

Changes and causes of variability in salinity and dissolved inorganic phosphate in the Irish Sea, English Channel, and Dutch coastal zone

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In an attempt to investigate the sources of variability in salinity and dissolved inorganic phosphate (DIP) in the English Channel, Irish Sea, and southern North Sea, time series (20–40 yr) of observations at four different stations were studied. Highest salinities and lowest DIP, both associated with the lowest residuals, were found at station E1 in the English Channel near Plymouth, which is assumed to be representative of the natural signal of Atlantic Water entering the shelf seas. The influence of freshwater run-off, reflected in lower salinities and, more recently, in increased DIP concentration, is clearly shown at the station near the Isle of Man in the Irish Sea and at two stations in the Dutch coastal zone. However, comparison of the time series at the four different stations revealed that, while the two stations in the Dutch coastal zone were correlated to some extent, there was no significant cross-correlation between the other stations. The conclusion is that physical, chemical, and biological processes in the different areas affect the natural variability of the Atlantic signal to such an extent that the different properties studied at the stations are not related.

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Key words: Atlantic influence, dissolved inorganic phosphate, English Channel and North Sea, eutrophication, Irish Sea, natural, salinity, trends, variability.

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Introduction

The North Sea is an open dynamic shelf sea; huge and variable amounts of oceanic water enter from the south through the Strait of Dover (Salomon and Breton, 1993; Salomon *et al.*, 1993) and from the north (Turrell *et al.*, 1992) and leave the North Sea through the Norwegian Trench (Furnes, 1992). The Irish Sea is much smaller than the North Sea, more enclosed and subject to relatively greater influence by freshwater run-off. The main residual flow is from south to north through St Georges Channel (Bowden, 1950; Bowden and Hughes, 1961), with a minor current entering from the north along the Irish coast. Varying physical, chemical, and biological signals present in Atlantic Ocean Water (Garrod and Colebrook, 1978; Diaz and Markgraf, 1992) influence in one way or another the Irish and North sea ecosystems (Mann and Lazier,

1991; Glantz, 1992; Svendsen and Magnusson, 1992). This was clearly demonstrated by the transit of water masses with relatively low salinities from East Greenland (late 1960s) to the North Sea (1977–1979), known as the “Great Salinity Anomaly” (Dickson *et al.*, 1988, 1992). The general conclusion of these studies is that climatic variability influences physical, chemical, and biological parameters and processes in the North Sea, albeit to an unknown extent (Svendsen and Magnusson, 1992).

As stated by Hempel (1978), ecosystem parameters and processes are not only affected by natural factors but also by human activities; for example, fisheries and discharge of nutrients. The concentration of nutrients increased sharply in the coastal zone of the continent during the 1970s (Klein and Van Buuren, 1992). In the Dutch Wadden Sea, it is also plausible that, besides cold winters (Beukema *et al.*, 1996), changes in nutrient load

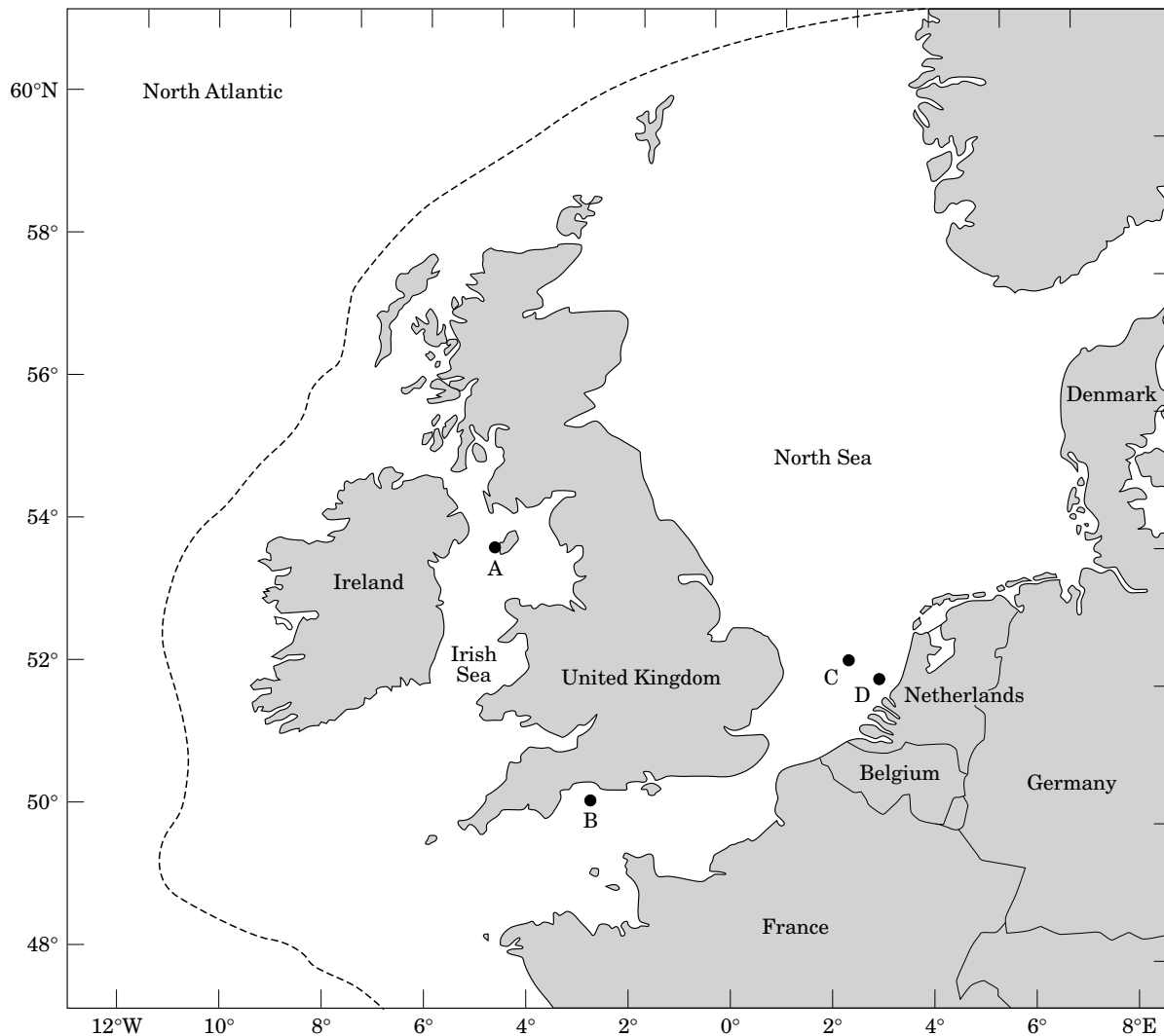


Figure 1. Map of the continental shelf and the North Sea with sampling locations. A: Port Erin in the Irish Sea; B: station E1 in the English Channel; C: 50–70 km offshore and D: 2 km offshore of the Dutch coastal zone.

affected primary and secondary production (De Jonge and Essink, 1991).

The objective of this paper is to study and explain changes in time series of salinity and DIP at four different stations on the continental shelf and to study the extent to which variability is communicated between these stations.

Material and methods

Salinity and dissolved inorganic phosphate (DIP) data from long-term time series have been analysed. Sample locations are indicated in Figure 1. The series from the Irish Sea off Port Erin (Station A) was continued with a weekly sampling interval from 1954 up to the present

and offers a view of the conditions in a relatively enclosed area, which is directly influenced by oceanic conditions. The English Channel data, collected monthly about 20 miles off Plymouth (E1; here Station B) from 1930 onwards, represents one of the longest time series of hydrographical data, which, however, was stopped in 1985 due to a reduction in funding. Data from 1954 to 1985 are used here as an index of near oceanic conditions. Data from the Noordwijk and Terheijde transects have been taken from a Dutch bi-weekly monitoring programme. On the basis of horizontal gradients and calculations of auto- and cross-correlations, the stations at 50 and 70 km offshore were considered representative of the open sea (Station C), whereas the station 2 km offshore (Station D) appeared

to be representative of the coastal zone (Laane *et al.*, 1994).

The analytical methods applied to measure the concentration of dissolved phosphate and salinity changed from test tubes to auto-analysers over the years, as described by Slinn (1974) for the Port Erin samples and by Atkins (1930) and later by Butler *et al.* (1979) for E1 in the English Channel. Dissolved phosphate was measured in samples from the Dutch coastal zone according to Strickland and Parsons (1960), with a present detection limit of $0.032 \mu\text{M}$ (s.d. = 1×10^{-3} ; Peeters *et al.*, 1991). Weichart (1991) and Dickson and Kirkwood (1992) concluded, after comparing different historical data for dissolved phosphate from the southern North Sea collected with different analytical methods, that historical dissolved phosphate data can be considered reliable since 1923. Here, we assume that analytical and methodological variations in salinity and DIP are small compared to the generally high *in situ* variability.

The different time series were made equidistant by calculating the monthly averaged value for different years (Delhomme, 1978; Van Leussen and Radach, 1994). From these values contour maps were made by gridding the data using kriging; the relation between data from December in one year and January in the following year has not been accounted for. Residuals were calculated by subtracting the quarterly mean values for all years from the quarterly mean for each year: trend corrections have not been made. Inter-annual variation was calculated as the moving average over 60 mo. Only surface samples of salinity and DIP were used. All data were obtained from the research database of the NOWESP project at the Institut für Meereskunde in Hamburg.

Results

As might be expected, highest salinities (rarely <35 psu) appear in the series of Station B in the English Channel (Fig. 2B) and lowest salinities at Station D in the Dutch coastal zone (not shown). Salinities over 35.3 occurred at Station B during the winter months of 1954–1968 and again between 1973 and 1975 during the latter period persisting over much of the year. The period of relatively low salinities at Station B in 1977 is possibly related to the river Loire outflow being advected together with Biscay water during the autumn influx. The influence of freshwater run-off was apparent at Station A. Average salinities were about 34.1–34.2, although there were noteworthy periods when values were either lower (e.g. at the end of the 1950s and beginning of the 1980s) or above average (1964 and early 1979). Compared to the other two stations, the range in monthly mean salinities was

relatively high at Station C (Fig. 2C) and even higher at Station D (not shown).

Residuals in salinity (without annual trend corrections) showed irregular patterns (Fig. 3). Excluding extreme values, residuals were only ± 0.3 – 0.4 at Stations A and B, but considerably higher at Stations C (± 0.6) and D (± 2 ; Fig. 3). Relatively long periods of up to 5 yr with salinities above or below the mean value were observed at all stations. Figure 4 shows moving averages (60 mo) of salinity at all four stations. An irregular pattern was observed at Station A in the Irish Sea but not at the other stations. Some fluctuations were common to all stations, e.g. a period of relatively low salinities occurred at the beginning of the 1980s at Stations A and B and also (of shorter duration) at Stations C and D. Salinities increased at the latter two stations (but not at A) during the 1990s. Nevertheless, cross-correlations between the long-term variation of salinity at Stations A, B, and C were clearly not significant, all coefficients being <0.24 .

At all stations there was a clear seasonal pattern in DIP concentrations, with highest values in winter and lowest in summer (Fig. 5A–C). The lowest concentrations were found at Station B throughout all years. Winter values never exceeded $0.7 \mu\text{M}$ and dropped below $0.5 \mu\text{M}$ during the 1960s (Fig. 5B). DIP concentrations at Station B started to fall below $0.3 \mu\text{M}$ during March and April during the period 1954–1985 and one month later at Station A (Fig. 5A). The duration of the summer minima remained almost the same at Station B during 1954–1985, but the end of this period moved gradually forward from October to August at Station A (Fig. 5A).

A clear trend in increasing winter concentrations of DIP was found at Station A in the Irish Sea, starting in the early 1970s and continuing into the 1990s (see also Fig. 6). At this station the highest summer values (generally $>0.1 \mu\text{M}$) were observed. They were even higher in 1974–1976 and particularly so in 1992–1993.

At Station C, the lowest annual DIP concentrations were found just after 1975. From this time onwards concentrations increased both during summer and winter. They reached a maximum value in the middle of the 1980s, but declined thereafter by more than 50% during the winter months of 1985–1993. During the period of increasing DIP at this station (1975–1983), the onset of the annual period of relatively low concentrations remained the same in spring, but the end of the period shifted from October (in 1975) to July–August in 1985, as observed also at Station A.

Residuals and trends (expressed as 60 mo moving averages) are presented in Figures 6 and 7, respectively. Residuals were smallest (generally about $\pm 0.1 \mu\text{M}$) at Station B, while the sign in the residuals changed from negative to positive values during the early 1970s at Station A (Fig. 6A). This marked increase in DIP at

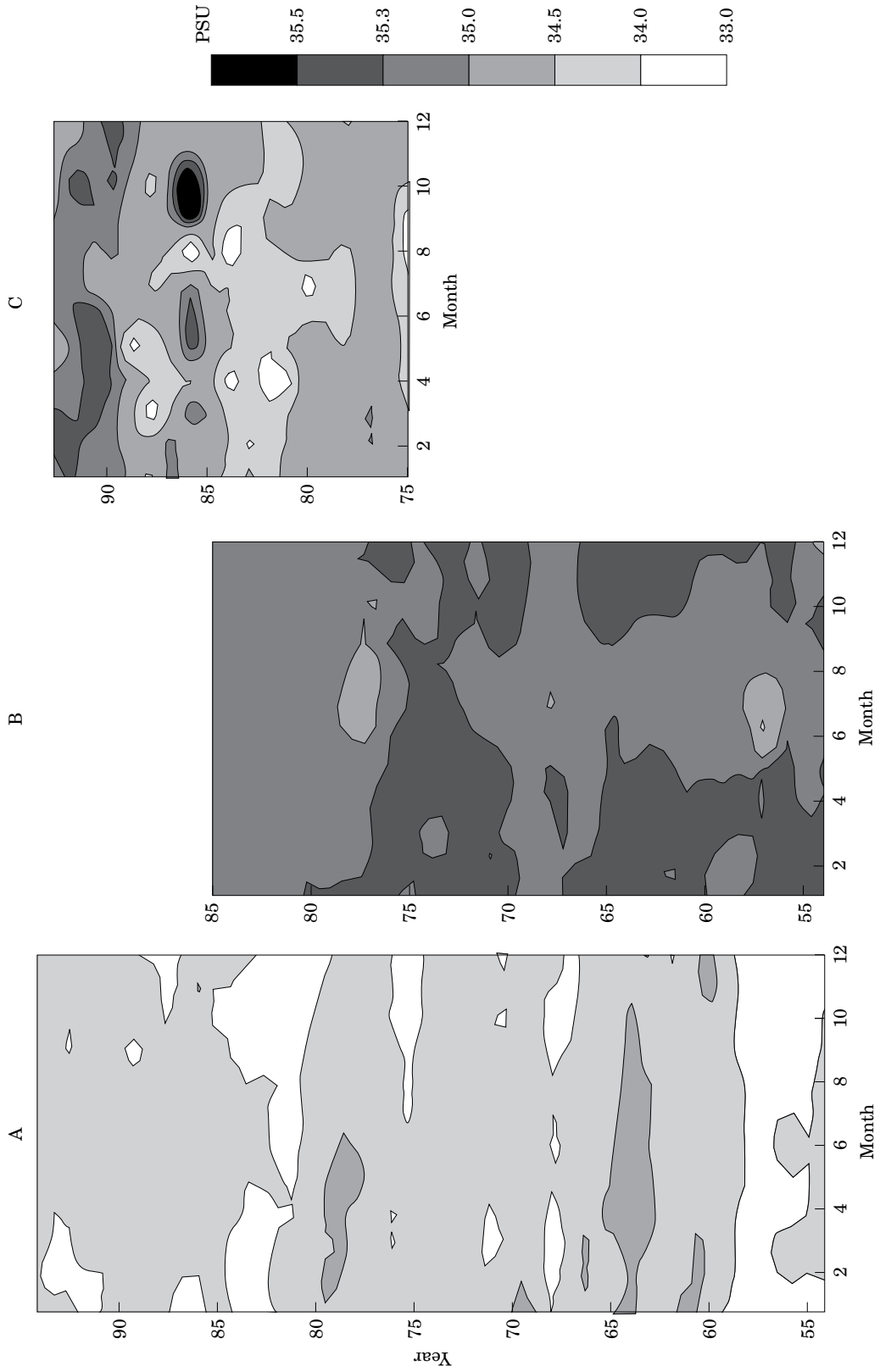


Figure 2. Annual cycles of salinity presented as monthly means at Station A (1954–1994), Station B (1954–1985), and Station C (1975–1993).

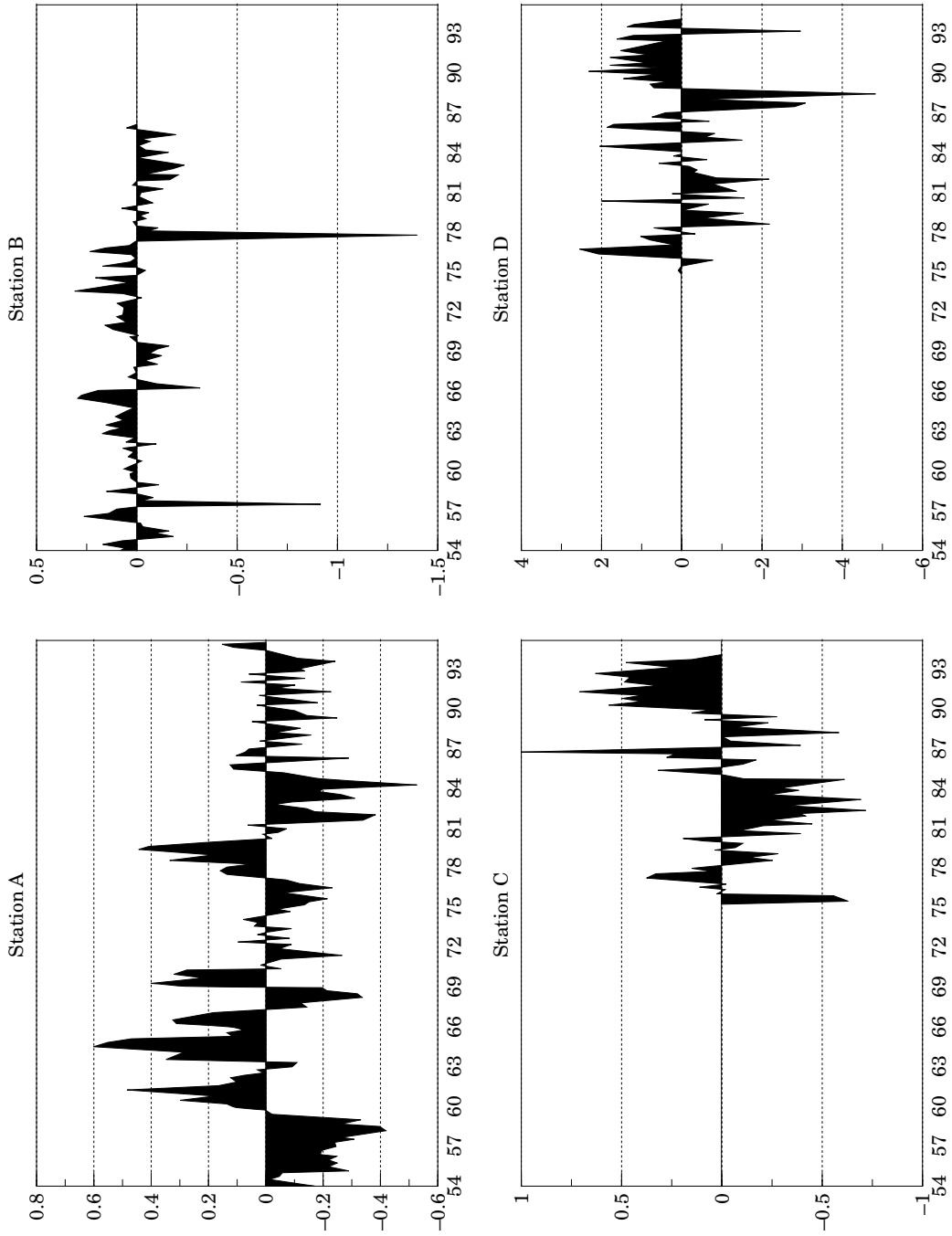


Figure 3. Residuals in salinity (PSU), calculated by subtracting the quarterly mean value for all years from the quarterly value for each year, at Stations A, B, C, and D.

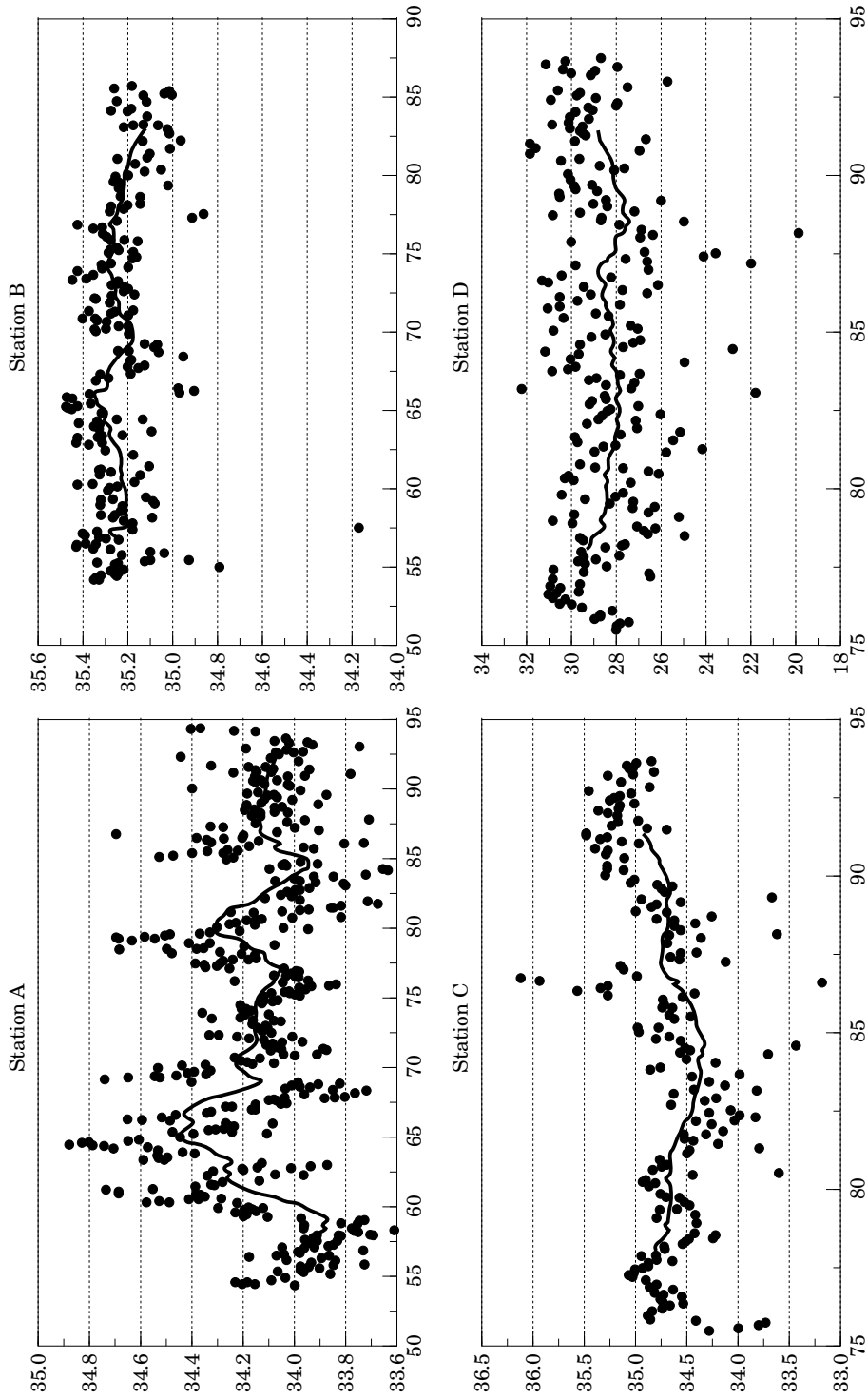


Figure 4. Trends in salinity (PSU) as moving average over 60 mo at Stations A, B, C, and D.

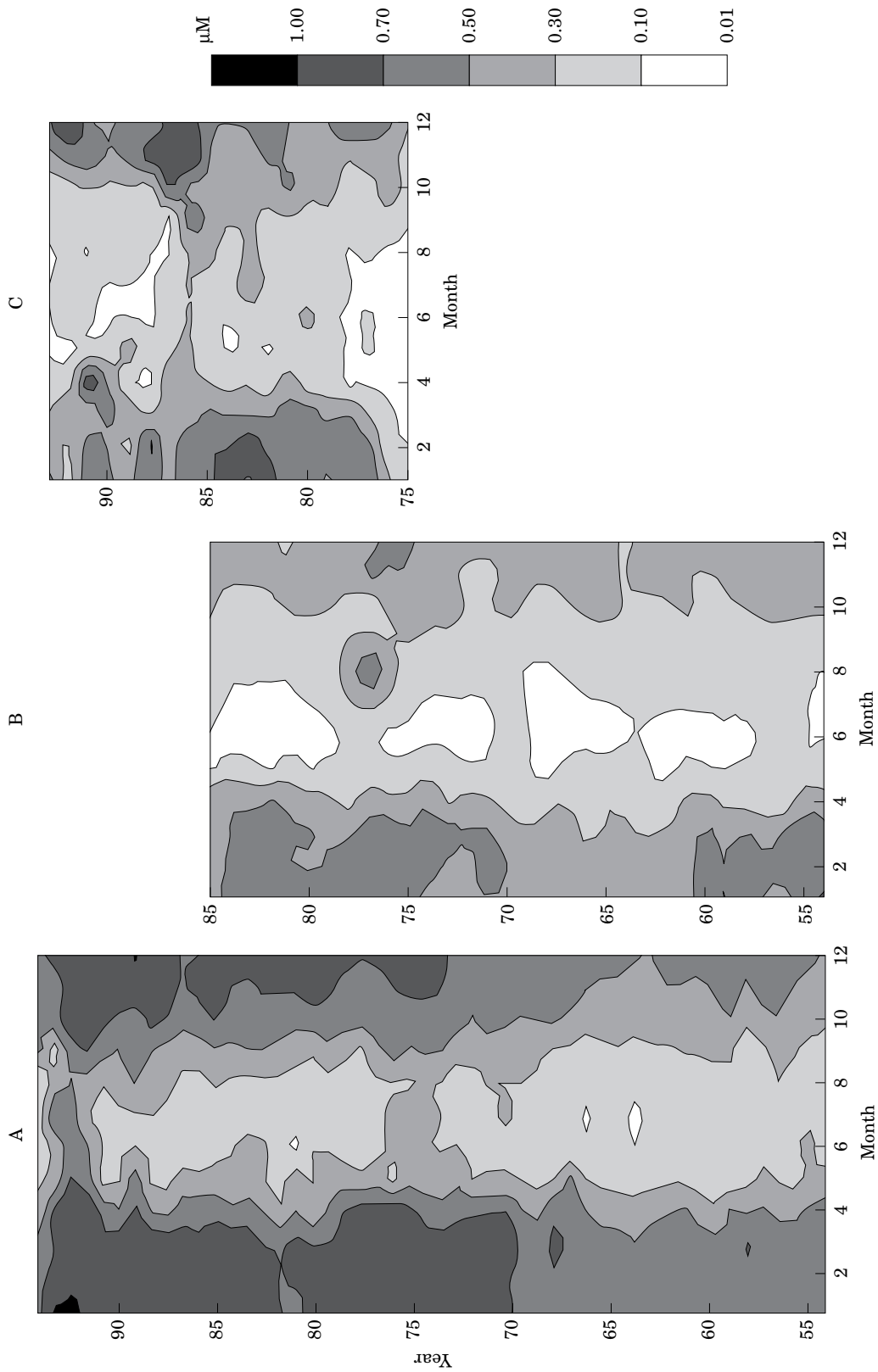


Figure 5. Annual cycles of dissolved inorganic phosphate (μM) presented as monthly means at Stations A, B, and C.

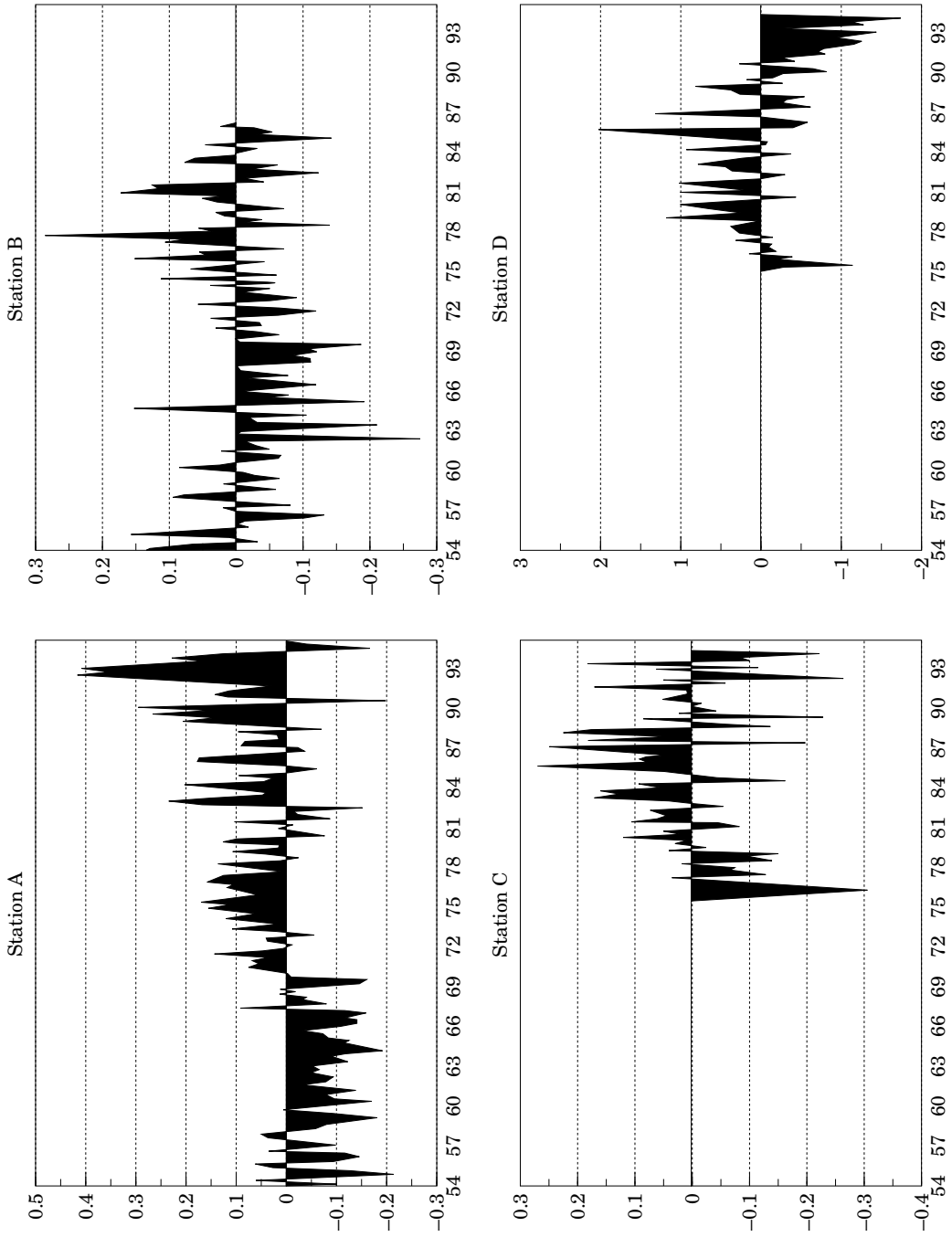


Figure 6. Residuals in dissolved inorganic phosphate (μM), calculated by subtracting the quarterly mean value for all years from the quarterly value for each year, at Stations A, B, C, and D.

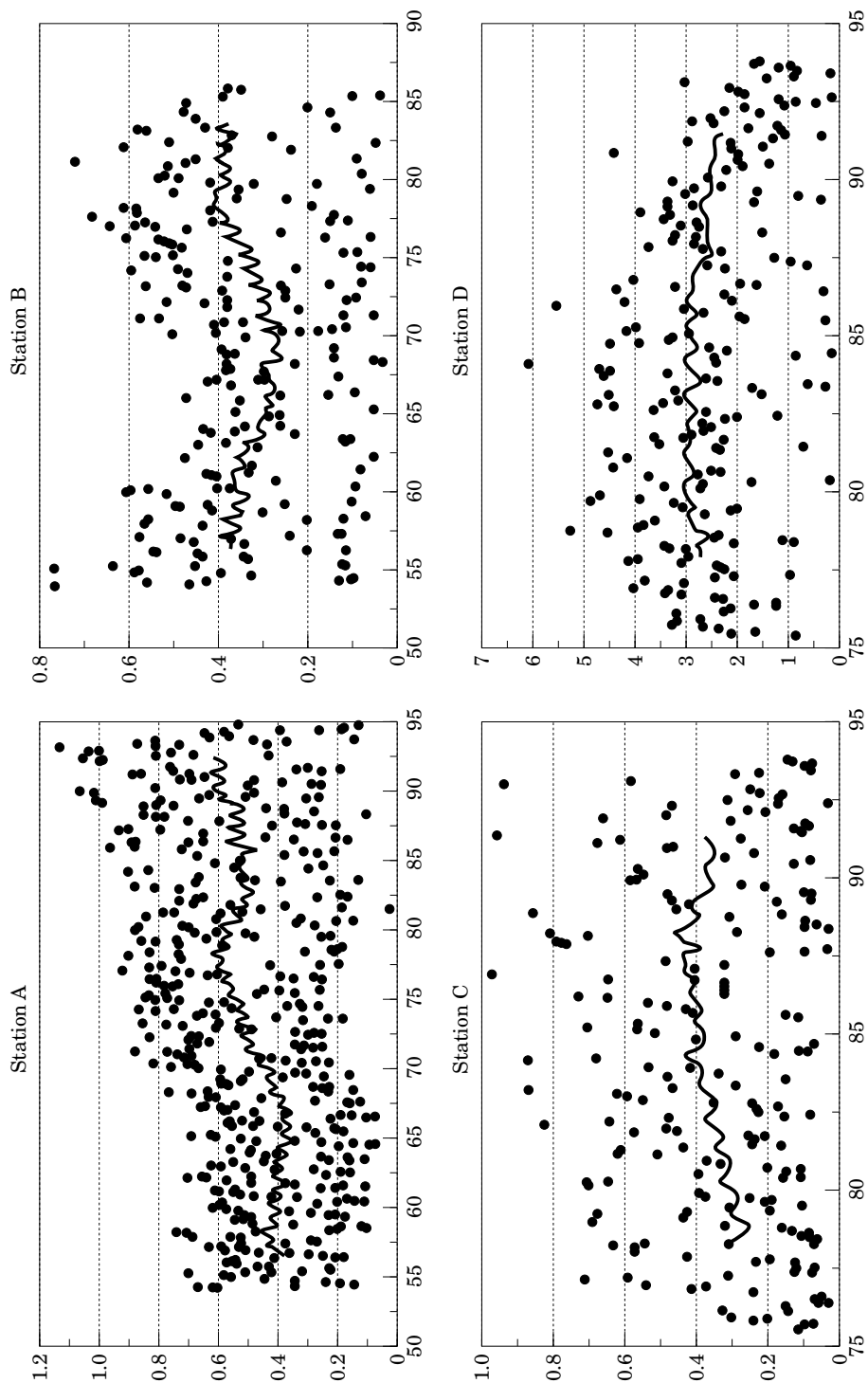


Figure 7. Trends in dissolved inorganic phosphate (μM) as moving average over 60 mo at Stations A, B, C, and D.

Station A and to a lesser extent at Station B is also apparent in Figure 7A, B. Comparison of these trends with the stations off the Dutch coast is difficult because of the shorter study period. However, the relatively high concentrations observed at both stations during the 1980s were followed by a decrease during subsequent years (Fig. 6C, D). Cross-correlations of DIP concentrations at Stations A, B, and C were not significant, all correlation coefficients being <0.23 .

Discussion

The time-series data reveal clear changes in salinity and DIP in the English Channel, Irish Sea, and southern North Sea. The highest salinities and lowest DIP were found at Station B (E1) in the English Channel, which may be considered to reflect the least modified signal of Atlantic Water. Freshwater run-off is probably responsible for decreased salinities in the Irish Sea and Dutch coastal zone.

As in many rivers, the concentration of DIP during the winter months ($0.40\text{--}0.5\ \mu\text{M}$) in the Irish Sea and Dutch coastal zone (Laane, 1992) has increased markedly as a consequence of human activities above natural background levels in the later 1960s and early 1970s. Furthermore, increased anthropogenic input of nutrients appears to have shortened the period of relatively low DIP concentrations during the summer months at Stations A, C, and D. Similar patterns of change were found at Helgoland in the German Bight (Becker and Kohnke, 1978; Radach *et al.*, 1990; Hickel *et al.*, 1993, 1994) and in the Baltic (Wulff and Rahm, 1988; Nehring, 1989). The relatively high DIP concentrations at Station A in the Irish Sea over the entire year are remarkable. However, chlorophyll concentrations in this area tend to be relatively low (Bot, pers. comm.). This may be brought about by exhaustion of nitrate, which appears to be the limiting nutrient during summer (Slinn, 1974). Laane *et al.* (1994) found a strong relationship between changes in DIP concentrations in the river Rhine and at Station D off the Dutch coast. This is in agreement with the results of Schaub and Gieskes (1991), who observed a positive correlation between discharge of the river Rhine and nutrient concentrations as well as phytoplankton biomass in the Dutch coastal zone.

At all stations, a variable signal around the average concentration of salinity and DIP was observed (Figs 3, 4, 6, and 7). The causes of this variability may partly be found in natural (physical, chemical, and biological) processes, but human activities, e.g. input of nutrients, industrial wastes etc., may play an important role, especially in recent years (Dickson *et al.*, 1992).

At first sight, it seems remarkable that no relationship appears to exist (even allowing for time-lag) between variations in salinity and DIP in the English Channel, Irish Sea, and Dutch coastal zone. However, the transit

time of surface water between Station B in the English Channel and Station C in the Dutch coastal zone is about 1–1.5 yr (Prandle *et al.*, 1994; P. Damm, pers. comm.). This timespan would appear sufficiently long for the original properties of the Atlantic Water to be drastically changed by local factors as the water mass progresses through the English Channel. Considerably shorter transit times (e.g. a few weeks) might be required to permit tracing of water properties between stations along the transfer route. This has been found possible for variations in freshwater discharge, and associated DIP, of Rhine water, which were detectable subsequently in the Dutch coastal zone, more clearly so at 2 km than at 50–70 km offshore. Elsewhere, Loeng *et al.* (1992) found that variations in salinity at stations close together in the Norwegian Sea and Barents Sea were linked to each other and closely related to meteorological conditions.

Local conditions are often complex, affecting both vertical and horizontal distribution of particular properties. For example, Postma (1978) and Brockmann *et al.* (1990) showed that strong vertical gradients in DIP concentrations are often present in the English Channel during the summer months. Similar vertical gradients in salinity and DIP are present in the Irish Sea to the west and southwest of the Isle of Man (Slinn, 1974). Vertical gradients in DIP and salinity are also present in the Dutch coastal zone. Giessen *et al.* (1990) described the vertical density field brought about by partial mixing of river and coastal waters in this area. Another source of variability is the direction from which ocean water is advected into the English Channel. Transects across the entrance to the English Channel (Laane *et al.*, 1993) have shown that DIP in winter is higher on the northern side, and in the northern Celtic Sea compared to the southern side and the Bay of Biscay (Williamson, 1956). The composition of water entering the English Channel will thus vary with wind and weather patterns and this may be one of the factors related to the slight trends observed in Figure 6.

The general circulation of the Irish Sea is particularly complex with freshwater run-off diluting the sea water and contributing nutrients of anthropogenic origin, while meteorological factors such as wind stress may completely modify the average circulation pattern (Dickson, 1987). A factor that will influence DIP is the proportion taken up by the spring production that is not fully mineralized by the end of the winter at the same location. Evidence from the English Channel Station B suggests that there is a balance between DIP and DOP, the dissolved organic component being higher when the inorganic component is lower (Butler *et al.*, 1979). There is also a possibility of variation in the amount of phosphorus carried forward in organic form as wintering organisms, and that this may vary on a decadal scale in relation to changes in abundance

of pelagic fish stocks (Southward, 1963; Southward and Boalch, 1986).

The general conclusion appears to be that, because transit times are long (a year or more), the signal of Atlantic Water is modified by coastal effects as it passes through the English Channel and Irish Sea to such an extent that no clear relationship in terms of salinity and DIP could be found between the stations in these areas investigated.

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