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Characteristics of Three-layer Circulation and inverse Surface Salinity Gradients in Two Small Semi-enclosed Danish Embayments

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Inverse surface salinity gradients were measured in two small Danish embayments. Three possible mechanisms are taken into account. In Knebel Vig the circulation and salinity distribution can be generated by tidal modification of the stratification at the entrance which is maintained by external dynamics rather than by fresh water discharged into the embayment. In Egens Vig the involved mechanisms can be coastal upwelling and difference in heating between shallow waters near the coast and deeper waters in the central part of the embayment.

Introduction

In estuaries with negligible river discharge circulation can be induced by mixing of an externally maintained density stratification (Hachey 1934; Hansen and Rattray 1972). At depth the resulting distribution of salinity has the normal positive seaward gradient. In the upper layer a negative seaward gradient is observed. Pritchard and Carpenter (1960) described the accompanying flow pattern, which is characterised by inward flow near the bottom and the surface and outward flow in between.

A mathematical model for this type of estuarine circulation was presented by Hansen and Rattray (1972) and further discussed by Hansen and Festa (1974), using similarity solution techniques.

Rattray and Hansen (1962) showed that a similar three-layer circulation could develop from normal estuarine circulation if a sufficiently large wind stress opposed surface flow.

Pritchard and Carpenter (1960) argued that this type of circulation is important as a flushing mechanism for Baltimore Harbor in the Chesapeake Bay. The outside density distribution was also suggested to be important for circulation in the Oslo fjord in Norway (Gade 1970) and in the Gullmarfjord in Sweden (Rydberg 1975). Similar characteristics were observed in two small Danish embayments Knebel Vig and Egens Vig in connection with sedimentological investigations (Christiansen et al. 1981, Christiansen and Lomholt 1980). Here the lower salinity layer originates from brackish waters in the Baltic, flowing out through the Danish sounds.

Regional Setting

Egens Vig is situated on the north coast of Kalø Vig (Fig. 1). The surface area is 4.0 km^2 and the volume is 15.7×10^6 m^3. Egens Vig is partly separated from Kalø Vig by a submarine moraine ridge with two inlets. There are practically no freshwater discharge into Egens Vig.

Knebel Vig is situated on the east coast of Kalø Vig (Fig. 1). A 750 m wide channel (only 240 m wide between the 2 m depth contour lines) with a maximum depth of 16 m and a cross-sectional area of 2,100 m^2 leads from Kalø Vig into the embayment. Knebel Vig has a surface area of 7.5 km^2 and a volume of 52.4×10^6 m^3. The only surface freshwater supply is a small brook with an average discharge of 0.15 m^3 s^{-1}.

Both embayments are microtidal with a tidal range of 0.40 m. They do not respond independently to meteorological effects, but responds strongly to the water exchange between the Baltic and the North Sea through the Kattegat. The water level fluctuates between the values of 1.5 m above and 1.2 m below DNN (Danish Ordnance Datum). Westerly winds give positive deviations while easterly winds give negative deviations.

There is considerable seasonal variation in mean sea level. Mean sea level is lowest (-0.18 m) in April and highest (+0.20 m) in November.

Methods

Salinity and temperature were determined in situ with salinometers type EIL-MC5. The accuracy is within ± 0.1 with regard to *S* 0/00 and ^{0}C. Measurements were made simultaneously from the research vessel »Genetica« and two rubber boats to eliminate to the best of our possibilities any changes in *S* and *T* as function of time.

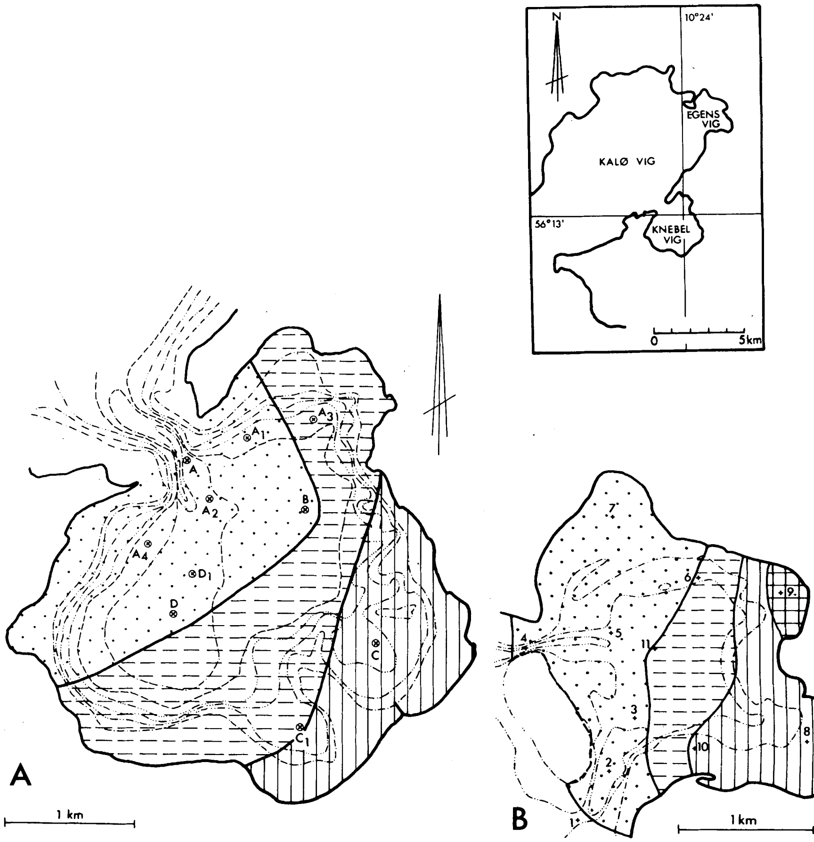

Fig. 1. Locational map showing: A) Hydrographical stations and surface salinity distribution (‰) in Knebel Vig. June, 3rd 1976. [dotted] 20,0-20,5 [dashed] 20,5-21,0 [vertical lines] 21,0-21,5. B) Hydrographical stations and surface salinity distribution (‰) in Egens Vig. April, 4th 1978. [dotted] 22,0-22,4 [dashed] 22,5-22,9 [vertical lines] 23,0-23,4 [grid] 23,5-23,9

Current velocity and direction were determined with two direct reading current meter, a Braystoke type MK II and an OTT type Muldedag.

Positions were determined by intersection from stations ashore and marked with buoys.

Wind velocity and directions were measured with self-recording Lambrecht Windmeters. In Knebel Vig we have used data from a local 4 m high mast. In Egens Vig we have used data from Aarhus about 20 km to the SW of the embayment.

Results

Knebel Vig

In Figs. 2A and 3 A are plotted some of the synchronous measurements of temperature and salinity at stations A, B and C covering every second hour within a tidal cycle on June 3, 1976. Current-measurements at station A were synchronous with measurements of temperature and salinity. Current-measurements at station B and station C were performed during the succeeding days, when water level variations were the same as on June 3, because of light winds (Fig. 4C).

At low water there is a three-layer circulation at station A and station B with inward currents in the top 8 m and close to the bottom. Currents are outgoing from 9-10 m depth just above the pycnocline. Surface salinity is highest at the head of the embayment. Temperature in the outgoing current is 13.4^{0}C, which is higher than temperatures both above and below the outgoing current. This could be indication of some properties of the outgoing current originating from downwelling of warmer surface water at the head of the embayment where there must be a rather strong vertical mixing.

At low current velocities four and two hours before high water no three-layer circulation were observed. Four hours before high water (Figs. 2B and 3B) both temperature- and salinity distribution in the vertical section are close to normal. Two hours before high water (Figs. 2C and 3C) signs of downwelling of surface water between station B and station C are observed both in the temperature and the salinity distribution. Salinity was highest at the surface at station C.

At high water (Figs. 2D and 3D) we observed three-layer circulation, with inward currents in the top 8 m and at the bottom and outgoing current from 9-10 m depth. There are evidences of entrainment at the bottom between station B and station C.

Two hours after high water (Figs. 2E and 3E) there are still signs of entrainment between stations B and C. Four hours after high water (Figs. 2F and 3F) both the temperature distribution and the salinity distribution are close to normal like four hours before high water. During this period the three-layer circulation was not observed.

Egens Vig

In the embayment we have no measurements of currents synchronous with measurements of salinity and temperature. From longitudinal profiles of temperature and salinity there seem to be at least two different factors which can establish an inverse gradient of surface salinity.

On June 20, 1978 there was a slightly higher salinity (19.8 0/00) at the head of the Vig, at station 9 than at the mouth 19.5 0/00 at station 1 (Fig. 5 B). The day was very sunny and calm (2-4 m/s) (Fig. 4 B). Therefore surface temperatures (Fig. 5A) are much higher at the shallow water stations (20.2^{0}C at station 9) than

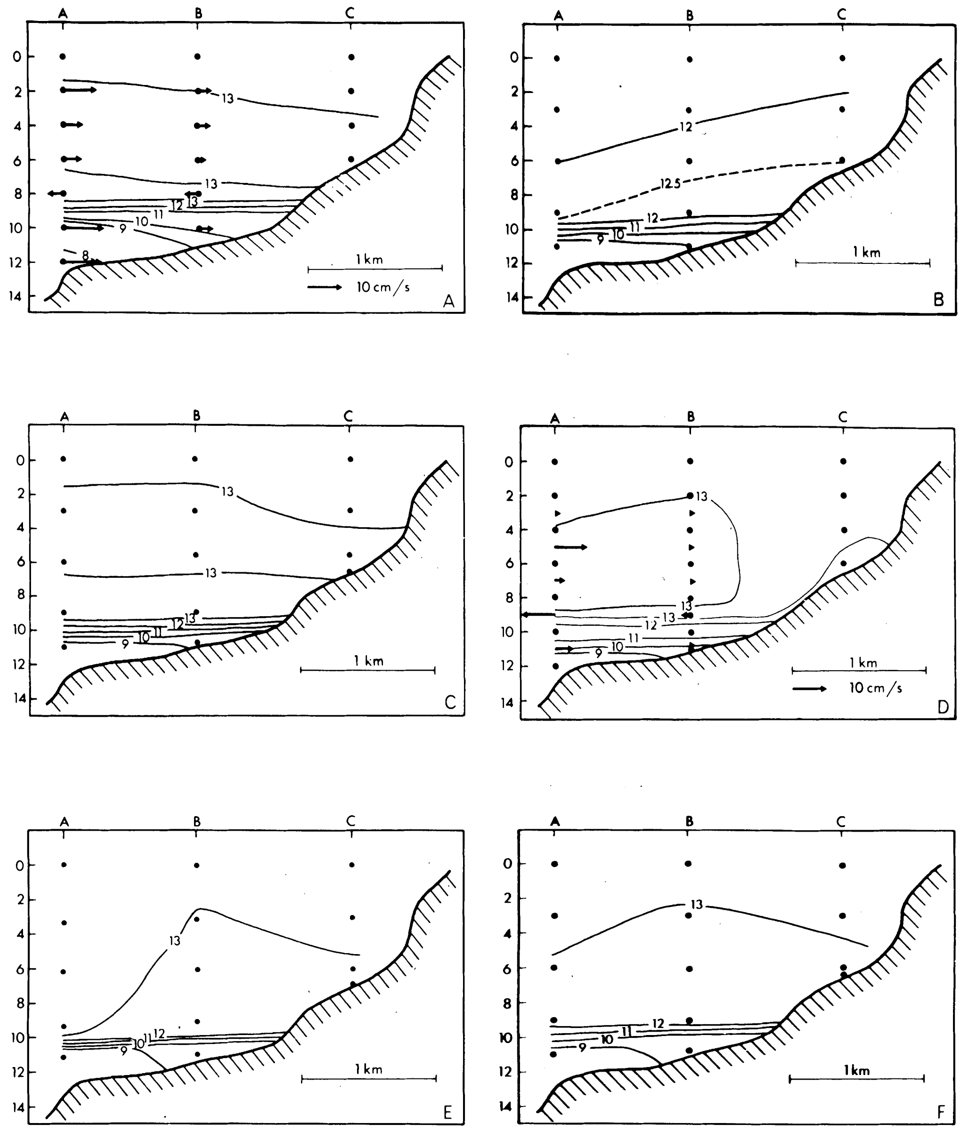

Fig. 2. Vertical temperature (°C) sections in Knebel Vig through stations A, B and C, June, 30th 1976. Arrows gives current velocities (cm s^{-1}). A) Low water, B) 4 hours before high water, C) 2 hours before high water, D) High water, E) 2 hours after high water F) 4 hours after high water.

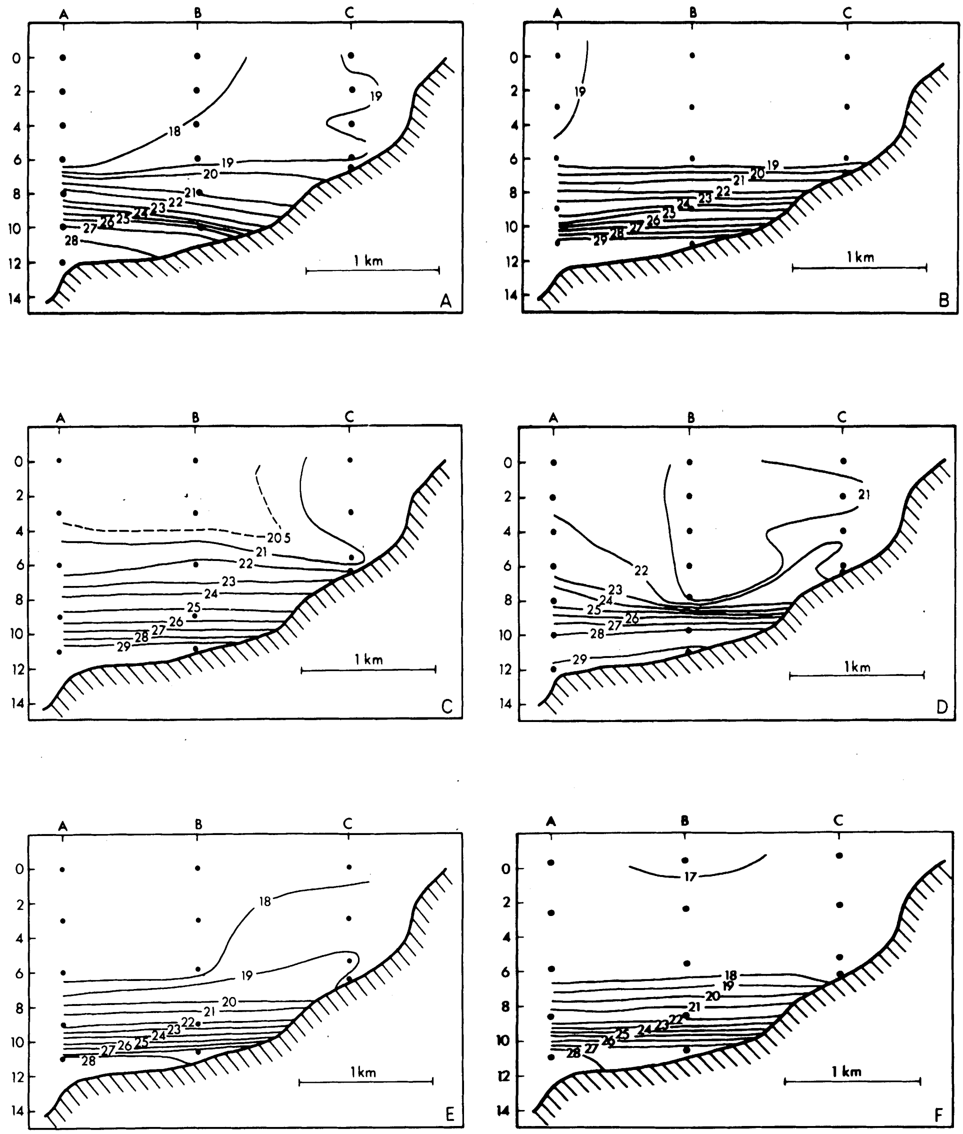

Fig. 3. Vertical salinity (S ‰) sections in Knebel Vig through stations A, B and C, June, 30th 1976. A) Low water, B) 4 hours before high water, C) 2 hours before high water, D) High water, E) 2 hours after high water F) 4 hours after high water.

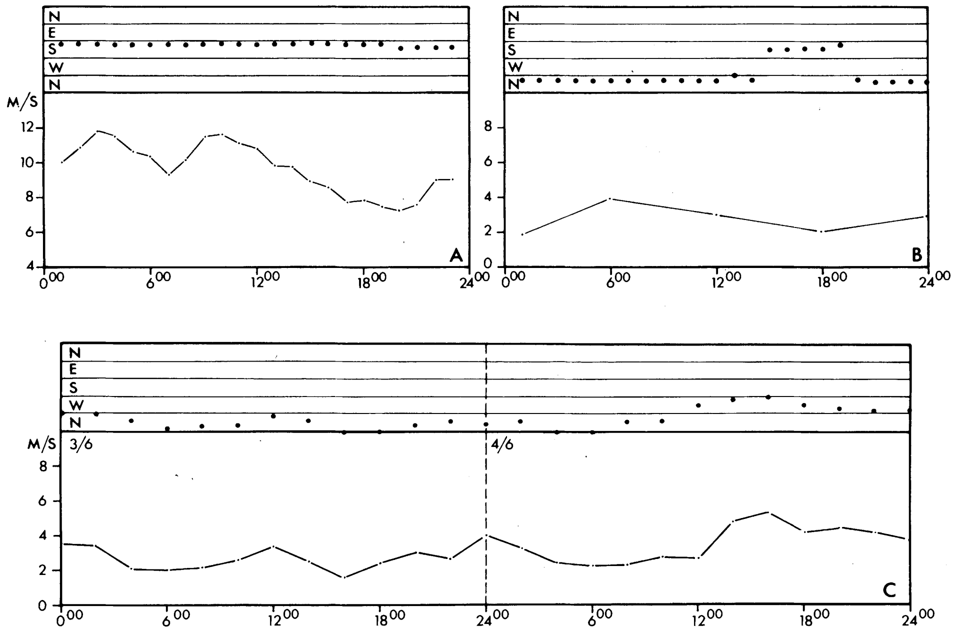

Fig. 4. Wind data during the investigations. A) Egens Vig. April, 28th 1978. B) Egens Vig, June 20th 1978. C) Knebel Vig, June 3-4th 1976. Note the different scales on the velocity axis.

at stations with relatively deeper waters (16.1^{0}C at station 1).

Using Penman's formula (Penman 1956) evaporation from the water surface can be estimated at 4 mm. If we assume that the consequent raise in salinity at station 9 (1 m water depth) is distributed over the top 25 cm of water this could explain the inverse salinity gradient in Fig. 5B. Fig. 5C shows that the effect of increased temperature on density more than compensates the effect of raise in salinity i.e. the apparent instability shown by the salinity curves is therefore apparent and not real.

On April 28, 1978 the inverse salinity gradient is more pronounced (22.1 ‰ at station 1 and 23.7 ‰ at station 9) (Fig. 6B).
The day was stormy, 8-12 m/s with winds from the ESE (Fig. 4A). The off-shore winds creates upwelling of bottom water with a higher density at stations at the head of the Vig. Fig. 6C shows that the density (expressed as σ_t) is 18.5 at the surface at station 9 and 17.4 at the surface at station 1. On this occasion the instability shown by the salinity curves is confirmed by the density curves.

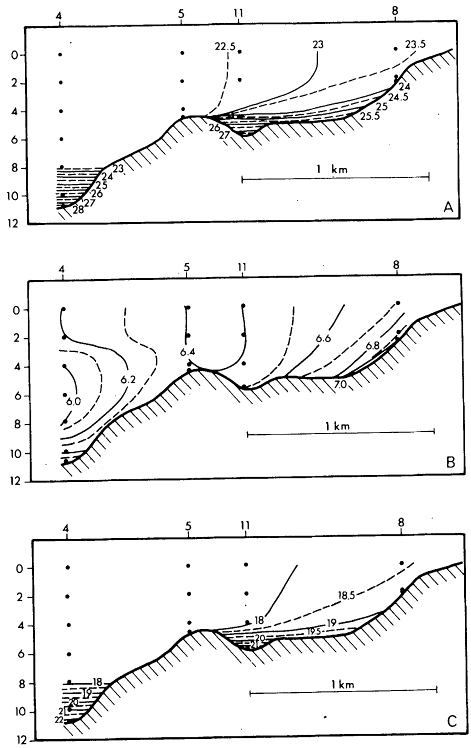

Fig. 5. Vertical sections in Egens Vig through stations 4, 5, 11 and 8. June, 20th 1978: A) Salinity distribution (‰). B) Temperature distribution (°C). C) Density distribution (σ_t).

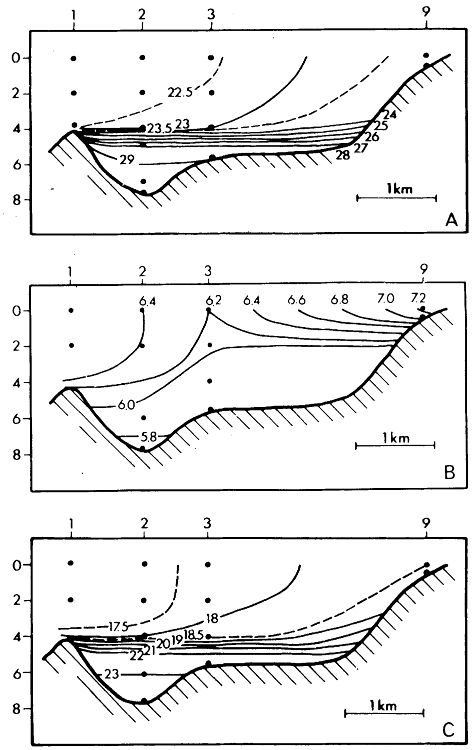

Fig. 6. Vertical sections in Egens Vig through stations 1, 2, 3 and 9. April, 28th 1978: A) Salinity distribution (‰). B) Temperature distribution (°C). C) Density distribution (σ_t).

Discussions

Long (1977) developed a theory for three-layer circulation in a estuary accompanying a two-layer structure in the body of water outside. Assuming uniform depth H of the fluids outside and inside the estuary, zero fresh-water influx, and equal thickness of the two layers of fluids outside the estuary he showed that a solution to the theory is that the outflowing water from the estuary has a thickness $d = H/2$ and a flux $q = HW\,(H\,\triangle b_o)^{1/2}/8$, where W is the width at the construction and $\triangle b_o$ the buoyancy difference between the two outside layers of water. He also showed that inside the estuary, far downstream, the outflowing fluid has a thickness aH, where

$$a = \frac{1}{2} [1 - (1 - \frac{W}{W_0})^{\frac{1}{2}}]$$

W_0 being width inside the estuary.

Testing this theory using data from Knebel Vig we found $aH = 0.8$ m. This is in good agreement with observations (see station B in Fig. 2A) which shows that aH is app. 1 m. Fig. 2A also shows that the thickness of the outflowing water at station A still is appr. 1 m. In theory the thickness of the outflowing water should be 6 m. A possible explanation of this inconsistency could be that station A still lies within the embayment (Fig. 1). An increase in thickness of the outflowing water should therefore be expected further out of the entrance to Knebel Vig.

In Knebel Vig there is little doubt that tidal mixing is responsible for creating the observed three-layer currents and the accompanying inverse salinity gradient. The three-layer currents are only observed when currents are strongest. The net-circulation June 3, 1976 being inflow at the top 8 m, outflow from there to the bottom. The Simpson-Hunter (1974) stratification parameter $h/_u3$ changes drastically between station B and station C because of the rising slope. The tide therefore creates the same mixing process as did the cylinder in the experiment of Hachey (1934) or the egg-beaters in the experiment of Long (1977).

Three-layer currents with inflow at mid-depths have been observed in Egens Vig under stormy (upwelling) conditions (Lomholt 1979). It still remains uncertain whether the generating force is the tide or the wind. At a much greater scale Boicourt and Hacker (1976) off the coast of Delaware observed that an offshore Ekman flow forced a return flow in the form of a strong mid-depth intrusion.

The observed inverse salinity distributions seem to have biological significance. Stations at the head of both Knebel Vig and Egens Vig are characterized as having more algae and other signs of higher water renewal than the rest of the embayment.

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