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RECENT INVESTIGATIONS OF THE FRONTAL REGION IN THE NORWEGIAN COASTAL CURRENT

by

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ABSTRACT

This study is a subproject of the Norwegian research program MARE NOR concerning the circulation and mixing processes in the frontal zone of the Norwegian Coastal Current. The investigation is based on hydrographic observations from transects across the Norwegian shelf off Lofoten/Vesterålen in 1991 and Svinøy in 1992. Exchange processes due to wind induced mixing and entrainment are considered. It will be shown that two subsequent transects along the Svinøy section reveal a frontogenesis process in raising the pycnocline more vertically towards the surface and thus enhancing horizontal density gradient in the frontal region. This enhancement of the front is caused by wind generated turbulence which is more effective in entraining dense water to the mixed layer in regions with shallow pycnocline. For the wedge shaped density profile of the coastal current, this process will result in an enhanced entrainment in the head area of the wedge. Additionally, the wind stress generates an Ekman drift in the mixed layer. Because of mixing and entrainment in the frontal zone it will be demonstrated by mathematical modelling that the frontal movement is much less than the Ekman drift, resulting in an anti-symmetrical circulation pattern in the frontal zone with upwelling on one side and downwelling on the other side.

1. Introduction

This study is a subproject of the Norwegian research program MARE NOR and deals with the circulation and mixing processes in the frontal zone of the Norwegian Coastal Current (NCC). As illustrated in Fig. 1, the NCC flows northward along the coast of Norway as a wedge shaped boundary current in an approximately geostrophic balance. The corresponding main frontal system off the coast is manifested in an interaction of the coastal current and ambient water of atlantic origin - the topographical steered northward flowing Norwegian Atlantic Current (NAC) - and is classified as a meso scale frontal system.

It is a paradox that while ocean fronts are defined as abrupt barriers between water masses inhibiting across-front circulation, the exchange processes have necessarily to take place in the fronts. The dynamic fronts have wide biological and ecological implications in the exchange of water properties as nutrients and fish egg and larvas. A necessary condition for property transfer across a front on top of any advection, is that the front must move relative to the fluid. In the NCC exchange processes have been related to a baroclinic instability mechanism through whirl shedding (McClimans, 1980) and to friction and mixing (Golmen and Mork, 1988). Off mid and northern Norway outburst of coastal water may reasonably take place due to barotropic instability of the NAC flowing northward along the shelf edge. Another phenomenon for exchange of water masses are so called filaments, observed off the coast of California for example. They are generated trough instability processes where waves and meanders grow into eddies and tongues (Flament et al, 1985).

Many processes act in maintaining and disrupting the frontal structure of the NCC. The objective of this study is to investigate the role of one simple mechanism - the wind induced mixing and entrainment - and how changing wind conditions may influence the development and circulation pattern of the front. Wind generated mixing in fronts have been studied in lot of papers and the most relevant investigations for this purpose have been performed by Wang (1990), Csanady (1984) and Dewey and Moum (1990). Csanady supposed wind-induced entrainment to be the dominant cross front transfer mechanism. He postulated entrainment of properties from the depth in an approximate horizontal frontal region and detrainment in a vertical area of 30 m depth near the surface. Dewey and Moum (1990) discussed frontal enhancement in filaments off the coast of California due to wind induced mixing. Wang et al.(1990) modelled the movement of the tidal front in the Celtic Sea related to changing wind conditions.

This study is based on field observations and theoretical considerations. It is another paradox that while mixing smooths out gradients and presumably destroys ocean fronts, it will be demonstrated that wind induced turbulence seems to enhance gradients in NCC front.

2. Observations

The hydrographic observations to be discussed were obtained in three transects across the Norwegian shelf. Fig. 2 shows a section to the west of Lofoten/Vesterålen in May 1991 and Fig. 3-4 two subsequent transects across Buagrunnen in April 1991, all CTD data collected by R/V Håkon Mosby. Dense CTD casts were taken in the frontal zone to improve the resolution of the hydrographic field. Figs. 5 and 6 show two subsequent transects along the standard Svinøy section in March 1992, collected by R/V G. O. Sars at the Marine Research Institute. Fig. 5 shows the section in a westward track and Fig. 6 the returning eastward track emphasising the dynamics in the frontal zone. Fig. 7 shows corresponding T-S observations from the cooling intake at 4 m depth, collected by a Gytre TS sensor. These observations show considerable deviations and are only applicable in resolving relative changes of the hydrography.

The transect in Fig. 3 was obtained during light winds while the subsequent section in Fig. 4 was obtained just after a period with south westerly winds of gale force. Similarly, on the westward Svinøy transect the wind conditions were light while the eastward transect was obtained just after a stormy wind event where northerly winds up to 25 ms^{-1} were observed over a 20 hours period. These occasional meteorological events have made it feasible to study frontal developments of the NCC due to changing wind conditions - frontogenesis - both for SW and N winds.

The Lofoten/Vesterålen section in Fig. 2 was obtained during gale NW wind of 10-15 ms^{-1}. The figure is shown just to illustrates two striking features observed frequently in the NCC front during northerly wind conditions; a sharp front with nearly vertical isopycnals trough the mixed layer and a westward excursion of mixed layer coastal water encountering the NAC.

The westward Svinøy transect in Fig. 5 shows a linear increase in the wedge-shaped density field with a corresponding wide frontal zone over the shelf edge region. The subsequent eastward transect in Fig. 6 however, obtained just after the storm event, shows a considerable development in the frontal region. The isopycnals in the mixed layer are raised in a more vertical feature and pressed together in a corresponding enhanced front. Comparing the westward and eastward TS observations in Fig. 7 a similar frontal development is indicated, showing a narrowing of the frontal zone on the eastward track. Additionally, a striking nose shape seems to develop in the head of the frontal region. This remarkable development with an enhancement of the front is presumably related to wind-induced mixing in the surface layer. Generally, wind-generated turbulence is more effective in entraining dense fluid into the surface mixed layer when and where the pycnocline is shallow. For the wedge-shaped NCC this surface-forced mixing will cause a more rapid increase in mixed layer density near the head of the wedge. This frontogenesis process will then rule out the vertical density contrast proximity to the head of the wedge and raise the pycnocline towards the surface in an enhanced horizontal density gradient. Additionally, the striking nose shaped front appears as a result of the spatial varying entrainment and mixing. This wind generated erosion of water below pycnocline in bringing more dense water into the surface layer is a crucial mechanism for transporting water properties for ex. nutrients, into the surface layer.

The hydrographic transects in Figs. 2 and 6 indicate offshore frontal movements during northerly winds. This lateral movement of the front is driven by the offshore Ekman transport. As shown by Csanady 1984, wind induced mixing and entrainment will cause the front to move slower than the Ekman drift. Consequently, a modified Ekman transport will generate vertical motions in the proximity of the frontal zone. Sea Soar transects in the NCC for example, have indicated circulation-patterns with upward motion on one side and downward on the other side of the front (Golmen and Mork, 1988). This circulation pattern does not correspond to common accepted theories showing downward motions in ocean fronts (Garvine, 1979).

The Figs. 3 and 4 show the response of the NCC to SW winds and they indicate a different frontal development compared with the northerly wind events. A striking feature of the frontal response is a contraction of the isopycnals in an sharper front without much change of position of the front. The striking different response of the NCC front for N and SW winds is caused by many factors. Among other things the Ekman drift is oppositely directed with an offshore transport for N and onshore for SW winds. The coupling between advection and mixing is also quite different where SW winds generate advection in direction of decreasing density and thus a deepening of the mixed layer. For N winds the effect due to advection will be opposite in increasing the vertical stability. These a-symmetric effects will cause different responses on the NCC front which will be demonstrated and discussed in the section to follow, based on mathematical formulations. It will also be demonstrated how changing winds affect the frontal circulation pattern, where opposite directed winds may reverse the circulation pattern.

3. Model

A model is proposed to explain wind-induced frontal enhancement, movement and circulation pattern in the front of the NCC. A two-dimensional, hydrostatic and linearized model will be considered, where the lower layer is assumed deep enough to be regarded as dynamic passive - a reduced gravity model. The NCC is simulated by assuming a geostrophically balanced alongshore current in the upper layer, described relative to a Cartesian coordinate system (illustrated in Fig. 8). The governing equations for the motion of the upper layer with density ρ and thickness h can be obtained

(1) $\bar{\rho} f v = p_x$

(2) $v_t + fu = \tau_z$

(3) $h_t + (\bar{u}h)_x = w_e$

(4) $(\rho h)_t + (\bar{u}h\rho)_x = w_e \rho_i$

Equations (1)-(2) derive from the horizontal components of the momentum balance, while eqs (3)-(4) turn out after a vertical integration of the conservation equations for volume and mass. u, v and w are respectively offshore, alongshore and vertical velocities and w_e is the entrainment velocity of deeper layer water with density ρ_i through the pycnocline. τ is the y-component of frictional stress and f the Coriolis parameter. Subscripts x, y, z and t signify partial derivatives, respectively and - vertical means.

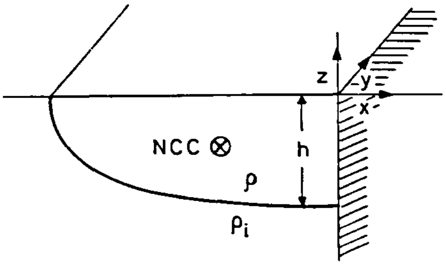

Fig. 8 Sketch of the model of the NCC as a reduced gravity model

The hydrostatic pressure for the upper layer may be splitted and written as

$$p = p_0(x,t) - \rho g z.$$

Making use of the condition of a dynamic passive deeper layer, yields

$$p_0 = \bar{\rho} g' h, \text{ where } g' = g(\rho_i - \rho)/\bar{\rho} \text{ is the reduced gravity.}$$

Thus, inserting p into (1) yields

$$v = \frac{(g'h)_x}{f} + \frac{g_x z}{f}$$

Integration of (2) over the upper layer results in the following equation for the across current transport

$$\bar{u}\, h = -\frac{\overline{v_t}\, h}{f} + U_E - U_F \tag{6}$$

where u and v denote vertical meaned velocities.

$U_E = \frac{T_w}{\bar{\rho} f}$ *is the wind induced Ekman transport for wind stress* T_w.

U_F is the boundary layer transport driven by friction at the interface. Making use of Ekman-type boundary friction, the offshore frictional transport turns out to be $U_F = D_e v/\pi$, where $D_e=\pi(2A_e/f)^{1/2}$ is the Ekman depth and A_e the eddy viscosity for the boundary layer.

The entrainment velocity w_e is presumably governed by wind and it is parameterized according to Price, 1979 as

$$w_e = k\frac{T_w}{\bar{\rho}\sqrt{g'h}} \tag{7}$$

It is outside the scope of this work to solve the problem completely, so the model will be discussed qualitatively and some conclusions will be drawn. It follows from eq (6), that the wind generates across-current transport and thus frontal movements according to three effects; the variability of the basic current, the wind-induced Ekman drift and the frictional Ekman transport at the boundary. Fig. 9 illustrates how these effects in combination with entrainment affect the NCC frontal zone with respect to the frontal shape, lateral movements and circulation pattern.

Variability of the along-shore basis current will be influenced by many factors as wind stress, boundary effects as piling up of water and changing baroclinicity of the density field and is thus difficult to interpret. Eq (6) shows offshore transport for accelerations of the basic current and onshore transport for retardation, respectively. Increase of the baroclinicity of the field will presumably accelerate the surface layer in a baroclinic jet in the frontal zone.

It follows from eq (6) that the cross-current component due to wind induced Ekman transport acts oppositely for N and S winds. As illustrated in Fig. 9(II), for northerly winds the Ekman drift will advect lighter water offshore with a component of the Ekman boundary transport in the same direction. For southerly winds (Fig. 9 (I)) the Ekman drift will advect denser water onshore while there still will be an off-shore component of the boundary transport acting oppositely. Consequently as illustrated in Fig. 9., additive Ekman-effects for northerly winds will cause a considerable off shore frontal movement, presumably of the order of Ekman speed, while opposite acting Ekman-effects during southerly winds will leave the front more stationary.

This asymmetry of wind-induced frontal movement will influence the frontal circulation pattern. As indicated in Fig. 9, the most striking vertical velocity proximity to the front will develop for southerly winds. There will be downwelling on the offshore side and up-welling on the on-shore side. Additionally, the effect of advection of denser water over lighter water will cause downwelling on the offshore side of the front and enhance this circulation pattern. For northerly winds the circulation pattern will be reversed, but because of larger frontal movements, vertical circulation will be less prominent.

Wind-induced frontal enhancement cannot be resolved from a two-layer model, an extension to a multi-layer model will be necessary. Due to the entrainment velocity w_e in (7), it follows that the entrainment rate will be greatest in proximity to the front. As illustrated in Fig. 9 the entrainment will affect the density field in raising the isopycnals in correspondence with observations discussed in the section above.

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Figure legends

Fig. 1. Major surface currents of Norwegian and adjacent seas.

Fig. 2. Hydrographic- temp and salinity- cross-section west of Lofoten. May 1991.

Fig. 3. Hydrographic- temp and salinity- section across Buagrunnen. April 7, 1991

Fig. 4. Hydrographic- temp and salinity- section across Buagrunnen. April 10, 1991

Fig. 5. Hydrographic- temp and salinity- section Svinøy, westward track. March 1992

Fig. 6. Hydrographic- temp and salinity- section Svinøy, eastward track. March 1992

Fig. 7. Hydrographic-temp and salinity- observations along the Svinøy section,4 m depth.

Fig. 8. Sketch of the model of the NCC as a reduced gravity model.

Fig. 9. Sketch of the wind-induced response of the NCC for southerly winds (I) and northerly winds (II). The figure indicates frontal development, lateral movement, enhancement through contraction of isopycnals and circulation pattern.

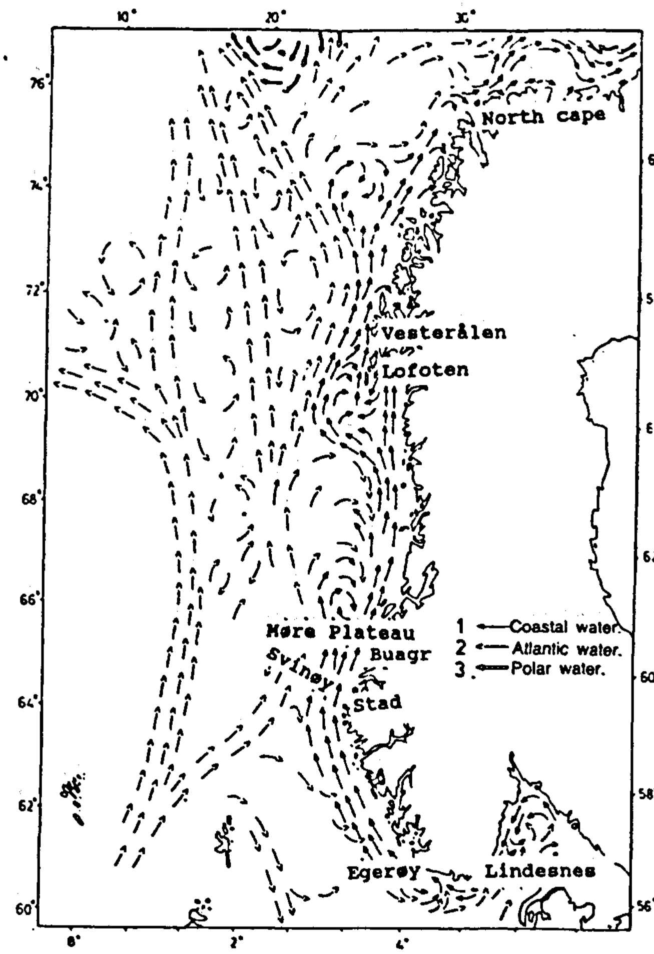

Fig. 1

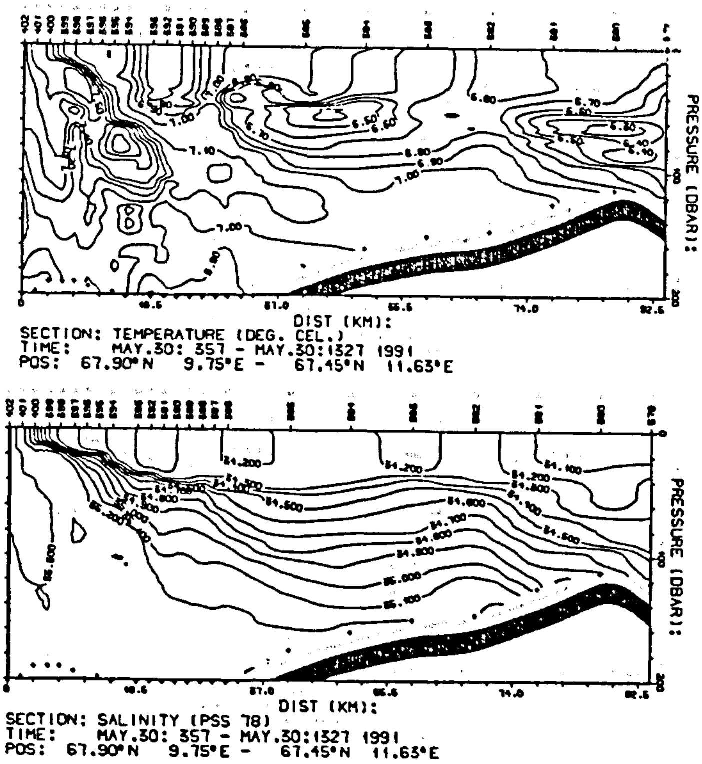

Fig. 2

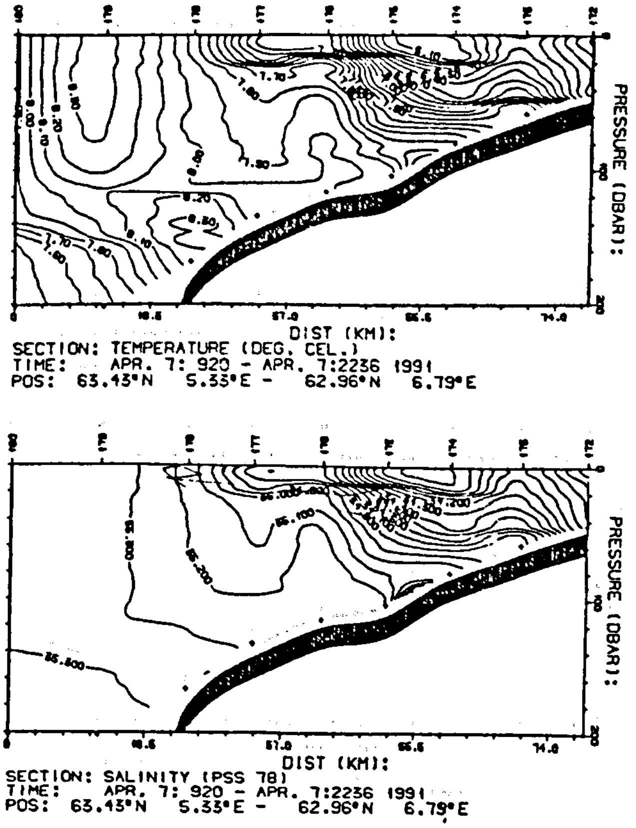

Fig. 3

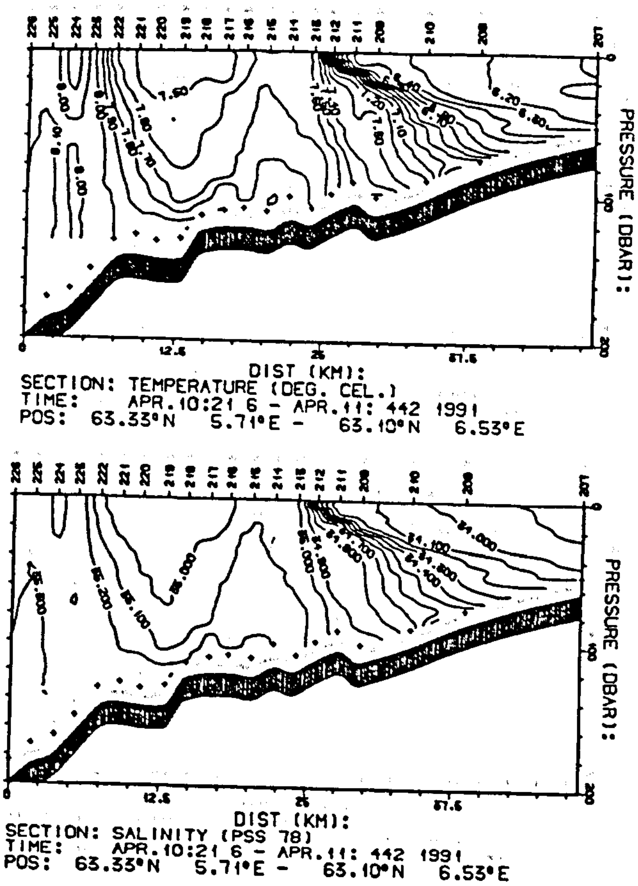

Fig. 4

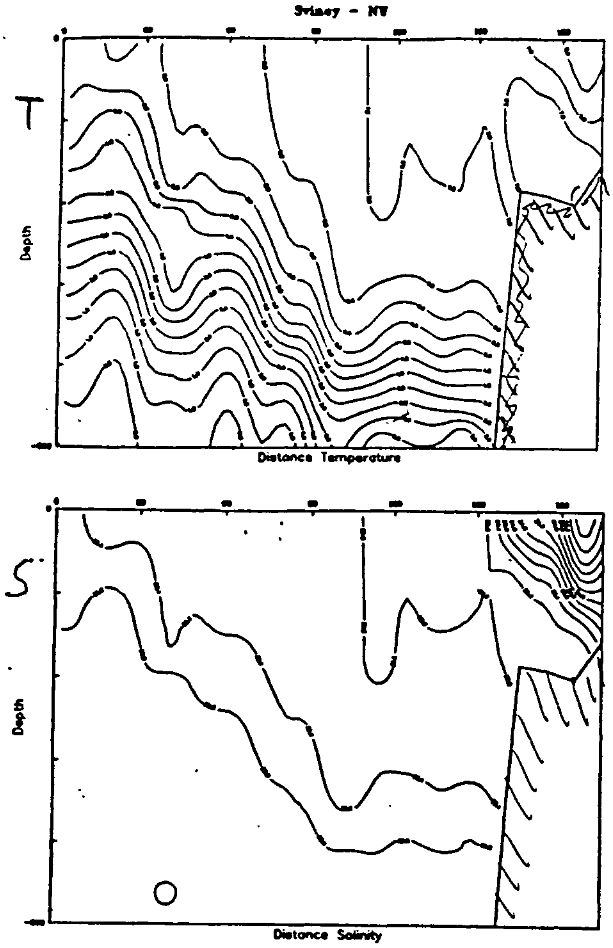

Fig. 5

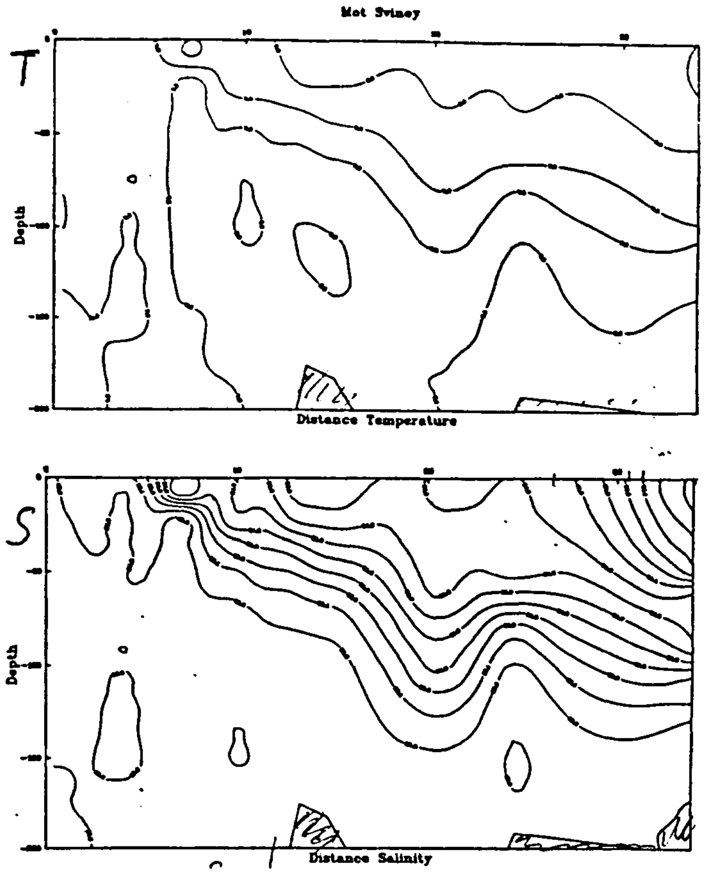

Fig. 6

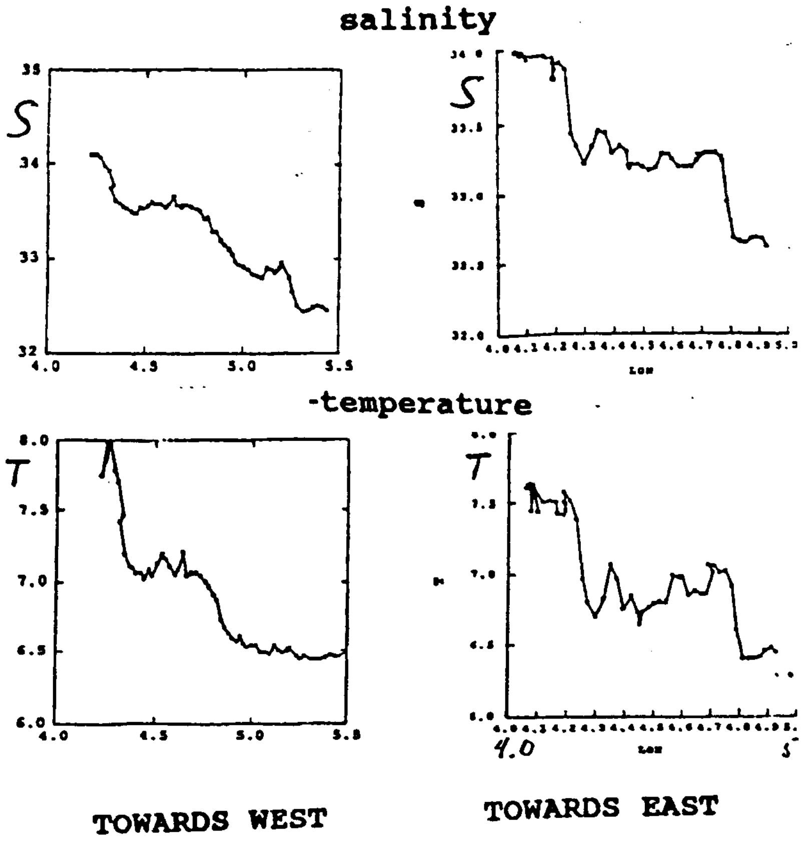

Fig. 7

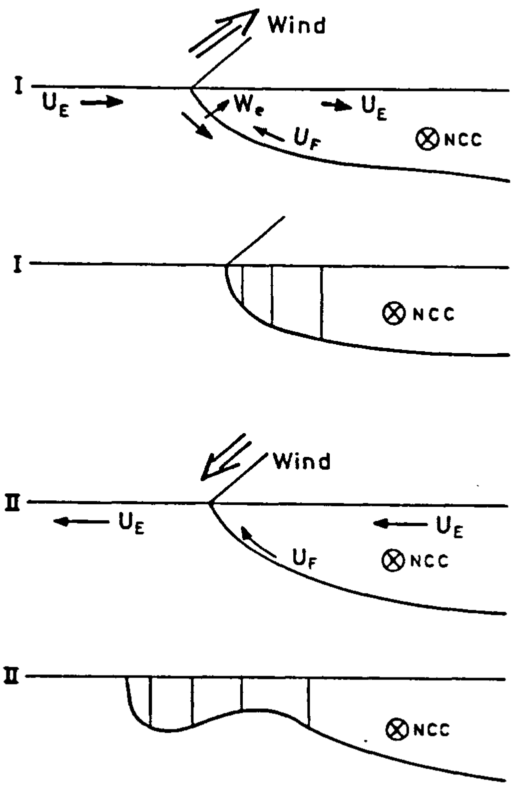

Fig. 9