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The Wind Influence on the Jutland Coastal Current Interpreted on the Basis of som Observations

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The Jutland Coastal Current (JCC) is a freshwater-influenced coastal current localised in the south-eastern part of the North Sea. Its main sources are the Elbe, the Weser, and the Ems, which run into the German Bight, as well as smaller rivers along the Danish west coast. Tides, buoyancy and wind mainly determine the flow field in the Jutland Coastal Current. The Ekman transport in the North Sea far away from land feeds the coastal current along the Jutland coastline within approximately one Rossby radius of the coastline. In this study the influence of the wind on the Jutland Coastal Current (JCC) is investigated on the basis of measurements of wind, salinity, nitrate and current. The wind determines the spatial extent of the current and only during south-southwesterly winds does the JCC flow into the Skagerrak. The major river discharge into the German Bight in 1995 was followed by a decrease in the salinity outside Hirtshals after only 21-45 days in connection with changing southerly and westerly winds. On the 50-hour time-scale the wind determines the gross and residual transport in the JCC as expected from the Ekman transport, together with minor contributions from the buoyancy and tide. The spatial nitrate distributions clearly indicate an inter-annual variation in the nitrate concentrations and thus influence the transport of nitrate.

Introduction

The North Sea has a residual cyclonic circulation driven by tides, buoyancy and wind (Lee 1970; Otto *et al.* 1990). The Jutland Coastal Current is a freshwater-influenced coastal current localised in the south-eastern part of the North Sea and con-

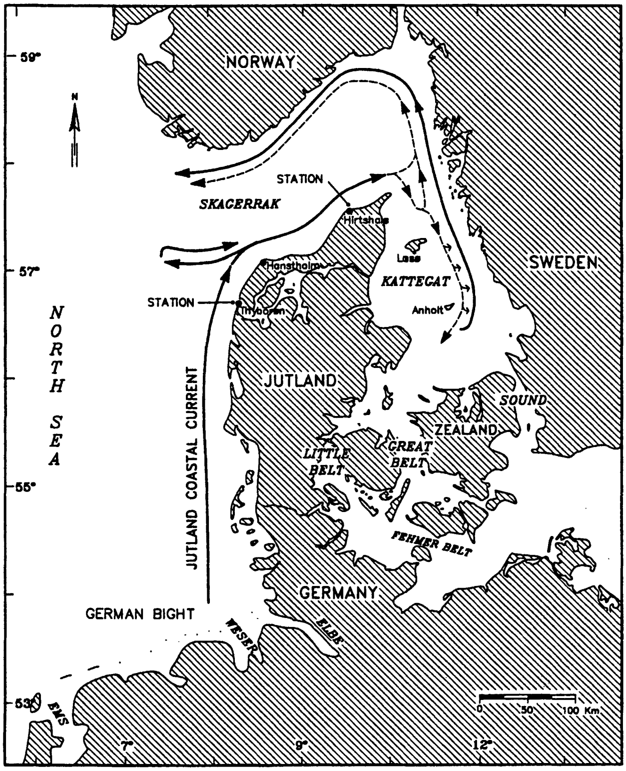


Fig. 1. Map of the considered area with indications of the fixed station measurements outside Hirtshals and Thyborøn and transport routes from the German Bight to either the Kattegat or the Norwegian Coastal Current.

tributes to the cyclonic circulation (Fig. 1). Its main freshwater sources are the Elbe, the Weser and the Ems, which run into the German Bight, as well as smaller rivers along the Danish west coast (approximately 15%). The Seine and the Rhine are, by definition, not contributors to the JCC. The river outflow near the German Bight area averages 1,352 m^3/s (Richardson and Jacobsen 1990). The annual-decadal variation in the river outflow into the German Bight has a definite effect on the annual-decadal variation in the surface salinity of the JCC: the lower the river outflow the higher the salinity and *vice versa* (Bolding 1990), and influences the amount of nitrogen flowing into the German Bight (Gerlach 1990). The JCC is a carrier of nutrients and pollutants from rivers in the south-eastern part of the North Sea to the Kattegat (*e.g.*, Heilmann *et al.* 1991; Dahlgaard *et al.* 1995; Højerslev *et al.* 1996; Skogen *et al.* 1997). Several numerical investigations of the current dynamics in the North Sea or parts of it are already in existence (see Hainbucher *et al.* 1987; Svendsen *et al.* 1996).

The semi-diurnal and diurnal tides dominate the tidal flow. The tidal flow often determines the instantaneous flow along the west coast of Jutland, but the residual velocity, due to non-linear influences, is only 1-2 cm/s (Backhaus and Maier-Reimer 1983; and Kristensen 1991). The density-driven velocity is also found to be 1-2 cm/s (Backhaus and Maier-Reimer 1983; and Kristensen 1991). The wind-driven flow field in the JCC is also significant (Jensen and Jónsson 1987; Kristensen 1991), especially on longer time-scales. The salt field is determined by the wind, tidal and density driven flow field, *i.e.* not only by the density-driven flow.

On the basis of the investigations carried out by Pedersen *et al.* (1988) and Kristensen (1991) the spatial extent of the JCC can be outlined as in the following (see also Jakobsen 1997). From salinity and temperature measurements made in the JCC area the water column is often nearly vertically mixed (Jensen and Jónsson 1987). During periods with winds coming from the WNW and the ESE the JCC water masses south of Hanstholm are almost stagnant (in agreement with the transport equation outlined later). Stagnant JCC water is also observed by Danielssen *et al.* (1997) for WNW winds. North of Hanstholm a current flows from the central and northern North Sea into the Skagerrak during periods with winds coming from the WNW and *vice versa* during periods with winds coming from the ESE (in agreement with Furnes 1980). At the onset of the wind, the JCC water masses north of Hanstholm either follow the current into the Skagerrak or separate and flow into the central North Sea. An indication of separated flow is also seen in Hainbucher *et al.* (1987). During periods with winds coming from the SSW and the NNE the JCC water masses south of Hanstholm are not stagnant. The JCC water flows towards the north and east into the Skagerrak during periods with winds coming from the SSW, *i.e.* the JCC is stretched. However, the water masses flow from the Skagerrak towards the German Bight during periods with winds coming from the NNE, *i.e.* the JCC is contracted (held back and widened). Recent studies by Danielssen *et al.* (1997) and Skogen *et al.* (1997) support the above description as the JCC is also found to be wind-driven and flows into the Skagerrak only during southerly winds.

Low saline water along the Jutland coast in the Skagerrak may be JCC water, but it may also be Norwegian Coastal Current water transported across the Skagerrak as a result of a widening of the current, *e.g.* during calm wind conditions (Rydberg *et al.* 1996) or by westerly to northerly wind conditions (Danielssen *et al.* 1997).

The Ekman transport in the central North Sea determines the transport along the west coast of Jutland (Kristensen 1991). The Ekman transport m_e (m^2/s) is related to the wind as follows

$$m_e = \frac{\rho_a C W^2}{\rho f} \tag{1}$$

where ρ (kg/m^3) is the reference water density, ρ_a (kg/m^3) is the air density, C (~1.5×10^{-3}) is the surface drag coefficient, W (m/s) is the wind speed, and f (~1.2×10^{-4} s^{-1}) is the Coriolis parameter. In the case of a wind perpendicular to the

Jutland coastline, it is expected that the Ekman transport will cease within one Rossby radius of the coastline (Csanady 1982), especially as the coastline is not infinite but turns abruptly into the German Bight. In the case of a wind parallel to the Jutland coastline, it is expected that the Ekman transport in the North Sea far away from land feeds a coastal current along the Jutland coastline within approximately one Rossby radius of the coastline. Thus, it should be possible to calculate the wind-induced transport along the west coast of Jutland on the basis of the following expression

$$Q = m_e \sin(\theta - \theta_0)\, x \qquad (2)$$

where Q (m^3/s) is the transport in the coastal current, θ is the wind direction, θ_0 (~90°) is a constant and x (m) is the distance from the German Bight and northward. Kristensen (1991) investigated Eq. (2) on the basis of results from a barotropic hydrodynamic model covering the North Sea (Vested *et al.* 1992) and found it to be valid with θ_0=117°. The transport relationship has not been tested on the basis of measurements.

In Jensen and Jónsson (1987) relations between coastal current and wind were also investigated, but the physical explanation was different. They considered an along shore momentum equation, but their considerations do not conflict with the considerations taken in this study. The present data treatment enables us to test the transport equation and to quantify the net and gross values of wind, tide and buoyancy contribution.

The paper is outlined as follows. First data and methods are revealed. Then, the anticipated dynamics of the JCC described above are investigated on the basis of the measurements. Finally, the results are discussed and the conclusions are drawn.

Field Measurements and Methods

Fixed station time-series measurements of wind are available from Thyborøn for the period 01.01.93-31.12.96. The position of the station is 56°42' N and 08°13' E. The wind is measured 31 m above ground and ground is 2 m above sea level. The factor which should be multiplied with the wind measured 31 m over land to obtain the wind 10 m over sea is estimated to be 1.08, but is not used in the following due to the uncertainty in the estimation and the relatively little importance. Time-series of river run off from the River Ems, the River Elbe and the River Weser are available for the period 09.94-10.95.

Spatial distributions of salinity, temperature and nutrients, *etc.* are available from four February surveys carried out in the years 1993-1996 covering the JCC and the south-western Baltic Sea area. A Niel Brown, Mark 3, measured the vertical salinity and temperature profiles. Nutrients are determined on the basis of water samples using standard procedures.

Fixed station time-series measurements of current, salinity and temperature are available from a position outside Thyborøn during the periods 11.04.95-16.06.95, 12.08.95-26.08.95 and 29.11.95-07.03.96. The position of the station is 56°40'57" N and 08°08'03" E. The local water depth is 20 m and the recorder is positioned 10 m below the surface. Current, salinity and temperature were recorded using an electromagnetic current meter type S4 produced by Inter Ocean, U.S.A. Also outside Hirtshals fixed station time-series measurements of current, salinity and temperature are available from North Jutland County for the period 11.03.93-23.05.95. The position of the station is 57°36'50" N and 09°55'00" E. The local water depth is 15 m and the two recorders are positioned 3 m below the surface and 1 m above the bottom, respectively. Current speed and direction, salinity and temperature were recorded using the upper electromagnetic current meter type S4 produced by Inter Ocean, U.S.A, while the lower current meter recorded only salinity and temperature.

Results

Comparison of Wind and Spatial Distribution

Four basic water masses were identified during the four February surveys: southwestern Baltic surface water (~8 PSU, ~5 μmol/l); JCC water (~25 PSU, ~90 μmol/l); central North Sea water (~34.5 PSU, ~5-10 μmol/l); and Atlantic water (~35.2 PSU, ~10 μmol/l). Spatial distributions of salinity and nitrate are shown in Figs. 2-5.

On the basis of the wind directions and speeds just prior to and during the 1993 survey (Fig. 2) and in connection with the 1995 survey (Fig. 4) and the earlier outlined dynamics of the JCC, we expect a mixture of the situation with cyclonic circulation in the Skagerrak and either a stretched JCC or a stagnant JCC south of Thyborøn. The wind directions just prior to the 93 survey varied from 210 to 300 degrees with wind speeds of 4-12 m/s, while during the survey the wind was very calm. The wind directions during the 95 survey varied from 210 to 300 degrees with wind speeds of 4-16 m/s (the strong winds had a direction of 300 degrees). The spatial distributions for February 1993 (Fig. 2) show a combination of the two distributions. The distributions for February 1995 (Fig. 4) show only central North Sea water flowing into the Skagerrak along the north-western coast of Jutland and thus the JCC must be stagnant south of Thyborøn (the current also seems to be widening).

During the 1994 survey (Fig. 3) we expect, on the basis of the dynamics of the JCC explained earlier, a mixture of the situation with anti-cyclonic circulation in the Skagerrak and either a contracting JCC or a stagnant JCC south of Thyborøn. The wind directions both before and during the 94 survey varied from 30 to 120 degrees with wind speeds of 4-16 m/s. The spatial distributions (Fig. 3) show a wide (contracted) JCC south of Thyborøn, *e.g.* note the 34 isohaline. The distributions also show that the central North Sea water is transported closer into the German Bight,

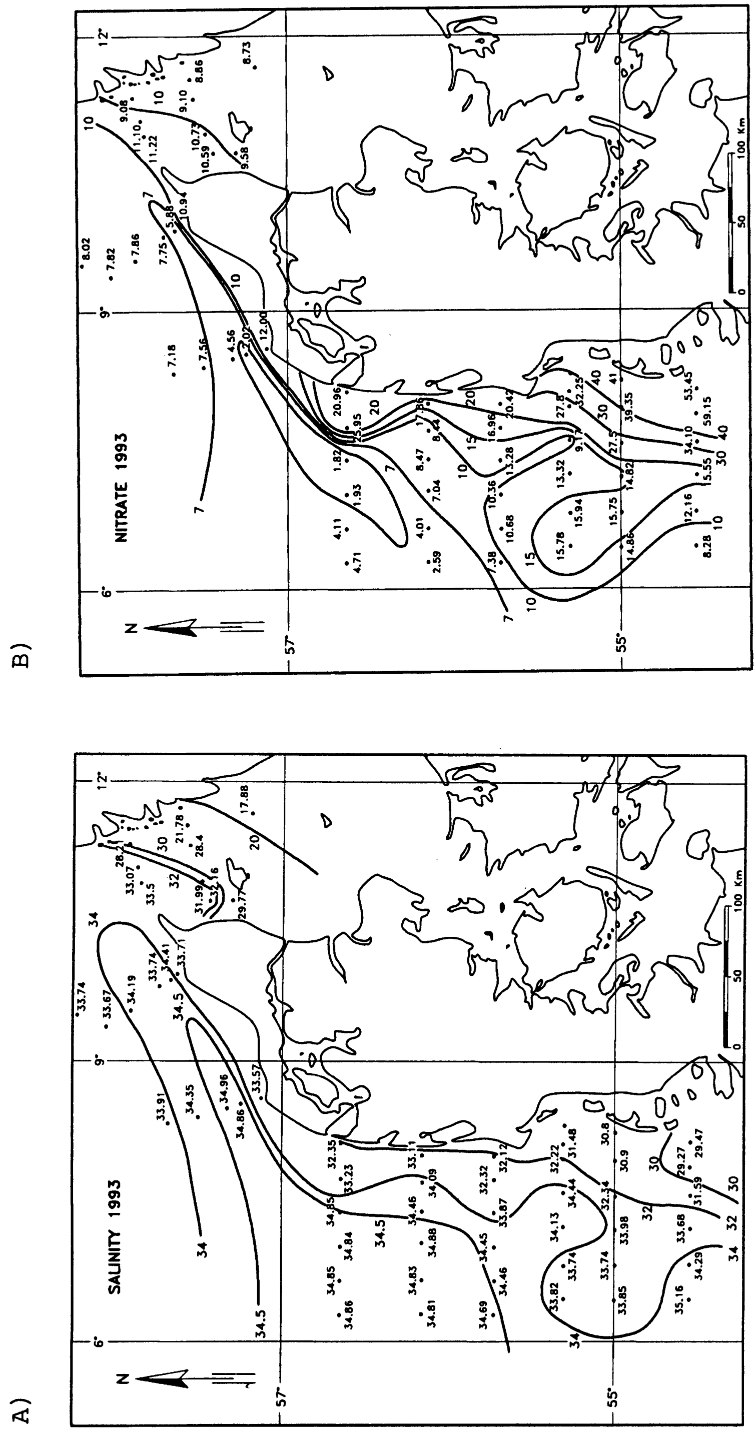
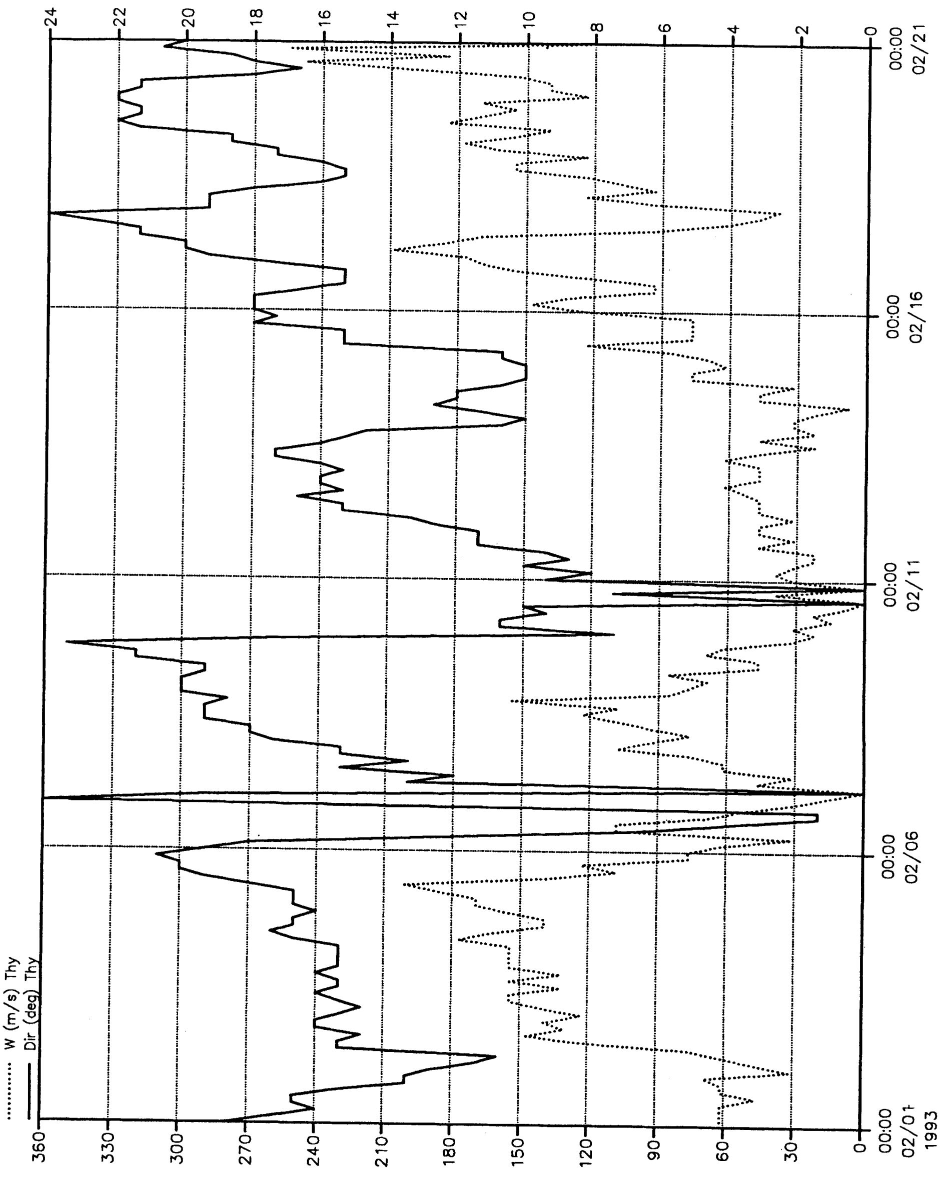


Fig 2. Spatial distributions of A) salinity (PSU); and B) nitrate (mmol/l); 1 m below surface during Feb 9-14, 1993, and C) wind variation in connection with the survey.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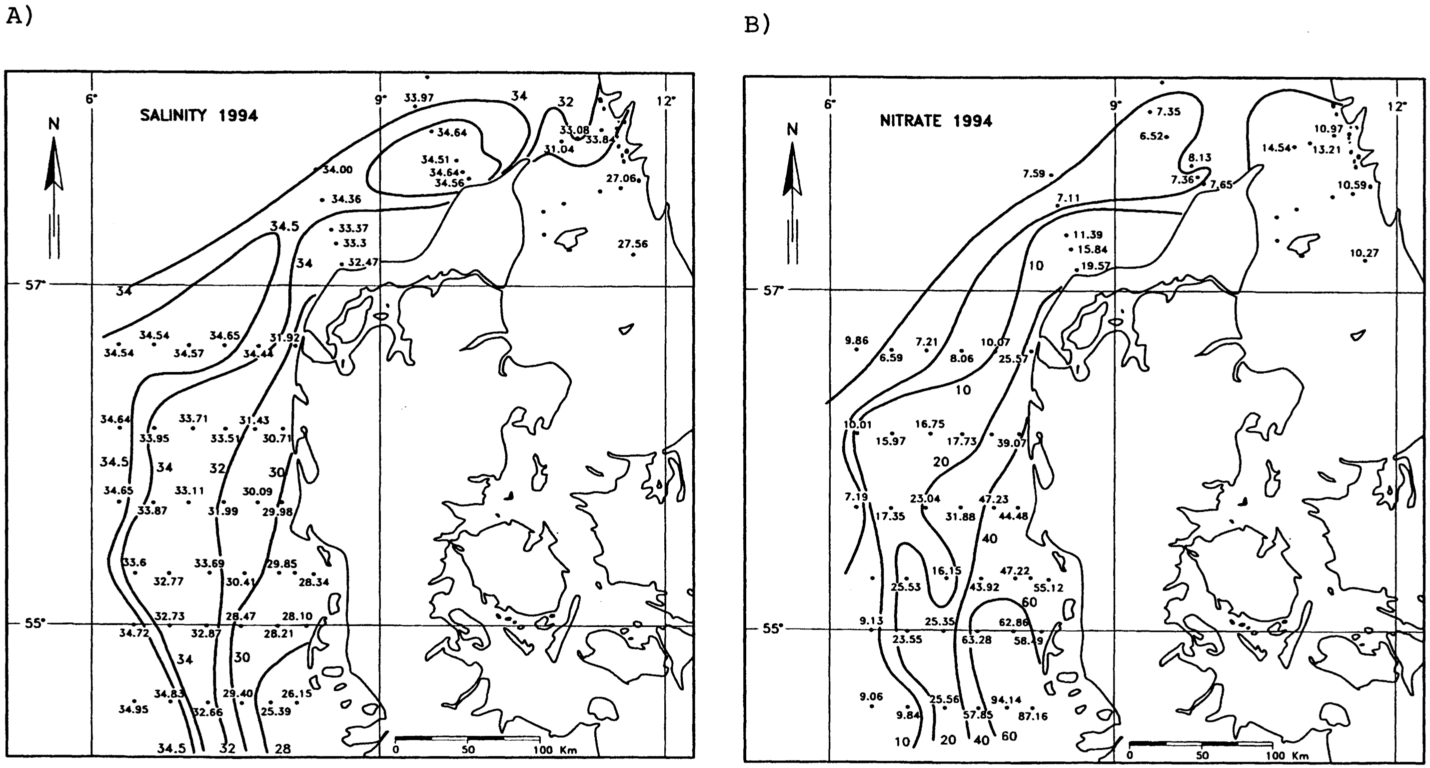
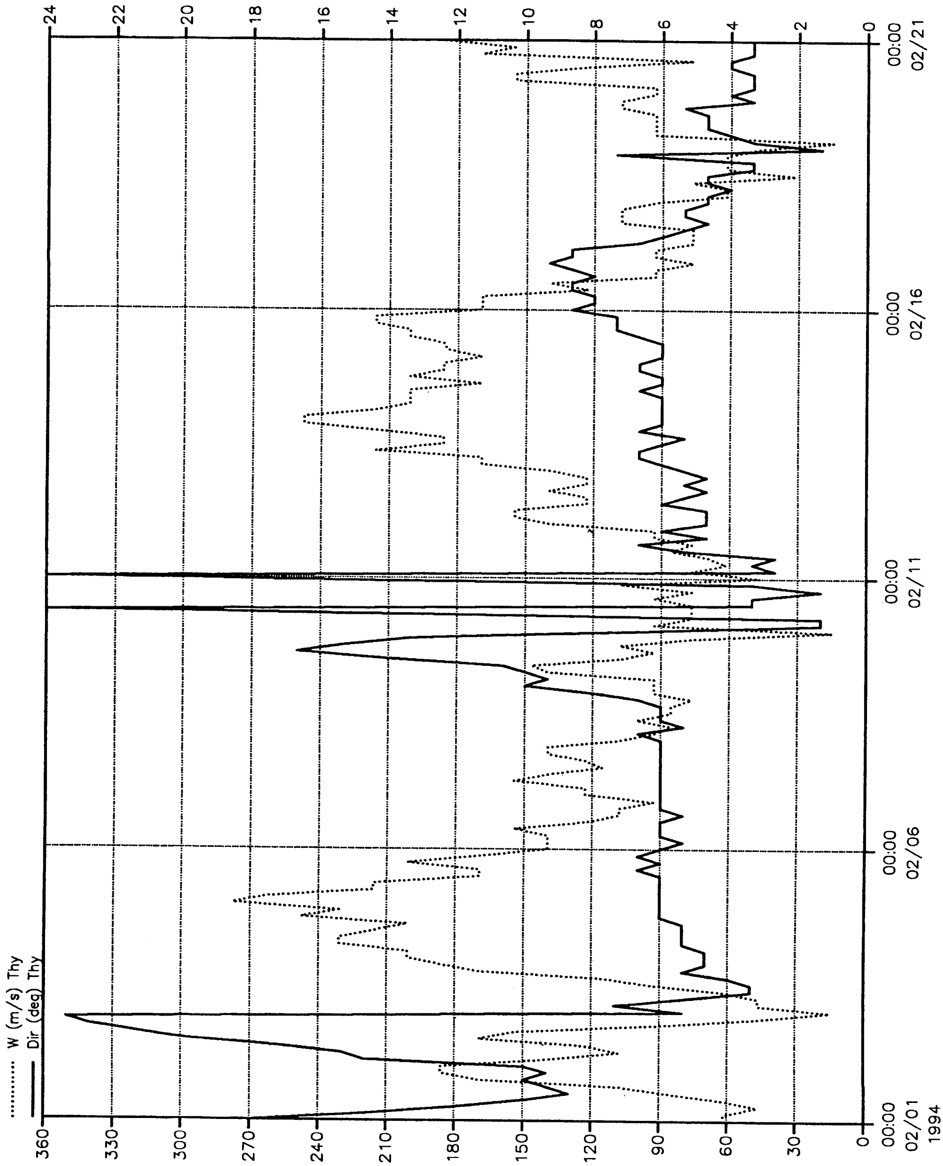


Fig 3. Spatial distributions of A) salinity (PSU); and B) nitrate (mmol/l); 1 m below surface during Feb 8-13, 1994, and C) wind variation in connection with the survey.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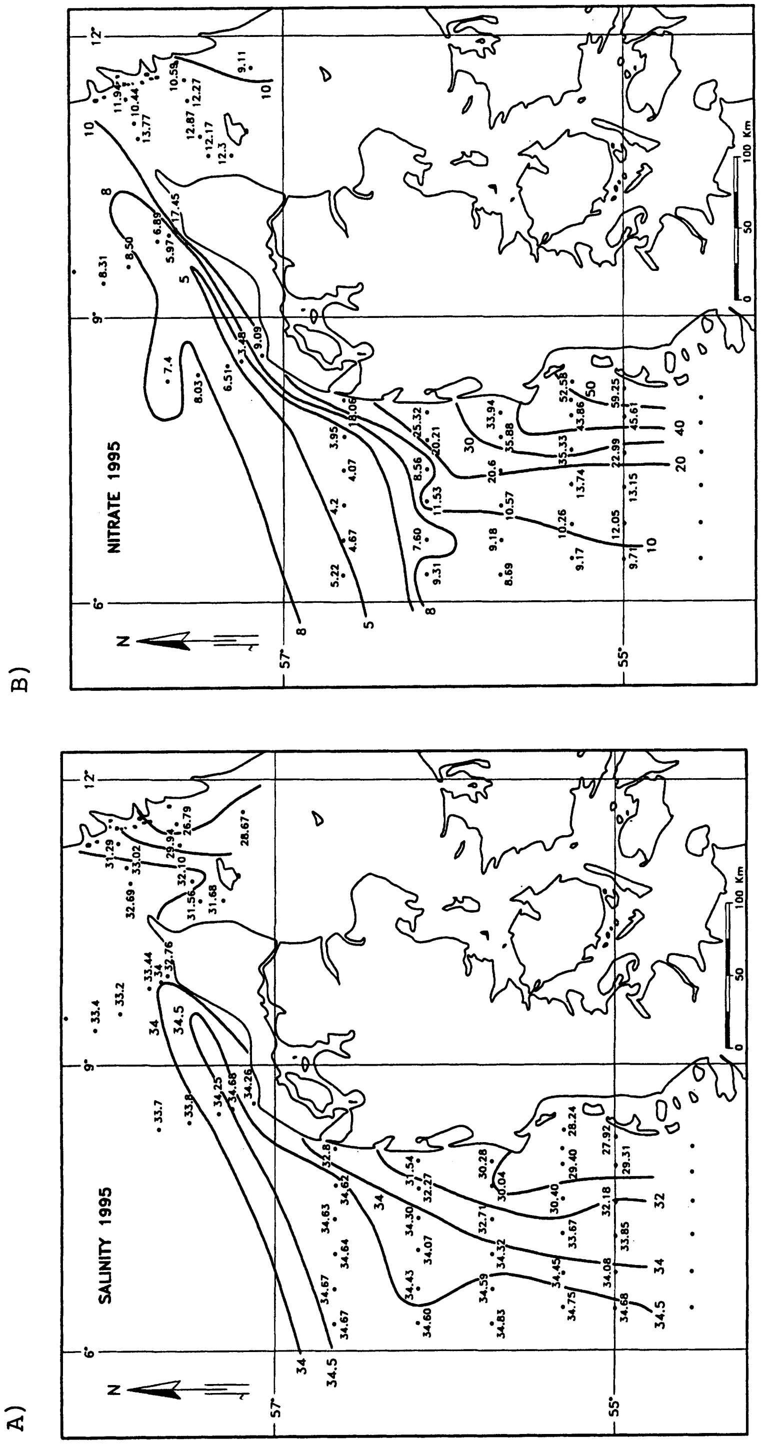
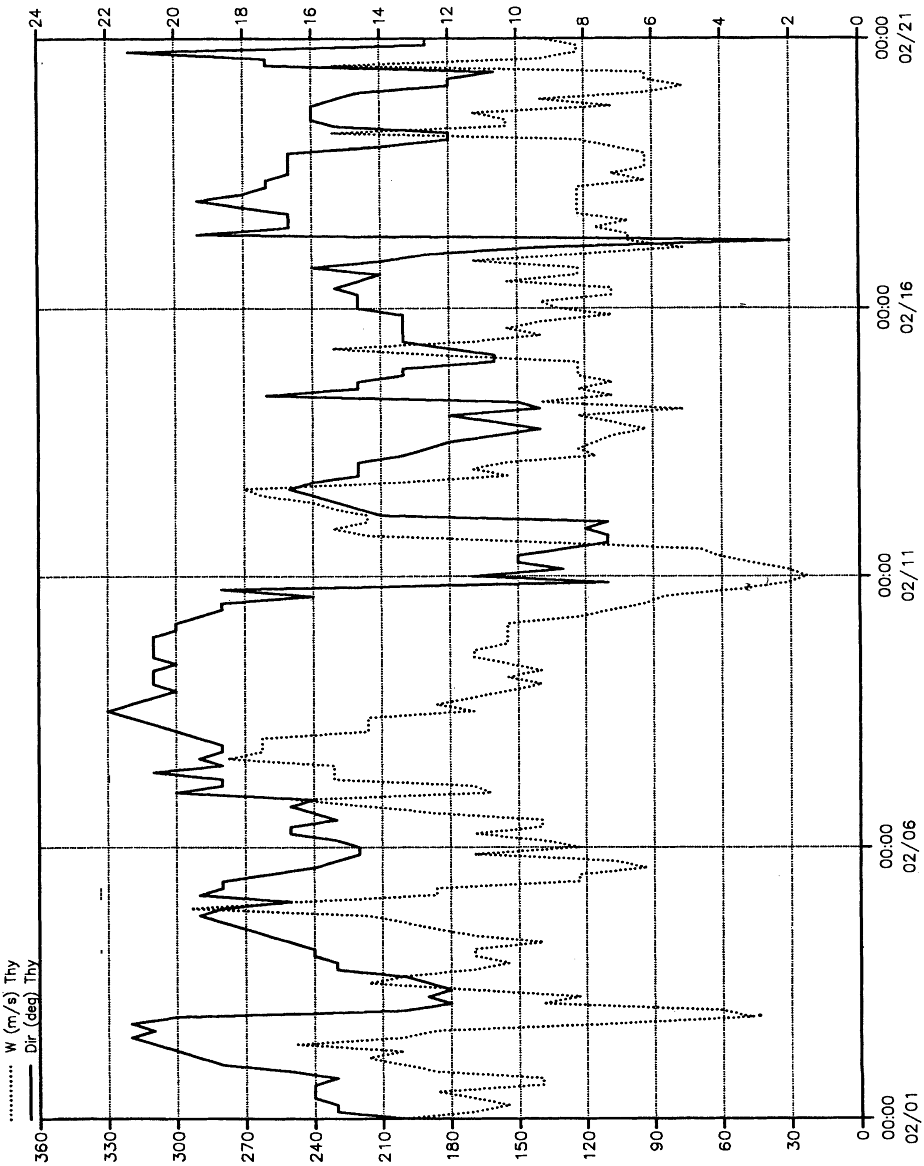


Fig 4. Spatial distributions of A) salinity (PSU); and B) nitrate (mmol/l); 1 m below surface during Feb 9-13, 1995, and C) wind variation in connection with the survey.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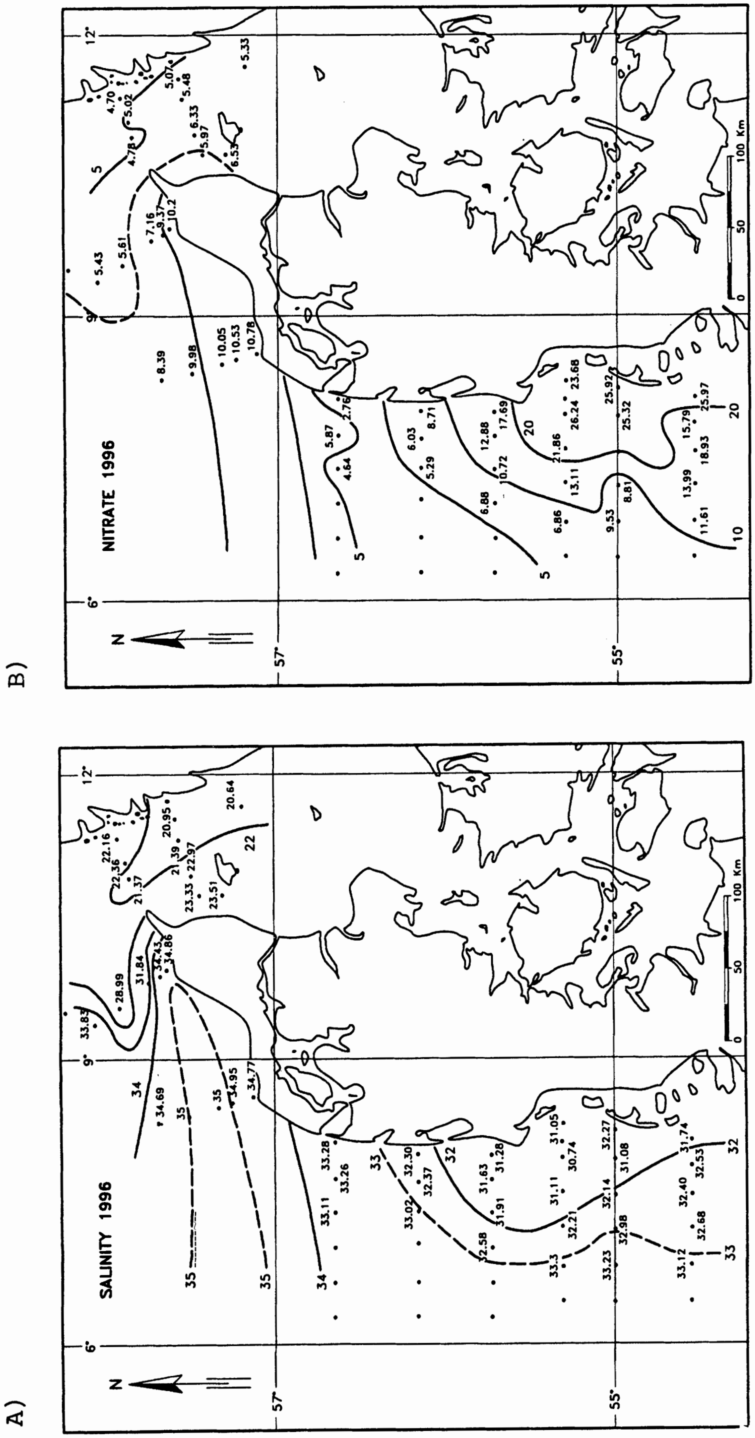
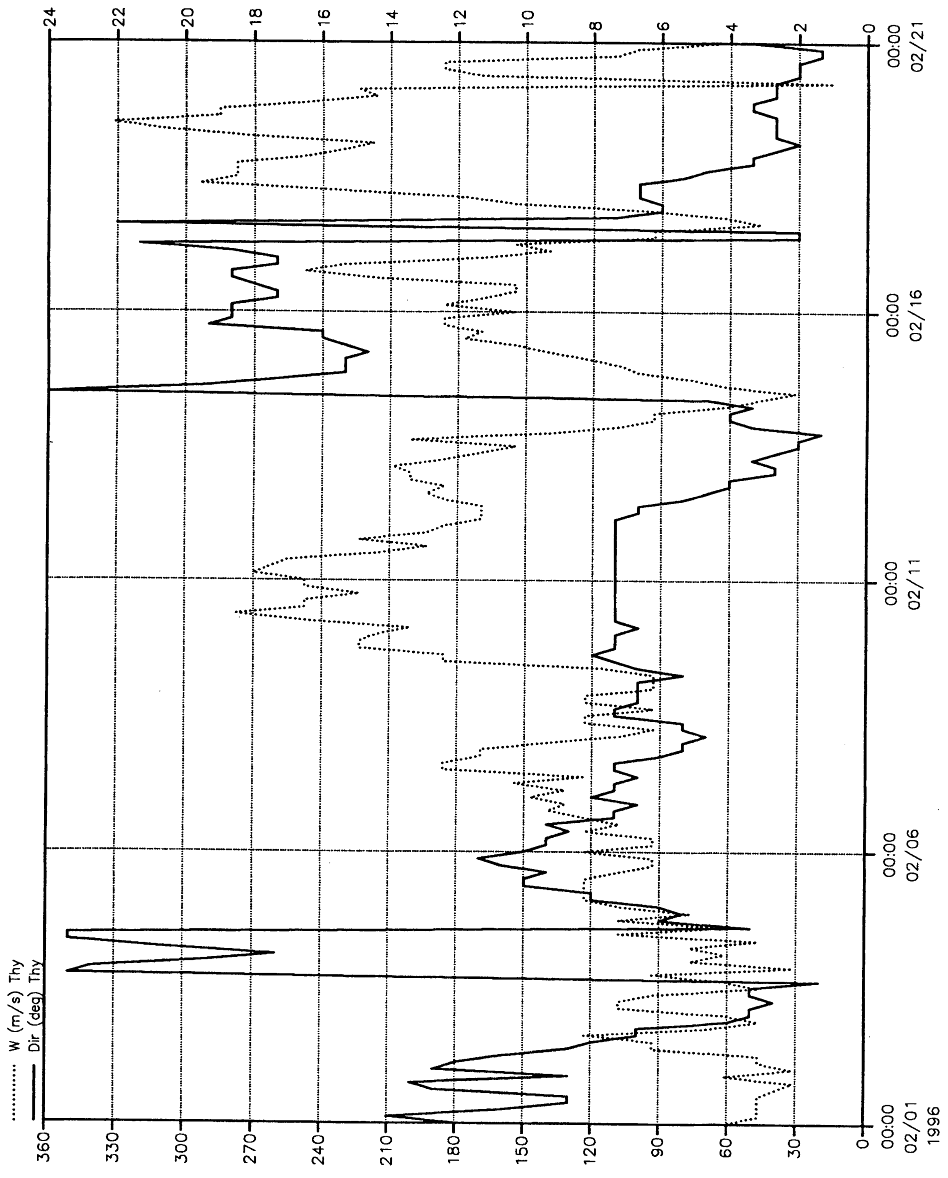


Fig 5. Spatial distributions of A) salinity (PSU); and B) nitrate (mmol/l); 1 m below surface during Feb 14-18, 1996, and C) wind variation in connection with the survey.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e.g. note the 34.5 isohaline. Note that the central North Sea water in the Skagerrak is actually 'broken' apart north of Hirtshals, though preferably the central North Sea water should be flushed out of the Skagerrak.

On the basis of the wind conditions prior to the 1996 survey (Fig. 5) we expect a situation with anti-cyclonic circulation in the Skagerrak and a stagnant JCC south of Thyborøn. The wind directions prior to the 96 survey were 120 degrees with wind speeds of 8-16 m/s, while for a short period during the middle of the survey the wind directions were 270 degrees. We expect the condition prior to the survey to be the determining condition. The anti-cyclonic circulation to the west transports the outflowing Kattegat surface water. North of Hirtshals only up-welling Atlantic water is observed, *i.e.* we assume that the JCC water has been transported to the North Sea. A stagnant (or contracting) JCC is observed south of Thyborøn.

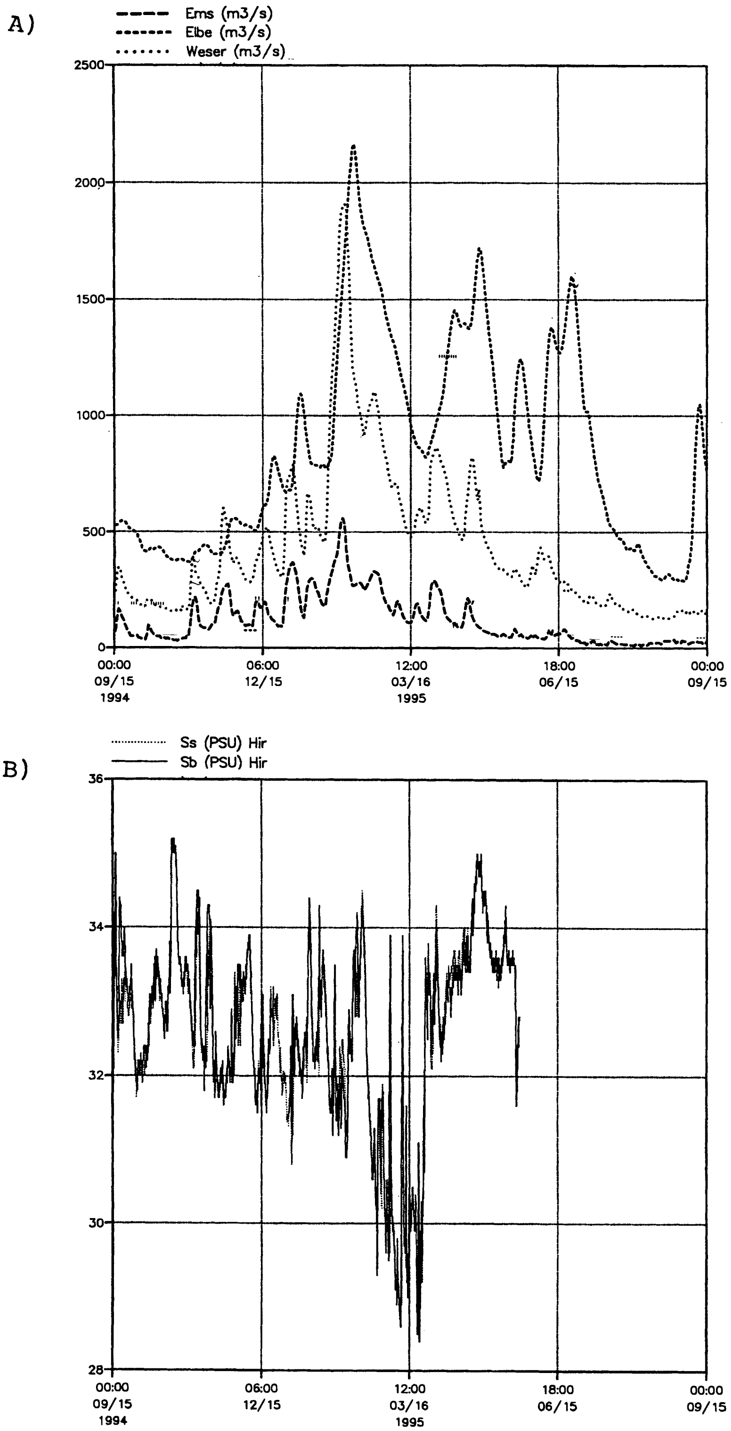
Dietrich (1957) investigated the surface salinity distribution in the southern and central North Sea after a period of persistent easterly winds in March 1955 (see *e.g.* figure in Otto *et al.* 1990). Also in that situation a very contracted JCC was found in the German Bight.

A situation with a separated JCC is not found in the observations. Hainbucher *et al.* (1987) showed indications of separated water masses west of Hanstholm and this supports the theory that JCC water is sometimes transported into the North Sea outside of Hanstholm.

The Major River Outflow in 1995

The transport of nitrate with the JCC water into the Kattegat takes place sporadically and not every year during the winter and early spring (Heilmann *et al.* 1991; Hansen 1990), but it is anticipated that this is related to the wind conditions. At the beginning of 1995, a very strong river outflow to the German Bight was observed (Fig. 6). Decreasing salinities at Hirtshals were observed in connection with changing southerly and westerly winds with a delay of approximately 21-45 days: the delay was taken between either the beginning of the increasing river outflow to the beginning of the decreasing salinity or between the maximum river outflow to the minimum salinity. The delay during this event was shorter than expected, as it was 1-2 months according to Heilmann *et al.* (1991), but as expected when considering the wind history.

Fig. 6. Variation of A) river outflow into the German Bight; B) salinity 3 m b.s. and 1 m a.b. outside Hirtshals; and C) wind at Thyborøn see p. 142; in connection with the major river outflow to the German Bight during January-February 1995.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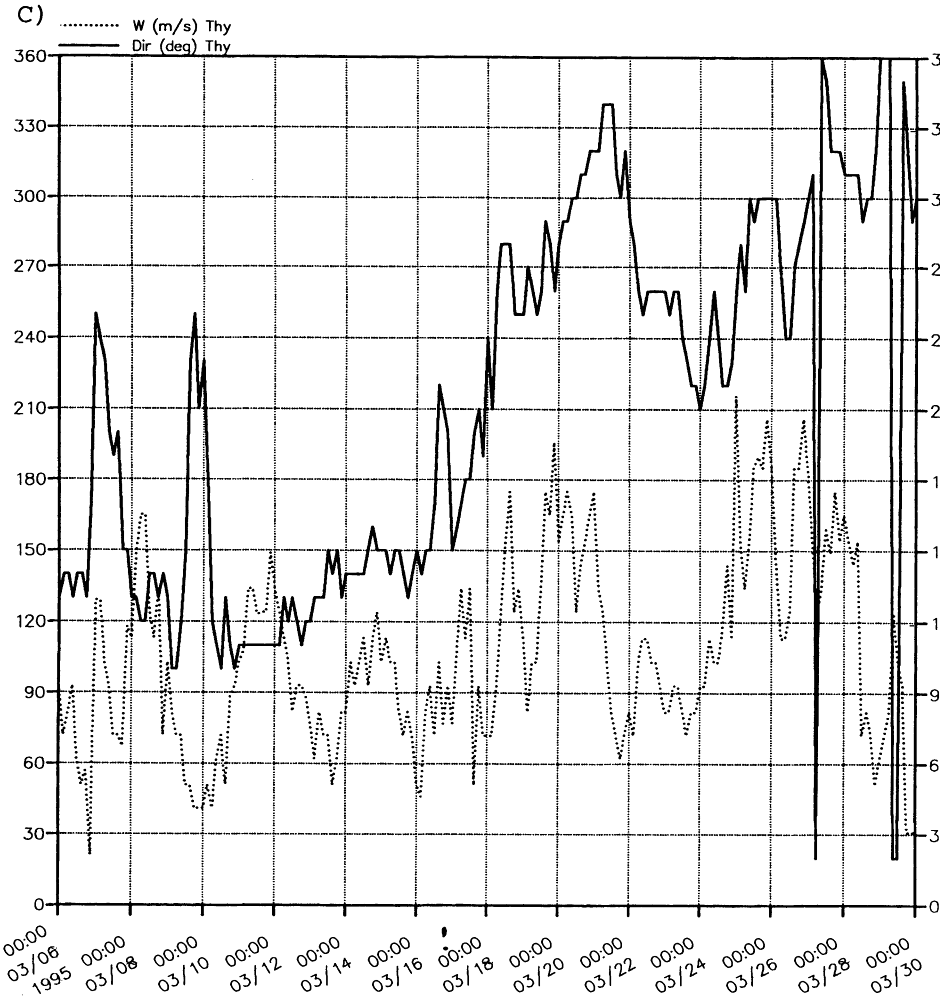

Fig. 6. C) wind at Thyborøn.

Comparison of Time-Series of Wind and Current

On the basis of the relation outlined in the introduction and the spatial current velocity correlation found in Jensen and Jónsson (1987) the current is related to the wind as given by the first term on the right-hand side of the following equation

$$\overline{u_M} = a_1 \overline{W^2 \sin(\theta-\theta_0)} + a_2 \overline{W^2 \cos(\theta-\theta_0)} + a_3 (1 - \frac{\overline{S}}{S_0}) + a_4 \qquad (3)$$

where u_M(m/ s) is the current in the main direction, θ_0(=117°) is a constant, S is the salinity, S_0(=33.5 PSU) is a constant and parameters a with indexes 1 to 4 are constants. On the basis of Eq. (1) and Eq. (2) the constant a_1 is derived to be

$$a_1 \cong \frac{\rho_a C x}{\rho f A_{JCC}} \tag{4}$$

where A_{JCC} (m^2) is the area of the JCC. As the constant angle is influenced by uncertainty the second term in Eq. (3) was also included, and may thus be seen as an evaluation of the constant angle. A simple expression of the buoyancy influence was also included by the third term in Eq. (3). It simply expresses that the lower the salinity of the coastal current the greater the buoyancy influence. The terms are averaged over 50 hours (4 tidal periods) to remove the short-term tidal signal while maintaining the wind influence (indicated by the over-lining in the equation).

For the Hirtshals station measurements the constants were determined to be $a_1 \cong$ 0.0027 s/m, a_2 = -0.00086 s/m, a_3 = 0.27 m/s and a_4 = 0.083 m/s. In the Hirtshals case the coefficient of determination (R^2) is 0.77 (Fig. 7A). The large-scale circulation in the Skagerrak is partly driven by the outflow from the Skagerrak (Rodhe 1996) and this will influence the tidal signal (a_4). Still, in Kristensen (1991) the residual tidal velocity in the Skagerrak is determined to be 0.06 m/s. It should be noted that in Kristensen (1991) the residual tidal flow was found to increase along the coast, or to be approximately six times larger at Hirtshals than at Thyborøn.

For the Thyborøn station measurements the constants were determined to be $a_1 \cong$ 0.0065 s/m, $a_2 \cong$ 0.0019 s/m, a_3 = 2.02 m/s and a_4 = -0.044 m/s. One storm event with fast changing wind directions was omitted from the data. The coefficient of determination (R^2) is 0.50 (Fig. 7B). However, uncertainty was expected as we only use wind measurements from one location in the North Sea and assume quasi-steady conditions. The a_1 obtained when inserting x=250 km and A_{JCC}=15 m times 40 km (Rydberg *et al.* 1996) into Eq. (4) is close to the value found by data analysis and thus supports the relation to the Ekman transport.

The gross and net values of the first three terms on the right-hand side of Eq. (3) were investigated on the basis of the time-series. The gross value is taken as the average numerical value:

$$\text{Gross Value} = N^{-1}\sum_{N} |\text{Value}|$$

The net value is taken as the average value:

$$\text{Net Value} = N^{-1}\sum_{N} \text{Value}$$

In the Hirtshals case the net values were 0.038 m/s, 0.008 m/s and 0.004 m/s, respectively, while the gross values were 0.110 m/s, 0.050 m/s and 0.009 m/s, respectively. Thus, the influences of the buoyancy (in the Thyborøn case) and the tides are significant on the 50 hours time-scale. The values stress the importance of the net wind stress on the net circulation.

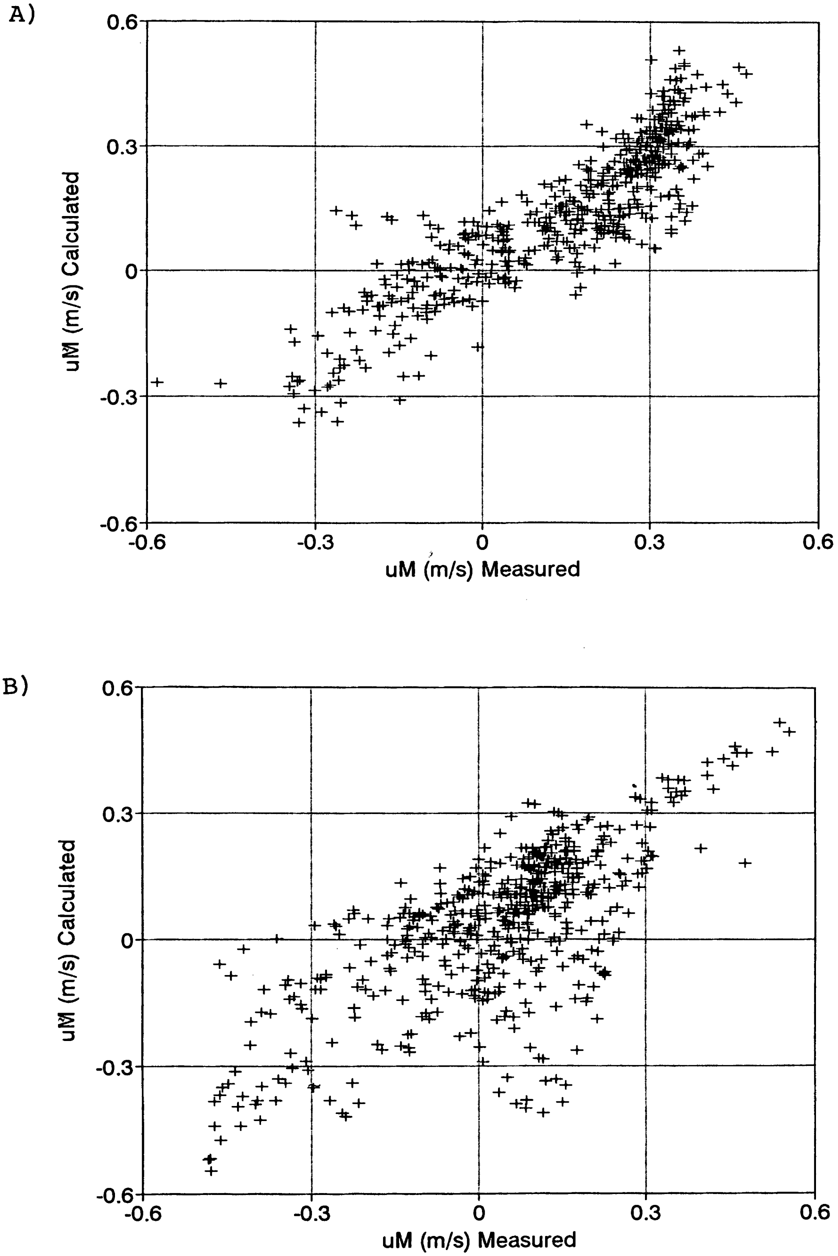

Fig. 7. Comparison of the measured current projected on the main direction outside A) Hirtshals during Marts 1993 to May 1995; and B) Thyborøn during April 1995 to Marts 1996; and the velocity calculated by (3).

Inter-Annual Variation in the Nitrate Concentrations

The spatial nitrate distributions (Figs. 2-5) clearly indicate an inter-annual variation in the nitrate concentrations in the JCC (and because of the correlation between the local river outflows also in the northern Kattegat). The highest concentrations in the JCC were found in 1995 (and 1994) and the lowest concentrations were found in 1996. The concentrations were typically three times higher in 1995 than in 1996. The inter-annual variation will influence the transport of nutrients with the inflows of JCC water to the lower layers in the Kattegat.

In 1993 and 1995 there were indications of a winter bloom in the central North Sea water flowing into the Skagerrak. The bloom decreases the nitrate concentration locally and thus nitrate is not conservative in the central North Sea water in the considered periods for some years. The bloom could not be identified in the chlorophyll measurements. The reason for the bloom is assumed to be winter blooming in the central North Sea at the Dogger Bank (Richardson and Olsen 1987). The blooming influences the amount of nitrate in the central North Sea waters flowing into the Kattegat.

Discussion

In many respects the spatial distributions of salinity and nitrate lived up to our expectations based on wind history. A situation with a separated JCC is not found in the observations, but even if a case with separated water masses were covered by a survey the monitoring programme would not measure the separated water masses. An independent numerical simulation also indicates the separation. Certainly the explanation of the wind influence on the spatial extent of the JCC cannot be rejected on the basis of the data analysis.

The arrival of the JCC to the Skagerrak after the major river outflow event in 1995, or more precisely its dependence on the wind history, gives (weak) support to the described behaviour of the JCC in relation to wind conditions. In connection with the major river outflow, the inflow of continental water to the eastern Skagerrak and the Kattegat began in mid February, but during the relatively short period from about March 7 to 24 1995 an especially high inflow to the Kattegat took place (Rydberg 1995). Consulting the wind measurements, a period with ESE winds is found prior to 17 March, which forces an outflow from the Kattegat, while a period with strong westerly winds is found from 17-28 March. It is very likely that it is the combination of, at first, easterly winds followed by strong westerly winds during the period 17-28 March, which forces the inflow event.

The transport formula gives a satisfactory description of the current field of the JCC in relation to wind conditions. The buoyancy and tides are also found to contribute significantly to the transport, and the contributions are quantified. The correlation is higher in the Hirtshals case than in the Thyborøn case, which at first glance may be surprising. The reason for this is twofold: a) the measurements collected at Thyborøn may be weakly influenced by the transport through Limfjorden; and b) the seasonal variability of stratification and current is bigger at the Thyborøn station (Jensen and Jónsson 1987; Pedersen and Kristensen 1990). Even so, not all problems are fully resolved by the analysis, *e.g.* the dependence of short-term changes in wind conditions is not investigated. 3-dimensional simulation of the JCC would be able to resolve some of these problems.

Conclusion

The spatial distributions of salinity and nitrate show a dependency on the dominating wind direction, but the separation of the JCC is not clearly resolved by the observations. The spatial nitrate distributions clearly indicate an inter-annual variation in the nitrate concentrations in the JCC, which influences the nutrient transport into the Skagerrak and possibly further into the Kattegat. The current only flows into Skagerrak during south-southwesterly winds. The major river discharge into the German Bight in 1995 was followed by a decrease in salinity measured outside Hirtshals after only 21-45 days in connection with changing southerly and westerly winds. The transport of the JCC on the 50-hour time-scale is mainly determined by the wind field over the North Sea (measured at Thyborøn) as expected from the Ekman transport, but is also influenced by buoyancy and tides.

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