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Horizontal and vertical exchanges and diffusion in the water masses of the Oslo Fjord

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KURZFASSUNG: **Horizontale und vertikale Austauschvorgänge und Diffusion in den Wasserkörpern des Oslofjords.** Der Wasseraustausch des inneren Oslofjords wird von einer Zirkulation innerhalb des Ästuars beherrscht. Die Advektion von Brackwasser erreicht Maxima im Frühjahr und Herbst, während sie im Winter und Sommer praktisch fehlt. In tieferen Schichten setzt die Zirkulation periodisch aus; hier ist ein Jahreszyklus feststellbar. Dieser Vorgang scheint in Beziehung zu den winterlichen Nordwinden zu stehen. Ein horizontaler Austausch erfolgt durch Gezeitenströme. Diese Form des Wasseraustausches ist vornehmlich während des Sommers von Bedeutung.

INTRODUCTION

In this lecture I shall give an account of the most important features and processes affecting the water exchange in the inner Oslo Fjord. I shall comment briefly on the general structure of the water masses of the fjord and discuss the various processes found to be of direct or indirect importance in the overall exchange system.

We have seen that the inner part of the fjord, consisting of the two basins, the Vest Fjord and the Bonne Fjord, is separated from the outer fjord by the Drøbak Sound where a submarine ridge forms a sill of maximum depth of 19.5 m.

For the present account, it is practical to divide the water in the fjord into two phases, a lower phase consisting of an almost homogeneous sea-water mass of salinities above 31 ‰; and an upper layer of more or less brackish water, having a salinity chiefly less than 30 ‰. The two phases are not separated by a sharp thermocline or halocline, as the salinity of the upper layer gradually increases with depth towards the salinity of the sea-water phase, making it sometimes hard to define an absolute boundary between the two. In both layers seasonal changes of the salinity occur, in the sea-water phase, however, strictly in connection with influx of water from outside and subsequent reduction of salinity by vertical exchange. In the upper layer the seasonal variation of salinity is coupled to the variation of local runoff and precipitation, and also, to a considerable extent, to the monsoon type wind system of the region. Thus, in the summer the surface salinity goes down to between 15 and 20 ‰, whereas in the winter long periods exist with practically no brackish water present in the fjord.

It follows from the above mentioned seasonal variations that the thickness of the upper layer of brackish water must vary accordingly. In summer, the sea-water phase is encountered usually below the 15 m level, sometimes even deeper than the sill depth of 19.5 m. In winter, the thickness of the brackish water layer is reduced to a few metres; often it is virtually absent.

Like most Norwegian fjords, the Oslo Fjord is one with excess runoff and precipitation. One would therefore expect that the corresponding estuarine circulation would determine the water exchange of the fjord. Although this is generally the case, seasonal changes of the runoff cause great variation in the flux of brackish water. Furthermore, various other factors seem to play decisive roles in determining the dynamics of the overall exchange system.

The water exchange and water renewal is brought about by several different processes. It is possible to divide these processes into two groups, one containing factors which lead to a net circulation of the water in the fjord, and the other referring to exchange processes where there is no net transport of water. In the first group, wind driven circulation and the estuarine circulation are the most important factors. Of the non-circulatory processes, tides and also short-period wind drifts appear to contribute significantly to the exchange. Each of the above mentioned processes, including interactions and related processes, will be discussed in the following.

VERTICAL EDDY DIFFUSION

Vertical eddy diffusion takes place at all levels in the fjord, leading to a gradual decrease of salinity at all subsurface depths. In periods where the deeper water masses in the fjord have been stagnant the salinity reduction has shown a remarkedly systematic variation (Figs. 1 and 2). On the basis of the diffusion coefficients obtained it is possible to predict, with reasonable accuracy, the salinity at all levels in the major basins of the fjord (Fig. 3).

The net water exchange caused by vertical diffusion is not particularly great. Thus, in the Bonne Fjord bottom water renewal via vertical diffusion amounts to about 1 % per week. The actual amount of renewal is much less, because the replacement water needs about 20 weeks to reach the bottom area. Water exchange in higher levels is much more extensive; it is of the order 1.6 % per week in 80 m depth, where the time needed for renewal water to reach this depth averages about 7 weeks. In terms of eddy diffusion, the coefficient varies from about 0.1 cm^2/sec at the 20 m level to about 1 cm^2/sec in deeper levels (Fig. 4).

Exchange conditions in the Vest Fjord are considerably better. The bottom water is renewed at a rate of about 6 % per week with water of an average "age" of 3.5 weeks. The corresponding figure for the 80 m level is 7.1 % per week. To reach this level the water needs on the average 2 weeks. Eddy diffusion in the Vest Fjord is up to ten times more intensive than in the Bonne Fjord.

The tendency of increased vertical exchange towards the outer parts of the fjord is a general feature. In the Skagerrak, the diffusion coefficient reaches oceanic values, being about ten times higher than in the Vest Fjord.

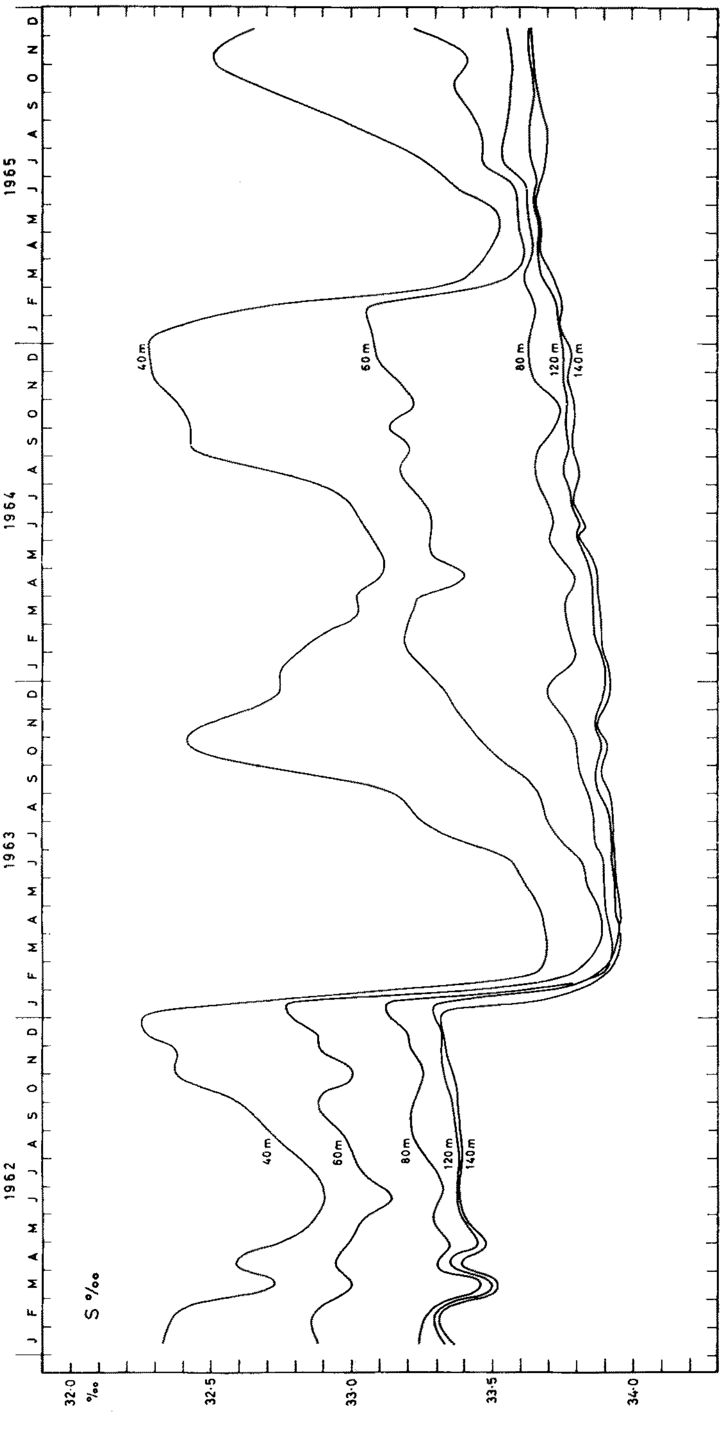

Fig. 1: Salinity variations in the deep water of the Oslo Fjord 1962 to 1965, Bonne Fjord

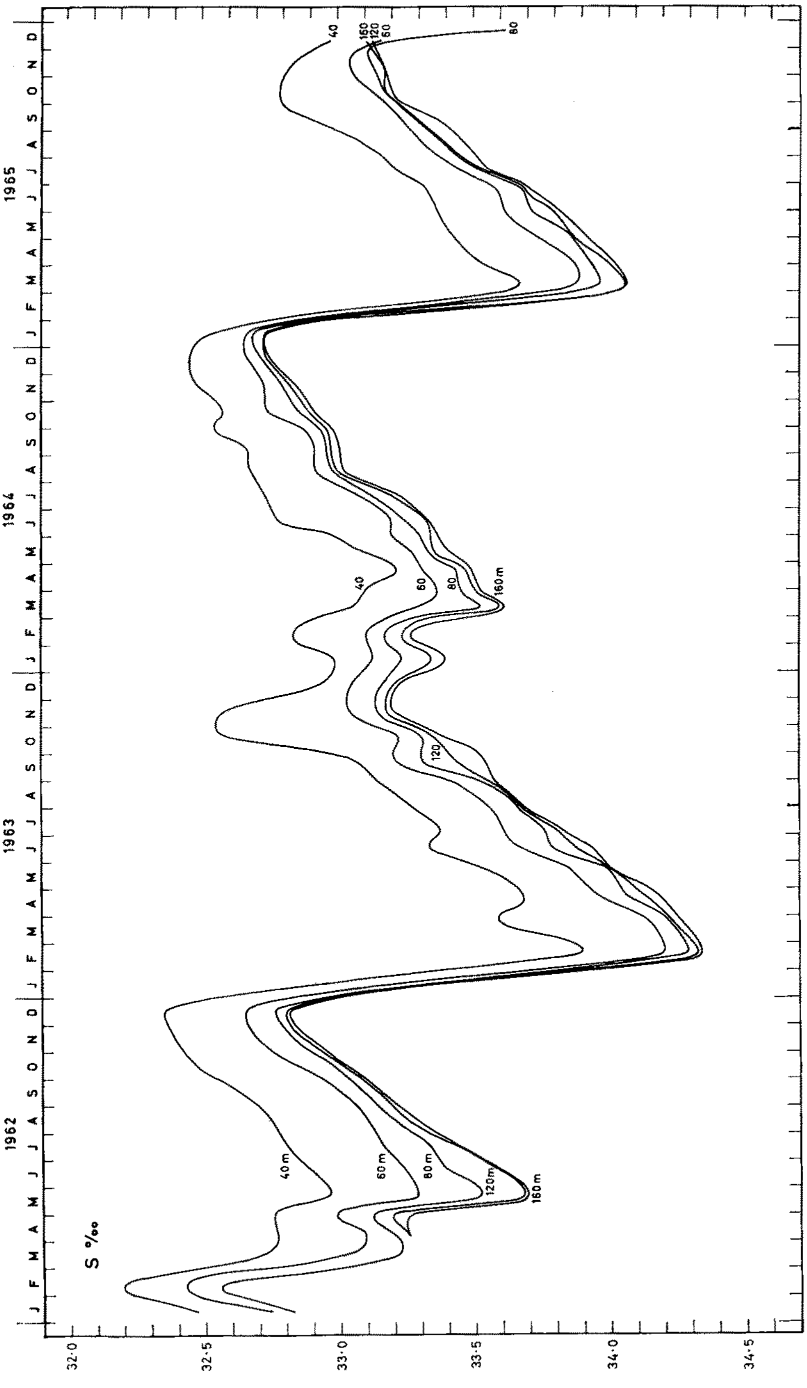

Fig. 2: Salinity variations in the deep water of the Oslo Fjord 1962 to 1965, Vest Fjord

Water renewal by eddy diffusion in the deeper parts of the fjords has little direct consequences for the quality of the water, since levels from which the renewal water originates, that is, the upper strata of the sea-water phase, are usually already polluted and have a low oxygen content. Only in periods of advective influx of sea-water to these levels does eddy diffusion exchange contribute significantly to the purification

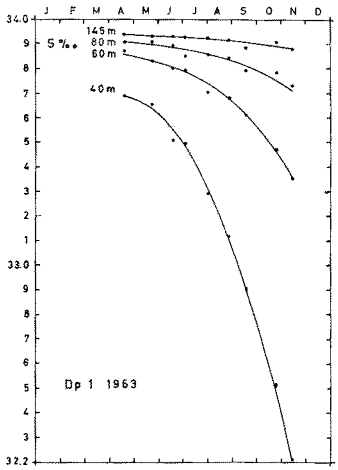

Fig. 3: Observed and computed salinities in the Bonne Fjord

of deeper water masses. Sea-water influx in the upper strata occurs a few times per year, and it seems not beyond hope that it could be increased artificially to such an extent that vertical eddy diffusion may lead to a significant purification of deeper water layers.

In the brackish layer, vertical eddy diffusion is of direct importance for the eddy transport of salt and thus for the entire estuarine circulation. It is, however, not feasible to employ the salt budget for the determination of diffusion coefficients, which can be obtained far more easily by harmonic analysis of the temperature field. Pertinent results show that the coefficient of vertical eddy diffusion has a minimum in the lower parts of the brackish phase with values of 0.05 cm^2/sec. Above this level the coefficient increases towards the surface where it reaches values of 1 to 10 cm^2/sec.

Through vertical eddy diffusion the entire deep water body in the Oslo Fjord becomes gradually less salty and thus steadily lighter. Presently this is the most important consequence of vertical eddy diffusion processes.

ADVECTIVE RENEWAL OF THE DEEP WATER

The deep water inside the Drøbak Sill is subject to gradual changes through vertical eddy diffusion; this is not the case with regard to the water outside the Drøbak Sill. Here, deep water is in open connection with the open ocean through the outer Oslo Fjord. The density stratification adjusts therefore quickly to the situation in the Skagerrak, and varies according to the seasonal changes there. Situations may then occur where the water outside the sill is heavier than at corresponding levels inside. If this is the case above sill level, sea-water from the outer fjord will flow into the inner basins where it will sink to depths of the same density. If the entering sea-water is heavier than the bottom water of the inner basins, it will sink to the bottom and accumulate there, lifting the entire body of the "old" water of the basin. At the same time, the excess water will leave the inner fjord at a near-surface level.

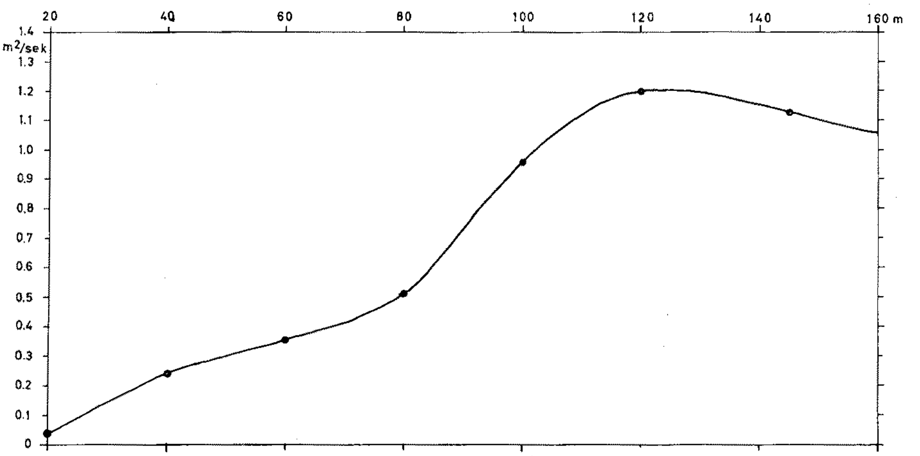

Fig. 4: Time averages of vertical eddy diffusion coefficients in the Bonne Fjord

During the period of observation such deep water influxes have been observed every winter. In the Vest Fjord this has created a renewal of the bottom water every time, and the volume of the entering sea-water has reached from the bottom (160 m) to levels from 55 m to 12 m from the surface (Figs. 1 and 2). Exchange is usually completed in two months, often in three weeks. In the Bonne Fjord, which is separated from the Vest Fjord by a ridge of a maximum depth of 50 m, the influx reached to the bottom only once (1963). In the remaining years, sea-water advection to the Bonne Fjord was observed in intermediate levels; but with the exception of 1965, these influxes consisted of "old" water displaced from the Vest Fjord. In these cases the "renewal" had little effect in increasing the oxygen content of the lower sea-water masses of the Bonne Fjord.

Efforts to disclose the causes for the deep water influx to the inner Oslo Fjord have revealed a striking correlation to the wind situation. All observed influxes took place during periods of predominant northerly winds; typically, the strongest influxes were correlated to the strongest mean northerly wind values. This situation is illustrated in Figure 5 where the 4-weekly N–S wind component is plotted against time.

The actual behaviour of the water in the Oslo Fjord during a period of deep water influx is demonstrated by the longitudinal cross section through the fjord in the middle of January 1963 (Fig. 6).

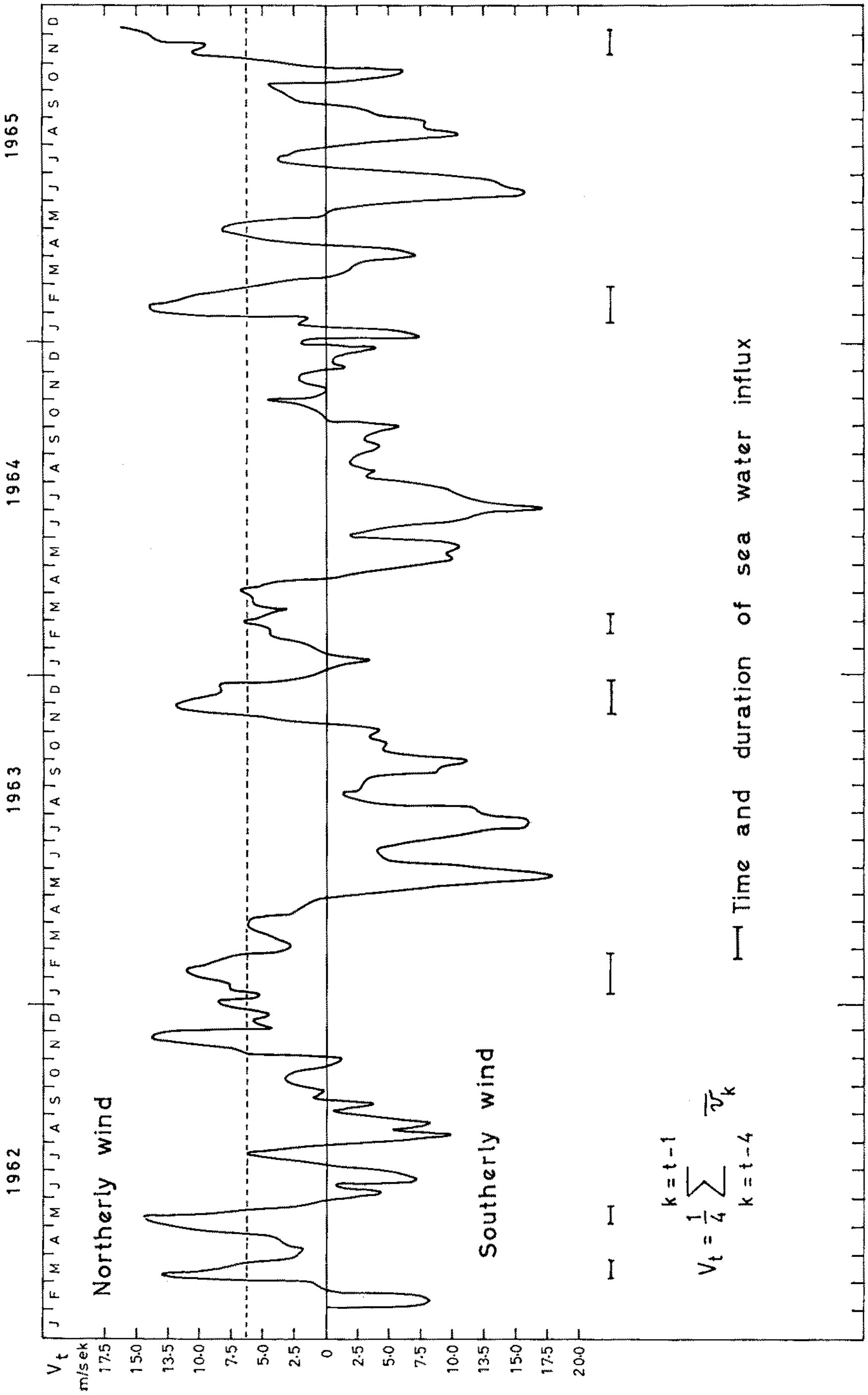

Fig. 5: 4-weekly sliding mean wind velocity N-S component, Fornebu

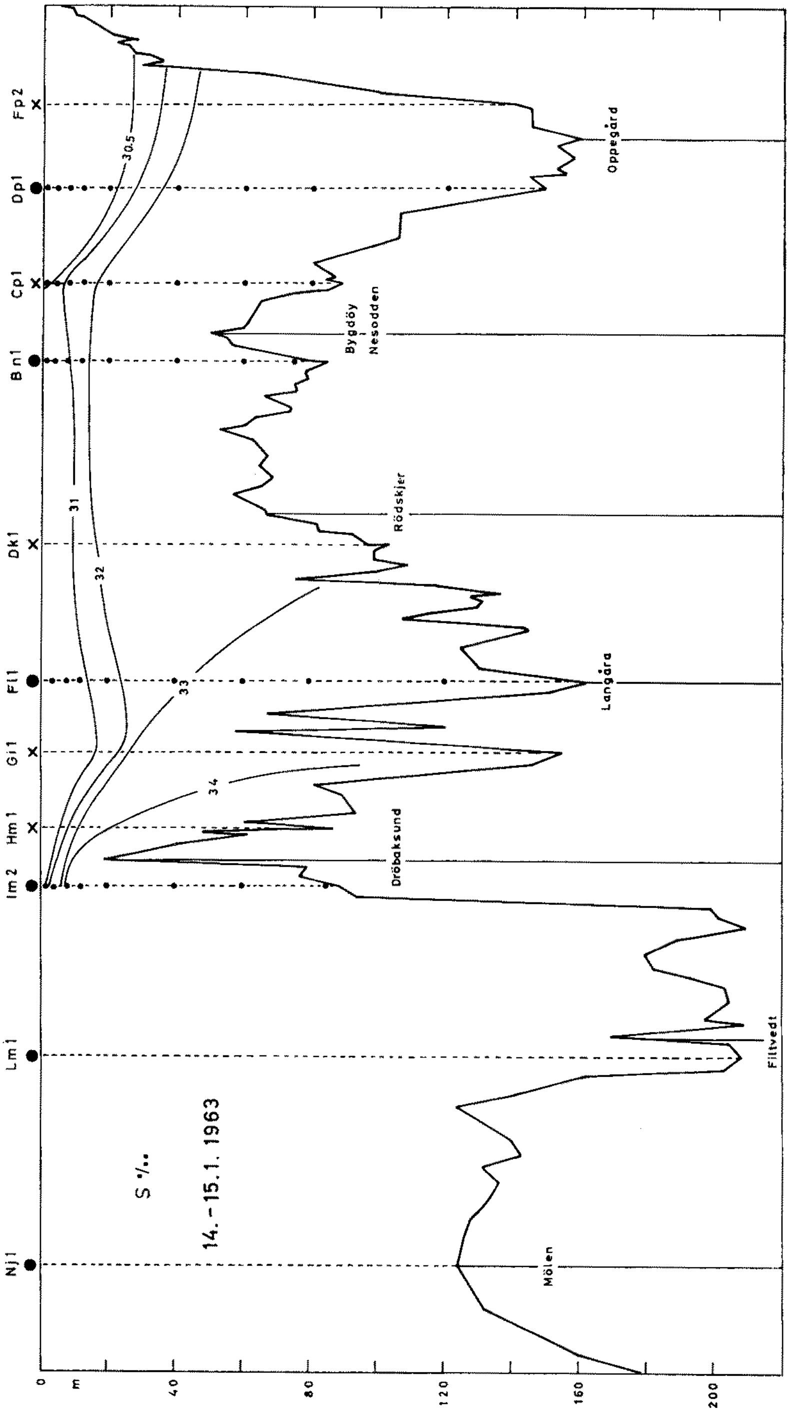

Fig. 6: Salinities in longitudinal section along the fjord, January 1963

WIND-DRIVEN CIRCULATION

The importance of wind effects for deep water exchange has already been stated. Deep water exchange not only depends upon the existence of sustained northerly winds, but it seems of some importance that there be not too much brackish water in the fjord. Conditions with little brackish water are found in winter and early spring before the onset of seasonal snow melting. Furthermore, it is necessary that the deep water of the inner basins through vertical diffusion has reached a sufficiently low density prior to the sea-water influx. This condition usually exists in the Vest Fjord, whereas in the Bonne Fjord this is evidently not the case.

Aside from the secondary deep water current discussed above, there is always a surface drift associated with sustained wind. In wintertime, winds blow mostly from the north. Their velocity culminates in January. In summer winds are more variable; they have predominantly south-to-southeasterly directions and a maximum in July. The general wind situation in summer is strongly modified by the sea and land breeze appearing on sunny days. The wind force may then increase in the afternoon. Late at night the wind will cease or change to northerly directions.

In spite of the above mentioned monsoon character of the wind system, winds in the Oslo Fjord region are generally weak and quite variable in direction. These conditions may be exemplified by a few values. During January, winds from north occur about 40 % of the time considered; their mean wind force is 2.1 Beaufort. Southerly winds, on the other hand, are found only in about 9 % of the time, with a mean force of 2.9 Beaufort. In about 30 % of the time the weather is calm. During July, northerly winds have been recorded 27 %, southerly winds more than 30 % of the time. Both wind directions are characterized by mean velocities of 2 to 2.6 Beaufort, southerly winds usually being stronger. Only in 15 % of the time the weather is calm.

It is obvious that the surface wind drift associated with the winds described above will, in general, be weak and only occasionally contribute significantly to the exchange mechanisms of the fjord. Actual current measurements in the Drøbak Sound fully support this conclusion. However, in periods where the other agents of exchange are neglectable, the wind effect may become important. During periods of sustained wind, the wind-driven circulation dominates all other forms of exchange, virtually leading to a complete renewal of the upper layers. The typical mechanism of this process can be illustrated by Figure 7 which shows the accumulation of brackish water by southerly winds during an otherwise normal summer situation. Northerly winds cause an opposite circulation as shown in Figure 8. However, sustained winds – moderate to fresh – lasting more than three or four days are very rare; they are not likely to occur more than a few times per year.

ESTUARINE CIRCULATION

The freshwater which is discharged into the inner fjord through many small rivers, appears to become rapidly mixed with the upper water layer and flows out of the fjord

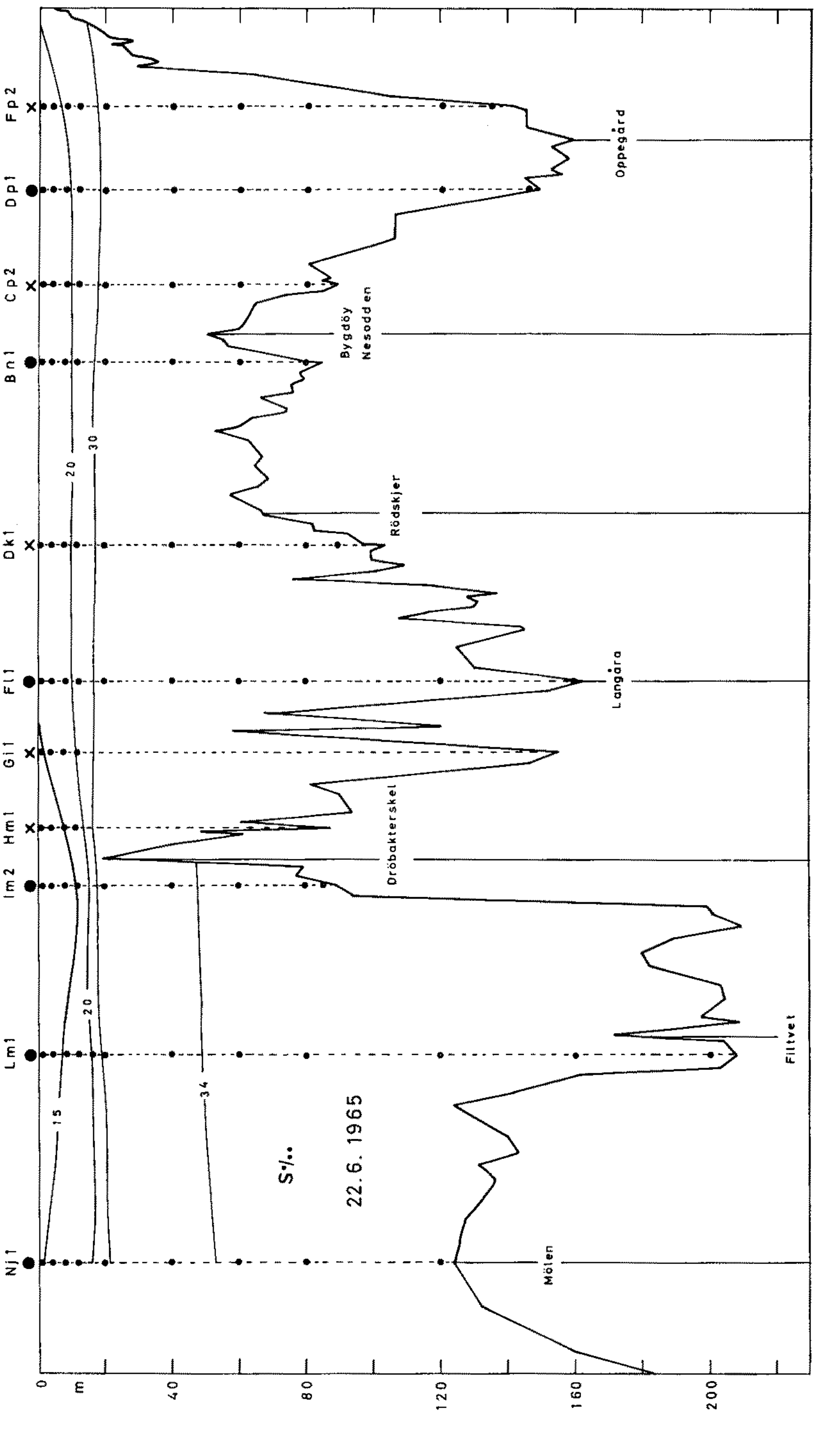

Fig. 7: Typical salinity distribution during southerly winds in summer

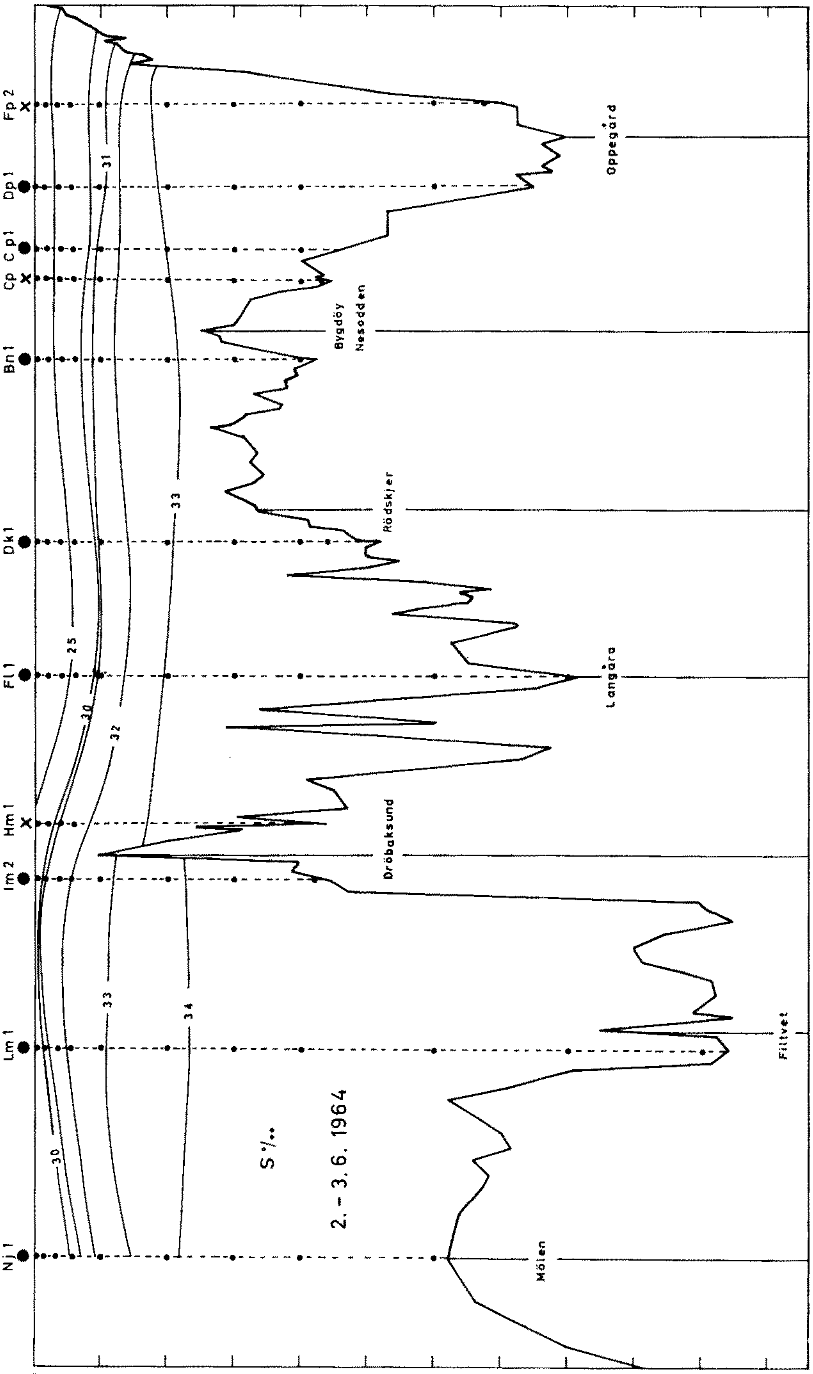

Fig. 8: Typical salinity distribution during northerly winds in summer

as part of the brackish surface current. Mixture occurs chiefly with the brackish water phase, only to a very small degree with the sea-water phase via vertical eddy diffusion.

As this mixing process constitutes a continuous consumption of both brackish water and sea-water, an undercurrent, directed towards the head of the fjord, is established in the lower brackish water and upper the sea-water phases. Brackish water entering the inner Oslo Fjord can thus not originate here, but must have been produced in the outer Oslo Fjord, mainly through discharges from the Drams River.

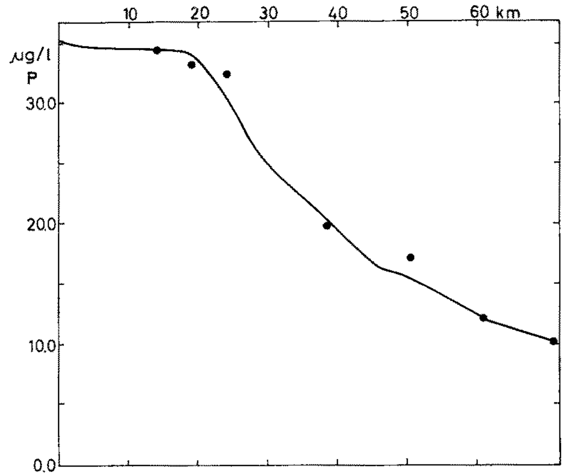

Fig. 9: Observed and calculated 0 to 12 m average orthophosphate concentrations. Distances measured from head of fjord

In spring and fall, the freshwater supply to the inner Oslo Fjord reaches average values of about 50 m^3/sec; the corresponding surface drift of brackish water attains velocities not more than a few centimetres per sec, and the theoretical flushing time for the brackish water in the Vest Fjord amounts to about 4 weeks. On a yearly basis, the flushing time is 8 weeks.

In summer, the amount of freshwater discharged into the inner fjord becomes so small that it barely exceeds surface evaporation; the flux of brackish water practically ceases. Nevertheless, surface salinities of the inner fjord remain fairly low due to the huge quantities of brackish water in the outer parts of the fjord. The Drams River reaches a maximum discharge in the middle of the summer.

In February snow accumulation, coupled with a low rate of precipitation, leads to a temporary halt in the flow of brackish water.

WATER EXCHANGE THROUGH HORIZONTAL EDDY DIFFUSION

At any time random motion can be observed in the surface layer. This motion causes a steady water mixing, tending to eliminate horizontal concentration gradients of a pollutant or of an other unevenly distributed constituent. Through tidal currents a form of eddy exchange also exists between the inner and outer Oslo Fjord, and between the various basins of the inner fjord. This exchange leads to a gradual water renewal in the fjord. The renewal is most effective in the southern part of the Vest Fjord; in the Bonne Fjord its effect is much less and more difficult to ascertain.

The most important causes of eddy transports in the fjord are tidal currents. Also wind generated surface currents are associated with appreciable eddy motion. However, the winds in the Oslo Fjord area are, on the whole, weak and the wind-driven turbulence minor relative to that of the tidal currents.

In the Oslo Fjord tidal variations are about 24 cm (32 cm spring and 18 cm at neap tide). Measurements of the tidal currents show that the motion is mainly confined to the brackish layer. Only in winter, when the brackish layer is practically absent, does the tidal motion penetrate significantly into the deeper water layers.

We have tried to determine the horizontal eddy diffusion coefficient via the dilution of various natural tracers. The most promising determination, so far, is based upon the budget of orthophosphate in winter. During calm periods horizontal eddy exchange by far dominates all other exchange processes. The eddy diffusion coefficient lies in the range of 10^6 to 10^7 cm^2/sec; applying these values to the diffusion equation, we have obtained solutions quite similar to the observed orthophosphate concentrations (Fig. 9).

SUMMARY

1. Both advective and diffusive processes are agents in the water exchange of the inner Oslo Fjord. The estuarine circulation is the most important form of water exchange. Analysis on a monthly basis has revealed great seasonal variations with peaks in spring and fall, and slack periods in winter and summer. The estuarine circulation is predominantly limited to the upper 20 m, comprising the zone of brackish water.
2. To a lesser extent also the entire body of sea-water in the fjord is involved through vertical eddy diffusion. Seasonally varying density conditions in the outer fjord prevent a continuous replenishment of the deeper sea-water layers. This water is renewed intermittently, and to a varying extent, by heavier water flowing in over the sill. The process takes place about every winter and appears to be controlled by the strengh and duration of the seasonal northerly winds.
3. Vertical eddy diffusion coefficients are computed in the sea-water phase on the basis of the salt budget. In the upper layers the vertical diffusion is determined from harmonic analysis of the heat wave resulting from surface heating and cooling.
4. Horizontal exchange in the upper layers also rises from diffusive processes. Tidal currents, however weak, are the main generating agent of turbulence, but also wind drift has significant effects when present. Horizontal eddy diffusion is determined from the budget of orthophosphate in winter. Diffusion coefficients are of the order 10^6 cm^2/sec, but reach 10^7 cm^2/sec in Drøbak Sound.
5. Drastic forms of water exchange take place under influence of fresh winds prevailing for more than four days. Both pure wind drift and secondary density currents occur.

Discussion following the paper by GADE

RAMSTER: Could it be that the winter inflow to the Inner Oslo Fjord is a consequence of the changing nature of the circulation of the North Sea during the year? We know the Atlantic inflows of the winters of the early 1920's, of 1930 to 1935, 1949 to 1951 and of the early 1960's were unusually strong. Is this another result of these strong inflow times?

GADE: Our studies so far have not given conclusive evidence that deep water influx is in any way determined by the hydrographic condition in the North Sea, but the wind conditions bringing about deep water exchange appear to be coupled with hydrographic events in the North Sea.

RAMSTER: With reference to the winter inflow at depths mentioned by the speaker: (1) Is it a sustained wind field or the occurrence of short-lived gales that triggers it off? (2) During which months does it occur?

GADE: (1) Short period winds of high strength have clearly the effect of initiating deep water influx. However, even with a very strong current velocity it will take several weeks to produce a significant exchange. Such conditions can be obtained only through sustained winds. (2) During the period 1961 to 1966 the deep water influxes took place in the beginning of the year and were all finished by May. However, previous investigations show that deep water influx also may take place at other times of the year. It appears that the quality of the water depends on the time of entering.