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Environment Canada
Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau
Environnement Canada

Vertical Transport in Brenda Mines Pit Lake

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NWRI Contribution # 96-86

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Title: Vertical Transport in Brenda Pit Lake

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NWRI Publication #:

Citation: Fourth International Conference on Acid Rock Drainage. Submitted for proceedings

EC Priority/Issue: This work was done as part of the MEND program and undertaken at the request of R. McCandless of Environmental Protection, EC Pacific and Yukon Region. The study was jointly funded by Brenda Technologies, CANMET and EC.

Current Status: The paper describes the results of .a field and modelling investigation of the Brenda Pit Lake in British Columbia. Sub–aqueous disposal of mine tailings is a technique whereby a mixture of water and finely ground rock is pumped to the bottom of a water body. Material from the slurry settles and consolidates forming a new lake bed with an overlying layer of water with high levels of dissolved material. The premise is that the water forms an inert cap, effectively containing the injected material. Environmental considerations require that the effectiveness of this storage method be explored.. Both the field data and the model confirm the capping effect of the relatively salty water in the pit.

Next Steps: Revise manuscript according to comments of reviewers.
Present paper at ICARD meeting June 1997.

ABSTRACT

Sub–aqueous disposal of mine tailings is a technique whereby a mixture of water and finely ground rock is pumped to the bottom of a water body. Material from the slurry settles and consolidates forming a new lake bed with an overlying layer of water with high levels of dissolved material. The premise is that the water forms an inert cap, effectively containing the injected material. Environmental considerations require that the effectiveness of this storage method be explored. Here, we describe a modelling application to the Brenda Pit Lake using an extended version of the lake and reservoir water quality model, DYRESM, incorporating algorithms for detailed ice cover, heat fluxes and also internal wave–driven boundary mixing. Sheltering and shading of the meteorological forcing is taken into account in the model. Both the field data and the model confirm the capping effect of the relatively salty water in the pit.

Keywords: Decommissioned Water-Filled Mining Pits, Water Quality Modelling

INTRODUCTION

The water quality of decommissioned mining open-pits presents two problems. First, as they fill with water from rain, surface runoff and ground water they may eventually overflow which could introduce contaminated water in excess of water quality guidelines into the surrounding watershed. Second, they offer convenient sites for the disposal of noxious mine tailings which then may enter the water column at the bottom and subsequently migrate upwards to the outflow. In order to develop some predictive capability to assess the potential of decommissioned mining pits for releasing hazardous materials into the environment we initiated a field program to better understand the mechanics of mining pits. Part of this endeavour attempted to gather field data suitable for running and evaluating the simulations of a water quality model. It is the goal of this paper to summarise the main findings of the observational program relevant to modelling and to present a contextual example of the application of a water quality model to the Brenda Mines pit lake. The location of our experimental site is given in Figure 1.

Pit Lakes

McCandless (Environment Canada) has compiled water quality data on seven pit lakes located in BC, the Yukon and Washington which are tabulated in Stevens et al.(1994). In one of the few reported studies Davis and Ashenburg (1989) describe the Berkeley Pit in Montana which has been filling for 13 years. They found substantial wall slumpage and uniform thermal conditions which may be an indication of inflows of warm ground water. In another study of a flooded mine pit, Tones (1982) indicated that the autumnal overturn is arrested by the presence of a sharp gradient in dissolved salts (chemocline). This pit has a history of dumping which may explain the chemocline. There is no evidence of ground water inflow to this pit. In the present study the depth of the pit is considered to be sufficient that wind-wave resuspension of tailings does not play a major role as in the case studied by Lawrence et al.(1991). From the literature the impression gathered of water–filled pits is that they have a wide range of physical and chemical properties.

The paucity of literature on deep pit–lakes suggests that the literature of analogous water bodies may offer some clues to their behaviour. A cross section of a crater lake, Pavin Lake (Martin, 1985) is compared to that of the Brenda Pit in Figure 2. While the morphology is remarkably similar it turns out that the literature on the mechanics of this type of lake is nearly as scant as that of pit lakes so offers little additional insight. The only study of mixing in a crater lake that we are aware of is for Crater Lake (Crawford and Collier, 1996) which has a depth to width ratio about a tenth of the Brenda Pit. As well in Figure 2, the various terms used in limnology are indicated. Perhaps the most important term in this study is monimolimnion which is a zone of stable fluid at the bottom which remains poorly mixed and is maintained by an inflow of salt laden water. Note that a hyperadiabatic temperature profile is indicated in the monimolimnion in Figure 2. As will be subsequently shown, this seemingly unstable thermal profile is stabilized by the presence of salt. As it is necessary to take into account the natural forcing of the water body by meteorological disturbances in a water quality model we first must consider the microclimate created by the sidewalls of the cavity. Seldom is the surface of a pit lake level with the surrounding terrain.

Sheltering and Shading Effects

Brenda Pit has at present steeply sloping and very steppy topography from 60 to 120m above the water surface of the lake, see Figure 2. The standard formula for wind speed reduction due to obstacles on the shoreline (USACE) yields a boundary layer adjustment length scale of eight times the obstacle height which in the case of Brenda Pit Lake exceeds its fetch length. A more realistic estimate of the speed reduction factor is obtained by reference to the boundary meteorology literature. Taylor and Lee (1984) provide relatively simple formulae based on the slope of the basin for an axisymmetric depression in an otherwise flat plane and for a topography composed of undulating hills and valleys. Both approaches for a half-slope of 0.3 yield reduction factors from 0.52 to 0.6 for unstable or neutral stability conditions. The situation in depressions for stable atmospheric conditions which is likely to occur frequently appears to be unknown. Taylor and Lee point out that the speed reduction factors can be decreased by up to 20% by the change of roughness from the rocky sidewall estimated to be in the order of 0.1m to the much smoother water or ice surface of roughness as small as 10^{-5}m. In the schematic of Figure 2 possible separation of the air flow into the pit is indicated which is likely to occur when the slope exceeds 0.25 as is the case here. In summary, there is some theoretical and empirical support for the specification of varying wind sheltering coefficients in a pit lake as it fills up. As will be evident subsequently there is a requirement to specify other meteorological inputs, namely solar radiation, air temperature, cloudiness and relative humidity. Solar radiation may be corrected for by published tables (T.V.A.) of solar elevation and length of the day provided the geometry of the shading sidewalls is well enough known.

In our study we mounted two meteorological stations, one on the rim of the pit at a height of 60m above the water surface and the other at the centre of the lake as depicted in Figure 2 for the sake of establishing transfer functions for the major forcing variables. Concurrently observed data series are compared with one another in Figure 3. First, there is some support for the wind speed reduction factors based on the boundary layer literature, especially at higher wind speeds where the errors in the individual measurements are apt to be smaller portion of the actual wind speed. A best-fit regression line through the data points of Figure 3 yields the relation for the wind speed reduction factor, α, in the pit, of α=0.838 +Uo(0.002Uo–0.045) where Uo is the wind speed in m/s at the rim station. In the case of the daily total of short wave radiation there is a shading reduction of 0.74 as might be expected during the shortest days of the year when the comparison was made. At other times we have assumed for the purpose of modelling that the reduction in solar radiation would vary from this limit to unity for the longest day of the year. While the field data suggest a 2^{o}C rise in air temperature over the lake on average, unfortunately there is no theory to suggest how this might apply to other pit lakes or to Brenda Pit Lake as it fills up. The situation with regard to relative humidity is even more distressing. Relative humidity is essential not only for the determination of the heat budget of the pit lake but also for its mass balance Due to equipment failure there were no overlapping data sequences so it was not possible to make a comparison. However, we noted during our experimental visits to the pit that sometimes the surface of the pit lake was covered by fog or fine mist. The relative humidity over the ice covered surface of the pit was slightly greater over a nineteen-day period than the nearby values at Peachland (Figure 1). Thus, the relative humidity ought to be higher at the water surface than in the surrounding vicinity of the pit. Our measured shading and sheltering factors were incorporated in the mathematical model of the water quality of the mining pit lake to be described in the following section. It is possible that the microclimate associated with the pit may not appreciably influence the heat budget of the pit due to compensating effects such as increased air temperature balancing reduced solar radiation. Once a mathematical model is fully formulated we ought to be able to test this assertion.

MATHEMATICAL WATER QUALITY MODEL

Model Selection

We maintain that a modelling approach which is based the underlying physical processes with a minimum of site specific parameterization should be more robust in the sense of offering more reliable predictions and applicable to a wider range of physical conditions. For the purpose of modelling the water quality of pit lakes we have chosen the model, DYRESM, which was originally developed for reservoirs (Fischer et al., 1979, 1981) and extended to lakes by Patterson et al. (1984). Later, Patterson and Hamblin (1988) added to the model the ability to simulate ice cover and snow cover. Rogers et al.(1994) modified the ice formation routine to better model temperate zone ice formation which has been implemented in the model by McCord (1996). The model DYRESM despite being restricted to variation in the vertical direction has received a wide application to lakes and reservoirs throughout the world; for an example of a recent application, see Boyce et al.(1993). The restriction to vertical variation is least problematic in pit lakes of all water bodies due to their extreme depth relative to horizontal dimensions. While Stevens and Lawrence (1995) noticed some minor lateral temperature variations they estimated that they would be rapidly homogenised. An important consideration for pit lakes is a model's ability to realistically treat inflows and outflows at any level but in particular, at the surface should the pit eventually overflow. Further, the model ought to be able to accurately simulate the such terms in the mass balance as evaporation which change as the surface area increases, so that the time of overflow can be predicted. Most importantly, the vertical transport of material should be based on the underlying physical processes and not arbitrarily prescribed. Since simulation periods of many decades or even centuries may be called for to assess potential for water quality exceedences computational efficiency is vital.

Model Modifications and Extensions to Pit Lakes

Pit lakes are most unusual in that they have very high ratios of depth to length (order unity) when compared to most natural lakes of order 10^{-3} to 10^{-6} with the possible exception of crater lakes, Figure 2. On account of the extreme ratio of the area of the bottom to the lake volume bottom mixing processes are expected to play a significant role. Herein, we describe a new algorithm for handling bottom mixing caused by the stirring of bottom currents due to internal waves. Another modification is the inclusion of double diffusive mixing (McDougall, 1983) arising from opposing vertical density gradients associated with dissolved salts and temperature stemming for either natural ground water inflows or the disposal of mine wastes in the pit.

Briefly, in the standard DYRESM model mixing processes are treated somewhat differently in the epilimnion and the hypolimnion. In the upper layer mixing is simulated by an integral approach based of the relevant terms in the turbulent kinetic equation of fluid mechanics (Fischer et al.,1979 and 1981) which accounts for the stirring action of wind and current shear, convective surface cooling (usually at night) and heating (usually during the day) including that due to the absorption of solar radiation. Parenthetically, it is mentioned that the absorption of short wave radiation varies widely from one water body to another and must be specified by field measurement. In this study we have estimated it from a single Secchi disc reading. Below the thermocline, the integral method is not applicable but instead, mixing is based on a semi-empirical formulation in which a fraction (approximately 5%) of the turbulent mixing energy goes to increase the potential energy of the water column. Thus, mixing in the deeper lake waters depends on the stirring by the wind and incoming rivers and on the overall stratification of the water column. This deep mixing varies from one day to the next as the meteorological forcing is usually specified daily. Unlike the version described in Fischer et al.(1979 and 1981) our standard mixing coefficient is vertically uniform in the hypolimnion.

As the vertical mixing depends on the rate stratification it is essential to accurately estimate the dependence of density on dissolved salts and temperature. In this study we have employed the relation, known as the equation of state, developed by Chen and Millero (1977) for lakes in general. However, it is noteworthy that the salts present in mine lakes are apt to be very different from those in lakes on average so that there is a clear need to make an individual determination of density dependence on dissolved constituents before the model can be applied.

Bottom Mixing

In a natural, deep and monomictic lake Wüest and Gloor (1995) have used measured currents at the bottom to show that bottom induced mixing can be a significant addition to the more standard vertical mixing schemes. Similarly, in the Central Basin of Lake Erie Ivey and Patterson (1984) employed measured currents to specify the contribution to mixing by bottom currents. They developed a bottom mixing scheme based on energy conservation principles which was consistent with that of the epilimnion described above. We adopt their scheme but extend it to include the storage of turbulent kinetic energy.

The vertical distribution of volume is descretized into a number of layers, three of which are illustrated schematically in Figure 4. The descretization is not intended to coincide with the mining benches shown in Figure 2. As each successive layer increases in area upwards there is a portion of area of layer i, A_i, that impinges on the bottom, A_i-A_{i+1}. If the current at the bottom is designated as u_i, then the bottom stress is according to standard practice, $C_D u_i^2$, where C_D is the bottom drag coefficient, $3x10^{-3}$. Taking the square root of the bottom stress, u_{b*}, as the characteristic scale for the bottom turbulent kinetic energy we have equation (1) for the energy balance integrated across the bottom mixed layer,

$$(C_T u_{b*}^2 + g'h)\frac{\Delta h}{\Delta t} = C_{K_b} u_{b*}^3 \qquad (1)$$

where Δ h is the incremental increase in the layer thickness over the bed in the elapsed time, Δt, g' is the so-called reduced acceleration of gravity reduced by the density difference between layer i and i-1 divided by the average density (ρ) of the two layers, and the coefficient, C_T, of 0.51 is based on standard mixed layer theory (Fischer et al., 1979) and C_{Kb} of 1.9 is the efficiency of stirring at the bottom (Hebbert et al., 1978). If the stirring energy is sufficient to entrain all the fluid of the layer above it or more in the allotted time, Δt, then the time step is reduced by a factor of two and the calculation repeated for the two sub-steps. At the end of each sub-step new volumes and properties are defined for each layer on the basis of the added volumes and conservation. At this point each new layer is checked to see if its volume lies within predefined limits. If not, then layers are either split or amalgamated as required.

The entrainment of less dense fluid from the layer above results in the water at the boundaries being less dense than that in the interior of the layer. This density difference creates a density contrast which drives a horizontal intrusion from the boundary to the interior and a consequent return flow. The net result is that the horizontal density contrasts are eliminated over the daily time step.

Unlike Ivey and Patterson (1984) or Wüest and Gloor (1995) we did not have access to measured bottom currents. In order to establish a daily profile of bottom flows we developed a method of calculating the velocity distribution based on the one-dimensional theory of wind-generated internal seiches and an idealised two-layer model. However, the horizontal speed of propagation of the vertically standing internal wave and the associated vertical profile of horizontal velocity was calculated from the modelled density distribution in the vertical as a vertical eigenvalue problem. This characteristic equation was solved, in turn, by the shooting method. The thicknesses of the two layers was also determined from the solution of the characteristic equation for consistency. Since we had access to ten-minute wind readings we calculated the wind stress from the north and east components of wind every ten minutes as well as the associated velocity profile. From the 10-min estimates of bottom velocity a daily average profile was constructed. Winds less than 0.2m/s were not accounted for. We did not attenuate wind generated internal waves during ice cover as they were observed in winter.

Whereas the boundary mixing scheme does not provide an eddy diffusivity as the standard hypolimnetic formulation does, nonetheless, it is of interest to calculate an effective eddy coefficient for the sake of comparison with the standard mixing scheme. Since by definition, the vertical eddy diffusivity, K_V, for mass is the buoyancy flux divided by the stability, N^2, we may estimate it from expression (2).

$$K_v = \frac{\partial \rho}{\partial t} / (\frac{\partial^2 \rho}{\partial z^2}) \tag{2}$$

Other Modelling Details

Lake geometry is represented in the model from known bathymetric data by means of vertical distributions of area and volume shown in Figure 5. These data are used in the model to establish the layer areas and volumes.

A bottom inflow of 700 m^3/d and of a salinity of 950 mg/l and temperature of 4.2 ^oC was inferred from the six temperature and conductivity profiles taken during the 220-day study period. No outflows were assumed.

All modelled density profiles were examined for the occurrence of opposing contributions to the vertical density gradient from salt and temperature. At the identified depths, an additional vertical eddy diffusivity of $5x10^{-6}m^2/s$ was added to the standard vertical mixing formulation to account for double diffusion as discussed above. This value was estimated again from the field profile data.

The relative humidity sensor failed at the rim station after only a few weeks of operation. Data were obtained from the nearby Peachland station on a daily basis and substituted for the missing data. Unfortunately longwave incoming radiation was not measured either. This essential term in the surface heat balance had to be supplied from an empirically based formula (Fischer et al., 1979) based on air temperature and cloud cover. As well, cloudiness was not measured so that it was estimated from the measured and theoretical clear sky radiation for a given day and a formula from the TVA report (1972). The model requires daily profiles of light extinction. No profiles were taken during the modelled period so that light extinction had to be estimated from the empirical expression, 1.6/Secchi depth, which gave an extinction coefficient of 0.11 m^{-1}.

The model was initialised with the temperature and dissolved solids profiles of October, 21, 1994 and run without adjustment for 220 days until May 26, 1995 when the rim observation station was decommissioned. The basic time step is one day although in our modified version sub-daily time steps as short as ten minutes are permitted.

RESULTS

Modeled distributions of temperature and salinity are compared to the observations in Figures 6 and 7. It is evident that while the main features are modelled realistically there are some differences in detail. The hypolimnetic mixing in the model is more vigorous than in the prototype leading to weaker gradients in temperature and salinity. We consider that this is likely due to the inclusion of double diffusive mixing in the model. Further evidence that is process may not be operative in Brenda Pit Lake is that our fine-scale temperature profiler did not exhibit the steplike features found in Lake Kivu (Newman, 1976). In future, an attempt to better quantify this effect should be made. Possible errors in the specification of the meteorology over the lake surface may be responsible for the small lag in the dates of ice formation and thaw. The salinity is seen to freshen in the field observations close to breakup. This is thought to be due the melting of the snow cover. Precipitation data were not available for use in the model.

The period of the internal seiche is a byproduct of the calculation of the bottom velocity profile. The minimum period was 1.4hr over the simulation period but during the summer when stratification is strongest this is likely to decrease to approximately one hour. Since a minimum of at least four wind values should be specified over the period of oscillation, hourly winds should not be used in the bottom velocity routine but rather at least 15 minute samples.

The profound effects of ice cover and relatively high salinity on vertical mixing in Brenda Pit-Lake are illustrated by reference to Crater Lake (Crawford and Collier,1996). They found that the salinity was only 10% of the pit lake and that Crater Lake remained free of ice. Thus, strong convective overturns occurred which resulted in the mixing of as much as one-quarter of the volume of the hypolimnion in a single episode. Both the model and the observations are in agreement that events of deep penetrative convection do not take place in Brenda Pit. As well, neither display has any indication of thermobaric mixing (Walker and Watts, 1995) that might be expected in deep temperate lakes in winter. Again, it is likely that the concentration of dissolved salts is too elevated to permit this process.

The absence of deep penetrative convection in the pit lake is further confirmed in Figure 8 where the behavior of the upper mixed layer as deduced from the model is shown along with predicted eddy mixing coefficients. Although the simulation period is less than a year it is highly unlikely that the mixed layer depth would at any time exceed 19m which occurred just before freeze-up. In general, the eddy diffusivity is higher near the bottom due to the addition of a double diffusive component which is usually confined to the deeper layers. It is interesting that the effect of bottom induced mixing in Figure 8b is still somewhat less than the conventional specification described in Figure 8a when double diffusive mixing is ignored. However, it remains substantially higher than molecular ($10^{-9}m^2/s$) so that it could be important for the mixing of salt in the monimolimion should the wind power be attenuated by the ice cover.

An illustration of how the model results can be employed in the management of water quality in a mining pit follows. Based on a conservative eddy coefficient from Figure 8a of $10^{-6}m^2/s$ and a characteristic time scale of the square of the depth divided by the diffusivity, the time required for a material introduced at the bottom in solution to diffuse over the 130m distance from the bottom to the base of the mixed layer is about 500 years provided conditions do not change.

CONCLUSIONS

Our field investigation was aimed at obtaining a base-line understanding of a hitherto unknown type water body and was successful in discovering some new processes in limnology. Unfortunately we did not have the resources that we would have desired for a thorough modelling study. For example, we lacked a complete specification of the driving forces. Key inputs such as relative humidity had to be assumed from other stations. While the autumn and spring seasons are likely to be the most crucial for vertical mixing and hence the near surface water quality we lacked a complete annual cycle of mixing. Furthermore, our model started late in the season, not long before the freezeup, so that the water body was isolated from the forces causing mixing over much of the evaluation period. It would be highly worthwhile to have suitable field data over a continuous 18-month period, long enough that the influence of the specified initial conditions would be "forgotten" by the model. If such a field and modelling programme were to be undertaken then a stable tracer such as sulphur hexafluoride should be introduced at the bottom of the pit and sampled at least monthly over the study period to validate the mixing scheme employed in the model. Attempts should be made to better quantify the effects of double diffusion and determine an equation of state for the pit water..

The result of such a programme of study would be a water quality model that with a minimum of "tuning" could supply the linkage between the loading from sub-aqueous deposits of mine tailings and the water quality of surface outflows. Such a calibrated model could provide assistance for monitoring programs and input to management decisions on the release of contaminant laden water from decommissioned mining pits. In model applications to mining pits where there is no prior environmental experience it is strongly advocated that a field and modelling investigation of the kind described in this study be undertaken.

ACKNOWLEDGEMENTS

We wish to thank R.McCandless for drawing the problems of concern in this study to our attention and for his encouragement during the study period. C. He assisted with the preparation of the contour plots, S.A.McCord kindly provided his code for the Rogers et al.(1995) ice and snow cover routine and C.Kocot of the Atmospheric Environment Service generously supplied supporting meteorological data. This study was funded jointly by CANMET, Brenda Process Technologies and Environment Canada.

REFERENCES

Boyce, F.M., P.F.Hamblin, L.D.D.Harvey, W.M.Schertzer and R.C.McCrimmon. 1993. Response of the thermal structure of Lake Ontario to deep cooling water withdrawals and to global warming. J.Great Lakes Res. 19(3) 603-616.

Chen, C.T and F.J. Millero, 1977 The use and misuse of pure water PVT properties for lake water. Nature, 266: 707–708.

Crawford, G.B. and R.W.Collier. 1996. Observations of a deep mixing event in Crater Lake, Oregon. Manuscript submitted for publication.

Davis, A. and D. Ashenberg, 1989. The aqueous geochemistry of the Berkeley Pit, Butte Montana, U.S.A. Geochem., 4: 23–36.

Fischer, H.B, E.J. List, Koh, T.Y.C., Imberger, J. and Brooks, N.H., 1979. Mixing in inland and coastal waters. Academic Press, 483p.

Fischer, H.B, 1981 Transport models in inland and coastal waters: proceedings of a symposium on predictive ability. Edited by H.B.Fischer, Academic Press, 542p.

Hebbert, R., J.Imberger, I.Loh, and J.Patterson 1979. Collie River underflow in the Wellington Reservoir. J. Hydraul. Div. Am. Soc. Civ. Eng. 105:553-546

Martin, J.M, 1985. The Pavin crater lake. In: Chemical Processes in Lakes, Strumm, W.(ed), 169–188.

McDougall, T.J. 1983. Double diffusive plumes in unconfined and confined environments. J. Fluid Mech. 133:321-343.

Ivey G.N. and J.C.Patterson, 1984. Vertical mixing in Lake Erie in summer. Limnol. Oceanogr. 29(3): 553-563.

Lawrence, G.A., P.R.B.Ward, and M.D.MacKinnon. 1991. Wind-wave induced suspension of mine tailings in disposal ponds-a case study. Can. J. Civ. Eng. 18(6): 1047-1053.

McCord, S.A. 1996. Artificial reaeration of lakes. Abstract in North American Lake Management Society Conf., Minneapolis, MN Nov. 1996

Newman, F.C. 1976. Temperature steps in Lake Kivu: a bottom heated saline lake. J. Phys. Oceanogr. 17:451-454.

Patterson, J.C., P. F. Hamblin and J. Imberger, 1984. Classification and dynamic simulation of the vertical density structure of lakes. Limnol. Oceanogr., 29(4), 845–861.

Patterson, J.C. and P.F. Hamblin, 1988. Thermal simulation of a lake with winter ice cover. Limnol. Oceanogr., 33(3), 323–338.

Rogers, C.K., G.A. Lawrence, and P.F. Hamblin, 1995 Observation and numerical simulation of a shallow ice–covered mid–latitude lake. Limnol. Oceanogr., 32 pp.

Stevens C.R.and G.A.Lawrence. 1995. Natural transport processes in water-filled mine pits and their relevance to subaqueous disposal: Final Report to CANMET. Dept. Civil Engrg., Univer. BC, Vancouver, BC.

Stevens C., G.A.Lawrence, C.K.Rogers and P.F.Hamblin. 1994. Modelling the thermal stratification of water–filled mine pits. Regional Manuscript Report MS 94–01 Environment

Canada, Pacific & Yukon Region.
Taylor, P.A. and R.J. Lee. 1984. Simple Guidelines for estimating wind speed variations due to small scale topographic features. Climatological Bulletin 18:3-31
T.V.A. 1972. Heat and mass transfer between a water surface and the atmosphere T.V.A. Rep. No. 0-6803.
Tones, P.I., 1982. Limnological and fisheries investigation of the flooded open pit at the Gunnar uranium mine. Saskatchewan Research Council, SRC Rep. C–803–10–E–82, 64pp.
United States Army Corps of Engineers, 1986. CE–QUAL–R1; A numerical one–dimensional model of reservoir water quality. Instructional Report, Environmental Lab., Vicsburg, Mississippi.
Walker, S.J. and R.G.Watts. 1995. A three-dimensional numerical model of deep ventilation in temperate lakes. J.Geophys. Res. 100:22,711-22,731.
Wüest, A. and M.Gloor, 1995. Bottom boundary mixing in lakes: the role of near sediment density stratification. IUTAM Symposium on Physical Limnology, Broome, Australia 385–398.

List of Figure Captions

1) Highway map of south-eastern BC showing locations of the Brenda, SIMILCO, and Highland Valley mines and the supplementary meteorological station.
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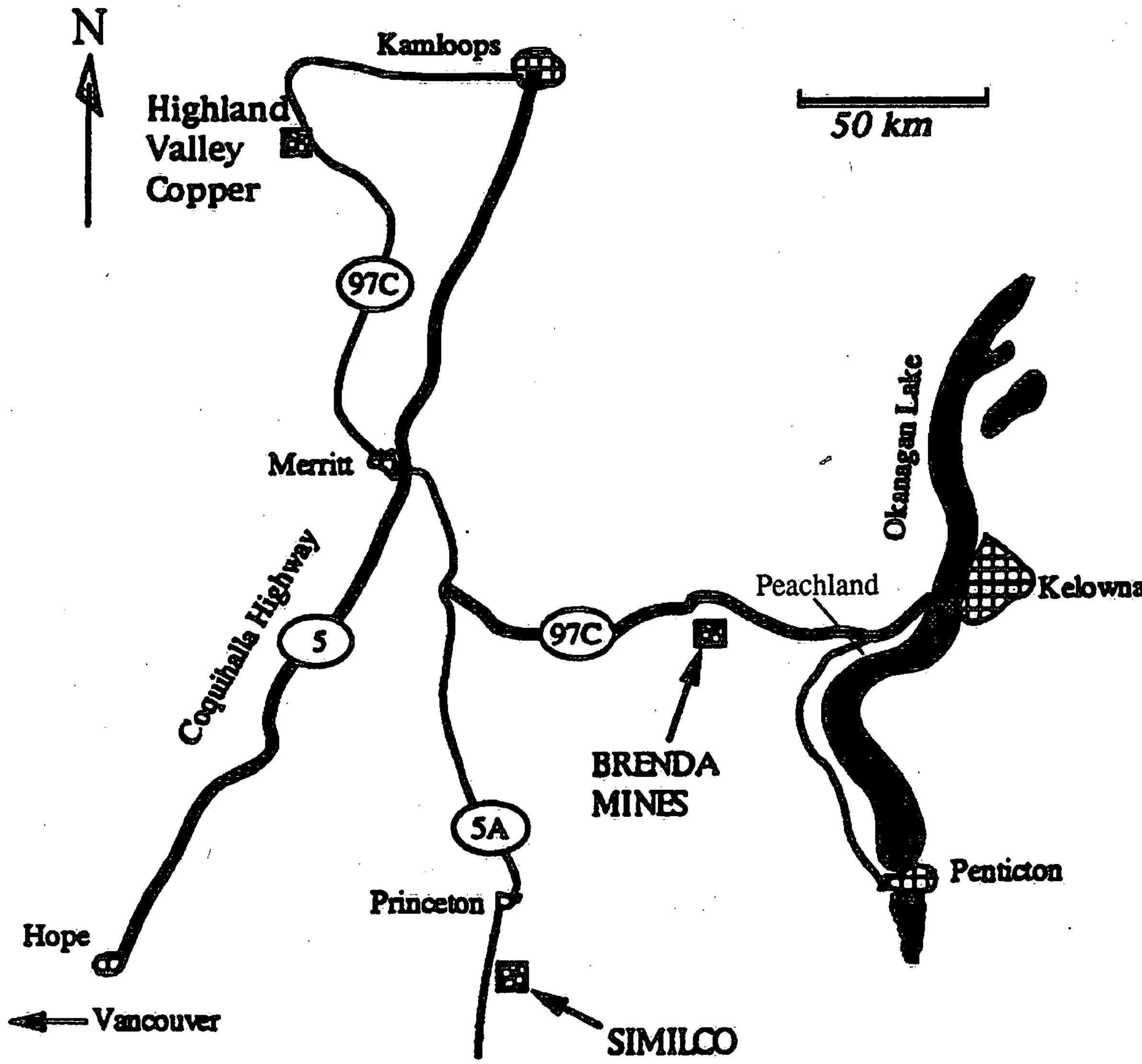
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Valley
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Okanagan Lake
Merritt
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MINES
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Penticton
Princeton
Hope
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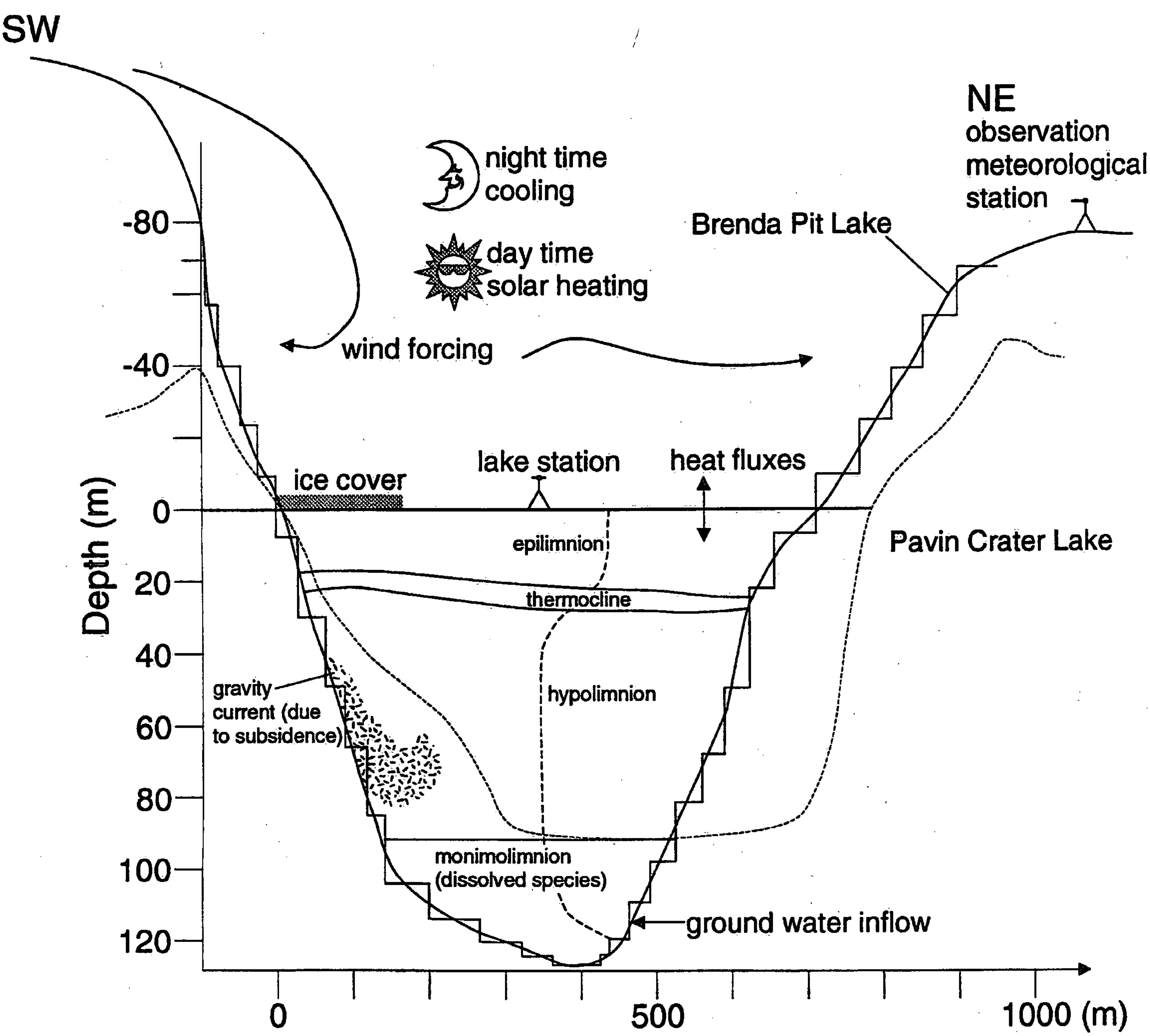
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observation
meteorological
station
night time
cooling
day time
solar heating
Brenda Pit Lake
wind forcing
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-40
0
20
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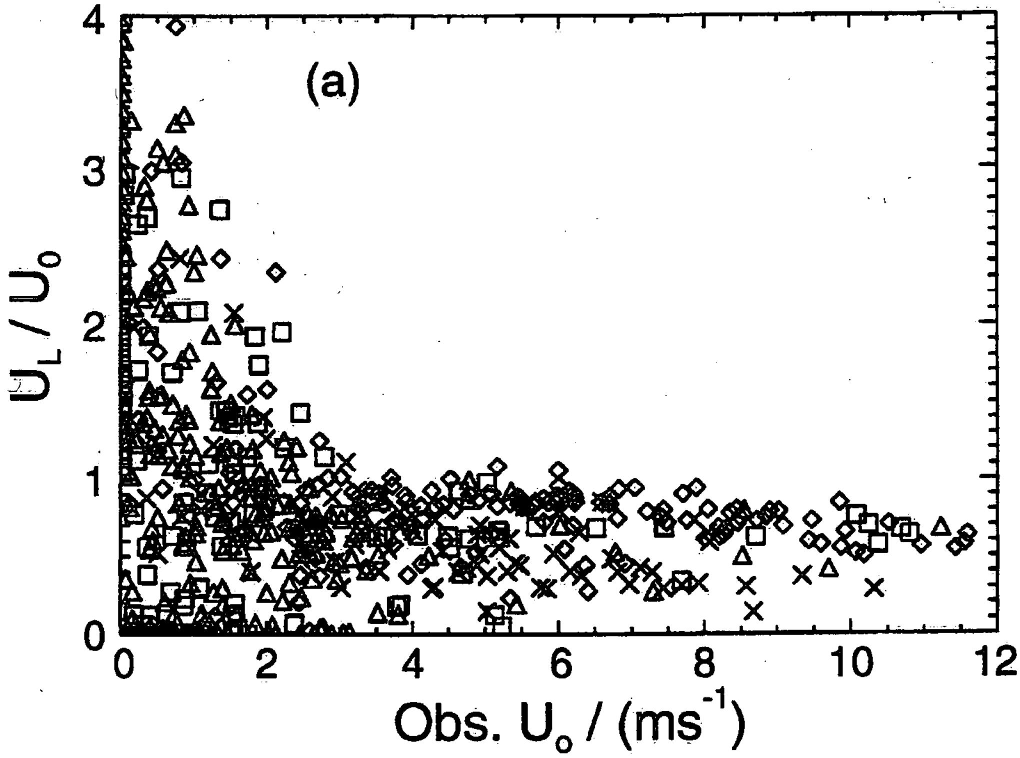
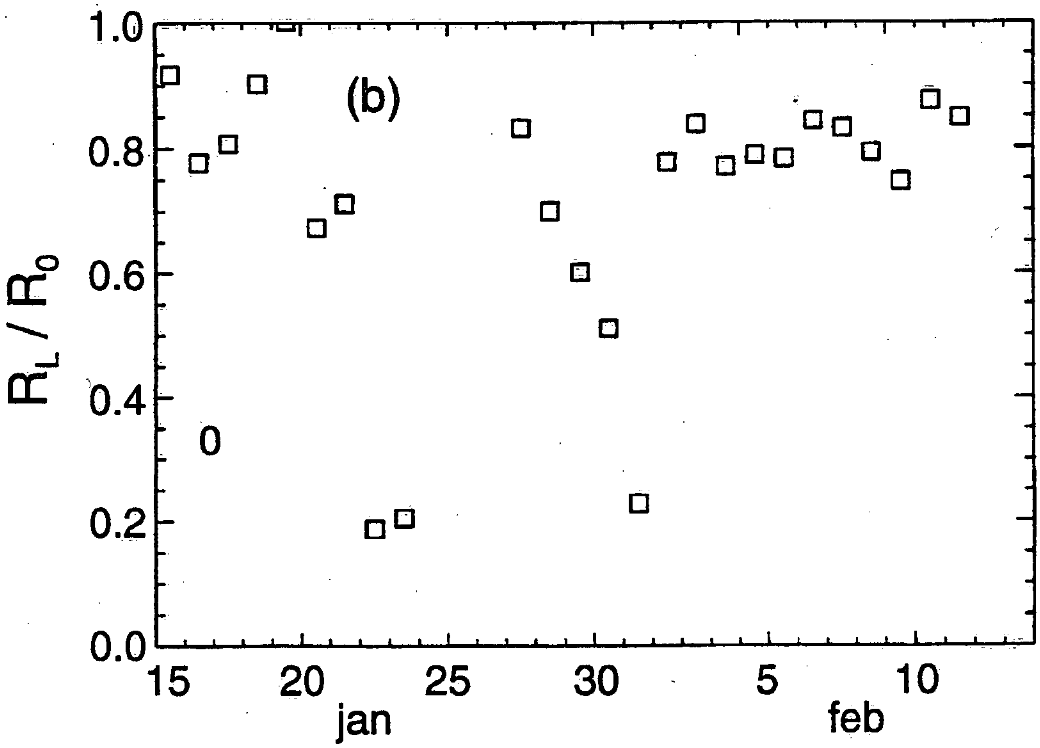
60
80
100
120
Depth (m)
ice cover
lake station
heat fluxes
Pavin Crater Lake
epilimnion
thermocline
hypolimnion
gravity
current (due
to subsidence)
monimolimnion
(dissolved species)
ground water inflow
0
500
1000 (m)

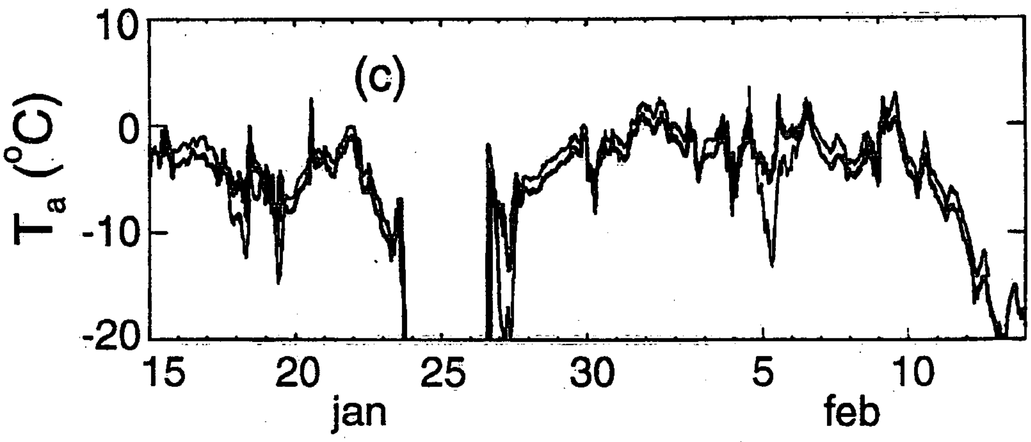
2



(a)
U_L / U_0
Obs. U_o / (ms^{-1})
0
2
4
6
8
10
12
1
3

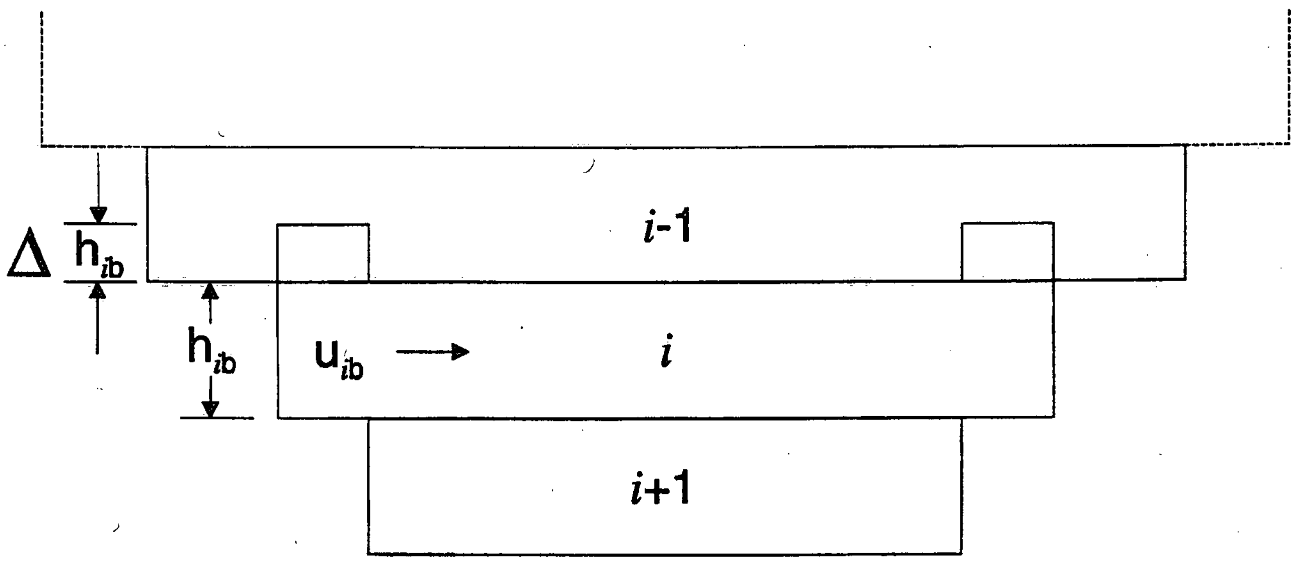


(b)
R_L / R_0
0
15
20
25
30
5
10
jan
feb
0.0
0.2
0.4
0.6
0.8
1.0

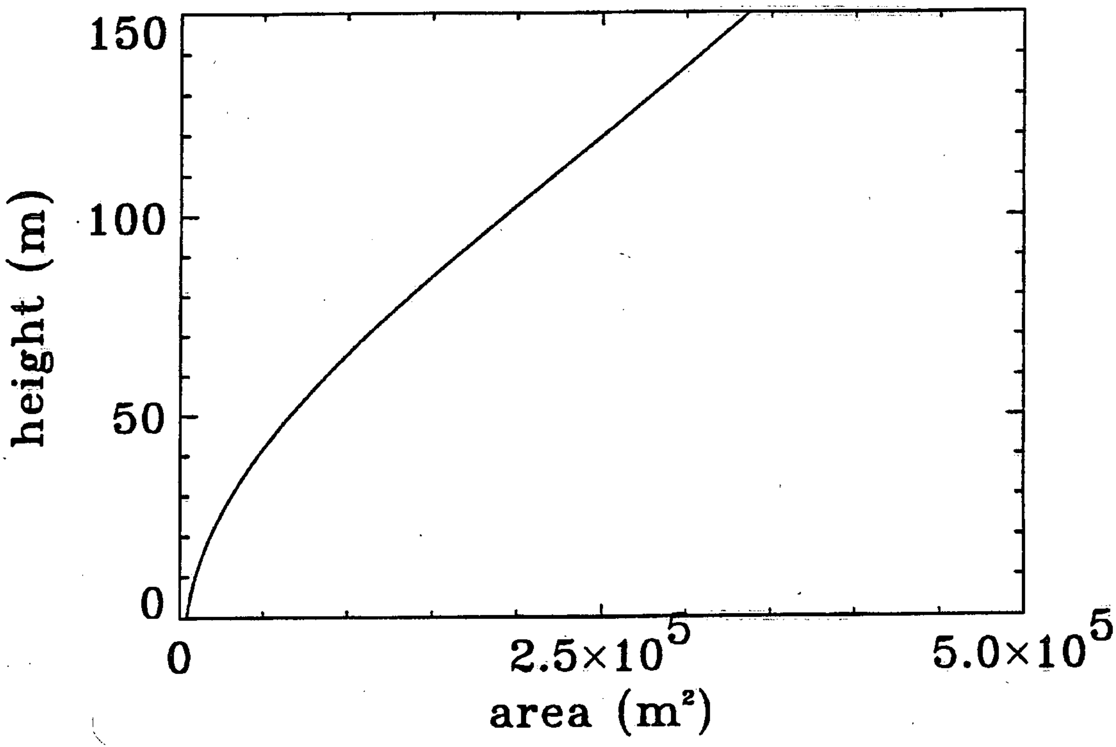


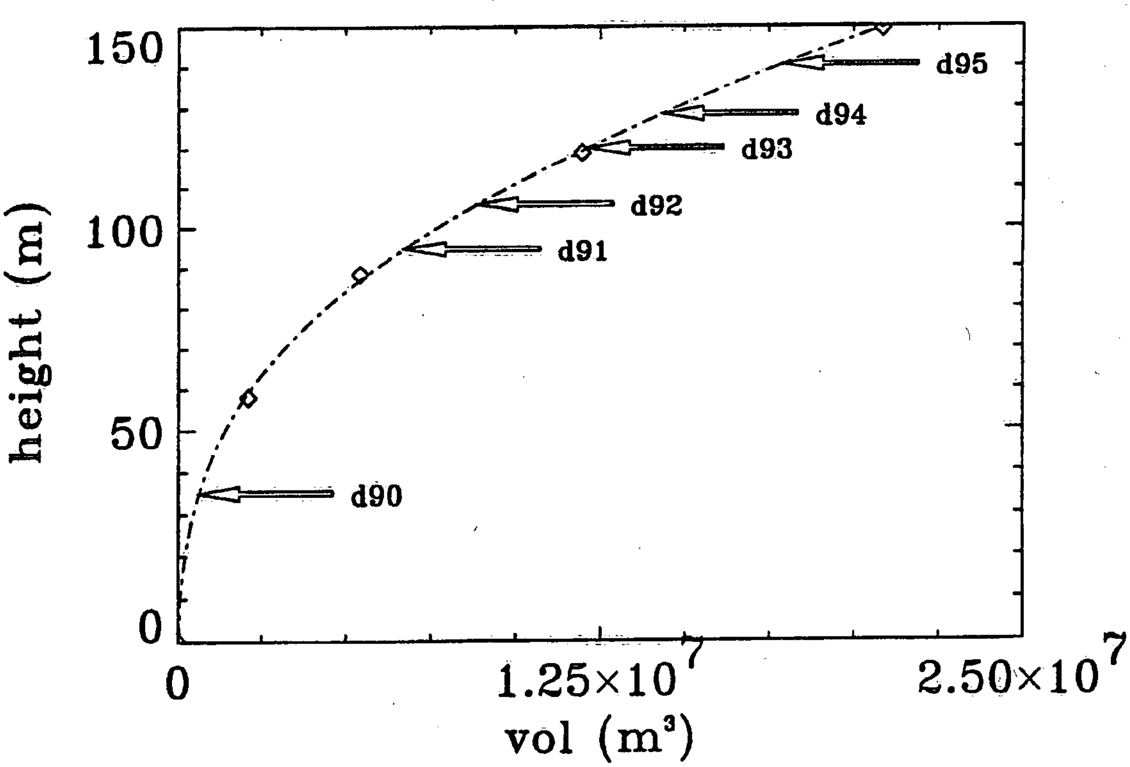
(c)
T_a (°C)
10
0
-10
-20
15
20
25
30
5
10
jan
feb

3

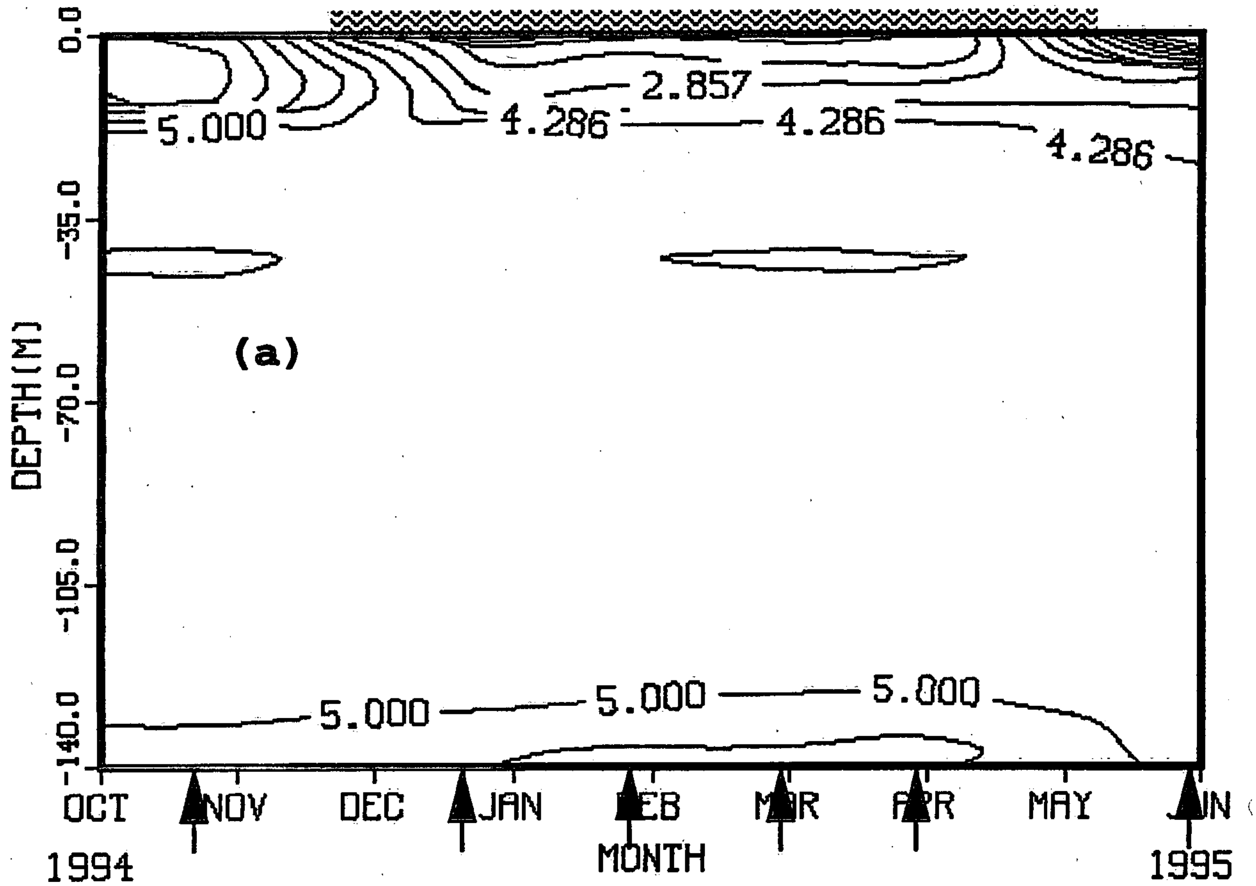


i-1
Δ h_ib
h_ib
u_ib
i
i+1

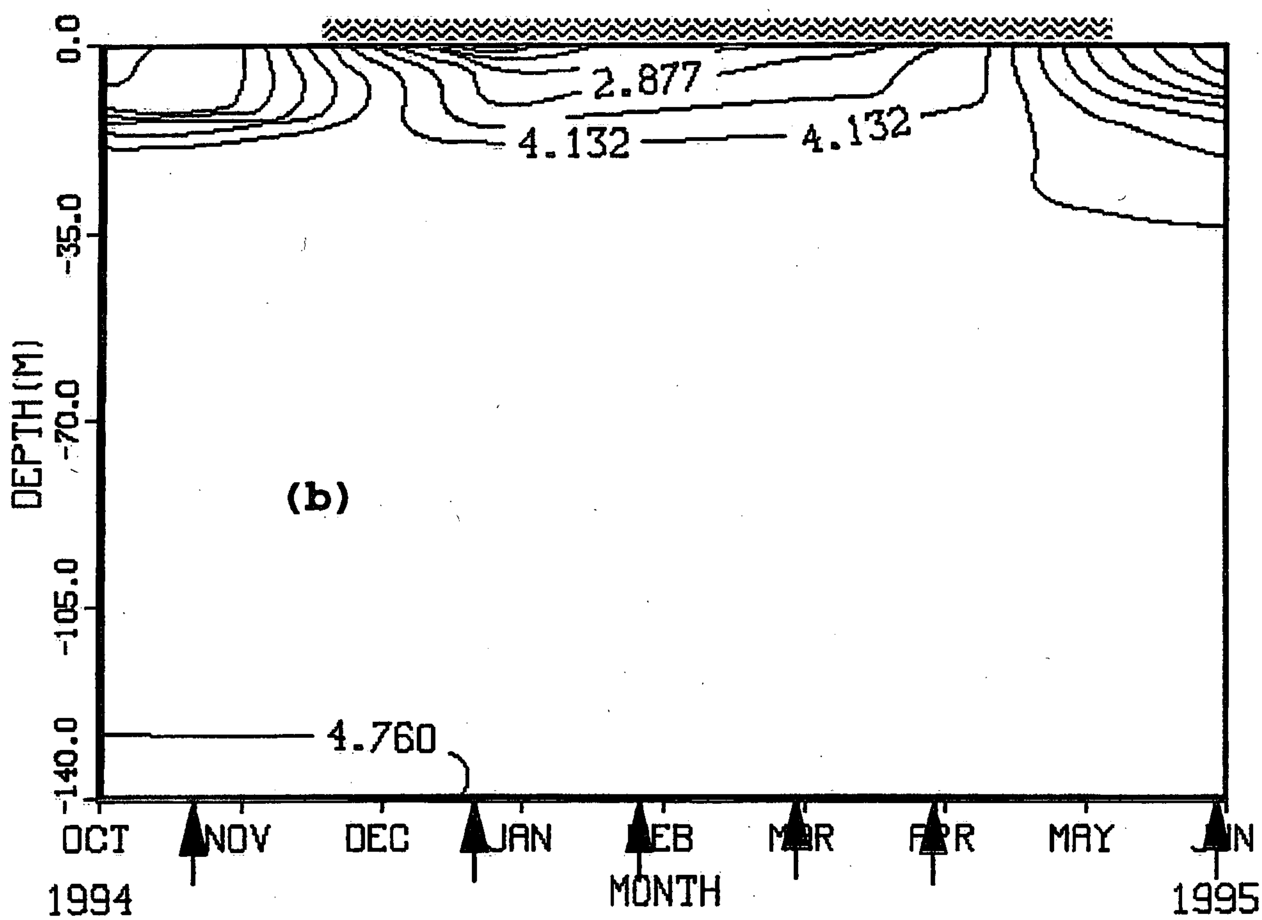

150
100
50
0
height (m)
0
2.5×10^5
5.0×10^5
area (m²)


d95
d94
d93
d92
d91
d90
150
100
50
0
height (m)
0
1.25×10^7
2.50×10^7
vol (m³)

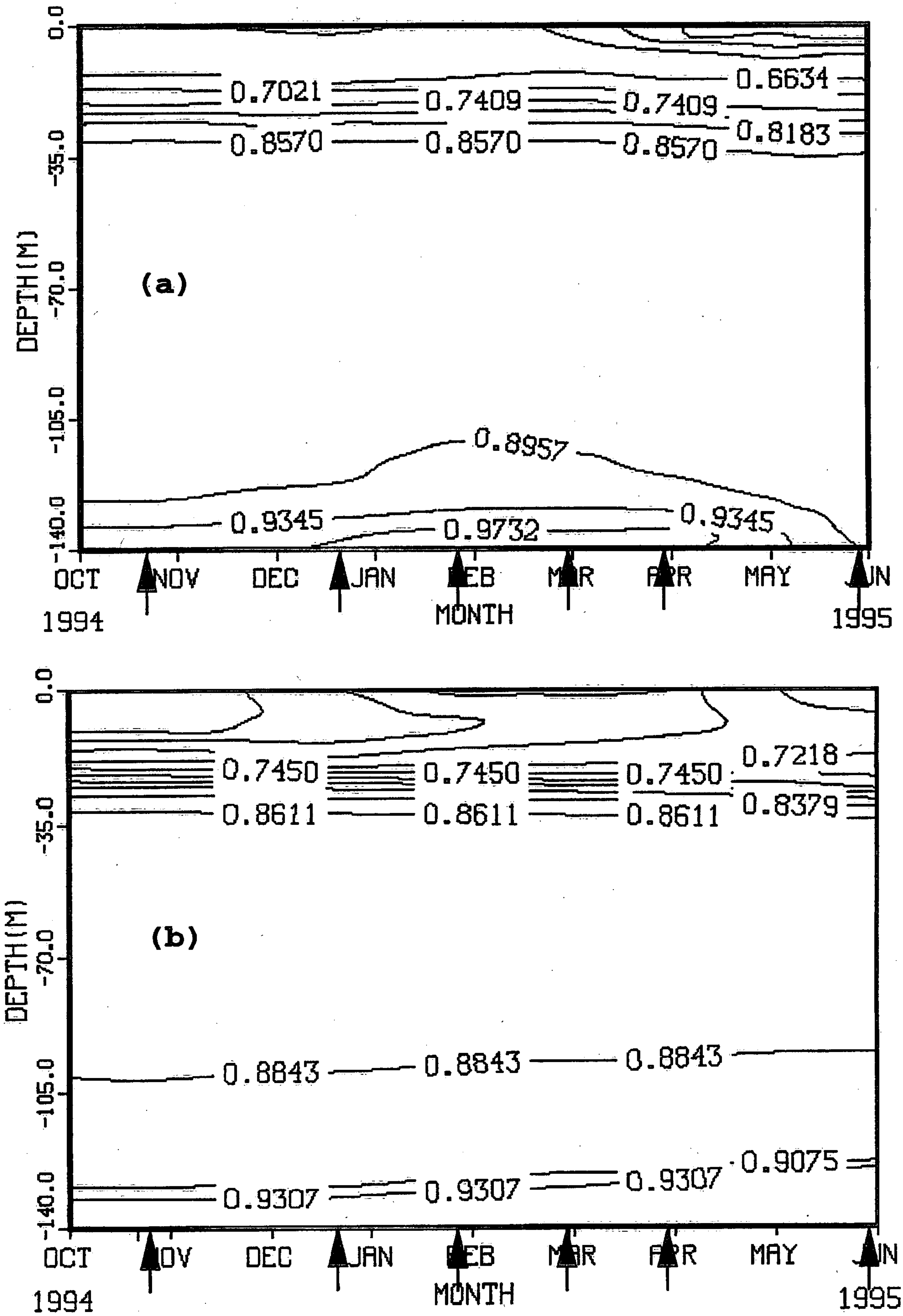
5

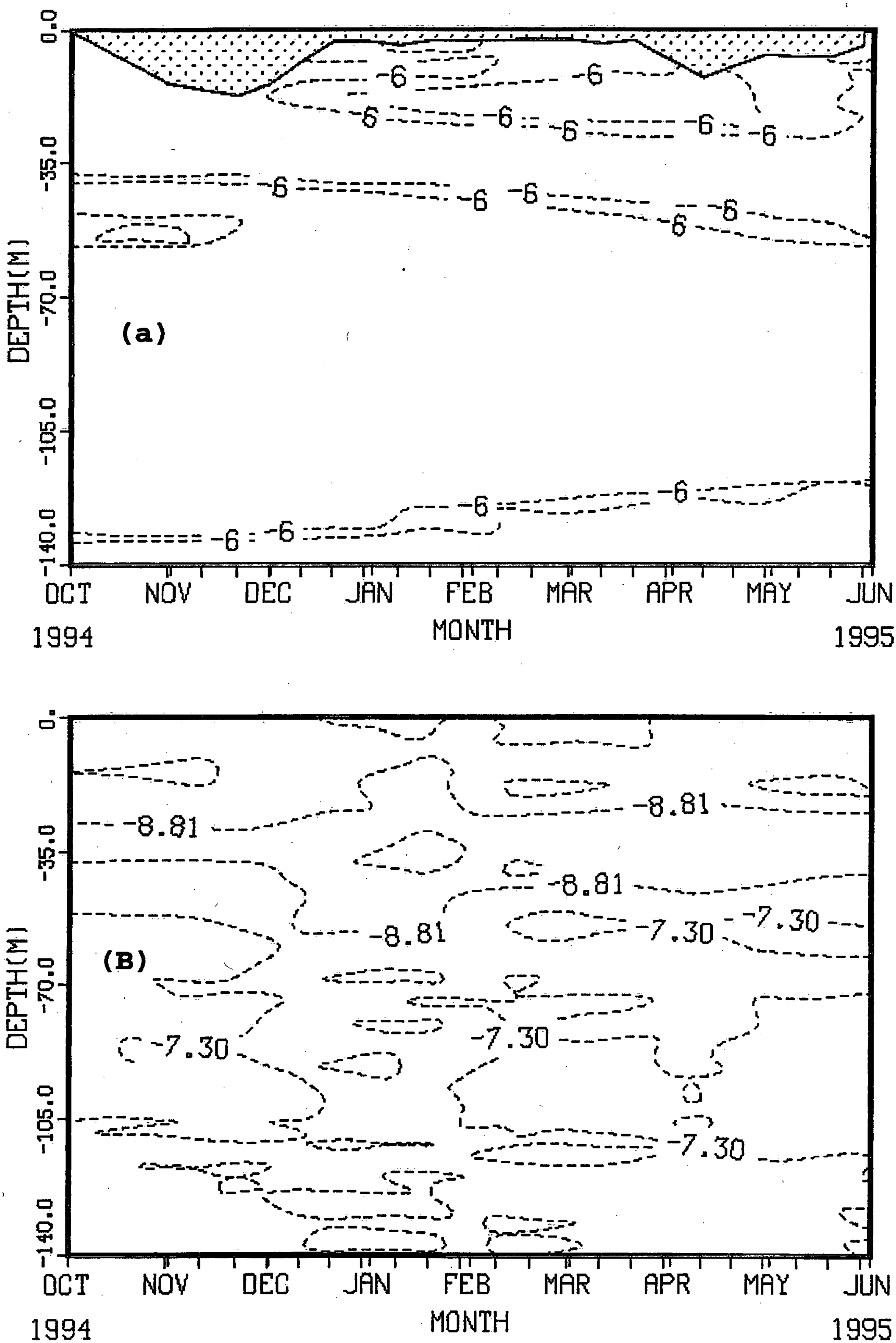


2.857
5.000
4.286
4.286
4.286
(a)
5.000
5.000
5.000
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (M)
OCT
NOV
DEC
JAN
MAY
MONTH
1994
1995



2.877
4.132
4.132
(b)
4.760
0.0
-35.0
-70.0
-105.0
-140.0
DEPTH (M)
OCT
NOV
DEC
JAN
MAY
MONTH
1994
1995


(a)
DEPTH(M)
0.0
-35.0
-70.0
-105.0
-140.0
0.7021
0.7409
0.7409
0.6634
0.8570
0.8570
0.8570
0.8183
0.8957
0.9345
0.9732
0.9345
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995
(b)
DEPTH(M)
0.0
-35.0
-70.0
-105.0
-140.0
0.7450
0.7450
0.7450
0.7218
0.8611
0.8611
0.8611
0.8379
0.8843
0.8843
0.8843
0.9307
0.9307
0.9307
0.9075
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995


(a)
DEPTH(M)
0.0
-35.0
-70.0
-105.0
-140.0
-6
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995
(B)
DEPTH(M)
0.
-35.0
-70.0
-105.0
-140.0
-8.81
-7.30
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
1994
MONTH
1995

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