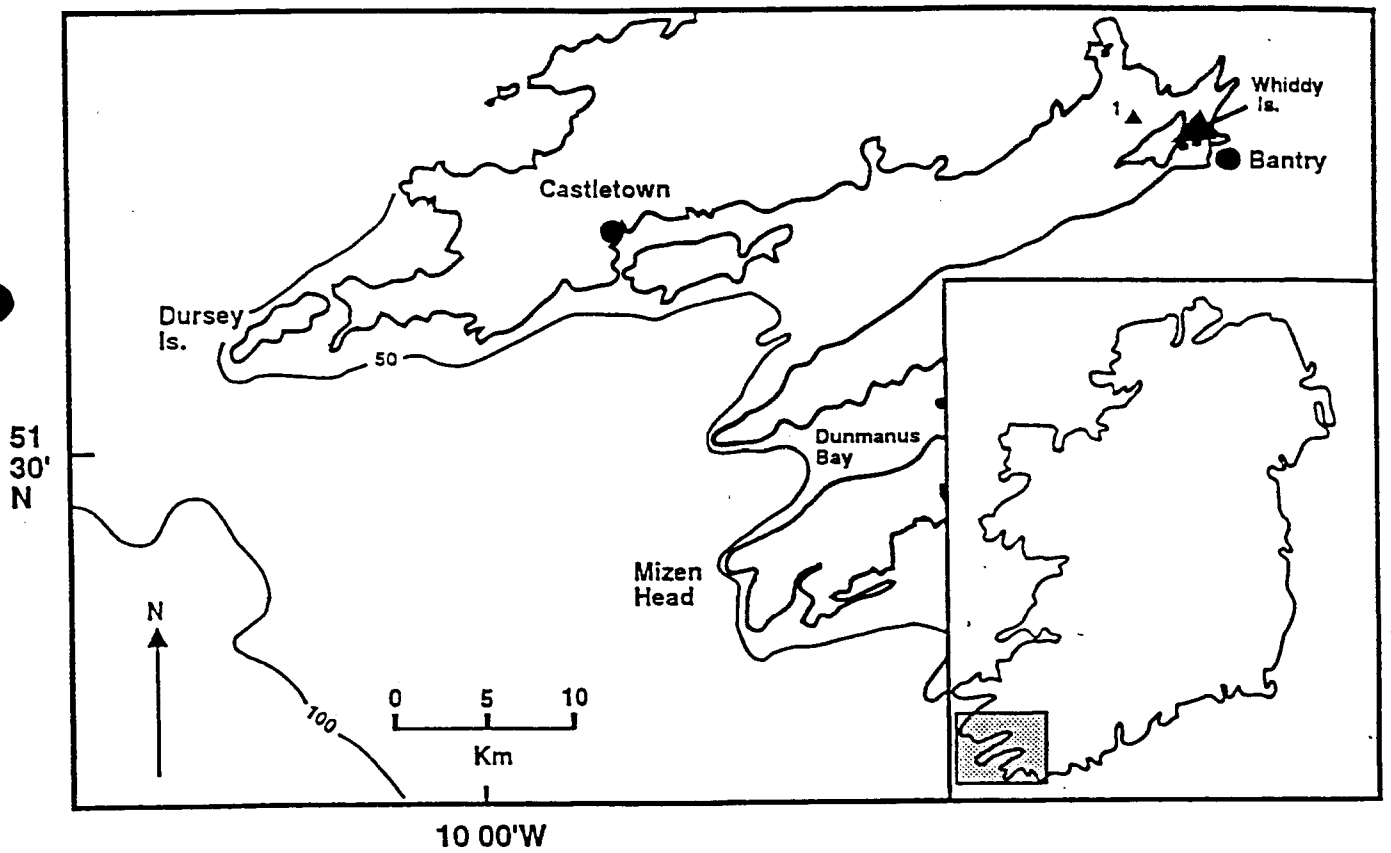


Fig. 1. Map showing location of Whiddy Island and Station 1 (▲) in Bantry Bay, south-west Ireland.

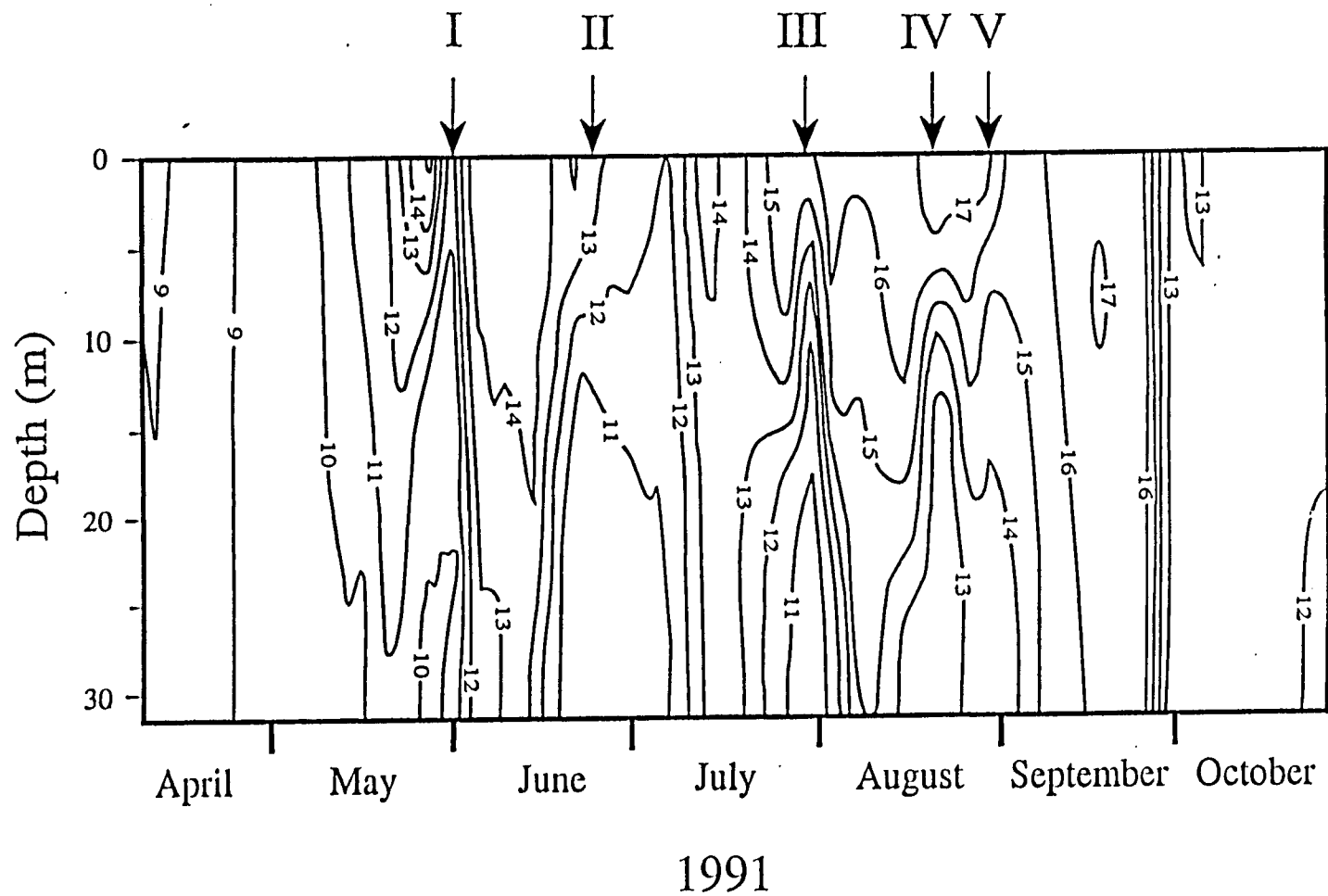


Fig. 2. Variation of temperature ($^{\circ}\text{C}$) with depth at Station 1, Bantry Bay, from 11 April to 25 October 1991. Roman numerals represent the five cool water incursion events.

Fig. 3

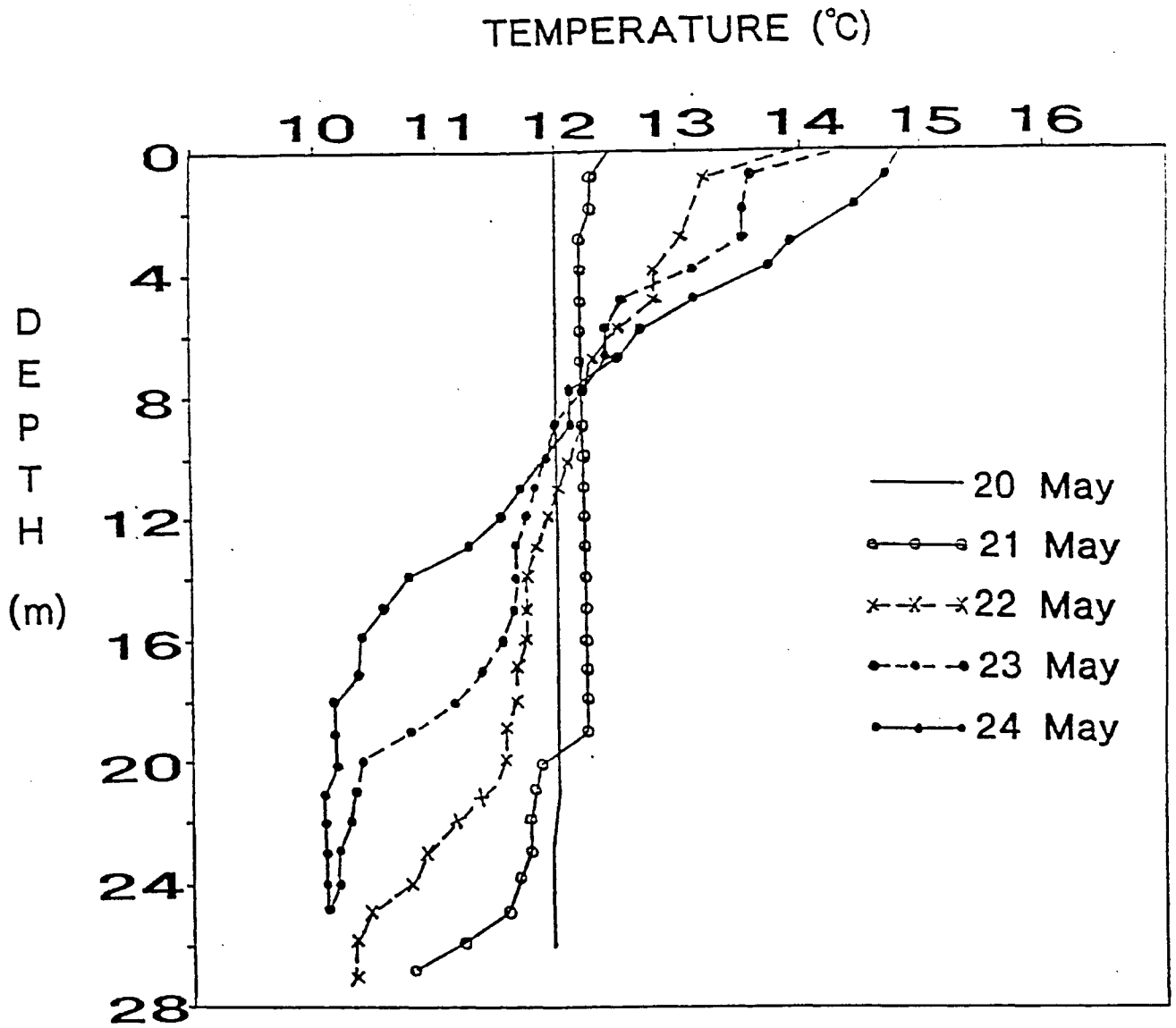


Fig. 3. Temperature - depth profiles at Station 1 during the cool water incursion event between 20 May and 24 May 1991.

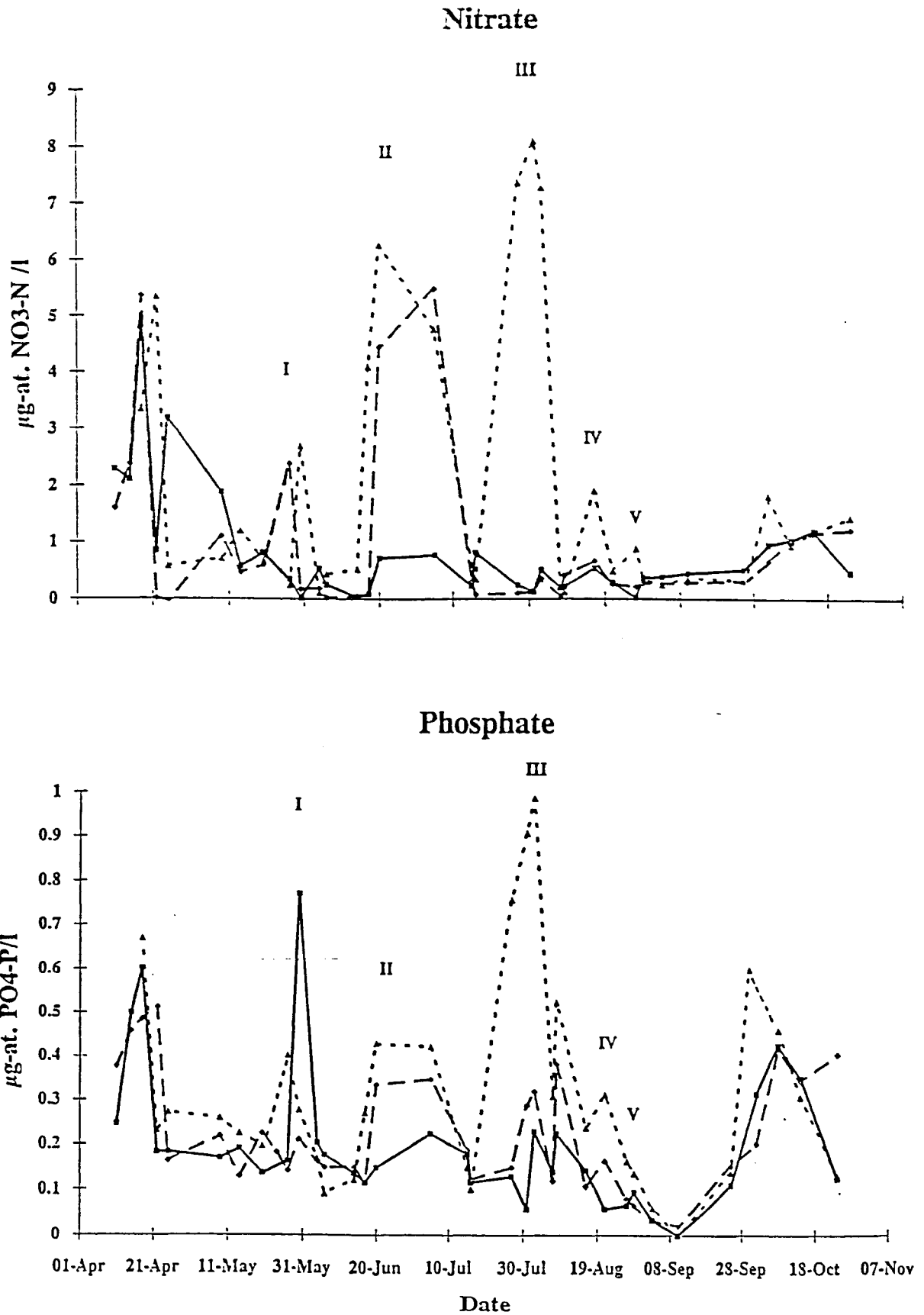


Fig. 4. Nitrate and phosphate concentrations at 1 m (■), 10 % light depth (◆) and bottom (▲) between 11 April and 25 October 1991. Roman numerals represent the five incursion events. Similar distributions were also observed for silicate.