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LONG-TERM MODELLING OF THE VERTICAL DISTRIBUTION OF MASS IN LARGE LAKES WITH APPLICATION TO LAKE CONSTANCE

by

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MANAGEMENT PERSPECTIVES

This study is the first application of a long-term water quality simulation model to a large lake. The model, DYRESM, includes as primary variables, temperature, dissolved solids and suspended sediments. The large Central European lake, Lake Constance, was chosen as a test of the model because of the ready availability of high quality hydrological, meteorological and limnological data over a 425-day period.

The main result was the remarkable overall agreement between the lakewide average temperatures and the calculations with a volume weighted rms error over the entire study of only 0.45°C.

This study was undertaken at NWRI during Dr. Hollan's visit in 1986 under the auspices of the Canada-Germany Scientific Exchange Agreement and the manuscript prepared during Dr. Hamblin's visit to Germany in 1987.

PERSPECTIVES - GESTION

La présente étude constitue la première application d'un modèle de simulation de la qualité de l'eau à long terme appliqué à un grand lac. Ce modèle, le DYRESM, comprend comme variables principales : la température, les matières solides en suspension et les sédiments en suspension. Le lac de Constance, un grand lac de l'Europe centrale, a été choisi pour mettre le modèle à l'épreuve car on disposait d'excellentes données hydrologiques, météorologiques et limnologiques sur une période de 425 jours.

Le résultat le plus frappant a été la corrélation remarquable, dans l'ensemble, entre la température moyenne du lac et les calculs; en effet, l'erreur quadratique moyenne pour toute l'étude n'était que de 0,45°C.

Cette étude a été entreprise à l'INRE au cours du séjour du D^r^ Hollan en 1986, sous les auspices de l'Accord Canada-Allemagne sur les échanges scientifiques, et le manuscrit a été préparé au cours du séjour du D^r^ Hamblin en Allemagne en 1987.

Long-term Modelling of the Vertical Distribution of Mass in Large Lakes with Application to Lake Constance

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Lake Constance is Central Europe's second largest lake (volume 47.6 km^3, length 62 km, width 13 km and mean depth 100 m). Over the past 34 years of declining water quality generally biweekly observations of temperature, suspended material and other limnological parameters were taken at several locations in this lake. It is the first two variables along with concurrent measurements of surface meteorology and hydrology of four of the main tributaries to the lake that form the basis of the present study. Although the lake may be modified by short-term three-dimensional dynamical processes (Hollan and Simons, 1978), observation shows that the annual stratification cycle is predominantly one-dimensional. From the 34 year data set we have chosen for a detailed study by means of a one-dimensional dynamic model the period from February 1, 1979 through March 31, 1980. This period was selected, because high quality input data for the river inflows and for meteorology were available. As well, there were synoptic profiles obtained during two surveys in 1979 employing a high resolution CTD-sonde by the Institute of Applied Physics in Kiel. This makes it possible to compare the one-dimensional simulations with three-dimensional distributions in the lake.

We use the simulation model, DYRESM, which has been developed by Imberger and Patterson (1981) and Fischer et al. (1979) to hindcast water quality for small storage reservoirs in Australia. This model has been adapted by Patterson et al. (1984) and applied to a very elongated intermediate-sized lake in the mountainous region of Canada. As the above studies were confined to temperature and salinity, Wei and Hamblin (1986) recognized the importance of including suspended solids as a component of water quality, particularly in lakes situated in glacierized basins. Such lakes are subject to sudden and substantial sediment loading as is the case with Lake Constance. Wei and Hamblin applied their extended model to a small Alaskan reservoir.

Neither the standard simulation model nor the modified version have been applied to lakes as large as Lake Constance except for the short-term simulation by Ivey and Patterson (1984) in Lake Erie. The purpose of the present study is to evaluate the applicability of the three component version of DYRESM to large lakes by means of direct comparison of the model results with field observations. In addition, we shall briefly discuss any model enhancements that may be required to improve its performance in large water bodies. This account is attended to be introductory and for a detailed elaboration the reader is referred to Hollan et al. (1988).

1. Field observations

The main body of Lake Constance is a fjord-like basin whose outline and bathymetry are shown in Fig. 1. The Alpenrhein and the Bregenzerach are the main tributaries whose annual average discharges amount to about 73% and 16% of the total flow, respectively. They enter at the eastern end and particularly for the Alpenrhein, subject the lake to the Alpine hydrological regime of high discharge with considerable load of suspended solids well after the development of stratification. Besides these two tributaries two minor inflows, the Argen and the Schussen, have been accounted for in the calculations. Their inflow locations are shown in Fig. 1. As an example, the discharge and associated time history of temperature, conductivity, salinity and suspended solid concentration are displayed in Fig. 2 during the simulation period. The salinity and suspended sediment loading are taken from the empirical formulae of Wagner and Wagner (1978), which are based on river discharge, while the remaining quantities have been directly measured. As to the other three inflows only temperature and discharge have been observed and for the remaining quantities corresponding empirical relations have been applied. It may be noted in Fig. 2 that the river inflow varies by a factor of approximately six and that high suspended sediment concentrations are associated with high daily discharges. In contrast to the Alpenrhein the occurrence of salinity minima with discharge peaks is strongly pronounced in the case of the three other rivers.

Meteorological observations consisting of daily averaged values of wind speed, air temperature, relative humidity, fraction of cloud cover and short wave solar radiation were provided by the German Weather Service from its station at Konstanz (Fig. 1). These data are considered to be representative of the main features of the air mass over the lake except for the infrequent Föhn winds coming down to the eastern end of the lake through the Alpenrhein valley. Since there were no direct measurements of incoming long wave radiation of this station, this input parameter was inferred from the mean daily cloud cover and air temperature according to the formula of Swinbank (TVA, 1972). The meteorology of the simulation period demonstrates that both winter seasons were generally mild. More frequent and strong wind events occurred during late autumn 1979 and winter 1980, while June and September-October 1979 were relatively calm periods. Besides the daily meteorological averages components of six-hour averaged winds are required for the calculation of shear at the base of the epilimnion due to basin-scale internal waves. These components of wind are resolved along the longitudinal axis of the lake (303^{o}) and the transverse axis (213^{o}), as indicated in Fig. 1.

Profiles of temperature were taken at approximately biweekly intervals depending on navigational conditions by a standard platinum resistance thermometer down to 50 m depth every meter and beyond that by reversing thermometers at greater depth intervals. The three selected stations are situated in the center of the western basin, at the central deepest point of the main basin and in the middle of the line of maximum width as shown in Fig. 1. In addition, at the two western stations measurements of light extinction were carried out on every other cruise from the surface down to 60 m depth.

For comparison with the calculated temperature profiles lake-wide averaged observations were determined by the depth-constant average of the measurements at the three selected sites. The three open lake stations minimized the effect of smearing of the profiles due to tilting of the isotherms, which is more pronounced in the near-shore region. These data will be displayed along with the model results below. The light extinction data were converted to suspended sediment concentration following a standard approach given in Hollan et al. (1988).

Finally, a short-term study with the high resolution profiler in November 1979 is presented. The two transects selected for comparison with the simulation on November 20 and on November 29 through 30 are depicted in a separate map in Fig. 1b.

2. Model Description and Extensions

Fairly current reviews of progress in water quality modelling in lakes are given by Orlob (1983) and Harleman (1986). The governing physical processes and numerical procedures incorporated in the model DYRESM are outlined by Fischer et al. (1979) and Imberger and Patterson (1981). Subsequent model extensions relevant to this application are discussed by Patterson et al. (1984) for lakes, by Wei and Hamblin (1986) for suspended sediments and by Patterson and Hamblin (1988) for ice cover.

The essential aspect of the numerical scheme is that the vertical structure is represented by a variable number of layers of different thicknesses. Layers form or disappear according to the development or reduction of the stratification. This kind of Lagrangian grid scheme avoids the artificial smearing of the natural step-like structure at the base of the epilimnion, when fixed grid schemes are applied. Moreover, it is computationally efficient; for example, only one layer need be given if the structure is homogeneous. The design philosophy of the model, namely the horizontal homogeneity of the lake, has the further advantage of reasonable computer costs. The 425 day long simulation period of the three component version for Lake Constance took about 40 minutes on the medium size computer of the National Water Research Institute.

The salient feature of the physics is that the vertical turbulent mixing formulation is semi-empirical in character in contrast to other simulation models which use empirical mixing schemes. For example the simulation model of Henderson-Sellers (1985) does not explicitly include the contribution to vertical mixing due to internal waves and to inflows and outflow.

While the mixing formulation for the epilimnion is given in terms of the standard treatment of the turbulent kinetic energy equation, two semi-empirical mixing laws based on the same underlying principle, namely that a certain fraction of the dissipation of turbulent kinetic energy goes to increase the potential energy of the lake, were examined for the thermocline and hypolimnion regions. The first approach is characterized by direct relation to the sum of the wind energy input per day and the daily release of potential energy of the inflowing rivers and an inverse relation to the depth dependent stability. In the second case suggested by Harleman (1986) the essential difference is that the mixing is inversely proportional to the mean potential energy per unit volume of the lake instead of the local stability.

Another important model extension results from the main wind forcing from south-westerly directions. Due to the geographical orientation of the lake (Fig. 1), the transverse wind component is, in general, about twice the longitudinal component. Therefore, it was necessary to extend the production of shear at the base of the epilimnion to include the transverse component of wind. This shear was allowed to build up until either one quarter period of the transverse internal seiche had elapsed or the transverse wind component changed sign whichever occurred first.

A further modification is the incorporation of particle settling in the river inflows, as they descend from the lake surface to their equilibrium depth. The bulk sediment settling velocity in these plunging river plumes was assumed to be two orders of magnitude greater than the lake settling velocity of 10^{-2} mm/sec. In particular, the best agreement between observed and calculated density profiles was achieved for a sediment sinking rate of 5 mm/sec in the river plumes. Unlike other applications quoted above in which the density dependence of the lake waters was taken from Chen and Millero (1977), the relation given by Wagner and Wagner (1978) for the main tributaries has been used to determine the density of the lake water from its temperature, salinity and suspended sediment load. The light extinction coefficients were derived from the field transparency observations down to 30 m depth.

3. Comparison of Model Results With Observations

The calculations were initialized with the nearly vertically uniform field data on February 1, 1979. Initial salinity data were taken from a seven-year average of monthly salinity measurements (G. Wagner, pers. com.). The model was run continuously until March 31, 1980. From the calculated temperature profiles we selected those depicting the strongly stratified season between July 23, 1979 and its end on December 12 given in Fig. 3. This comparison exibits a reasonable overall agreement with the observations. Two distinct discrepancies appear on September 17, and October 23, 1979. In both cases the epilimnion temperatures and thicknesses are underestimated. On the other hand, the thermal stratification is evidently well simulated on July 8. Besides the comparison of individual profiles the model results are complemented by temperature-depth time histories in Fig. 4a and 4b. The calculated isotherms clearly demonstrate over the entire simulation period the ability of the model to accurately reproduce the annual cycle of thermal stratification in Lake Constance. A remarkable agreement is evident by the simultaneous development of the intense near surface stratification at the beginning of June and August. The same is true for the deepening of the epilimnion at the end of October. The temperature field returns to a nearly uniform state in February 1980 in good agreement with the observations. Statistically, the time averaged volume weighted rms temperature error is 0.45^{o}C over the whole simulation period.

The synoptic temperature transect taken by the high resolution profiler (Kroebel, pers. com.) demonstrates the near horizontal uniformity of the temperature structure on November 20 (Fig. 5a) despite the relatively weak stratification and windier conditions during the first half of this month. The epilimnion had deepened to 25 m which compares well to the calculation (Fig. 5b), though its temperature differs by about 0.5^{o}C. Due to a rain storm between November 5 and 10 there was a strong inflow event with increased suspended load. This is inferred by the example of the isopleths of attenuation of blue light on the same transect presented in Fig. 5c. The increased levels of attenuation associated with this event are found at the depth of 35 m. After a ten day period of autumnal cooling under calm conditions there is remarkable agreement between the measurements of the near synoptic longitudinal transect and the numerical approach displayed in Fig. 6a and 6b. The calculated deep temperatures slightly exceed the observations as in the previous comparisons.

Up to this point the calculations have employed the vertical mixing specification suggested by Harleman (1986). In a further numerical experiment to determine the sensitivity of vertical mixing below the epilimnion to the original DYRESM formulation it was found that the volume weighted rms temperature error was about twice the previously mentioned error. The Harleman formulation resulted in a decreased mixing during the well stratified summer period and increased mixing during the spring and autumn relative to the standard approach.

Finally, we want to demonstrate that the numerical model may be employed to generate hypotheses on the nature of time and depth dependent distributions of other components of water quality. These hypotheses may be tested by properly designed field experiments. In the present study two parameters have been calculated, namely, suspended sediments and salinity. Fig. 7 shows the slow settling of the increased suspended matter, which enters the lake starting in May. Evidentally, this pulse reaches the bottom by early winter. It is apparent in Fig. 7 that the loading from the previously mentioned storm in November, is too small in comparison to the main spring sediment input. The other example shown in Fig. 8, is the annual cycle of dissolved solids. There is a pronounced summer minimum in the thermocline region which is slowly dispersed by vertical diffusion and inflow processes. Another feature is the near temporal constancy in the hypolimnion. In winter 1979/80 deep convective overturn appears to be arrested at about 140 m depth. This overall yearly behaviour is in qualitative agreement with the seven-year averaged observations made available by Wagner (pers. com.).

4. Conclusions

The good correspondence between the model results and the field observations indicates that with appropriate modification such as improved mixing in the deep layer and inclusion of transverse wind forcing of internal waves the one-dimensional modelling approach may yield useful results for such large lakes. Furthermore, the dynamical simulation proved the consistency between the observed hydrological fields and the physical response.

The study also indicates a number of possible improvements in the routine data collection for the lake. In particular, dissolved solid concentrations and suspended sediment profiles should be added to the regular sampling program. While temperature is now monitored at the outflow, the previously mentioned parameters should be included also. More information is also necessary on suspended sediment particle size, mineralogy and organic fraction in the lake and at the mouths of the major inflows. Knowledge of meteorological forcing should be improved by additional measurements at other sites of the lake, by the direct measurement of longwave radiation and by the study of the modification of air mass over the lake.

The necessity for improved specification of vertical mixing in long-term simulations in large lakes is demonstrated in this study. Further application of the semi-empirical prescriptions for mixing studied herein would be fruitful. Much effort is required both theoretically and observationally to establish a firmer foundation for vertical mixing processes in large deep lakes, especially those dominated by strong river inputs.

The ability to accurately account for the annual cycle of stratification suggests that the long-term climatology of the lake could be studied at least for the last 30 years with existing data. This analysis would cover the strong interannual variability such as the response to the ice-covered winter in 1962-1963. In the field of hydrology long-term trends in evaporation and water balance could be examined as well as the influence of anthropogenic changes in the hydrological regime of the Alpenrhein. A version of the model exists although not as yet verified in large lakes that includes additionally dissolved and particulate phosphorus and dissolved oxygen (Mc Crimmon, 1987). This model may be applied to the simulation of biological and nutrient chemical distributions of Lake Constance and thus improve the analysis of the annual limnological state given in the reports of the International Commission on the Protection of Lake Constance (IGKB). Furthermore, the simulation model provides an accurate means of interpolating between field observations both in space and in time.

It would be valuable to conduct applications to other large lakes in order to substantiate the various parameterizations of the physical processes involved. We believe that a comparison of the model performance on a wide range of forcing conditions and basin geometries will enhance the understanding of the stratification in large lakes.

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FIGURE CAPTIONS

Fig. 1. Bathymetry of Lake Constance and measurement sites.

a: Routine survey stations (Ü, F, L) selected for the comparison with the calculations; weather station (W) at Konstanz; inflow sites of the rivers Alpenrhein (Al), Bregenzerach (Br), Argen (Ar) and Schussen (Sh). A 50 m contour interval is used for depth. The lake-oriented system for decomposition of the wind is shown in the insert.

b: Transects with the Kiel-Multisonde, November 20 and November 29 through 30, 1979. The sites of the vertical profiles are given by full circles and the station numbers in italics. Open circles indicate the stations U, F, L.

Fig. 2. Daily inflow data of the Alpenrhein during the period of simulation.

a: Discharge in 10^6 m^3/d.
b: Temperature in °C.
c: Conductivity in μS/cm.
d: Salinity in g/l (calculated, see text).
e: Suspended load in g/l (calculated, see text).

Fig. 3. Comparison of the calculated and observed temperature profiles from July 23 through December 12, 1979. Solid line: calculation. Dots: measurements. Depth scale upwards from the greatest depth (252 m below chart datum).

Fig. 4. Time-depth distribution of temperature (°C) from February 1, 1979 through March 31, 1980. (a) Calculation. (b) Observation. The measurement dates are indicated on a separate scale marked by solid and open triangles. Upward pointing solid triangles indicate volumetrically weighted averages for stations U and F while solid downward triangles are averages of stations F and L. Open triangles represent measurements from only one station (upward: F, downward: L). Depth scales defined as in Fig. 3.

Fig. 5. a: Transverse temperature cross-sections, stations 264 - 268 (see Fig. 1b).

b: Calculated temperature profile on November 20, 1979.

c: Attenuation of blue light (455 nm).

Fig. 6. a: Longitudinal transect of temperature (°C).

b: Calculated profile on November 30, 1979. The measurement stations on this central transect (see Fig 1b) are selected from a lake-wide survey on a zig-zag shaped course on November 29 (stations 385 - 389 from 17 h through 18.47 h) and on November 30 (stations 392 - 407 from 10 h through 17.11 h).

Fig. 7. Time-depth distribution of the suspended sediment (mg/l), from February 6, 1979 through March 24, 1980. Same numerical experiment as shown in Fig. 4a.

Fig. 8. Time-depth distribution of salinity (mg/l) for the same simulation period and calculation as in Fig. 7.

Fig. 1a

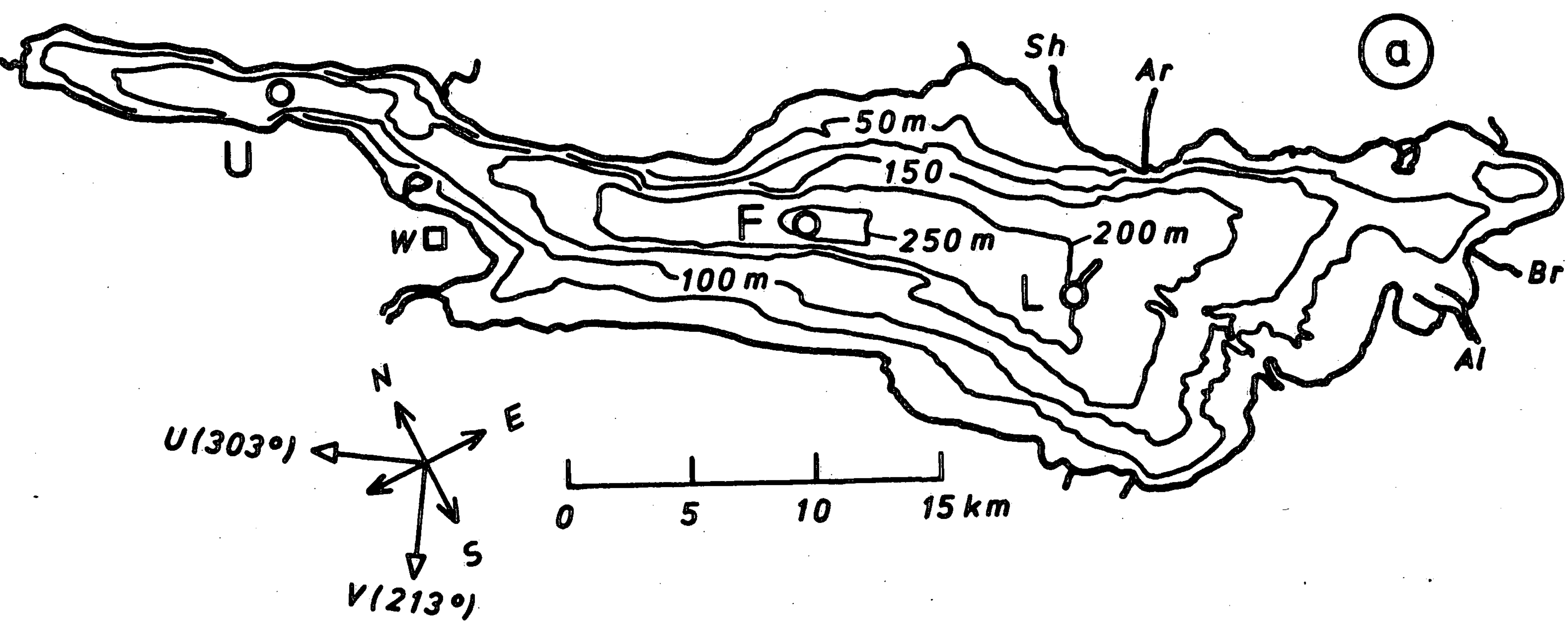

a
Sh
Ar
50 m
150
200 m
250 m
100 m
F
L
U
W
Br
Al
N
E
S
U(303°)
V(213°)
0
5
10
15 km

Fig. 1b

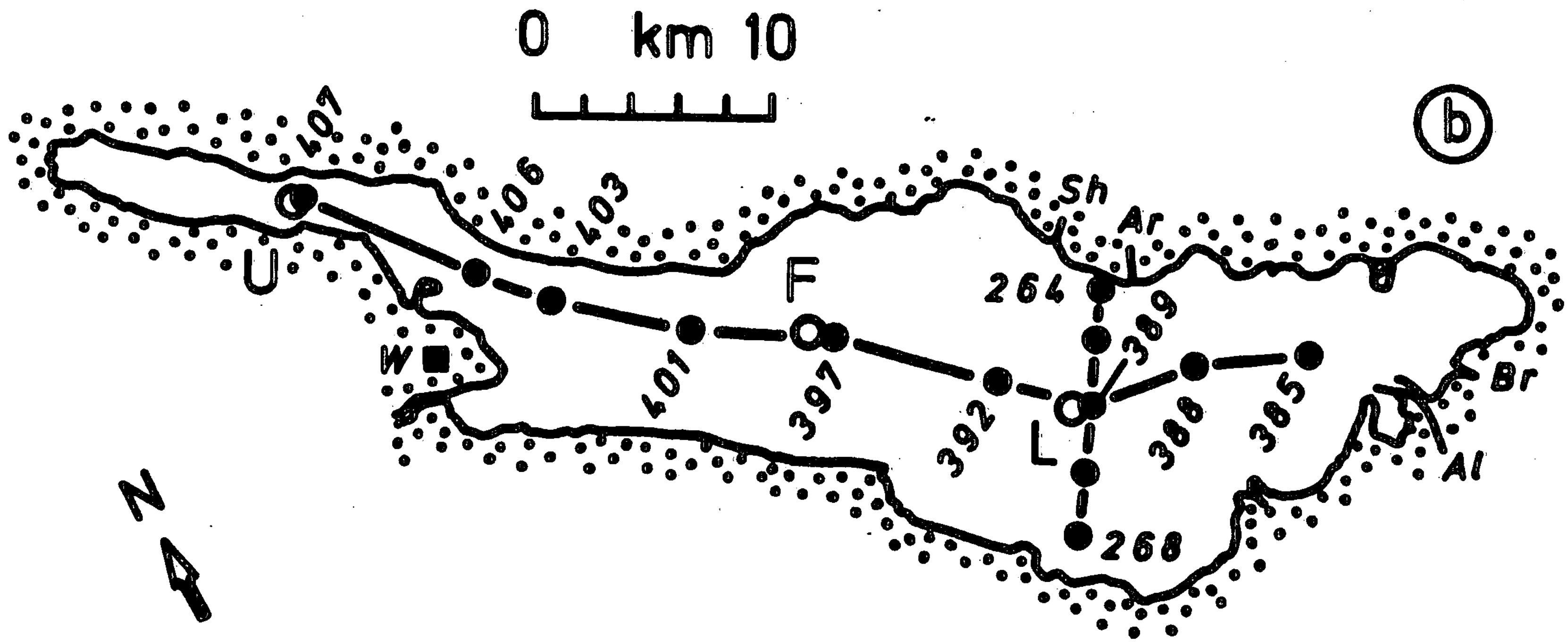
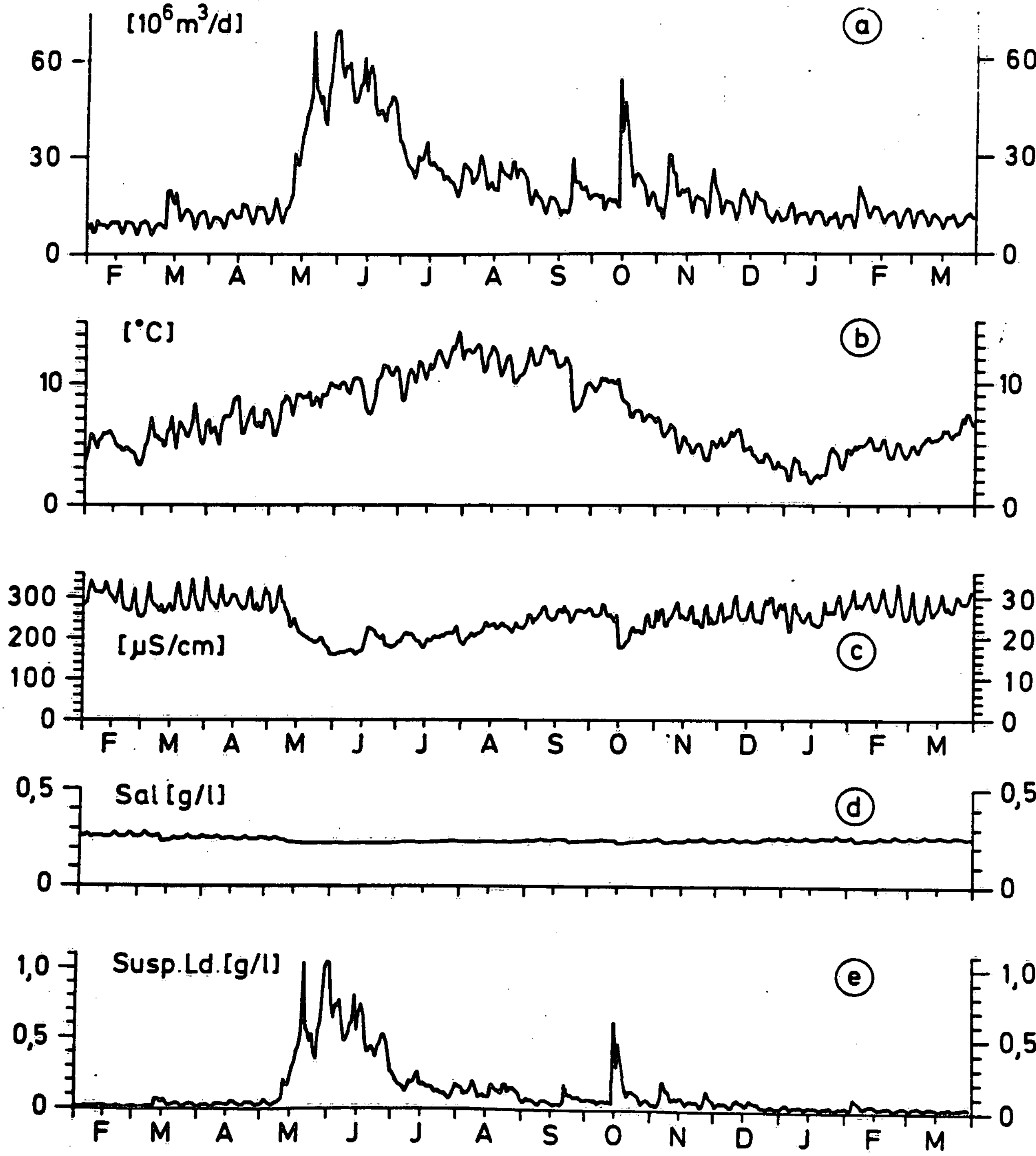

0 km 10
b
407
406
403
U
W
F
401
397
392
L
264
Sh
Ar
389
388
385
268
Br
Al
N

Fig. 2



[10⁶m³/d]
(a)
60
30
0
F M A M J J A S O N D J F M
[°C]
(b)
10
0
300
200
100
0
[μS/cm]
(c)
F M A M J J A S O N D J F M
0,5
Sal [g/l]
(d)
0
1,0
Susp.Ld.[g/l]
(e)
0,5
0
F M A M J J A S O N D J F M

Fig. 3

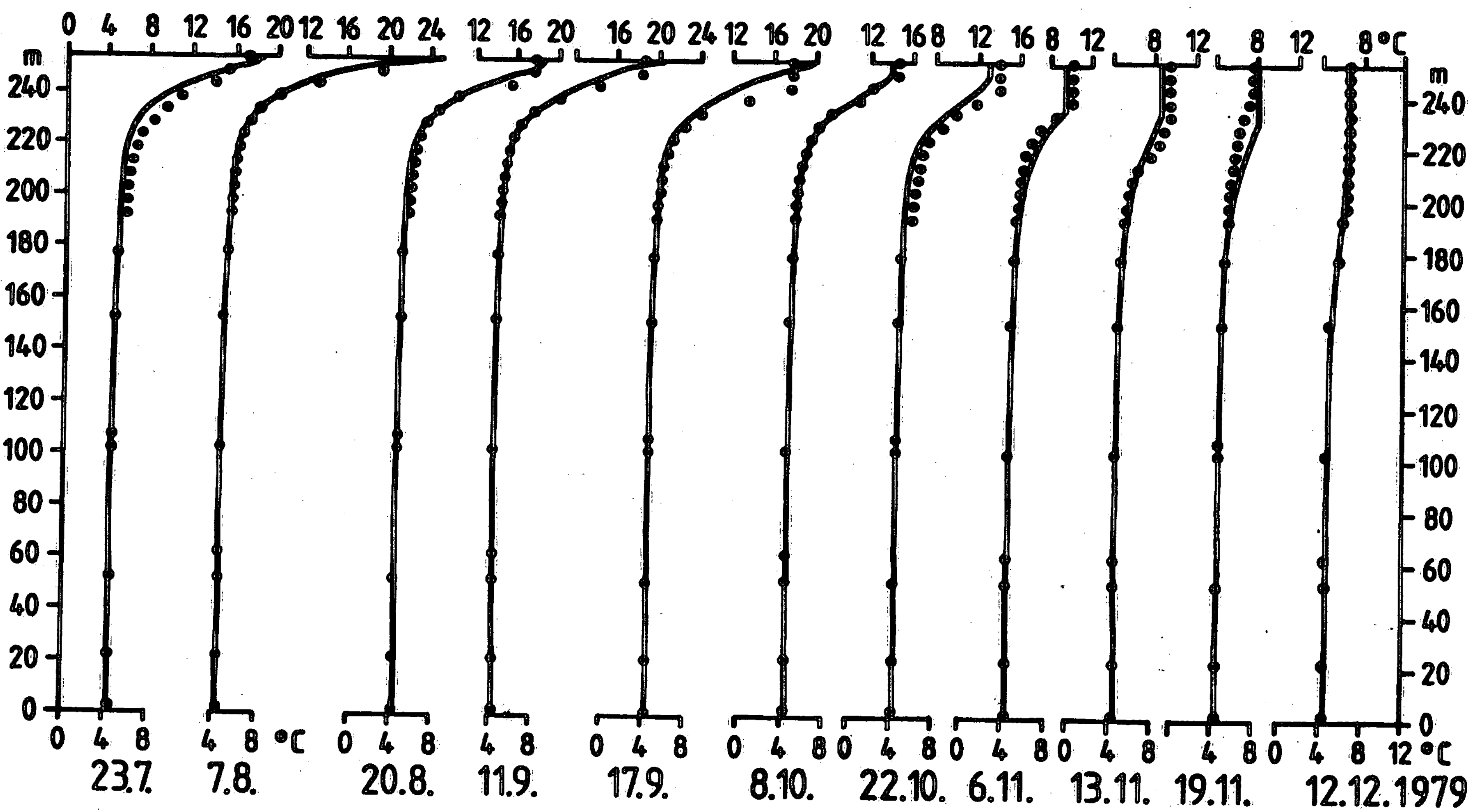
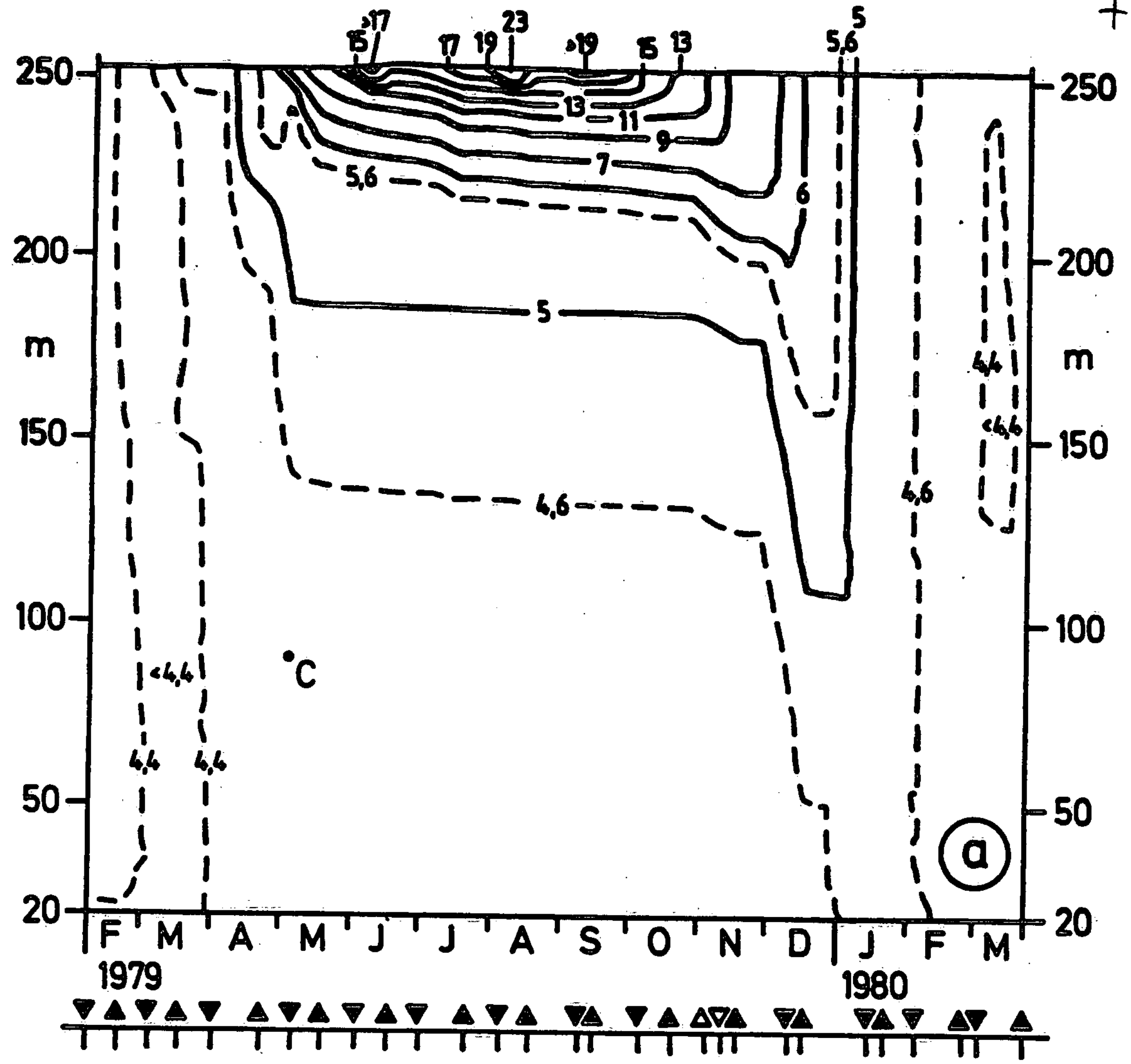
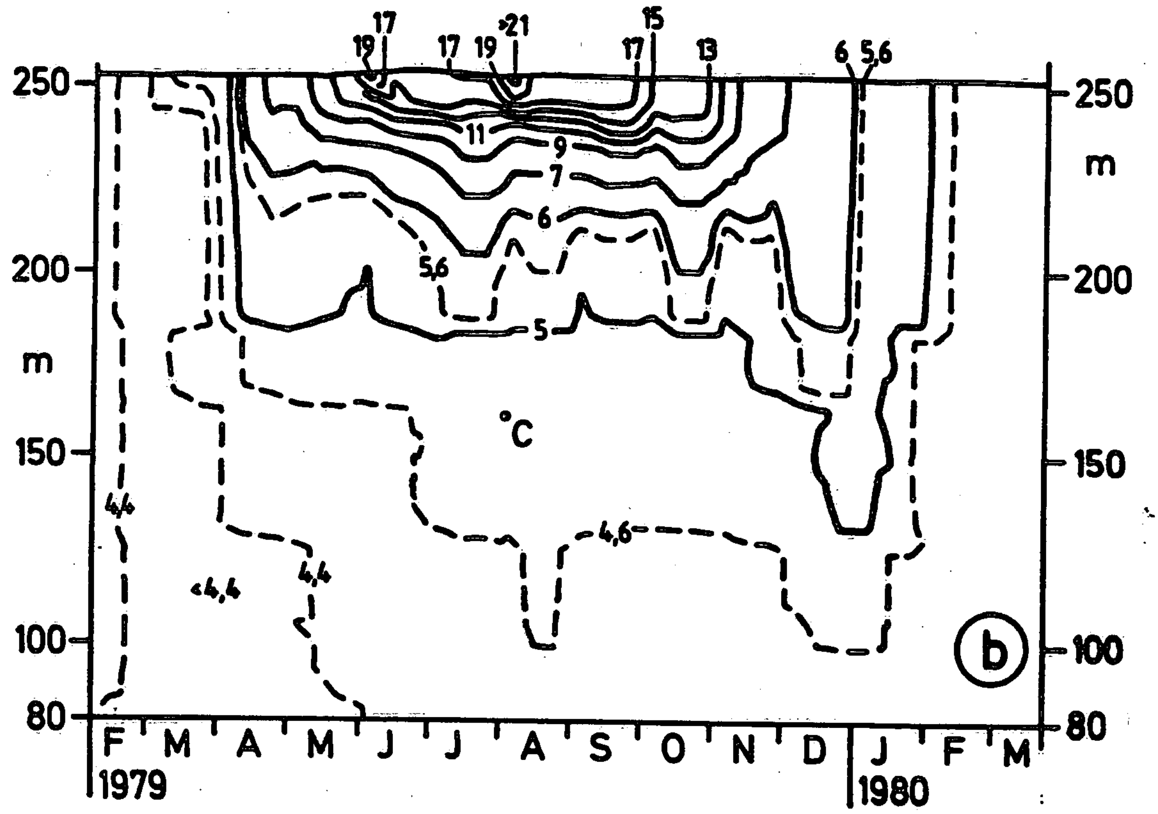


Fig. 4a



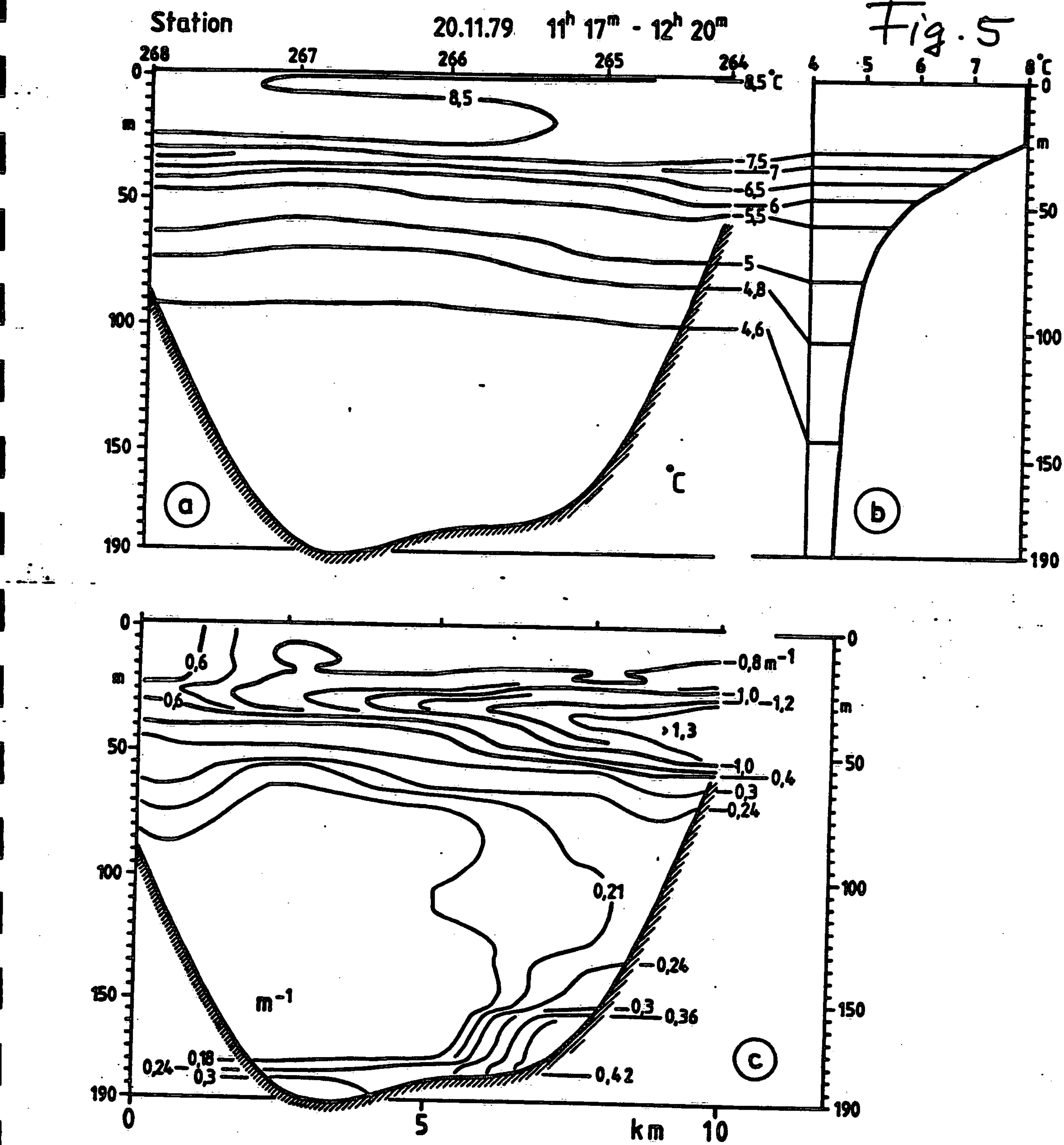
250
200
150
100
50
20
m
°C
a
F M A M J J A S O N D J F M
1979
1980

Fig. 4b



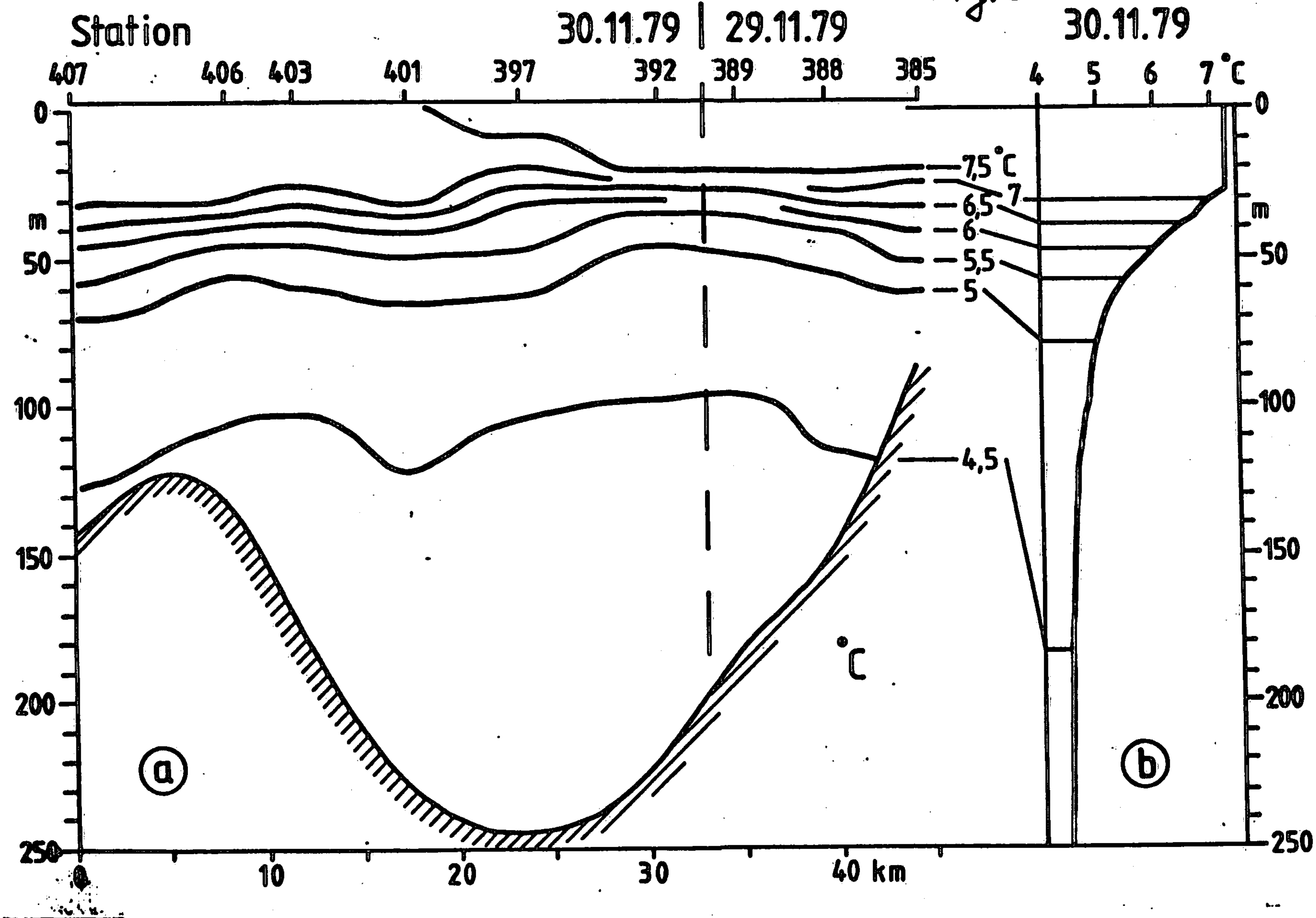
250
200
150
100
80
m
°C
b
F M A M J J A S O N D J F M
1979
1980

Fig. 5



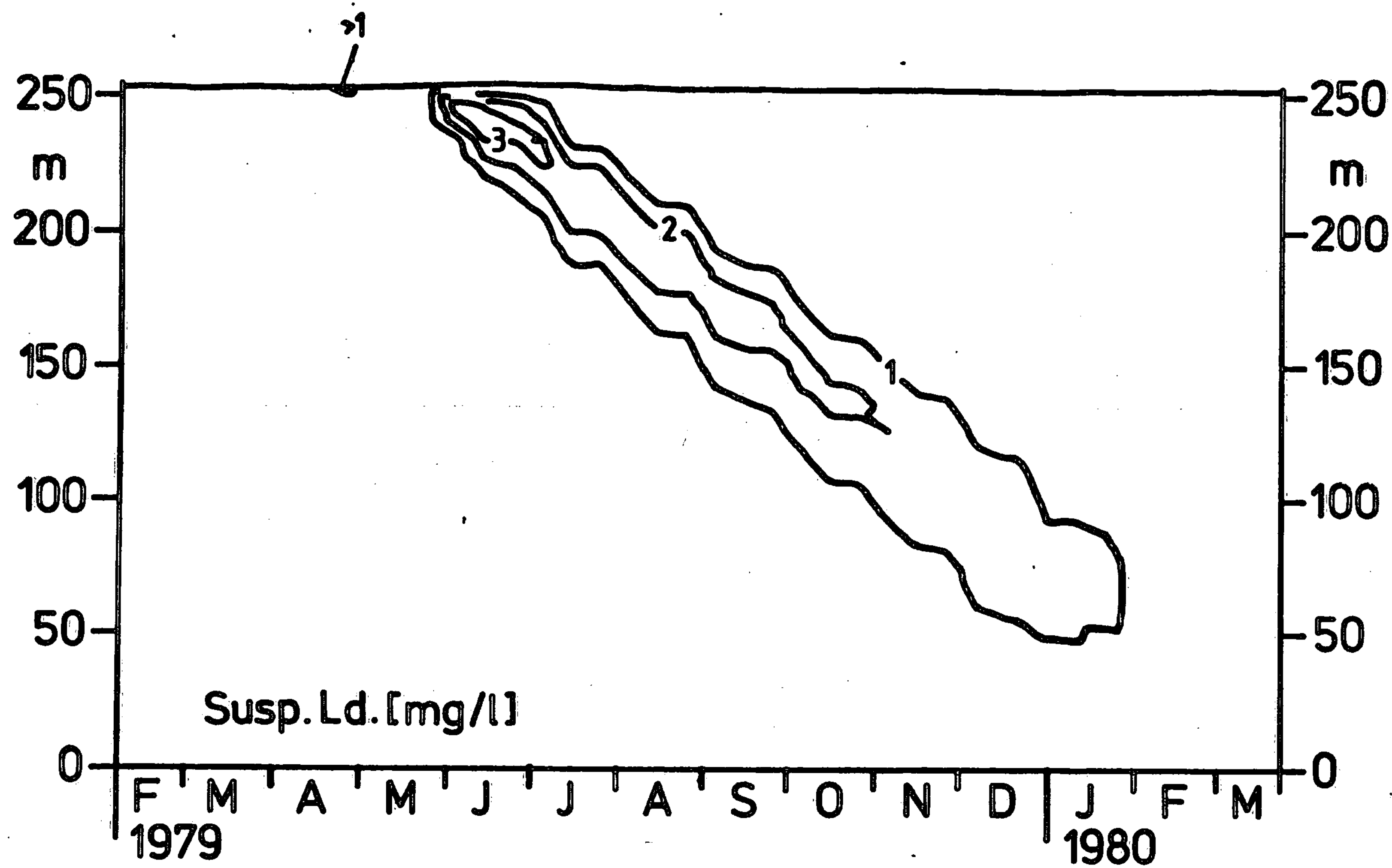
Station
20.11.79 11h 17m - 12h 20m
268
267
266
265
264
8,5 °C
8,5
7,5
7
6,5
6
5,5
5
4,8
4,6
°C
a
b
4
5
6
7
8 °C
m
0
50
100
150
190
0,6
0,6
0,8 m-1
1,0
1,2
>1,3
1,0
0,4
0,3
0,24
0,21
0,24
0,3
0,36
m-1
0,24
0,18
0,3
0,42
c
0
5
km
10

Fig. 6



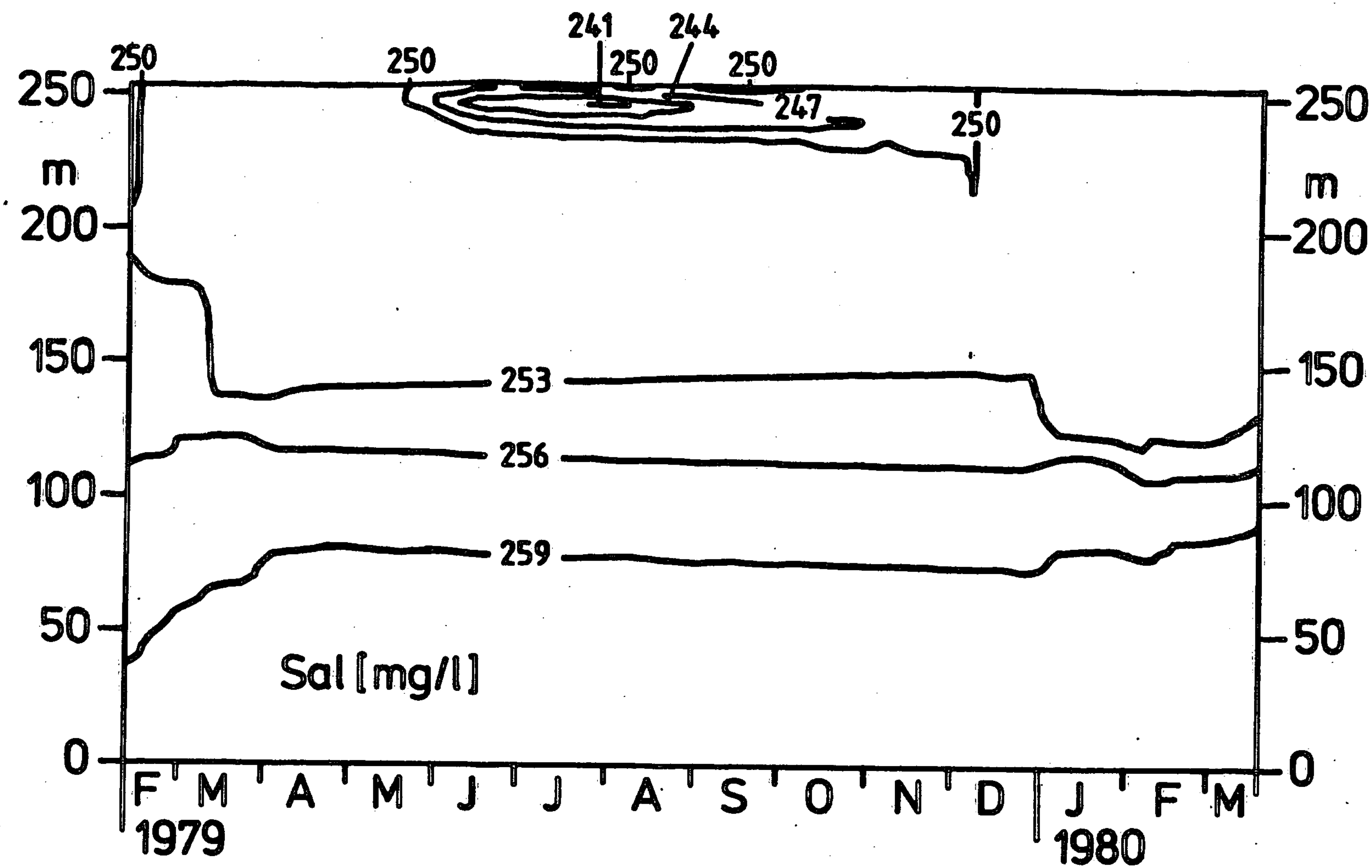
Station
30.11.79 | 29.11.79
30.11.79
407
406
403
401
397
392
389
388
385
4
5
6
7 °C
0
m
50
100
150
200
250
7,5 °C
7
6,5
6
5,5
5
4,5
°C
a
b
0
10
20
30
40 km

Fig. 7



>1
250
m
200
150
100
50
0
3
2
1
Susp. Ld. [mg/l]
F
M
A
M
J
J
A
S
O
N
D
J
F
M
1979
1980

Fig. 8


250
250
241
250
244
250
247
250
253
256
259
Sal [mg/l]
m
250
200
150
100
50
0
F M A M J J A S O N D J F M
1979
1980