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On the existence of a deep countercurrent to the Norwegian coastal current in Skagerrak

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ABSTRACT

Current measurements indicate that there is a semi-permanent countercurrent below the Norwegian coastal current in Skagerrak. Comparison with local windstress, earlier findings from laboratory experiments and model simulations indicates that the Coriolis force, horizontal pressure gradients and vertical entrainment by the surface current may be the driving forces of this countercurrent, while the windstress is a modifying factor.

1. Introduction, previous investigations

In order to estimate the current regime of the Norwegian coastal current in Skagerrak, various methods have been tried. Helland-Hansen (1907) and Rodhe (1977) obtained direct current measurements from an anchored ship, Tomzcak (1968) employed self-recording current meters, Kobe (1934), Svansson and Lybeck (1962), Tomzcak (1968) and Dahl (1977) have calculated the geostrophical current velocity based on hydrographic observations. The direct current measurements carried out by Helland-Hansen and Tomzcak showed great variations both in direct-tion and magnitude. Tomzcak's measurements at 402 m and 510 m in the Norwegian trench showed that although the residual current went into Skagerrak at 402 m and out of Skagerrak at 510 m, the daily mean current reversed for some days at both levels. Rodhe (1977) found from pendulum current meter measurements along the section Kristiansand–Hanstholm that there is almost always an anticlockwise circulation in Skagerrak below 100–200 m. Ingebrigtsen (1977) showed by experiments carried out in a tank on a rotating table that a countercurrent may exist below a surface coastal current when freshwater is discharged along the coast.

2. Current measurements off Arendal in 1977

On August 18, 1977 two Aanderaa current meters (RCM4) were put out at 58°14′N, 09°02′E (12.5 nautical miles off the shore). The water depth at this position is 404 m. The position is shown in Fig. 1 (site A), and the bottom profile from site A perpendicular to the coast is shown in Fig. 2. The current meters were placed 30 m below the surface and 9 m above the bottom. The measurements at 30 m were interrupted after 35 days when the surface buoy drifted away. The current meter at 395 m continued to work another 5 days, then the sub-surface buoy collapsed and the current meter sank to the bottom. Due to malfunction in the decoder, the current meter at 395 m did not record satisfactorily the first 3 days.

The mean speed is defined as

$$v = \frac{1}{N} \sum_{i=1}^{N} |\mathbf{v}_i|$$

where N is the total number of observations, and $\mathbf{v}_i$ is the velocity. The residual current $\mathbf{v}_r = (1/N)\sum_{i=1}^{N} \mathbf{v}_i$ and the stability $\beta = |\mathbf{v}_r|/v \cdot 100\%$ for the two time series are given in Table 1. The table shows that the current for both times series is very

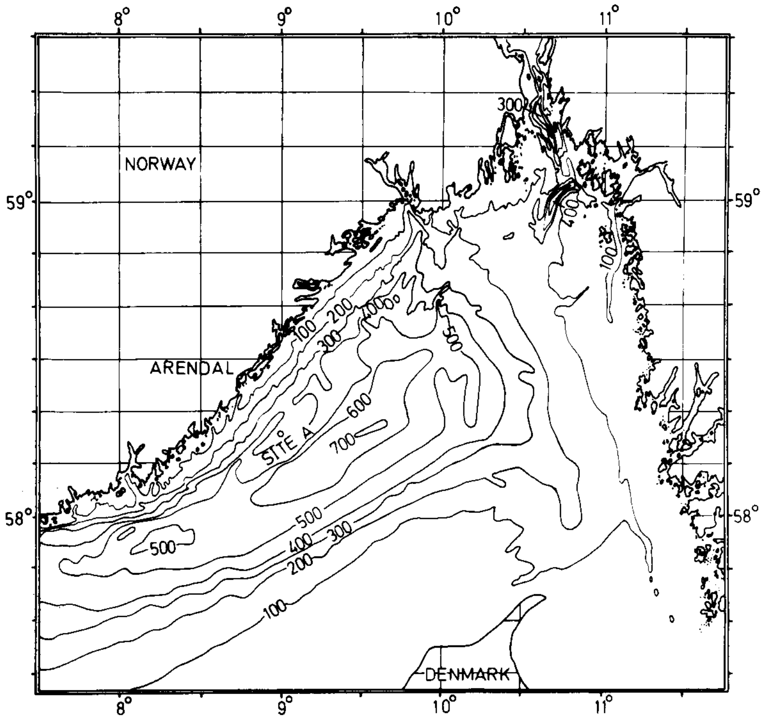

Fig. 1. Map showing the position of site A and the Skagerrak area (after O. Holtedahl).

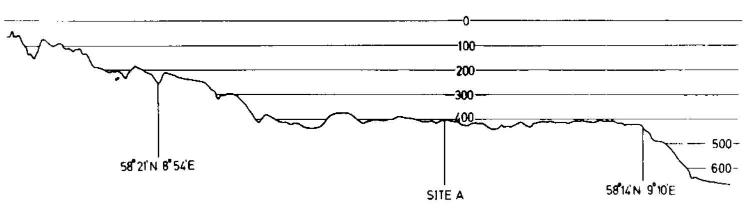

Fig. 2. The bottom profile between Arendal (Torungen) and site A. Depth in meters.

Table 1. *Mean speed (v), residual velocity ($\mathbf{v}_r$), direction and stability (β) of the measurements from 30 and 395 m at site A in August–September 1977*

Depth (m)	v (cm s^{-1}	$\mathbf{v}_r$ (cm s^{-1})	°	β (%)
30	27.0	24.7	232	91.5
395	2.0	1.6	40	78.4

stable. The direction for the residual current at 30 m is almost parallel to the coast. The residual current at 395 m is directed almost opposite to the current at 30 m.

3. Discussion

The progressive vector diagrams for both time series are shown in Fig. 3. The upper scales show the daily mean current velocity (DMCV), while the lower scales show the particle displacement ($\sum_{i=1}^{N} \mathbf{v}_i \Delta t$ (Δt = 600 s)). Fourier analysis of the velocity components normal to and along the coast of the measurements obtained at 395 m shows that there are no significant components in the velocity spectrum with periods shorter than 60 h. In fact, all components except the mean value are smaller than the resolution of the current meter (0.3 cm s^{-1}).

The Fourier amplitude spectrum for the velocity

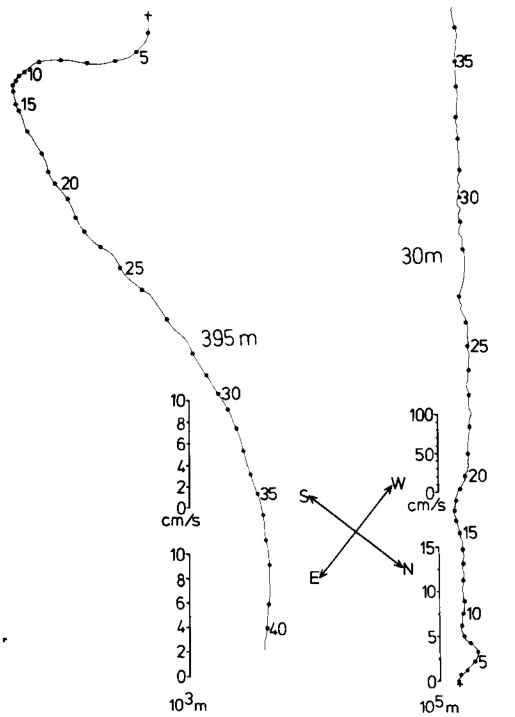

Fig. 3. Progressive vector diagrams at 30 and 395 m. Numbers in figure indicate relative dating which starts at 18 August 1977. Upper scales show the magnitude of the daily mean current velocity (DMCV) and lower scales show particle displacement.

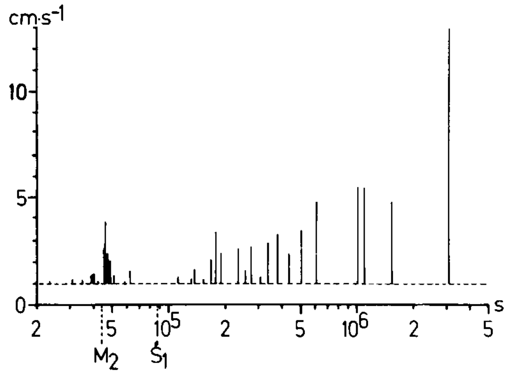

Fig. 4. Fourier amplitude spectrum for the velocity component along the coast at 30 m for the period 18 August–22 September 1977.

component along the coast at 30 m is shown in Fig. 4. The figure shows that there are significant components with periods between M_2 ($\sim$4.47 × 10^4 s) and the inertia period ($\sim$5.1 × 10^4 s), but also that there are greater components of much longer periods. It should be noted that the tide along the Norwegian coast in Skagerrak is semidiurnal. For this area the ratio $T = [O_1 + K_1]/[M_2 + S_2]$ between the main diurnal and semidiurnal tidal components is approximately 0.15. At 30 m, the greatest semi-diurnal tidal component is only 4.7 cm s^{-1}, while the residual current is 24.7 cm s^{-1}. The characteristic tidal "loops" are not found in Fig. 3, nor is there any reverse in the main current either at 30 m or at 395 m.

From Fig. 3, it can be seen that there are significant variations in the DMCV at both levels. If these variations are compared with variations in the windstress, it may be seen that there is some coupling between the variations in the windstress and variations in the DMCV. Fig. 5 shows the components of the windstress normal to (towards 315°) and along (towards 225°) the coast, computed from wind measurements obtained at Torungen lighthouse near Arendal. The windstress τ has been computed by the formula

$$\tau = C_d \rho u_{10}^2$$

where ρ is the density of air, u_{10} is the wind velocity at 10 m and C_d is the surface drag coefficient. C_d has been computed according to Miller et al. (1972) as

$$C_d = (1.0 + 0.07 \times u_{10}) \times 10^{-3}$$

The starting time (day 0–18 August 1977) is the same in Figs. 3 and 5. In the period day 5—day 25, when the windstress is directed nearly 180° opposite to the main surface current direction, the DMCV at 30 m is smaller than in the period day 29–day 37 when the windstress is small or is directed in the same direction as the main surface current. It should be noted that the direction of the DMCV at 395 m is almost opposite to the direction at 30 m. The current in this area can therefore not be barotropic. It seems that the local windstress over Skagerrak can not be the driving force of the deep countercurrent, either as a barotropic or as a baroclinic response. As mentioned above, Ingebrigtsen (1977) has shown by experiments in a tank on a rotating table that a deep countercurrent may exist below a surface coastal current, when fresh water is discharged from the coast. Under stationary conditions, Ingebrigtsen found that the ratio between the surface velocity and the deep layer

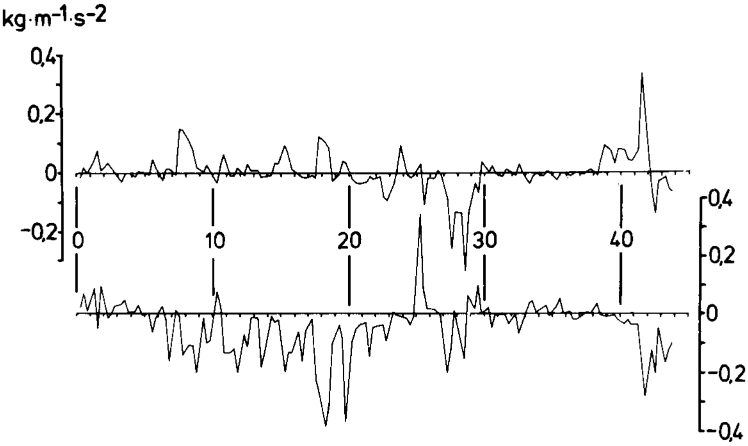

Fig. 5. Windstress towards 315° (upper) and along the coast, towards 225°, computed from wind measurements at Torungen lighthouse near Arendal. Horizontal scales show relative dating which starts at 18 August 1977.

velocity is approximately 6, while the ratio between the residual currents found at 30 m and 395 m is approximately 15. The good agreement of the ratios found indicates that the driving forces in the laboratory experiment the earth's rotation and horizontal density gradients, may be of major importance to explain the dynamic of the countercurrent found at site A. It should also be noted that Mork (1977) has simulated the coastal current in a model where fresh-water supply, mixing and entrainment were parameters of major importance. Mork found good agreement between field observations and model calculations if the entrainment coefficient was given a suitable value. By reasons of continuity vertical entrainment will set up a compensation current. It is therefore possible that the countercurrent found may also be partly explained as a compensation current set up by vertical entrainment by the coastal surface current.

To summarize, the deep countercurrent found below the surface coastal current along the Norwegian coast in Skagerrak may be a permanent phenomenon driven by horizontal density gradients or as a compensation current put up by vertical entrainment of high density water into the coastal current, or most probably, a combination of both. There is evidence that the windstress may have an impact on the countercurrent by baroclinic response to piling up of water in the inner Skagerrak by northeasterly windstress or increased transport out of Skagerrak by southwesterly windstress, but it seems justified to assume that the local windstress is only a modifying factor, not the driving force of the deep countercurrent found.

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О СУЩЕСТВОВАНИИ ГЛУБОКОВОДНОГО ПРОТИВОТЕЧЕНИЯ НОРВЕЖСКОМУ ПРИБРЕЖНОМУ ТЕЧЕНИЮ В СКАГЕРРАКЕ

Измерения скорости указывают на существование квазипостоянного противотечения под Норвежским береговым течением в проливе Скагеррак. Сравнение с локальным напряжением ветра, предыдущие результаты лабораторных экспериментов и моделирования указывают, что сила Кориолиса, горизонтальные градиенты давления и вертикальное проникновение поверхностного течения могут быть факторами, вызывающими это противотечение, в то время как напряжение ветра является лишь модифицирующим фактором.