PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Circulation Phenomena and Frontal Dynamics of the Norwegian Coastal Current

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Circulation phenomena and frontal dynamics of the Norwegian coastal current

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After a short general description of the Norwegian Coastal Current, some recent investigations concerning its variability are reviewed.

The variability caused by meteorological effects and fresh water fluxes is shown to be the dominant feature. The coastal current not only responds to local wind-forcing but is also a signal channel of sea-level variations in the North Sea as a whole. The variability at times manifests itself as mesoscale waves and eddies. The subsurface frontal region is characterized by interleaving of coastal and Atlantic water, and strong mixing. Lateral and longitudinal frontal motions are dealt with in relation to plumes of brackish water from the fjords and outbreaks of brackish and/or warm water masses from the Skagerrak. The inflow of Atlantic water through the Norwegian Trench, and the formation of deep and bottom water in Skagerrak are discussed.

Introduction

The aim of this paper is to review some of the oceanographic research, both theoretical and experimental, that has been done on the Norwegian Coastal Current in recent years. New insight into the dynamics and circulation processes of this complex current system results partly from the joint scientific effort through the project 'The Norwegian Coastal Current', which began in 1975, and partly from the general increased interest in coastal oceanography. The discussion will focus on the theoretical aspects of coastal phenomena. Many relevant investigations and theoretical works could have been taken into account. However, I see my task primarily as a presentation of research that has been directed towards the Norwegian Coastal Current.

General description

The Norwegian Coastal Current has traditionally been referred to as the continuation of the Baltic Current, mainly because its low salinity can be attributed to the brackish outflow from the Baltic. The surplus of fresh water from the Baltic amounts to 450 km^3 per year but it will be seen from figure 1 that the contribution from other sources, mainly the southern North Sea and the Norwegian coast, is considerable. Figure 2 shows the average surface salinity in May which clearly demonstrates the main sources. The mean circulation of the North Sea is governed by three main branches of inflowing Atlantic water and the outflow of the Norwegian Coastal Current. The most pronounced Atlantic Current branch is guided by the western slope of the Norwegian Trench into the Skagerrak and seems to be steady throughout the year. In the summer the Atlantic water of this branch becomes partly overlaid by warmer and less saline coastal water. The core of Atlantic water can, however, be traced as a salinity maximum.

The other major branch of Atlantic water runs south along the east coast of Scotland but seems to depart from the coast and become guided eastwards by bottom topography (Dooley 1974).

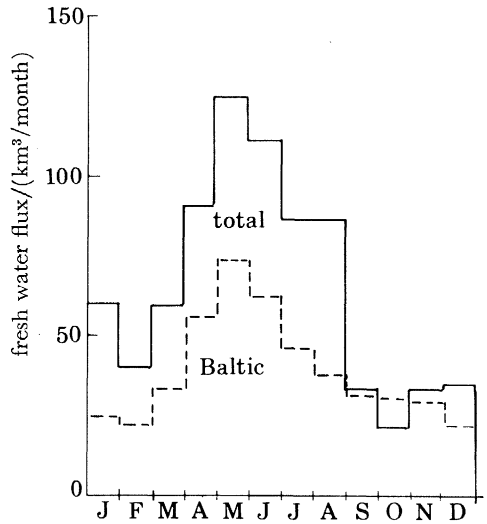

FIGURE 1. Annual distribution of fresh water fluxes from the Baltic, and the North Sea as a whole (south of 62° N).

FIGURE 2. Average surface salinity in May

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The third branch should be some unspecified residual flow through the English Channel. If the North Sea circulation is considered as a steady process, Knudsen's formulas expressing salt and volume balance readily give a coastal transport in terms of salinities and fresh water flux of the order of 10^6 m^3 s^{-1}. The fresh water flux is only 2–3% of the total transport. There are, however, great uncertainties in such budgets mainly because the salt flux due to variable currents has been neglected.

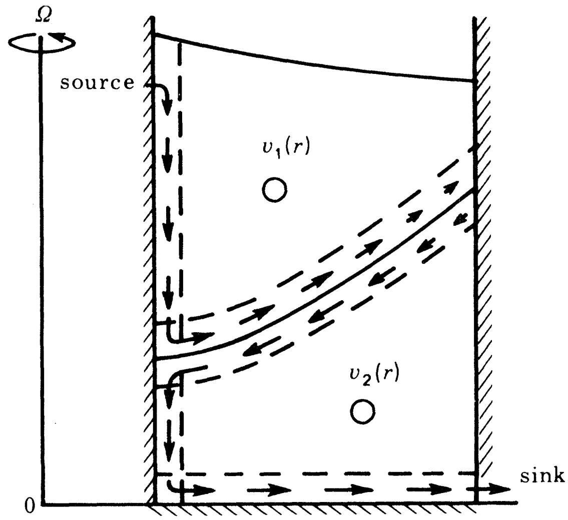

FIGURE 3. Illustration of cross circulation in Mæland's (1981) two-layer-rotating-annulus model. The relative azimuthal circulation is anticyclonic in both layers.

CIRCULATION DUE TO BUOYANCY FLUXES

The density of coastal water is almost completely determined by salinity in a near linear relation. Thus we may associate the sloping of isohalines with a current profile. It is also natural to look at the fresh water fluxes as a possible driving mechanism of the coastal current. Various laboratory experiments have lent support to this idea (for example, Ingebrigtsen 1978; Vinger *et al.* 1981; Griffiths & Linden 1980). The mean circulation induced by buoyancy fluxes in the experiment is somewhat obscured by baroclinic instabilities. Still it is found that a typical feature of the flow is a gradual velocity decrease laterally away from the viscous boundary layer. This is contrary to what may be expected from inviscid fluid theory and may therefore be attributed to Ekman layer friction between layers. Mæland (1981) in a theoretical study of a similar problem finds, indeed, that the interface Ekman layer plays an active role. An interesting result of this study is that the horizontal flow has constant relative vorticity. The model is illustrated in figure 3. I have studied the combined effect of fresh water fluxes from a line source and entrainment (Mork 1981). In this reduced-gravity one-layer model, the velocity profile becomes linear with a maximum at the coast. The model and resulting flow are illustrated in figure 4. The coastal wedge widens laterally as the square root of time and deepens vertically with time. The key parameter is the entrainment coefficient which has been chosen as 10^{-4} to obtain a reasonable value of the maximum longshore velocity 14 cm s^{-1}. In reality entrainment is related to mixing agencies, mainly wind stress and internal parameters like density difference and/or Richardson number. The model does, however, demonstrate the

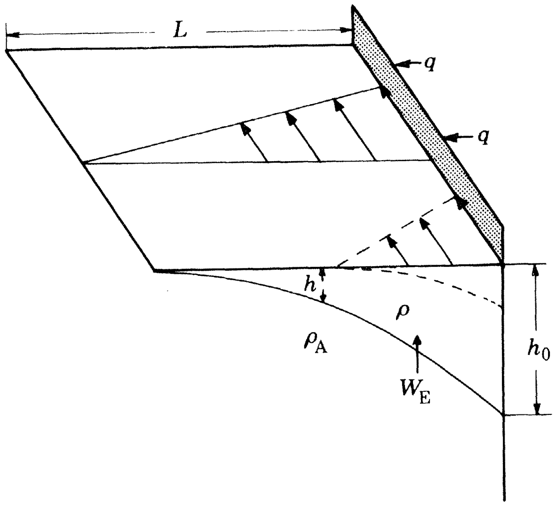

FIGURE 4. The coastal edge and flow patterns at two stages of development in the entrainment model.

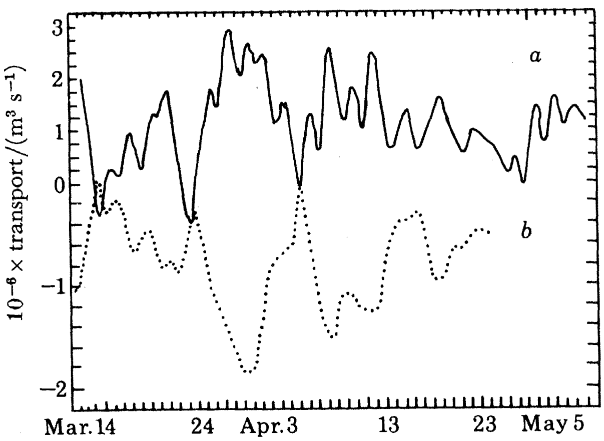

FIGURE 5. Transport as a function of time at (*a*) a section across the Norwegian Trench 59° 20′ N, and (*b*) a shelf section 58° 20′ N, west of the Trench, during March–May 1976 (after Furnes 1980).

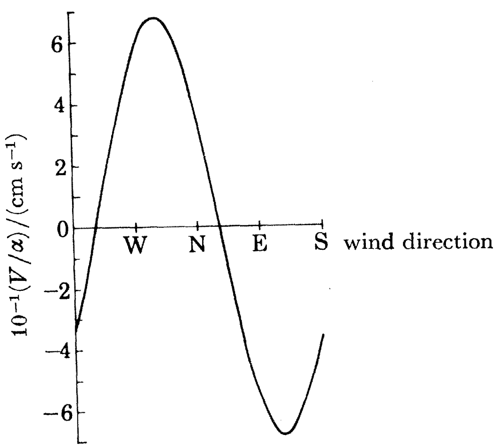

FIGURE 6. Coastal current (V/α) as a function of wind direction from models of Furnes (1980) and Davies & Heaps (1980). Positive values for current represent an outflow.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

main role of entrainment. By using realistic values of fresh water fluxes it is found that the establishment of a current similar to the Norwegian Coastal Current takes about 100 days.

Wind effects

The variability of the coastal current as observed in hydrographic surveys and by current measurements can often be directly related to the wind. The in–out experiment during JONSDAP-76 has revealed many interesting features of the wind-driven North Sea circulation. Studies have been made by Riepma (1980), Furnes & Sælen (1977) and Davies (1979). Figure 5 shows calculations of transport against time at two sections. One section covers the Norwegian Trench and the other is situated on the shelf west of the Trench. The variation in coastal transport is great, from zero to 3×10^6 m^3 s^{-1}, and is clearly linked with meteorological conditions.

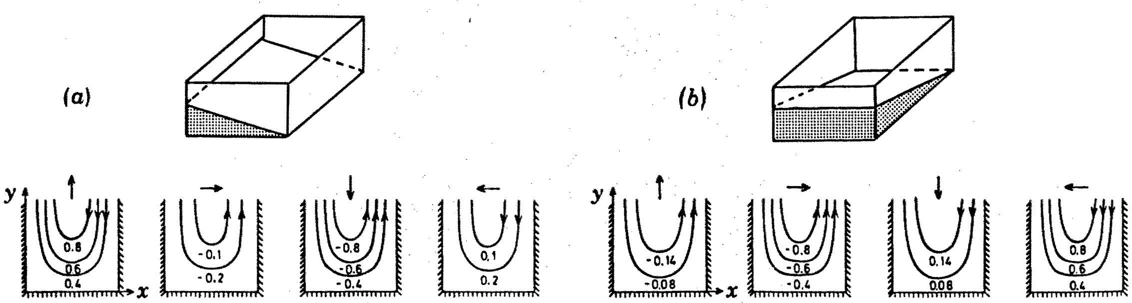

Figure 7. Model results for circulation for different winds in relation to bottom topography. (After Furnes 1980.).

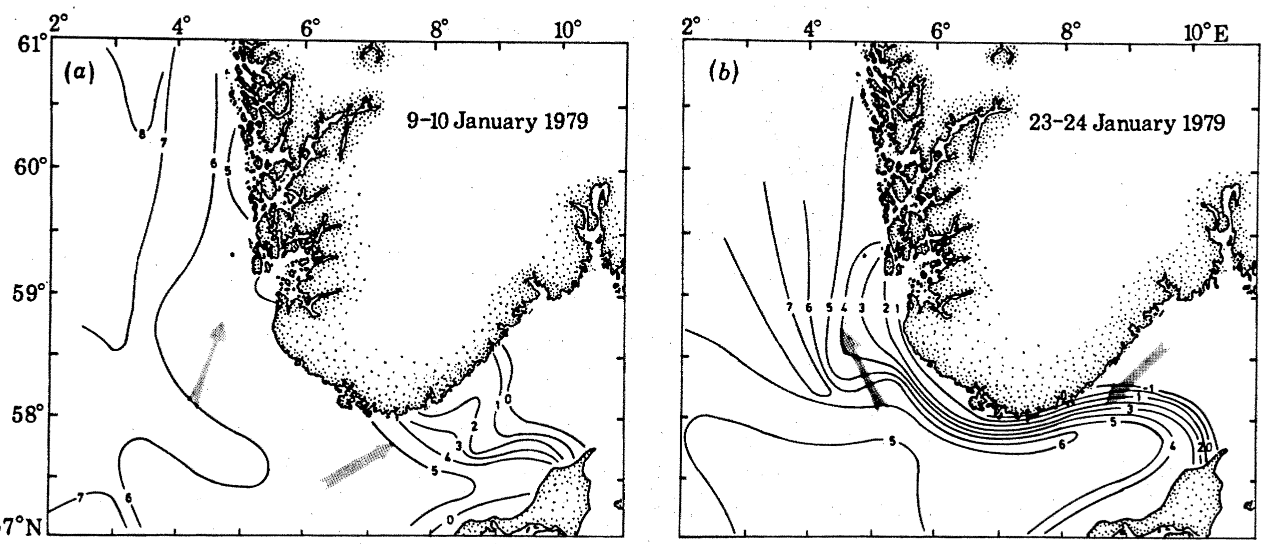

Figure 8. The isotherms (°C) show (*a*) blocking and (*b*) the following outbreak. Wind directions are indicated by arrows. (After Aure & Sætre 1981.)

Consideration of pressure differences indicates that geostrophic winds from the west are associated with high transport values. This is quite significant and will be discussed further. Transport calculations for the western section give a remarkable mirror image of the eastern coastal transport, demonstrating a balance of in–out wind-induced transports. The conclusion that can be drawn from this is that the Norwegian Sea circulation responds quickly to wind forces. This has also been verified by the numerical models of Heaps (1969) and Davies (1979). Obviously bottom topography plays an important role in the transport patterns. Davies & Heaps (1980) and Furnes (1980) have examined the effect of the Norwegian Trench and bottom slopes of the North Sea for different winds. The remarkable common result is shown in figure 6. Northwesterly winds are seen to give a maximum transport for the coastal current, contrary to

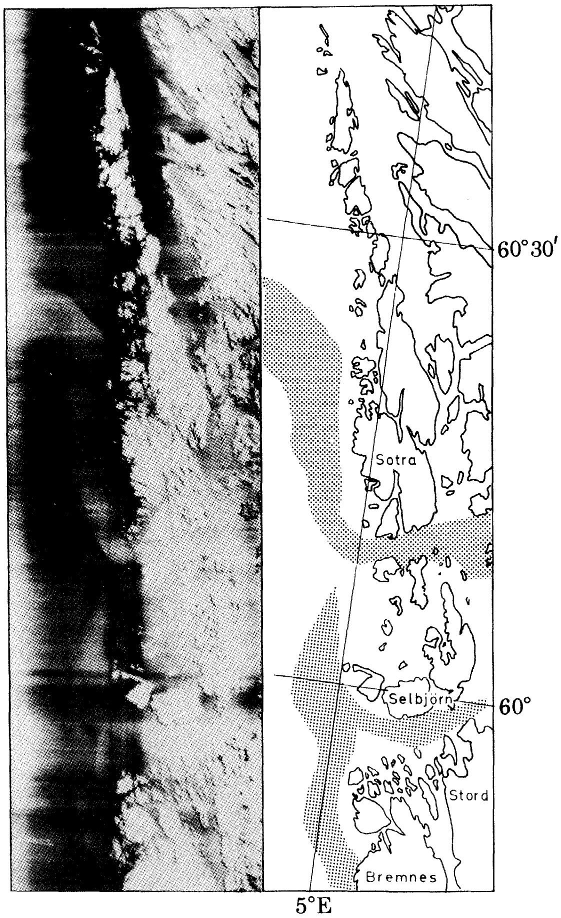

FIGURE 9. Infrared image showing plume of cold fjord water (NORSEX-79).

Ekman's theory of wind-driven coastal circulation. On closer examination, however, and by taking the whole North Sea basin into account the result can be explained, as Furnes (1980) has done (see figure 7). A bottom topography resembling the North Sea gives rise to a strong cyclonic circulation during northwesterly winds. Pingree & Griffiths (1980) using a two-dimensional numerical model of the North Sea derive maximum transport northwards through the Norwegian Trench for southwesterly winds. The disagreement may partly be due to the fact that they consider the Trench flow as net transport between Shetland and Norway and not only as coastal transport. So far we have only discussed barotropic effects of wind with response times of the order of one day, corresponding to the travel time of a Kelvin wave around the North Sea. We shall now consider baroclinic effects.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Blocking and internal bores

Aure & Sætre (1981) have investigated blocking and outbreaks of brackish water in the Skagerrak. South and southwesterly winds will obviously keep back light surface water in the Skagerrak. An example of blocking and the following outbreak is shown in figure 8 with the aid of surface isotherms. During blocking a temperature front builds up. When the wind slackens or attains an easterly component an internal bore starts to propagate along the Norwegian coast. The speed of propagation and the lateral width correspond roughly to the phase speed and the deformation radius of internal Kelvin waves.

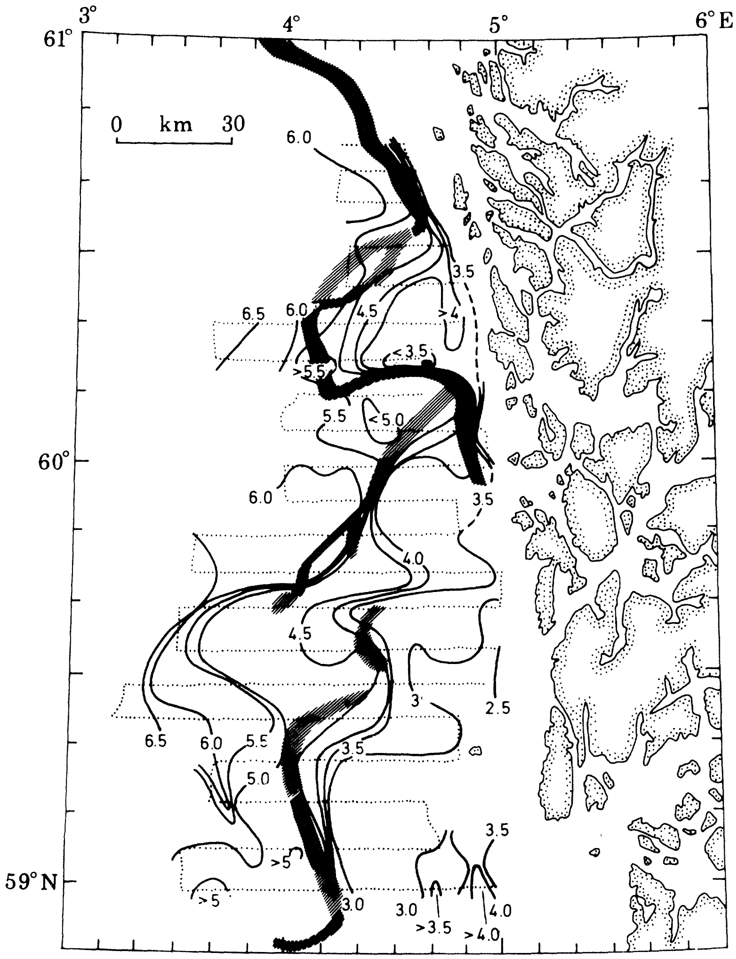

Figure 10. *In situ* surface isotherms (°C), and front positions (thick lines) as determined by satellite images, during 15–18 March 1979 (NORSEX-79).

An analogous case has been studied by Stern (1979) and Bach-Lien Hua (1979), both theoretically and experimentally. The studies were limited to uniform potential vorticity and thus they were not directly applicable to the Skagerrak. However, the main characteristics of the flow are presumably similar. Instabilities develop at the edge and the flow tends to break away from the wall after some distance of propagation. A similar phenomenon, but on a smaller scale, can be observed when plumes of fjord water enter the coastal water (figure 9). Such events are likely to occur in spring and can be interpreted as compensation flows when heavy

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

coastal water runs over the sills renewing deep fjord water. It is quite remarkable that the plume of 5 km width conserves its properties for such a long distance even after departing from the coast.

Frontal dynamics

Wind has been shown to be an important cause of variability of the coastal current. The picture is not complete, however, without a discussion of the manifestations of variability,

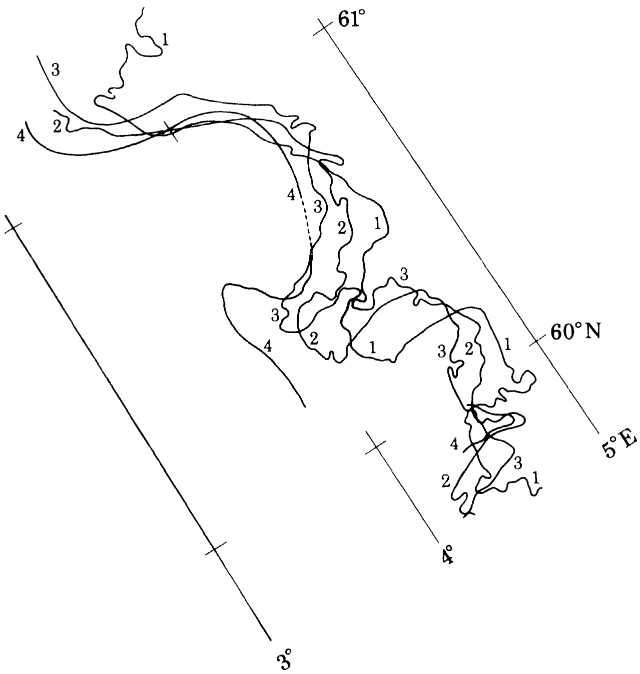

Figure 11. Front positions at four different times from satellite infrared images (NORSEX-79): 1, 16 March 1979; 2, 17 March 03h06; 3, 17 March 13h07; 4, 18 March.

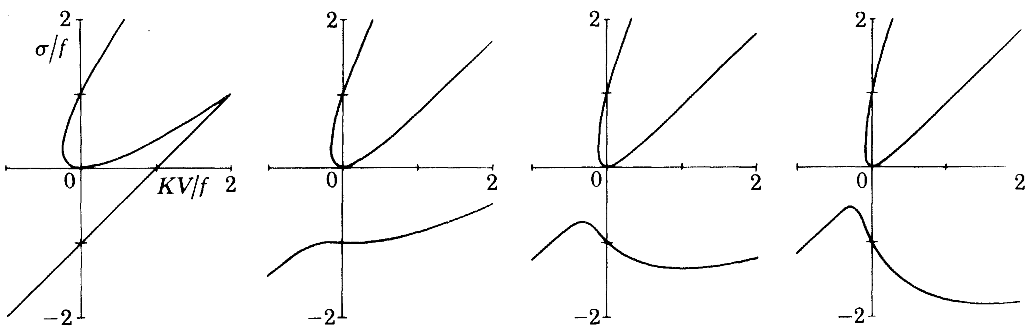

Figure 12. Frequency–wavenumber relations of frontal wave and intertial waves for different lateral modes (Mork 1980)

whether wind-induced or caused by other factors. The most striking manifestations are the mesoscale frontal waves and associated eddies. Satellite i.r. images have helped to reveal the patterns of these phenomena. The dynamic feature of the coastal wedge cannot always be detected by surface-temperature variations, but in certain seasons, mainly winter and early

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

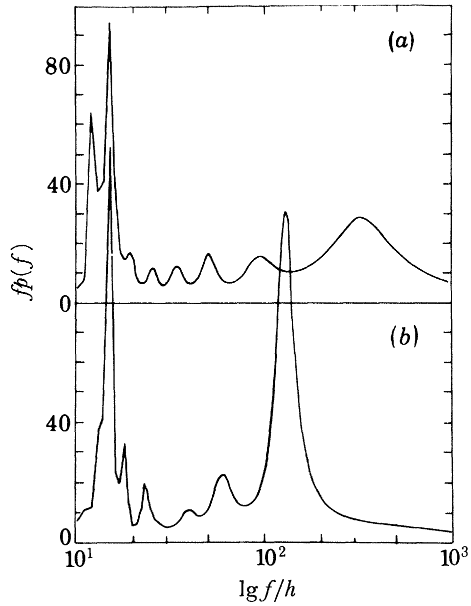

FIGURE 13. Spectra of current velocities during JONSDAP-76: Easterly (*a*) and northerly (*b*) components at 40 m depth in the Norwegian Trench, 59° 20′ N.

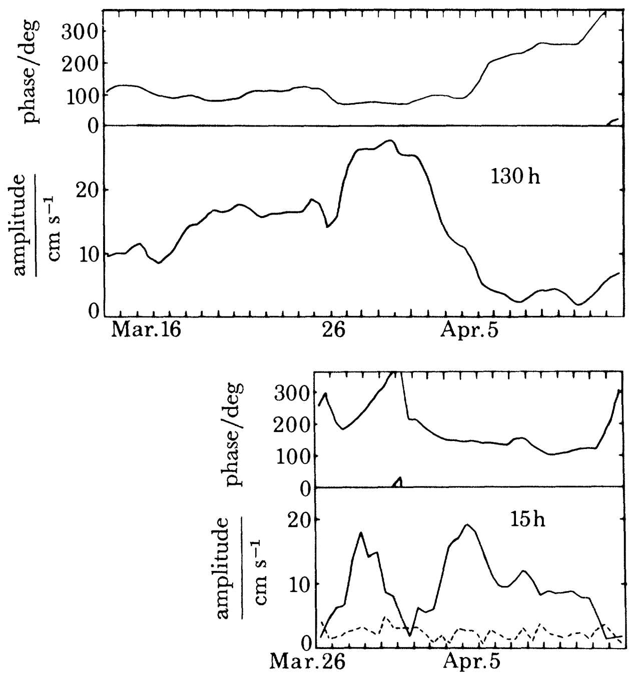

FIGURE 14. Phases (top) and amplitudes (bottom) of harmonic constituents of current-meter time series (see figure 13). The rotary components of inertial oscillations of period 15 hours are obtained from complex demodulation of the time series. Only the phase of the energy containing a component with clockwise rotation is shown. The phase and amplitude of the 130 hour constituent are obtained from harmonic analysis of the easterly current component.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

spring, temperature and salinity variations are closely connected. The satellite data and *in situ* observations (figure 10) as obtained during the NORSEX-79 programme are representative of the dynamical processes. Frontal wave patterns are easily recognized with wavelengths of the order of 80 km. From successive pictures of front positions (figure 11) the speed of propagation was estimated to be 17 cm s^{-1} northwards, corresponding to a wave period of

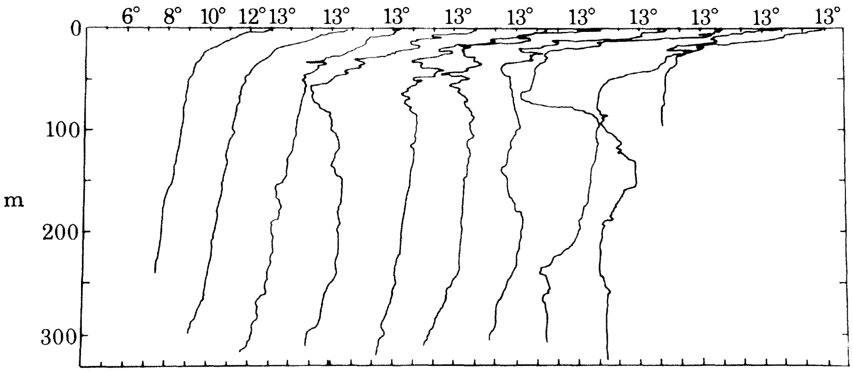

FIGURE 15. Temperature profiles from stations in the Fedje–Shetland section (from Tørresen 1979).

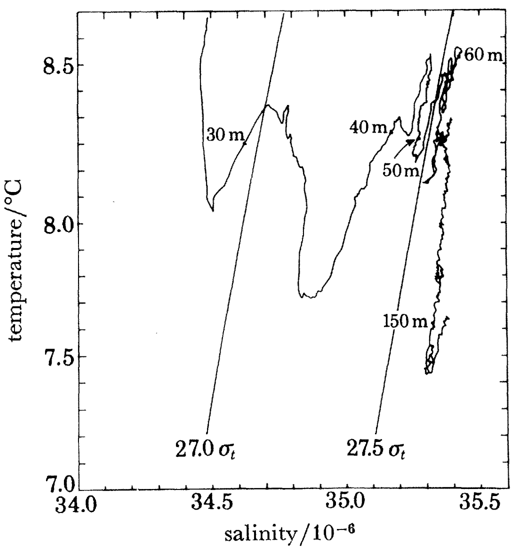

FIGURE 16. Temperature–salinity diagram in the coastal current as obtained with the aid of a profiling CTD drop sonde (from Tørresen 1979).

five days. The large amplitudes and eddy structures make it doubtful whether such motions can be associated with linear wave theory. However, it is likely that the waves have developed as perturbations on the mean flow in the form of free infinitesimal waves. Variable wind stress may be the triggering factor, and the wave motion is probably governed by baroclinicity and bottom topography. Thus baroclinic instability is the most likely cause of frontal waves. However, the wavenumber–frequency relation may be adequately represented by a reduced gravity model. In such a model (Mork 1980) there are infinitely many lateral modes, eigenmodes, but to each mode there corresponds three frequency–wavenumber relations: one is the frontal wave solution and the other two represent inertial waves. It is interesting that only the first two modes contain inertial oscillations of period larger than the local inertial period, $2\pi/f$, within the actual wavenumber band (see figure 12).

Analysis of time series of current measurements in the coastal current and on the shelf frequently reveals periodic motions other than the tidal ones (Koltermann 1980). Generally there are several peaks in the velocity spectra but in the special case chosen (figure 13) there are only two dominant wave periods; 15 hours and 130 hours. The time series are from a current meter 40 m deep in the deep part of the Norwegian Trench during JONSDAP-76.

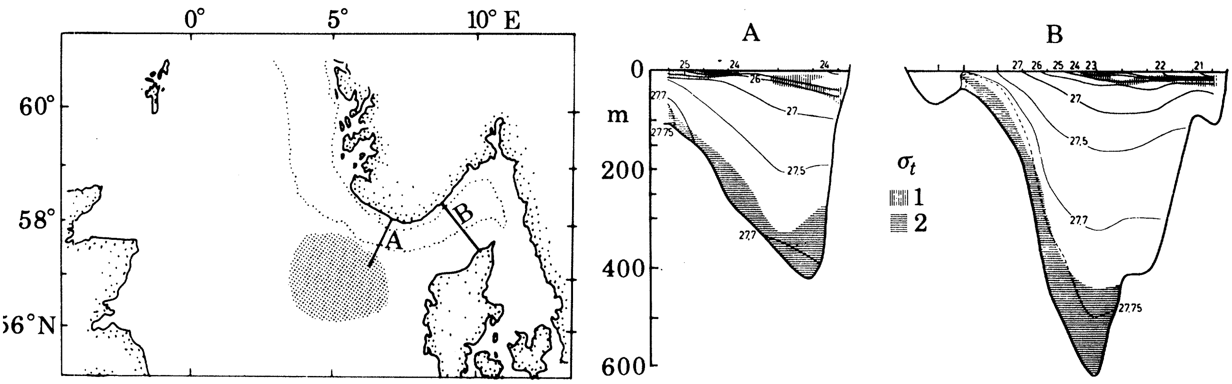

FIGURE 17. The map shows the possible origin of bottom water and position of two sections, A and B, The distribution of σ_t and minimum static stability (hatched area at bottom) are shown during 10–12 May 1979 in the Norwegian Trench and the Skagerrak, with the Norwegian coast to the right (After Ljøen 1970).

Results from harmonic analysis and complex demodulation of time series are depicted in figure 14 and it is seen that phases are constant for a long time when amplitudes are significant. Of the 15 hour components, that with clockwise rotation is dominant. Accordingly it is claimed that the two periods correspond to the frontal wave solution and inertial oscillation.

Mixing processes

Frontal wave instabilities and eddy shedding are important mechanisms for lateral exchange processes as they are also the most likely origins of isolated pockets of coastal water within the Atlantic water. There are also some interesting mixing phenomena on smaller scales. Figure 15 shows temperature profiles at stations in a section normal to the coast (Tørresen 1979). The small-scale irregularities signify interleaving of coastal and Atlantic water. This can also be seen as sawtooths in the temperature–salinity diagram from a drop sonde CTD (figure 16). The mixing process of greatest biological significance besides coastal upwelling is probably the combined effect of lateral excursions of the frontal edge and wind-stirring of the top layer. High concentrations of chlorophyll are also found along the frontal boundary as well as in upwelling coastal regions.

Renewal of deep water in the Skagerrak

The renewal of bottom water in the deep Skagerrak basin is not regular. Renewal is most likely to occur in cold winters, in February and March, when bank water of the North Sea

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

has become dense enough to replace older basin water. The dynamics of the formation of bottom water in the Skagerrak has not been studied, but the process is probably similar to that described by Smith (1974) and Killworth (1977). Their theories deal with plumes of dense heavy water running down an inclined plane, where gravity forces, bottom friction and entrainment are the governing factors besides rotational effects.

Ljøen (1970, 1981) has investigated hydrographic conditions during bottom-water formation and figure 17 shows one typical extreme situation in a cold winter when renewal took place. The densest water and minimum stability are found on the bottom slope from the banks down to the deep trench. After an extensive renewal several years may elapse before the next. The dilution of deep basin water by diffusion processes is quite slow. Several years of mild winters may give rise to another mechanism of renewal as pointed out by Ljøen. Instead of cold shelf water, direct inflow of saline Atlantic water down the Trench becomes the source of renewal. Thus the deep water of the Skagerrak is a record of extreme oceanographic conditions which in turn may be related to climatic variability.

Driving forces

One of the possible driving mechanisms of the coastal circulation has already been mentioned: the combined effect of fresh water fluxes and mixing by wind or tides. However, it has been shown by Davies (1981) that the residual wind-driven circulation of the North Sea is annually cyclonic, giving an average coastal transport of $10^6\ m^3\ s^{-1}$. Flather (1981) has calculated the coastal transport resulting from Stokes drift of tidal wave motions and obtained the value $0{\cdot}2 \times 10^6\ m^3\ s^{-1}$. The Atlantic influence must not be forgotten either and it is natural to question what the circulation of the North Sea would have been without fresh water fluxes and local wind-forcing.

Conclusion

Some of the main features of the Norwegian Coastal Current and possible causes of its variability have been pointed out. There is some uncertainty about the driving forces since the observed transport can be explained by wind forces alone, or by buoyancy fluxes alone. The relative importance of these effects can probably be found from the splitting of transports into barotropic and baroclinic parts. The frontal wave motions have been discussed in the light of observational evidence. The role of bottom topography has not been investigated, but the low frequency variability is probably related to both topography and baroclinicity. Pronounced topographic features like banks may also give rise to trapped vortices as demonstrated by Eide (1979).

Little is known about the cross circulation in the Norwegian Coastal Current. Theoretically the fresh water flux from the land should favour coastal upwelling (Piatrafesa & Janowitz 1979), while frictional forces have the opposite effect. The observed cross circulation seems to be dominated by wind effects.

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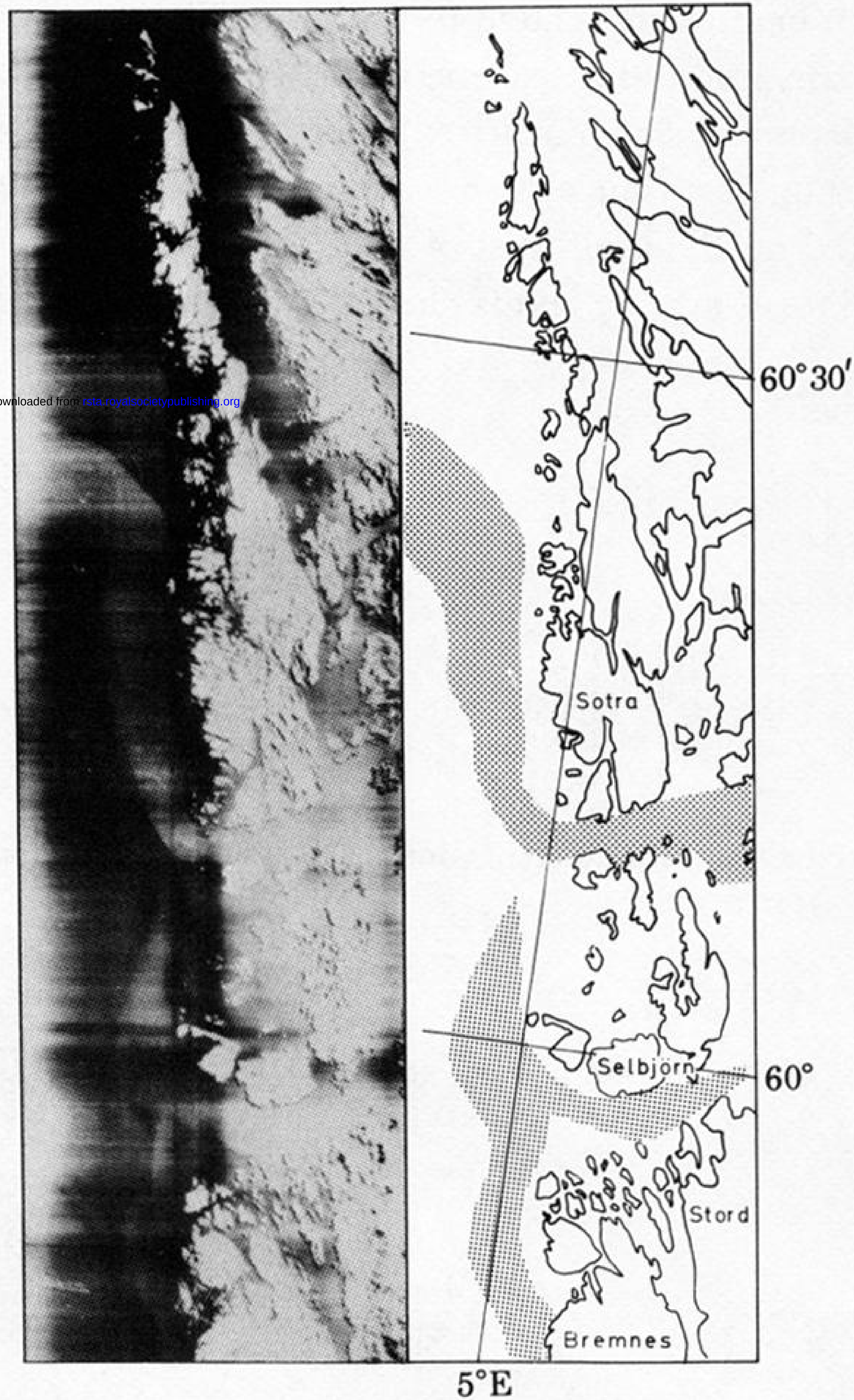

IGURE 9. Infrared image showing plume of cold fjord water (NORSEX-79).