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THE POTENTIAL OF THE JUTLAND COASTAL CURRENT AS A TRANSPORTER OF NUTRIENTS TO THE KATTEGAT.

by

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Abstract.

Annual fluctuations and distributions of nitrate during the 1980s in areas along the Danish west coast and in the northern Kattegat have been examined and compared. Transport of nitrate brought about by the Jutland Coastal Current (JCC) along the Danish west coast from the easter North Sea to the northern Kattegat seems to occur sporadically during the winter/early spring months. However, such events do not seem to occur every year. Quantification of the actual transport of nutrients to the Kattegat via the JCC is not possible until the relative transport of waters from the JCC and the rest of the North Sea into the Kattegat has been determined.

Introduction.

During the last decade, considerable attention has been directed towards hypoxia/anoxia events in the bottom waters of the Kattegat. Eutrophication from anthropogenic sources (and the resulting increase in primary production and decay of organic material in the bottom layers) is believed to be the cause of the increased frequency and distribution of these events (Ærtebjerg,

1987).
The declining trend in bottom layer oxygen concentrations and the increasing trend in nutrient concentrations in the Kattegat have been described by Andersson & Rydberg (1988) and Olsen (1990).

In connection with efforts to reduce nutrient input (eutrophication), a number of mass balances of nutrient inputs to the Kattegat have been constructed (i. e. Richardson and Ærtebjerg, 1991). However, there is still considerable uncertainty concerning the relative importance of the various sources.

Nitrogen loading during the last decade from adjacent rivers into the coastal waters of the southeastern North Sea has been high (Gerlach 1990). This is reflected, for example, in the increase in winter nitrate concentrations found at the Helgoland Reede (1962 - 1984) in the German Bight (Radach and Berg, 1985). Therefore a good deal of interest has been focused on the Jutland Coastal Current (JCC) as a potential source carrying nutrient rich continental coastal waters from the German Bight along the Danish west coast and into the Kattegat.

The purpose of this project was to investigate the role of the JCC in transporting nutrients from the German Bight to the Kattegat.
In order to quantitatively assess the importance of the JCC, knowledge about the magnitude and origin of the water volumes entering the northern Kattegat is needed. Unfortunately, a satisfactory description of these conditions is still lacking. Our approach, therefore, has concentrated on an examination of the chemical characteristics of the relevant water masses. In particular, we focus on nitrate concentrations and annual patterns in nitrate distribution in an attempt to elucidate the JCC's role in transporting nitrate to the Kattegat.
As the hydrography of the Skagerrak is quite complicated and, as yet, poorly understood, we operate with the simplification that two incoming water masses are potential contributors to the renewal of the Kattegat bottom waters. These two water masses have their origin in

a) - water of salinity < 34 o/oo along Jutland's west coast, here referred to as the JCC. This current is not continuous but rather induced primarily by south- to westernly winds (Pedersen et al 1987, Kristensen 1991). This means that within a short period (ca. 1 month), the JCC exhibits a continous as well as an interrupted pattern. While interrupted, it often forms a pool of low salinity water (< 34 o/oo) at the bend of the Jutland westcoast south of Hanstholm. The fate of this pool can either be that it becomes diluted by the nutrient poorer North Sea water or that it, after a short break due to unfavourable (wind) conditions, continues into the Skagerrak. Biological activity can also reduce the available nutrients in the waters of the JCC "pool".

b) - northern North Sea (water of salinity > 34 o/oo).

Nitrogen has often been identified as the limiting macronutrient for phytoplankton production in the Kattegat (i. e. Richardson & Ærtebjerg, 1991). The dominant inorganic form of nitrogen, and that for which sufficient data exist to enable an analysis such as the present to be carried out, is nitrate. In addition, nitrate is the dominatant nutrient in the JCC. Therefore, this investigation has been limited to examining nitrate concentrations. It would, of course, also be highly relevant to carry out similar analyses on total nitrogen as well as organic carbon data.

Materials and Methods.

Data.

For the present investigation, we have received data from several monitoring authorities and from the databank of the International Council for the Exploration of the Sea (ICES). These data sources are listed in the following survey:

Donator of data	Covered area	Time equidistance
Biologische Anstalt Helgoland, Hamburg	German Bight (Helgoland Reede)	Few days during 1980 - 1985.
Institute of Marine Research, Bergen	The Eastern North Sea	Various.
Flødevigen Biological Station, Arendal	The Hirtshals - Torungen transect	Less than a month (except 1987).
The ICES Database	All incl. areas	Various.

We have chosen to examine the annual fluctuations in nitrate concentration in three areas along the Danish west coast and in one area in the northern Kattegat. These areas are described in the following survey:

"Name" of area	Position	Characteristics: 1) Selected interval of depth 2) Selected salinity criterium 3) Period covered by the data.
The German Bight	53°50'N - 55°00'N 7°50'E - 8°40'E	1) 0 - 15 m. 2) None. 3) 1980 - 1990.
The coastal area near Hirtshals	57°20'N - 57°43'N 9°30'E - 10°00'E	1) 0 - 30 m. 2) None. 3) 1980 - 1991.
The Norwegian Trench	57°56'N - 58°15'N 9°00'E - 9°30'E	1) 100 - 400 m. 2) None. 3) 1980 - 1991.
The northern Kattegat	57°20'N - 57°40'N 10°30'E - 11°35'E	1) 25 - 50 m. 2) > 31 o/oo. 3) 1971 - 1990.

Fig. 1 shows the areas selected for the study.

General data treatment.

To select data from the actual areas and to generate average values over the chosen interval of depth, programs in Fortran 77 has been constructed.
Plots have been made in SAS (Statistic Analysis System).
The examinations has been carried out at the Danish Institute for Fishery & Marine Research.

Results.

The annual fluctuations in nitrate concentrations in the coastal area near Hirtshals and in the German Bight during the period 1980 - 1990 are shown in Fig. 2.
Although the seasonal patterns in nitrate concentrations are similar for both regions, very different patterns in the detailed distributions of nitrate concentrations in the German Bight and near Hirtshals emerge. Some of the high concentrations observed in the area near Hirtshals may be explained by transport of nitrate from the German Bight along the coast. If such peaks are related then a transport time of about 1 - 2 months is indicated. This is in agreement with hydrographic estimates for transport in this region (Kristensen, 1991).
However, not all peaks in nitrate concentrations in the German Bight are followed by peaks in concentrations near Hirtshals. For example, the peaks in nitrate concentrations often found in the German Bight during March are not reflected in peaks near Hirtshals.
It is also important to note that, while there appears to be an increase in the nitrate concentration found in the German Bight during the 1980s (confirmed by Prof. Dr. Hickel, Biologische Anstalt Helgoland in Hamburg (pers. com.)) there does not, with the exception of 1989, seem to be a comparable increase near Hirtshals.

The annual fluctuations in nitrate concentration in the coastal area near Hirtshals and in the Norwegian Trench on the Hirtshals - Torungen transect during the period 1980 - 1991 are shown in Fig. 3.
Concerning the coastal area near Hirtshals, it is clear that due to biological activity, the nitrate concentration fluctuates during the annual primary production cycle, as it is often seen in coastal waters.
These fluctuations are not seen in the deeper water of the Norwegian Trench. From Fig. 3 can be seen, that the nitrate concentrations in the coastal water near Hirtshals seldom significantly exceed the concentrations found in the North Sea water (i. e. The Norwegian Trench). When this occurs it is only during the months of winter/early spring in 1981, 1989 and 1990.

Fig. 4 relates nitrate concentration and salinity for the coastal area near Hirtshals during the period 1980 - 1991.
Two important observations can be made from this figure:
1) - nitrate concentration exceeding 10 μM appear only during the months of winter/early spring and in relatively low salinity water < 33.5 o/oo.
2) - water of relatively high salinity (> 34.0 o/oo) carries nitrate concentration below 10 μM during all months.

Fig. 5 shows the annual fluctuations in nitrate concentration in the bottom waters of the northern Kattegat and in the coastal area near Hirtshals during the period 1980 - 1990.
The two curves are very similar. The seasonal signal in the bottom water in the northern Kattegat indicates that this water has a recent past record in coastal surface water. The similarity in the two curves suggests that bottom water in the Northern Kattegat may have its origin in water that recently has been located off Hirtshals. If this is the case, the time delay in the appearence of peaks in nitrate concentration near Hirtshals and in the northern Kattegat may be explained by the duration of transport.

In fig. 6, the fluctuations in nitrate concentrations in the bottom water in the northern Kattegat are illustrated together with the concentrations found in the deep water of the Norwegian Trench.
It can be seen that, during the winter/early spring in 1981, 1982, 1987-1989 the nitrate concentrations in the northern Kattegat exceeded the concentrations found in the Norwegian Trench. The seasonal cycle observed in nitrate concentrations in the northern Kattegat bottom water is not observed in the deeper water of the Norwegian Trench.
During summer months the nitrate concentrations in the northern Kattegat are always found to be below the concentrations found in the Norwegian Trench.

Nitrate concentrations shown as a function of salinity (bottom water) in the northern Kattegat during the 1980s are shown in Fig. 7.
Generally, nitrate concentrations above 10 μM are found during the winter/early spring. These are usually related to salinities within the range of 31 to 34 o/oo.

Fig. 8 shows the annual fluctuations in nitrate concentration in the bottom water of the northern Kattegat during the period 1972 - 1990.
It is clear that events where the nitrate concentration exceeds 10 μM occur in the last ten years of the period. These "peaks" in nitrate concentration are generally found during the winter/early spring.

Discussion and Conclusions.

Although a thorough understanding of nutrient transport to and turnover in the Kattegat is still lacking, it is assumed that the recorded increase in frequency and intensity of anoxia and hypoxia in these waters during the 1980s is related to an increased eutrophication (Ærtebjerg, 1987).

Before remedial actions to reverse this eutrophication can be undertaken, it is important to identify which of the potential nutrient sources to the Kattegat have changed (increased) during the last 20 - 30 years.

The North Sea provides the Kattegat with approximately 50 % of its annual nitrogen input (Anon., 1991). Thus, any changes in nutrient transport via the North Sea can potentially be of great importance to the nutrient budget of the Kattegat.

The North Sea's input to the Kattegat via Skagerrak must, however, be considered as being composed of at least two components, the "open or Northern North Sea" and the Jutland Coastal Current (JCC) which can be considered as an extension of the continental coastal waters. A number of studies (i. e. Pedersen et al., 1988 ; Jacobsen and Richardson, 1990; Kristensen, 1991; Poulsen, 1991) have demonstrated that the relative distributions of the water masses belonging to these different components are very much under the influence of the wind speed and direction. Thus, under some conditions (especially those with a prevailing south/southwest wind), the JCC can extend into the Skagerrak and its waters potentially be transported into the Kattegat. Under other wind conditions, the extension of the JCC is such that it is unlikely to affect transport of nutrients to the Kattegat.

There is no evidence of a major change in nutrient concentrations in the open North Sea. In addition, it seems intuitively unlikely that major changes in nutrient concentrations in the northern North Sea would have occurred as a result of anthropogenic activities. It is, however, well known that significant increases in nutrients have occurred in European coastal waters (Gerlach, 1990). Thus, if a major increase in nitrate input via the North Sea to the Kattegat has occurred, it is reasonable to expect it to have done so through the JCC.

Unfortunately, it is not yet possible to quantify the amounts of North Sea water entering the Skagerrak/Kattegat from the two respective sources (i. e. "Jutland Coastal Current" and "North Sea"). Until the actual transport from these sources is known, it will not be possible to quantify the JCC's role in transporting nutrients to the Kattegat.

From a chemical point of view, however, it is relevant to examine the concentrations of nutrients in the waters of the JCC at a location off the northern coast of Denmark (i. e. where the JCC can have entered the Skagerrak). The argument here is that as nutrients are not conservative, they can be removed via biological activity or due to dilution by more nutrient poor water during the transport of water along the Danish west coast. Only nutrients that are actually present at the entrance to the Skagerrak have the potential of being transported into the Skagerrak and, ultimately, the Kattegat.

This study has shown that the concentrations of nitrate observed along the northern Danish coast, in waters which correspond with respect to salinity to the JCC, are considerably lower than those observed in the German Bight. This is, of course, a function of both dilution and biological activity (Pedersen et al., 1988).

The seasonal patterns in the distribution in the concentrations of nitrate found off the north Danish coast (Hirtshals) are similar to those observed in the German Bight (i. e. high during the winter and low during the summer, Fig. 2). However, it is not possible to see all of the peaks in nitrate concentration observed in the German Bight reflected in the nitrate distributions near Hirtshals. In particular, the large peak in nitrate concentrations observed annually in the German Bight during the month of March does not seem to affect nitrate concentrations in the area near Hirtshals during the following period. (Transport time from the German Bight to the Skagerrak has been calculated to be on the order of 1 - 3 months, Kristensen, 1991).
Another apparent difference between the distributions in the nitrate concentrations in the German Bight and near Hirtshals is that concentrations in the German Bight have increased during the 1980s, (Hickel, pers. com.). Such an increase cannot be identified in the data material for the area near Hirtshals.
Thus, where there are similarities between the patterns of nitrate distribution in the German Bight and the Skagerrak, it seems clear that the potential contribution of the JCC to transport of nutrients to the Kattegat cannot be evaluated only by considering the amounts of nutrients entering the German Bight.

The seasonal patterns in the distributions of nitrate concentrations in the area near Hirtshals and in the bottom water of the Kattegat (Fig. 5) resemble each other much more closely than those of the German Bight and near Hirtshals (Fig. 2). The seasonal troughs peak in the nitrate concentrations argue for an immediate past history as "surface" water for the bottom in the northern Kattegat. "Surface" water in this case is used to refer to the euphotic zone, in contrast, for example, to the deeper waters of the Norwegian Trench, where nitrate concentrations remain more or less constant throughout the year at about 10 μM (Fig. 3). The similarity in the distributions near Hirtshals and in the bottom water of the northern Kattegat <u>may</u> also argue for waters entering the northern Kattegat having had an immediate past history near Hirtshals. Support for this argument can be found in Fig. 4 and Fig. 7 which illustrate that the high nitrate concentrations in both areas are related to salinities in the same range (31 to 34 o/oo).

Assuming that the inflow from the North Sea to the Kattegat ultimately originates from either the northern North Sea or the JCC, then the JCC is only of interest as a potential carrier of excess nitrate to the Kattegat in periods in which nitrate concentrations exceed those in the northern North Sea. Fig. 3 shows that the greatest concentrations of nitrate in the JCC near Hirtshals occur in the months of winter/early spring. Thus, the available data material indicates, that it is reasonable to expect the greatest potential contribution by the JCC to nutrient transport to the Kattegat to occur during winter/early spring. This is also a reasonable assumption given that biological activity (i. e. turnover of nutrients) will be at a minimum during the months of winter/early spring ("early spring" refers to the period before the onset of the phytoplankton bloom).

Given the concentration of nitrate in the deeper waters of the Norwegian Trench (ca. 10 μM, see Fig. 3) and winter concentrations of nitrate in surface waters of the northern North Sea during Jan/Feb in the 1980s (8-10 μM, Nielsen and Richardson, 1989, and Jan/Feb data taken from the ICES databank 1984 - 1989), we have arbitrarily chosen to regard concentrations exceeding 10 μM nitrate in JCC water during the months of winter/early spring as representing periods in which the JCC can be of potential importance as an "unusual" or "excess" nitrate carrier to the Kattegat.

The data presented here (Fig. 3) indicate that such winter/early spring peaks in nitrate concentration can be observed in JCC water during the 1980s (1981, 1989 and 1990). It must be noted, however, that due to the sporadic nature of these events, the sampling is difficult. Thus, peaks can have occurred which are not (or not completely) reflected in the data set. The most dramatic peak is observed in 1989. This peak can be followed into the bottom waters of the northern Kattegat. Indeed, Ærtebjerg (1990) has reported that it was possible to follow JCC water with high nitrate concentrations into the bottom water of the southern Kattegat in 1989. It is worth noting with respect to this event that winds during the winter/early spring 1989 were unusually dominated by south/southwesterly winds (Sehested-Hansen et al., 1990). Southerly winds are those which give the JCC the greatest potential of reaching the Skagerrak/Kattegat (Poulsen, 1991).

Ærtebjerg notes (pers. com.) that despite yearly monitoring since 1974, this 1989 event was the first unequivical indication of a major nitrate transport from the JCC to the Kattegat that has been observed. Longterm data series (taken from the ICES databank) and covering the period from 1972 - 1990 for nitrate concentration in the bottom waters (Salinity > 31 o/oo) of the northern Kattegat (Fig. 8) indicate that major nitrate transport events from the North Sea to the Kattegat may also have occured in 1981 and 1982. Less dramatic peaks are noted in 1987 and 1988.

In summary, the chemical data presented here suggest that the JCC has the potential to transport exceptional amounts of nitrate to the Kattegat during winter/early spring months, but that such transport only occurs sporadically. This sporadic transport to the Kattegat is most likely a function of the wind setup and need not necessarily occur in all years.

In order to quantify the effect of these exceptional JCC inflow events on the total nitrogen budget of the Kattegat and, thus, to evaluate the potential contribution of the JCC to oxygen depletion in the southern Kattegat, it will be necessary to quantify the actual water transport in these events and determine how often they occur. It is, however, already possible to determine that there is no simple cause and effect relationship between years in which a transport of nitrate from the JCC to the Kattegat can potentially be identified and the severity/extention of hypoxia/anoxia in the Kattegat.
Hypoxia/anoxia events in the southern Kattegat and Belt Seas have occurred in a number of years in which no large transport of nitrate from the JCC to the Kattegat can be traced. By contrast, in 1989, when there is good evidence of an exceptional transport event of nitrate from the JCC to the Kattegat, the intensity and extension of oxygen depletion was less than in, for example, 1988.

Thus, considerable research effort is still required to elucidate the contribution of the Jutland Coastal Current to the nutrient transport to the Kattegat and the potential role of this nutrient in the observed oxygen depletion events.

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Figure legends.

In the following figure legends "average nitrate concentrations" refer to an average nitrate concentration made over the chosen interval of depth for the respective area (see the survey on p. ?).

Fig. 1
Map showing the different areas.

Fig. 2
The solid line shows the average nitrate concentration (μM) from the coastal area near Hirtshals, while the dotted shows the average concentrations in the German Bight in the period 1980 - 1991.

Fig. 3
Average nitrate concentrations (μM) from the coastal area near Hirtshals (solid line). The dotted line represents average nitrate concentrations from the Norwegian Trench. The time scale is 1980 - 1991.

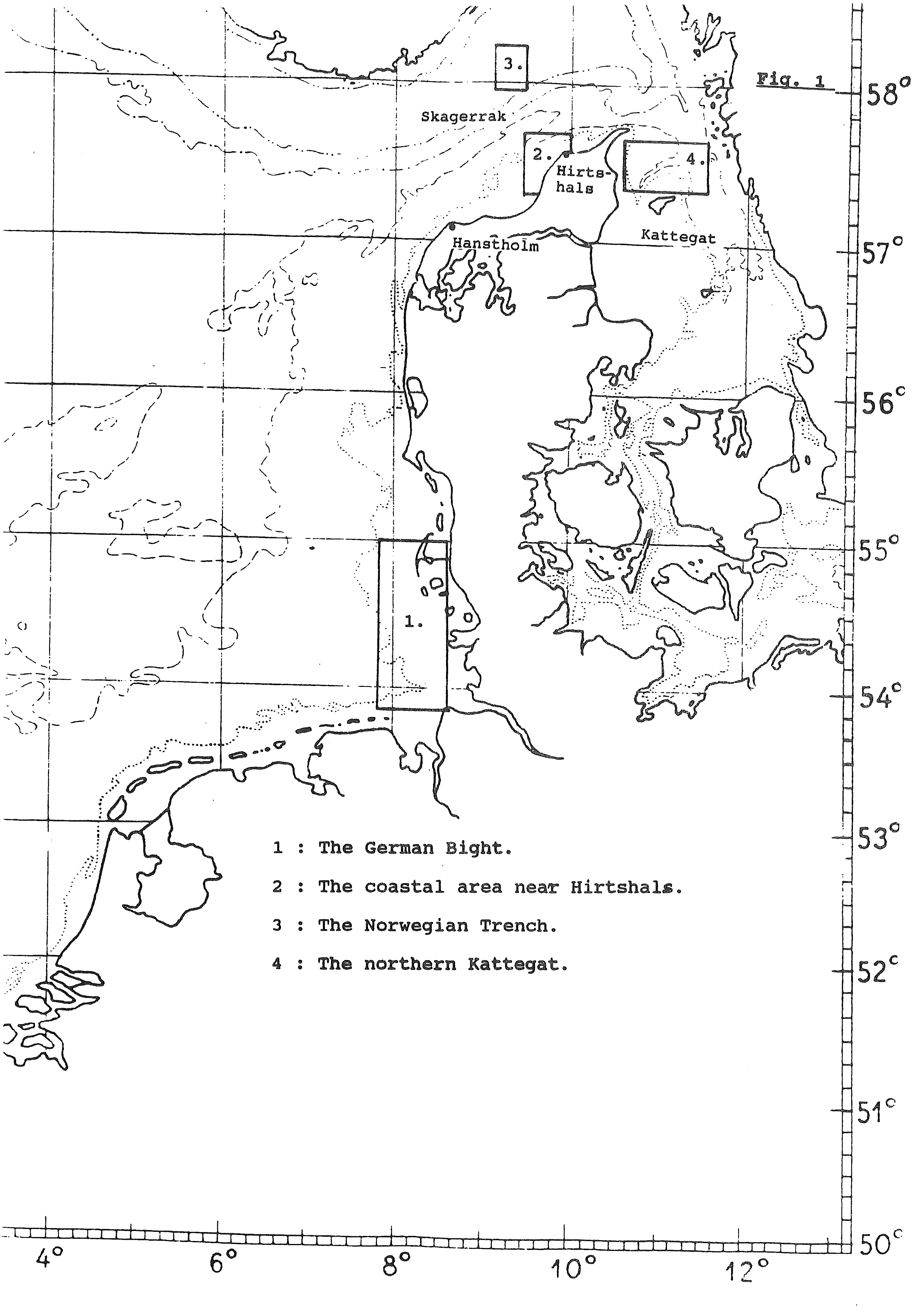
Fig. 4
Nitrate concentrations (μM) versus salinity in the period 1980 - 1991 from the coastal area near Hirtshals.
"Diamonds" represent the months: December,..,March, - while "plusses" represent the remaining months.

Fig. 5
Average nitrate concentrations (μM) from the northern Kattegat are shown by the solid line, while the dotted line represents average nitrate concentrations from the coastal area near Hirtshals. The time scale is 1980 - 1991.

Fig. 6
Average nitrate concentrations (μM) from the northern Kattegat (solid line). The dotted line represents average nitrate concentrations from the Norwegian Trench. The time scale is 1980 - 1991.

Fig. 7
Nitrate concentrations (μM) versus salinity in the period 1980 - 1990 from the northern Kattegat.
"Diamonds" represent the months: December,..,March, - while "plusses" represent the remaining months.

Fig. 8
Average nitrate concentrations (μM) from the northern Kattegat in the period 1972 - 1990.


3.
Skagerrak
2.
Hirts-
hals
4.
Hanstholm
Kattegat
1.
1 : The German Bight.
2 : The coastal area near Hirtshals.
3 : The Norwegian Trench.
4 : The northern Kattegat.
58°
57°
56°
55°
54°
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52°
51°
50°
4°
6°
8°
10°
12°

Fig. 1

Fig. 2

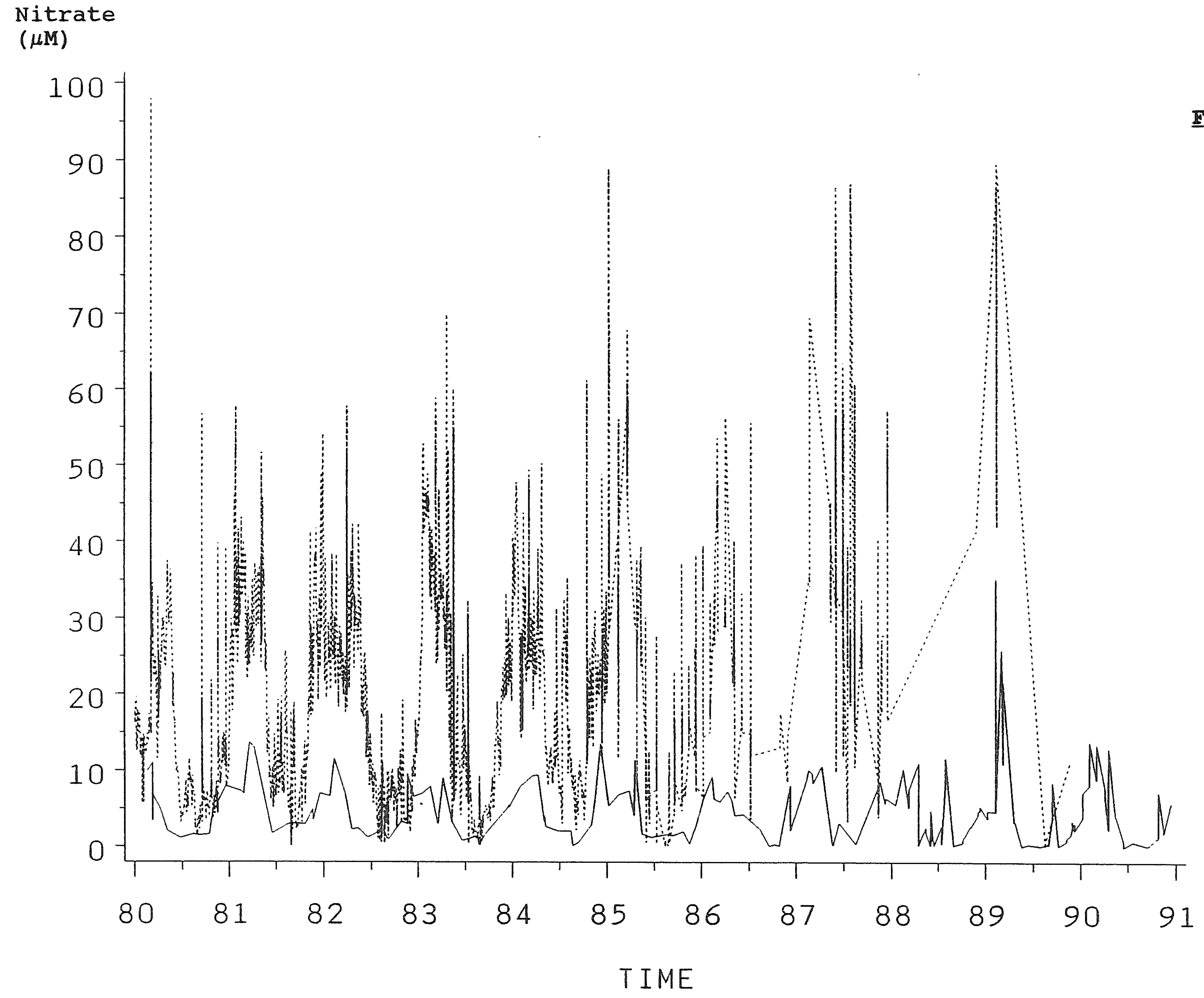
Nitrate
(μM)
100
90
80
70
60
50
40
30
20
10
0
80
81
82
83
84
85
86
87
88
89
90
91
TIME

Fig. 3

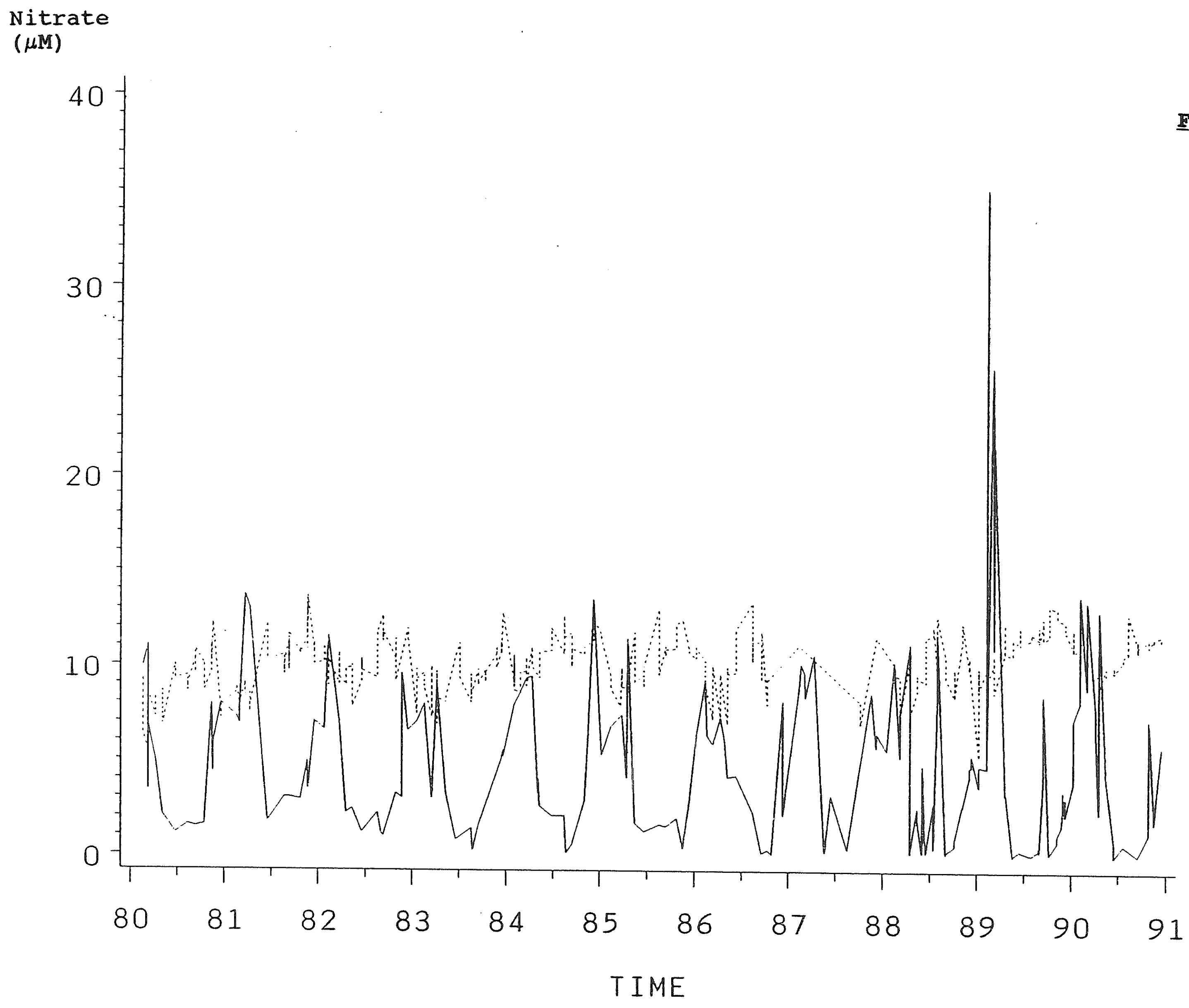

Fig. 4

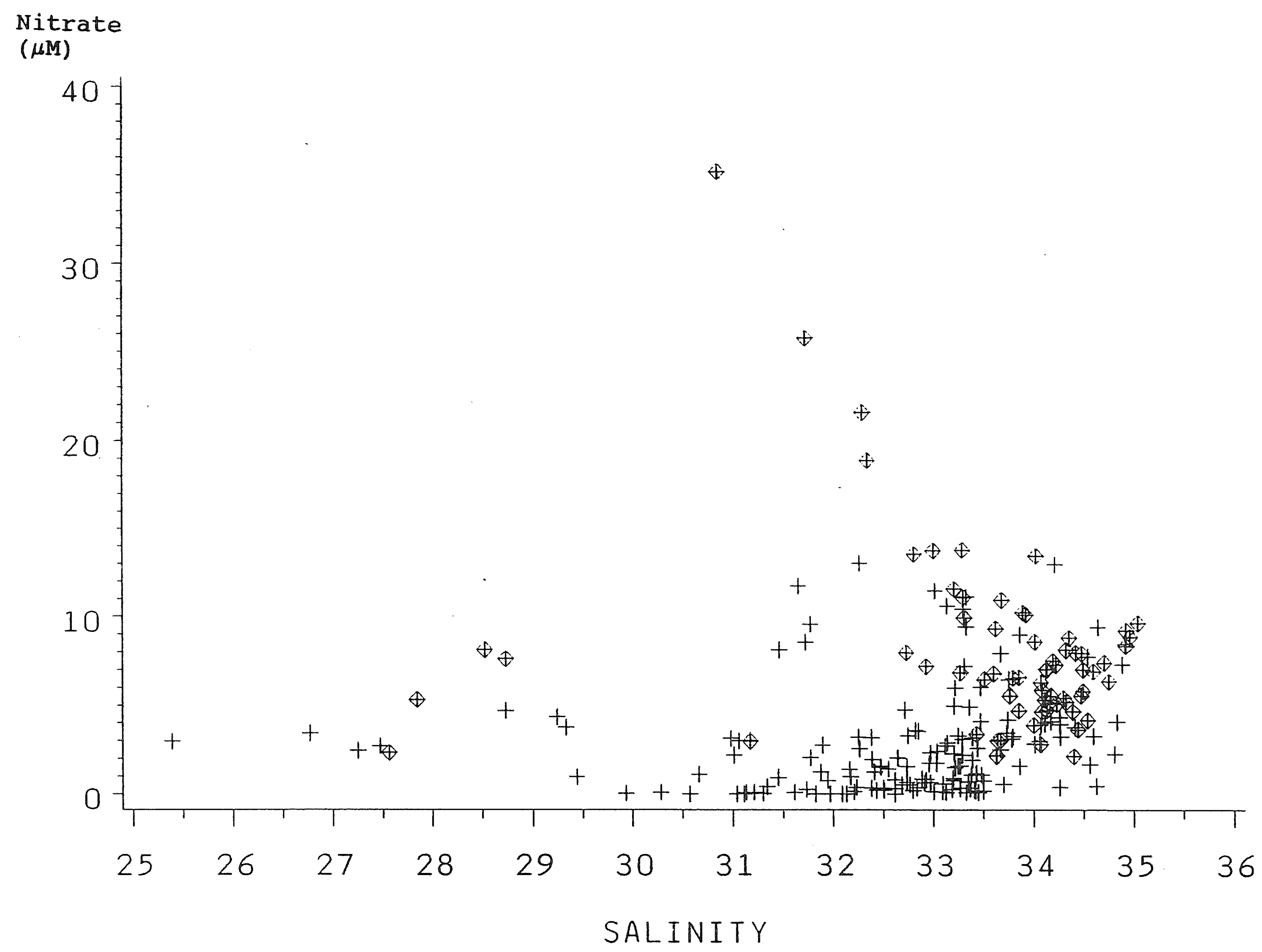
Nitrate
(μM)
40
30
20
10
0
25
26
27
28
29
30
31
32
33
34
35
36
SALINITY

Fig. 5

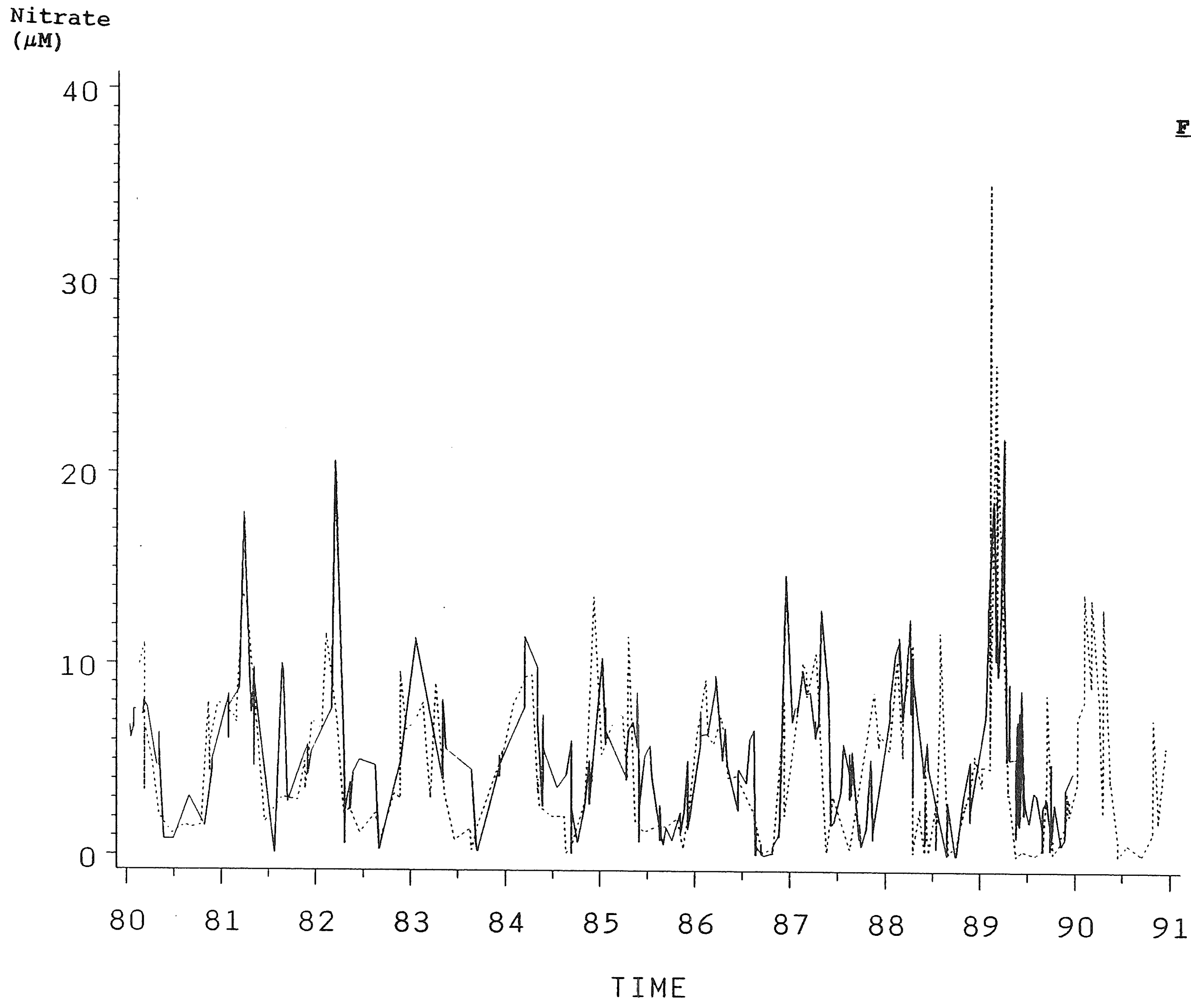

Fig. 6

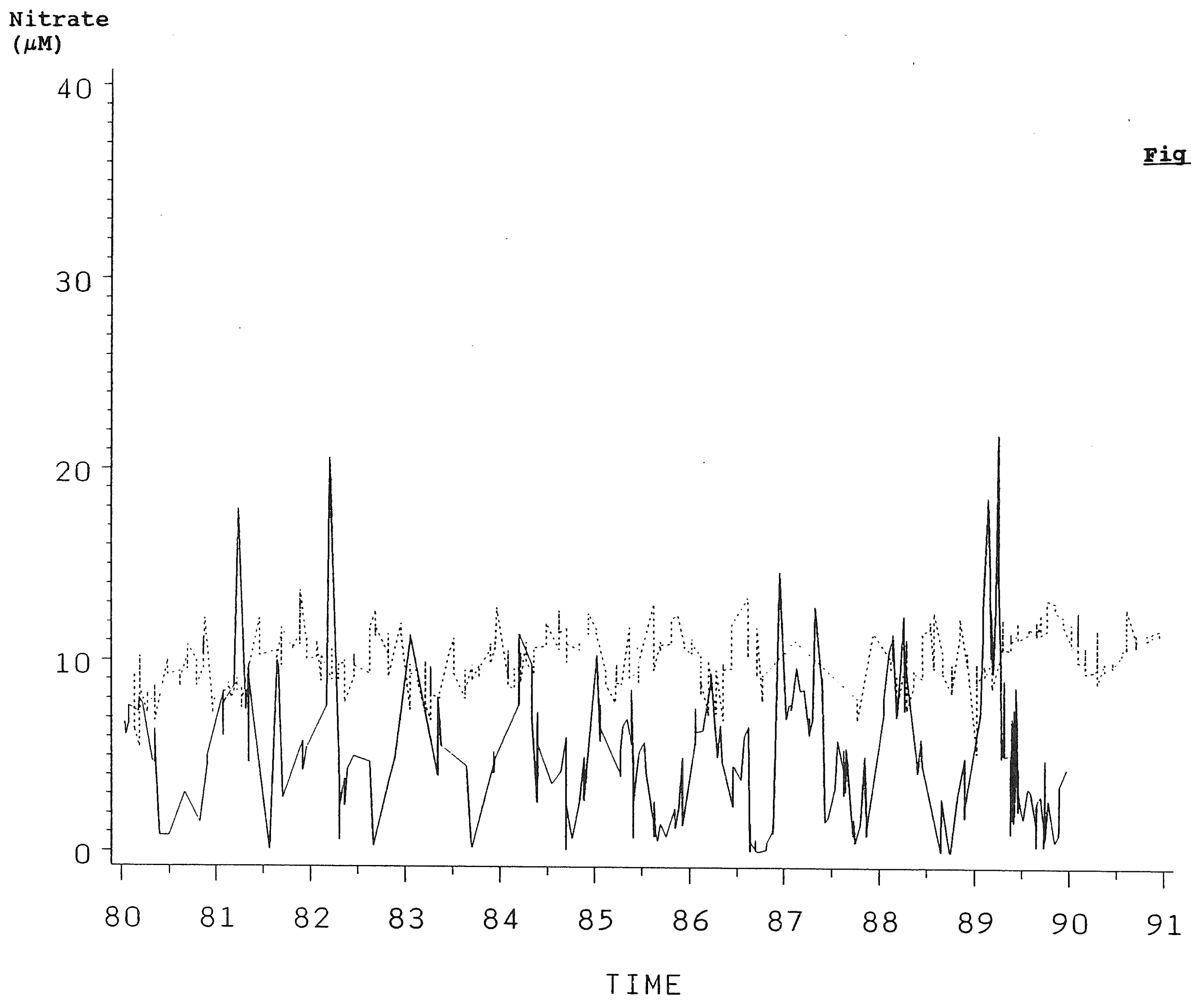

Fig. 7

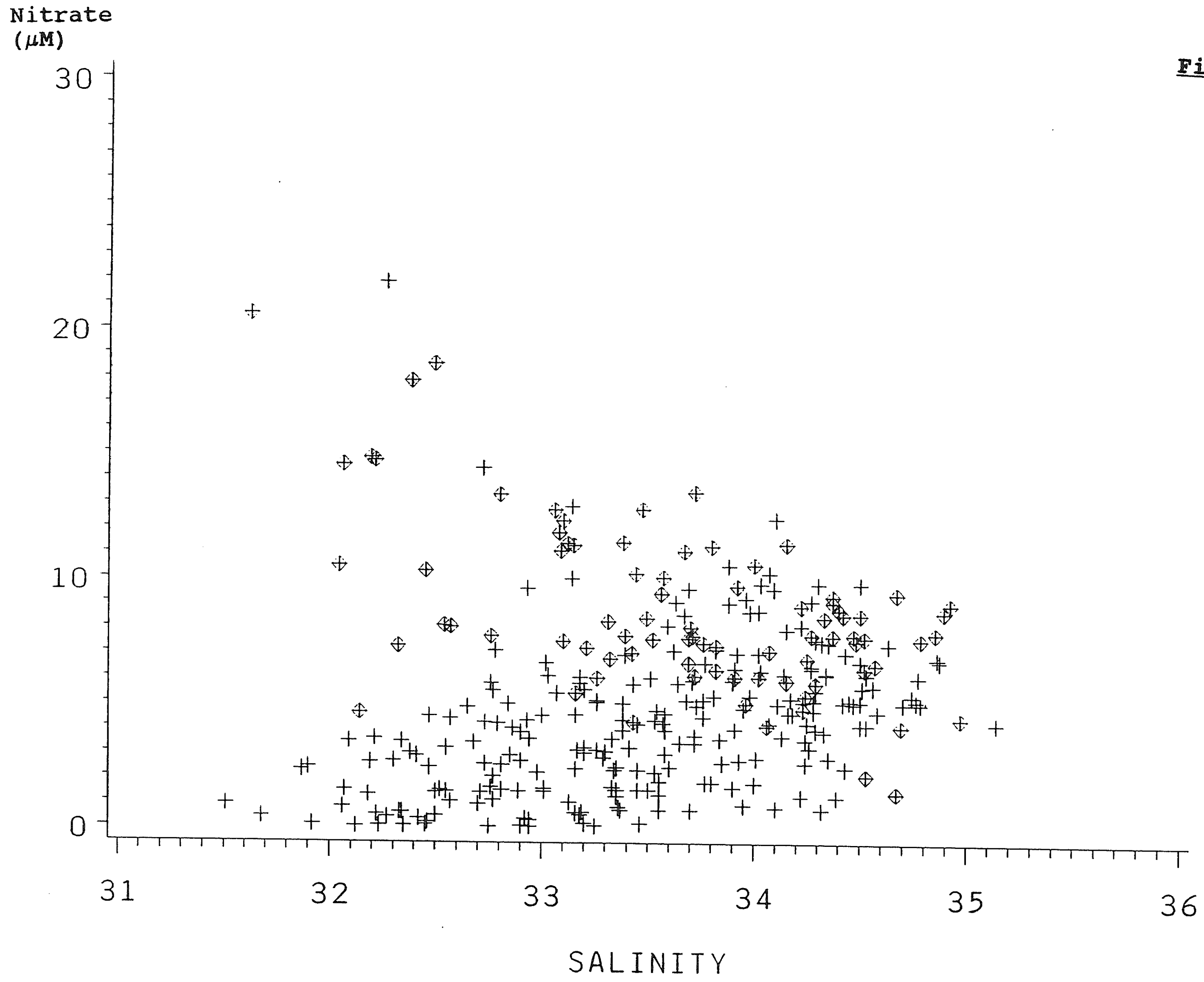

Fig. 8