Computer Simulation of the
Ground Thermal Regime in the
First Year After Drainage of
Illisarvik Lake

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INTRODUCTION

The drainage of lakes by natural means in the Mackenzie Delta has been occurring for several thousand years. Many lakes are at present in a position where they will soon drain by normal geomorphic processes, such as shoreline erosion. In August 1978, Illisarvik Lake (unofficial name), located on Richards Island in the Mackenzie Delta (fig. 1) and on the verge of self drainage, was drained artificially. The experiment was undertaken to investigate the growth of permafrost in the western Canadian arctic under naturally occurring field conditions. The overall objectives were to increase the knowledge of permafrost properties and of the processes involved in permafrost growth (redistribution of moisture, ice segregation, rate of frost line penetration and associated heave for example) and thus lead to a better understanding of both natural permafrost processes and problems relating to northern development. By artificially draining a lake predrainage characteristics could be observed to describe the initial physical conditions.

The drained lake experiment is a multidisciplinary study involving scientists from several institutes; principally the University of British Columbia, the federal departments of Energy, Mines and Resources, Environment and Indian and Northern Affairs and the University of Waterloo. The experiment comprises a three phase program: predrainage, drainage and post-drainage. The main activities include monitoring of the ground thermal regime, of the microclimatic regime and of geocryologic phenomena such as patterned ground, ice segregation, lake bottom heave, and growth of the active layer (Mackay, 1980).

The Earth Physics Branch is involved in the ground thermal studies at Illisarvik. To date 24 boreholes have been drilled to depths of 90 m below lake bottom and instrumented with multithermistor cables to monitor ground temperatures. Analysis of the predrainage thermal conditions will enable the determination of the natural equilibrium permafrost distribution and hence the minimum age and thermal history of the lake. The continued monitoring of post drainage temperatures and the analysis of permafrost aggradation in the lake bottom will enable the determination of the new equilibrium permafrost distribution.

In this report the freezing of the talik in the first year after drainage is modelled by studying the surface energy balance, the above-ground microclimatic regime together with the ground thermal regime. The computer simulation based on a program developed by Smith (1977) models the ground thermal regime using an approach which treats the ground heat flux as a component of the surface energy balance. Ground temperatures are predicted for a single site, borehole 78-9 drilled prior to drainage and monitored in the first year afterwards.

Agreement between the simulated and observed ground temperatures is good, despite many necessary assumptions in the input parameters, but for the moment does not warrant further modelling of the freezing of the talik. In order to pursue the microclimatic modelling further both an extensive geotechnical programme and a year-round weather gathering programme are necessary.

ILLISARVIK

Illisarvik Lake is located 60 km due west of Tuktoyaktuk, N.W.T. on a peninsula of Richards Island. Permafrost thicknesses in the vicinity are generally greater than 450 m (fig. 2) and mean annual ground temperatures range from -8° to -10°C. Illisarvik measured some 300 by 600 m and reached

4.5 m at its deepest point. Investigations during the winter before drainage (Hunter et al., 1980; Judge et al., 1980) included a bathymetric survey (fig. 3a) and ground temperature installations to establish the size and shape of the talik (fig. 4). The unfrozen lake bottom sediments extended to 35 m below ice level. The location of the boreholes is shown in figure 3b; borehole 78-9 was selected for this study.

The generalized geology of the lake bottom sediments was determined during drilling for ground temperature installations and from observations during drainage (Mackay, 1980; Hunter et al., 1980). An organic rich layer extending up to 10 m below the winter ice level underlies the lake bottom; lenses of gravel are locally interspersed. Beneath the organic layer lies a fine to medium grained sand with local silty zones.

To date few measurements of the soil physical and thermal properties have been made. Shallow cores obtained by the University of Waterloo for isotope studies will be used for acoustic and electrical studies and for grain size, moisture and density determinations. Washed samples from the hydraulic drilling of the temperature observation holes could also be used to grossly determine some of the unknown properties.

From the temperature observations prior to drainage the mean annual lake bottom temperature was observed to be around 3°C with lake bottom temperatures ranging throughout the year from 1° to 10°C (Judge et al., 1980). In the summer of 1979, one year after drainage, a meteorological station was established at Illisarvik (Anderson in Hunter, 1980). From May through to September, air temperatures and precipitation were recorded. This information was of little use for the computer simulation as the records were not continuous throughout the few months the station operated and pertinent weather details such as incoming solar radiation, wind speed and humidity were not observed.

The borehole chosen to model permafrost aggradation was located in 2 m of water prior to drainage, 60 m from the shoreline. The borehole was selected because of the availability of post drainage ground temperature logs and because of its simple lithology: a 2.5 m organic layer overlying a sand layer. Its temperature logs extend to 23.8 m below lake bottom. These temperatures are plotted in figure 6a and listed in table 1, from drainage onwards. From these plots the extrapolated mean annual lake bottom temperature prior to drainage is estimated to be 2.8°C.

COMPUTER SIMULATION AND MICROCLIMATIC DATA

A simplified flow chart of the computer program is shown in figure 5. The program is structured in the following way. Weather data and microclimatic site-specific characteristics (albedo, aerodynamic roughness, wetness) are input and used to constrain the surface energy balance at a specified site. The components of the energy balance (RN: net radiation, LE: evaporation, H: convective transfer of heat into the air and S: soil heat flux) are expressed as a function of the surface temperature. An iterative solution of this equation gives the equilibrium surface temperature from which the individual components are calculated. The surface temperature is used as a boundary condition together with the ground thermal properties to predict ground temperature distribution. An implicit finite difference form of the heat conduction equation is used. Complex stratigraphy and latent heat effects are accomodated. A few minor changes were made to the original program in order to model changes in wetness associated with Illisarvik drainage.

The albedo and wetness values used for the first year after drilling are listed in table 2. Immediately after drainage the lake bottom sediments are fully saturated, thus wetness was assigned its highest value and the albedo set accordingly. The lake bottom had little opportunity to dry out as winter set in soon afterwards. However, by the following summer, in July, the surface sediments had dried out and a lower wetness of .50 was assigned. During the winter the lake bottom is blown clear of snow. Thus the albedo was taken to be that of snow in the winter, although snow accumulation was assumed to be nil. The smooth unvegetated lake bottom was assigned a constant roughness value of 0.1 cm.

The soil thermal properties shown in table 3 were taken from the literature (Lachenbruch, 1970; Brown, 1964 and Oke, 1979). The porosity for the organic layer was set at 80%, for the sand layer at 30%.

The temperature log taken on August 10, 1978, three days before drainage was input as the initial ground temperature matrix. The log was extrapolated to a depth of 30 m and a temperature of -1.5°C was fixed for this depth throughout the program.

As there were very few weather data available from Illisarvik, information from nearby stations operated by the Atmospheric Environment Service was selected. The station at Tuktoyaktuk probably most closely resembles Illisarvik; both are located on the coast in the Mackenzie Delta. Unfortunately because of the delay in the publication of these weather reports not all the information for the first year after drainage was available. Values not available were taken from the same month in the previous year. Mean daily temperatures, percentage of cloud cover, wind speed, relative humidity and atmospheric pressure were recorded or calculated from observations recorded at Tuktoyaktuk. Mean daily radiation values were taken from the Inuvik station as it was the closest which measured incoming radiation. A comparison of the percentage of cloud cover at Tuktoyaktuk and Inuvik revealed that these were quite similar. Thus Inuvik radiation values may not be too large, as one might have anticipated since coastal stations are usually cloudier and foggier. The coastal clouds are low and thus a cloud type factor of .88 (see Appendix F, Smith, 1977), for strato cumulus, was assigned throughout the year. The weather data is listed in table 4.

RESULTS AND DISCUSSION

Temperatures in the ground temperature matrix were generated for every 50 cm. The simulated temperatures are listed for every metre in table 5 for the same days as actual temperature observations were recorded in the borehole. The simulated ground temperature profiles are plotted in figure 6b. For each date, the simulated and measured profiles were also plotted together for comparison (appendix). The simulated temperatures follow the same trends as the measured values. The September log reveals that although surface temperatures have cooled down the warm summer temperatures have continued to penetrate at depth. The March and May logs indicate the lake bottom is cooling in response to the cold winter temperatures. In July cooling continues at depth while the surface layer warms.

The large spacing (3 m) of the measured ground temperatures resulted in very few observations being recorded in the top organic layer (2.5 m). As well, a few of the logs lack some of the uppermost readings. Whether the uppermost sensor at 0 m is actually recording surface temperatures, or slightly above or below, is also uncertain - whereas the simulated temperature for 0 m is the calculated surface temperature. However, despite these facts the annual temperature waves in the organic layer agree well, with perhaps slightly more variability in the simulated temperatures.

In contrast, the magnitude and depth of penetration of the temperature wave in the underlying sand layer are less in the simulated temperature profiles than in the observed. By the end of the first year the model predicts that cooling should have only occurred down to 13 m below lake bottom. The measured temperatures reveal that the whole profile has cooled; temperatures are 0.4°C colder towards the bottom.

Some small portion of this cooling observed below 15 m in the borehole might be due to the dissipation of the drilling disturbance. The borehole was drilled in April 1978 and temperatures may not yet have reached equilibrium values by August. However,this would probably not account for a 0.4°C change, since jet drillholes usually return to within 0.1°C of their equilibrium temperatures in the first month after drilling.

Comparing the actual and predicted cooling at 9 m reveals the former is on the order of 0.9°C whereas the latter is around 0.5°C. If we assume that the model, in determining the radiation balance, predicts the correct soil heat flux component, then a higher conductivity is needed in the sand layer and perhaps a lower volumetric heat capacity in order to allow greater penetration and a larger amplitude of temperature change.

On the other hand if we assume that the heat flux (either in or out) in the sand layer is not large enough but that the thermal properties for the sand are good estimates, then the thermal properties in the organic layer would probably need to be changed - lower the conductivity and perhaps increase the volumetric heat capacity.

Measurements of the unfrozen thermal conductivities of unconsolidated core samples from Kugmallit Bay, offshore Mackenzie Delta (Hunter et al., 1976) revealed a distinct difference between sands and gravels (2.61 ± 0.29 $Wm^{-1}K^{-1}$) and silts and clays (1.47 ± 0.10 $Wm^{-1}K^{-1}$). These results suggest that the thermal conductivity value selected for the model's unfrozen sand might be too low. Hunter et al. point out that insufficient experimental observations exist to relate lithology with thermal conductivity with any degree of confidence in frozen soils, whereas relationships exist for unfrozen soils given information on composition, effective porosity and moisture content.

POSSIBLE REFINEMENTS AND FUTURE WORK

The computer model used here involves a one dimensional analysis, whereas the growth of permafrost beneath the lake bottom is three dimensional. When reducing the analysis to one dimension it is therefore best to select a borehole which is far away from the shoreline and close to the lake centre. The choice of borehole 9 was perhaps not the most appropriate. The temperature at 30 m was set at -1.5°C; however, this is not a fixed boundary and for future predictions, several years into the future, the model would be artificially constrained. In addition, given the possibility of moisture movement both in frozen and unfrozen soils the model's assumption of heat transfer by conduction alone could be questionned.

The sensitivity of the model to soil properties and site characteristics could be gaged by arbitrarily varying these parameters. This process might be sufficient to correct the discrepancies between the simulated and the observed ground temperatures. However changes in the input cannot normally be justified without further observations of conditions at the lake site (to better determine wetness, albedo, cloud type, snow thickness) and measurements of soil properties. The sensitivity analysis will determine which of these parameters are most crucial for field measurement or observation.

In order to determine whether the soil thermal parameters are in error, measurements of the soil thermal and physical properties should be made. A more intensive effort to gather soil data such as grain size, density and moisture content, and to measure the thermal properties of the frozen and unfrozen soils (conductivity and heat capacities over the temperature range from -10° to +10°C) is needed.

Modifications to the weather input could be made once AES records become available for the complete year after drainage. Some weather data might also be available for comparison from present and past base camps of oil companies in the Mackenzie Delta (eg. Shell Farewell, Imperial Bar C and Gulf Swimming Point). In order to best improve the weather information, the establishment of a year-round meteorological station at Illisarvik, with an increase in the types and number of observations, is needed. These observed parameters should include incoming solar radiation, temperature, wind speed, cloud cover, vapour pressure, precipitation. An accurate determination of the surface energy balance of the drained lake bottom could then be made.

The analysis could then be extended to include several boreholes, particularly some further from shore. A future refinement of the microclimatology modelling would be to attempt a two dimensional analysis. These microclimatic simulation tests will, combined with field observations, be important in the understanding of the active physical processes in the formation of permafrost.

Successive microclimatic monitoring and modelling at five year intervals as the lake bottom becomes revegetated could prove one of the most effective means of studying the impact of the biosphere on the surface energy balance of northern terrains.

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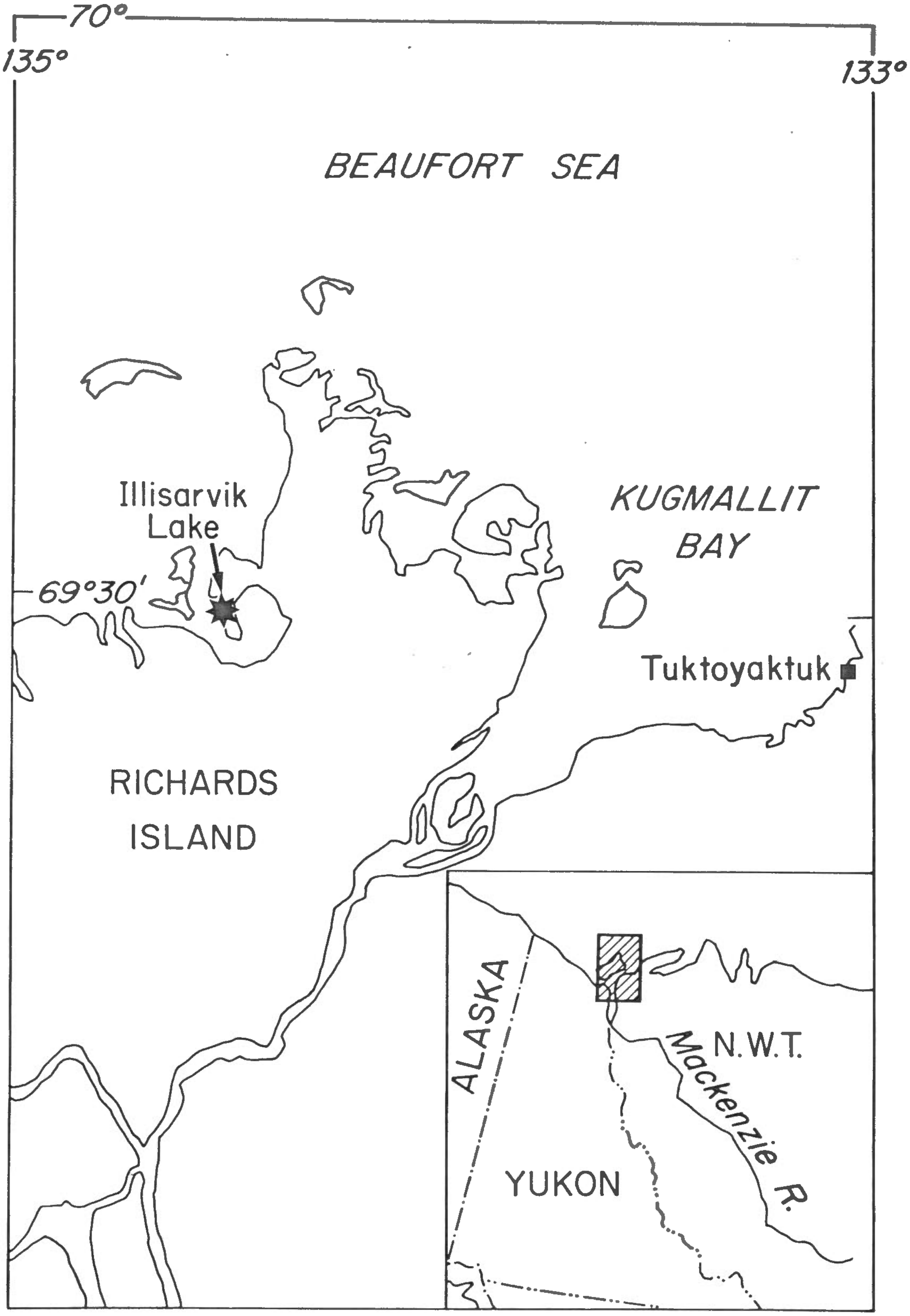


Figure 1. Location Map, Illisarvik Lake, Mackenzie Delta.

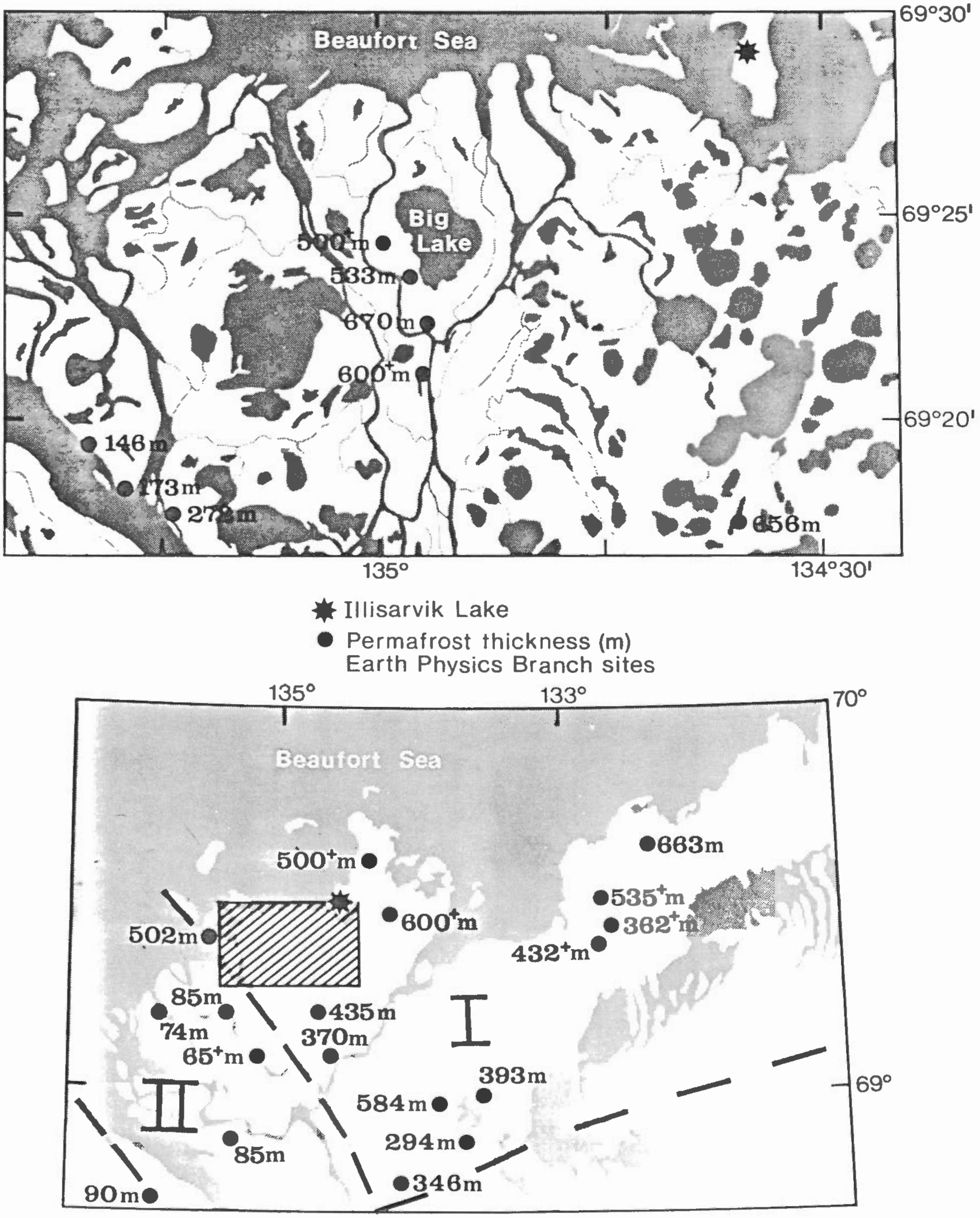


Figure 2. Permafrost thickness in the Mackenzie Delta (bottom map) and in particular in the vicinity of Illisarvik Lake (top map).

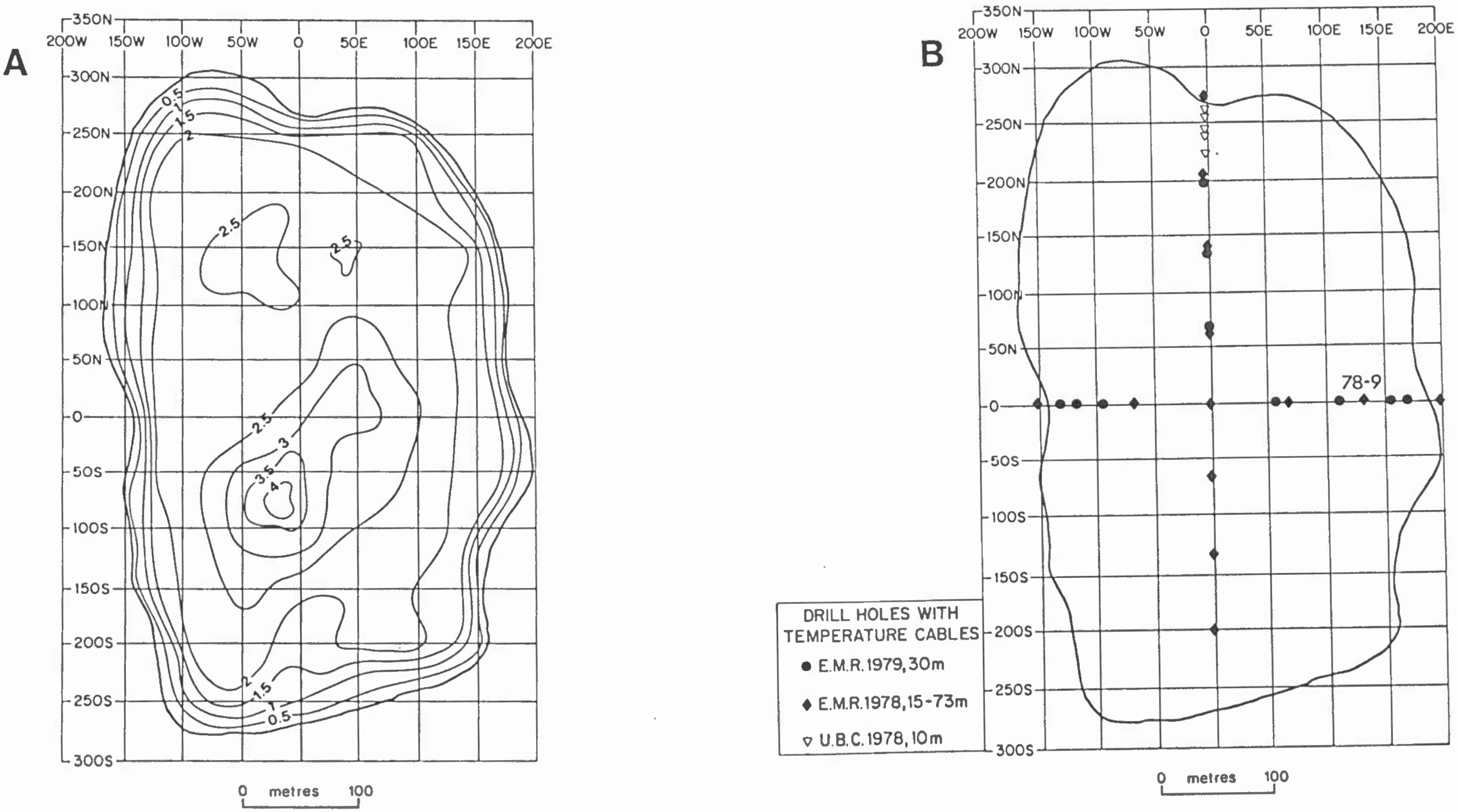


Figure 3. a) Illisarvik Lake bathymetry (m) and measurement grid

b) Illisarvik Lake ground temperature installations

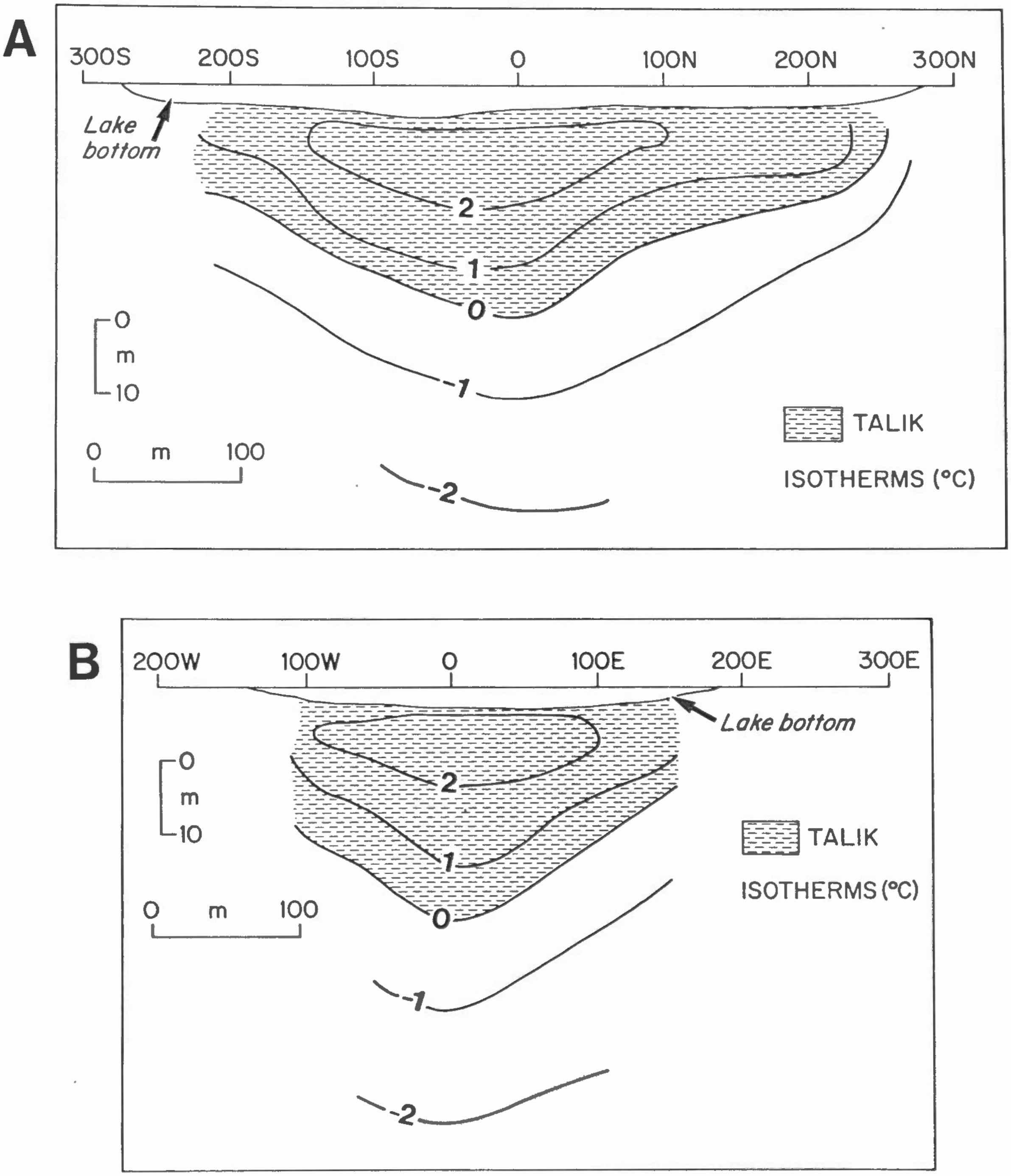


Figure 4. Isothermal cross-sections prior to drainage of Illisarvik Lake

a) North-South section b) East-West

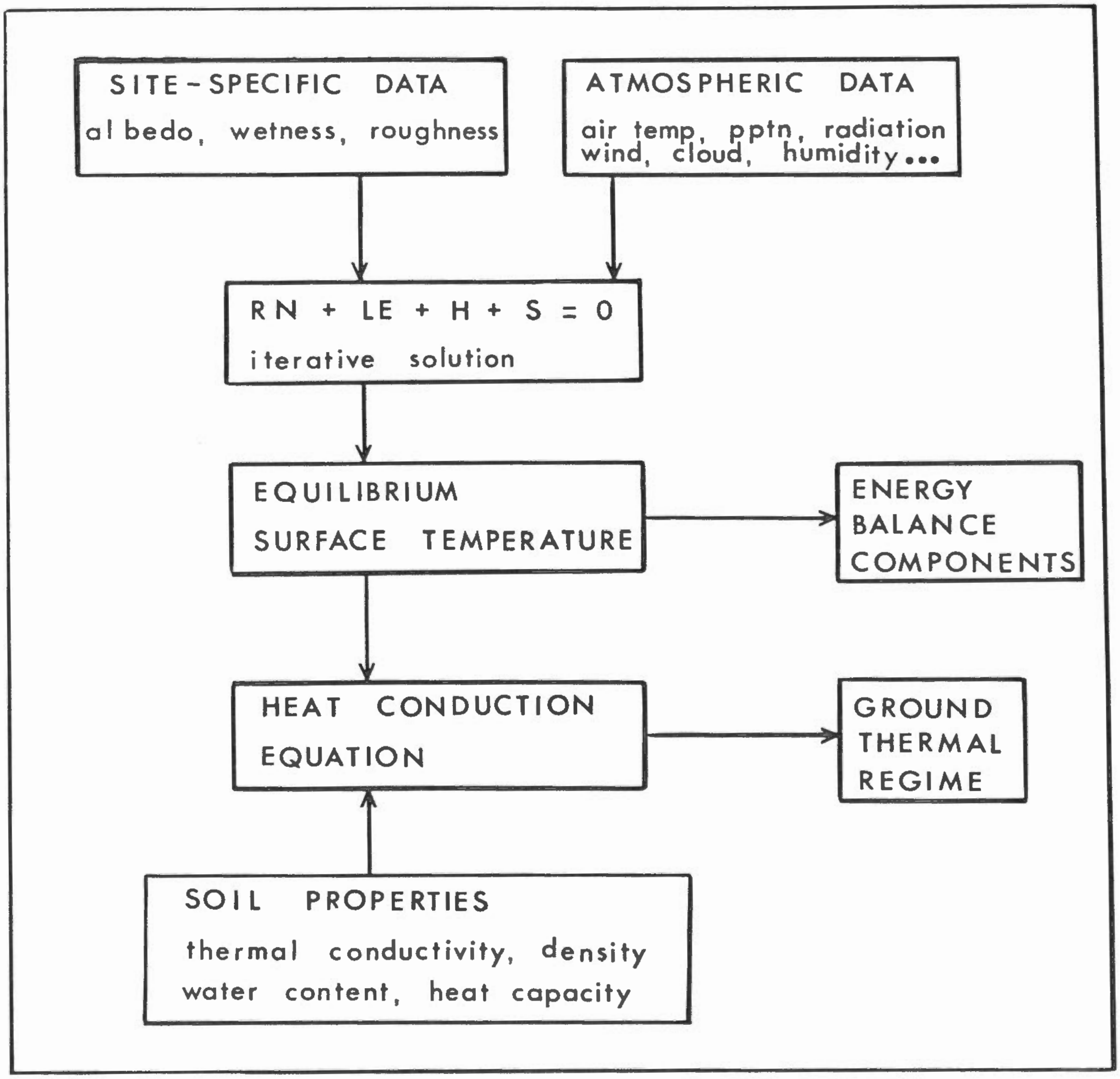


Figure 5. Flow chart of the microclimatic and ground thermal regimes program (RN: net radiation, LE: evaporative heat flux, H: convective transfer of heat into the air and S: soil heat flux).

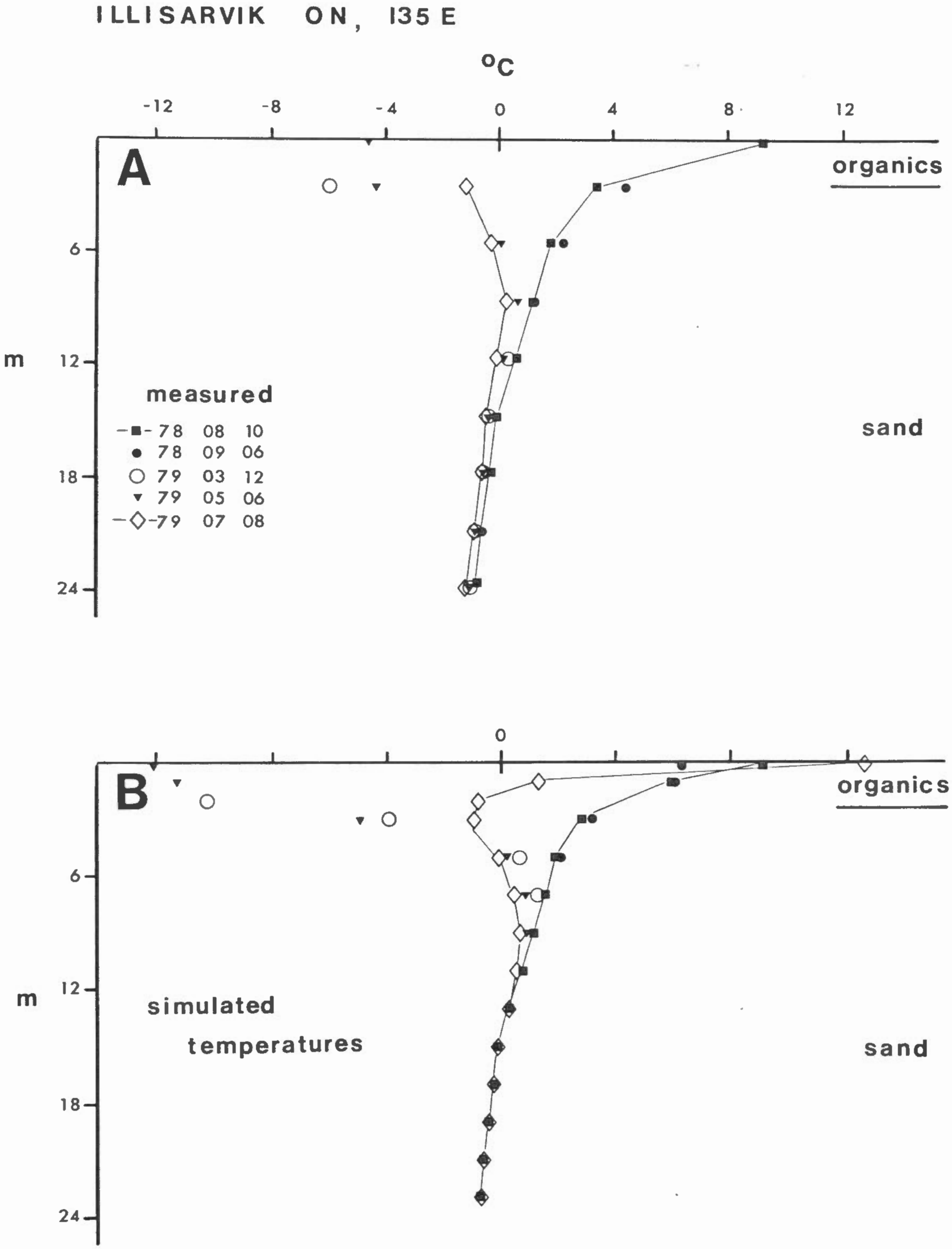


Figure 6. a) Measured temperature logs at borehole 78-9, first year after drainage.

b) Simulated ground temperatures in the first year after drainage.

TABLE 1

Temperature logs recorded at Illisarvik 78-9 in the first year after drainage

	Temperature (°C)				
Depth (m)	78/8/10	78/9/6	79/3/12	79/5/6	79/7/8
0.0	9.26			-4.62	
2.5	3.37	4.44	-6.00	-4.35	-1.15
5.5	1.82	2.21		.04	-.28
8.6	1.16	1.16		.62	.24
11.6	.57	.55	.30	.13	-.11
14.7	-.13	-.13	-.39	-.44	-.49
17.7	-.35	-.40	-.55	-.59	-.65
20.8	-.65	-.68	-.82	-.88	-.92
23.8	-.86	-.84	-1.01	-1.10	-1.22

TABLE 2. ALBEDO AND WETNESS VARIATIONS

MONTH	ALBEDO	WETNESS
August	.16	1.26
September	.25	1.00
October	.82	1.00
November	.82	1.00
December	.82	1.00
January	.82	1.00
February	.82	1.00
March	.82	1.00
April	.82	1.00
May	.40	1.00
June	.16	.75
July	.24	.50

TABLE 3. SOIL THERMAL PROPERTIES

	CONDUCTIVITY (Wm^{-1} K^{-1})	VOLUMETRIC HEAT CAPACITY (Jm^{-3} K^{-1})
Organic layer:		
frozen	2.3	1.88×10^6
unfrozen	0.5	4.19×10^6
Sand layer:		
frozen	2.9	1.93×10^6
unfrozen	1.7	2.84×10^6

TABLE 4. ILLISARVIK WEATHER DATA, DAILY MEANS

MONTH	Rs (Wm^{-2})	CLOUD COVER (dec. frac.)	Tair (^{o}C)	WIND SPEED (ms^{-1})	R.H. (dec. frac.)	Patm (kPa)
August	195.7	.70	7.6	5.25	.84	101.27
September	74.0	.65	5.0	6.00	.88	100.77
October	28.6	.70	-11.9	9.67	1.00	100.99
November	4.8	.50	-15.7	4.98	.90	101.32
December	.05	.41	-24.0	5.96	1.00	101.07
January	1.2	.41	-23.3	4.78	1.00	102.16
February	26.0	.44	-23.1	4.08	.67	101.69
March	82.9	.50	-22.0	5.22	.90	101.89
April	176.0	.24	-17.5	3.72	1.00	101.90
May	227.0	.61	-8.6	5.17	.97	101.90
June	260.0	.69	2.6	4.78	.83	101.12
July	233.0	.49	10.2	5.44	.83	101.32

R_s = incoming solar radiation

Tair = air temperature

RH = relative humidity

Patm = atmosphere pressure

TABLE 5.

Temperature profiles predicted from model for first year after drainage

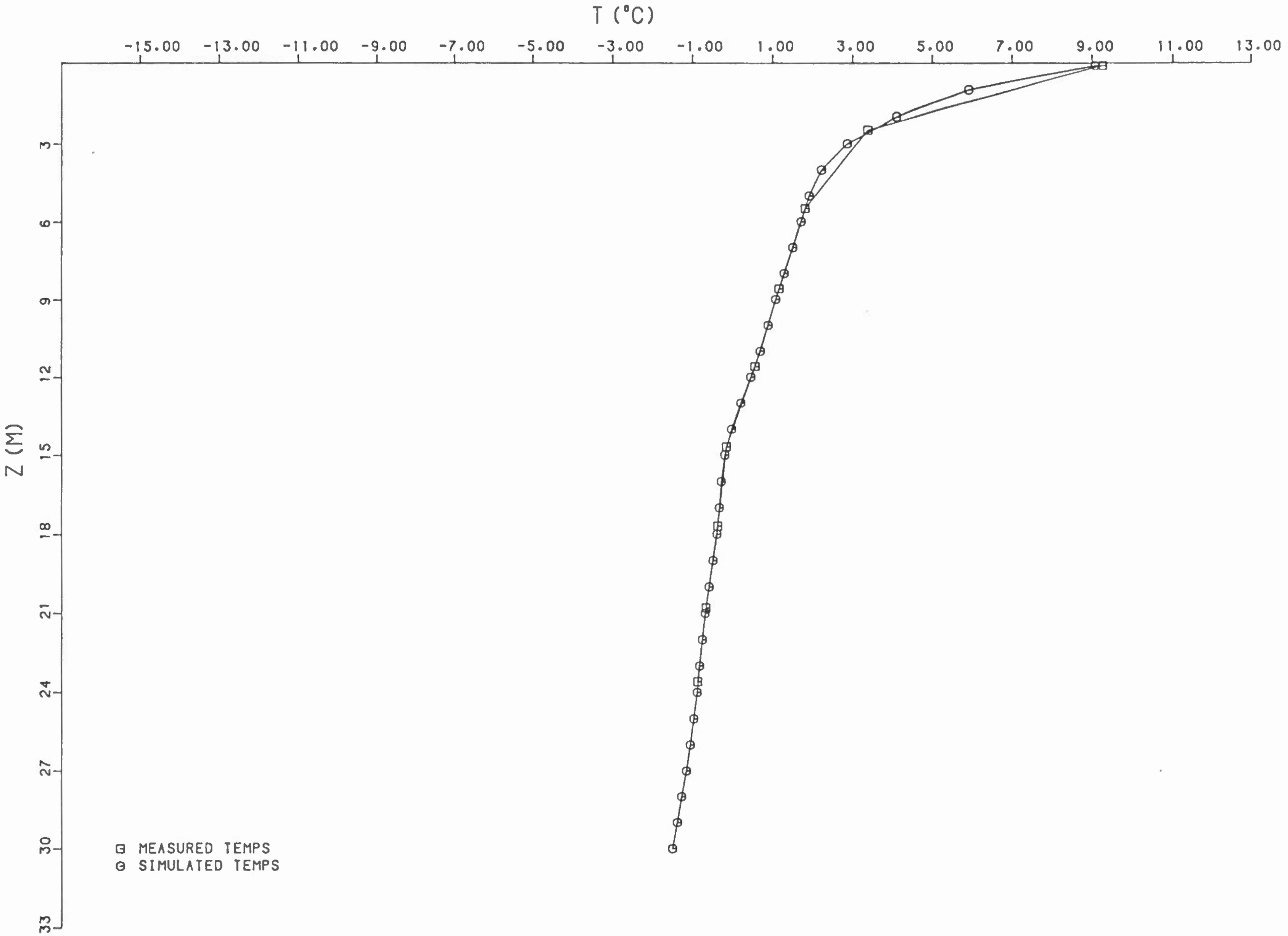
	Temperature (^{o}C)				
Depth (m)	78/8/10	78/9/6	79/3/12	79/5/6	79/7/8
0	9.08	6.25	-22.58	-12.05	12.61
1	5.91	5.96	-16.46	-11.27	1.31
2	4.09	4.23	-10.16	-8.61	-.69
3	2.87	3.17	-3.89	-4.91	-.94
4	2.23	2.52	-.03	-.88	-.88
5	1.92	2.07	.66	.14	-.07
6	1.72	1.76	1.12	.55	.22
7	1.51	1.52	1.30	.81	.44
8	1.29	1.30	1.29	.93	.58
9	1.08	1.09	1.14	.91	.64
10	.89	.89	.94	.81	.61
11	.70	.68	.70	.64	.52
12	.47	.46	.45	.45	.39
13	.23	.23	.23	.23	.23
14	.0	.01	.04	.04	.05
15	-.17	-.16	-.13	-.12	-.11
16	-.26	-.25	-.24	-.23	-.23
17	-.31	-.31	-.31	-.31	-.31
18	-.37	-.37	-.39	-.39	-.39
19	-.47	-.47	-.47	-.47	-.47
20	-.57	-.57	-.57	-.57	-.57
21	-.67	-.67	-.66	-.66	-.65
22	-.74	-.74	-.74	-.74	-.73
23	-.81	-.81	-.81	-.81	-.81
24	-.87	-.88	-.88	-.89	-.89
25	-.96	-.96	-.98	-.98	-.99
26	-1.05	-1.06	-1.08	-1.09	-1.09
27	-1.15	-1.17	-1.19	-1.19	-1.19
28	-1.27	-1.28	-1.29	-1.29	-1.29
29	-1.38	-1.39	-1.40	-1.40	-1.40
30	-1.50	-1.50	-1.50	-1.50	-1.50

APPENDIX

Measured and Simulated Profiles,
Borehole 78-9, First Year
After Drainage.

224 ACTUAL AND SIMULATED TEMPERATURES - DRAINAGE

69 29.0 N 134 34.8 W/O



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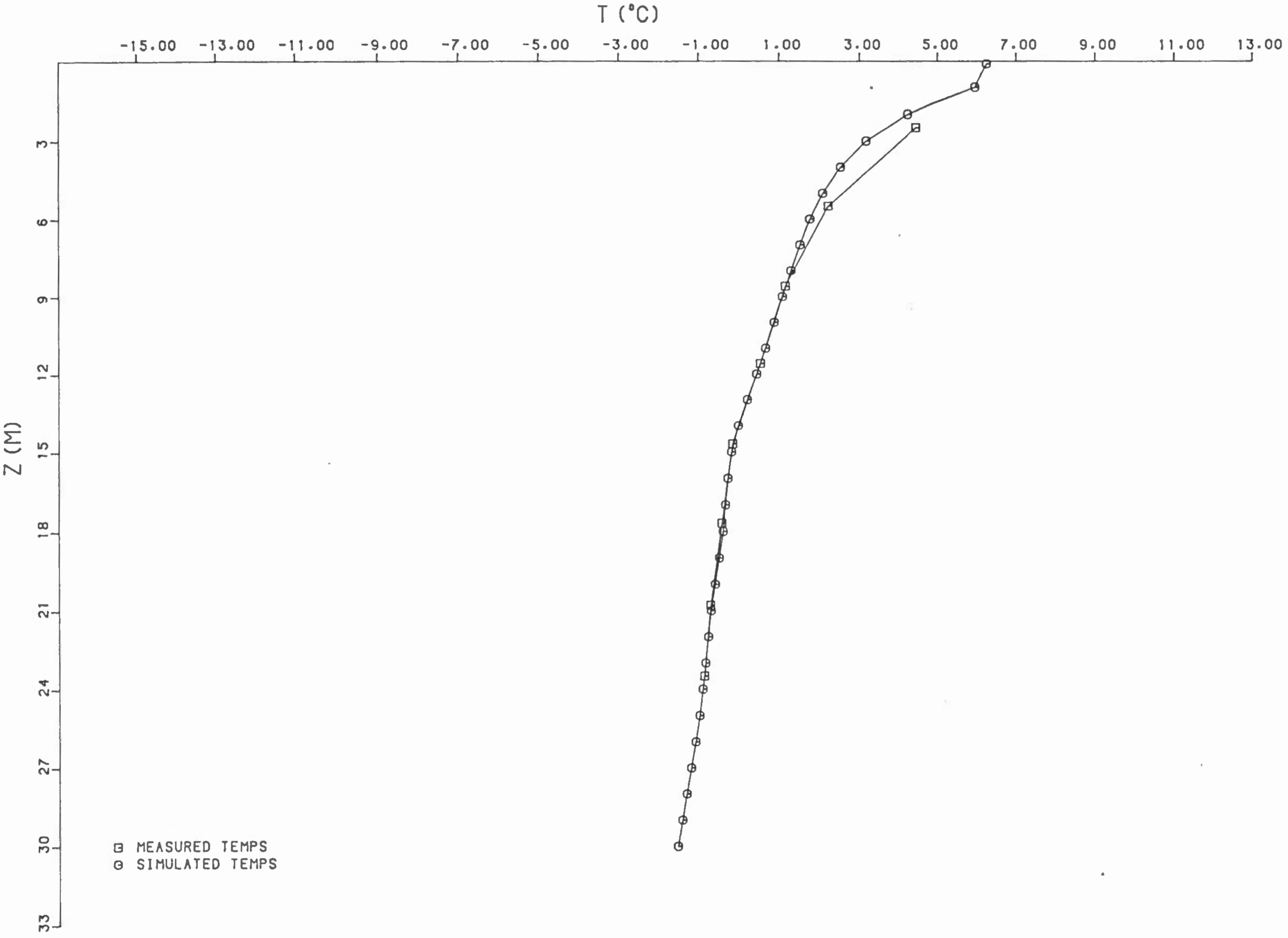

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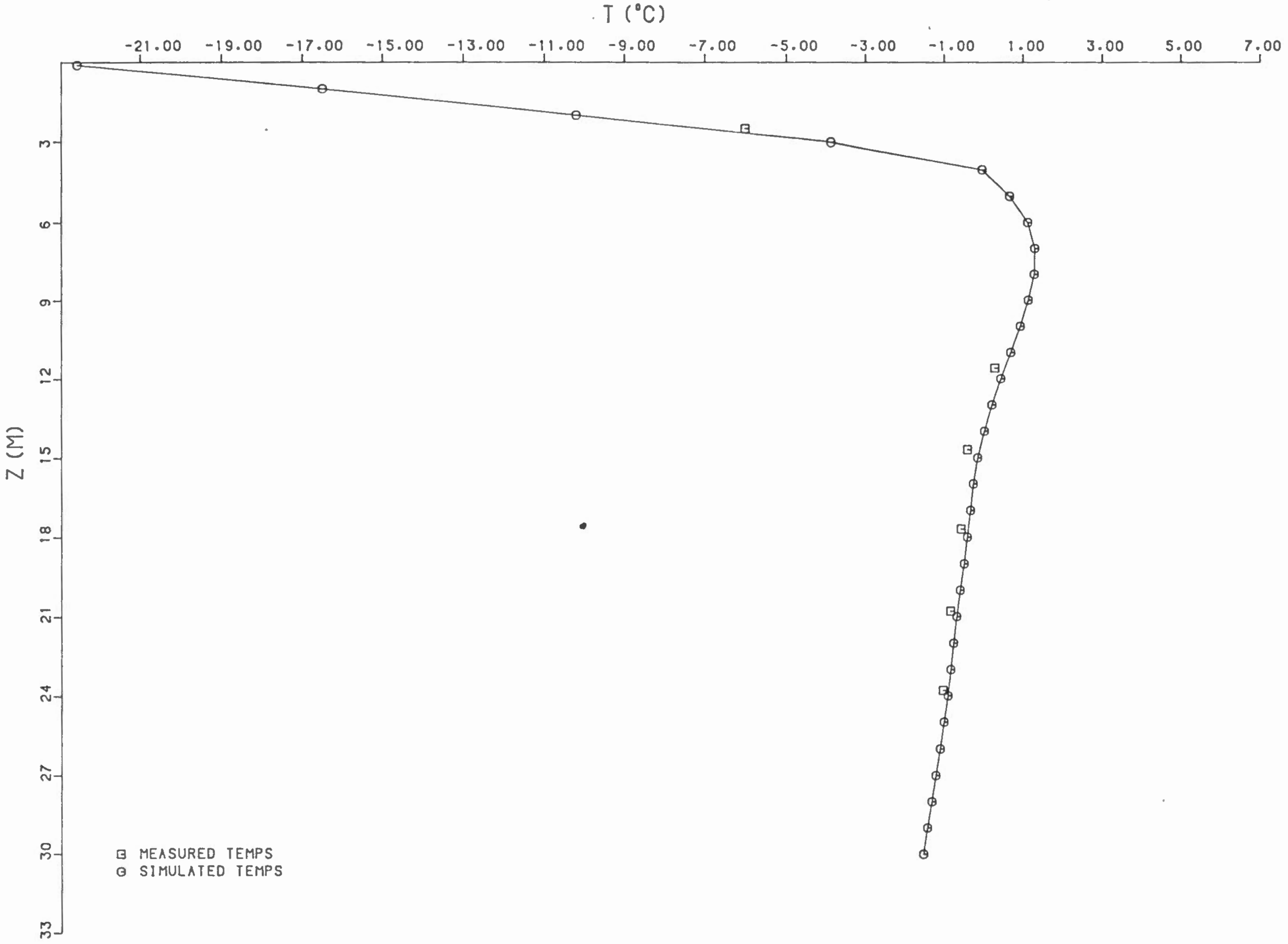

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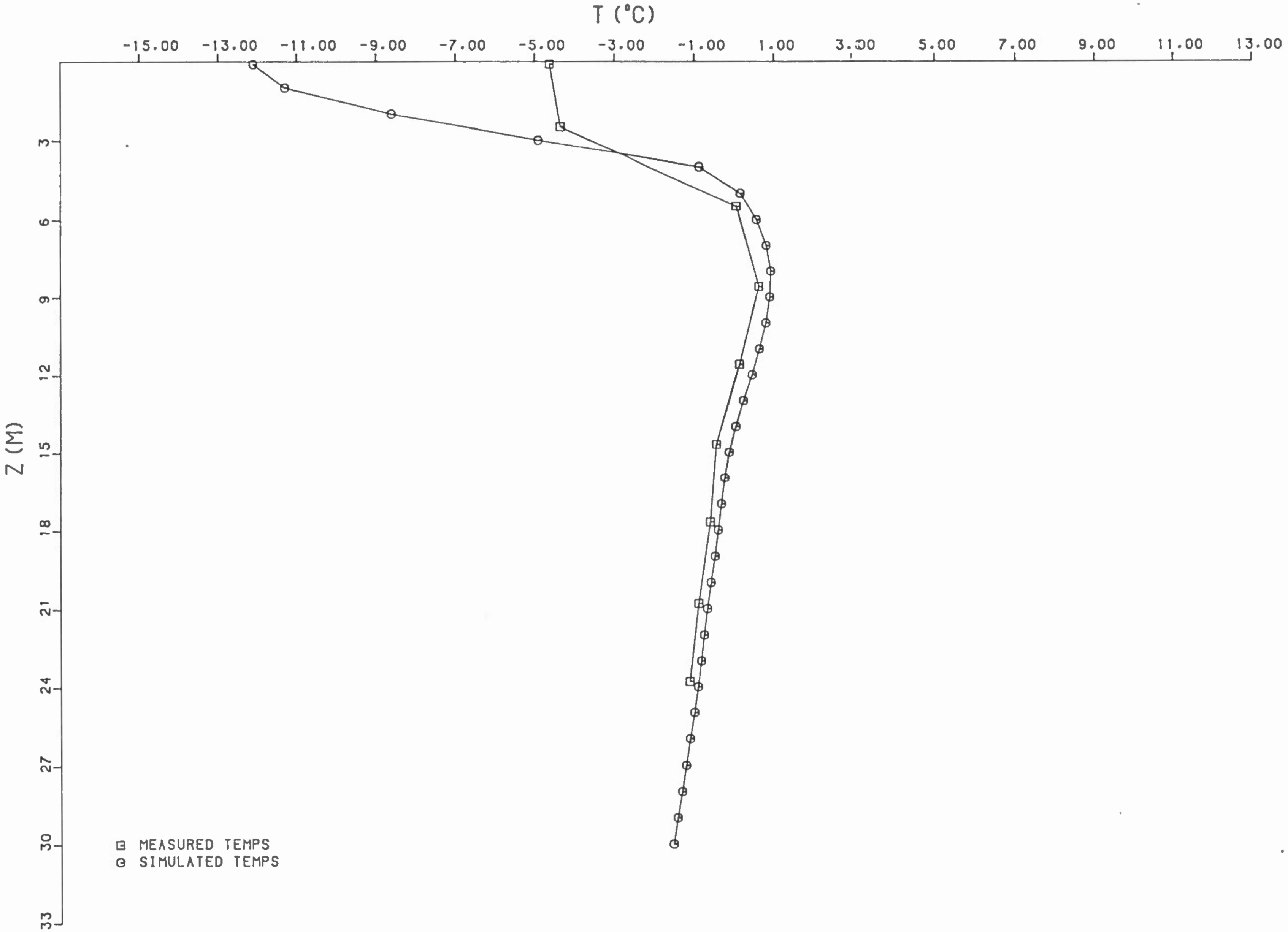

224 ACTUAL AND SIMULATED TEMPERATURES, 79 07 08

69 29.0 N 134 34.8 W/O