School of OCEANOGRAPHY

Towed Thermistor Chain Observations in FRONTS-80

by

C. A. Paulson, R. J. Baumann, L. M. deWitt, T. J. Spoering and J. D. Wagner

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Observations of temperature and pressure in the upper 100 m were taken with a towed thermistor chain in January 1980 north of Hawaii. The observations were taken as a part of a cooperative investigation of the North Pacific subtropical front entitled FRONTS-80. The chain was towed on four occasions over a total of 700 nautical miles between latitudes of 26 and 34 degrees N. The observations were averaged over sequential 30-s intervals and cross-sections of temperature and temperature profiles were plotted.

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The observations show that the surface expression of the North Pacific subtropical front was composed of multiple fronts having temperature contrasts ranging from a few tenths to about 2°C. The horizontal gradients of surface temperature were as large as 0.5°C in 300 m. Vertical temperature gradients associated with the fronts were both positive and negative. Changes in surface temperature across the fronts were usually, but not always, associated with salinity changes tending to minimize the change in density. On one occasion a 2°C change in temperature across a front with no change in salinity was observed.

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G. Ross Heath
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The design and construction of the thermistor chain were carried out by the Technical Planning and Development Group at Oregon State University under the direction of Rod Mesecar. We gratefully acknowledge the cooperation of the officers, crew and scientists aboard the NOAA Ship OCEANOGRAPHER, Gerald C. Saladin, commanding and Stanley P. Hayes, Chief Scientist. This research was supported by the Office of Naval Research through contract N00014-79-C-0004 under project NR 083-102.

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INTRODUCTION

This report presents observations of temperature in the upper ocean obtained by use of a towed thermistor chain. The observations were taken as a part of a cooperative investigation of the wintertime North Pacific subtropical front entitled FRONTS-80. An overview of the experiment together with preliminary results from each of the principal investigators is given in a report edited by Paulson and Niiler (1980).

The objectives of the towed chain investigation in FRONTS-80 were:

- To describe the spatial variability of temperature and salinity across the front.
- To describe the characteristics of the internal wave field near the front.
- To describe mixing processes associated with the front.
- To compare our measurements with those of other investigators.
- To test improved conductivity sensors.

INSTRUMENTATION

The thermistor chain consisted of sensors, electrical conductors, plastic fairing, a strain member and a 450 kg lead-filled depressor. The fairing was manufactured by Fathom Oceanology. The thermistors were manufactured by Thermometrics (Model P-85) and had a time constant of about 0.1 s (D. Caldwell, personal communication). The thermistors were molded into sections of fairing together with bridge/amplifiers. Power and signals were transmitted by electrical conductors running through the tail sections of the fairing. The thermistors were calibrated in the laboratory prior to the experiment.

Pressure sensors were also installed on the chain. The pressure sensors were manufactured by Kulite and were installed in tail sections of fairing together with bridge/amplfiers in a fashion similar to the thermistor electronics. The pressure sensors were calibrated in a pressure bomb prior to the experiment. Prototype conductivity sensors were also installed on the chain. Unfortunately they did not operate sufficiently well to provide data of value.

The locations of the sensors relative to the depressor are shown in Table 1. The instrumented section of the chain was 82 m in length. The total length of the chain was 120 m.

Signals from the sensors were recorded, processed and displayed by use of a minicomputer system manufactured by Digital Equipment Corporation (PDP 11/05). Calibrated cross-sections and vertical profiles of temperature were plotted simultaneous to data acquisition.

A more complete description of the thermistor chain system is given by Spoering and Paulson (1980).

Table 1. Location and operation of sensors on the towed chain. The stations have either a temperature, conductivity or pressure sensor installed denoted by T, C or P. The distance along the chain from the depressor to the sensors is denoted by S which has units of "chain-meters." One chain-meter equals 40 in or 1.016 m.

Channel No.	Station	S Chain-Meters	Operating Sensors (yes = y) Run 1	Run 2	Run 3	Run 4
0	T0	8.5	y	y		
1	C0	9.0				
2	T1	9.5				
3	P0	11.0	y	y	y	y
4	T2	13.0			y	y
5	T3	17.0	y	y		
6	T4	21.0	y	y		
7	T5	24.5	y	y		
8	C1	25.0				
9	T6	25.5		y		
10	T7	29.0	y	y	y	
11	T8	33.0	y	y	y	y
12	T9	37.0		y		y
13	T10	40.5	y	y		
14	C2	41.0				
15	T11	41.5		y	y	y
16	T12	45.0	y	y	y	
17	P1	47.0	Y	Y	Y	Y
18	T13	49.0	y			
19	T14	53.0	y	y	y	y
20	T15	56.5	y	y		
21	C3	57.0				
22	T16	57.5	y	y	y	y
23	T17	61.0	y		y	y
24	T18	65.0	y	y	y	
25	T19	69.0		y	y	y
26	T20	72.5	y	y		
27	C4	73.0				
28	T21	73.5	y	y	y	y
29	T22	77.0	y	y	y	y
30	T23	81.0	y	y	y	y
31	T24	85.0	y			
32	P2	87.0				
33	T25	88.5	y		y	y
34	C5	89.0				
35	T26	89.5	y	y	y	

OBSERVATIONS

The thermistor chain was towed by the NOAA Ship OCEANOGRAPHER north of Hawaii on four occasions during the month of January 1980. The tow tracks for each of the four runs are shown in Figures 1 and 2. The times at the beginning and end of each run are given in the captions of the figures. The positions at two-hour intervals from the beginning of each run are plotted in Figures 1 and 2 and are given in Table 2. The tow track was determined from a combination of satellite fixes and dead reckoning. Tow speeds tabulated in Table 2 were determined from satellite fixes and from a time series of the output of the ship's speed log which was recorded simultaneous to towing. Tow directions tabulated in Table 2 are determined from satellite fixes and from a time series of the output of the ship's gyro. The depths of the highest and lowest temperature measurements are also tabulated in Table 2. The depths of sensors were determined from a combination of the pressure measurements and a model of the configuration of the chain under tow. The model is described by Baumann et al. (1980) supplemented by material in Appendix D of this report.

The temperature observations were low-pass filtered by computing sequential 30-s averages. Filtering removes variations caused by surface gravity waves and the pitch, roll and heave of the ship. The filtered observations are shown in Appendices A, B, and C.

An example of the frontal structure observed near 33°N is shown in Figure 3. Immediately following 0910 there was a small temperature inversion below an isothermal surface layer. Just after 0940, warming began at a depth of 94 m and progressed upward. The temperature of the surface layer remained nearly uniform in the vertical, although its depth and temperature varied in the horizontal. Following 1030 warming occurred near the surface

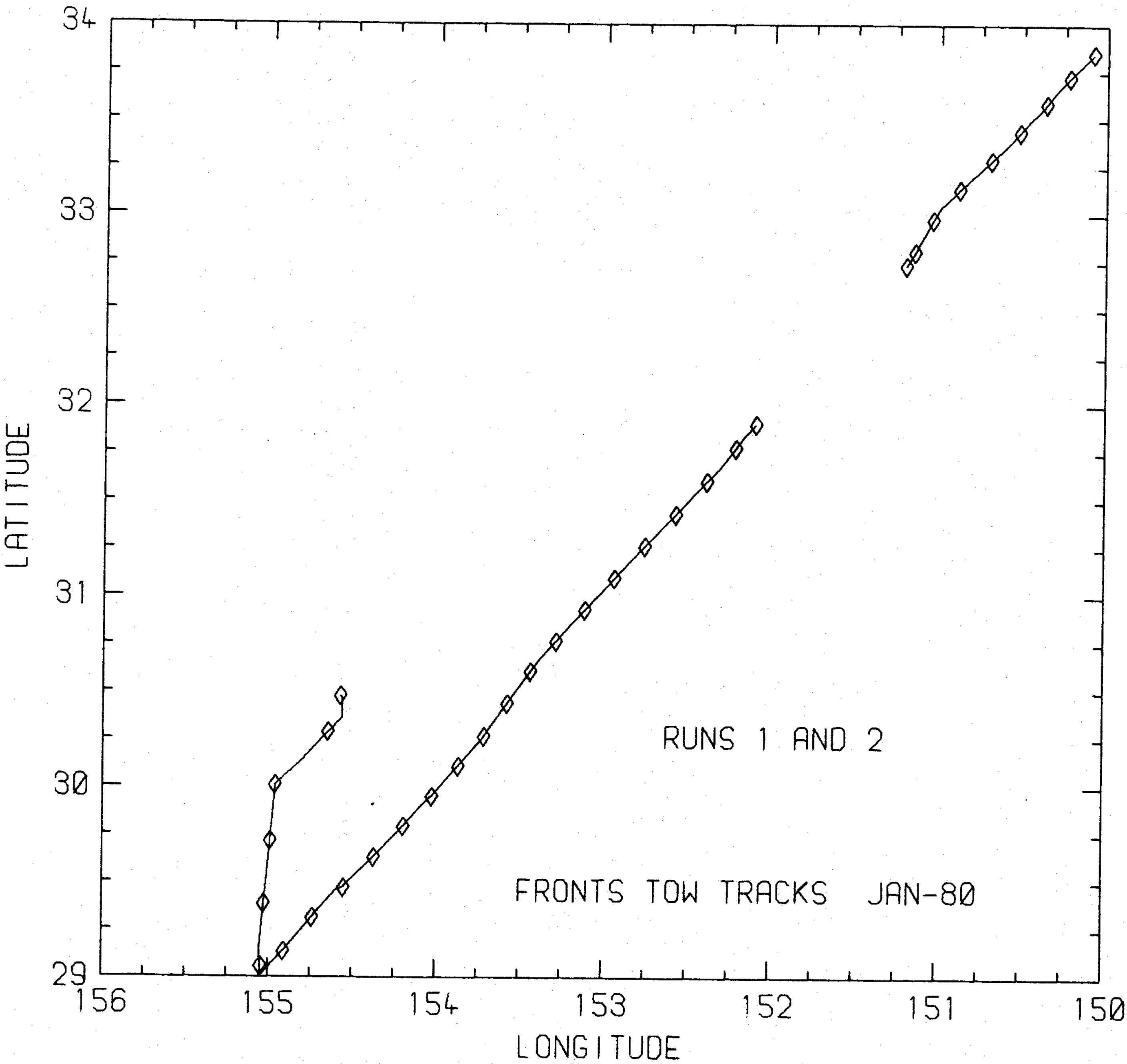

Figure 1. Track of the towed thermistor chain during Runs 1 and 2. Run 1 began near 34N,150W at 0040 GMT, 16 January 1980, and ended at 1600 on the same date. Symbols (diamonds) are plotted at the beginning and end of the track and in two-hour intervals from the beginning. Run 2 began near 32N,152W at 0520 GMT, 17 January 1980 and ended at 0245, 19 January. As in Run 1, symbols are plotted at the beginning and end of the track and in two-hour intervals from the beginning. The turn to the north at 29N occurred at 1655 GMT, 18 January 1980.

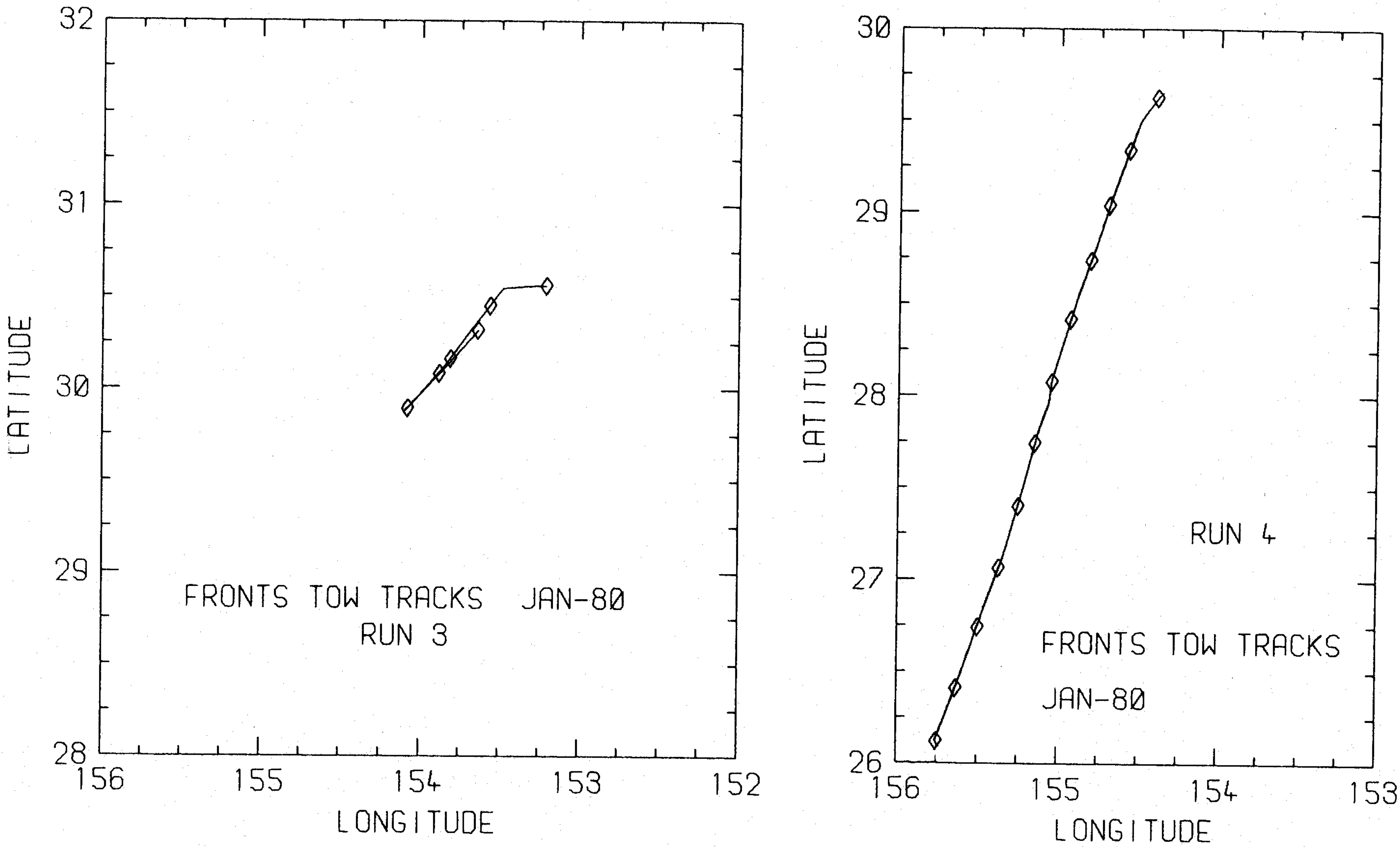

Figure 2. Track of the towed thermistor chain during Runs 3 and 4. Run 3 began near 30.5N, 153.2W at 0700 GMT, 25 January 1980, and ended at 1700 on the same date. The turn toward the southwest occurred at 0820 GMT. A course change of 180° was made at 1312 GMT. Run 4 began near 29.6N, 154.4W at 1900 GMT, 27 January 1980 and ended at 1650, 28 January. The symbols in both tracks are plotted at the beginning and end of each track and at intervals of two hours from the beginning.

Table 2. Navigation during tows and depths of the highest and lowest temperature measurements on the chain during FRONTS-80. Positions are tabulated at the beginning and end of each run and at two-hour intervals from the beginning. The positions were determined from navigational satellite fixes and dead reckoning. Distance traveled, tow direction from positions and the ship's gyro, and tow speed from positions and the ship's log are tabulated for intervals subsequent to the given times and positions. Tow direction from the gyro and tow speed from the ship's log were corrected to agree in the mean with directions and speeds determined from the satellite fixes.

Run No.	Date (Jan GMT)	Time (GMT)	N. Lat. (deg)	N. Lat. (min)	W. Long. (deg)	W. Long. (min)	Dist. (km)	Nav. Dir. (deg)	Gyro Dir. (deg)	Nav. Speed (m/s)	Log Speed (m/s)	T-Depths Top (m)	T-Depths Bot. (m)
1	16	0040	33	51.12	150	04.98	19.05	223.4	223.5	2.65	2.42	15.2	96.7
		0240	33	43.62	150	13.50	20.12	220.7	223.1	2.79	2.88	14.6	95.5
		0440	33	35.40	150	21.96	21.99	221.4	224.9	3.05	3.00	14.4	95.0
		0640	33	26.46	150	31.38	23.16	223.8	228.0	3.22	3.16	14.1	94.4
		0840	33	17.40	150	41.70	24.35	225.7	227.9	3.38	3.25	14.0	94.0
		1040	33	08.22	150	52.92	23.32	219.6	221.3	3.24	3.26	14.0	94.0
		1240	32	58.50	151	02.52	21.07	208.3	213.9	2.93	2.84	14.7	95.6
		1440	32	48.48	151	08.88	9.57	209.8	214.4	1.99[1]	2.24[1]	15.3	97.1
		1600	32	43.98	151	11.94	-	-	-	-	-	-	-
2	17	0520	31	54.00	152	05.46	18.22	219.9	215.7	2.53	3.35	8.0	87.7
		0720	31	46.44	152	12.90	25.16	219.2	216.3	3.49	3.52	7.7	86.9
		0920	31	35.94	152	22.98	25.75	223.1	219.9	3.58	3.50	7.7	87.0
		1120	31	25.74	152	34.08	25.75	223.7	219.6	3.58	3.54	7.7	86.8
		1320	31	15.66	152	45.30	25.33	222.6	218.9	3.52	3.52	7.7	86.9
		1520	31	05.58	153	56.10	24.99	222.3	216.7	3.47	3.44	7.8	87.3
		1720	30	55.62	153	06.66	24.40	222.4	217.3	3.39	3.39	7.9	87.5
		1920	30	45.84	153	16.98	23.02	219.2	215.8	3.20	3.39	7.9	87.5
		2120	30	36.18	153	26.10	22.83	215.9	215.9	3.17	3.16	8.2	88.5
		2320	30	26.16	153	34.50	23.29	214.3	218.3	3.24	3.38	7.9	87.6
	18	0120	30	15.78	153	42.66	22.91	220.3	227.1	3.18	3.09	8.3	88.7
		0320	30	06.30	153	51.90	23.20	221.5	229.6	3.22	3.09	8.5	88.7
		0520	29	56.94	154	01.50	24.11	223.0	229.7	3.35	3.32	8.0	87.8
		0720	29	47.40	154	11.70	24.70	223.6	226.3	3.43	3.32	8.0	87.8
		0920	29	37.74	154	22.26	24.98	224.7	225.7	3.47	3.34	8.0	87.8
		1120	29	28.14	154	33.18	25.01	225.3	221.2	3.47	3.38	7.9	87.6
		1320	29	18.60	154	44.16	25.75	220.8	217.5	3.58	3.35	8.0	87.7
		1520	29	08.04	154	54.54	26.98	-[2]	-[2]	3.75[2]	3.42[2]	7.9	87.4
		1720	29	03.30	155	02.82	36.54	003.2	010.1	5.08	5.04	4.5	76.4
		1920	29	23.04	155	01.56	36.60	005.1	007.8	5.08	4.91	4.8	77.5
		2120	29	42.78	154	59.58	32.70	005.3	-	4.54	4.65	5.4	79.6
		2320	30	00.42	154	57.66	43.38	044.2	043.2	6.02	6.00	2.2	67.5
	19	0120	30	17.22	154	38.82	23.97	-[3]	-[3]	4.70	5.67	3.0	70.6
		0245	30	28.44	154	34.32	-	-	-	-	-	-	-

Table 2. (con't)

Run No.	Date (Jan GMT)	Time (GMT)	N. Lat. (deg)	N. Lat. (min)	W. Long. (deg)	W. Long. (min)	Dist. (km)	Nav. Dir. (deg)	Gyro Dir. (deg)	Nav. Speed (m/s)	Log Speed (m/s)	T-Depths Top (m)	T-Depths Bot. (m)
3	25	0700	30	33.66	153	12.42	38.88	-[4]	-[4]	5.40	5.43	3.6	68.4
		0900	30	27.18	153	33.60	39.74	216.9	215.5	5.52	5.39	3.7	68.8
		1100	30	09.96	153	48.48	39.76	221.1	218.0	5.52	5.41	3.6	68.6
		1300	29	53.76	154	04.80	36.26	-[5]	-[5]	5.04	5.23	4.0	70.2
		1500	30	05.16	153	52.86	33.33	043.1	047.4	4.63	5.19	4.1	70.6
		1700	30	19.08	153	38.04	-	-	-	-	-	-	-
4	27	1900	29	37.62	154	23.52	36.26	-[6]	-[6]	4.99	5.36	4.4	69.0
		2100	29	20.34	154	33.72	35.42	200.2	196.8	4.92	5.34	4.5	69.2
		2300	29	02.34	154	41.28	35.39	198.1	196.8	4.91	5.33	4.5	69.3
	28	0100	28	44.16	154	48.06	37.65	198.6	197.0	5.23	5.38	4.4	68.8
		0300	28	24.84	154	55.44	39.02	197.1	196.8	5.42	5.39	4.4	68.8
		0500	28	04.68	155	02.46	38.41	195.0	193.9	5.34	5.38	4.4	68.8
		0700	27	44.58	155	08.52	39.29	195.3	193.8	5.46	5.37	4.4	68.9
		0900	27	24.06	155	14.82	38.86	197.4	196.8	5.40	5.43	4.3	68.4
		1100	27	03.96	155	21.84	38.34	200.1	196.5	5.32	5.44	4.2	68.3
		1300	26	44.46	155	29.82	38.91	199.9	196.4	5.40	5.38	4.4	68.8
		1500	26	24.66	155	37.86	34.23	200.7	196.5	5.19	5.31	4.6	69.5
		1650	26	07.32	155	45.12	-	-	-	-	-	-	-

[1]Slow decrease in speed from 1330 to 1430 as the wind and seas picked up (ship made constant turns during this period).

[2]Course changed at 1655 hours from 220 to 003 speed also increased.

[3]Course change at 2320 hours from 003 to 040.
Course change at 0152 hours from 035 to 015.
Course change at 0200 hours from 015 to 345.

[4]Course change at 0820 hours from 270 to 218.

[5]Course change at 1312 hours from 222 to 042.

[6]Course change at 1959 hours from 221 to 199.

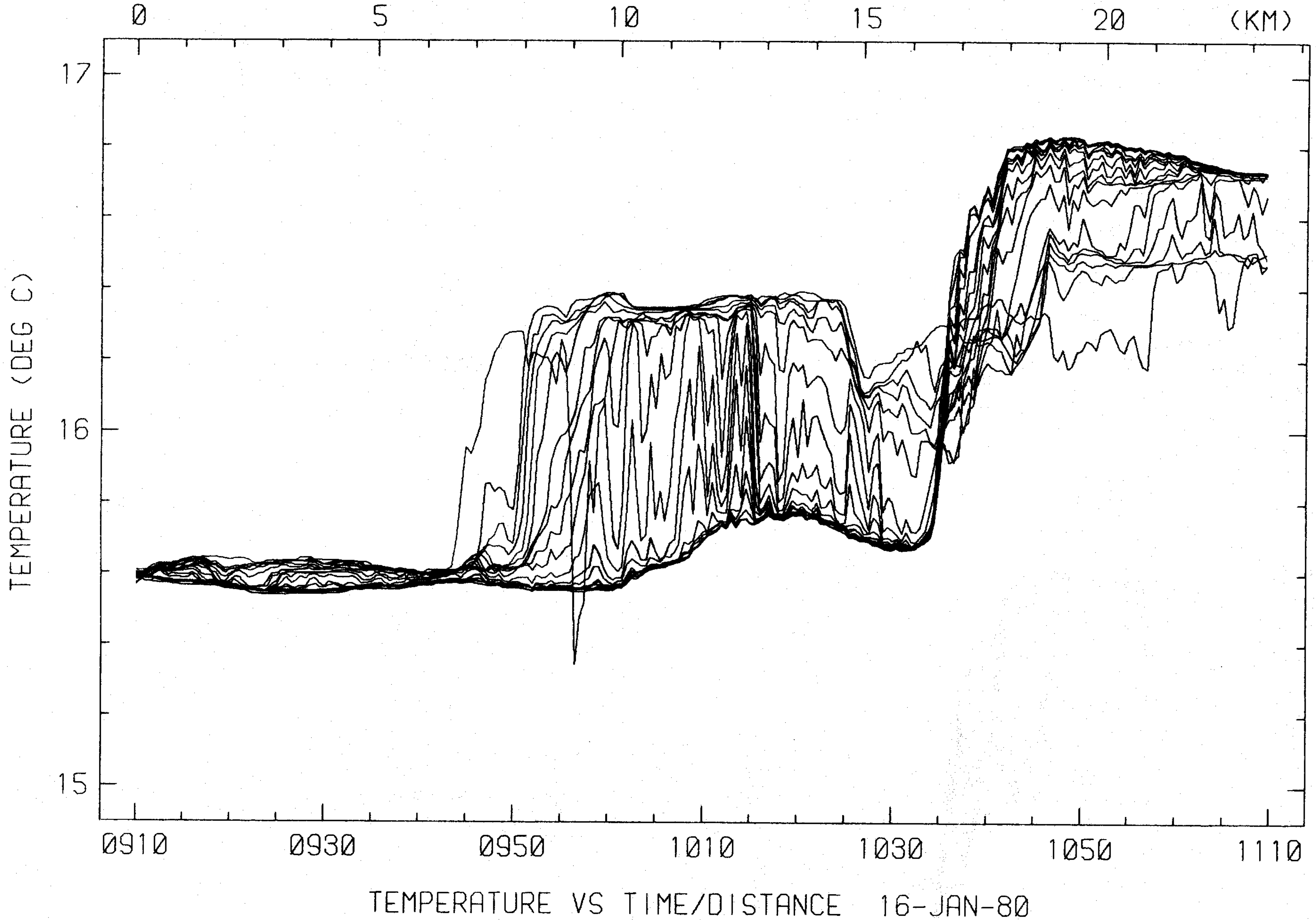

Figure 3. An example of frontal structure observed near 33.3°N, 150.0°W during FRONTS-80. The temperature sensors are distributed between depths 14 to 94 m.

and the temperature gradient changed sign with warm water overlying cold water. The cold spike at 0955 occurred at a depth of 94 m and is believed to have been caused by the upward displacement of cold water in the seasonal thermocline. Most of the fronts observed during the experiment were not as complex as the example shown in Figure 3 in that they did not exhibit a reversal of vertical temperature gradient.

A second example of frontal structure is shown in Figure 4. As shown in Figure 2, the tow direction at 1130 GMT was toward the southwest. Sudden warming together with stratification was encountered at 1236. This was followed by sudden cooling and vanishing stratification at 1255. A course change of 180° was made at 1312 and the same warm dome was observed while towing toward the northeast. The temperature structure is remarkably symmetric with respect to 1312 GMT. The width of the warm dome is a little greater on the tow toward the northeast, but this might be accounted for by a variation in tow speed and by traversing the warm dome in a slightly different location.

A third example of frontal structure observed near 26.6°N is shown in Figure 5. The change in surface temperature of nearly two degrees across the front was the largest observed during the experiment. The maximum horizontal temperature gradient at the surface exceeds 1°C/3 km.

Near-surface observations of temperature and salinity were taken aboard the NOAA Ship OCEANOGRAPHER throughout the experiment. Hourly positions from the bridge log are plotted in Figure 6 as a function of time. Hourly observations of temperature, salinity and density are plotted in Figure 7, also as a function of time. Temperature in a sea chest at a depth of about 5 m was measured continuously and hourly samples were logged. Water from the sea chest was pumped to the lab and circulated through a container where conductivity and temperature were measured continuously by use of a CTD

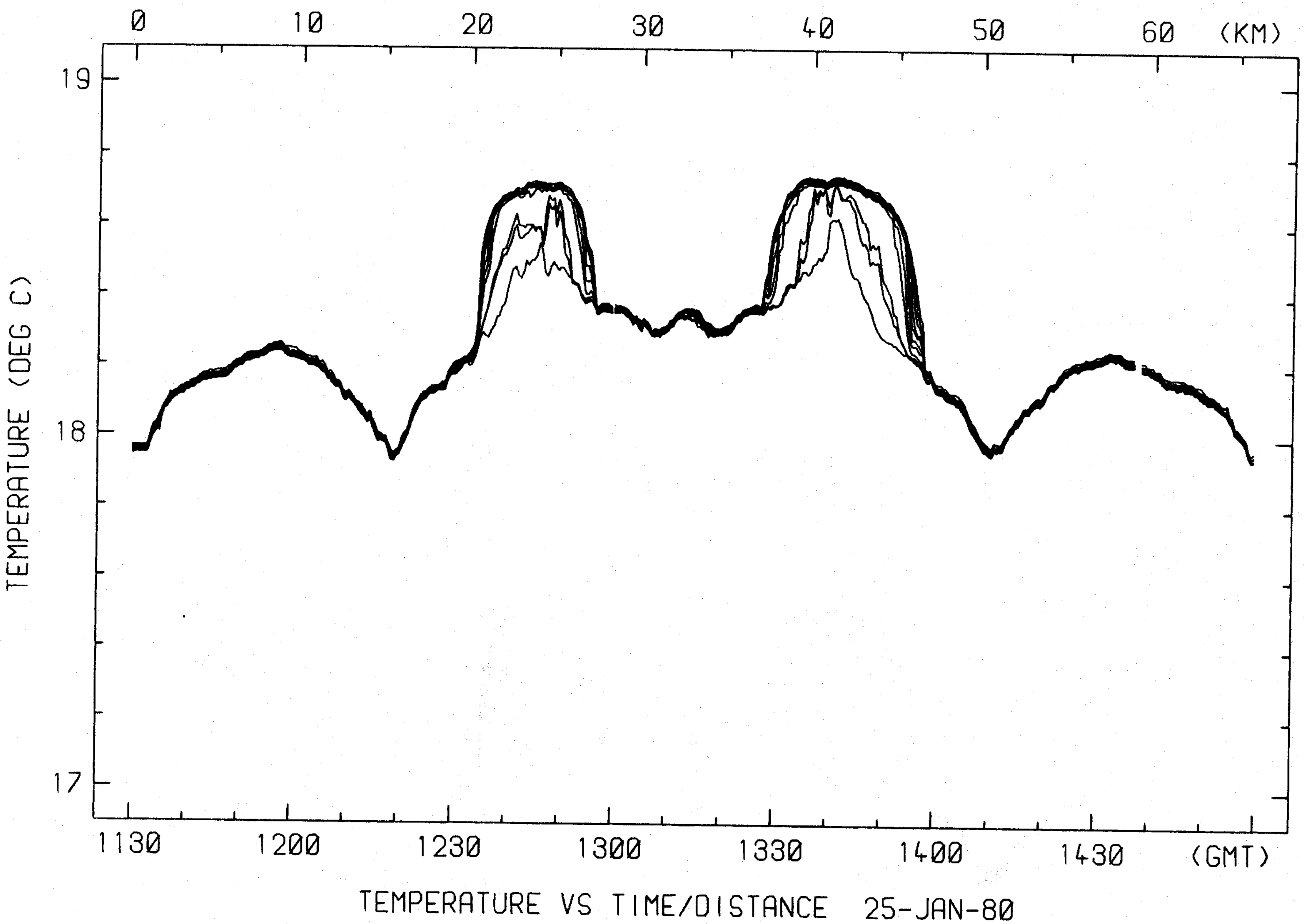

Figure 4. An example of frontal structure observed during Run 3. There was a 180° course change at 1312. Temperature sensors were distributed between depths of 4 and 70 m.

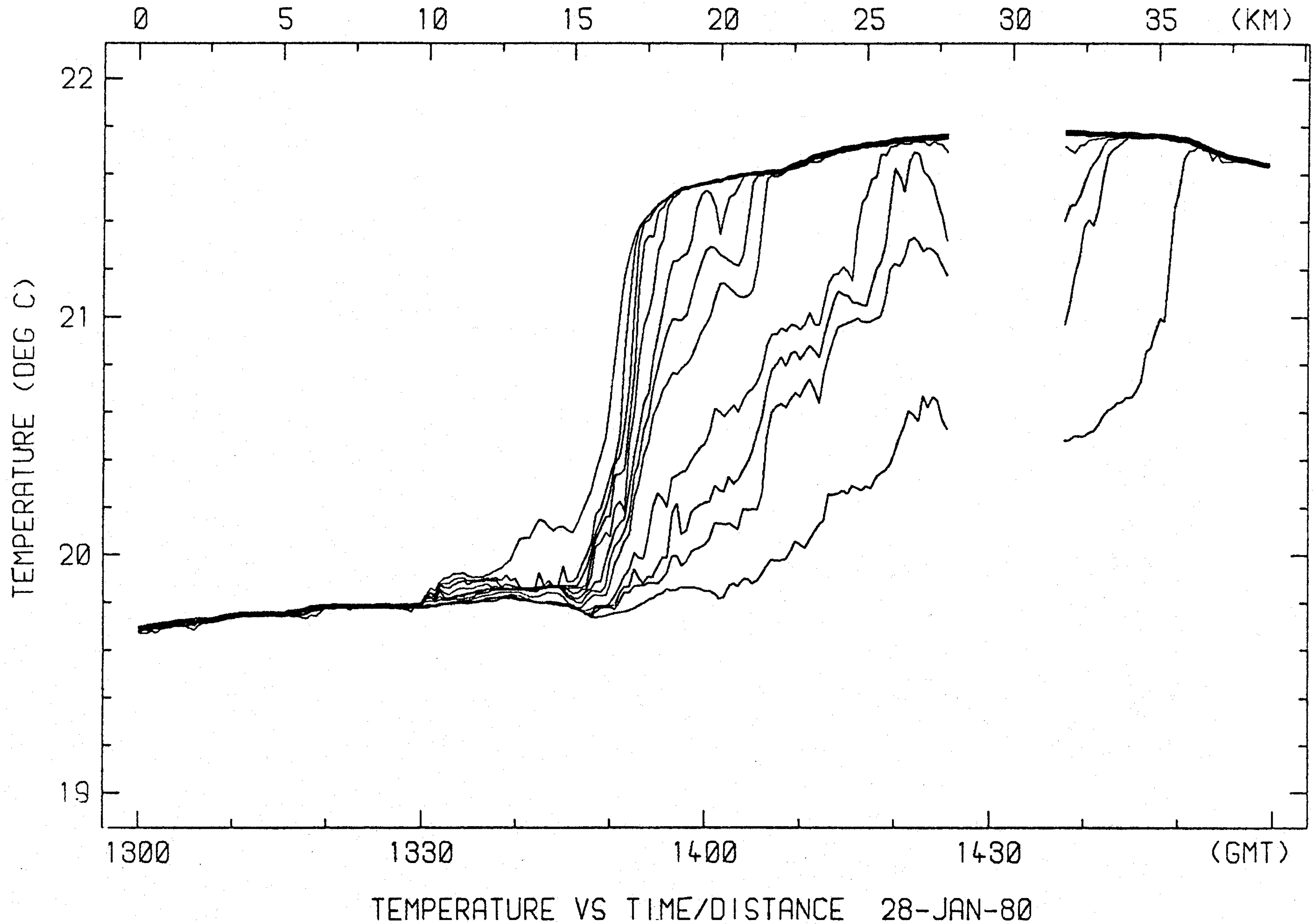

Figure 5. An example of frontal structure observed during Run 4 near 26.6°N. Temperature sensors were distributed

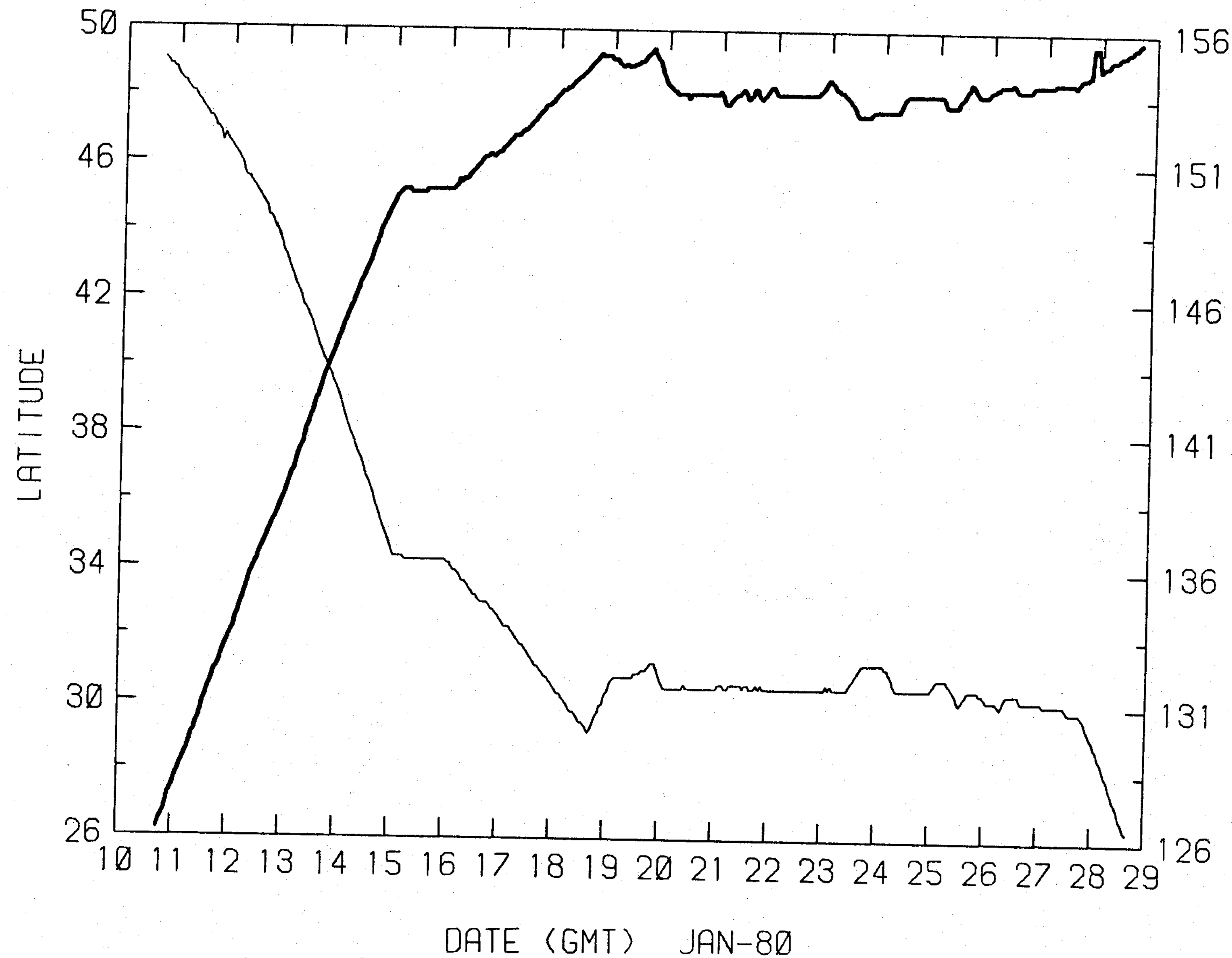

Figure 6: Hourly positions of the NOAA Ship OCEANOGRAPHER during FRONTS-80. The thin line is N. latitude and the thick line is W. longitude.

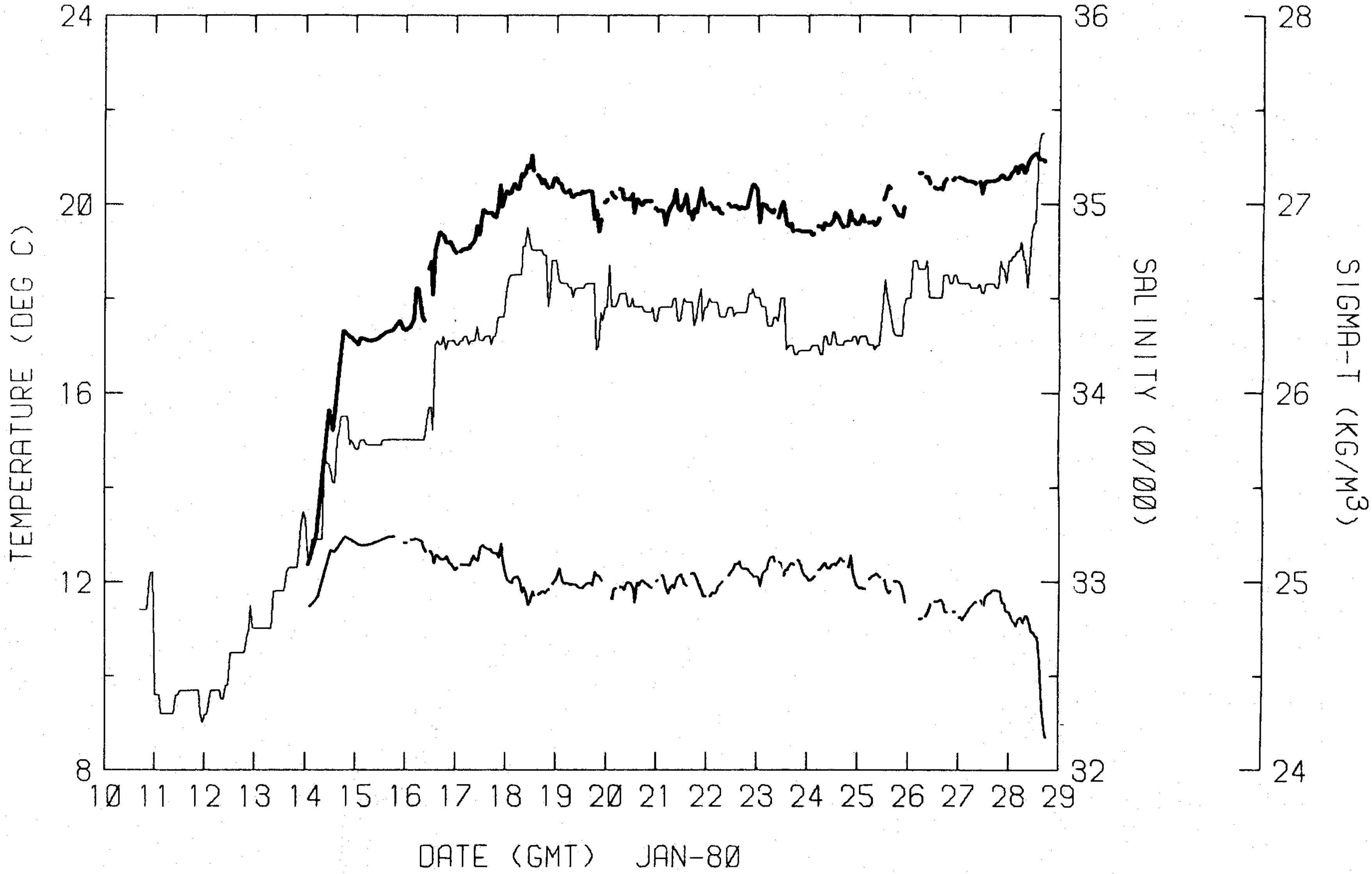

Figure 7. Observations from the NOAA Ship OCEANOGRAPHER of near-surface intake temperature (light line), salinity (heavy line), and density (intermediate line).

(Bisset Berman Model 9040). Hourly values were logged and water samples were also taken each hour. Salinity of the samples was determined by use of a salinometer and occasionally by titration. A time series of salinity determined by the three aforementioned methods appears in Figure 8. Some of the obviously erroneous values have been removed. The difference between salinity from the CTD and from the salinometer and titration is shown in Figure 9. The mean difference is about 0.02 $^{o}/oo$ with little evidence of systematic variation during the experiment.

The variations in surface salinity and density shown in Figure 7 are useful for interpreting temperature structure of the type shown in Figures 3-5. Variations in surface temperature and salinity tend to be in phase, with some exceptions, thereby reducing fluctuations in density. The increase in surface temperature shown in Figure 3 (16 January) was associated with an increase in salinity resulting in a small change in density. However, the increase in temperature shown in Figure 5 (28 January) was associated with negligible change in salinity and a correspondingly large change in density (~ 0.5 σ_t).

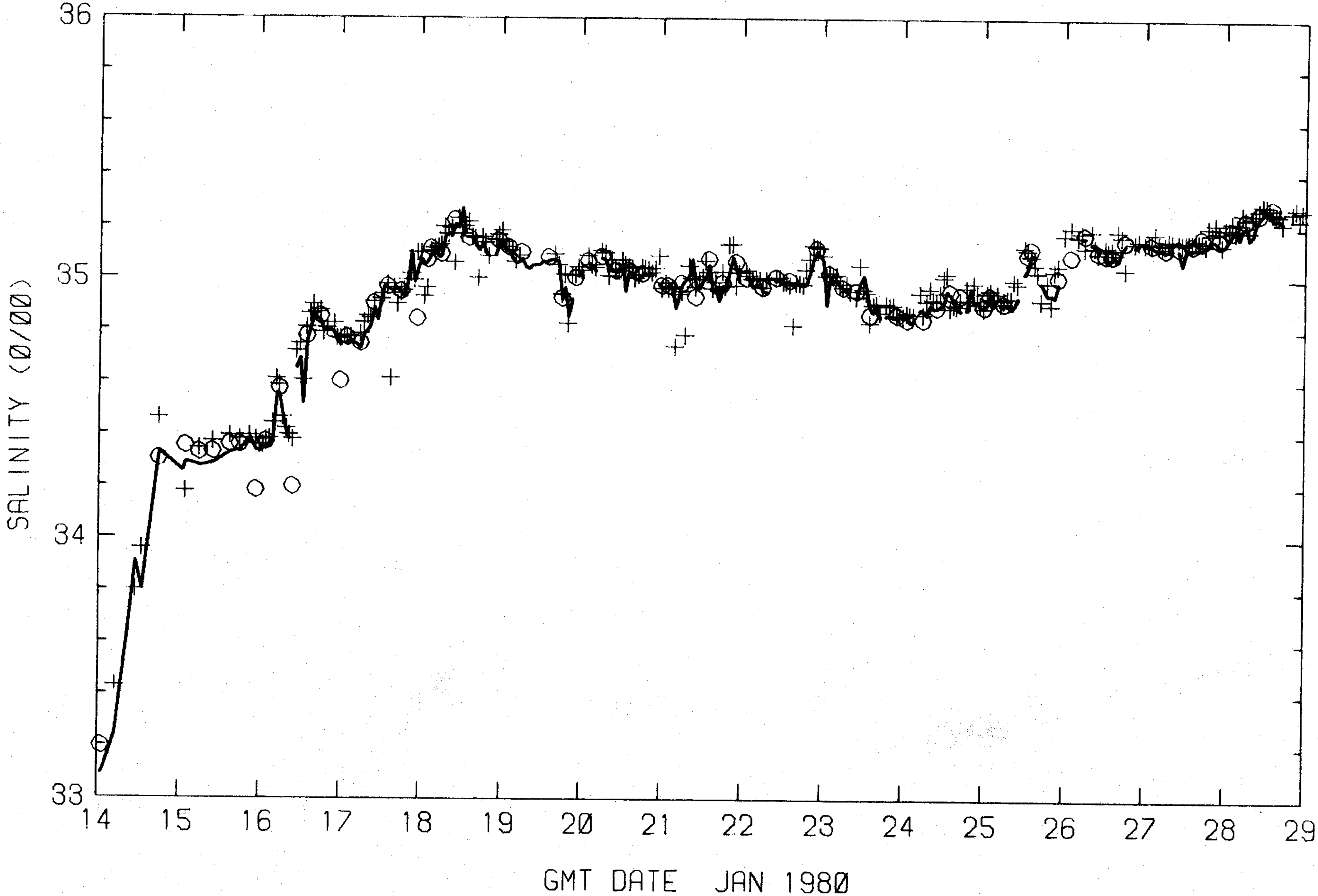

Figure 8. Observations of near-surface intake salinity from the NOAA ship OCEANOGRAPHER. The solid line is from a CTD, + and o are from samples evaluated by use of a salinometer and by titration respectively.

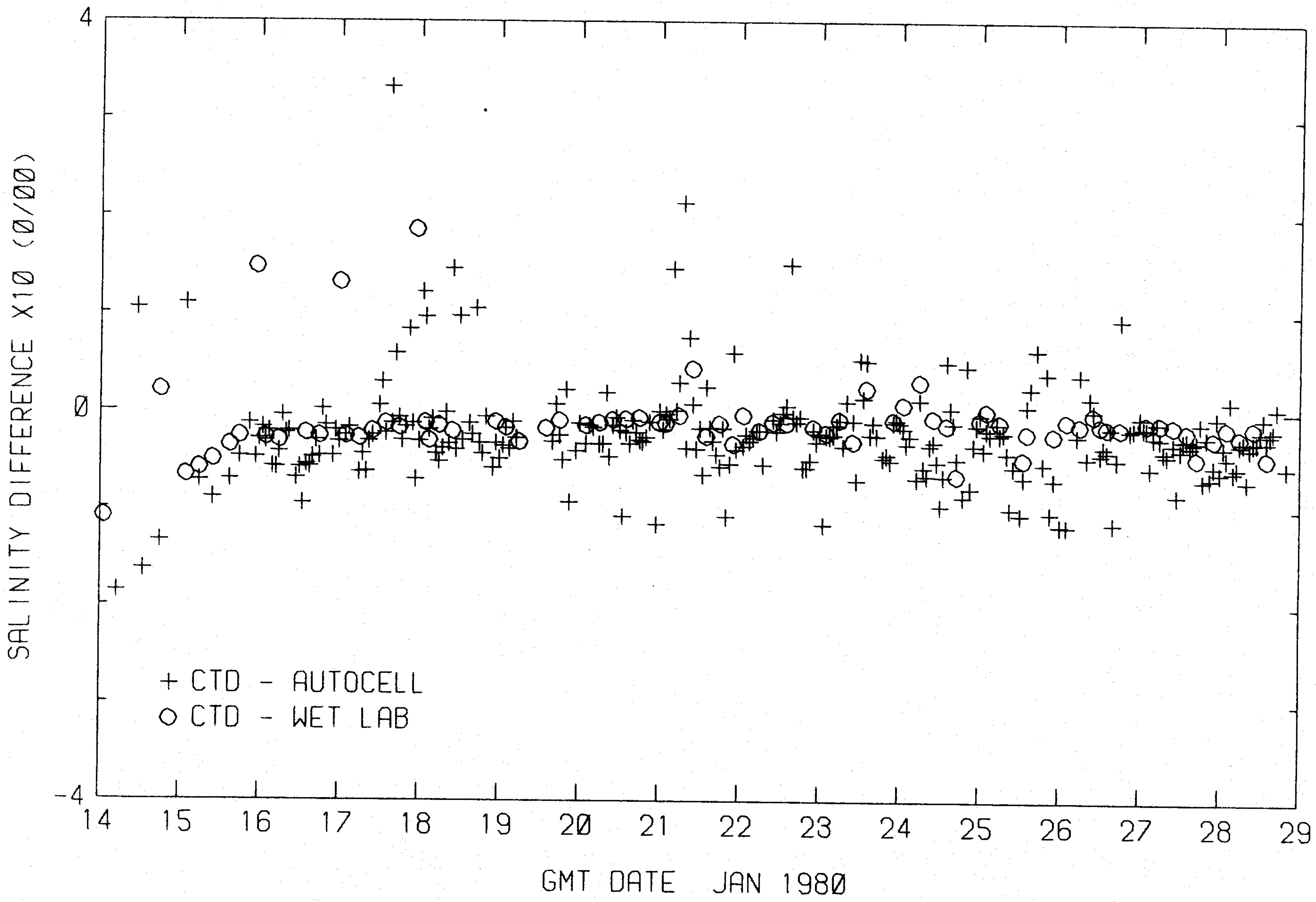

Figure 9. Observations from the NOAA ship OCEANOGRAPHER of near-surface intake salinity determined by use of a CTD minus salinity samples evaluated by a salinometer (+) and by titration (o).

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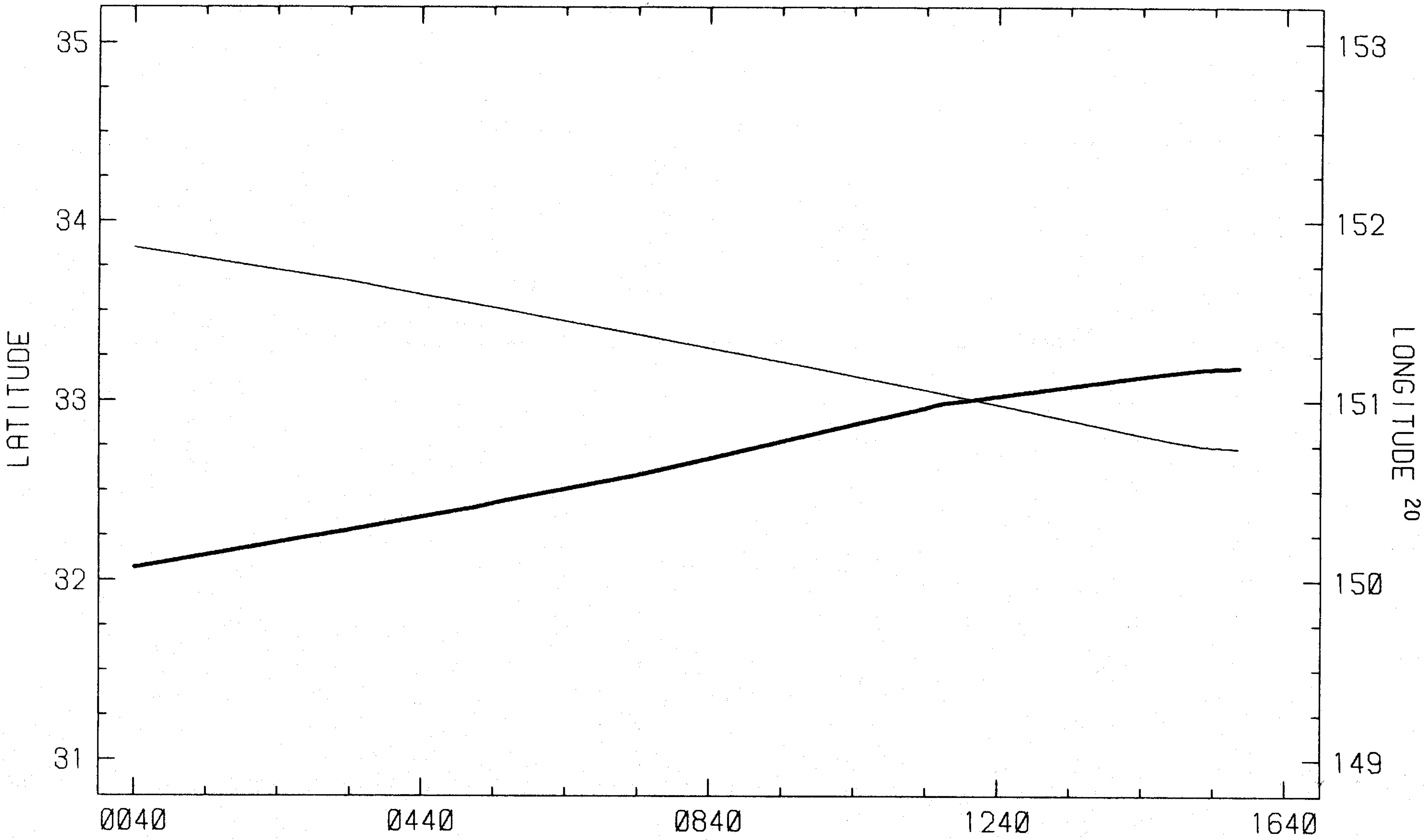
APPENDIX A

Highest and Lowest Temperature vs Time

On the following pages are 5 plots of the tow track of the thermistor chain given as north latitude (thin line) and west longitude (thick line) vs time. Following the tow tracks are 5 plots of the highest (thick line) and lowest (thin line) temperature measurements vs time. The depths of these measurements are given in Table 2. The temperature measurements are low-passed, computed by averaging over sequential 30-s intervals.



LATITUDE,LONGITUDE VS TIME
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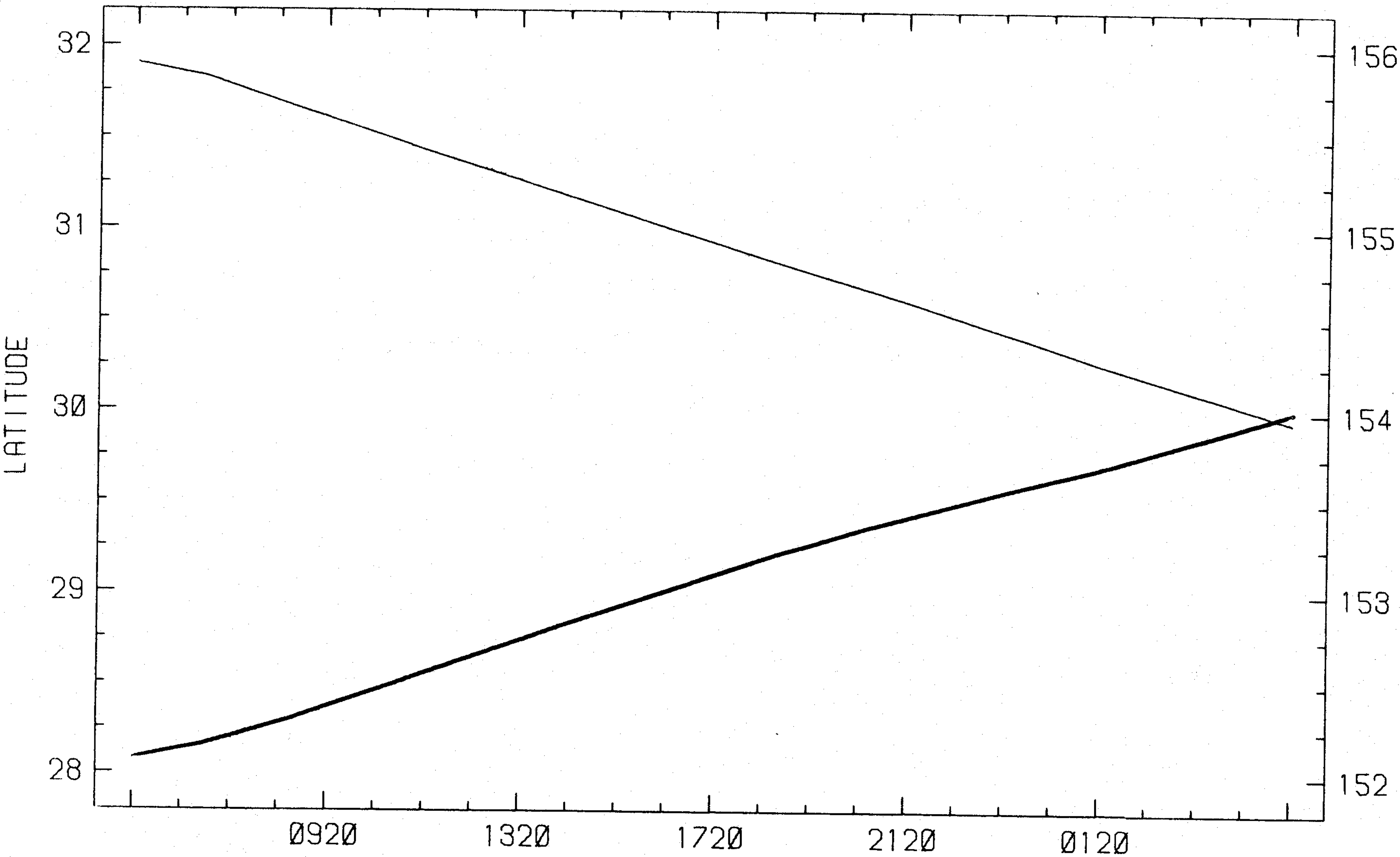
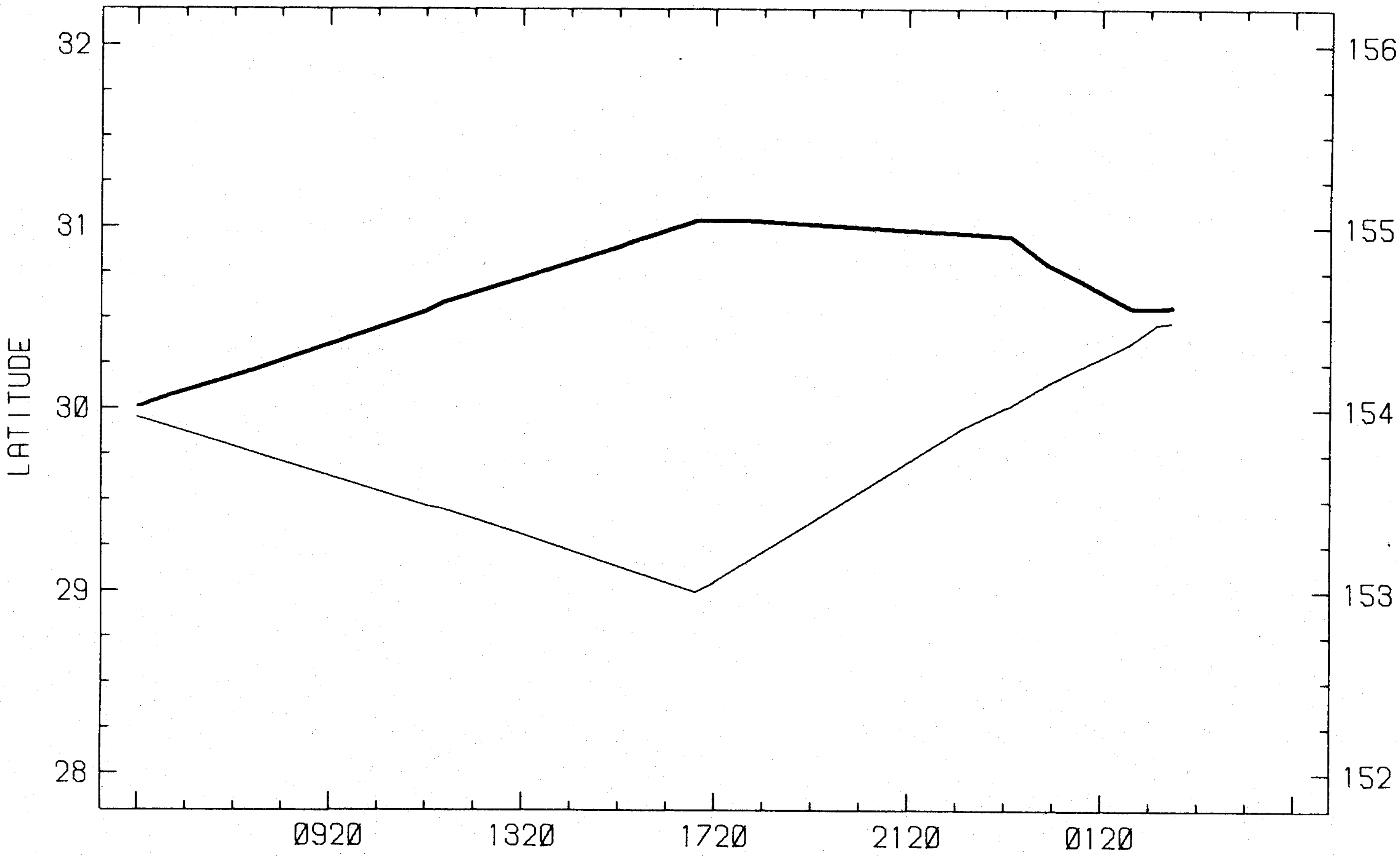
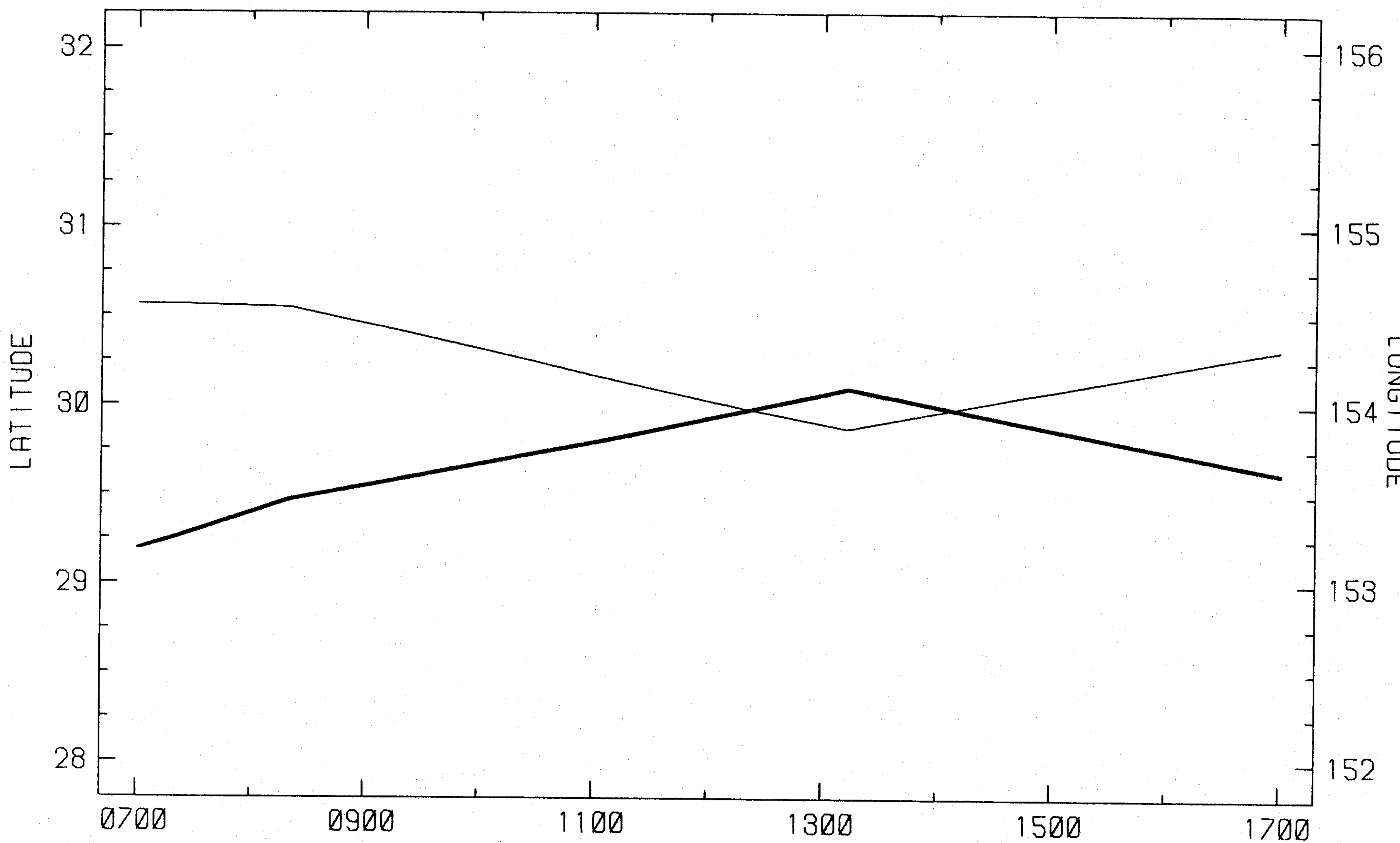


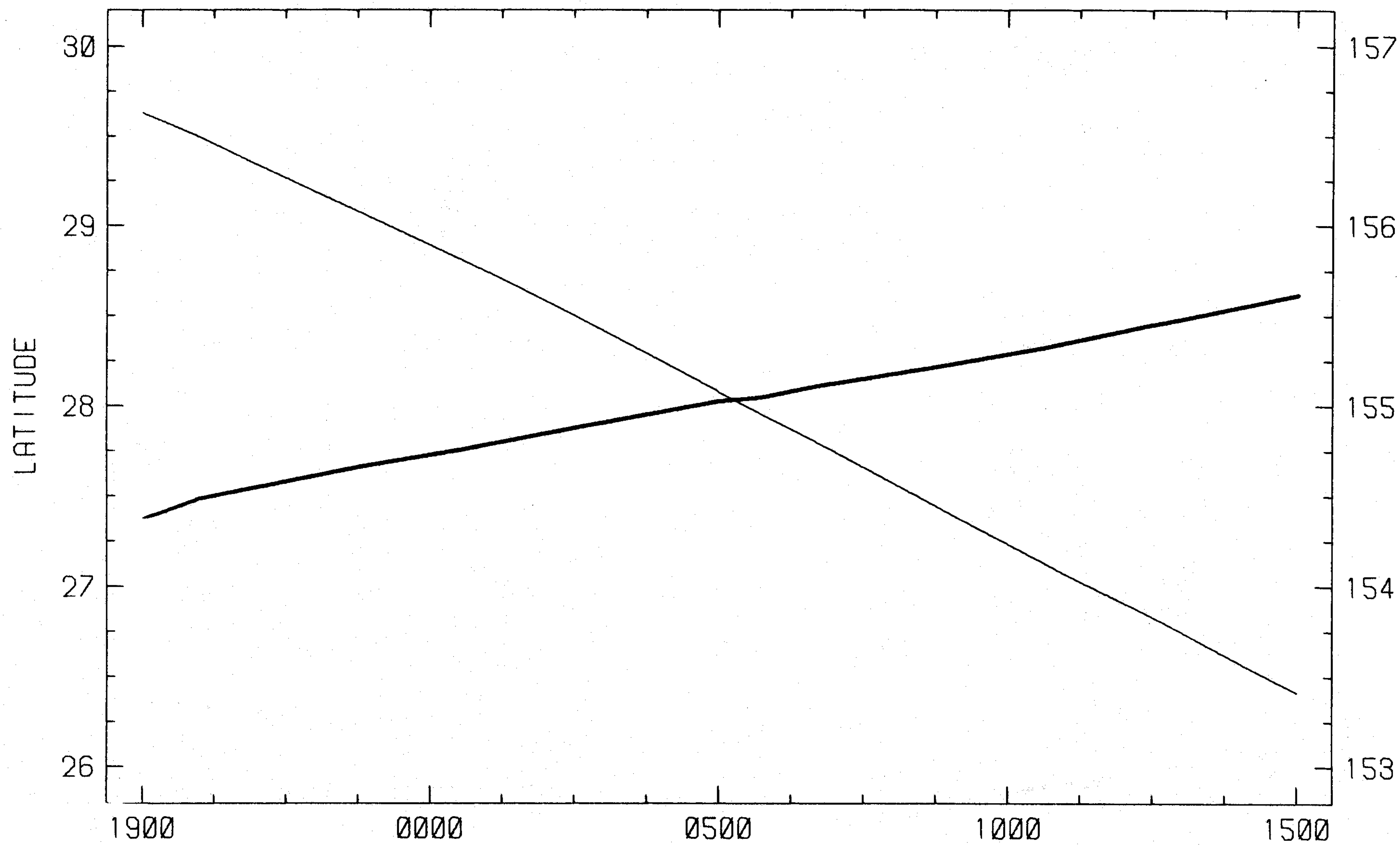
LATITUDE, LONGITUDE VS TIME
17, 18-JAN-80



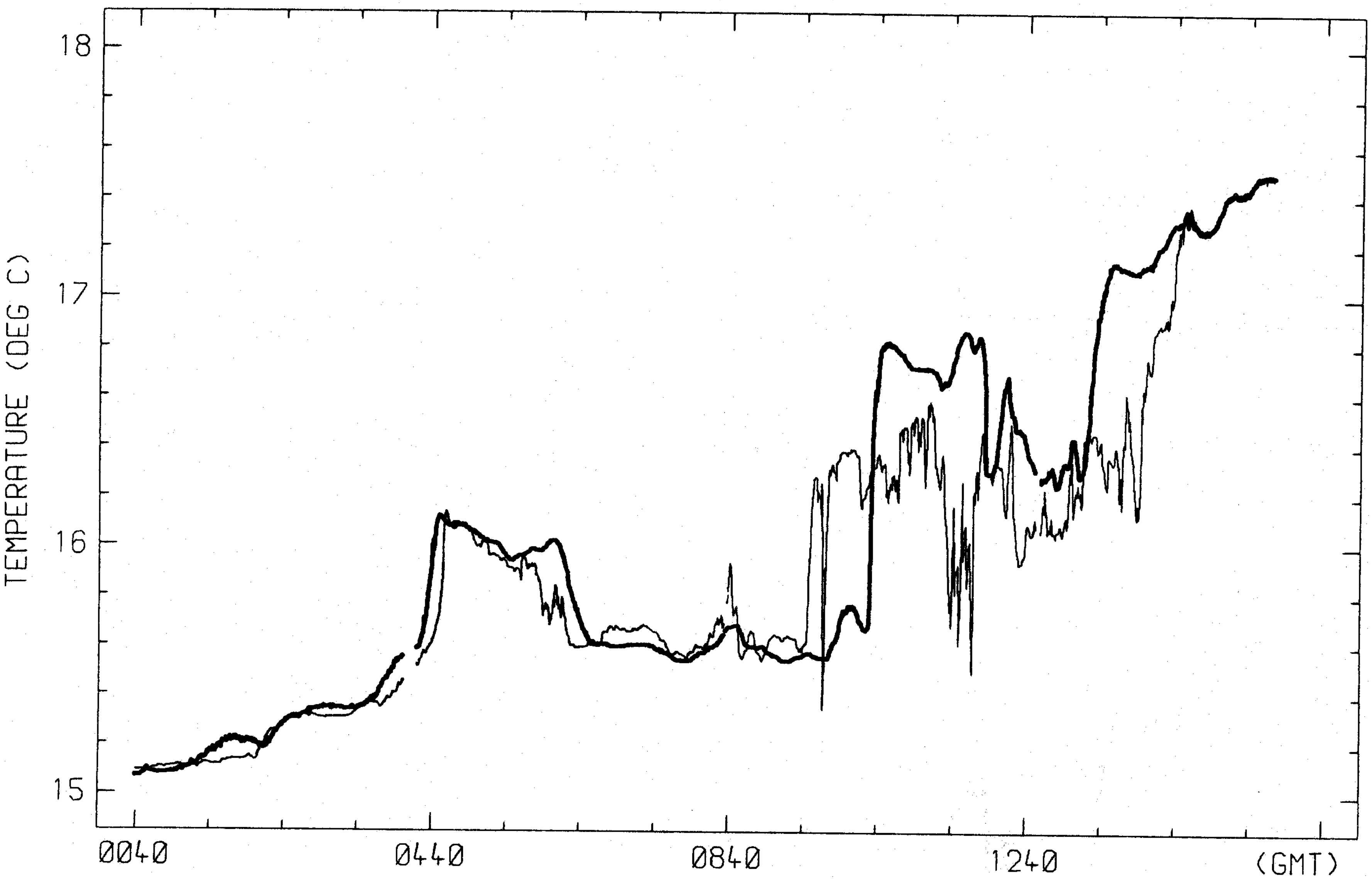
LATITUDE,LONGITUDE VS TIME
18,19-JAN-80



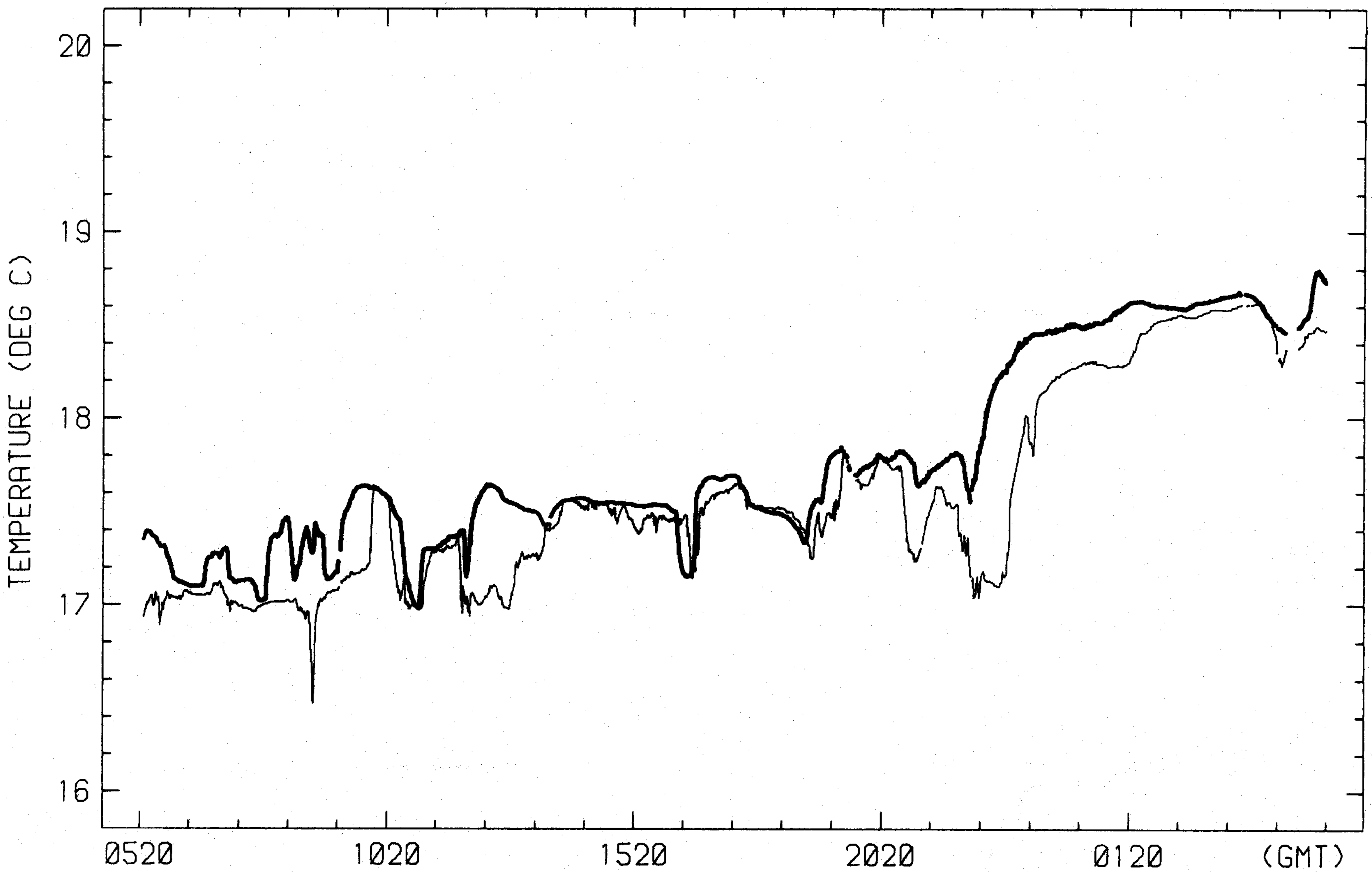
LATITUDE,LONGITUDE VS TIME
25-JAN-80



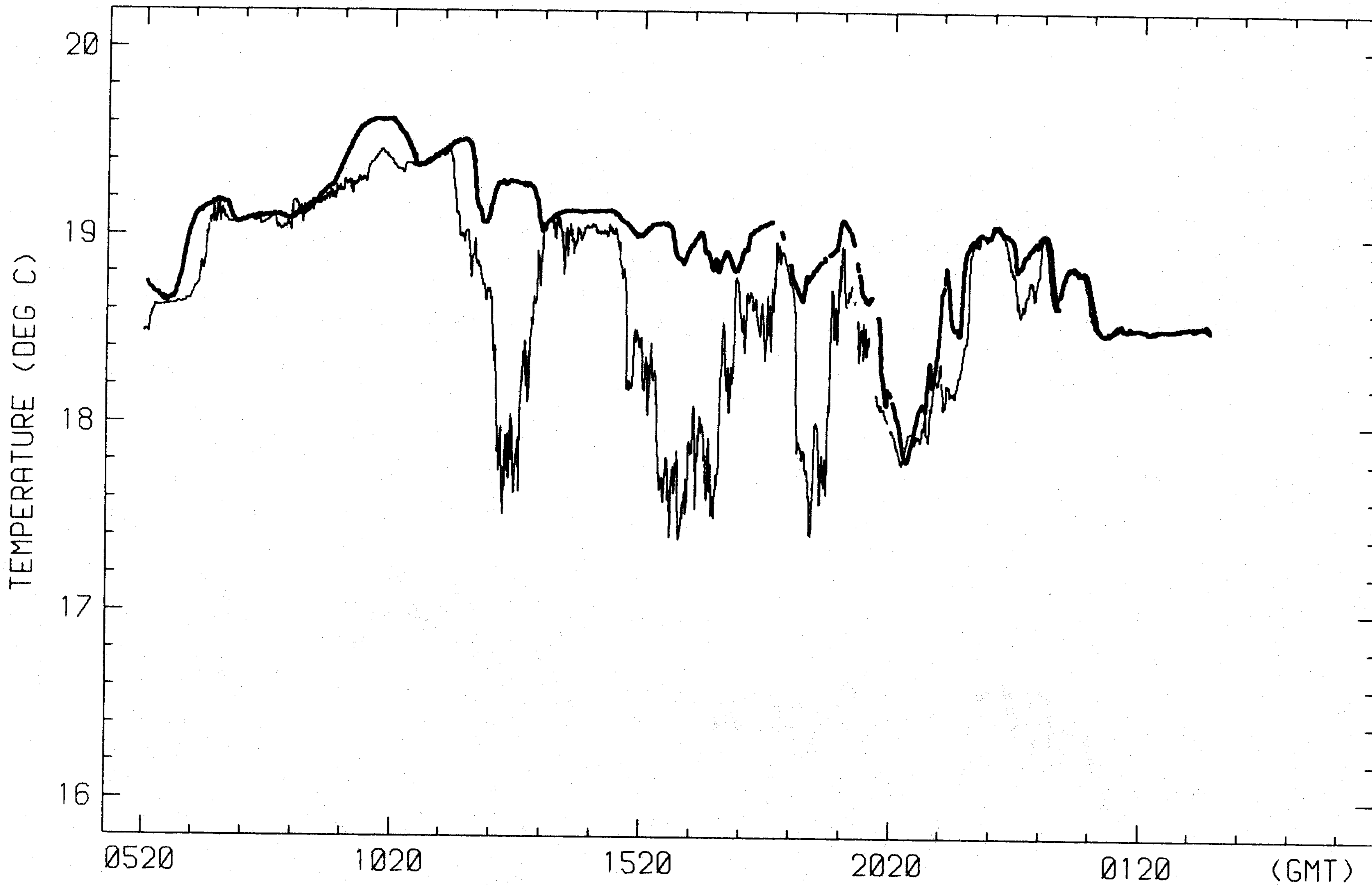
LATITUDE,LONGITUDE VS TIME
27,28-JAN-80



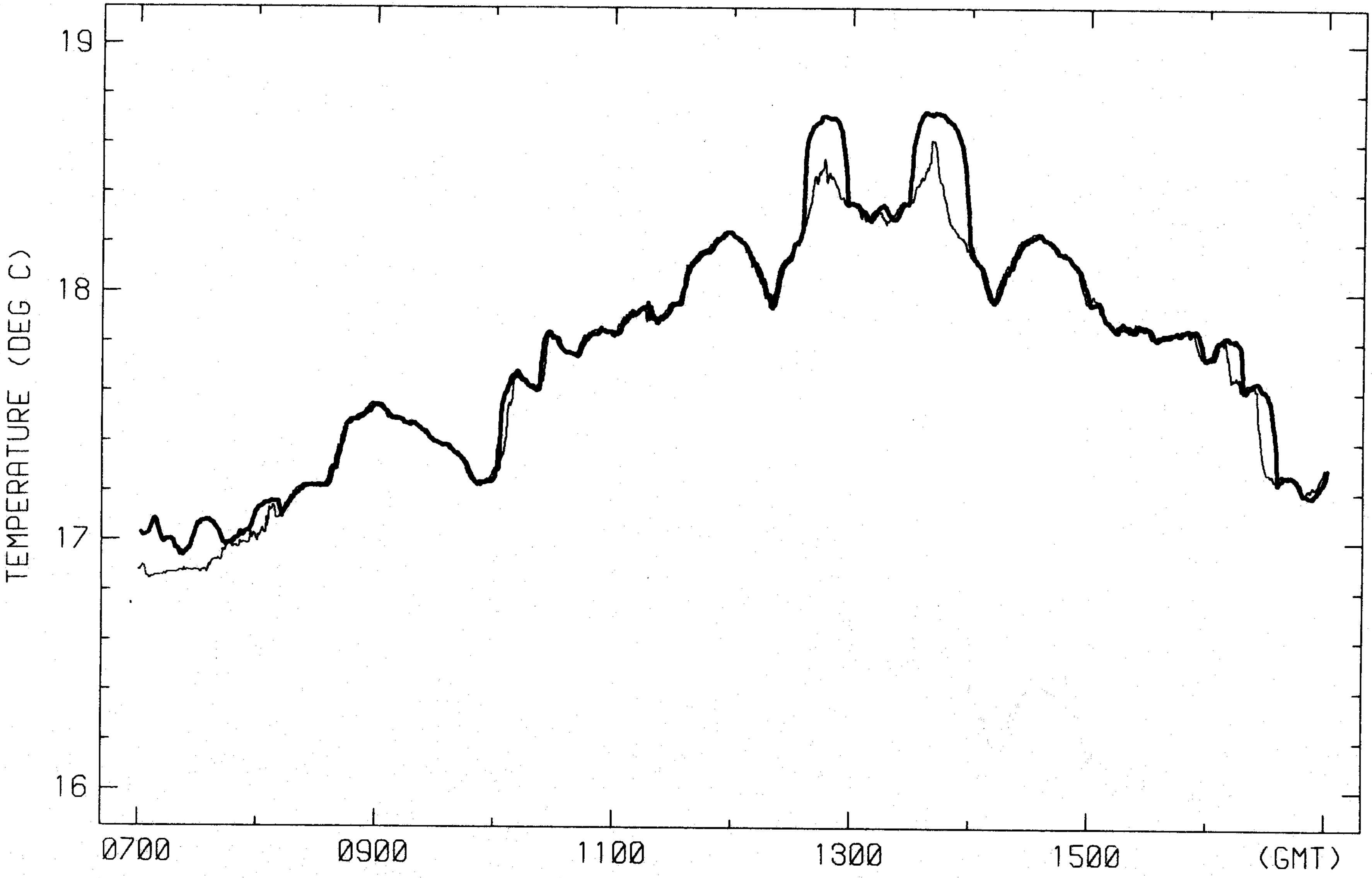
TEMPERATURE VS TIME 16-JAN-80



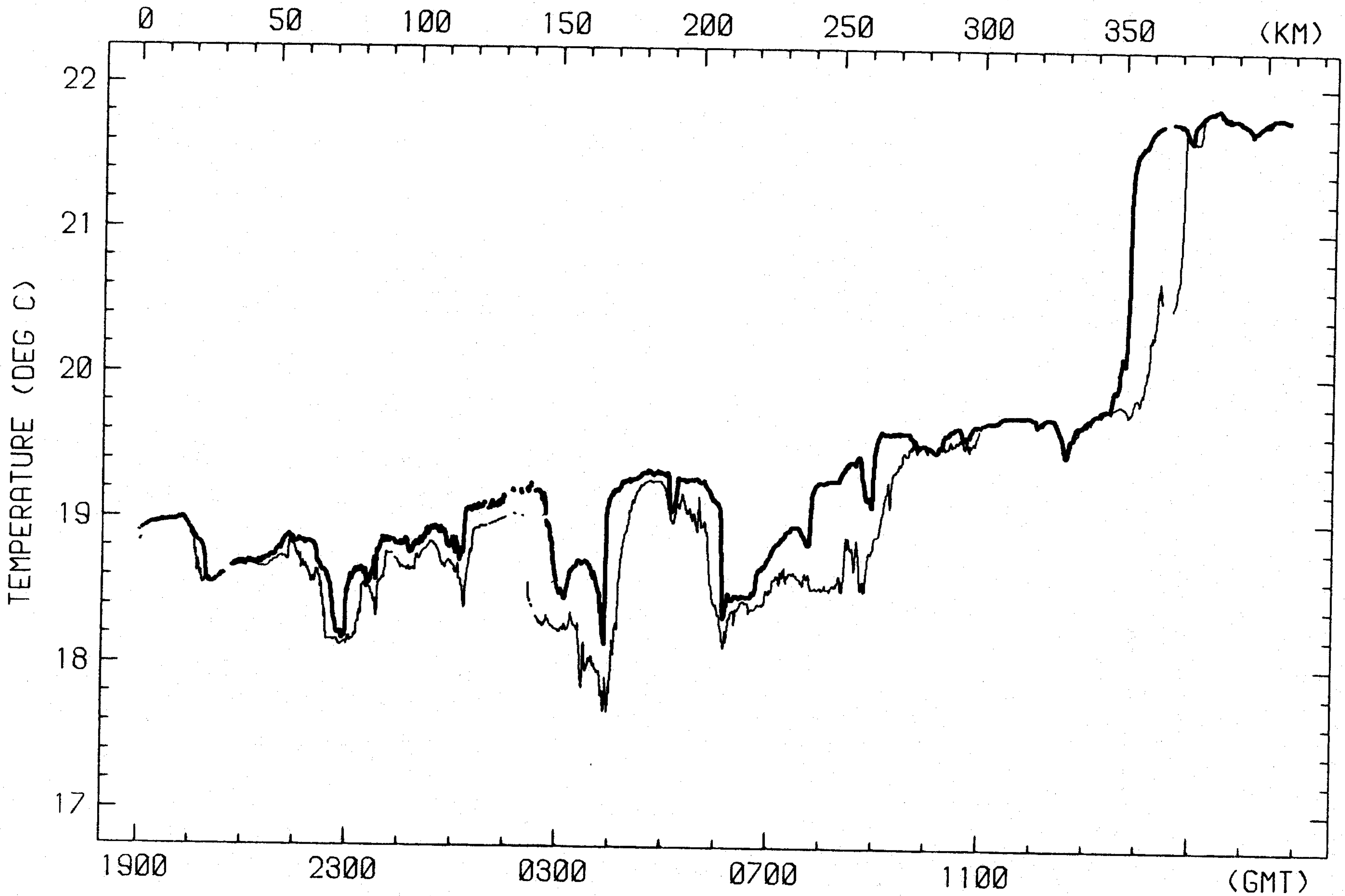
TEMPERATURE VS TIME 17,18-JAN-80



TEMPERATURE VS TIME 18,19-JAN-80



TEMPERATURE VS TIME 25-JAN-80

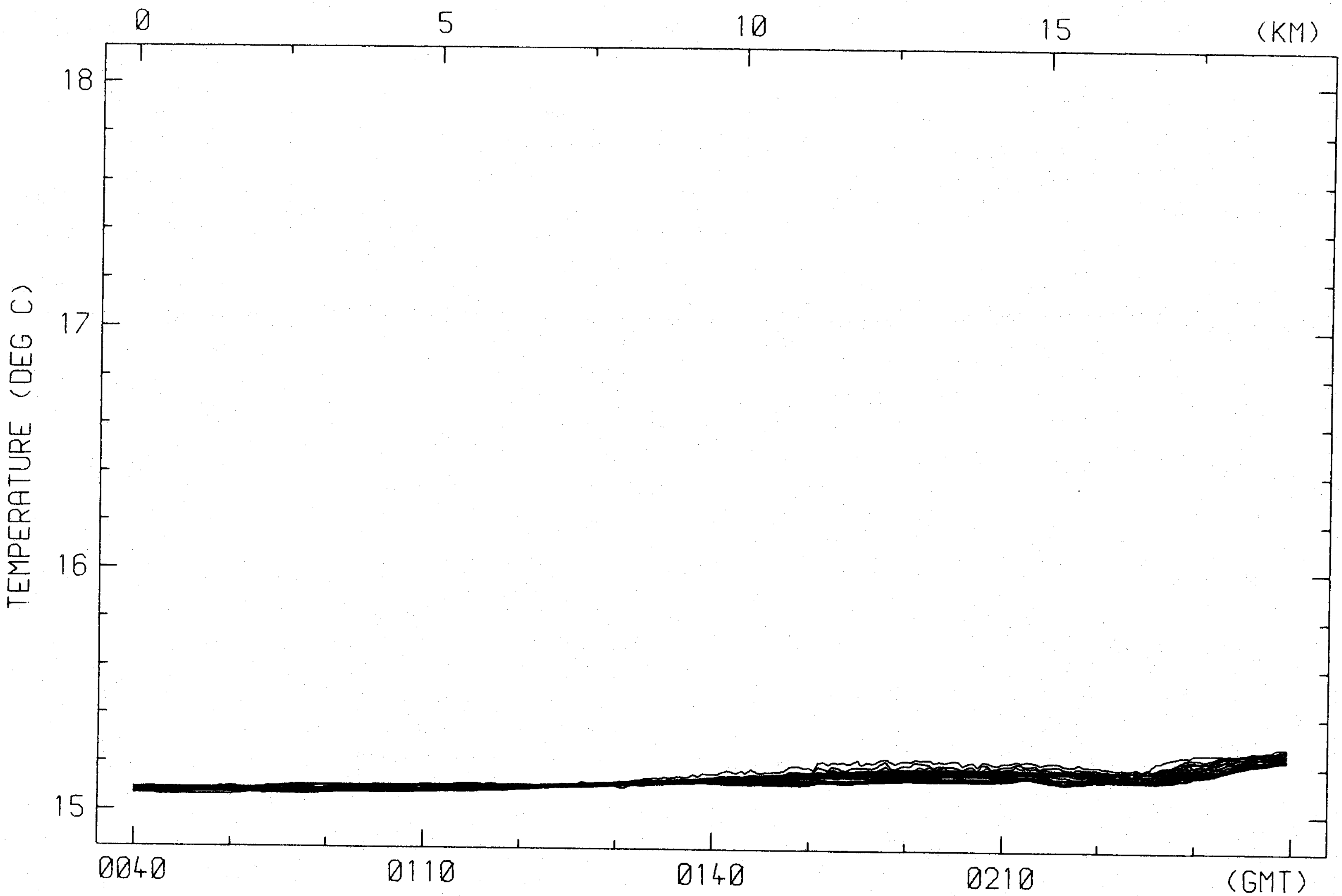


TEMPERATURE VS TIME/DISTANCE
27,28-JAN-80

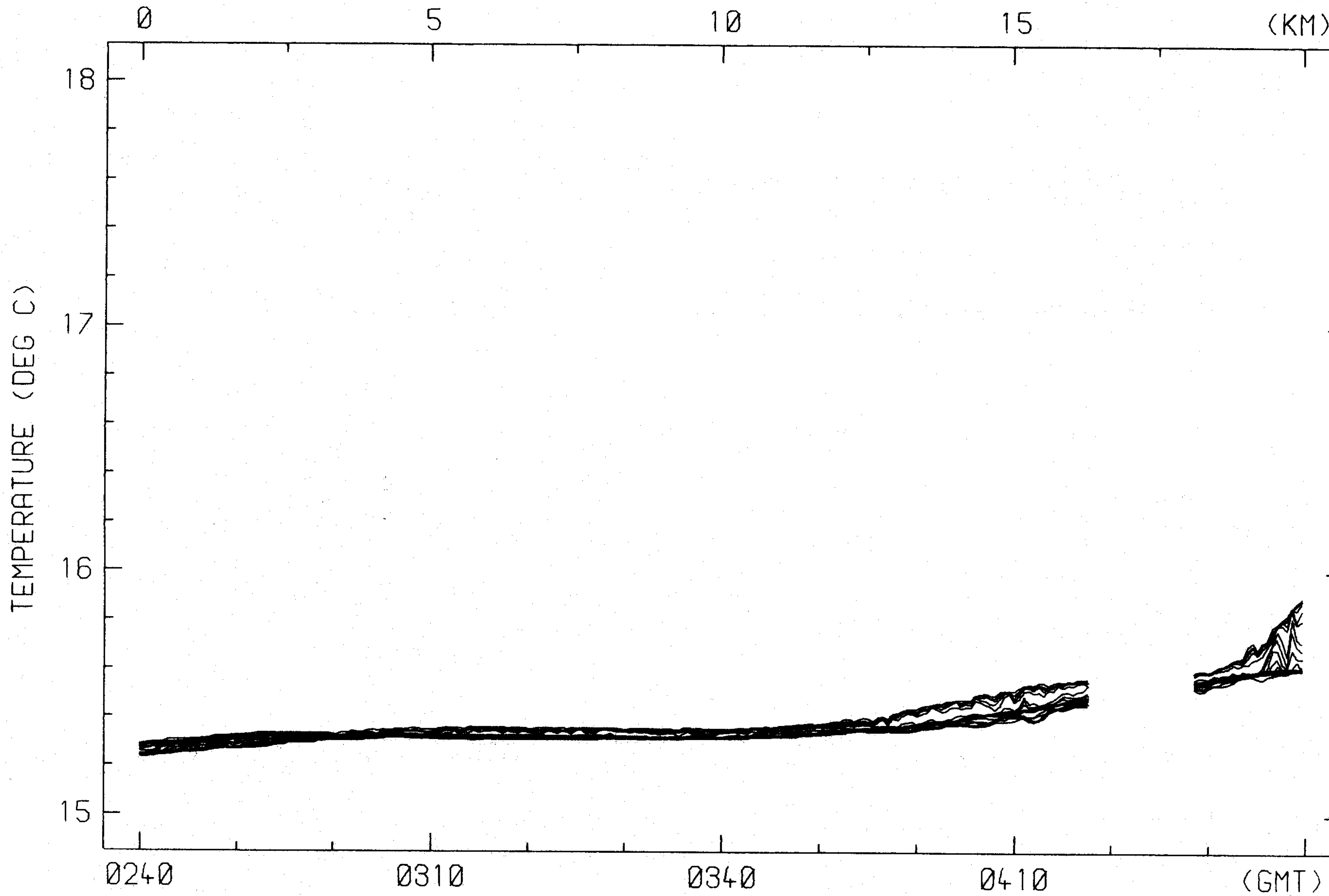
APPENDIX B

Temperature Cross-Sections

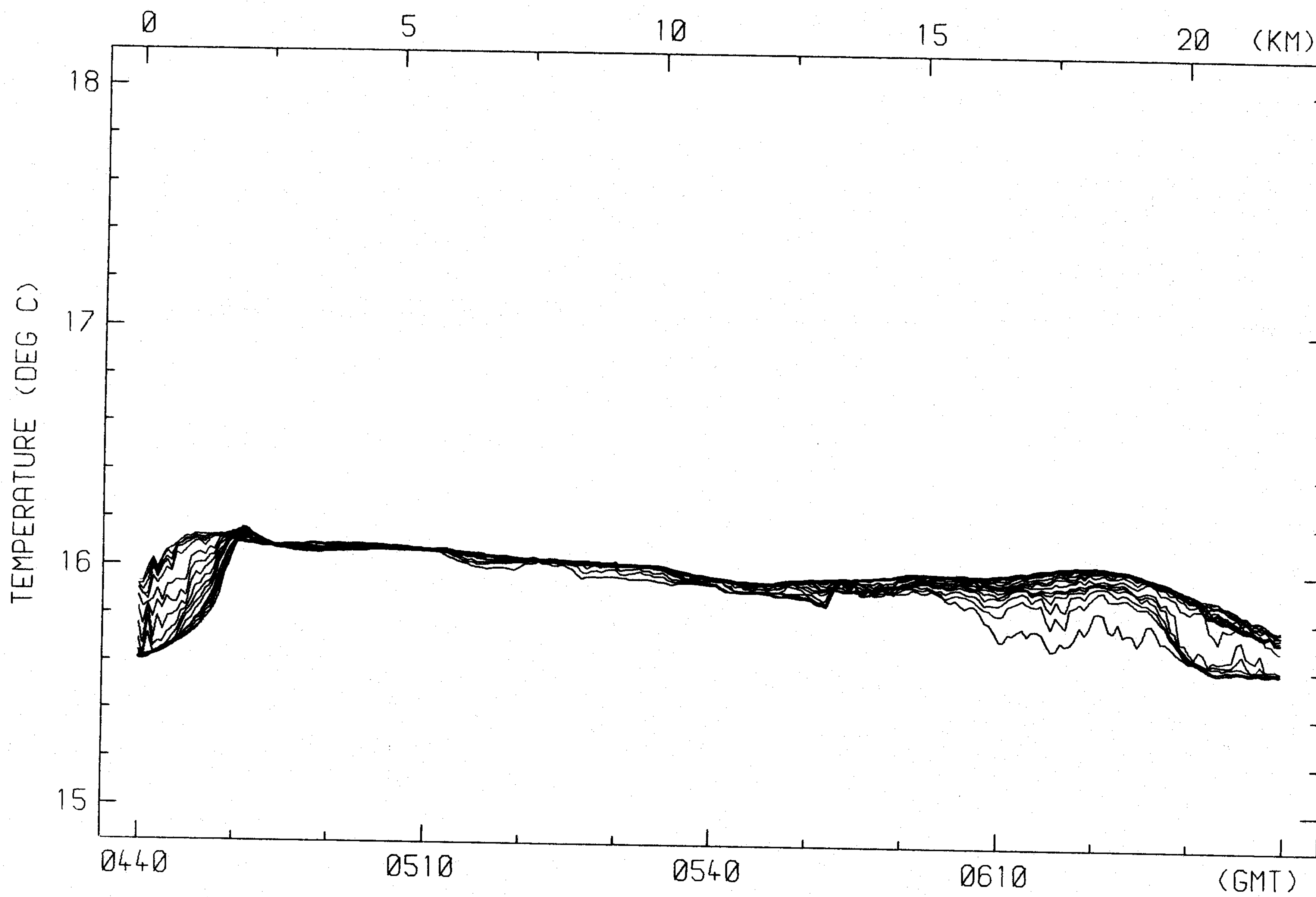
On the following pages there are plots, one for each two-hour period from the beginning of each run, of temperature measurements as a function of time and distance along the tow. The operating temperature sensors are shown in Table 1. In the case of operating sensors one meter apart, only one of the measurements was plotted. The tow speeds and directions and the depth of the highest and lowest temperature measurements are given in Table 2. The temperature measurements are low-pass filtered, computed by averaging over sequential 30-s intervals.



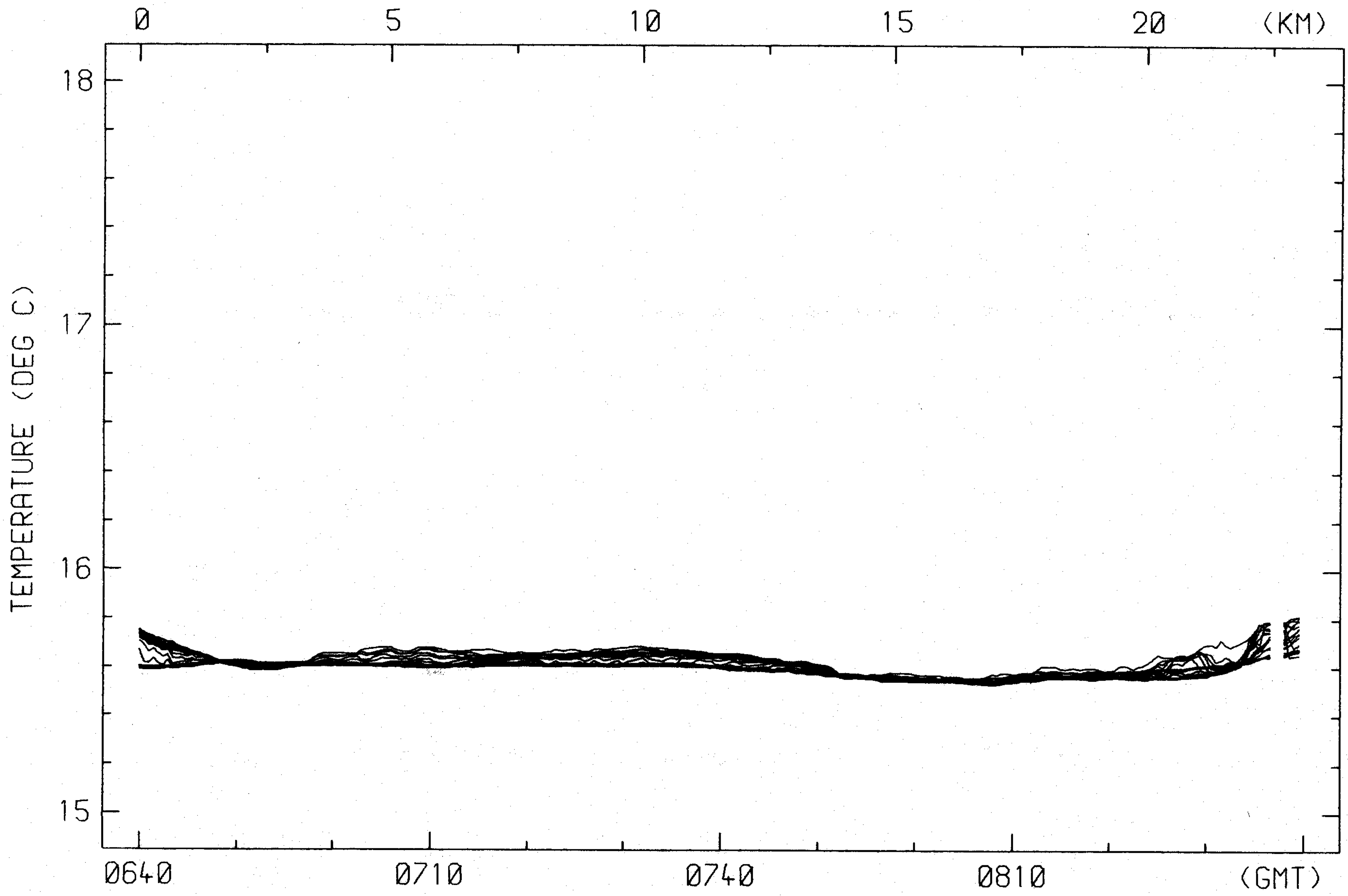
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 04.98, 33 51.12 TO 150 13.50, 33 43.62



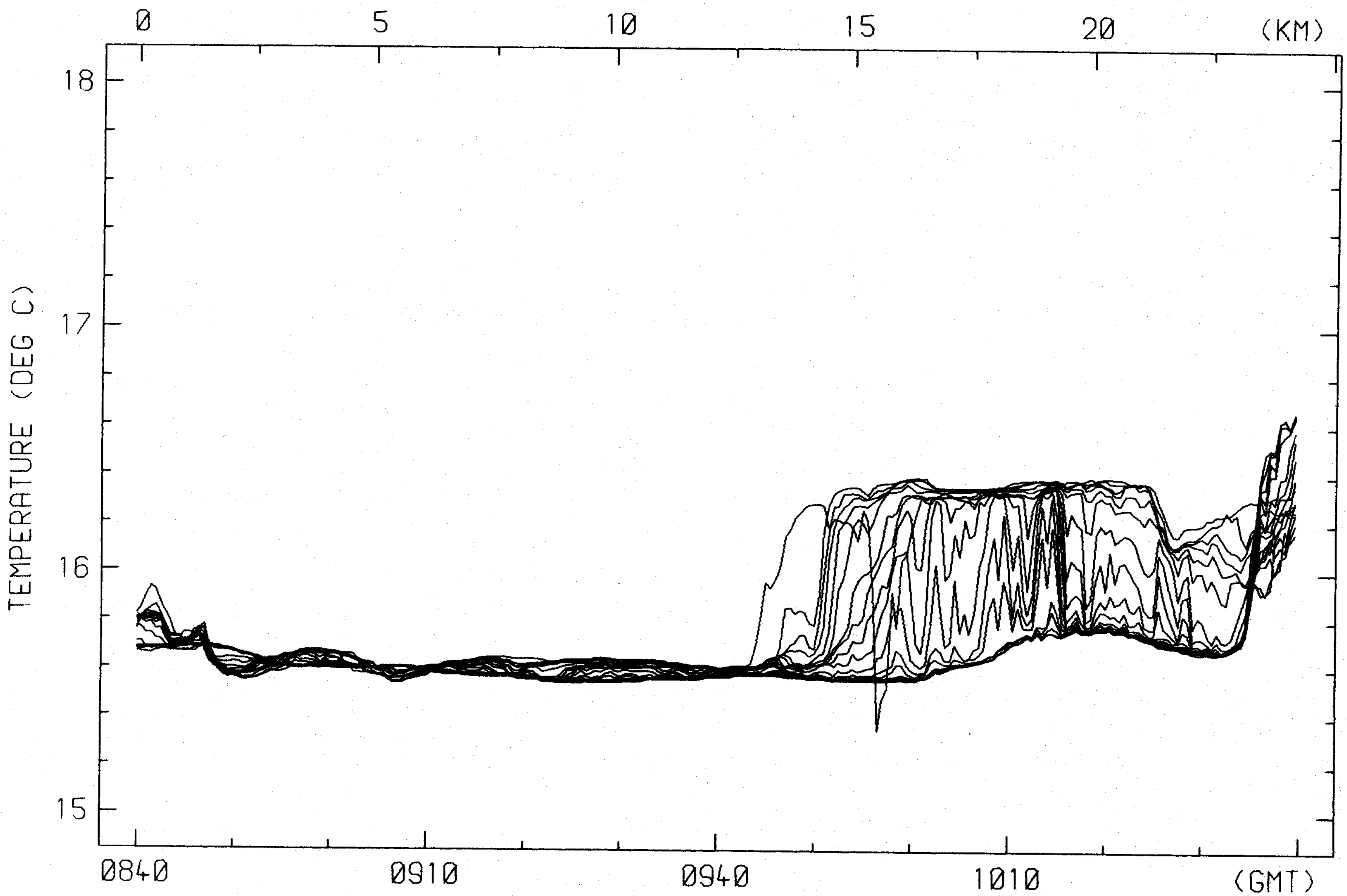
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 13.50, 33 43.62 TO 150 21.96, 33 35.40



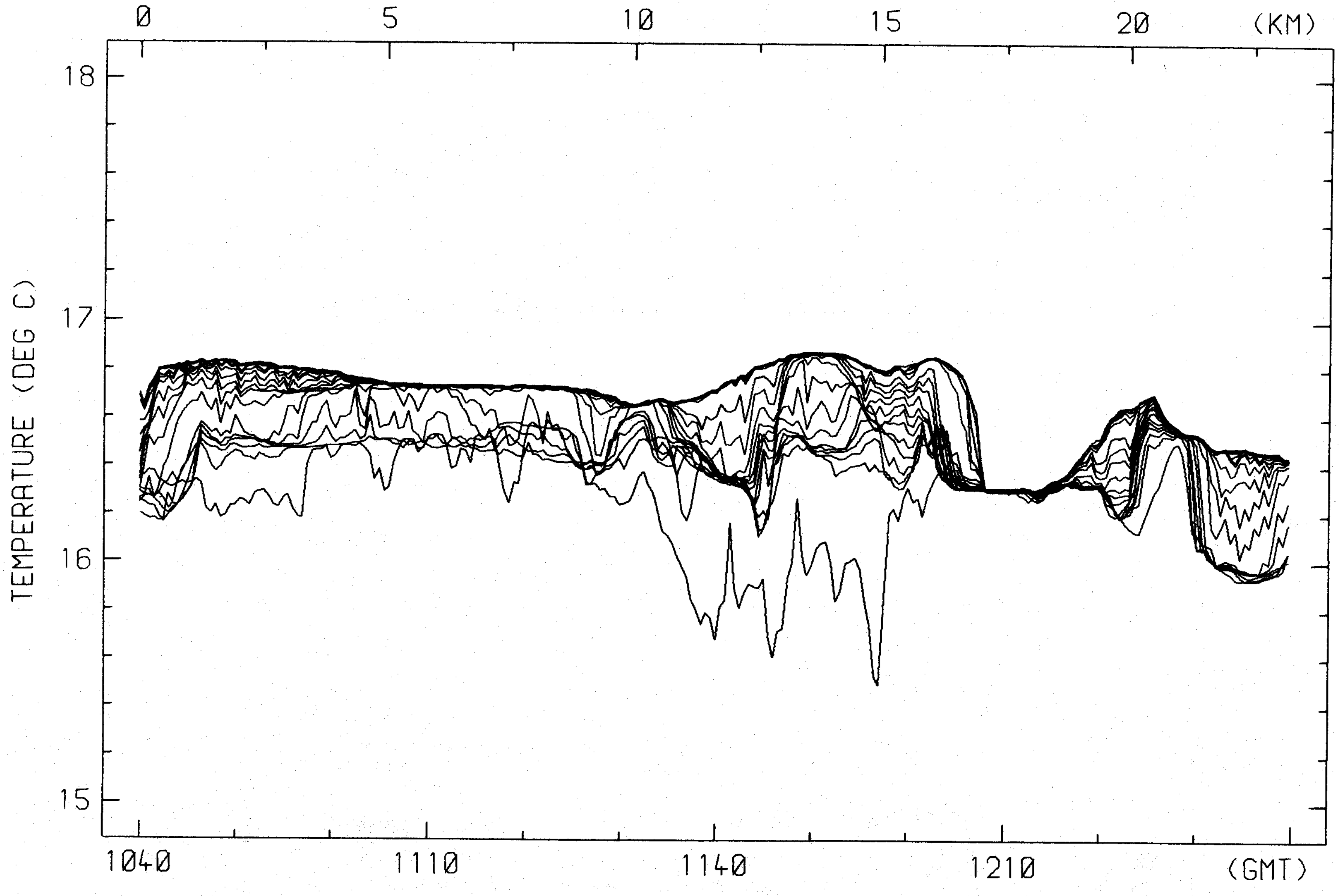
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 21.96, 33 35.40 TO 150 31.38, 33 26.46



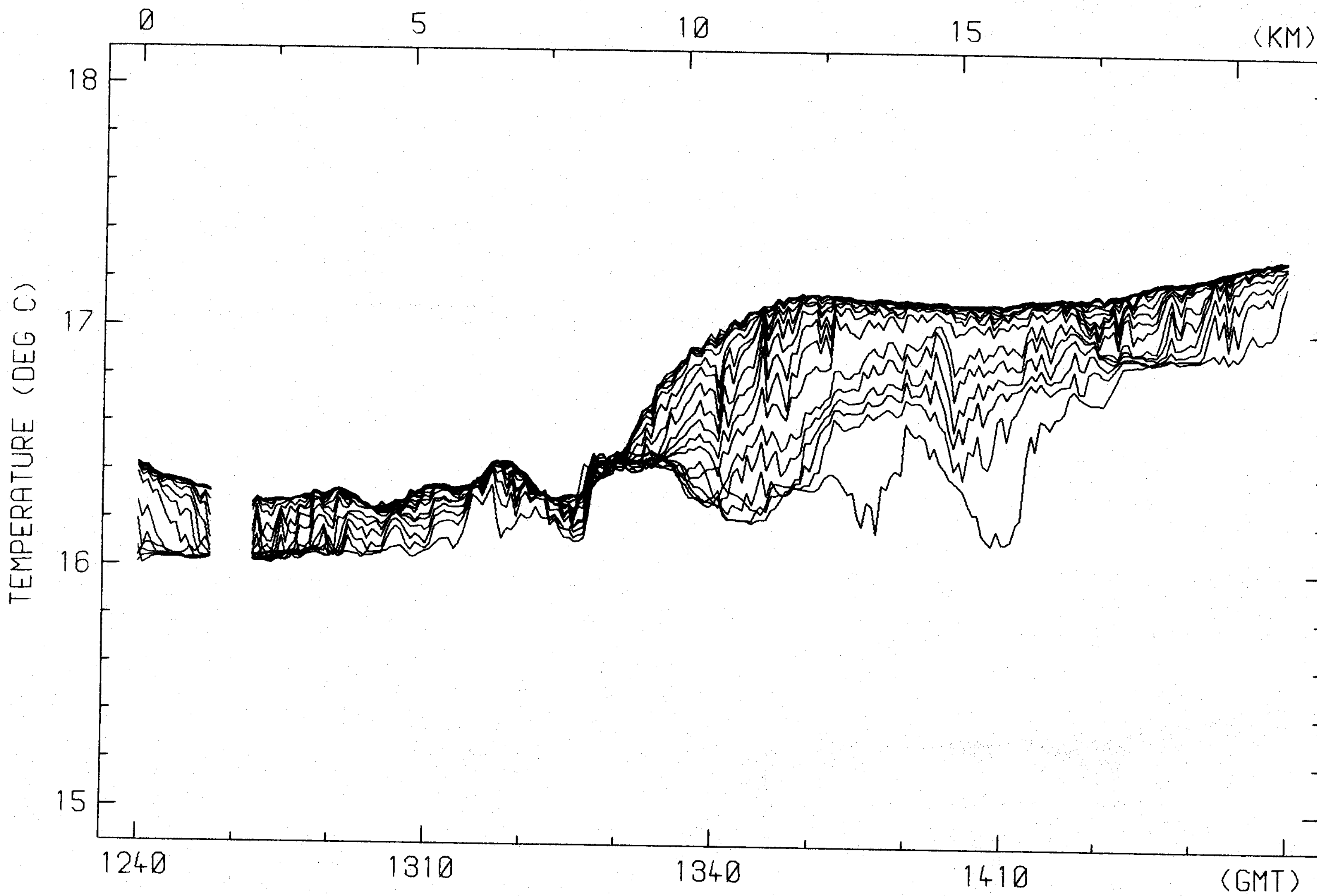
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 31.38, 33 26.46 TO 150 41.70, 33 17.40



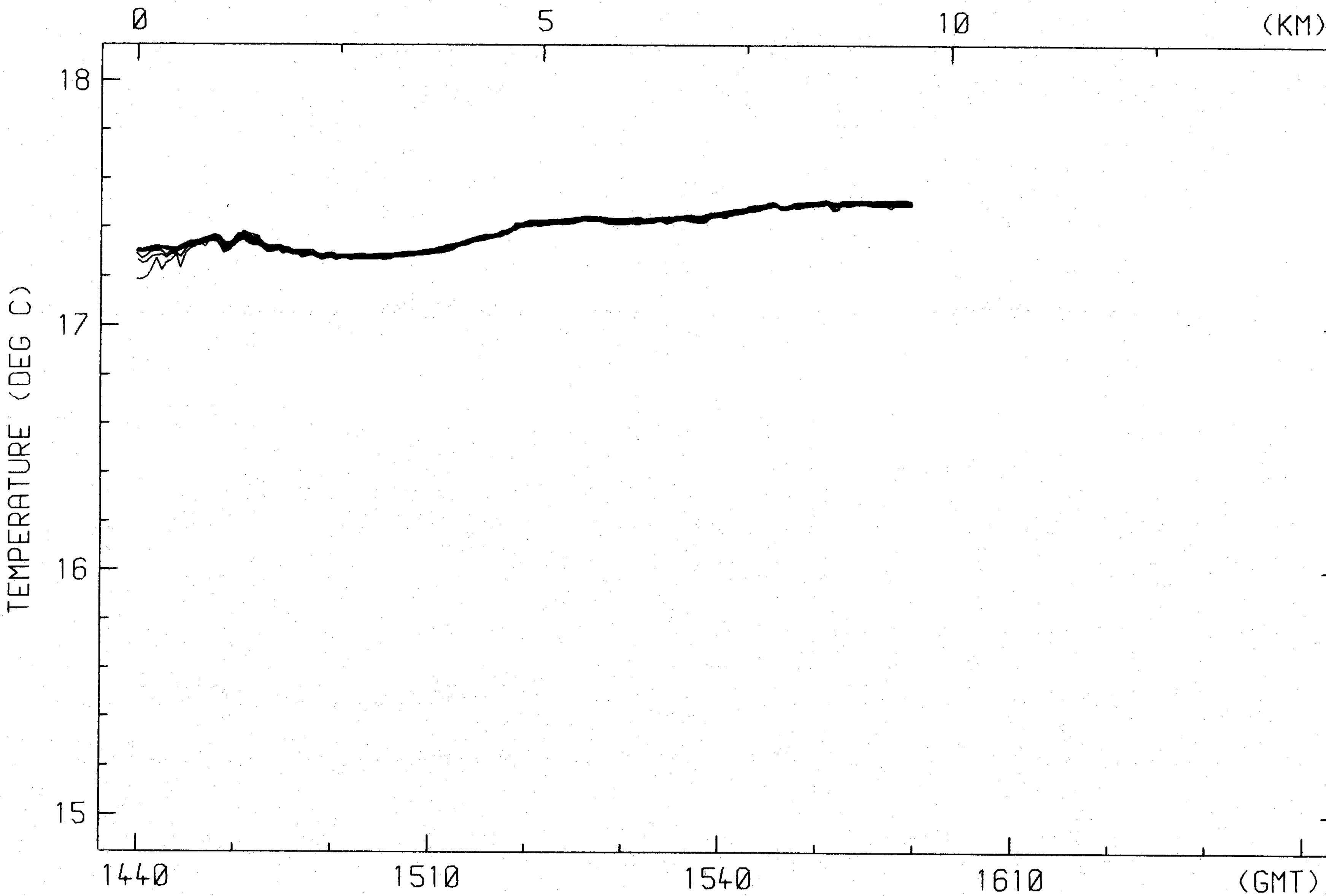
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 41.70, 33 17.40 TO 150 52.92, 33 08.22



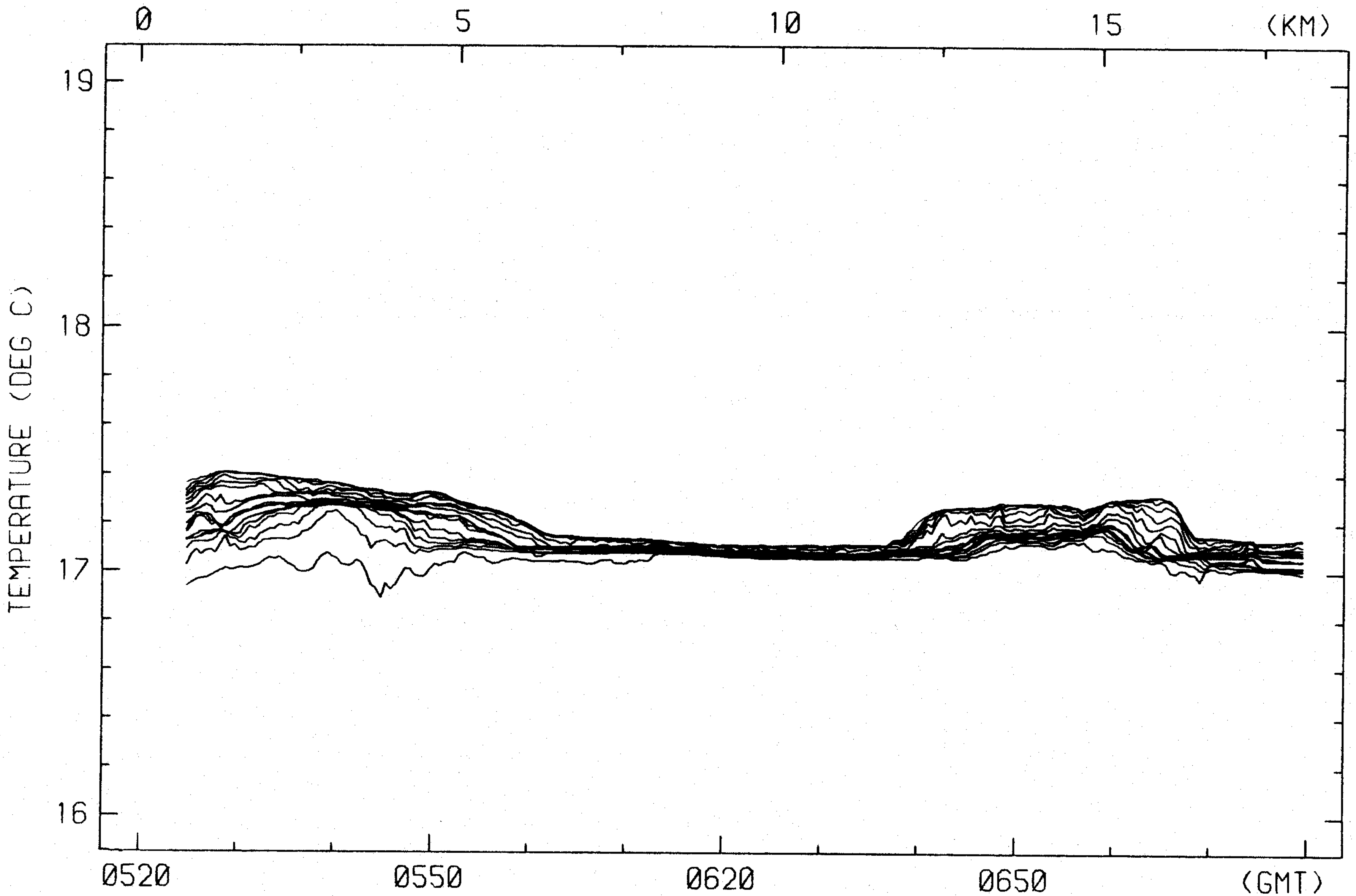
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
150 52.92, 33 08.22 TO 151 02.52, 32 58.50



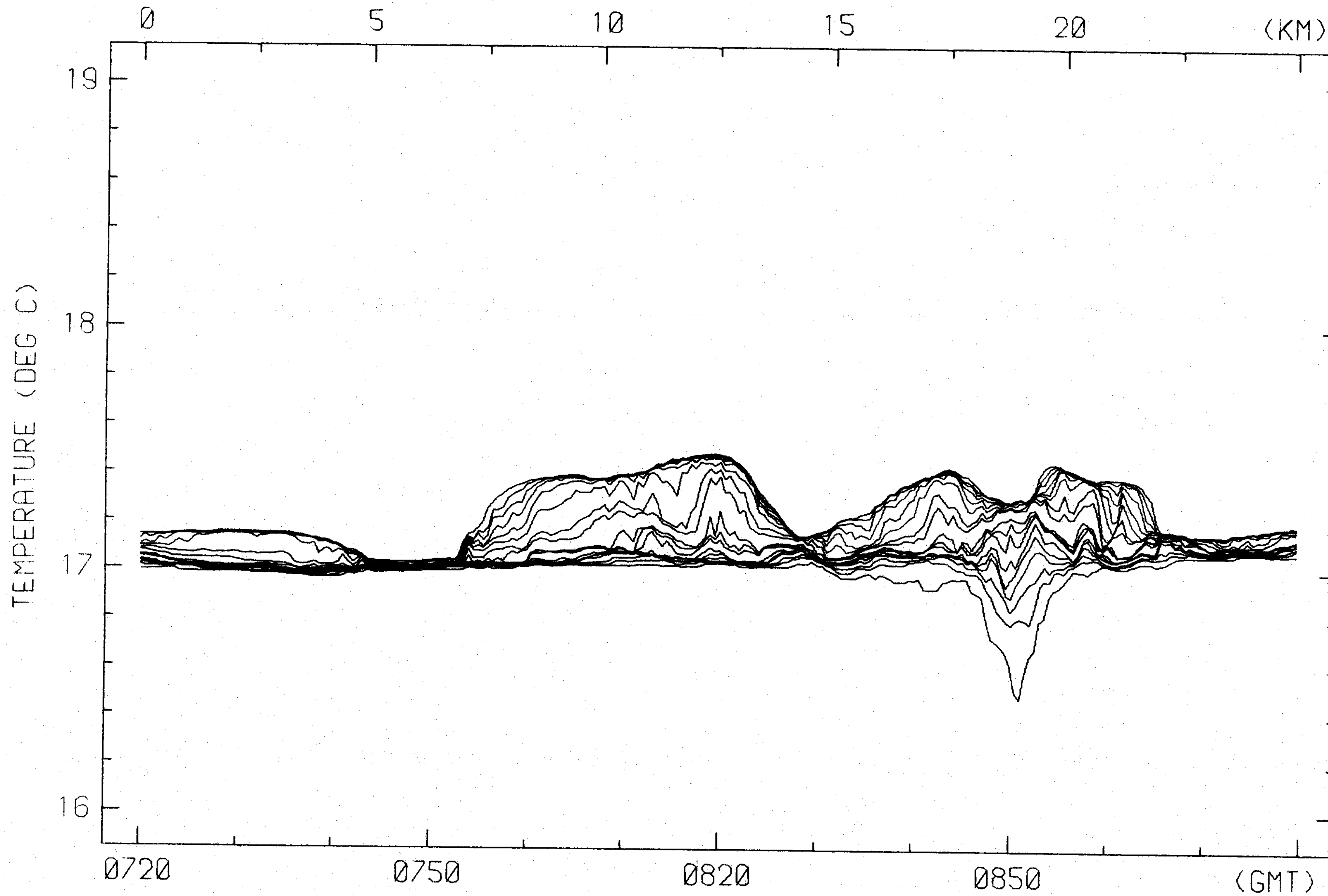
TEMPERATURE VS TIME/DISTANCE 16-JAN-80
151 02.52, 32 58.50 TO 151 08.88, 32 48.48



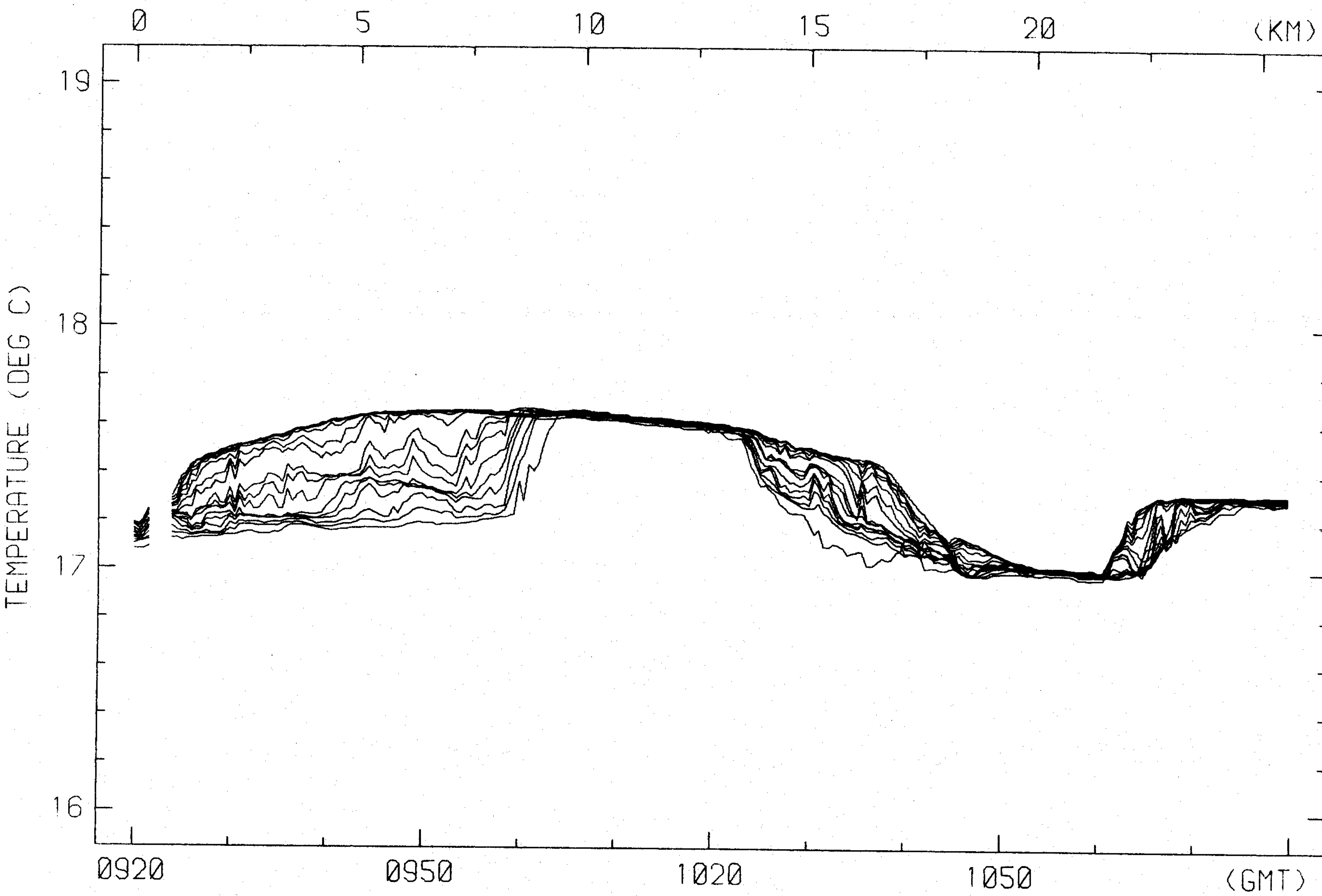
TEMPERATURE VS TIME/DISTANCE 16-JAN-8Ø
151 Ø8.88, 32 48.48 TO 151 11.94, 32 43.98



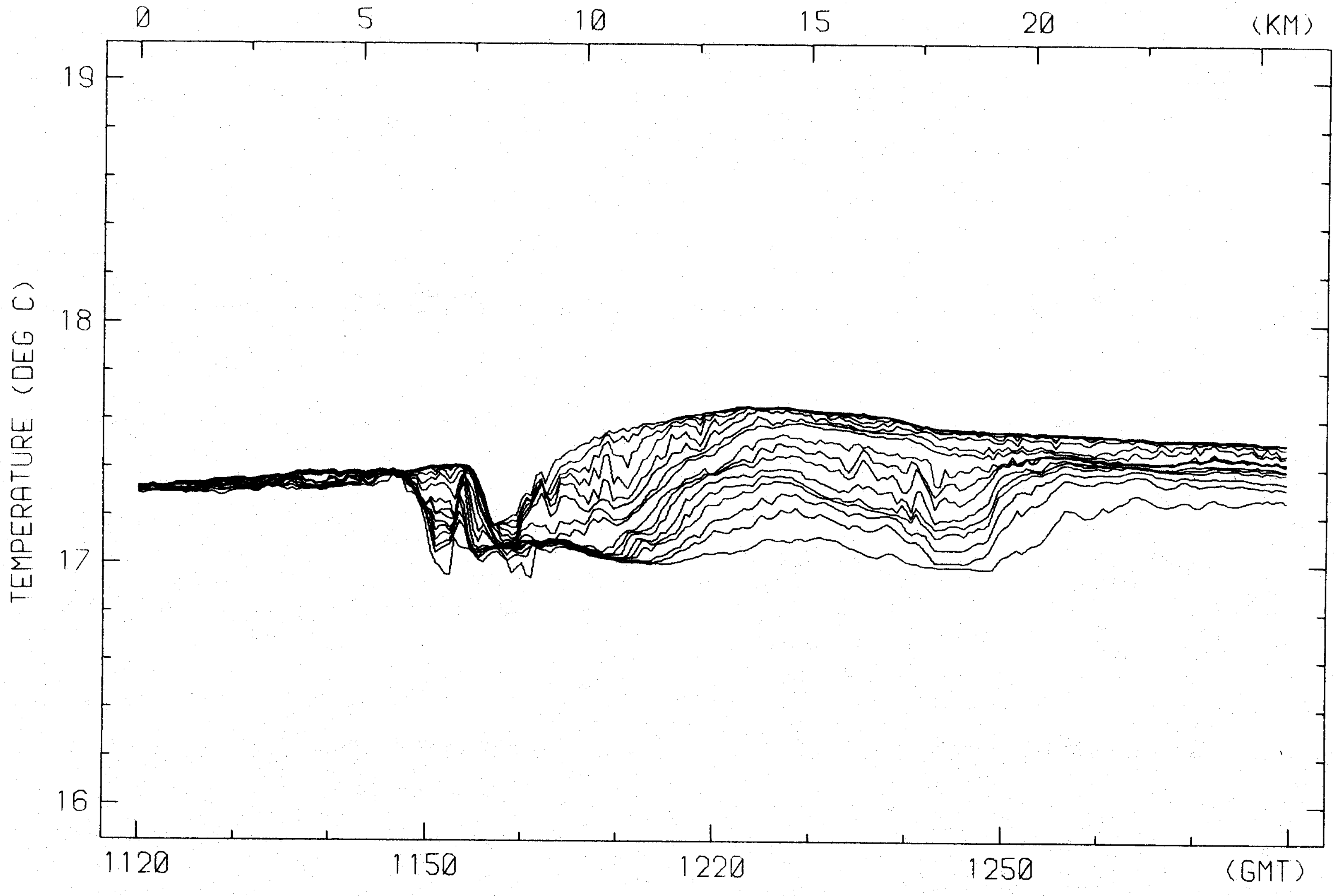
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 05.46, 31 54.0 TO 152 12.90, 31 46.44



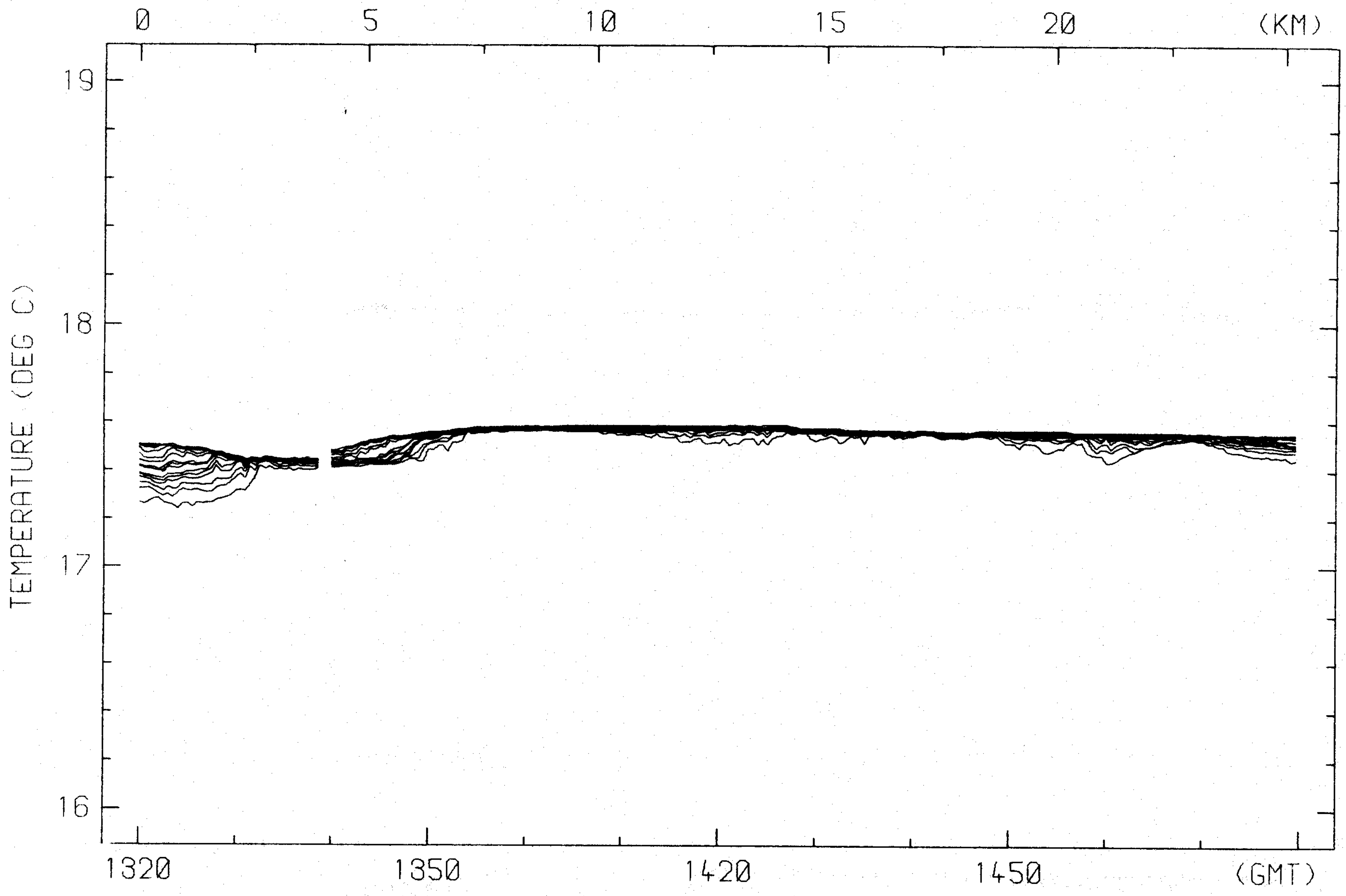
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 12.90, 31 46.44 TO 152 22.98, 31 35.94



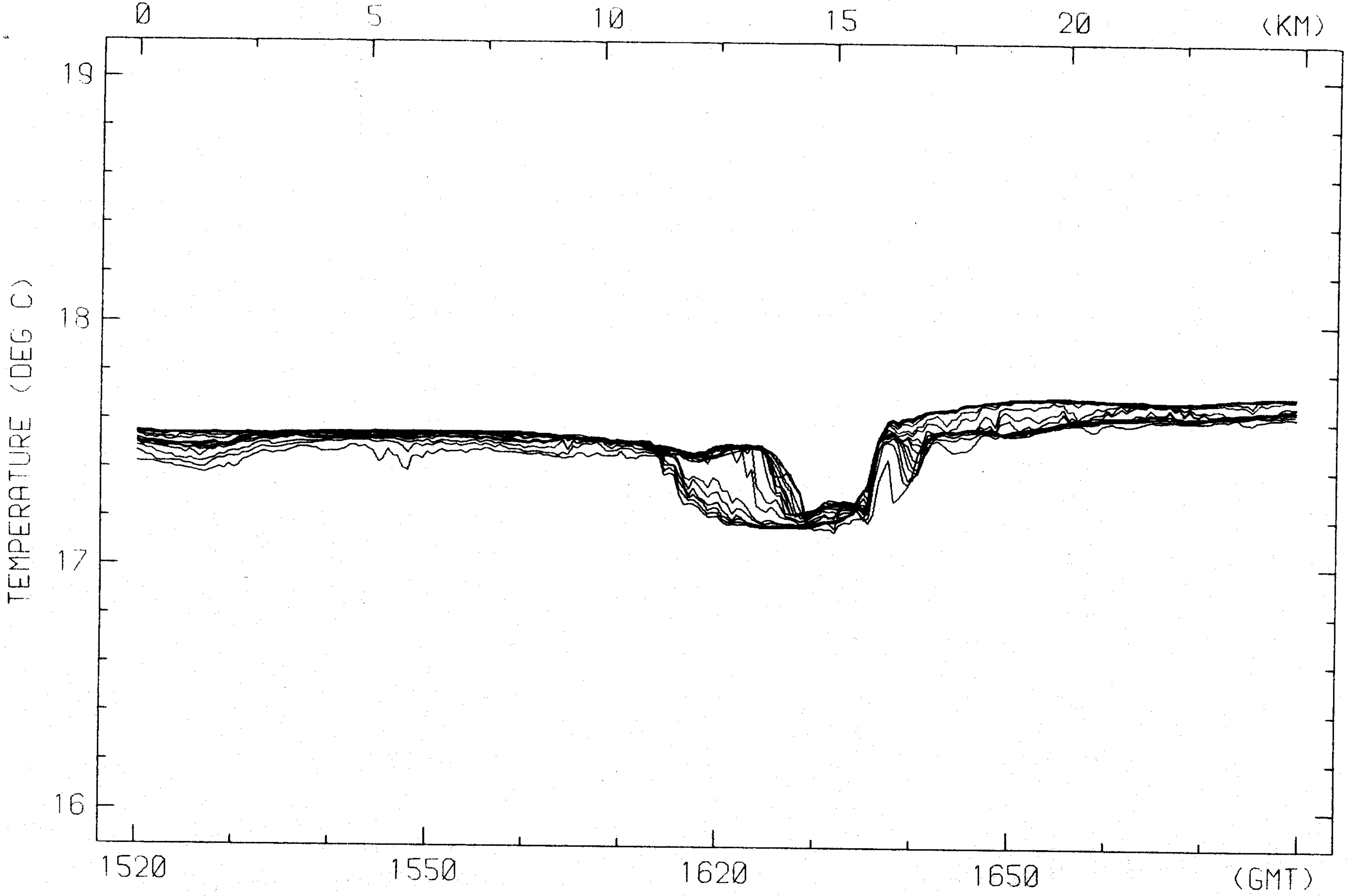
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 22.98, 31 35.94 TO 152 34.08, 31 25 74



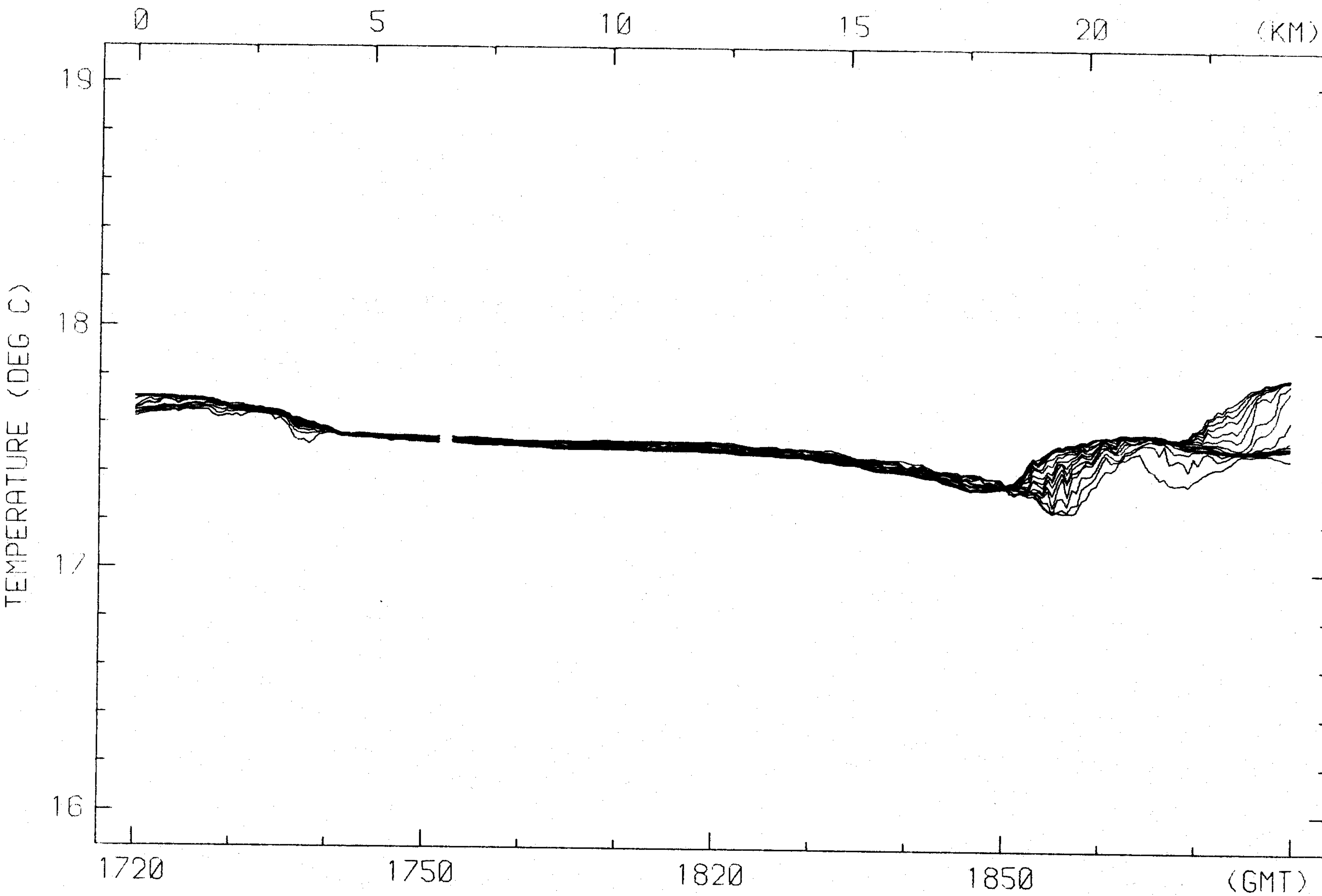
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 34.08, 31 25.74 TO 152 45.30, 31 15.66



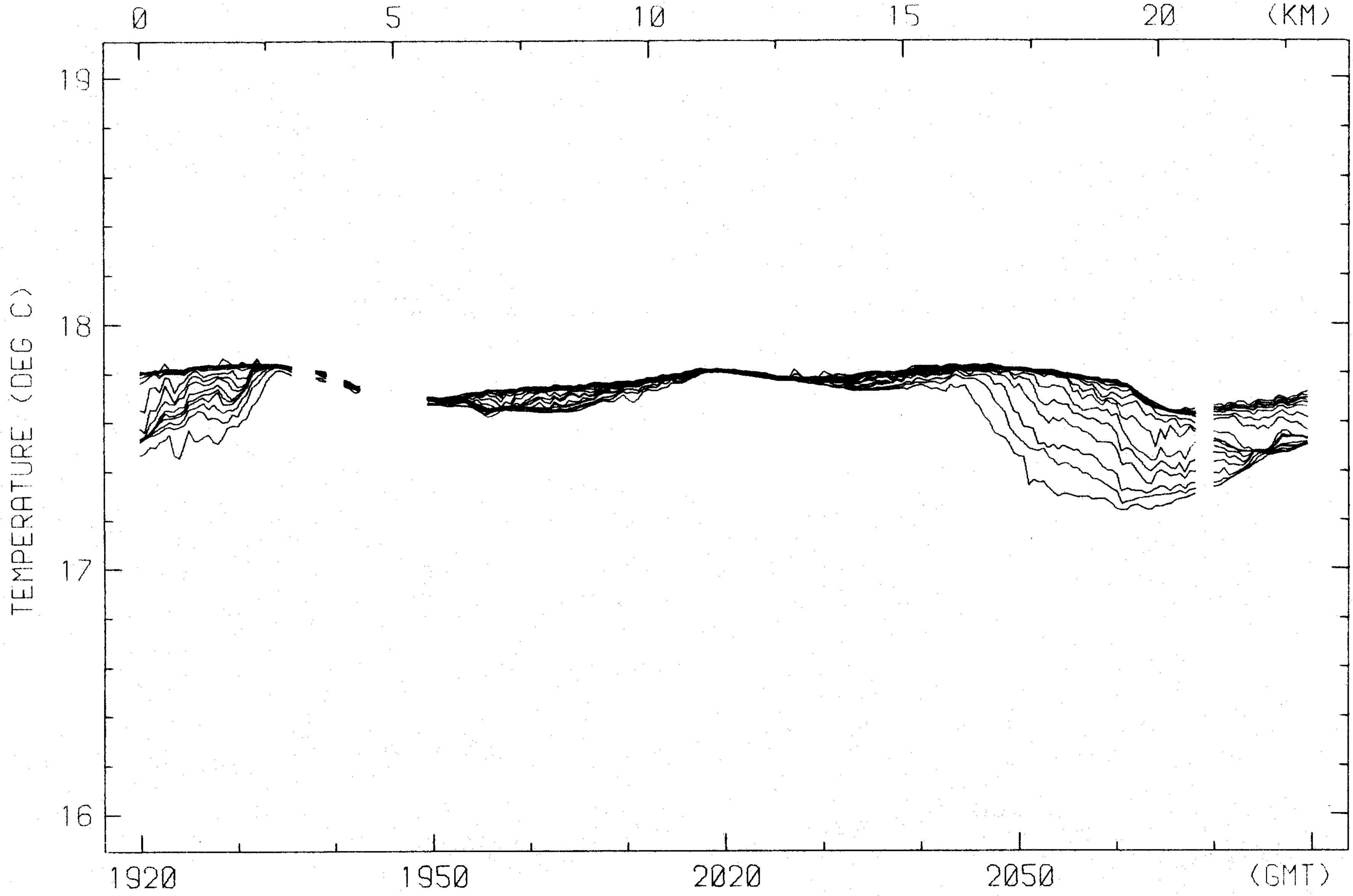
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 45.30, 31 15.66 TO 152 56.10, 31 05.58



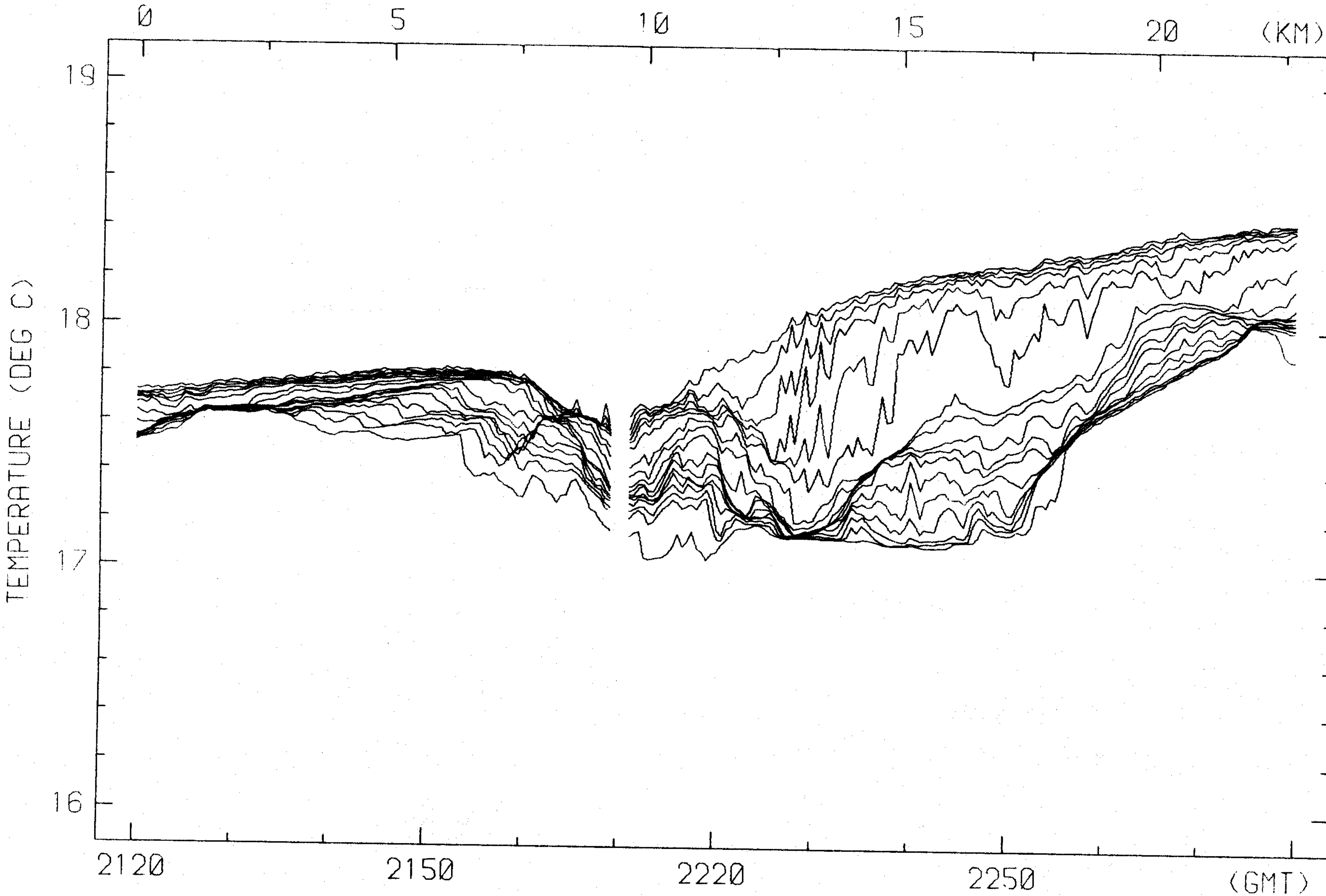
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
152 56.10, 31 05.58 TO 153 06.66, 30 55.62



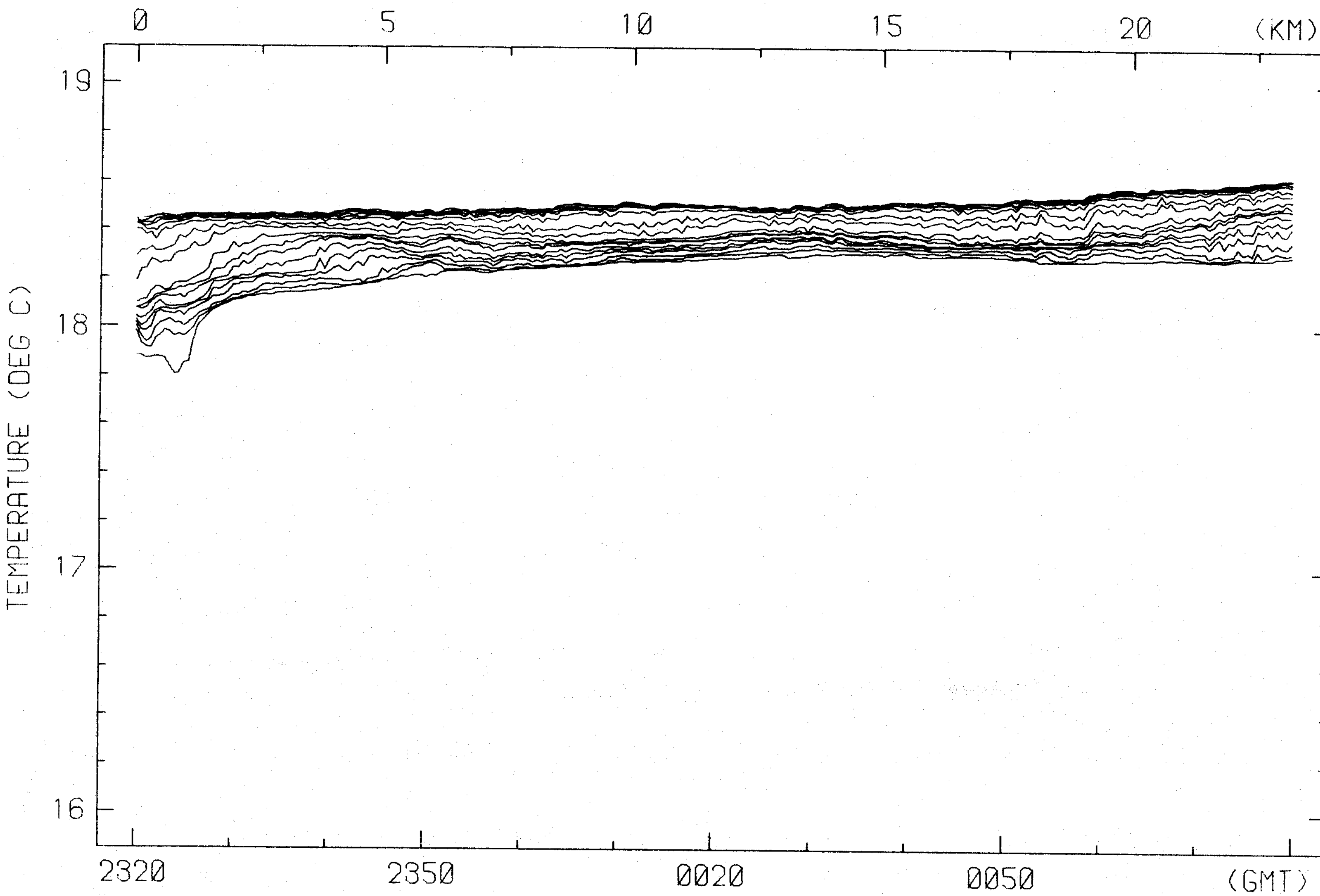
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
153 06.66, 30 55.62 TO 153 16.98, 30 45.84



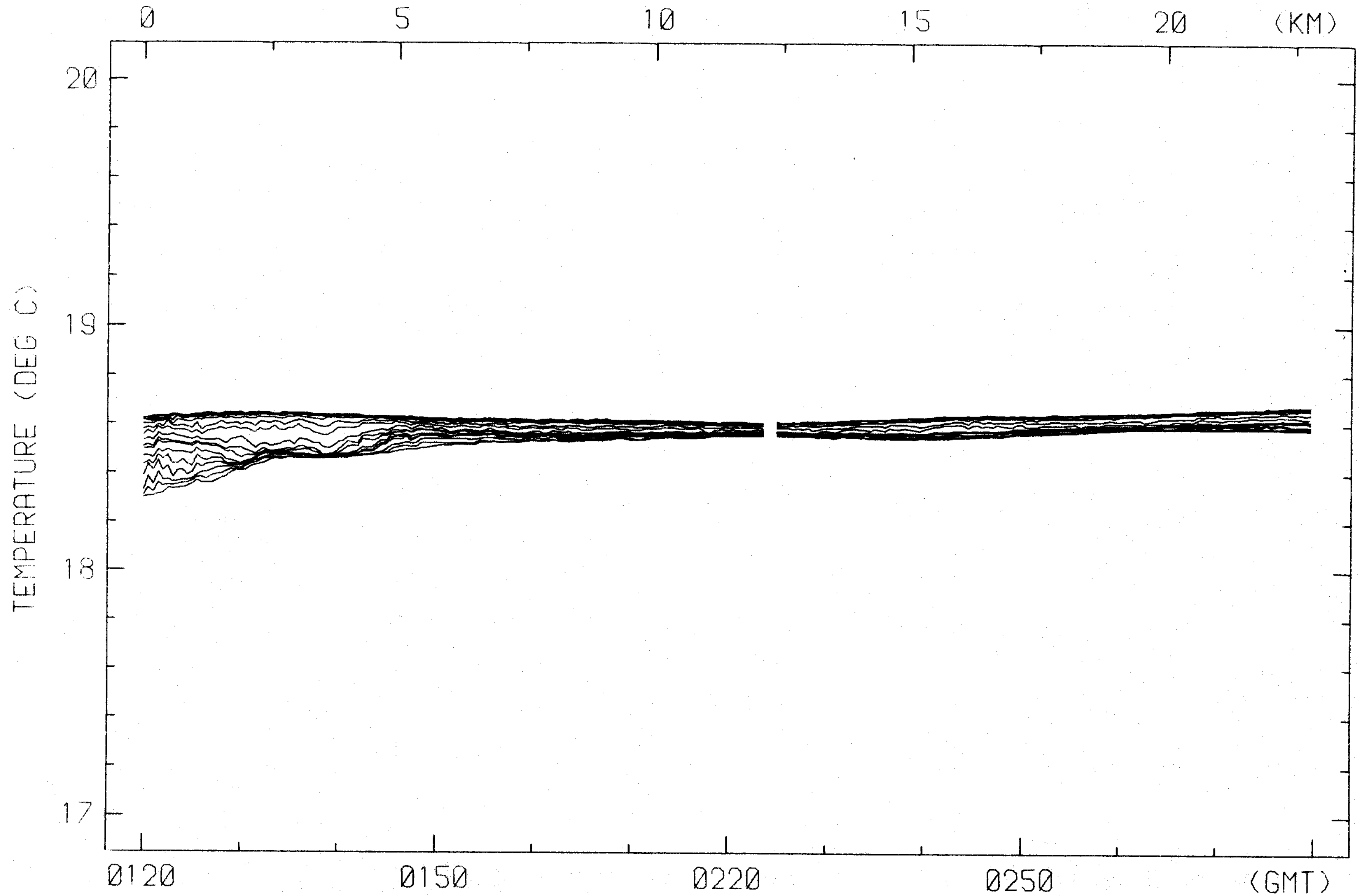
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
153 16.98, 30 45.84 TO 153 26.10, 30 36.18



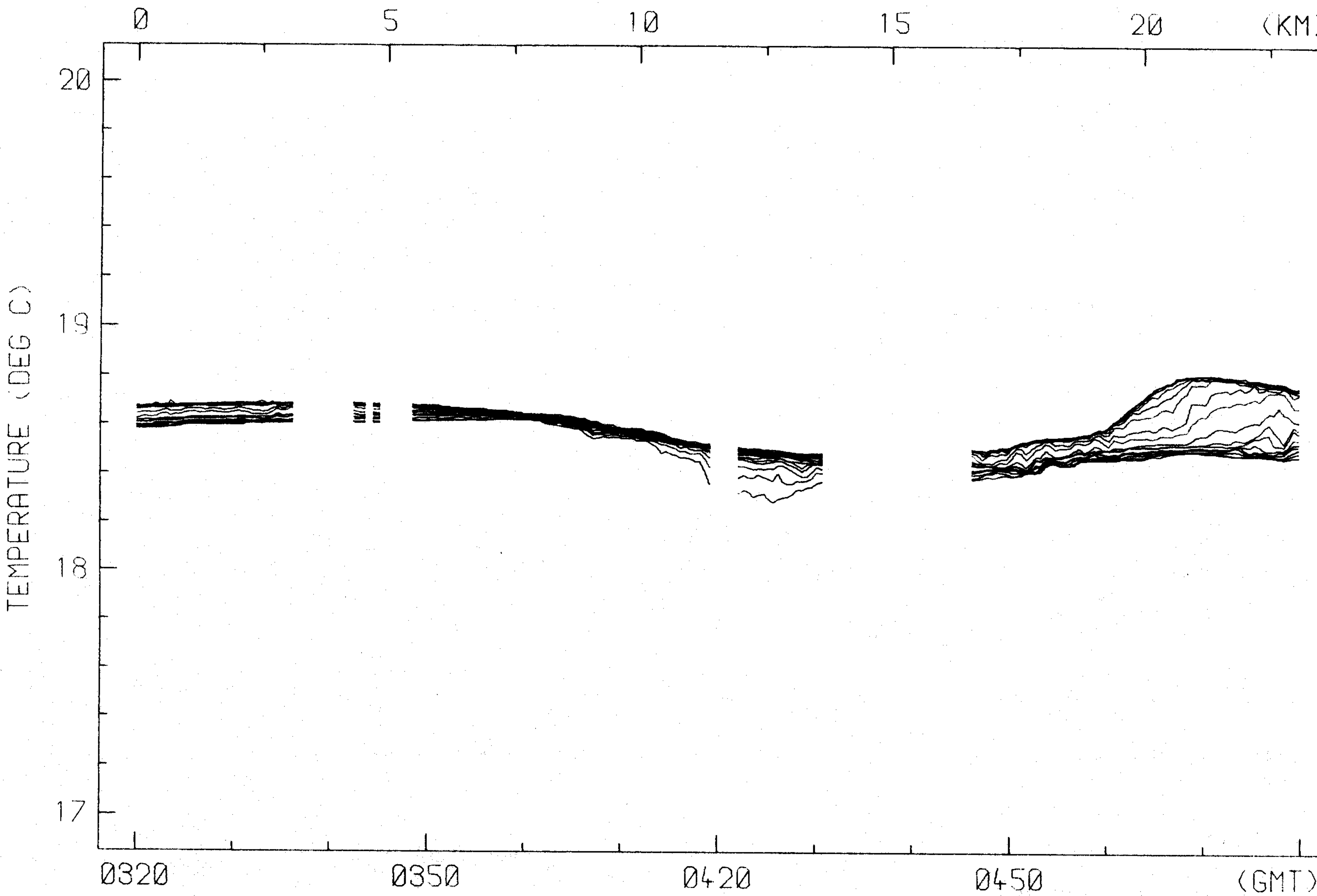
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
153 26.10, 30 36.18 TO 153 34.50, 30 26.16



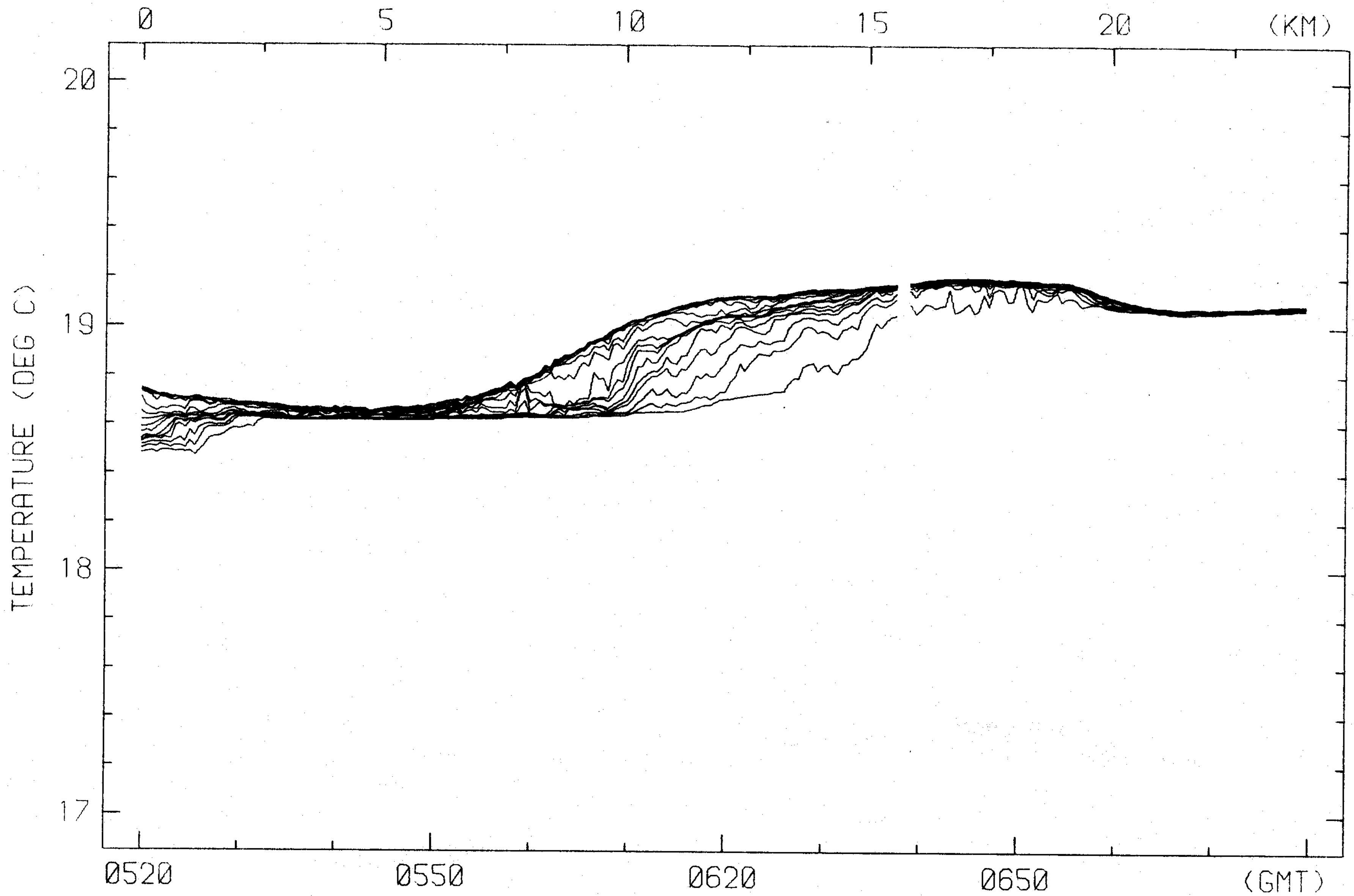
TEMPERATURE VS TIME/DISTANCE 17-JAN-80
153 34.50, 30 26.16 TO 153 42.66, 30 15.78



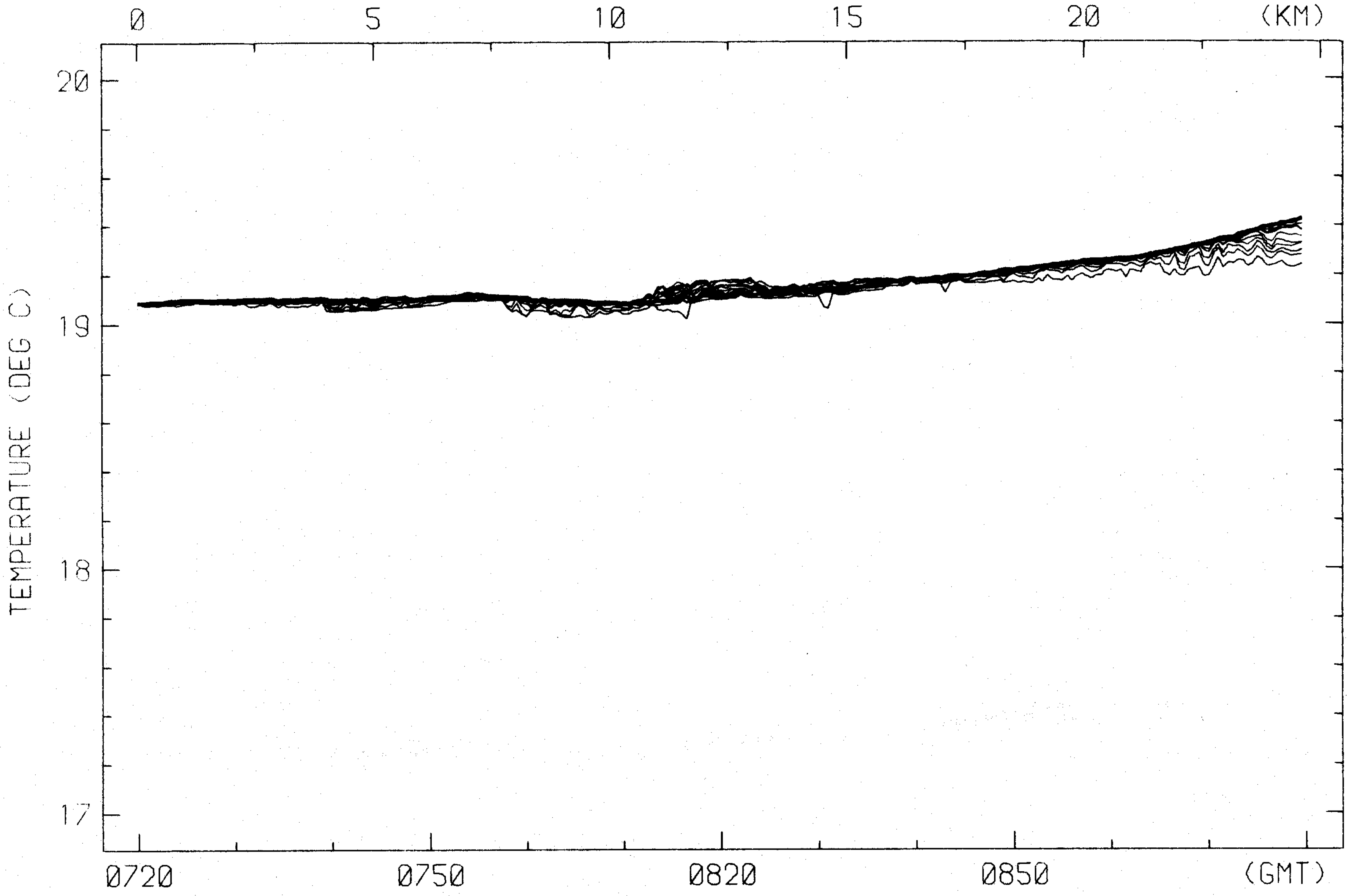
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
153 42.66, 30 15.78 TO 153 51.90, 30 06.30



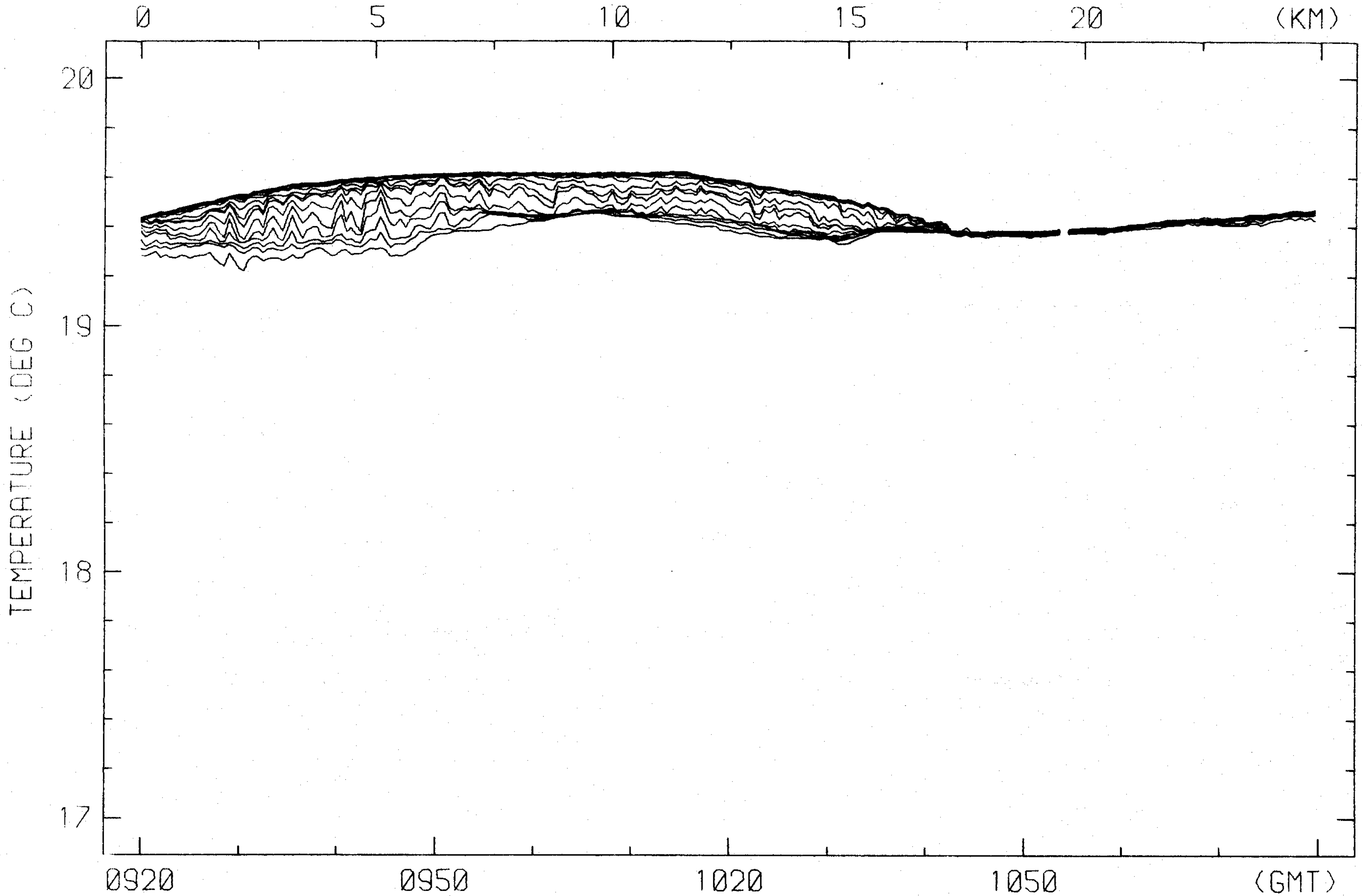
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
153 51.90, 30 06.30 TO 154 01.50, 29 56.94



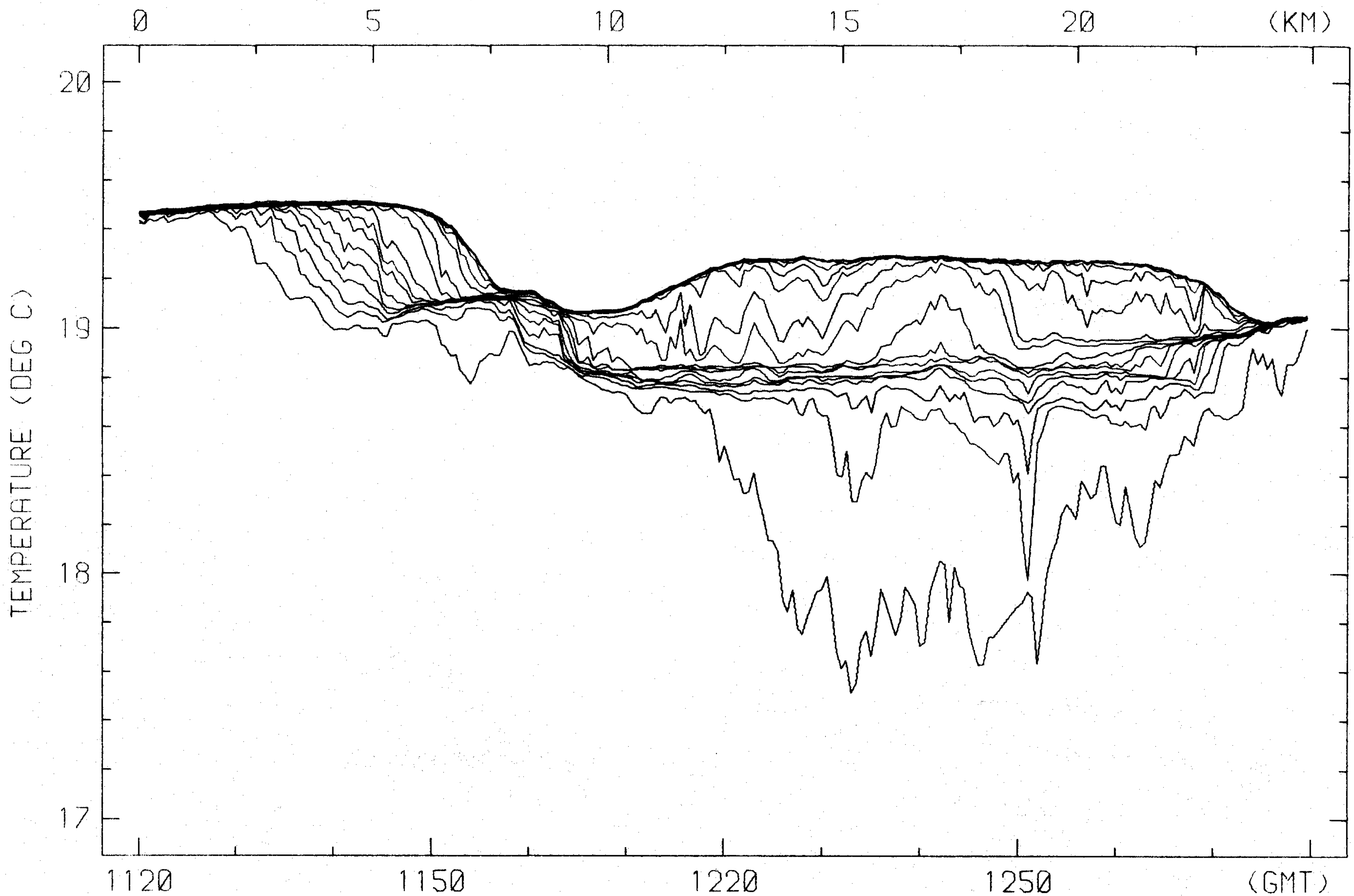
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 01.50, 29 56.94 TO 154 11.70, 29 47.40



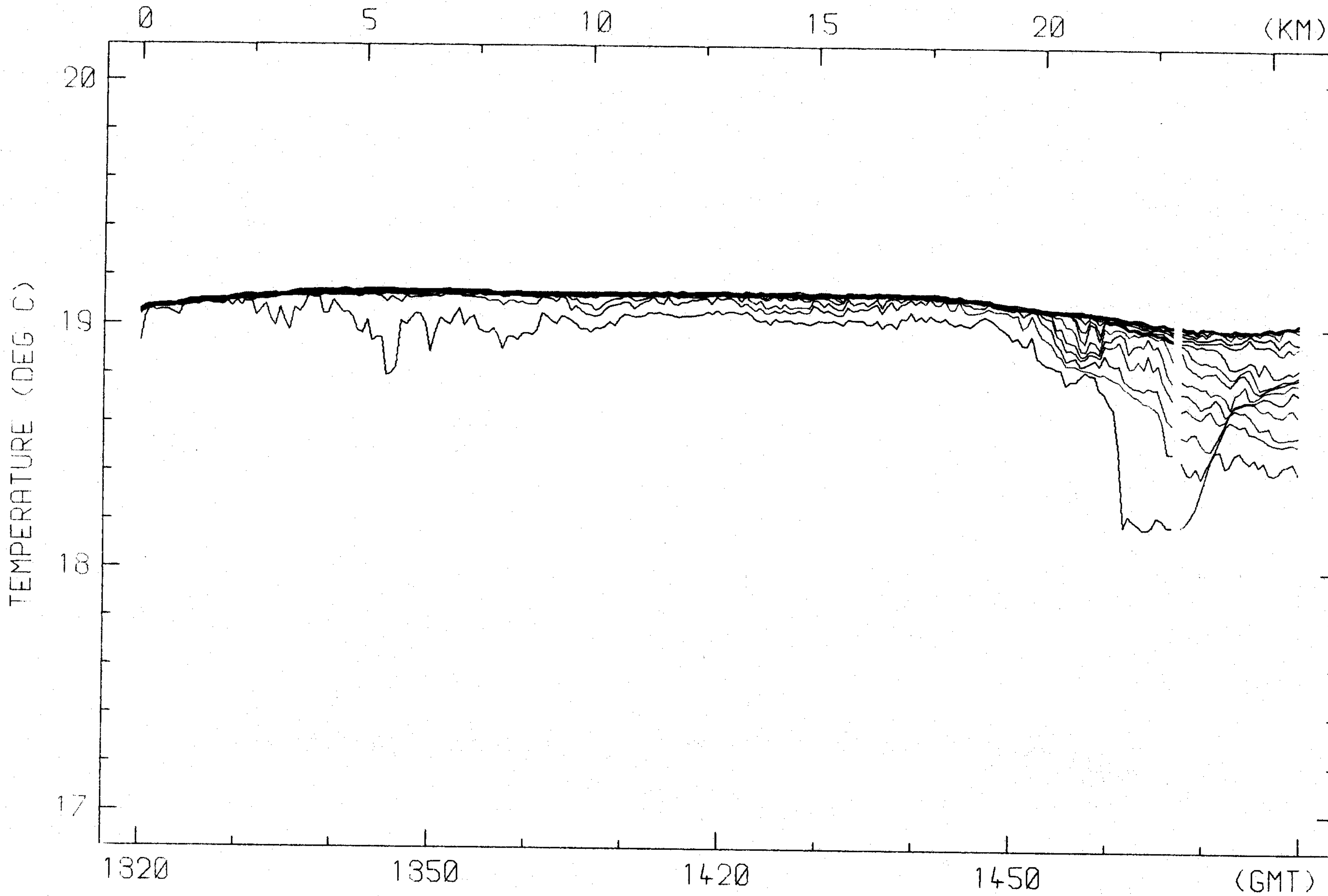
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 11.70, 29 47.40 TO 154 22.26, 29 37.74



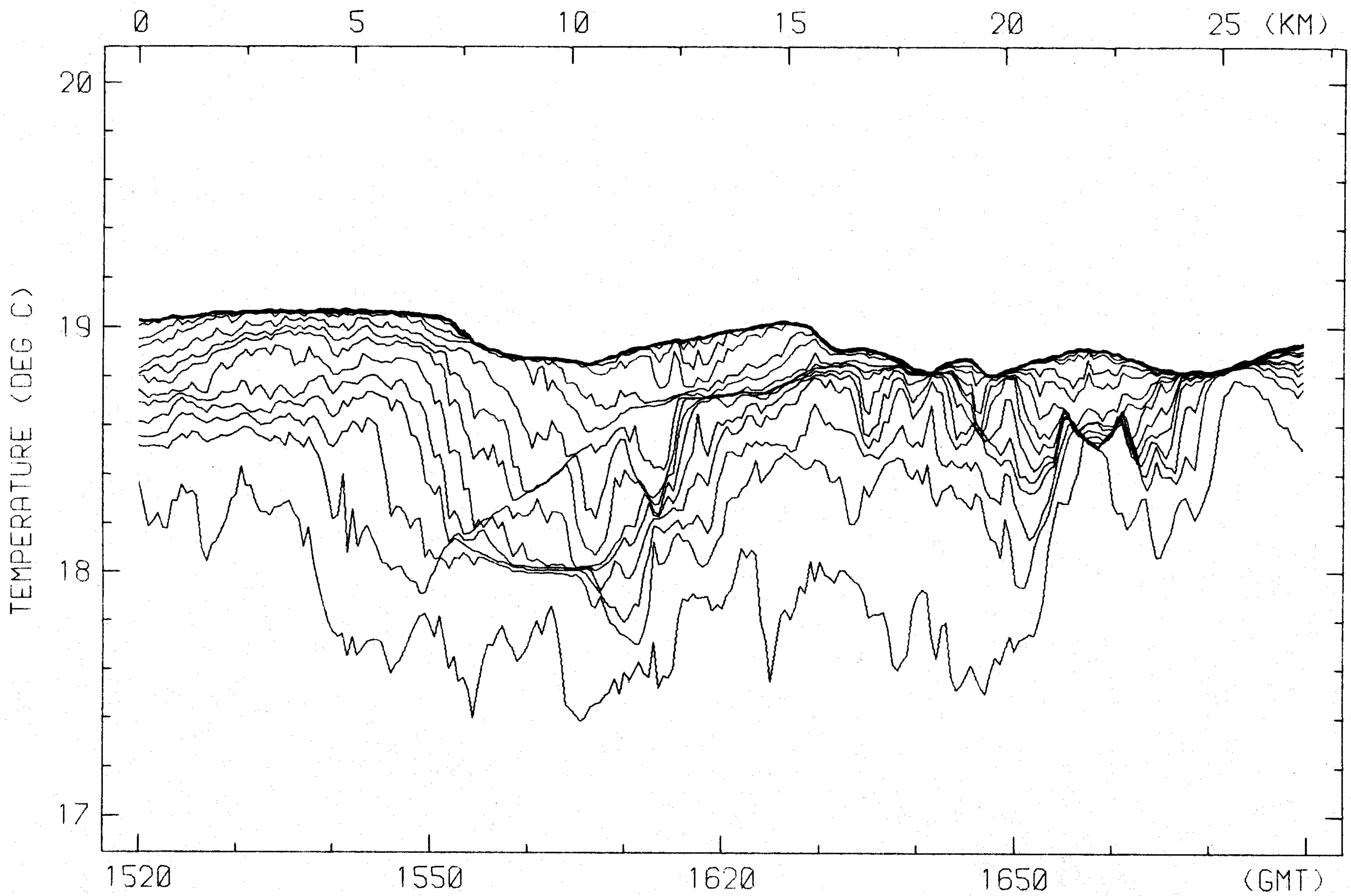
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 22.26, 29 37.74 TO 154 33.18, 29 28.14



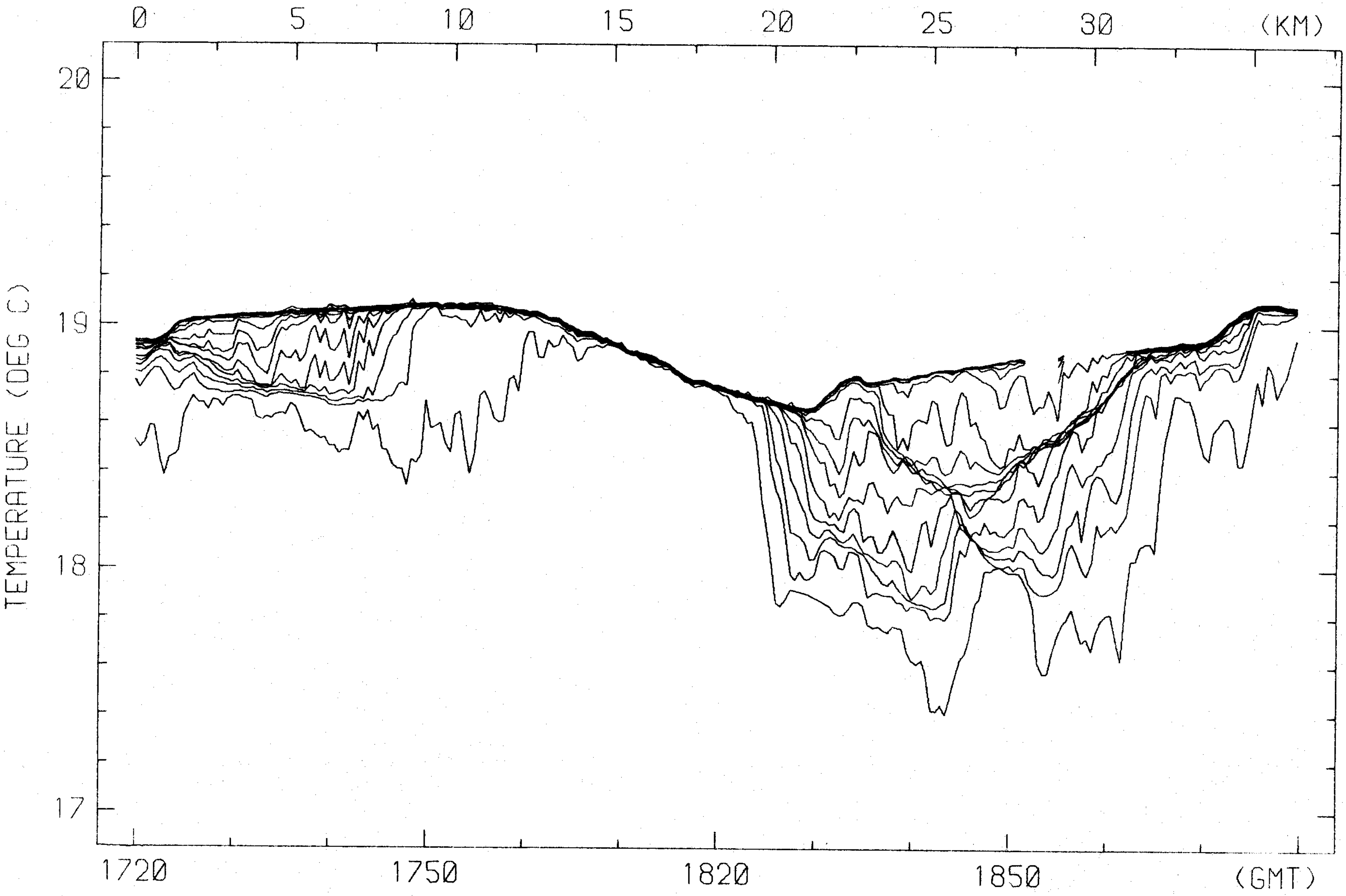
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 33.18, 29 28.14 TO 154 44.16, 29 18.60



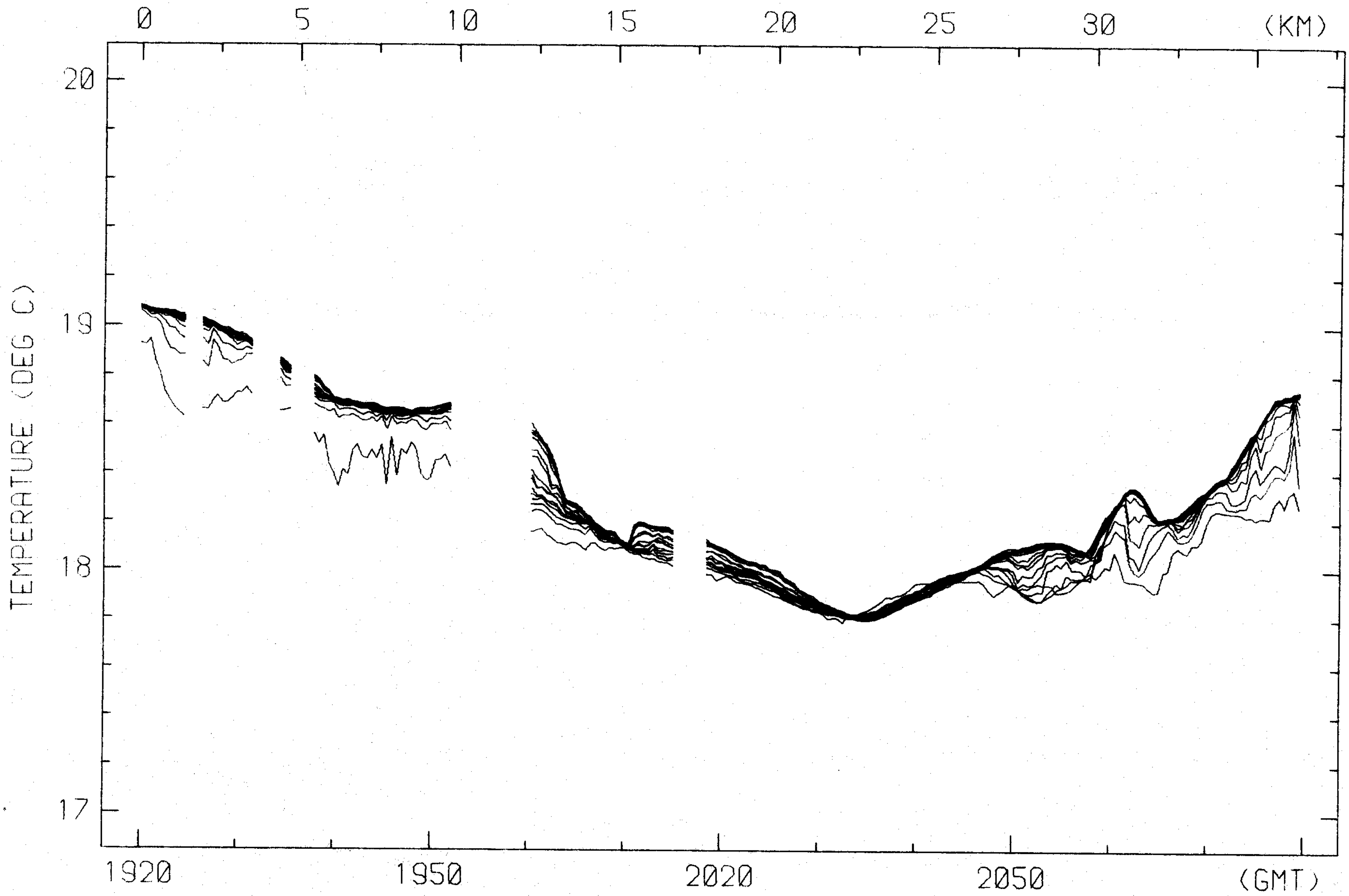
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 44.16, 29 18.60 TO 154 54.54, 29 08.04



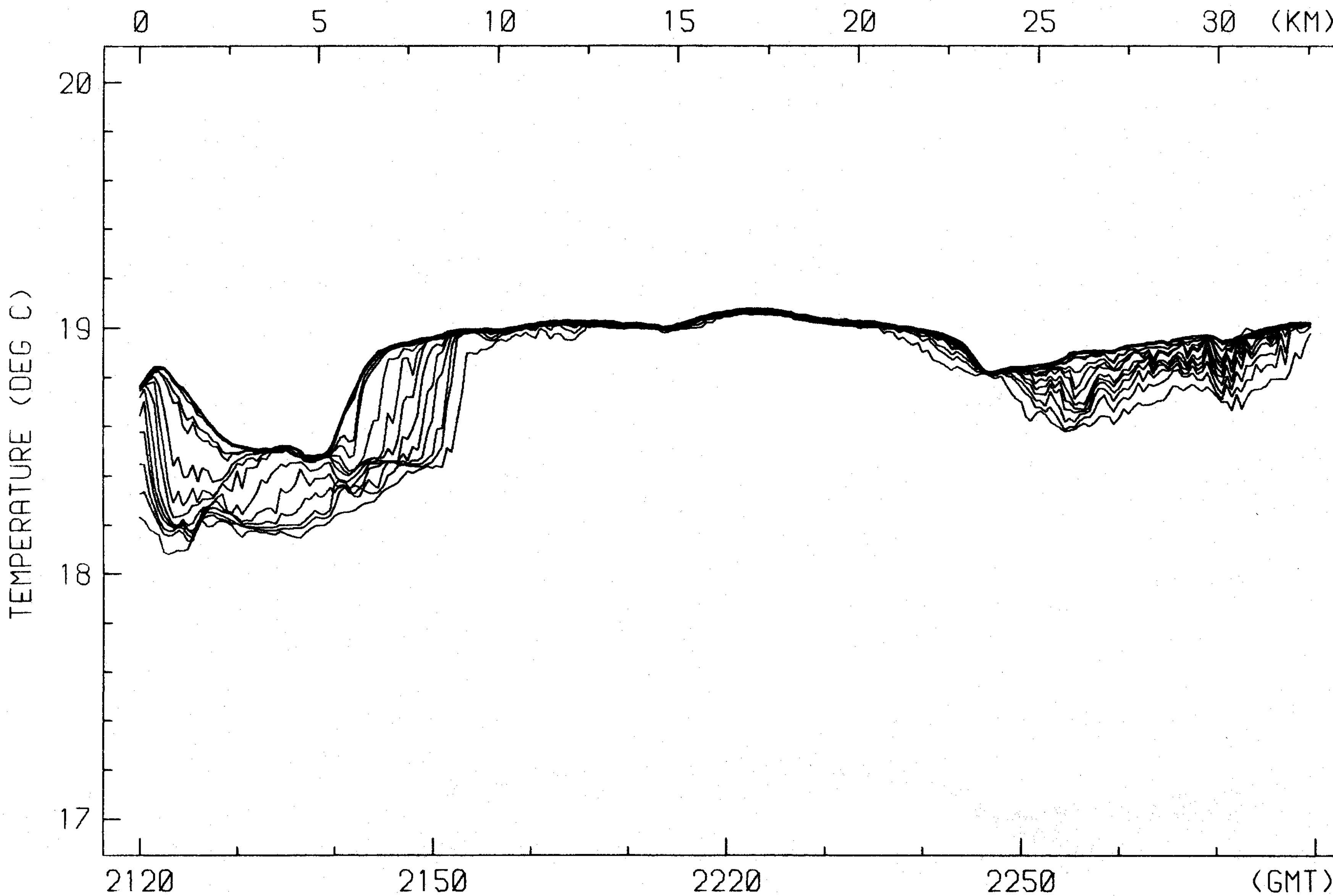
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 54.54, 29 08.04 TO 155 02.82, 29 03.30



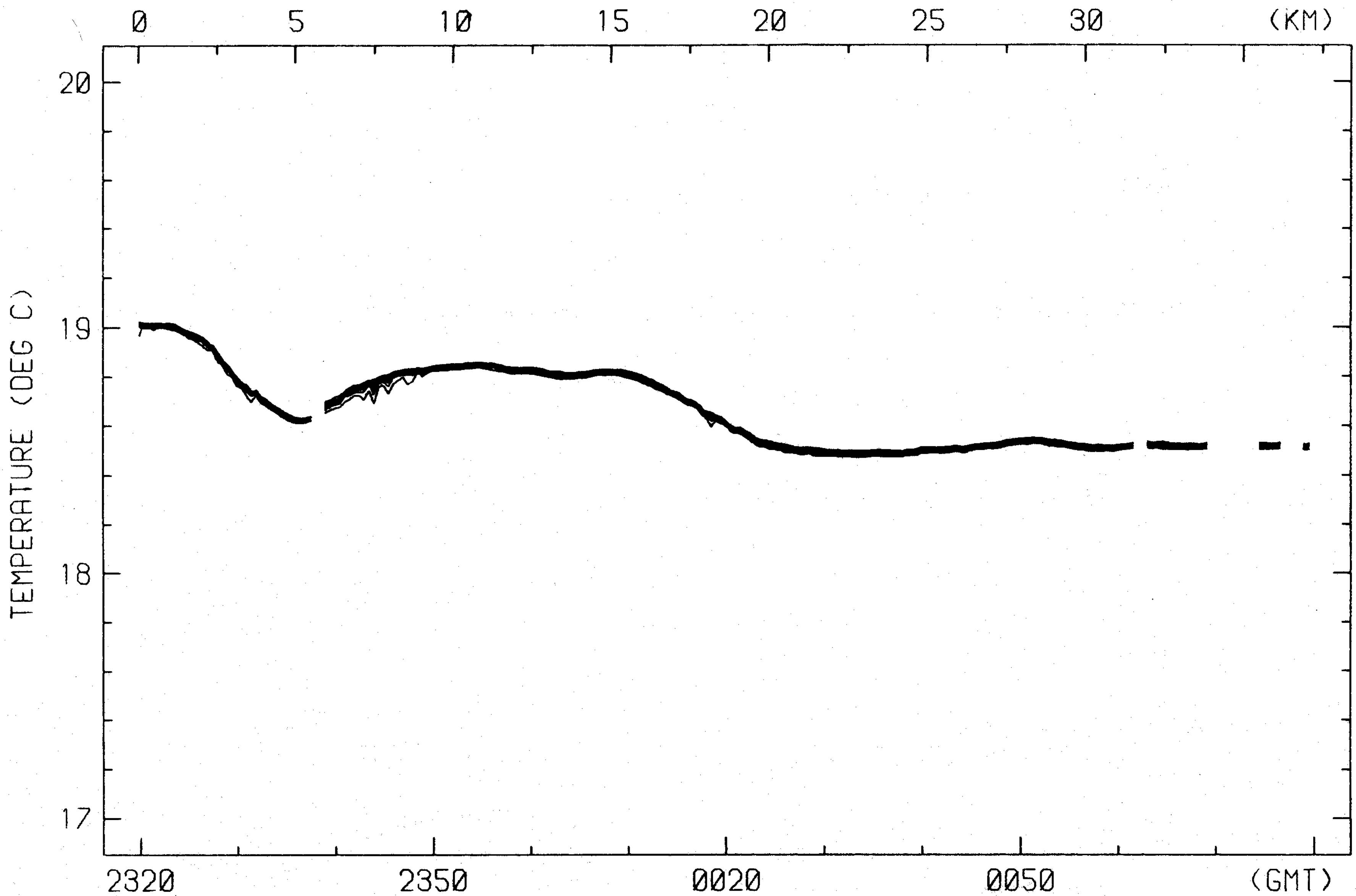
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
155 02.82, 29 03.30 TO 155 01.56, 29 23.04



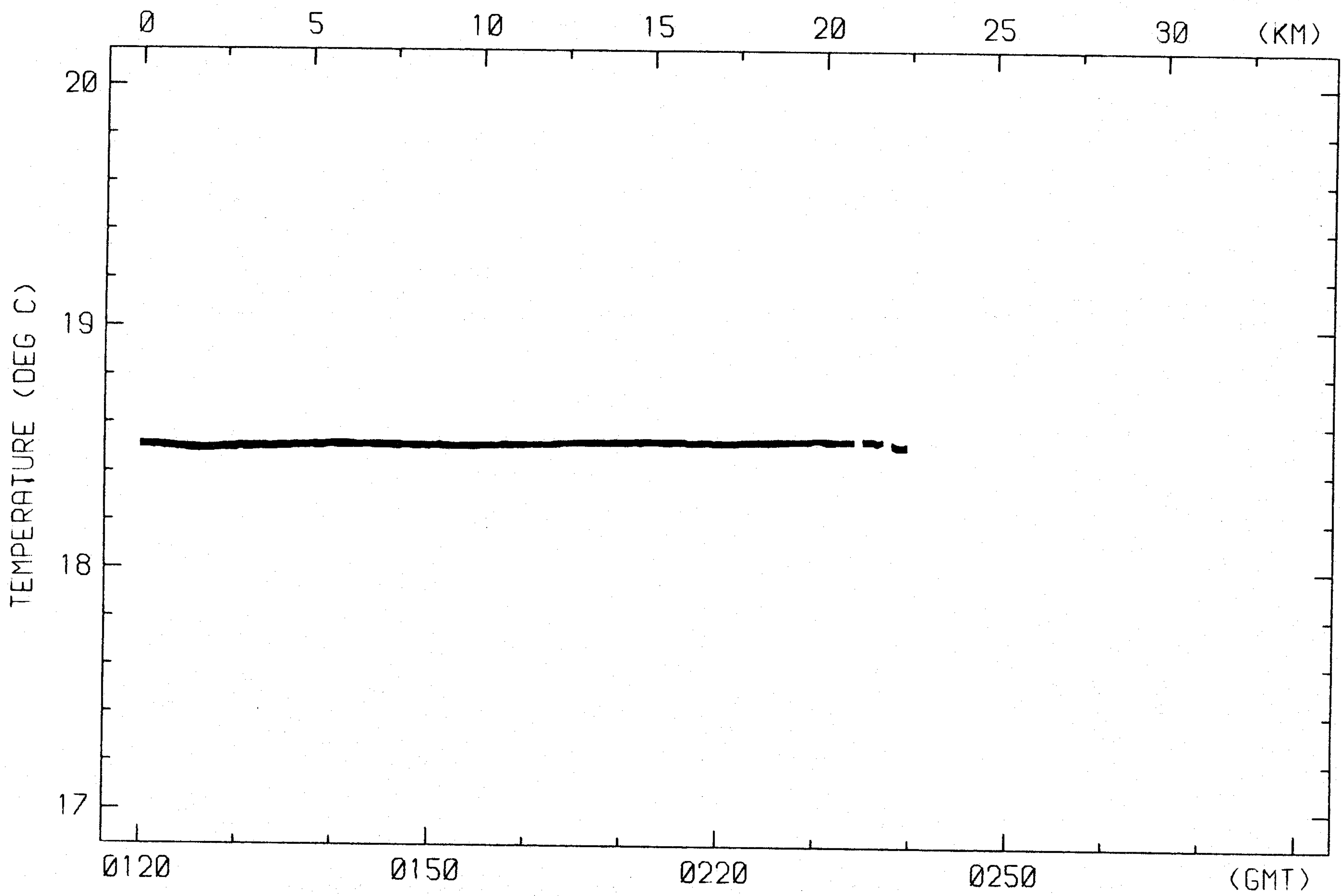
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
155 01.56, 29 23.04 TO 154 59.58, 29 42.78



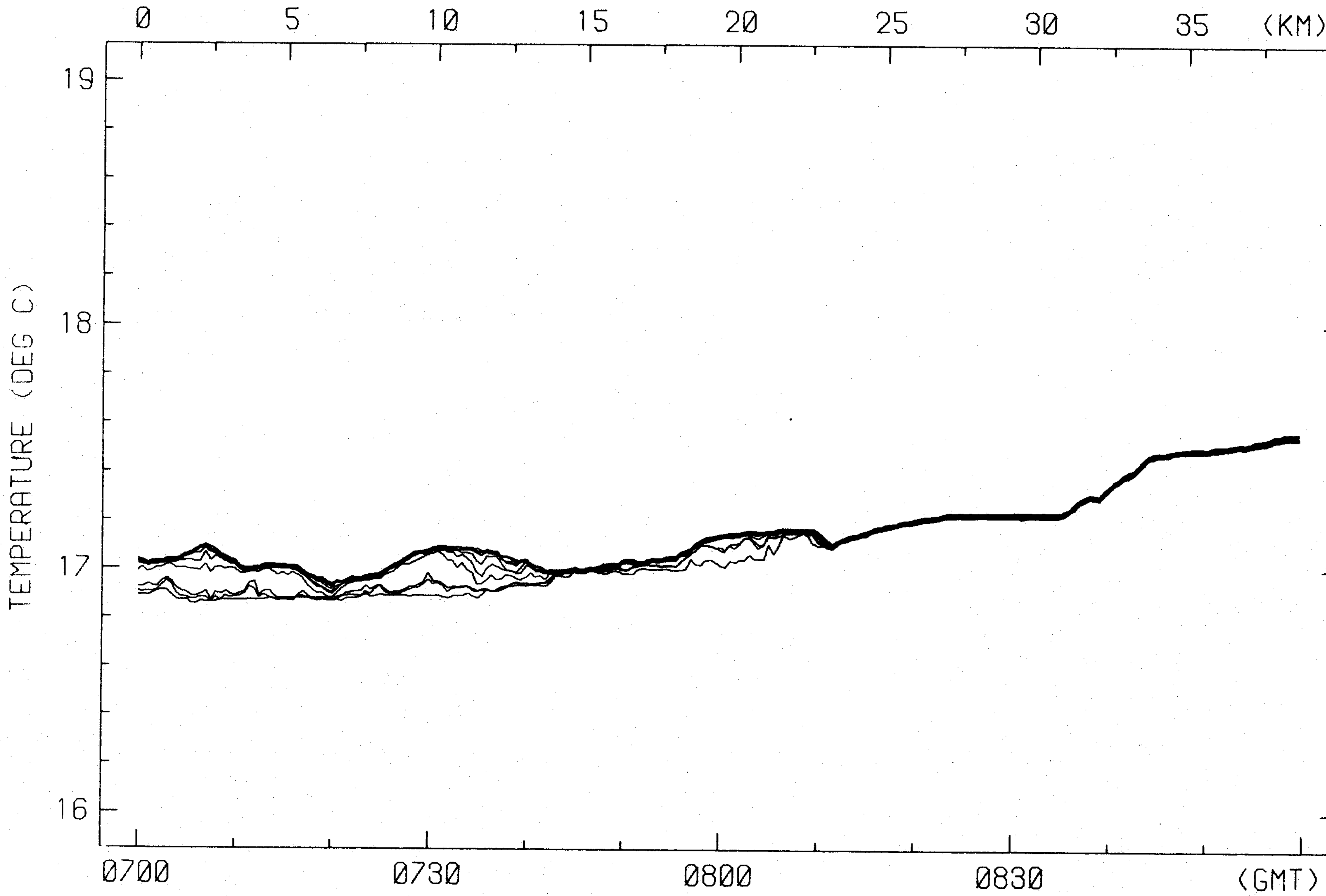
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 59.58, 29 42.78 TO 154 57.66, 30 00.42



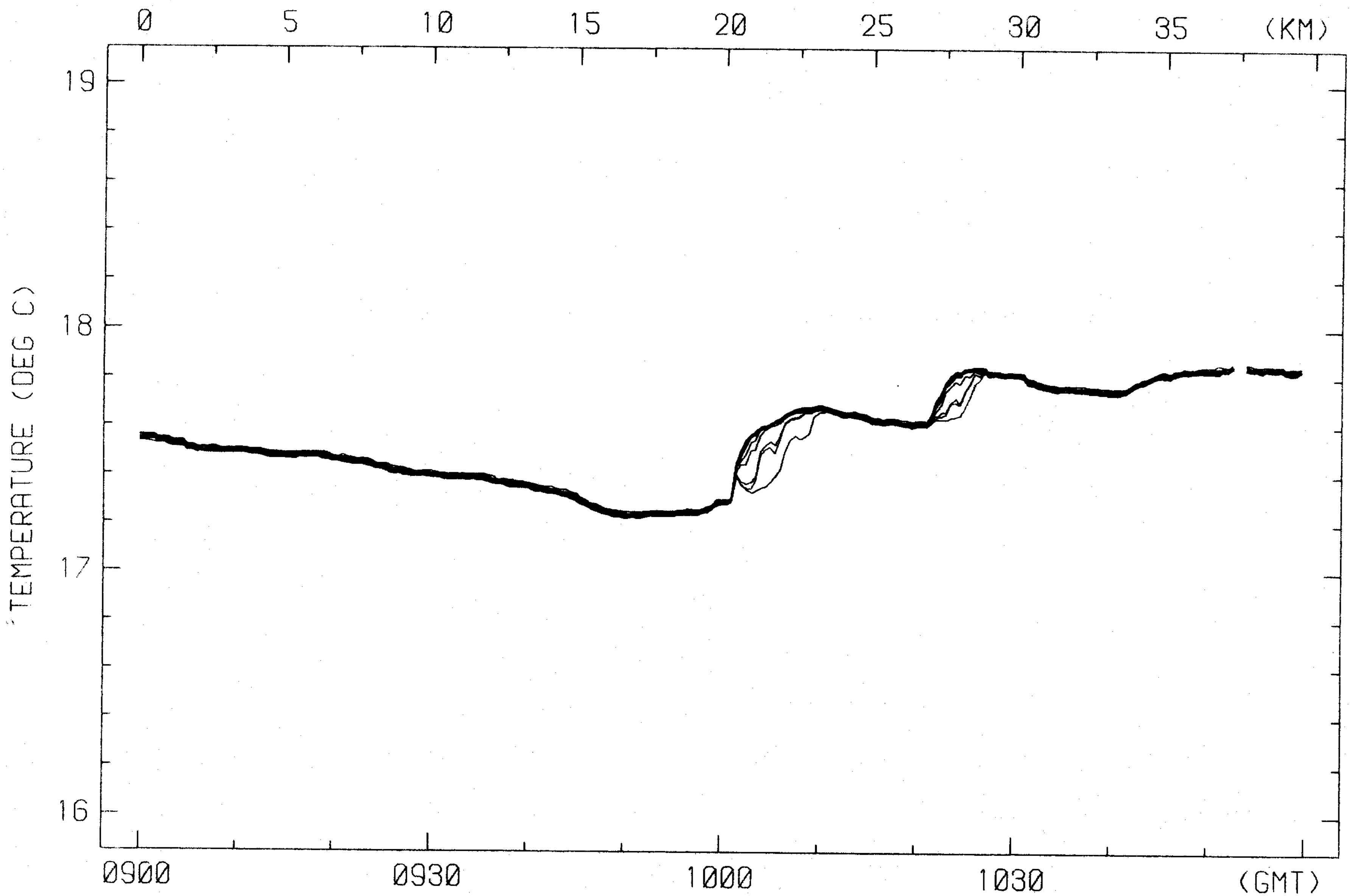
TEMPERATURE VS TIME/DISTANCE 18-JAN-80
154 57.66, 30 00.42 TO 154 38.82, 30 17.22



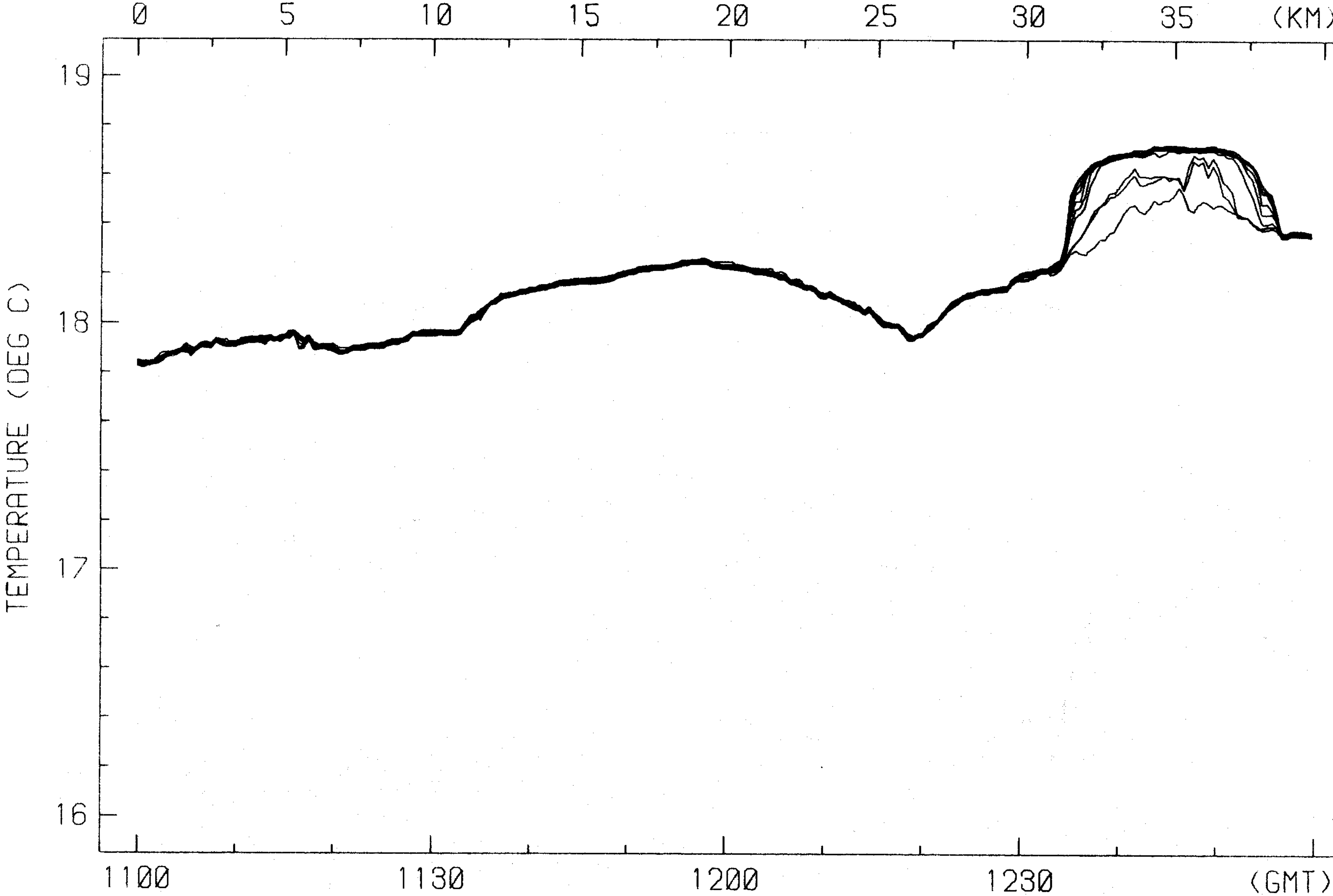
TEMPERATURE VS TIME/DISTANCE 19-JAN-80
154 38.82, 30 17.22 TO 154 34.32, 30 28.44



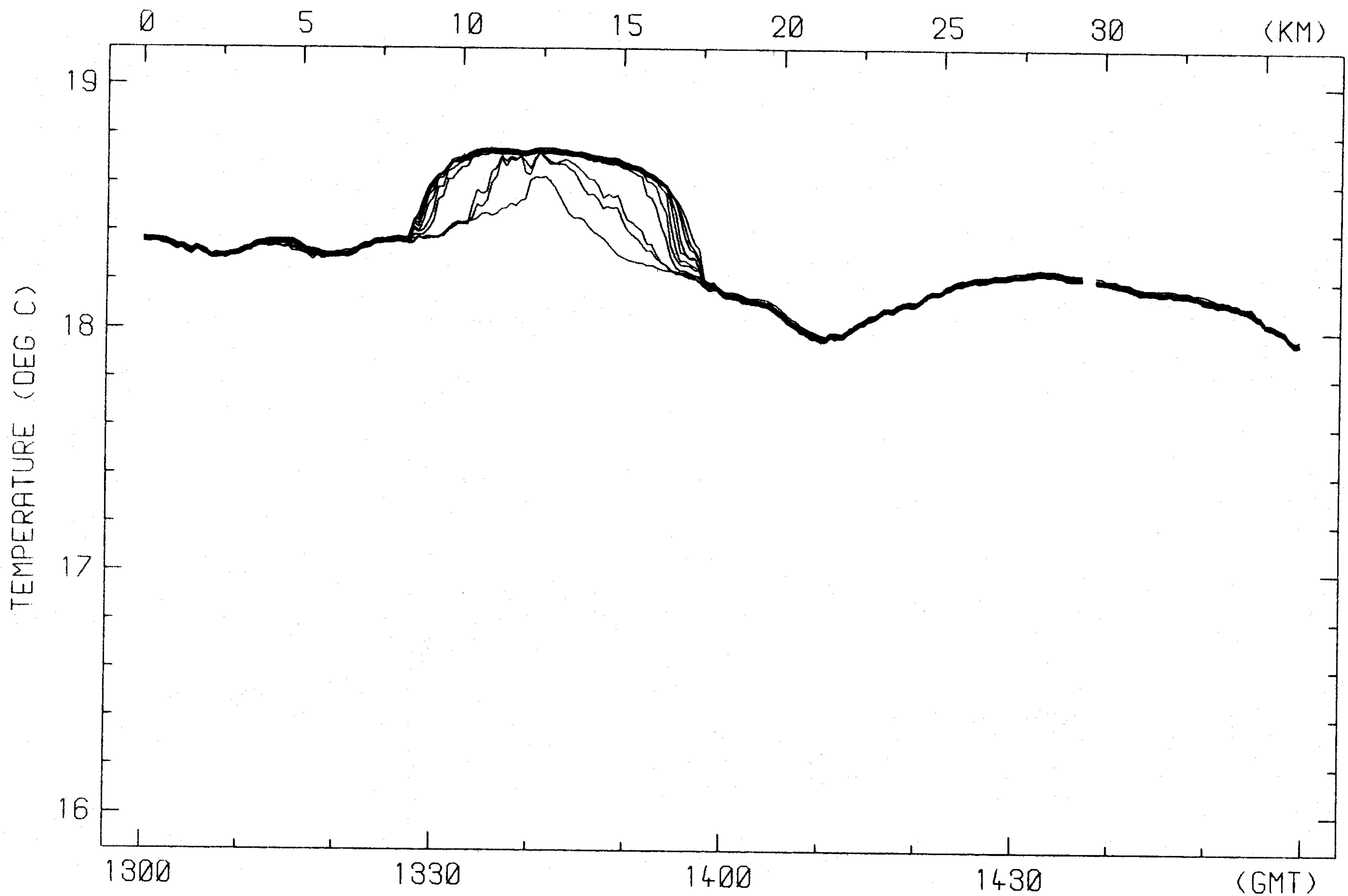
TEMPERATURE VS TIME/DISTANCE 25-JAN-80
153 12.42, 30 33.66 TO 153 33.60, 30 27.18



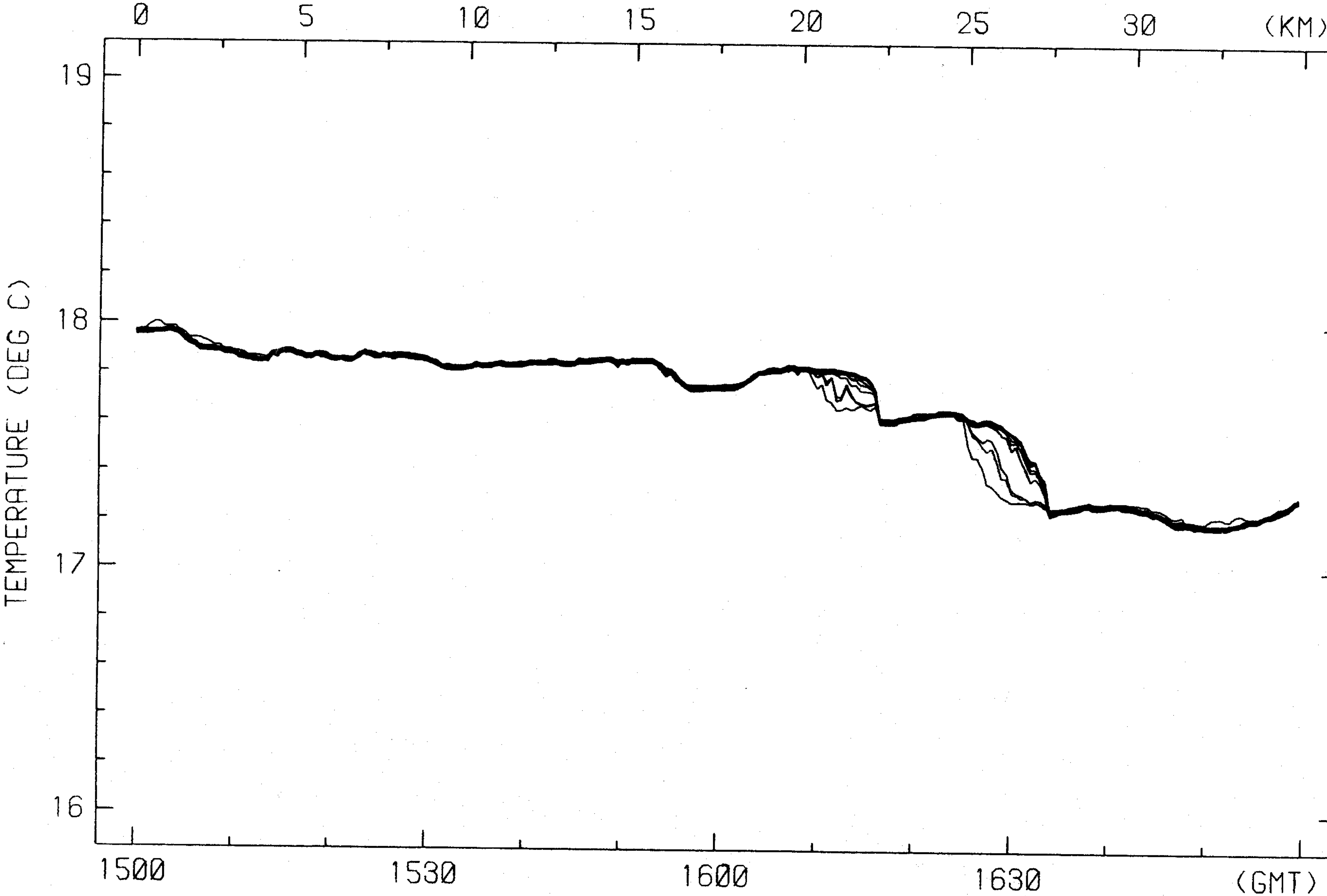
TEMPERATURE VS TIME/DISTANCE 25-JAN-80
153 33.60, 30 27.18 TO 153 48.48, 30 09.96



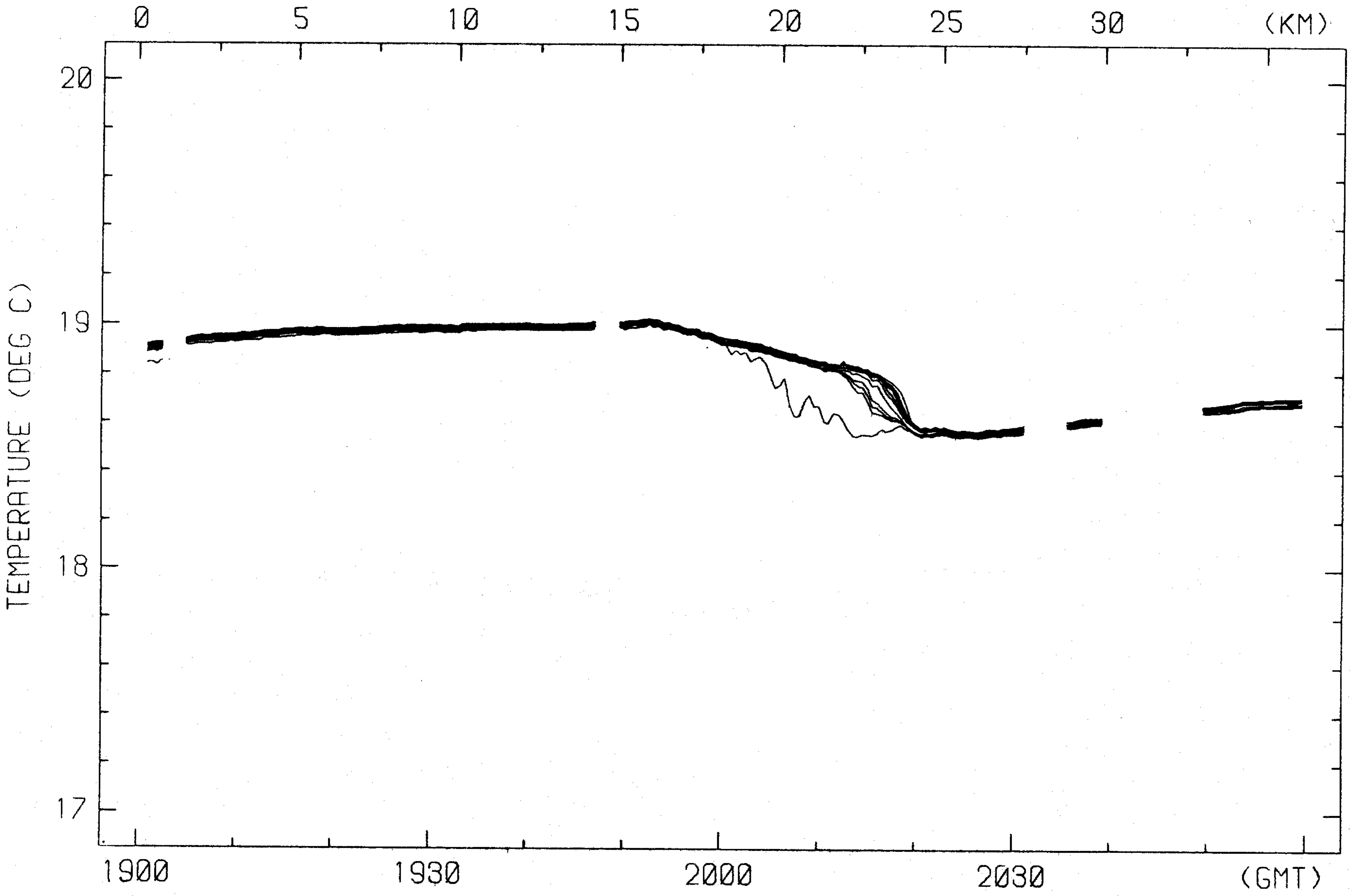
TEMPERATURE VS TIME/DISTANCE 25-JAN-80
153 48.48, 30 09.96 TO 154 04.80, 29 53.76



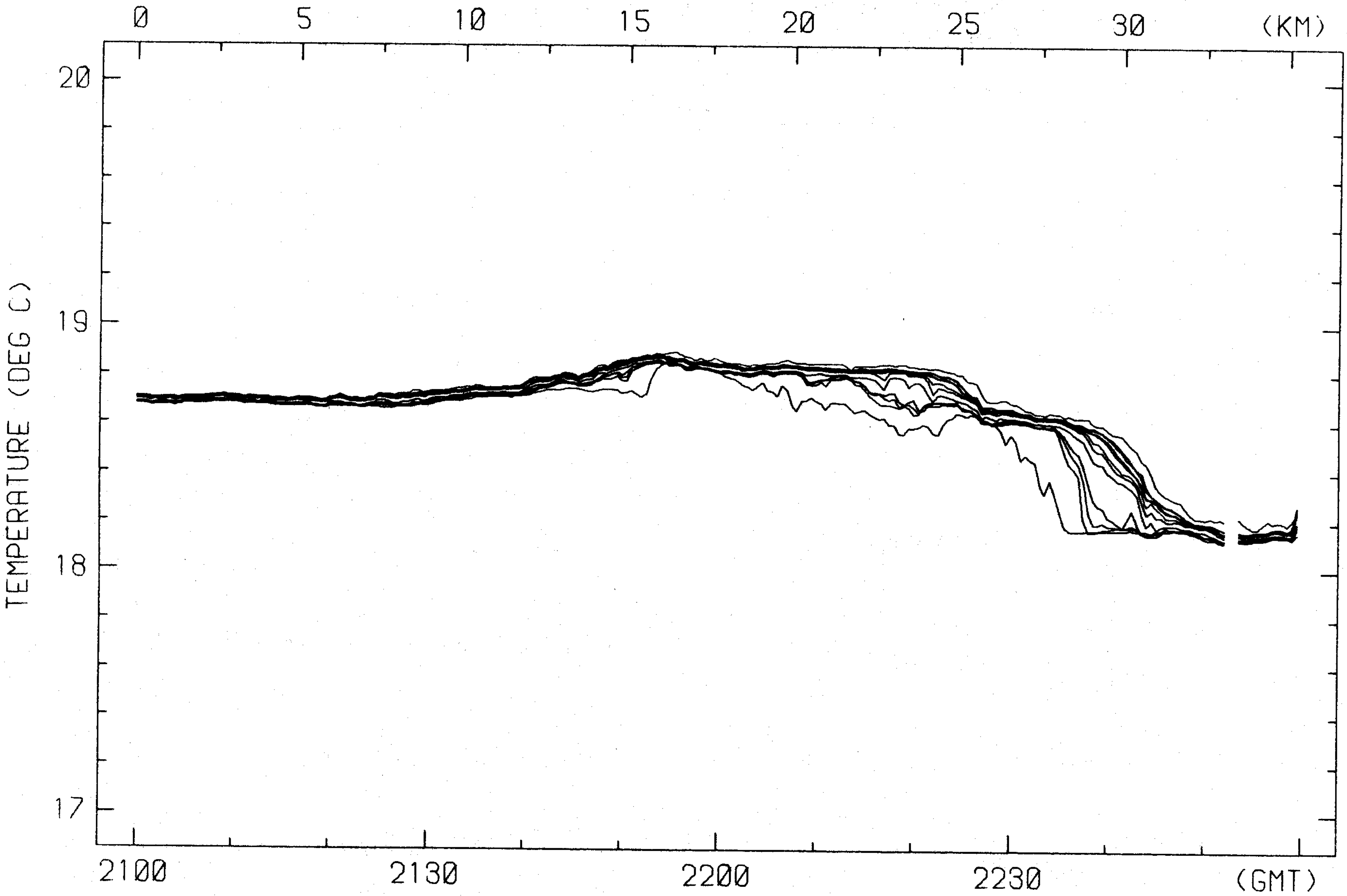
TEMPERATURE VS TIME/DISTANCE 25-JAN-80
154 04.80, 29 53.76 TO 153 52.86, 30 05.16



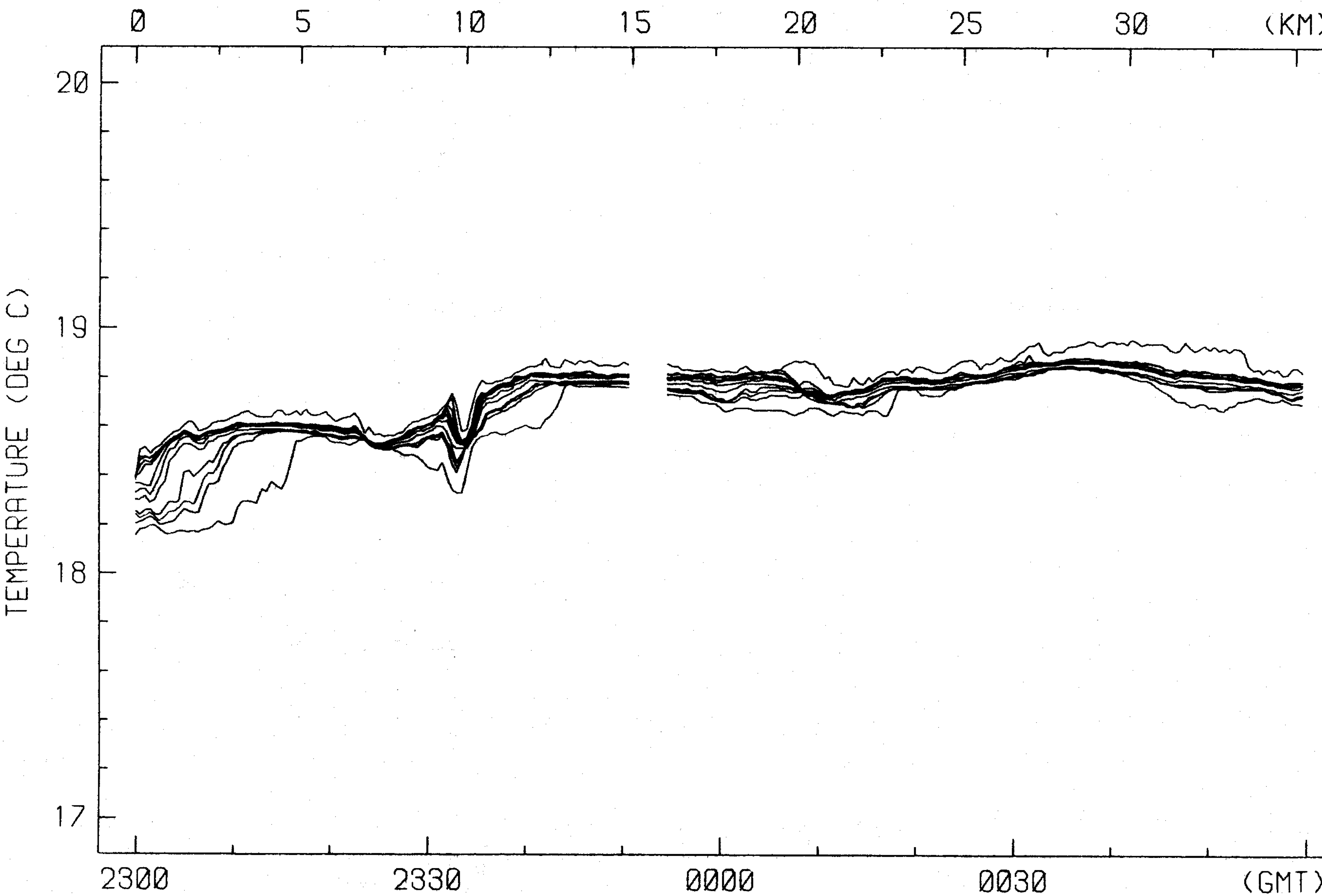
TEMPERATURE VS TIME/DISTANCE 25-JAN-80
153 52.86, 30 05.16 TO 153 38.04, 30 19.08



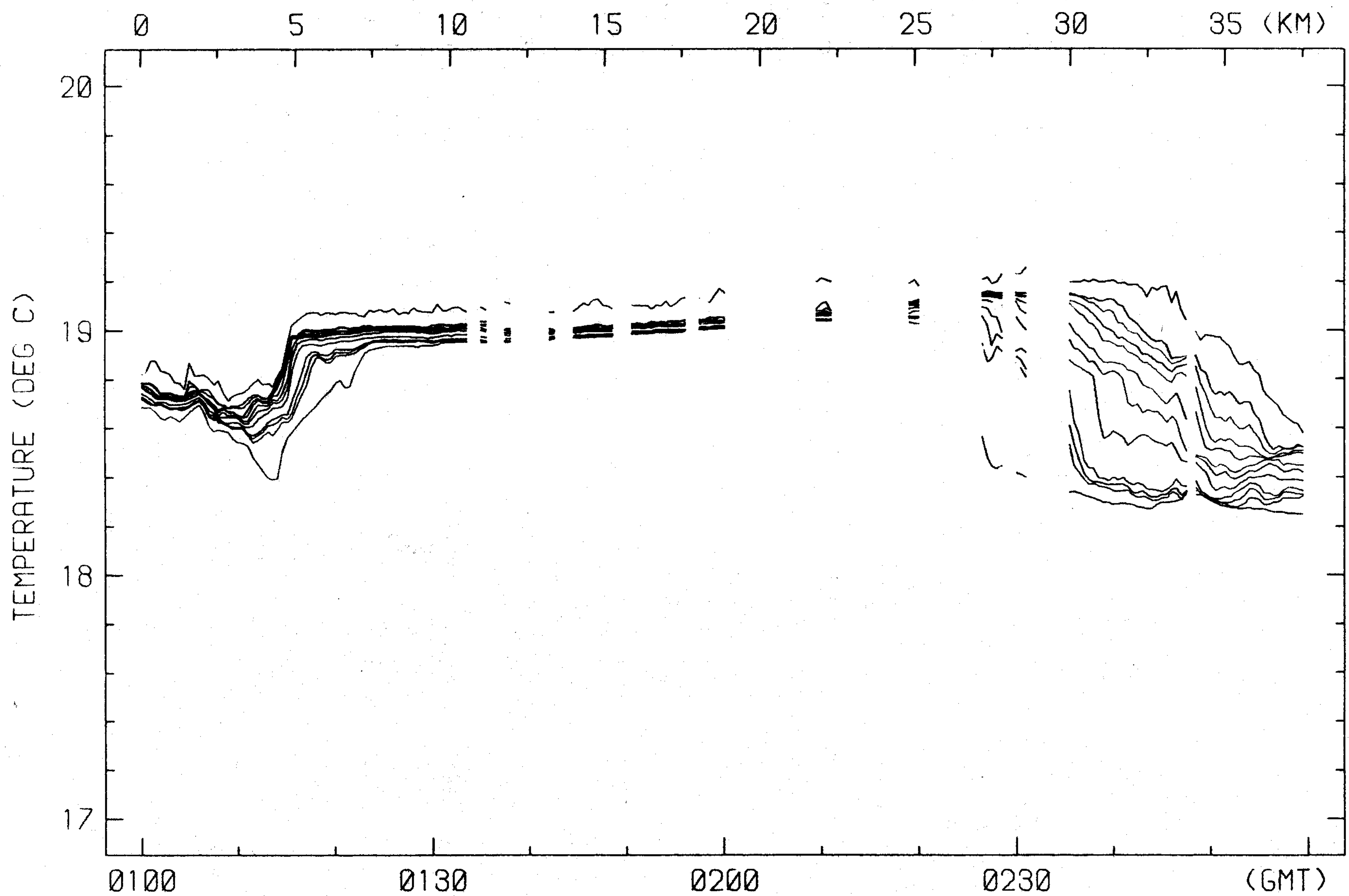
TEMPERATURE VS TIME/DISTANCE 27-JAN-80
154 23.52, 29 37.62 TO 154 33.72, 29 20.34



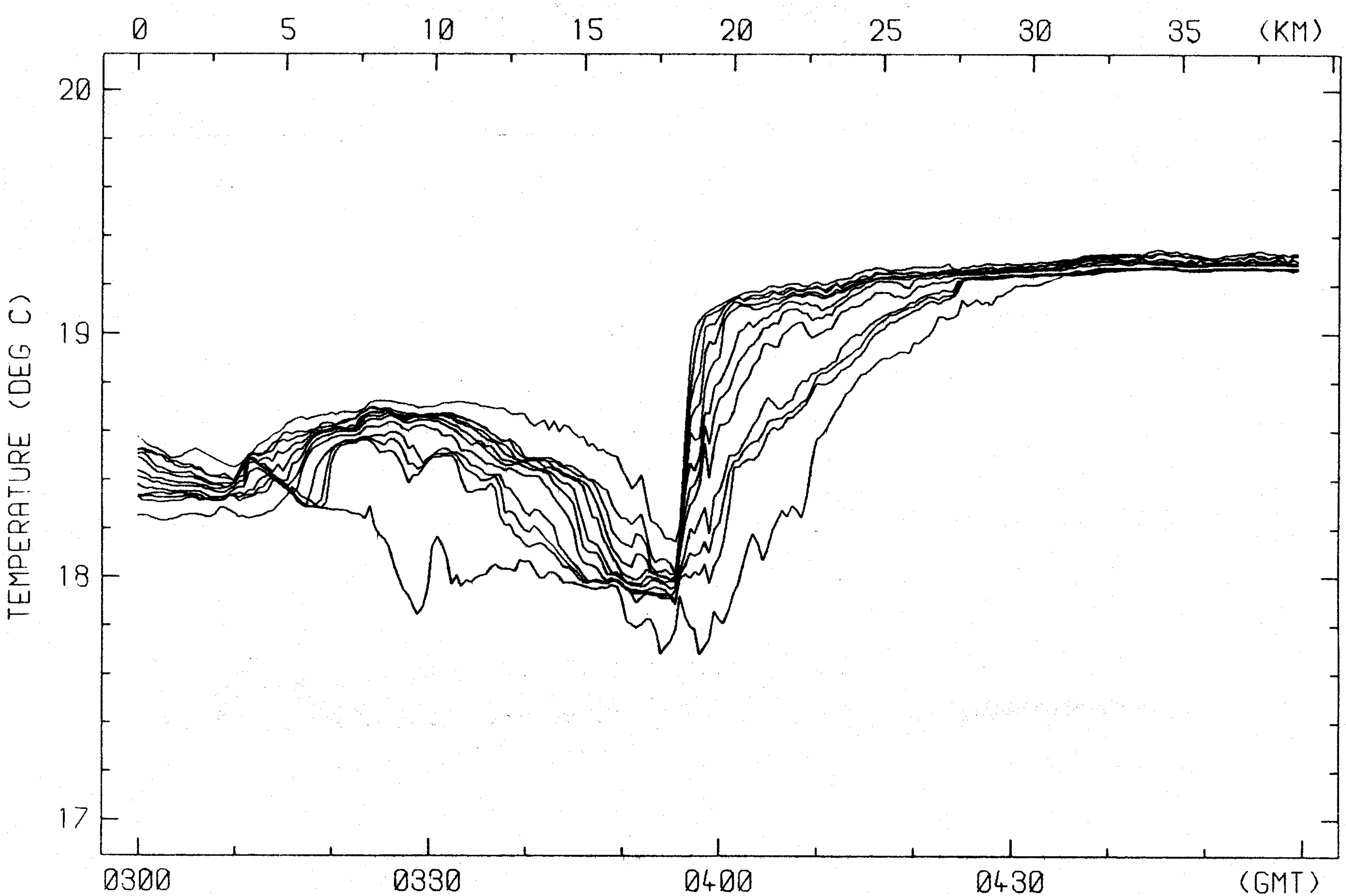
TEMPERATURE VS TIME/DISTANCE 27-JAN-80
154 33.72, 29 20.34 TO 154 41.28, 29 02.34



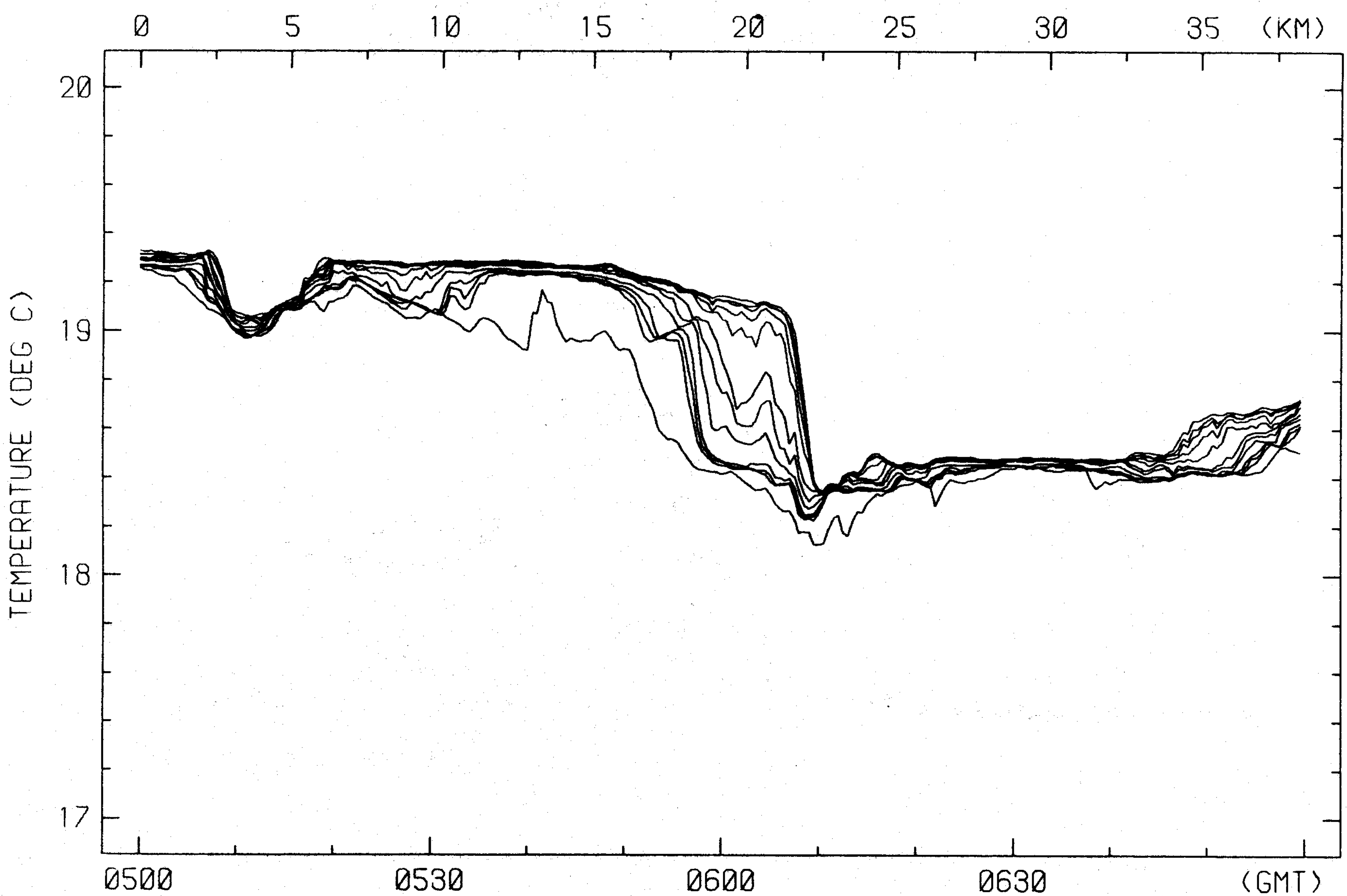
TEMPERATURE VS TIME/DISTANCE 27-JAN-80
154 41.28, 29 02.34 TO 154 48.06, 28 44.16



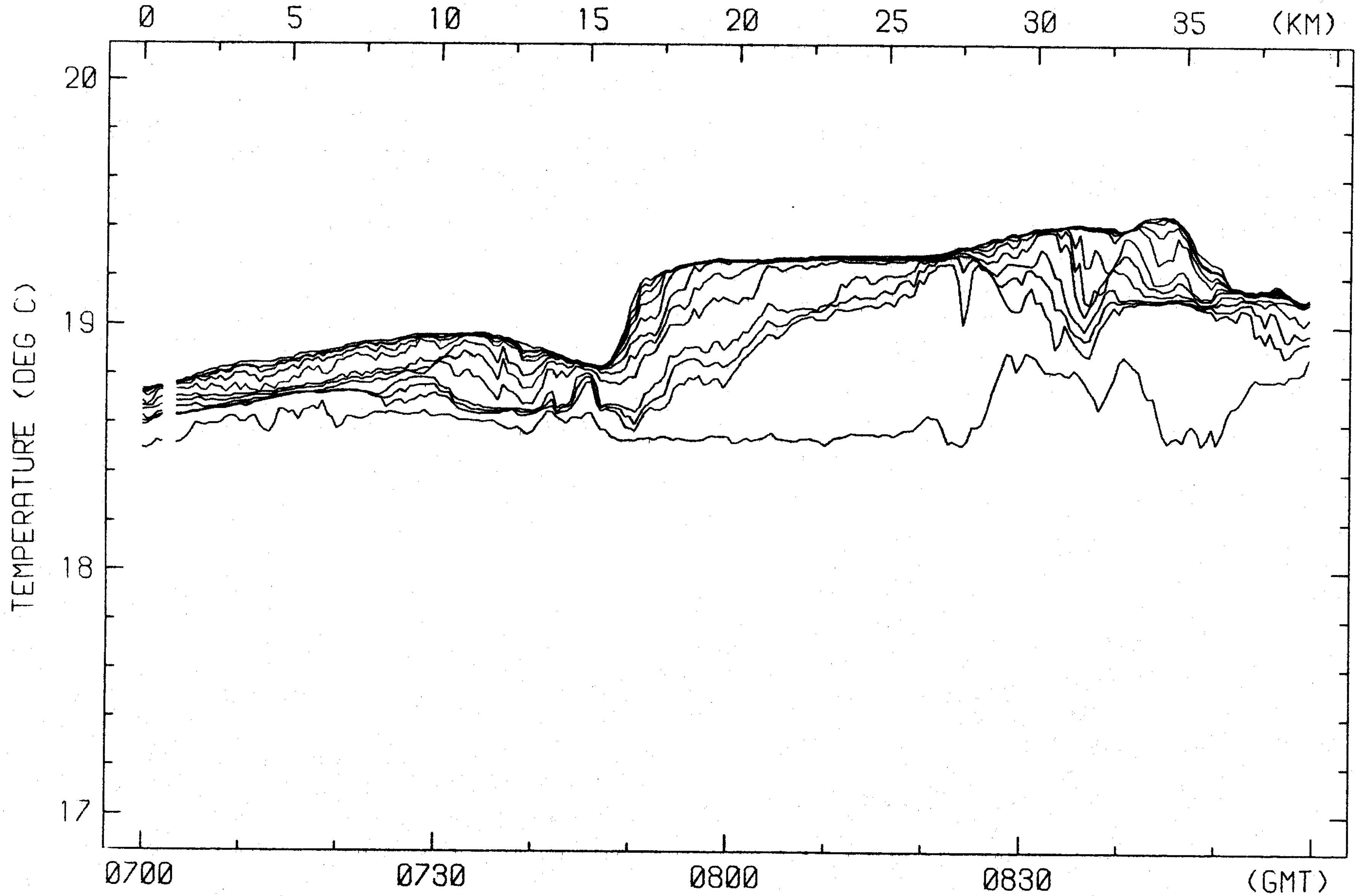
TEMPERATURE VS TIME/DISTANCE 28-JAN-80
154 48.06, 28 44.16 TO 154 55.44, 28 24.84



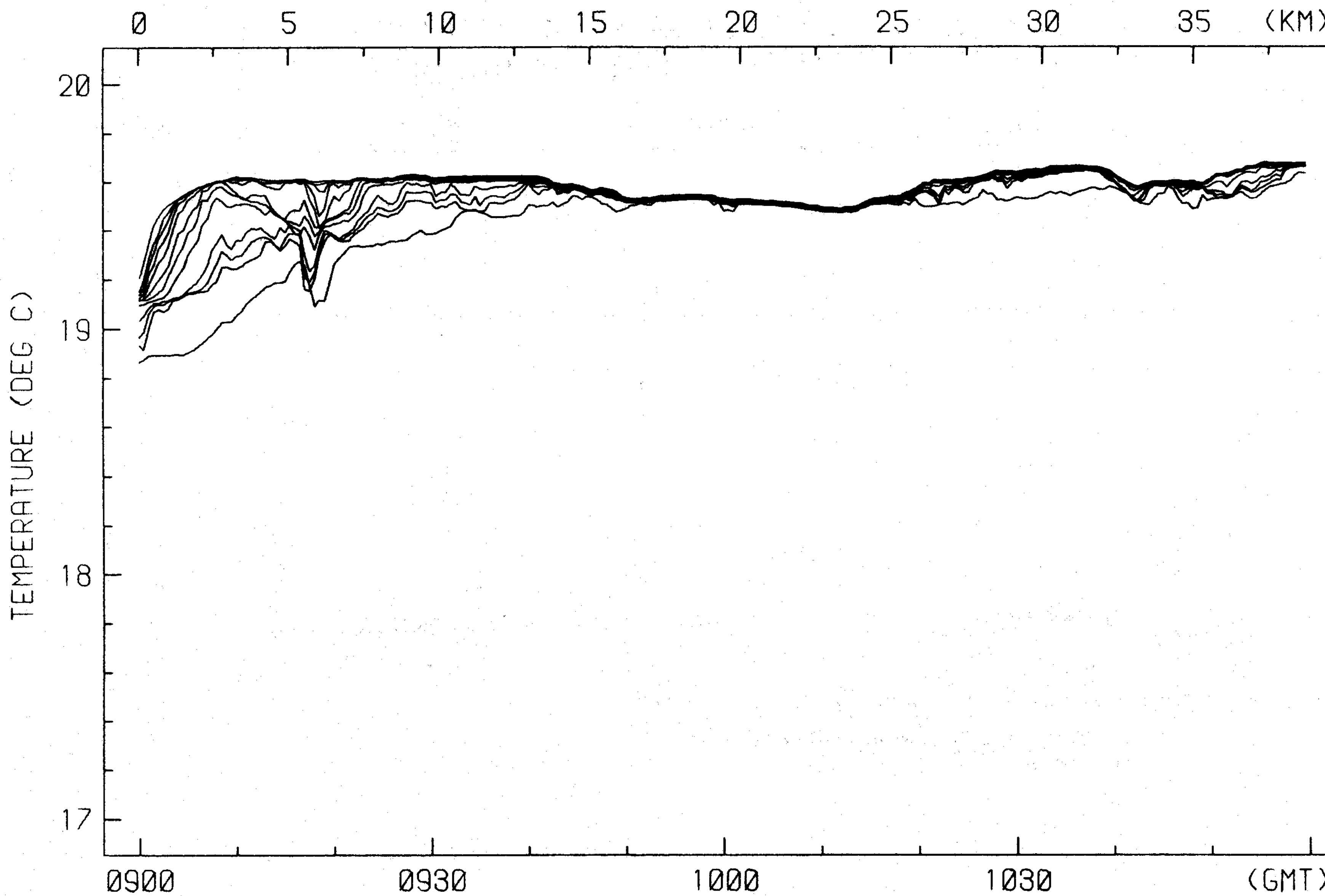
TEMPERATURE VS TIME/DISTANCE 28-JAN-80
154 55.44, 28 24.84 TO 155 02.46, 28 04.68



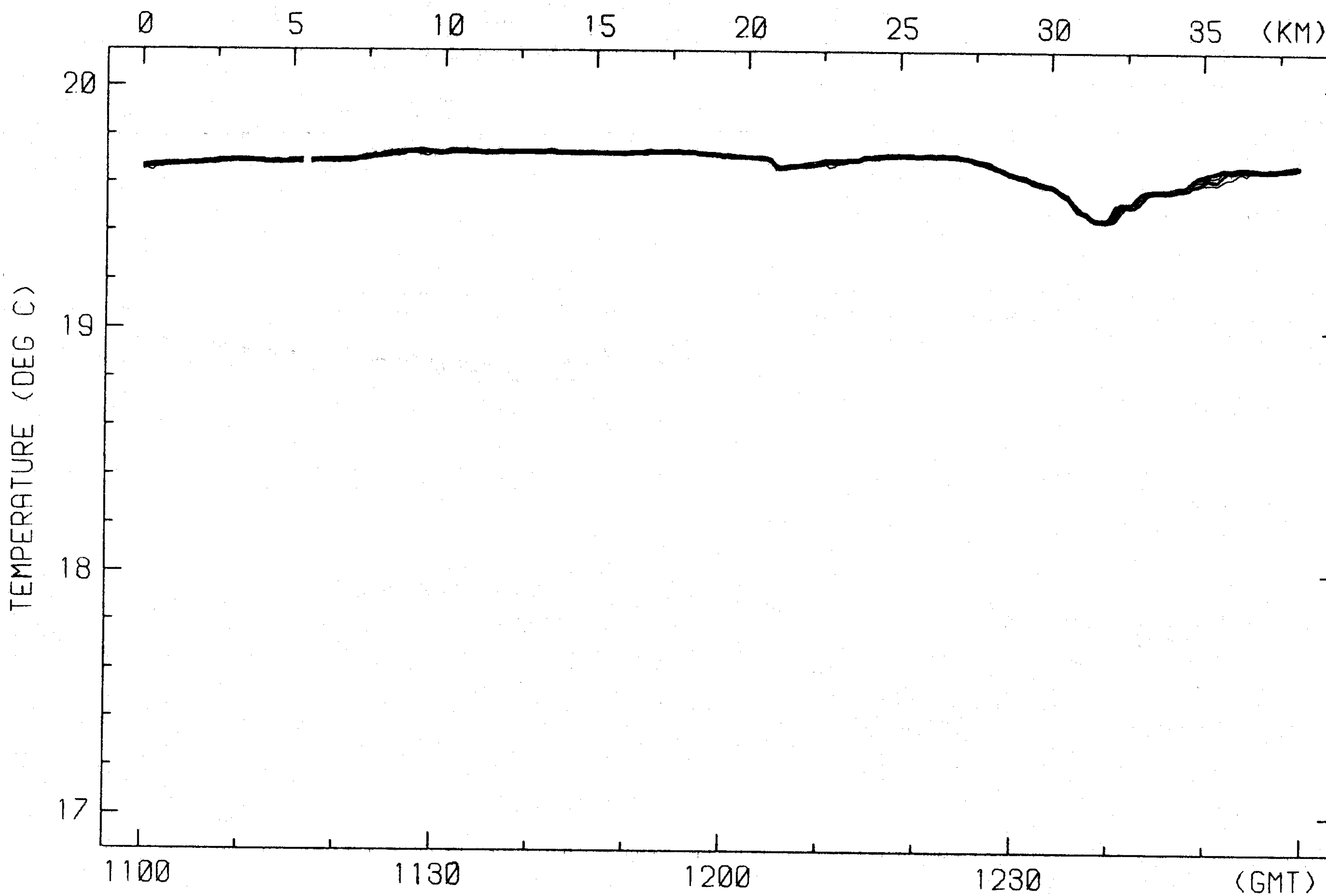
TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 02.46, 28 04.68 TO 155 08.52, 27 44.58



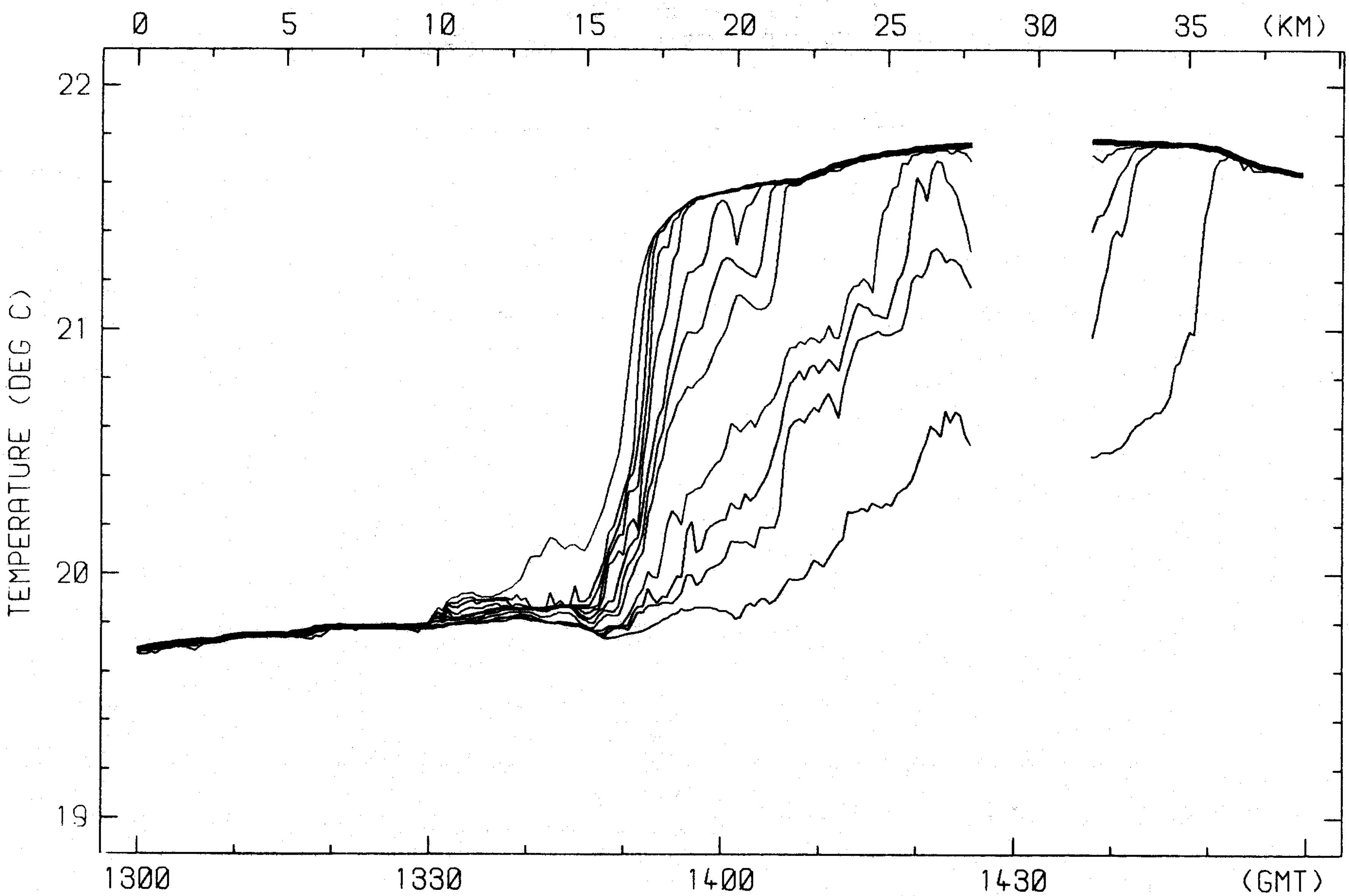
TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 08.52, 27 44.58 TO 155 14.82, 27 24.06



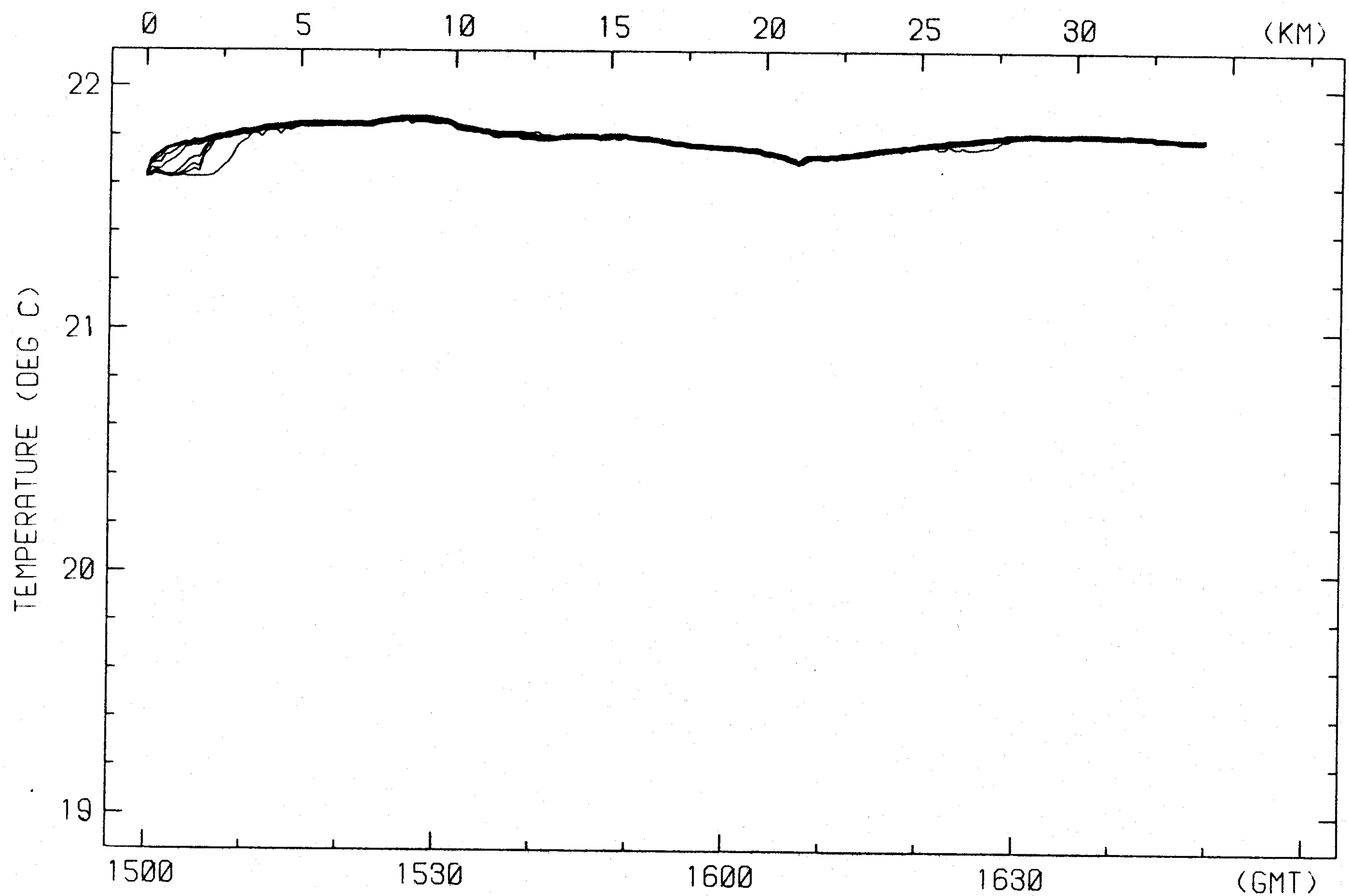
TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 14 82, 27 24.06 TO 155 21.84. 27 03.96



TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 21.84, 27 03.96 TO 155 29.82, 26 44.46



TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 29.82, 26 44.46 TO 155 37.86, 26 24.66



TEMPERATURE VS TIME/DISTANCE 28-JAN-80
155 37.86, 26 24.66 TO 155 45.12, 26 07.32

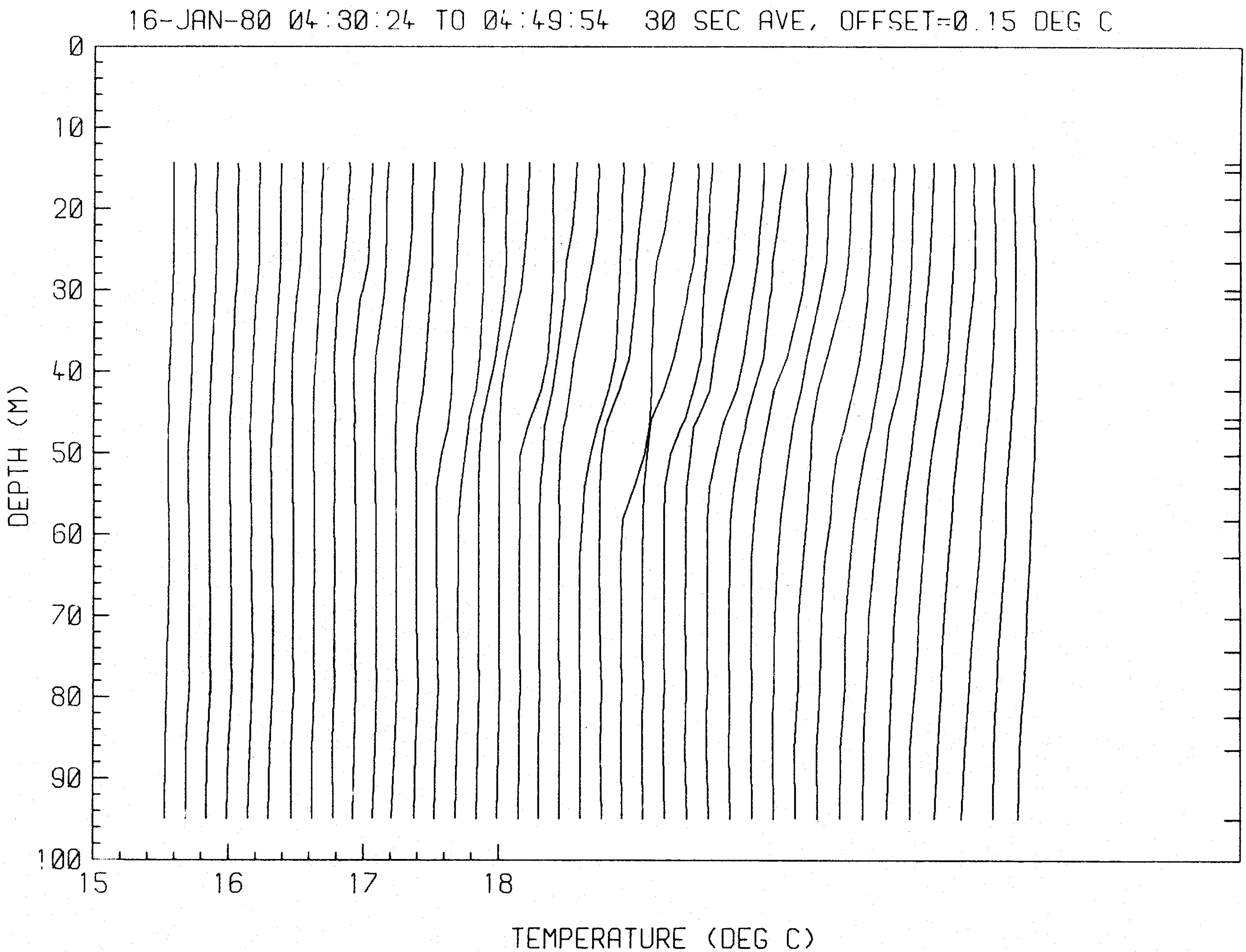
APPENDIX C

Temperature Profiles

On the pages following Table 3 are plotted sequential temperature profiles observed during tows of the thermistor chain. Intervals for plotting were selected to include periods when frontal structure was observed. The intervals are given in Table 3. Each profile is an average over 30 s of measurements. The depths of the thermistors are marked on the right side of each illustration. The temperature scale on the abcissa is correct for the first profile at the left of each illustration. Subsequent profiles have their temperature scale shifted 0.15°C from their predecessor. Missing profiles are indicated by a black dot.

Table 3. Intervals for which temperature profiles are plotted.

Run No.	Date (Jan GMT)	Time Begin (GMT)	Time End (GMT)
1	16	0430	0450
		0620	0640
		0820	0900
		0940	1440
2	17	0525	0550
		0630	0710
		0750	0910
		0930	1120
		1150	1300
		1610	1650
		1850	1930
		2050	2200
		2220	2330
	18	0500	0520
		1130	1320
		1440	1720
		1820	1840
		1902	1920
		2050	2118
		2120	2200
		2250	2310
		2313	2320
3	25	1320	1400
4	27	2220	2350
	28	0100	0120
		0240	0420
		0540	0610
		0740	0930
		1330	1420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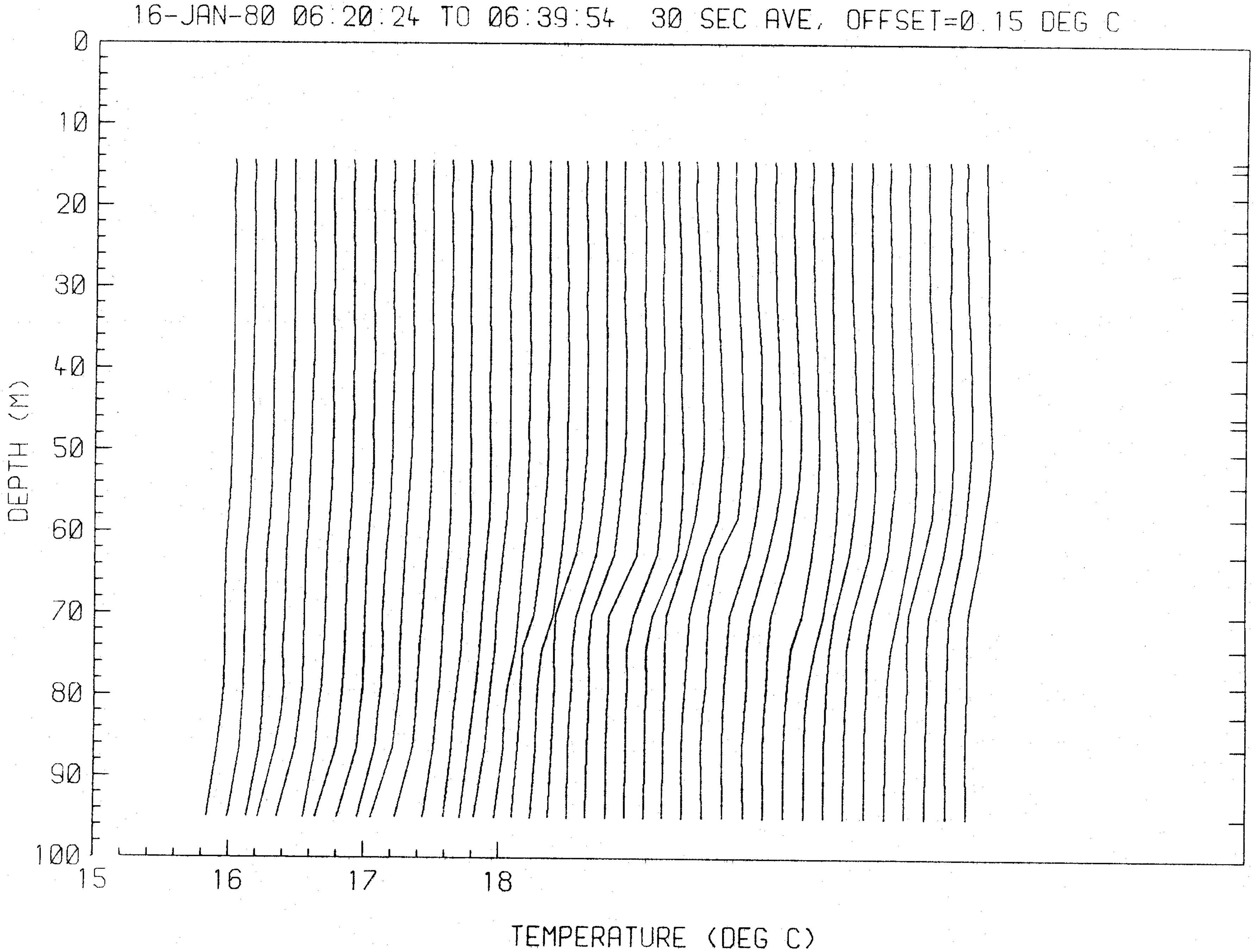
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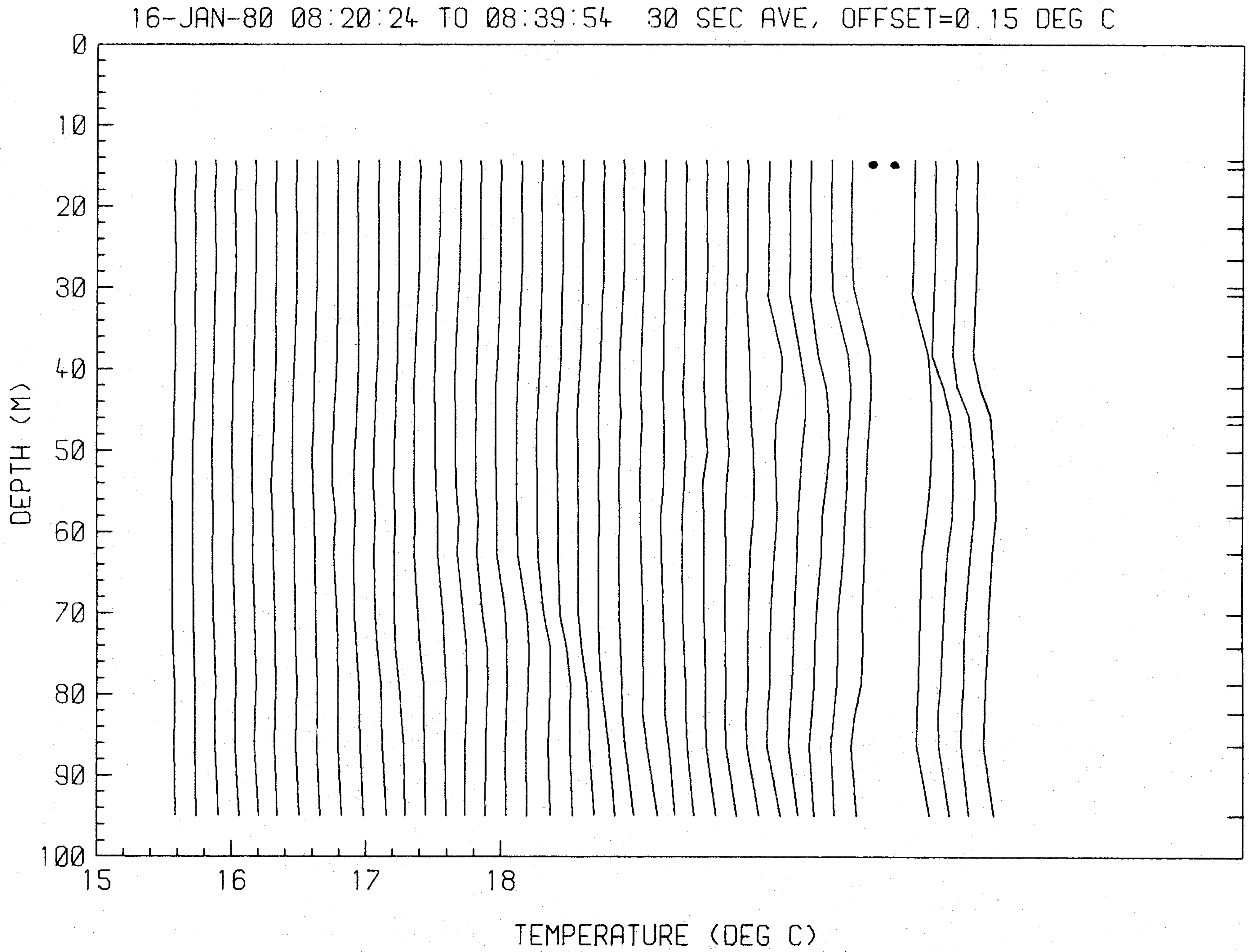
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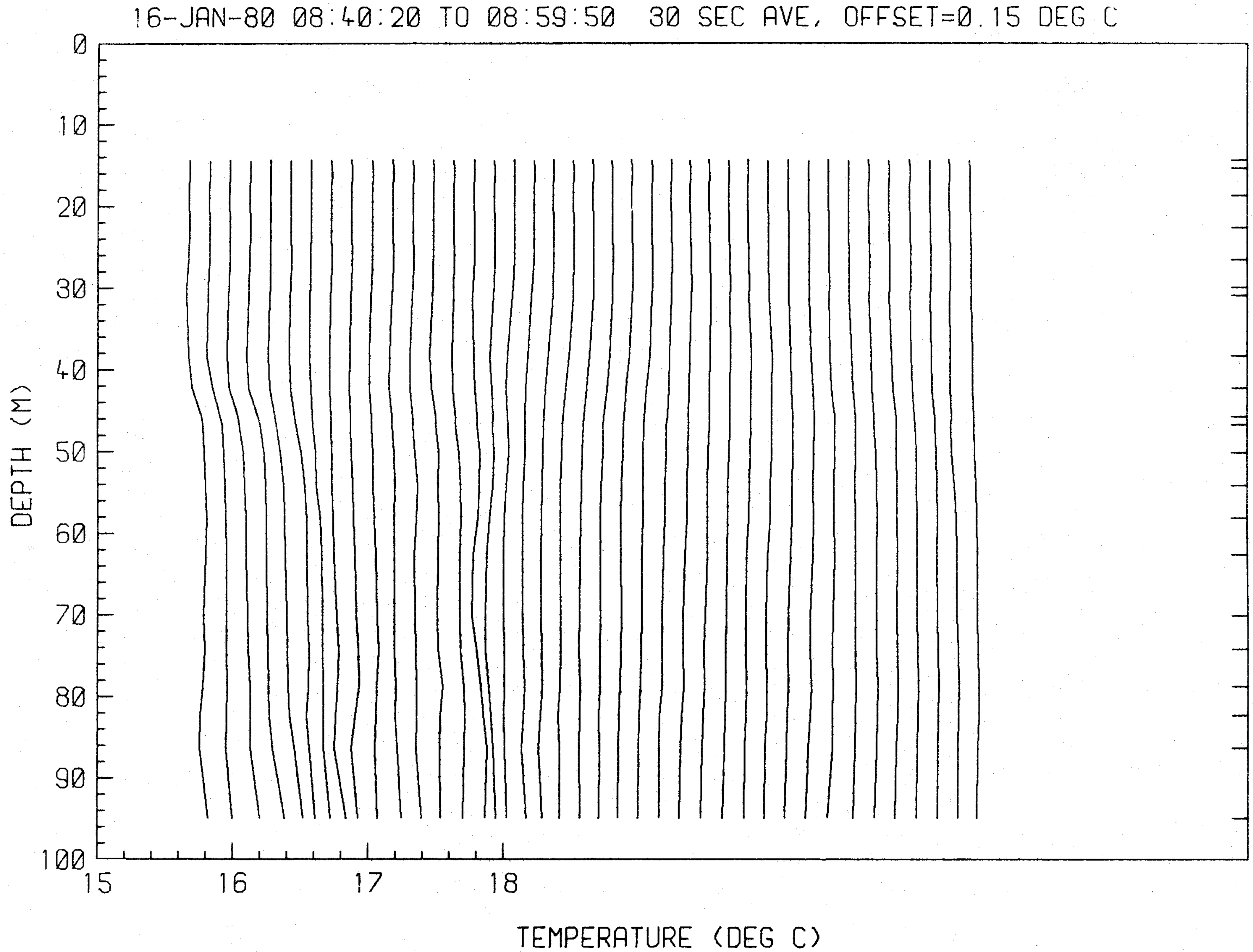
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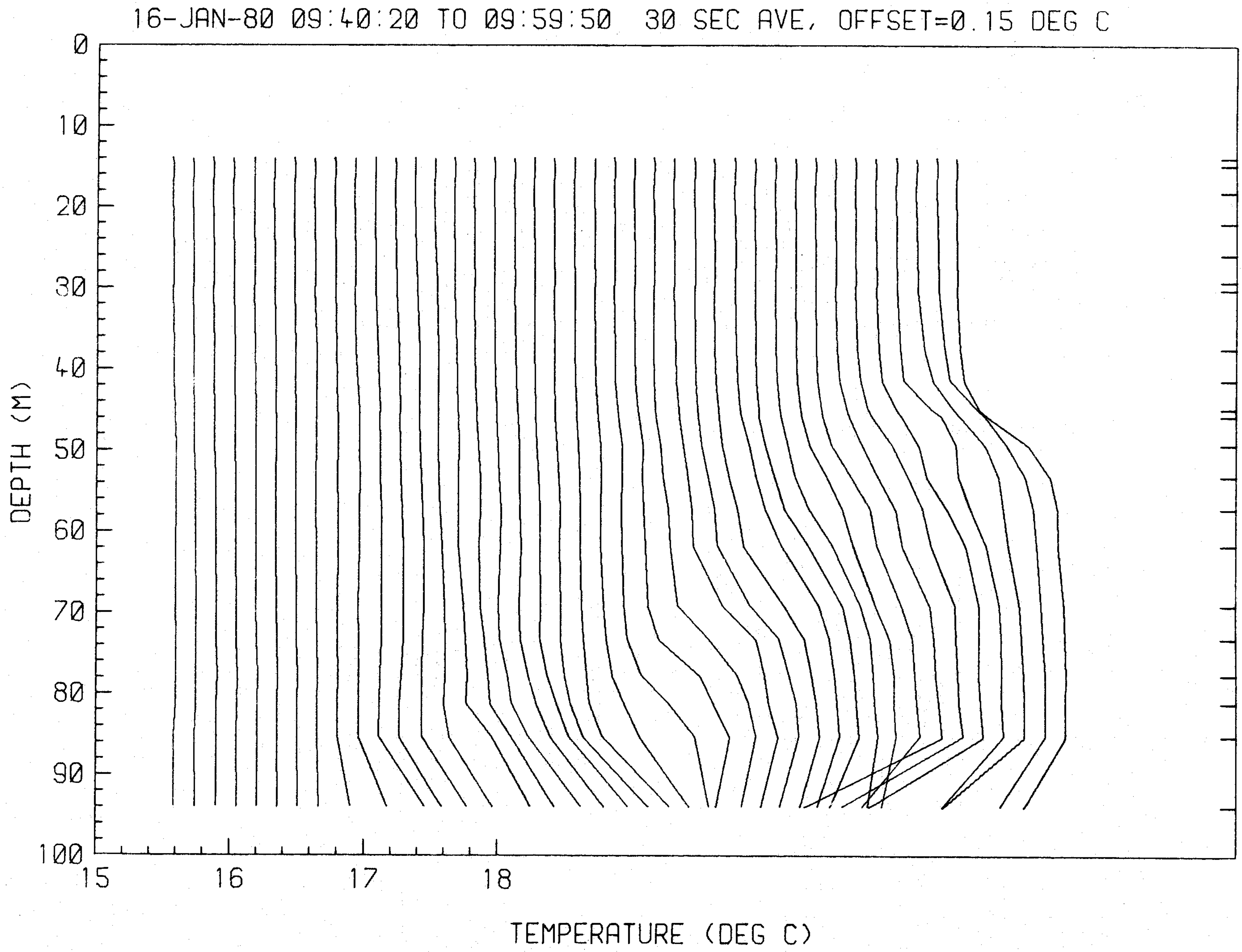
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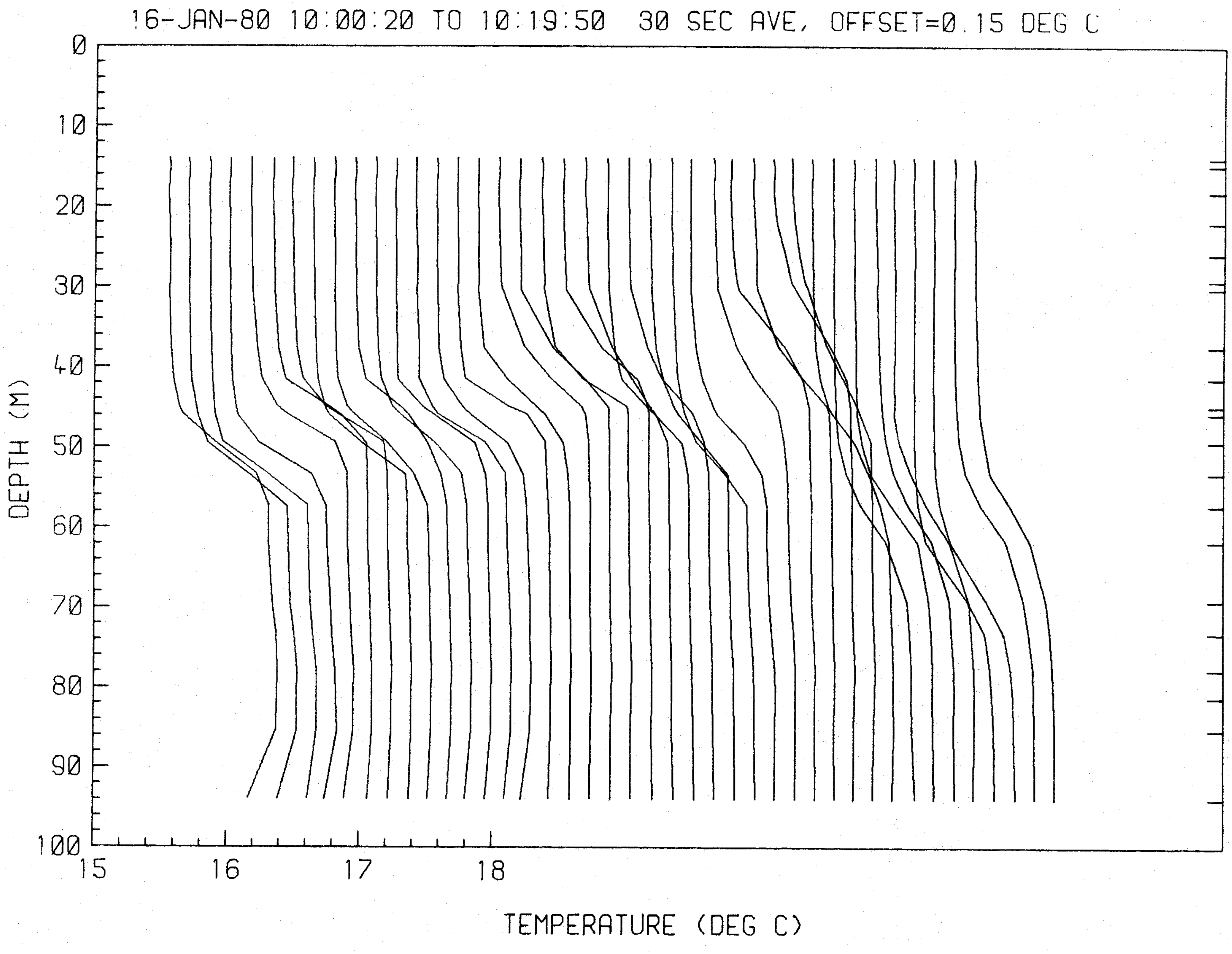
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TEMPERATURE (DEG C)

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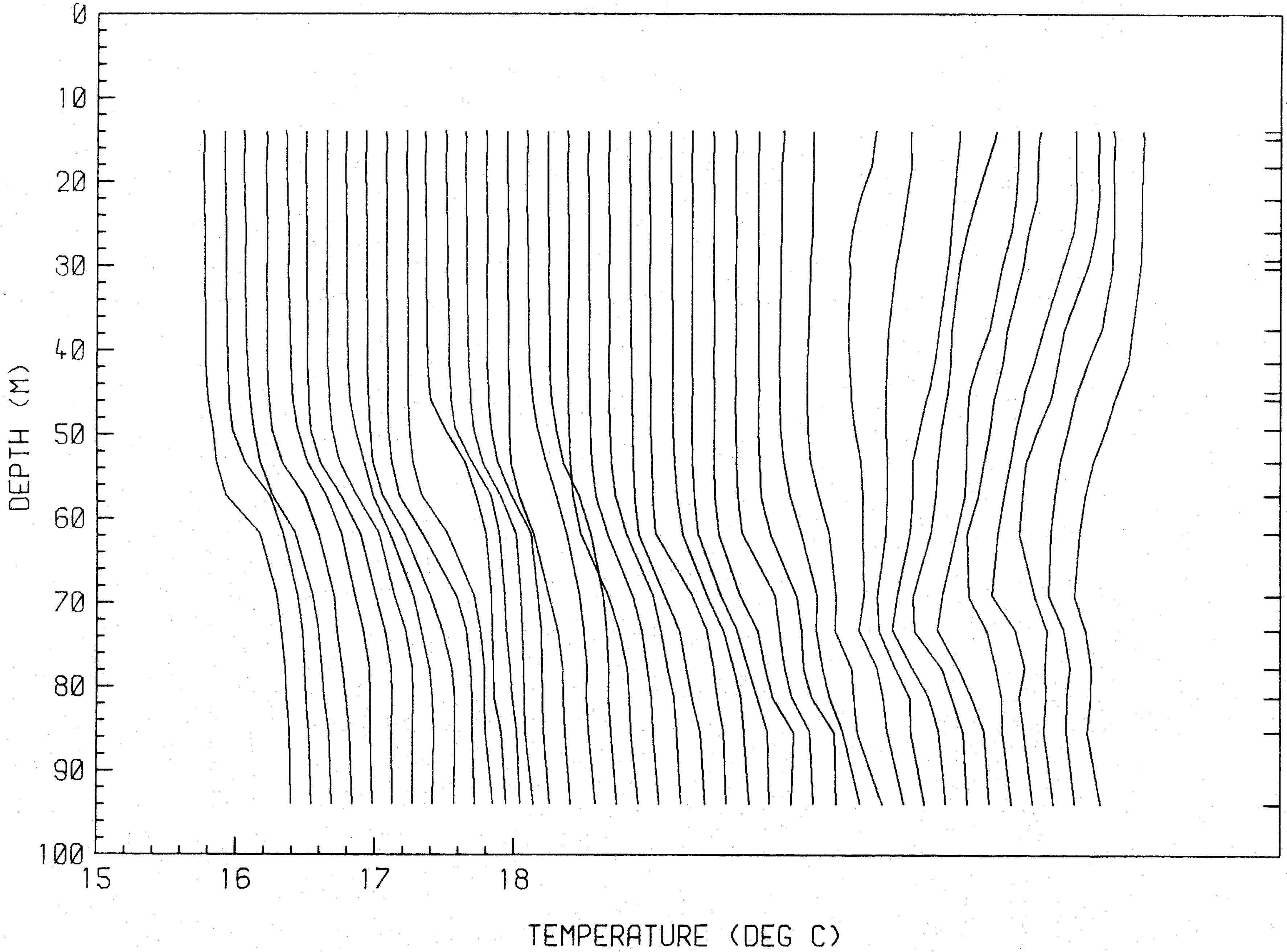

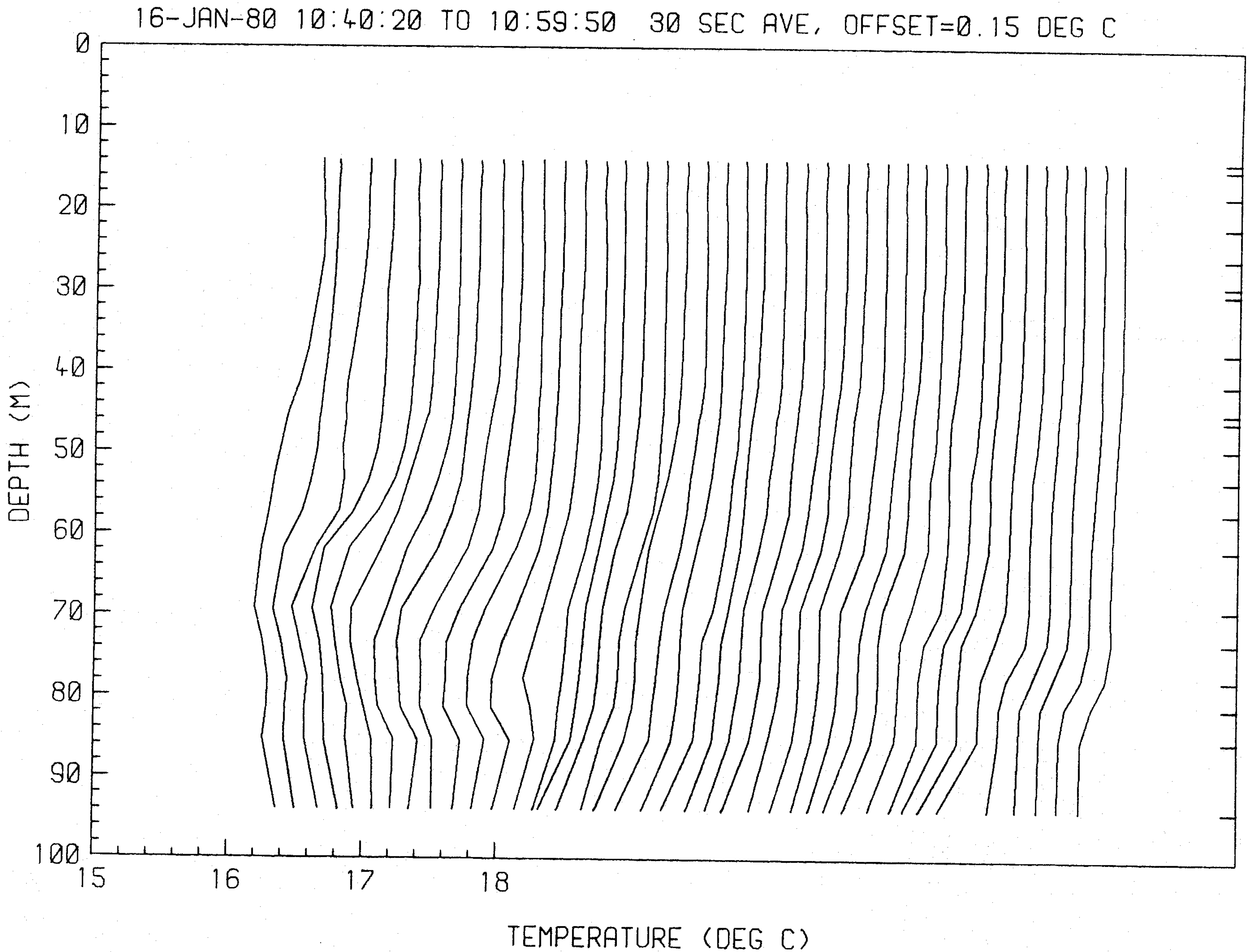
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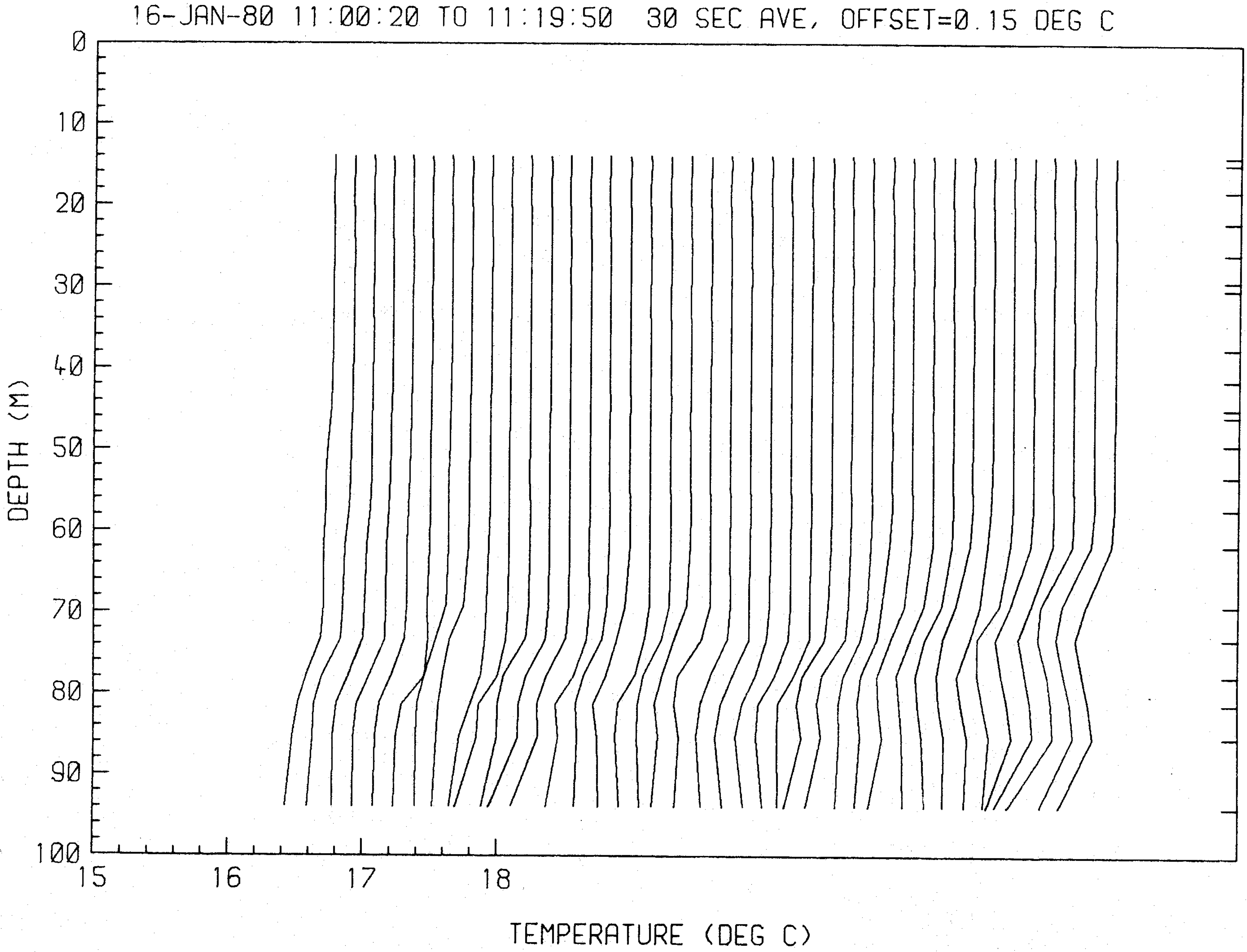
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TEMPERATURE (DEG C)

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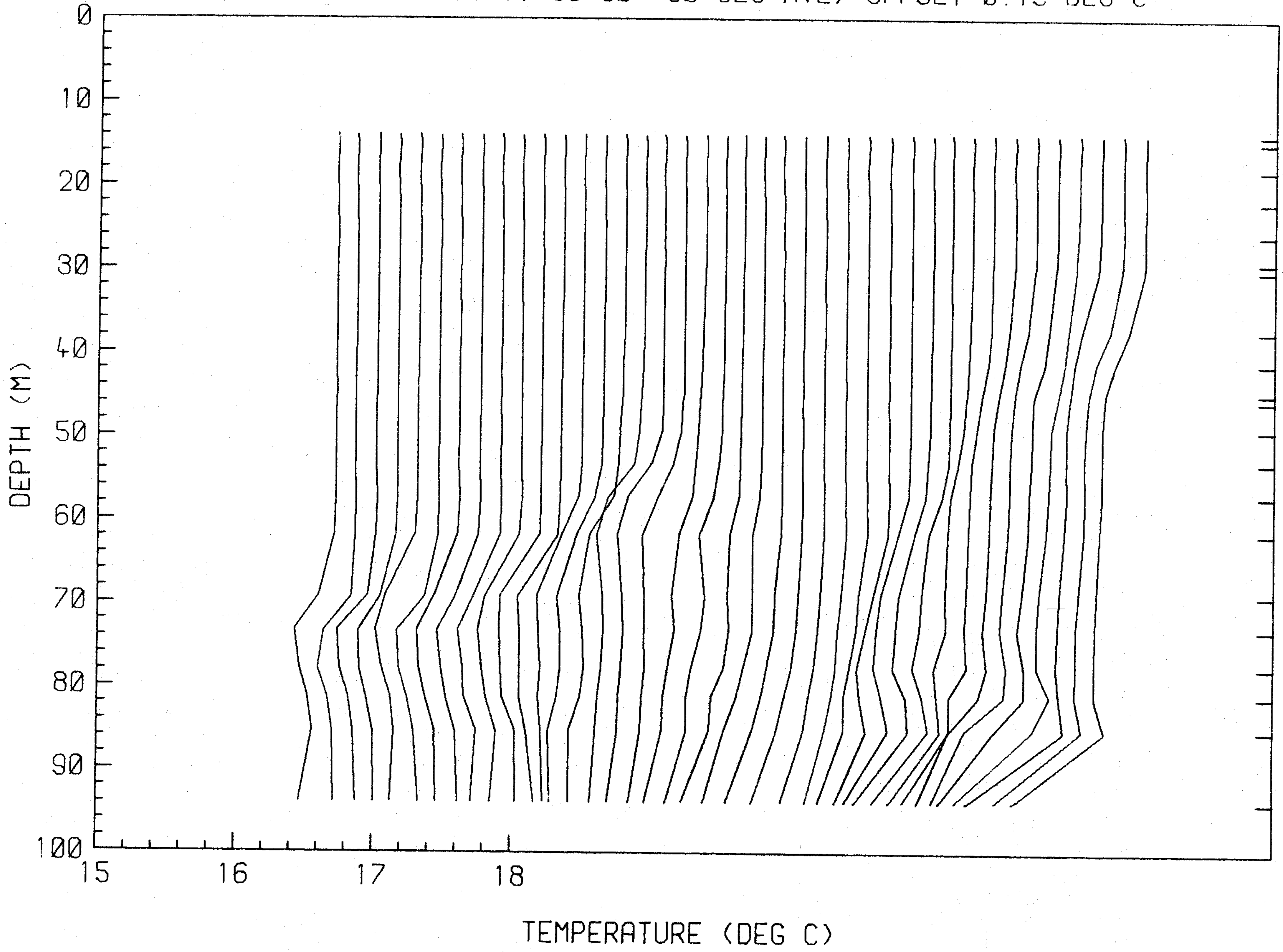

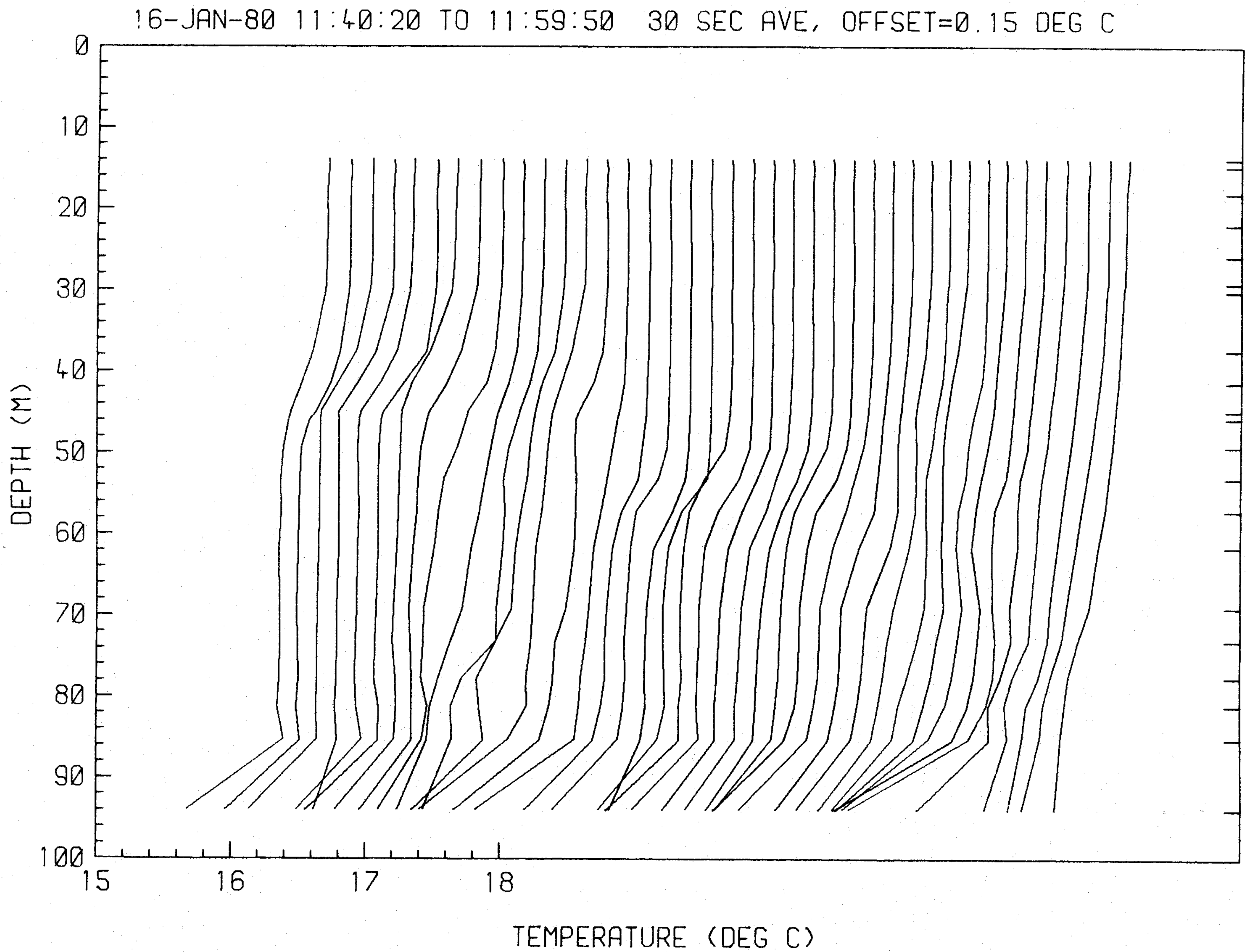
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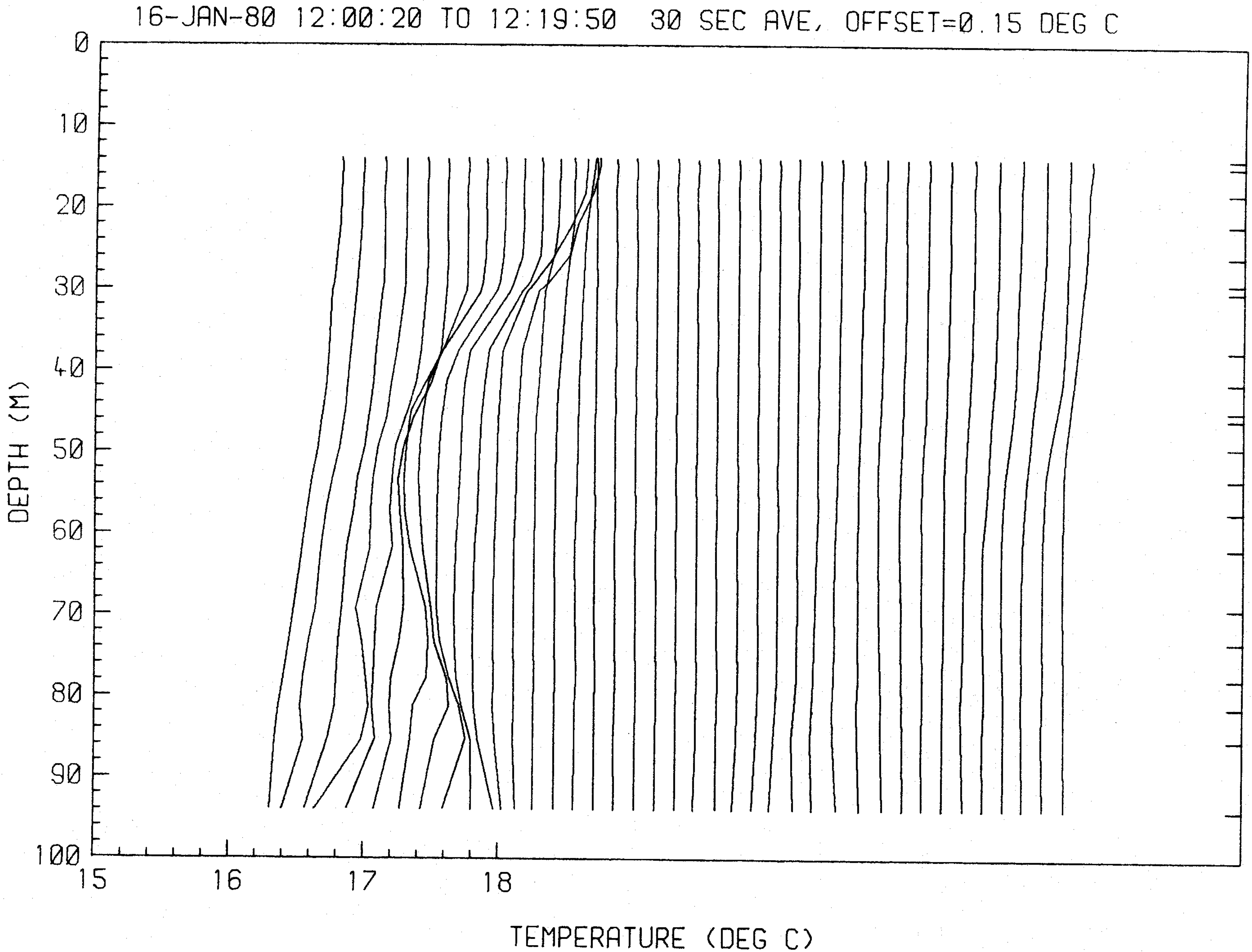
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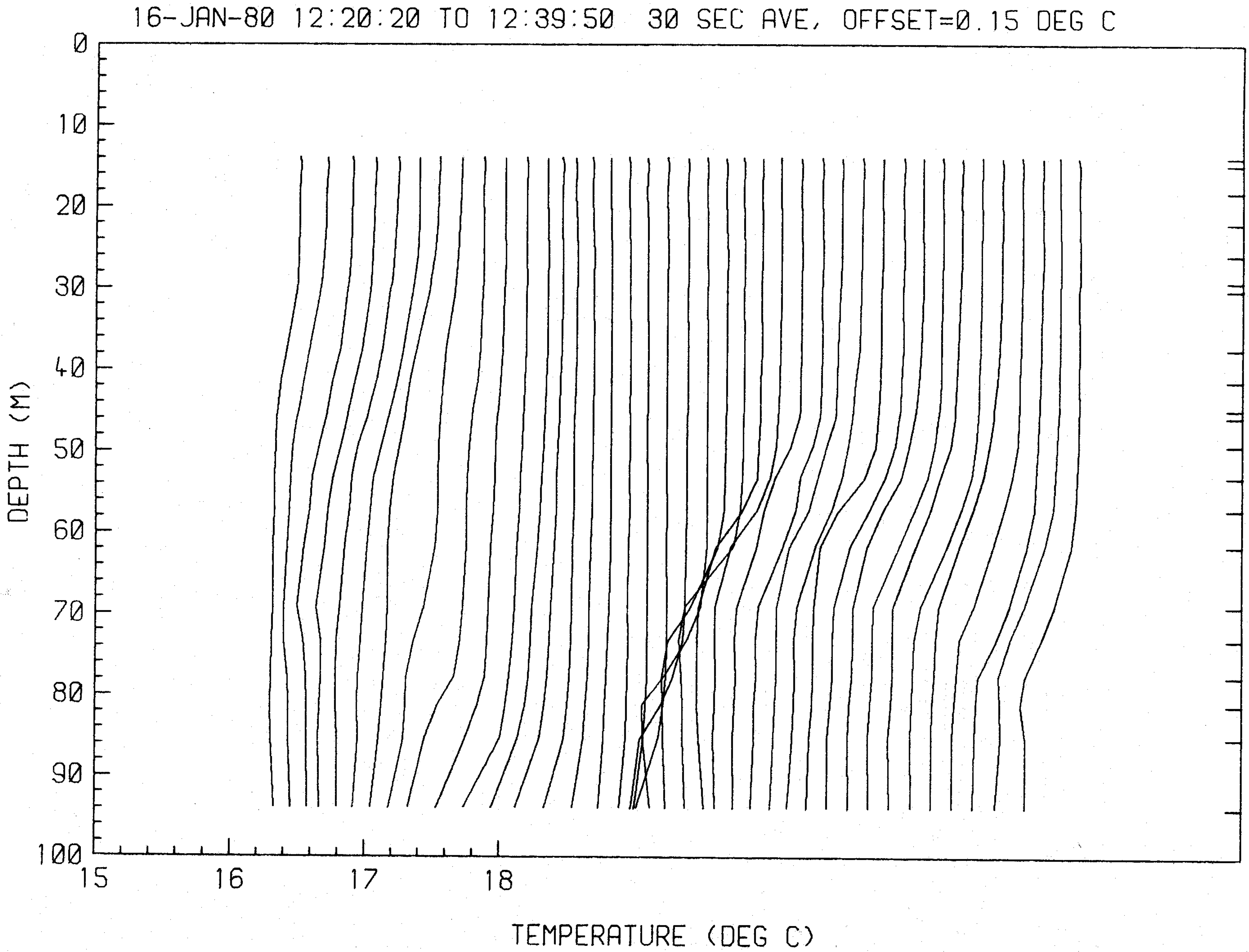
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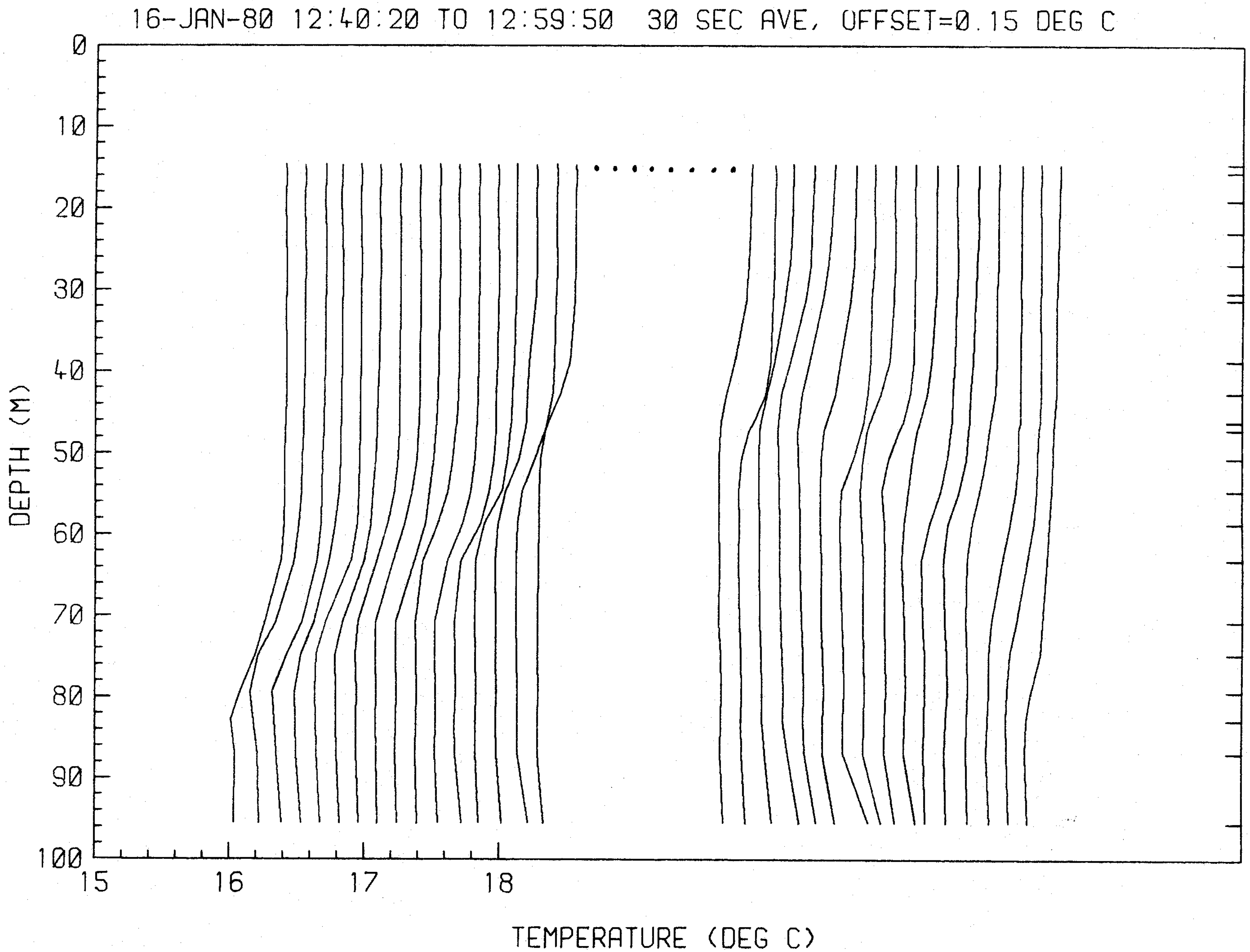
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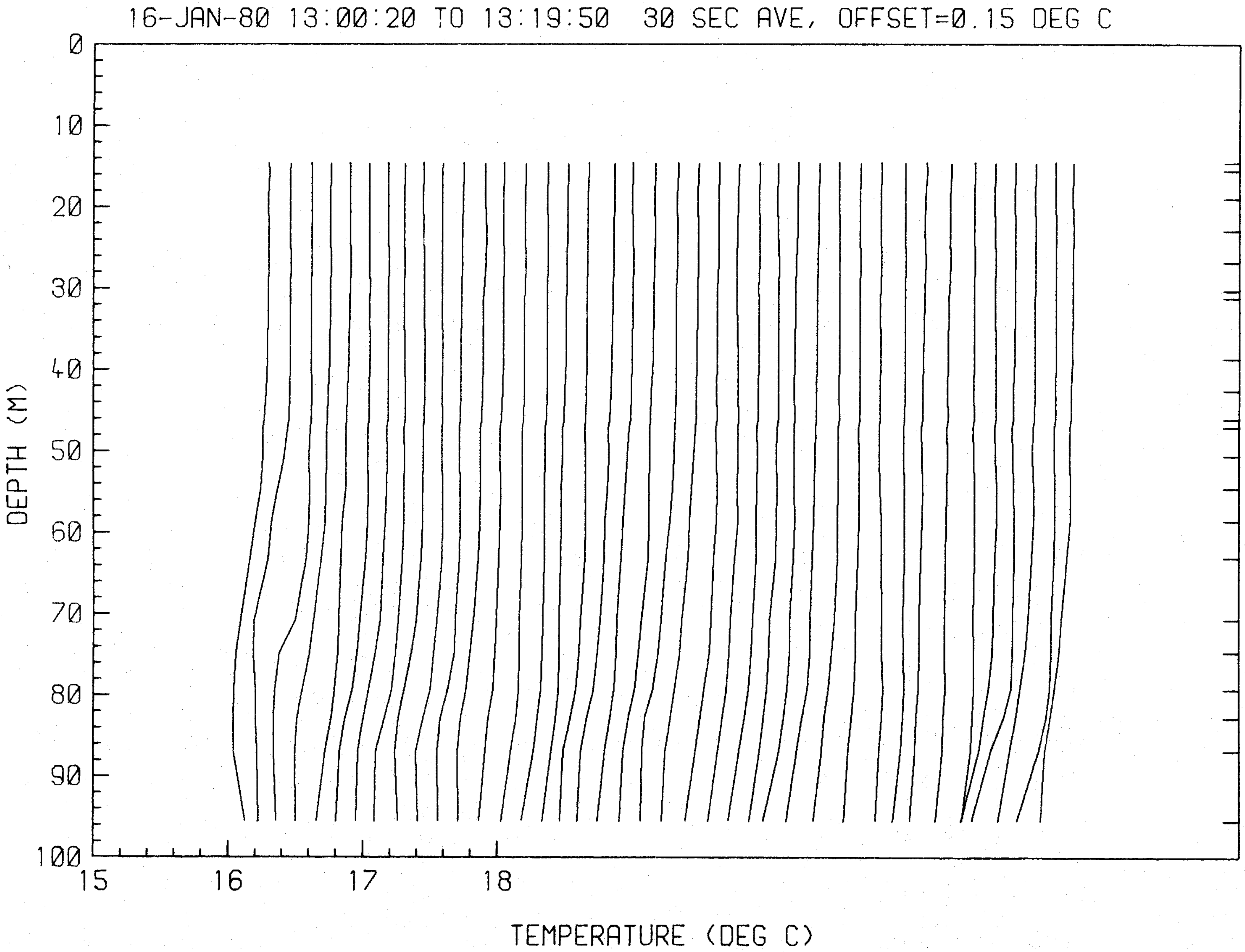
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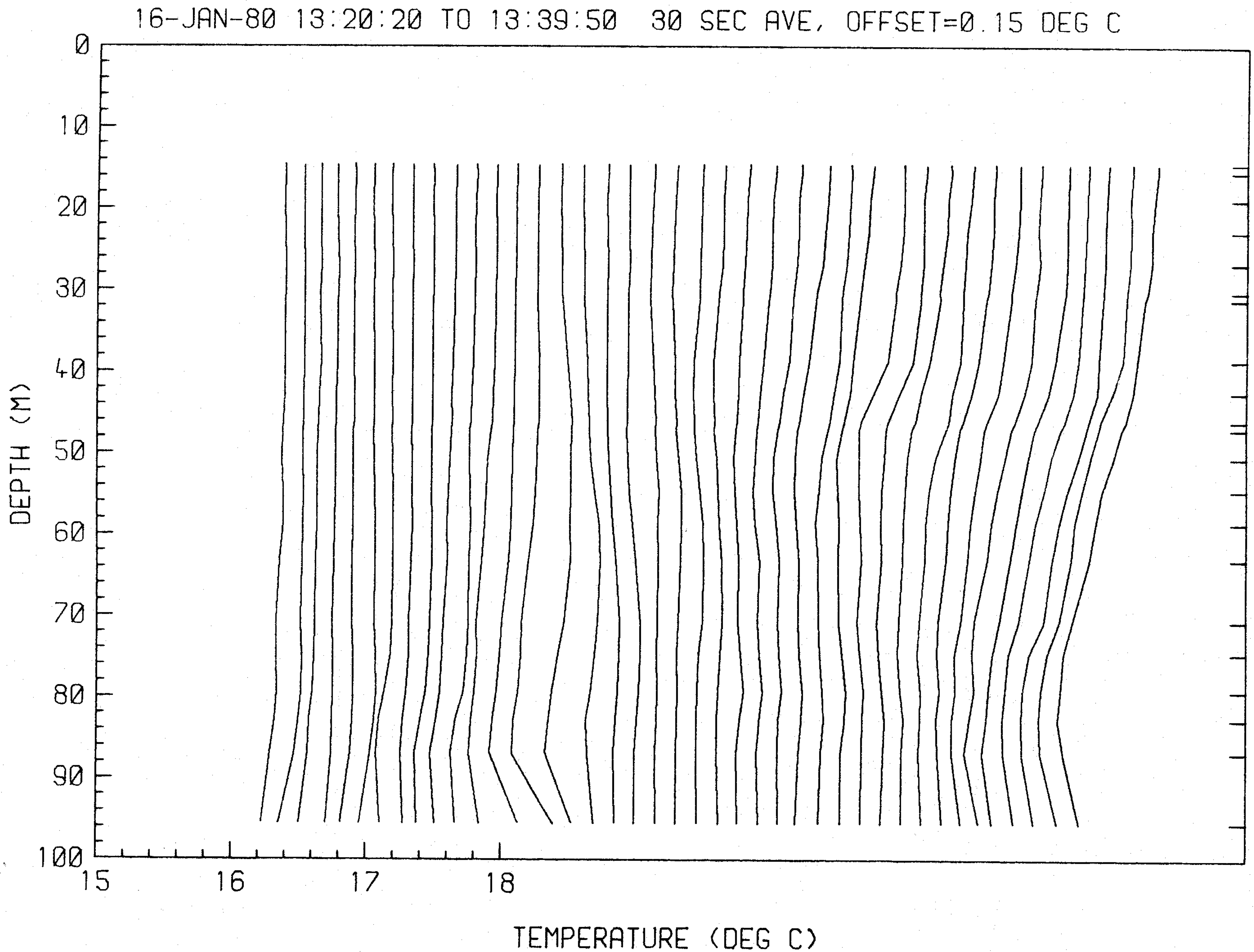
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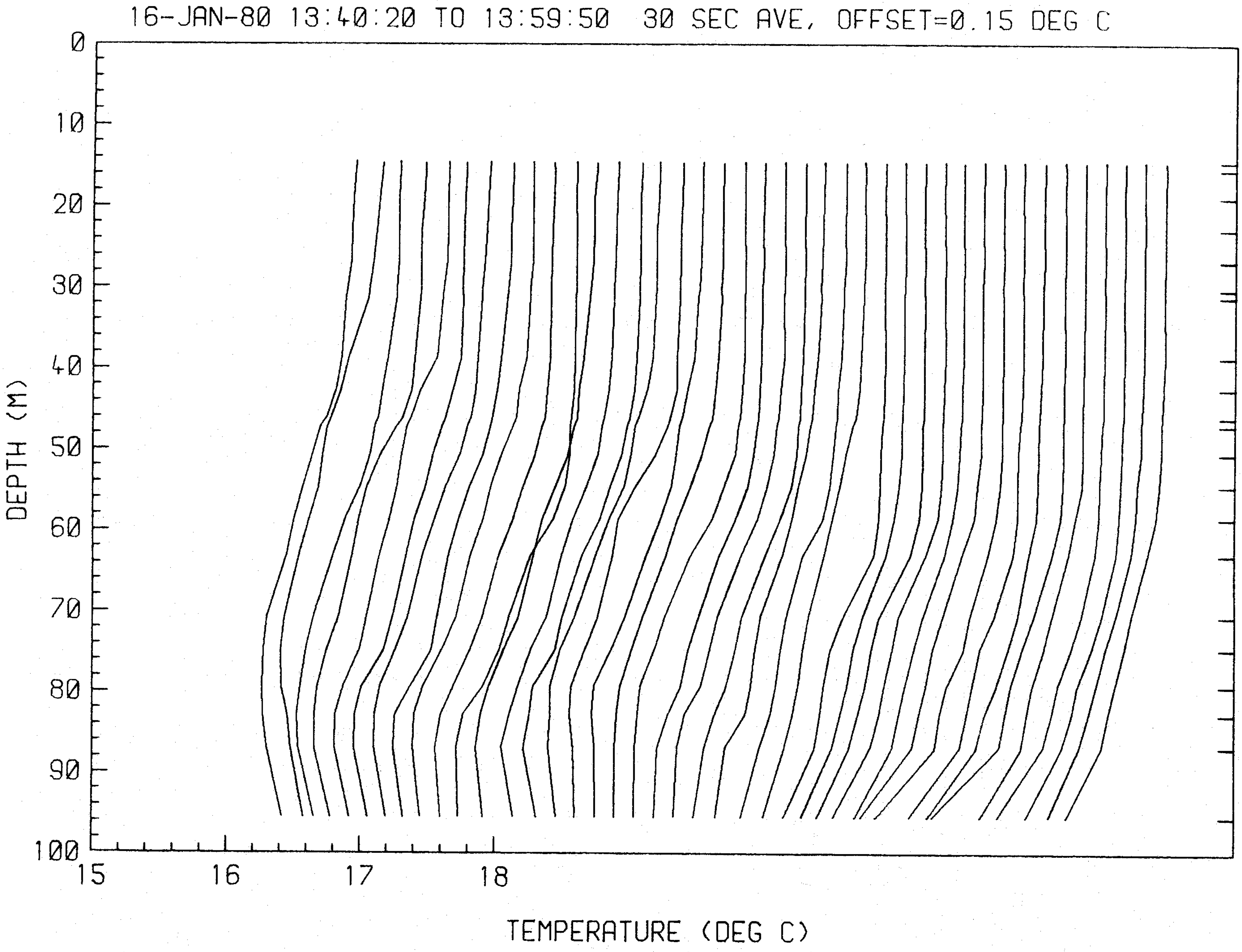
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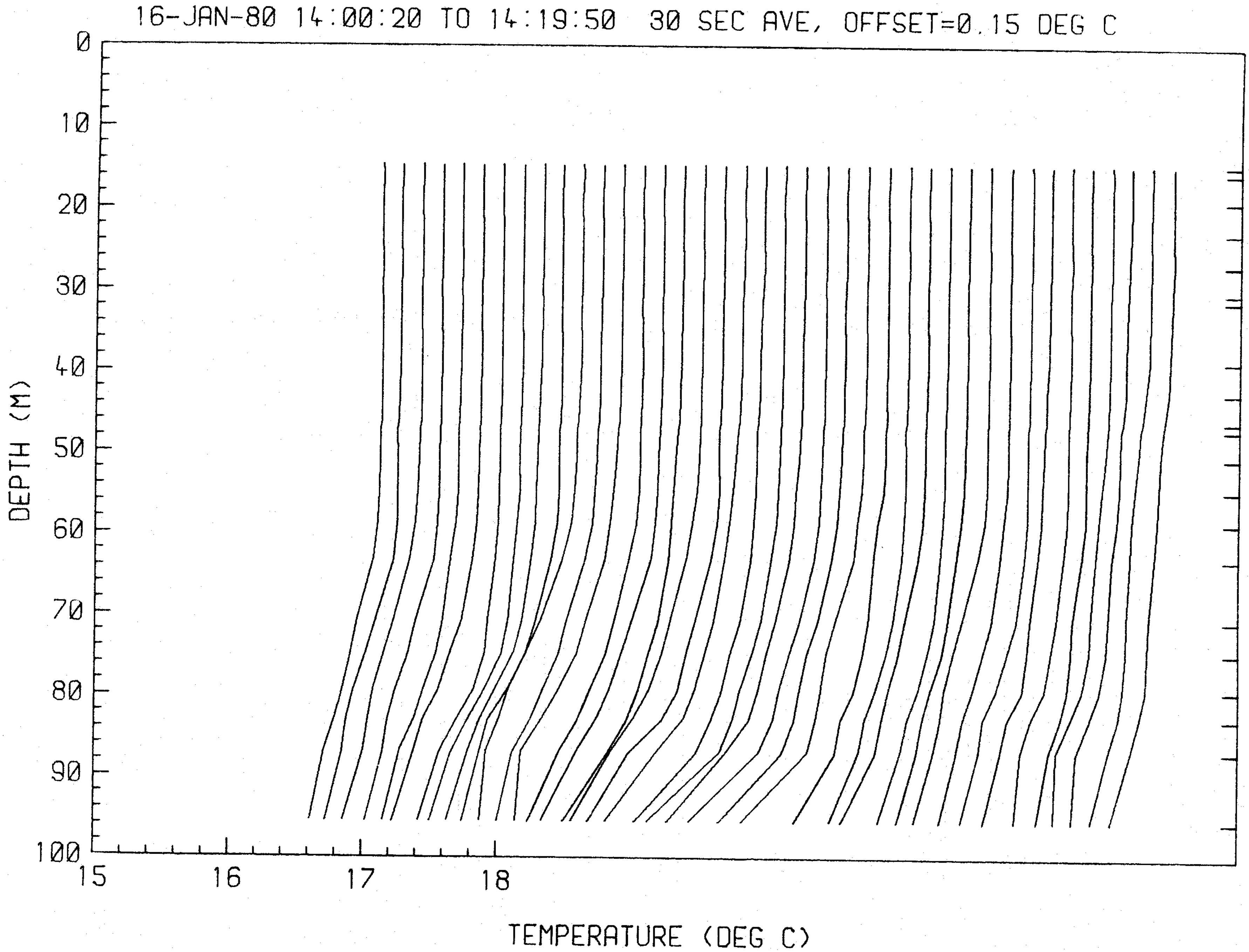
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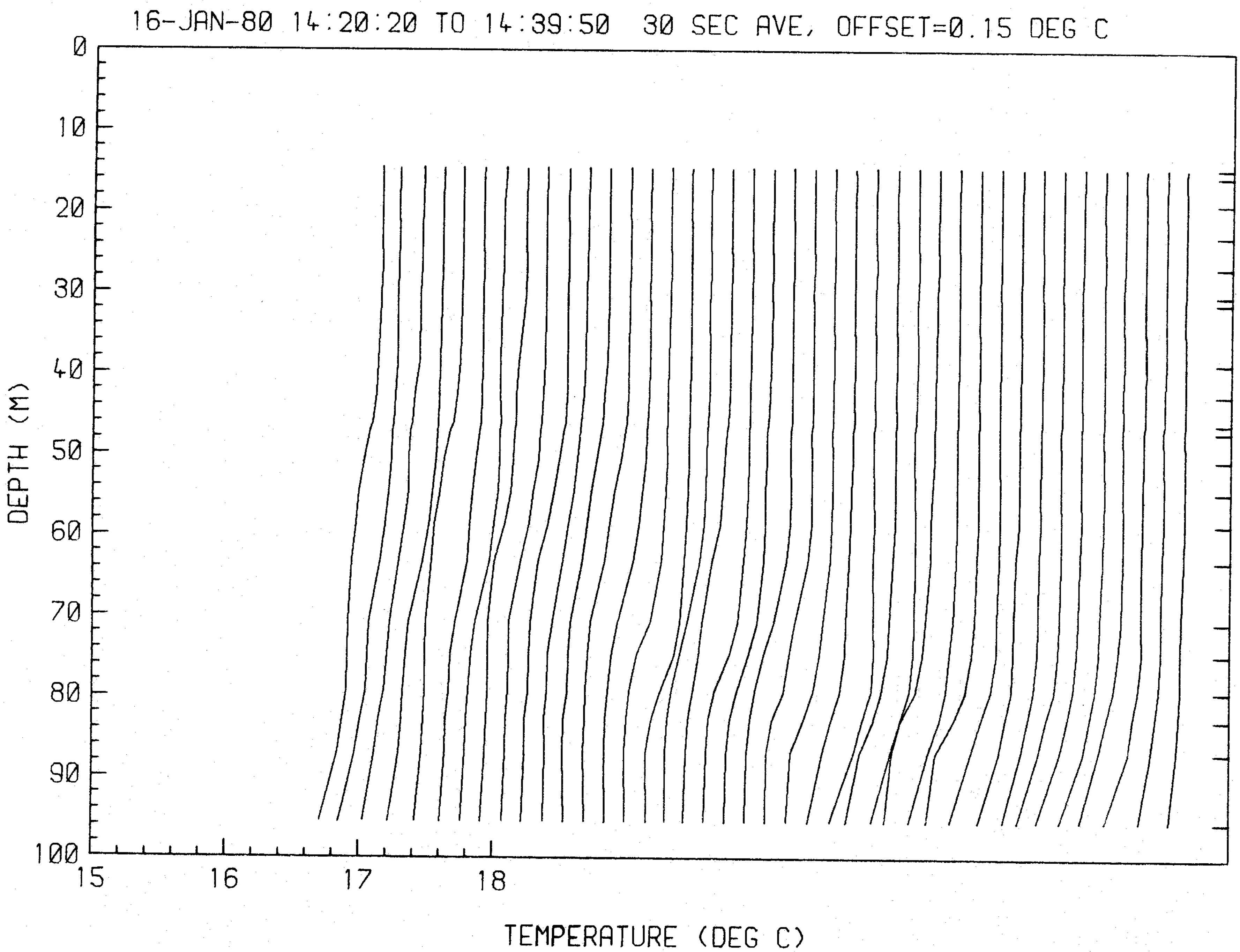

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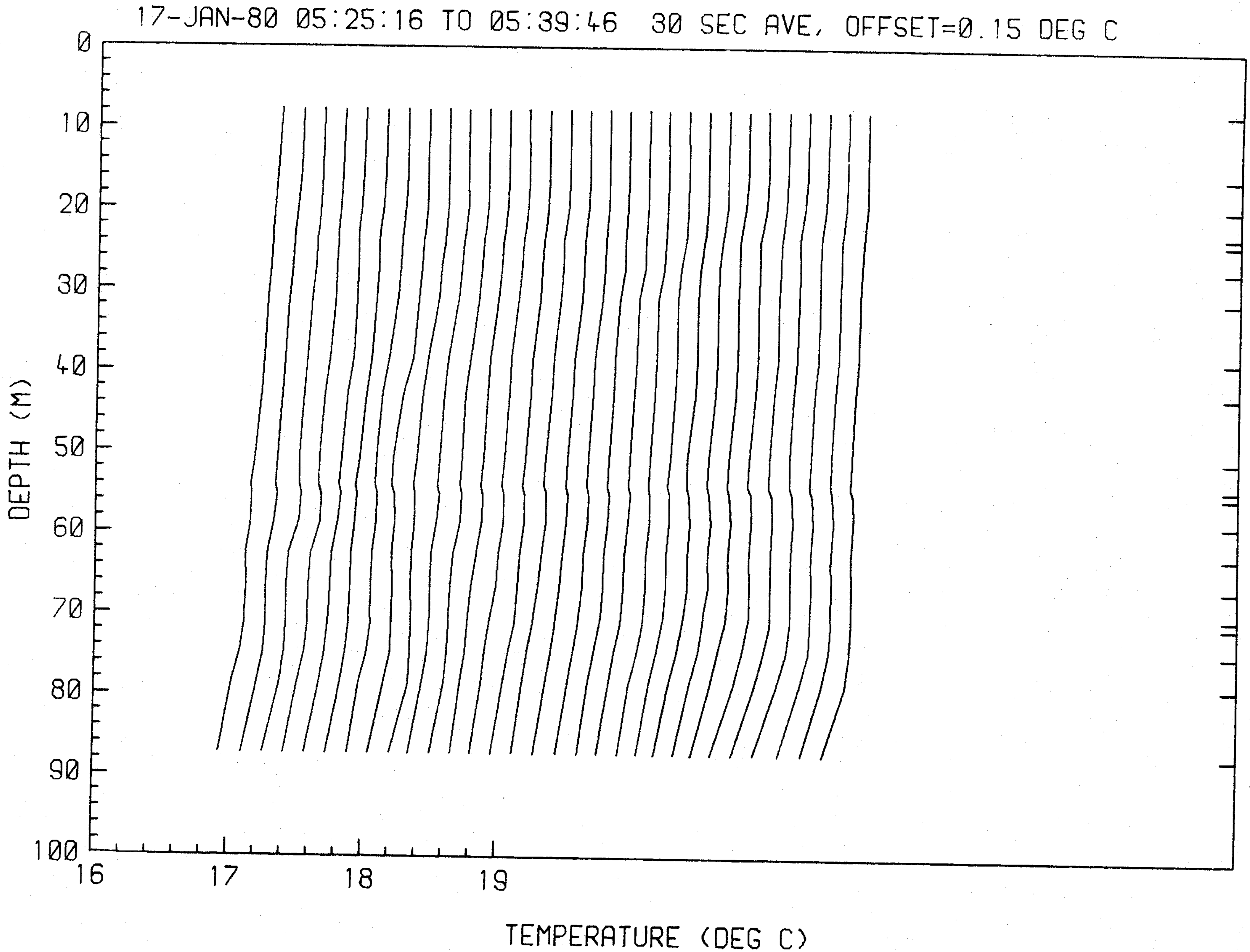
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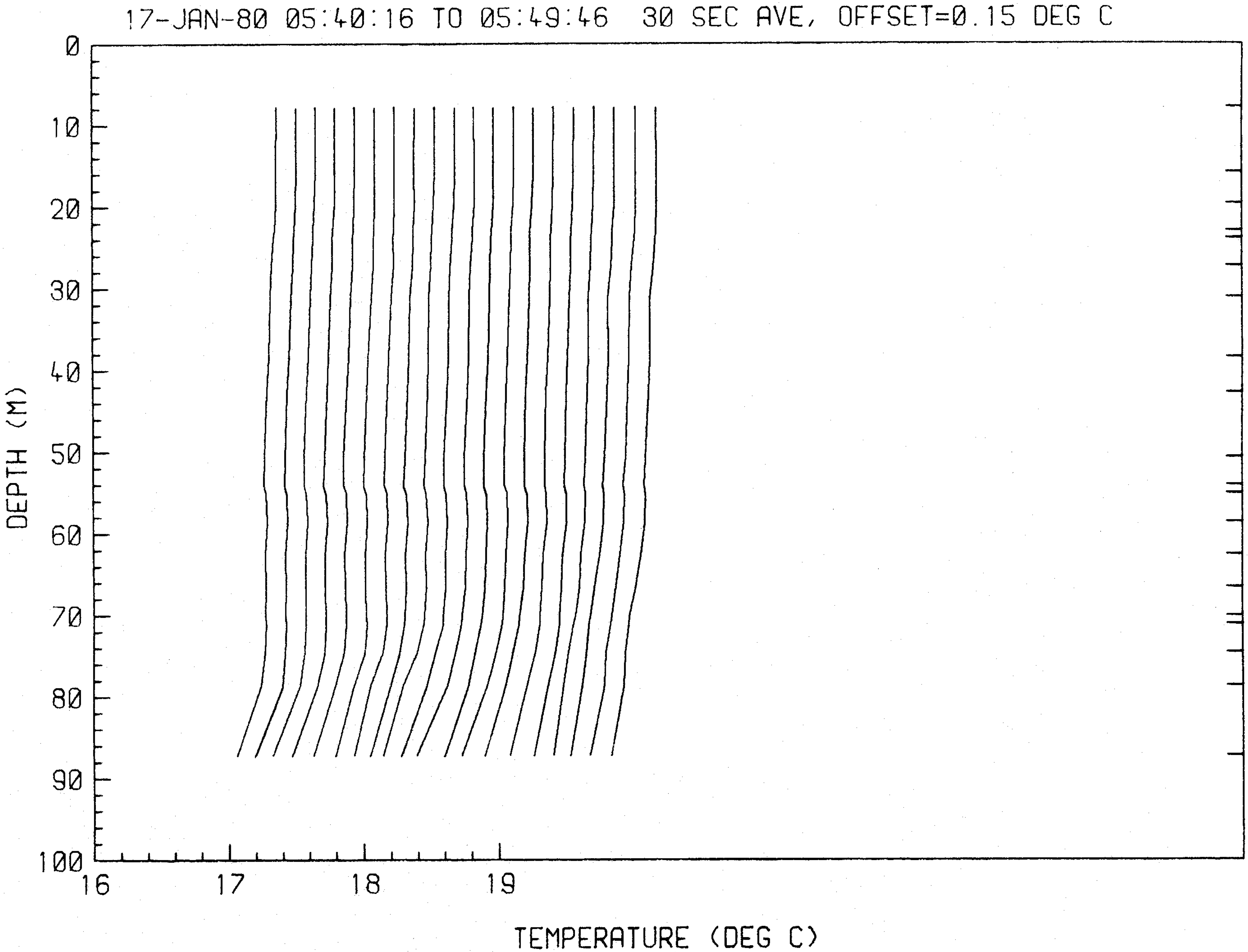
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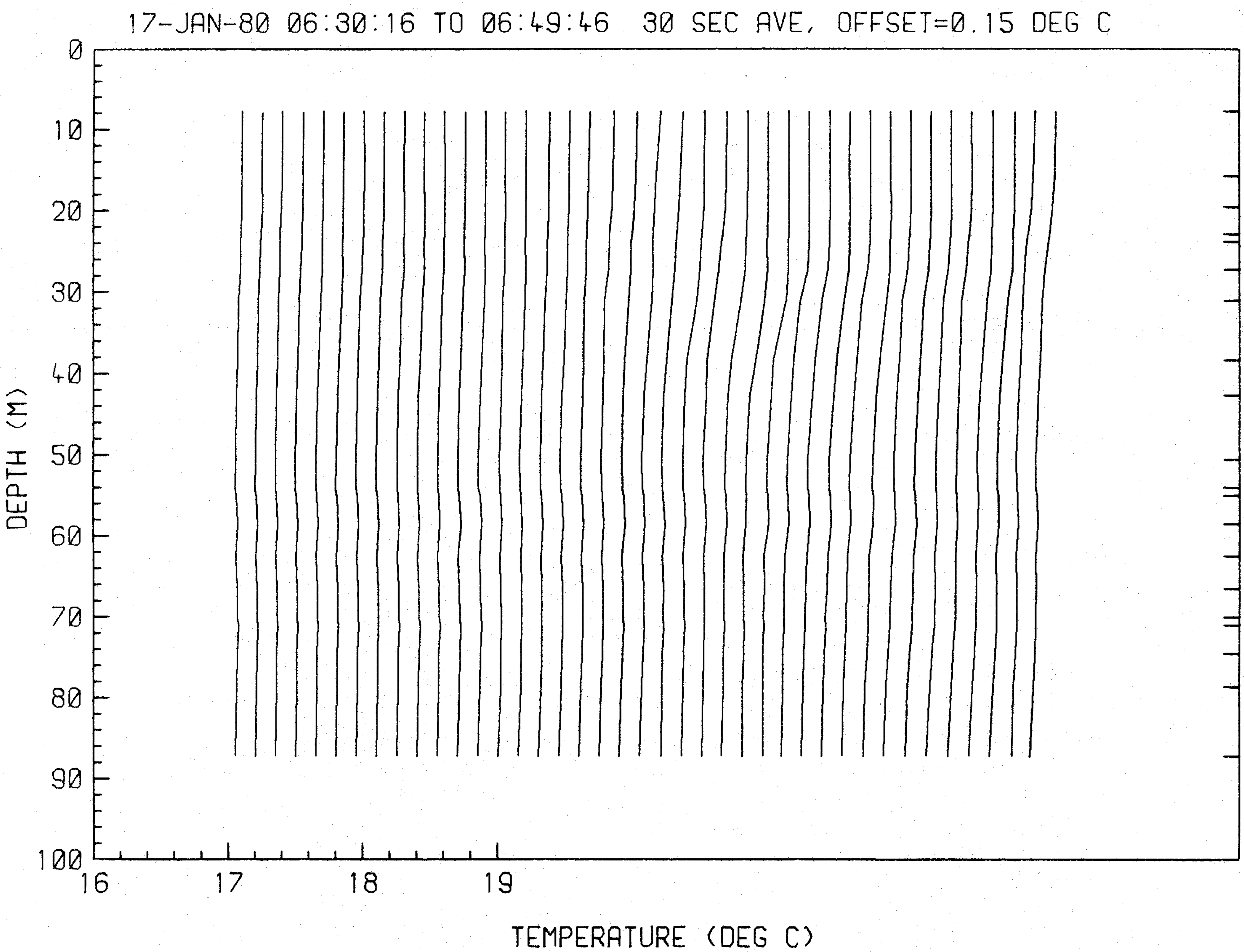
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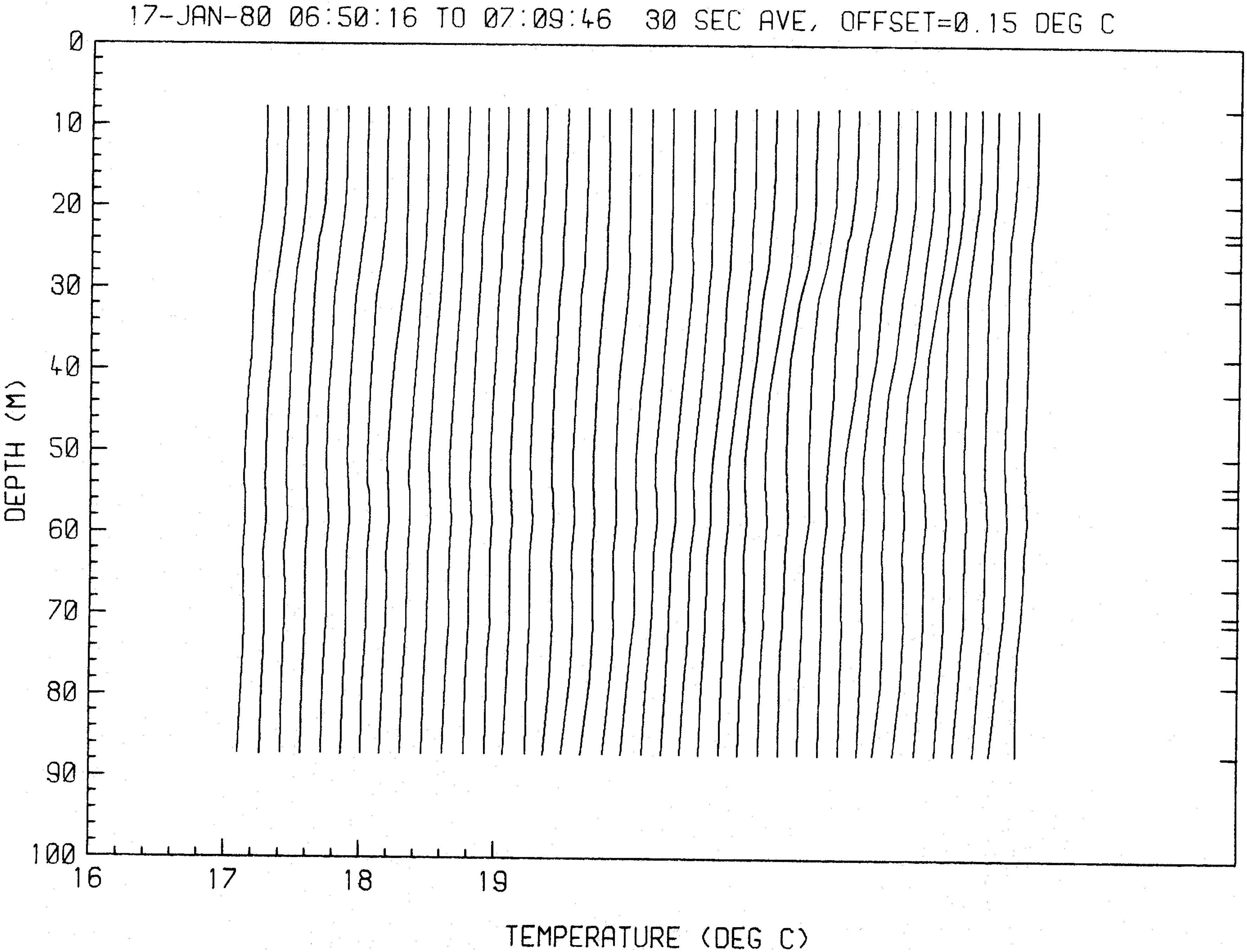
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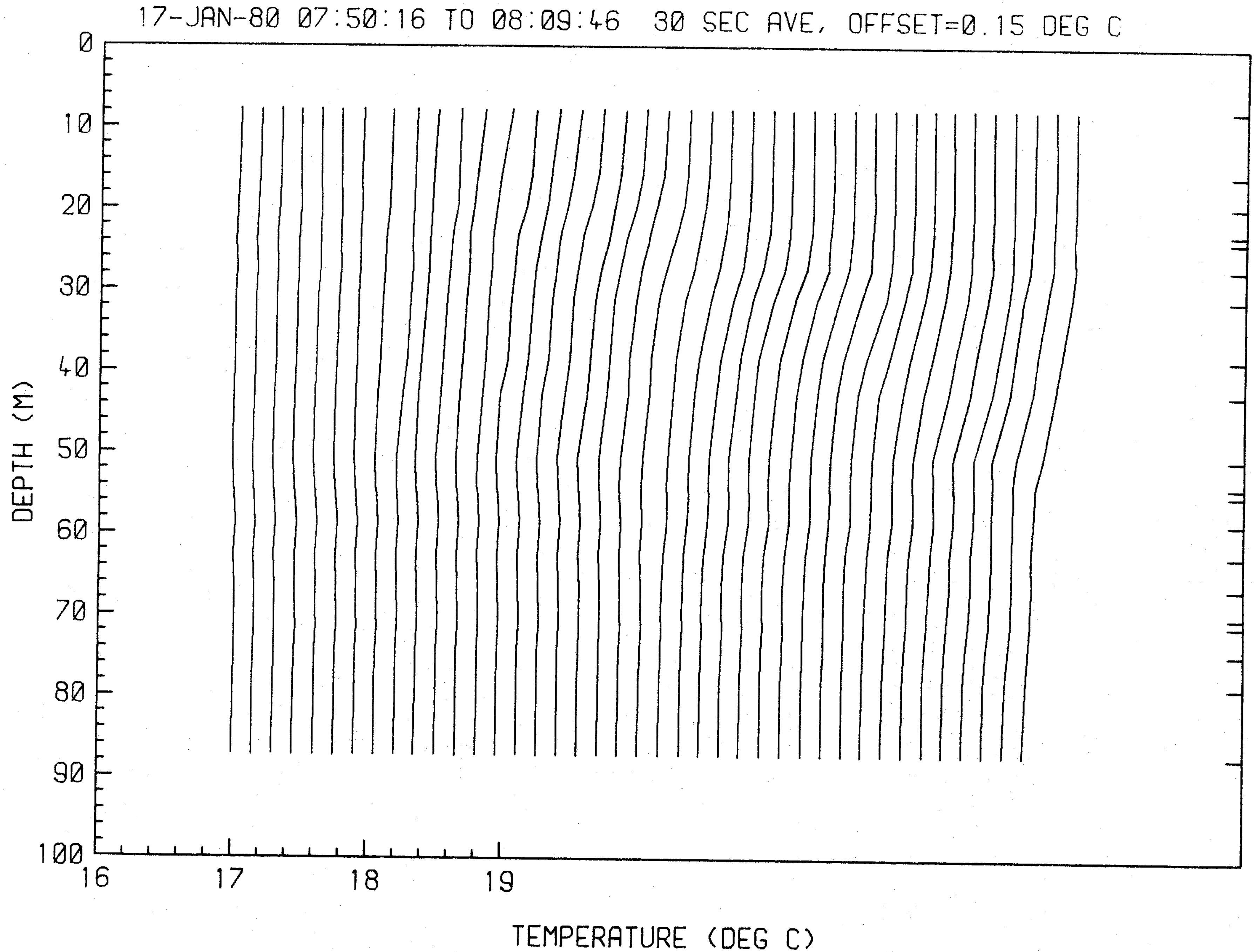
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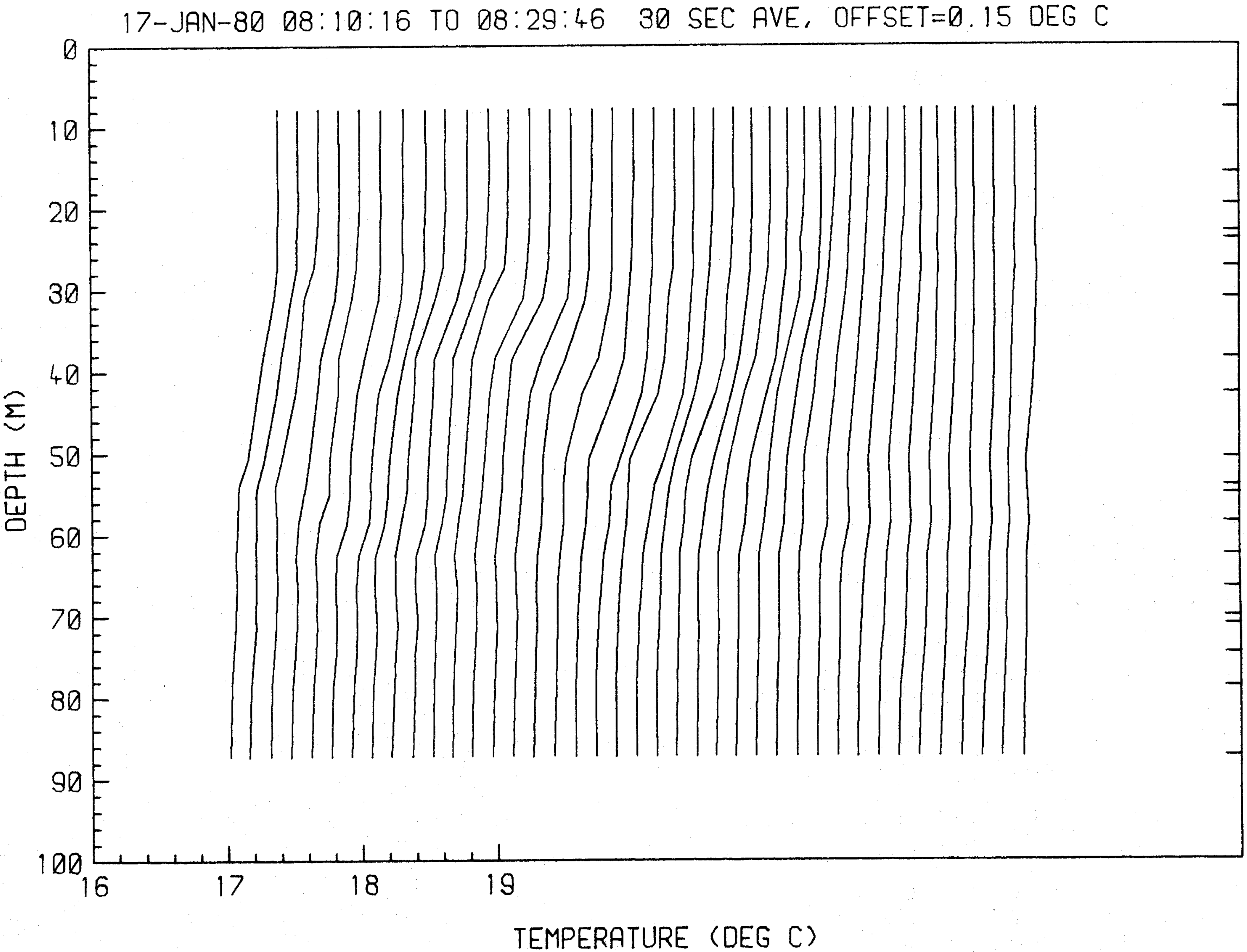
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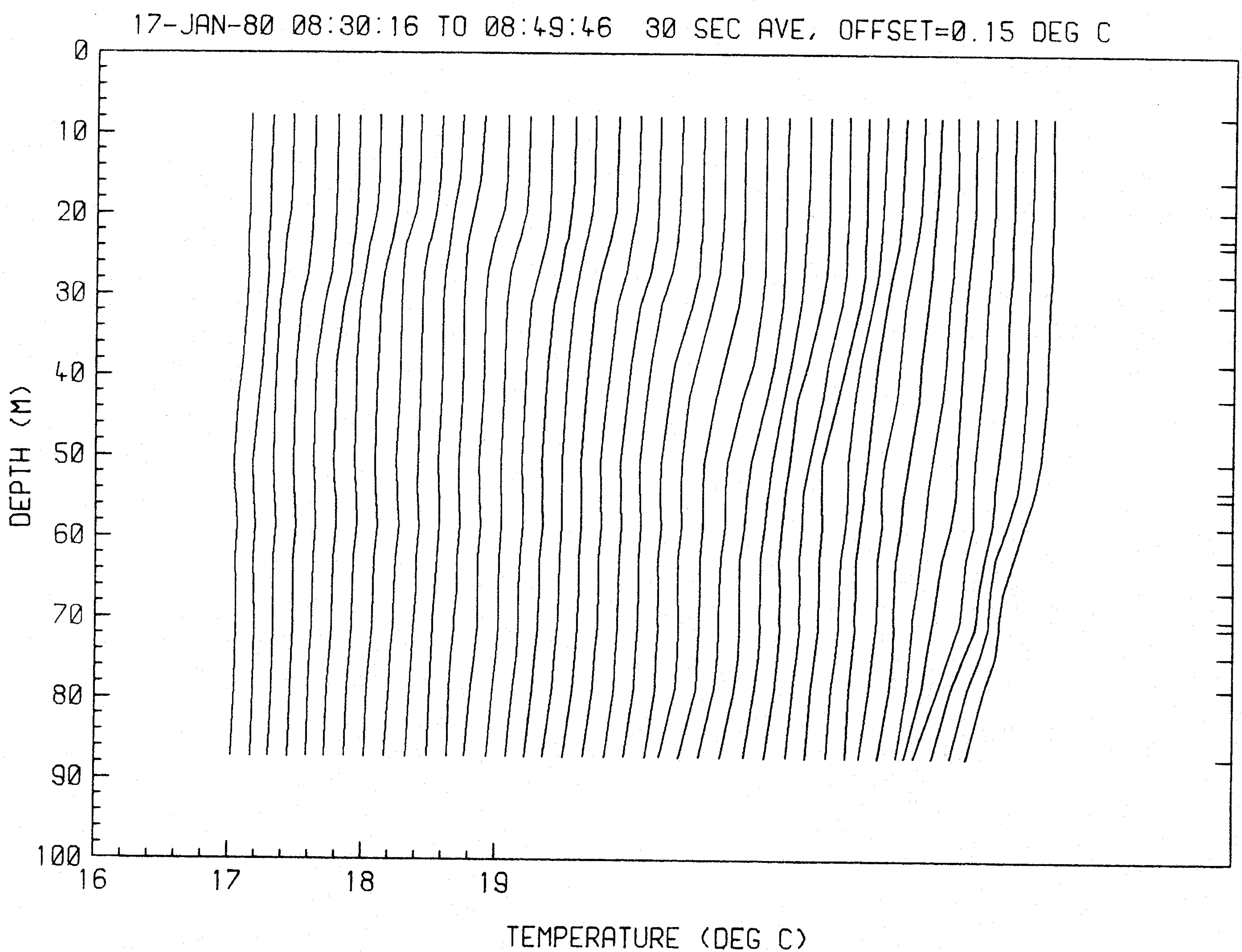
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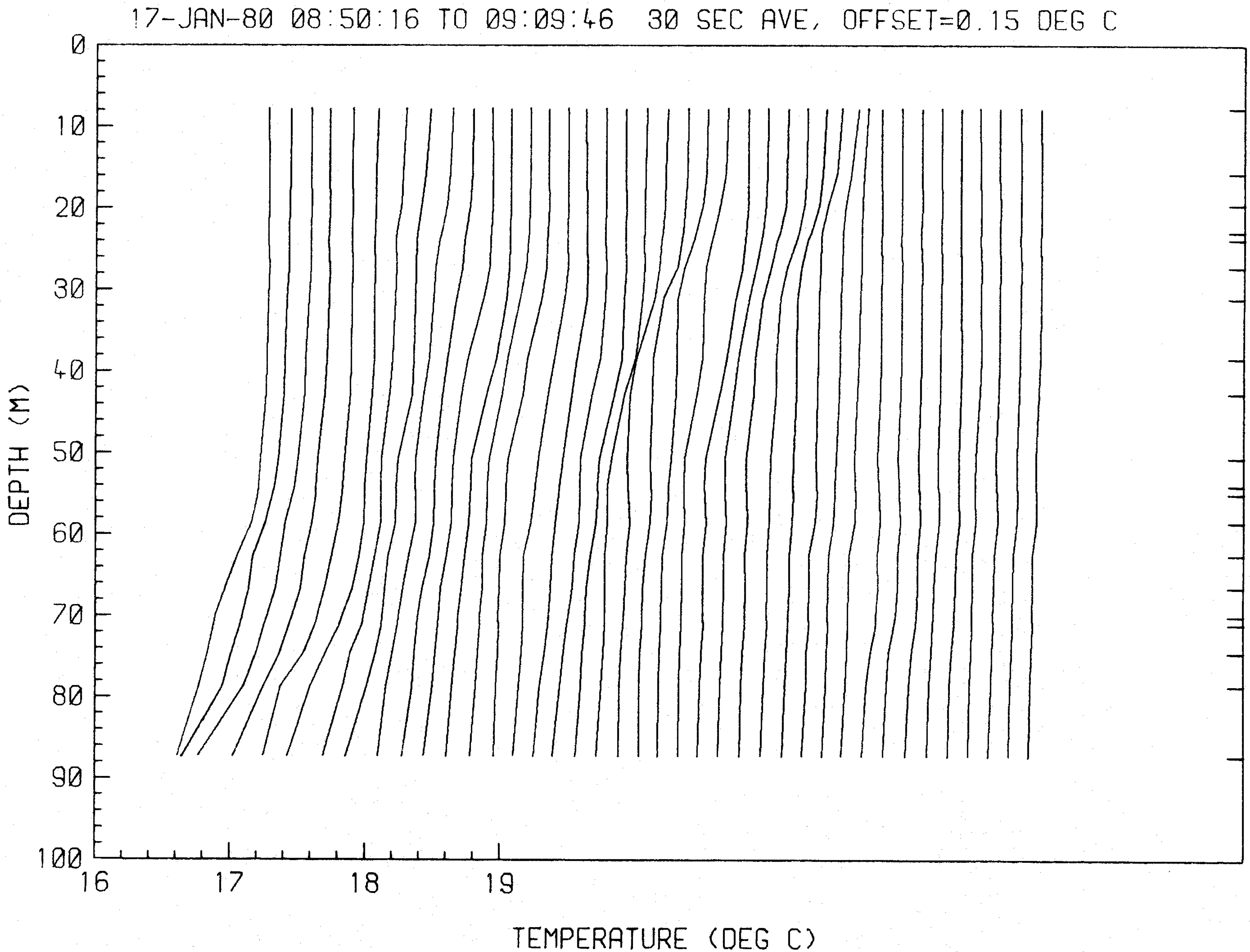
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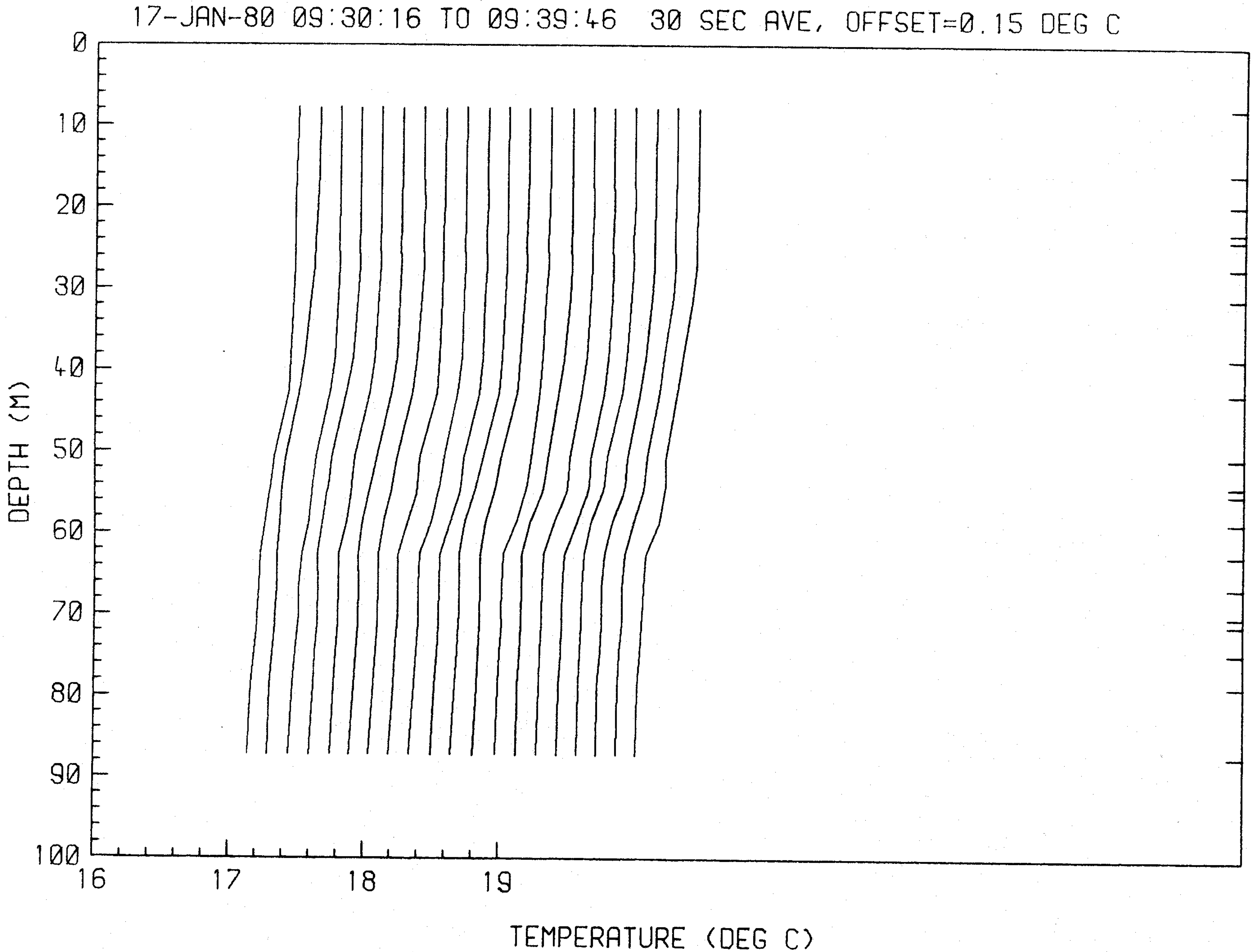
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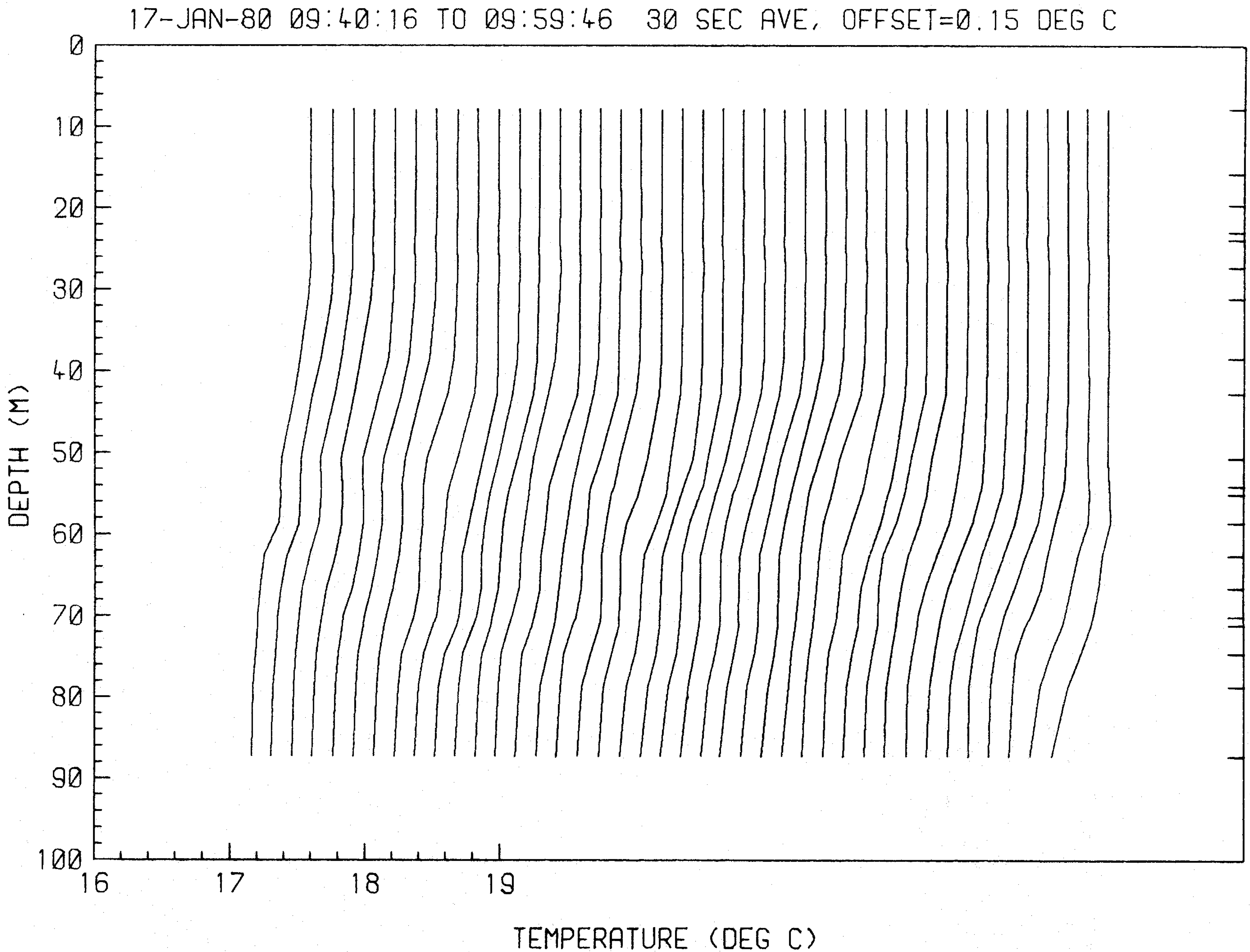
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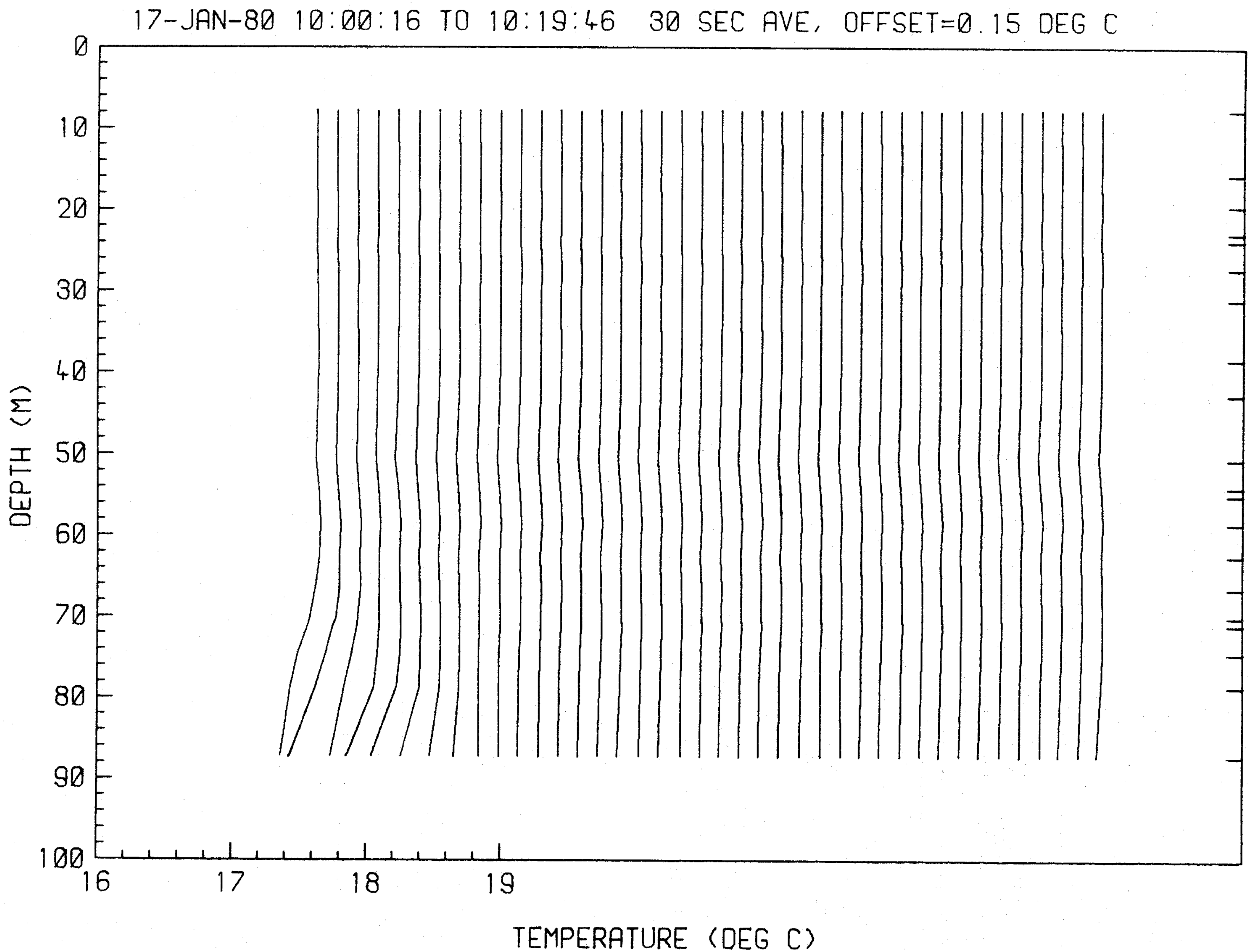
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TEMPERATURE (DEG C)

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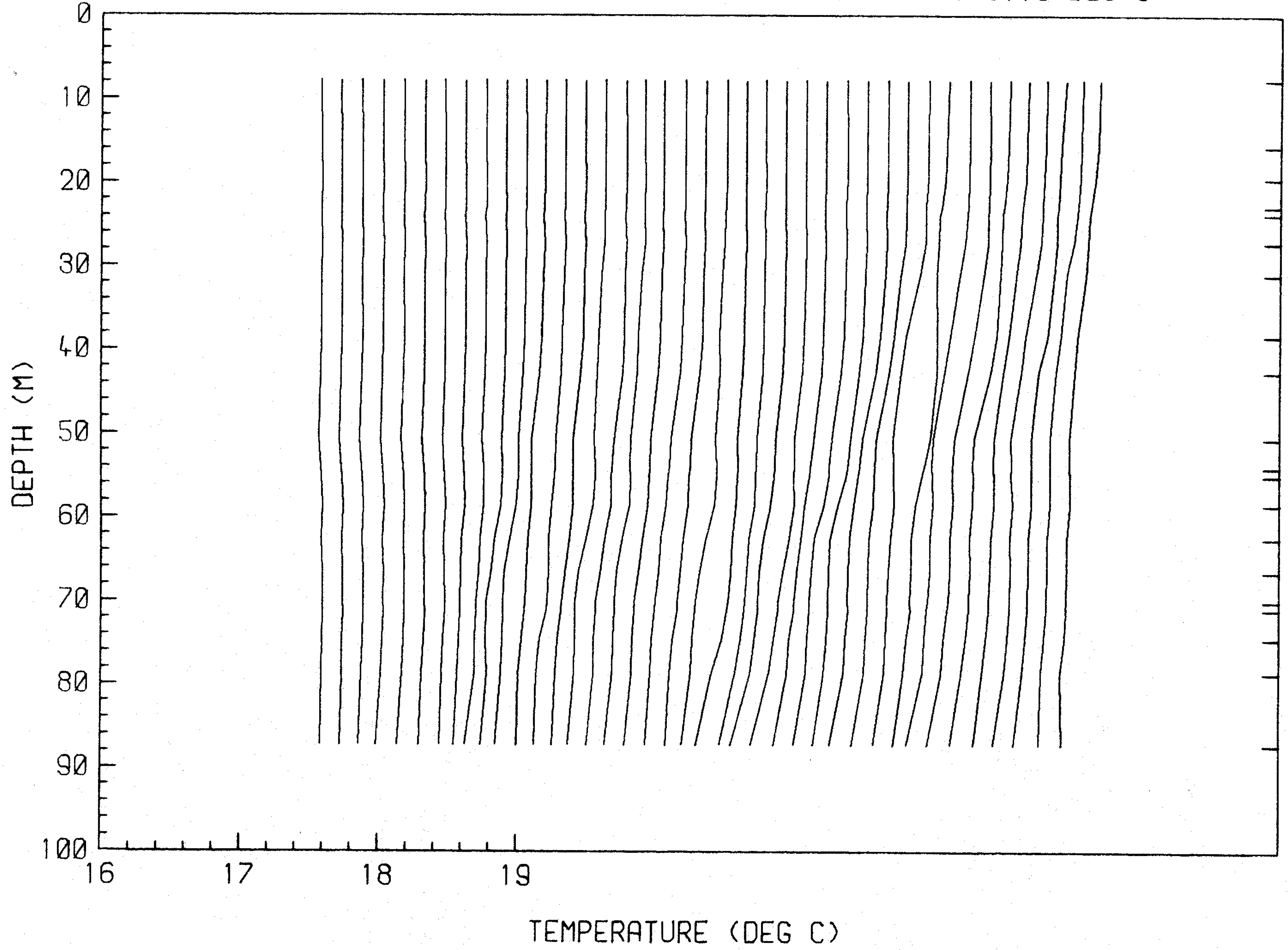

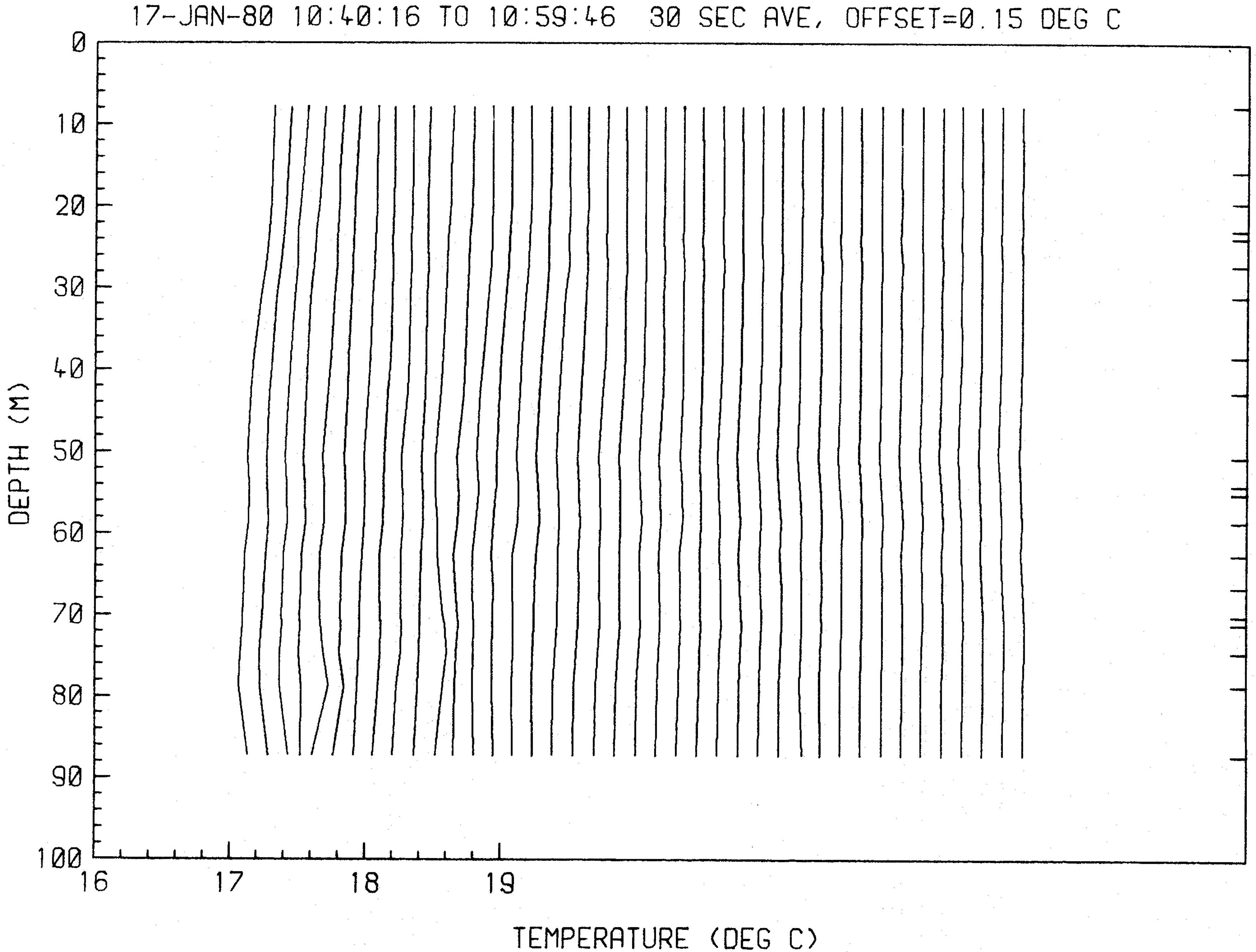
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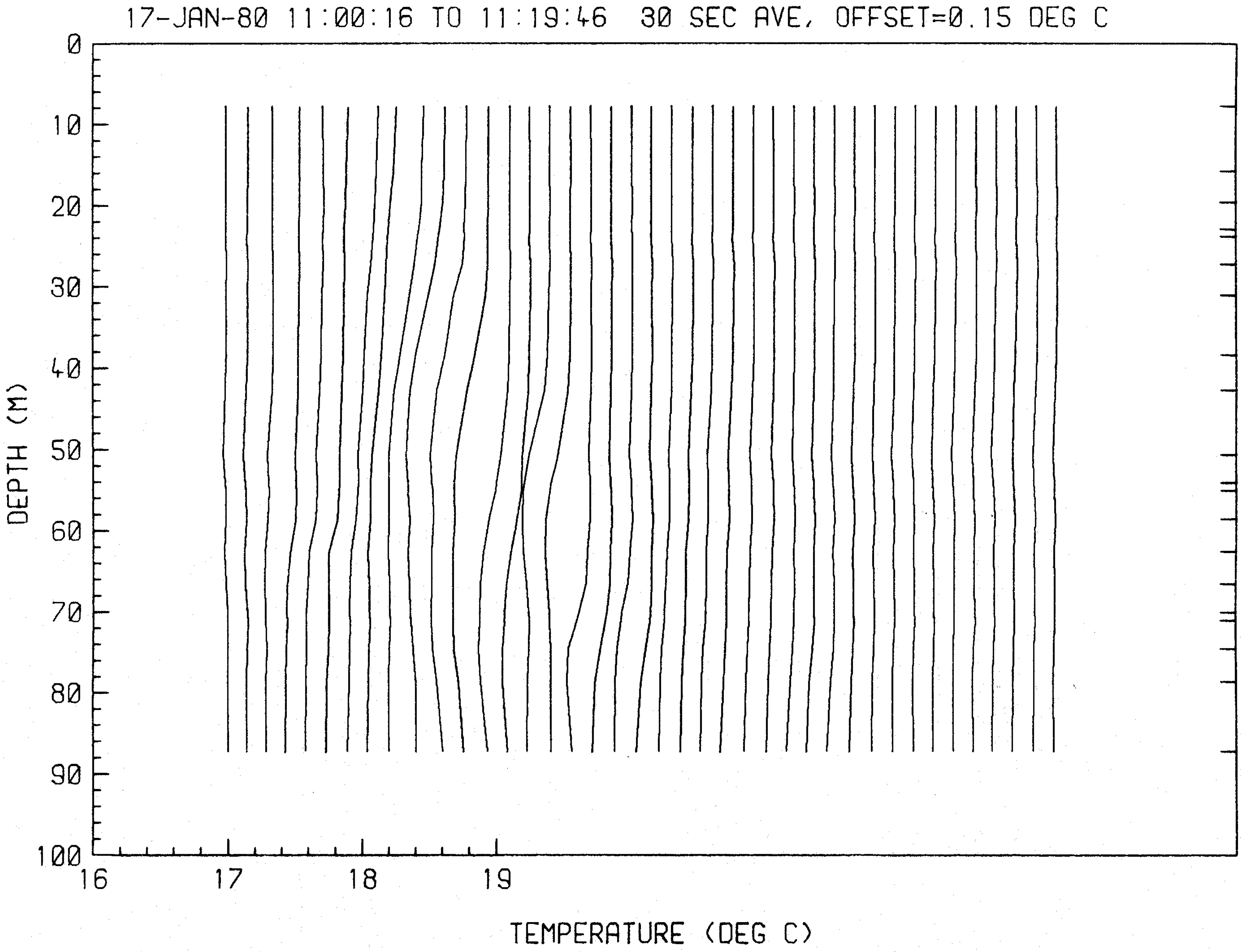
TEMPERATURE (DEG C)



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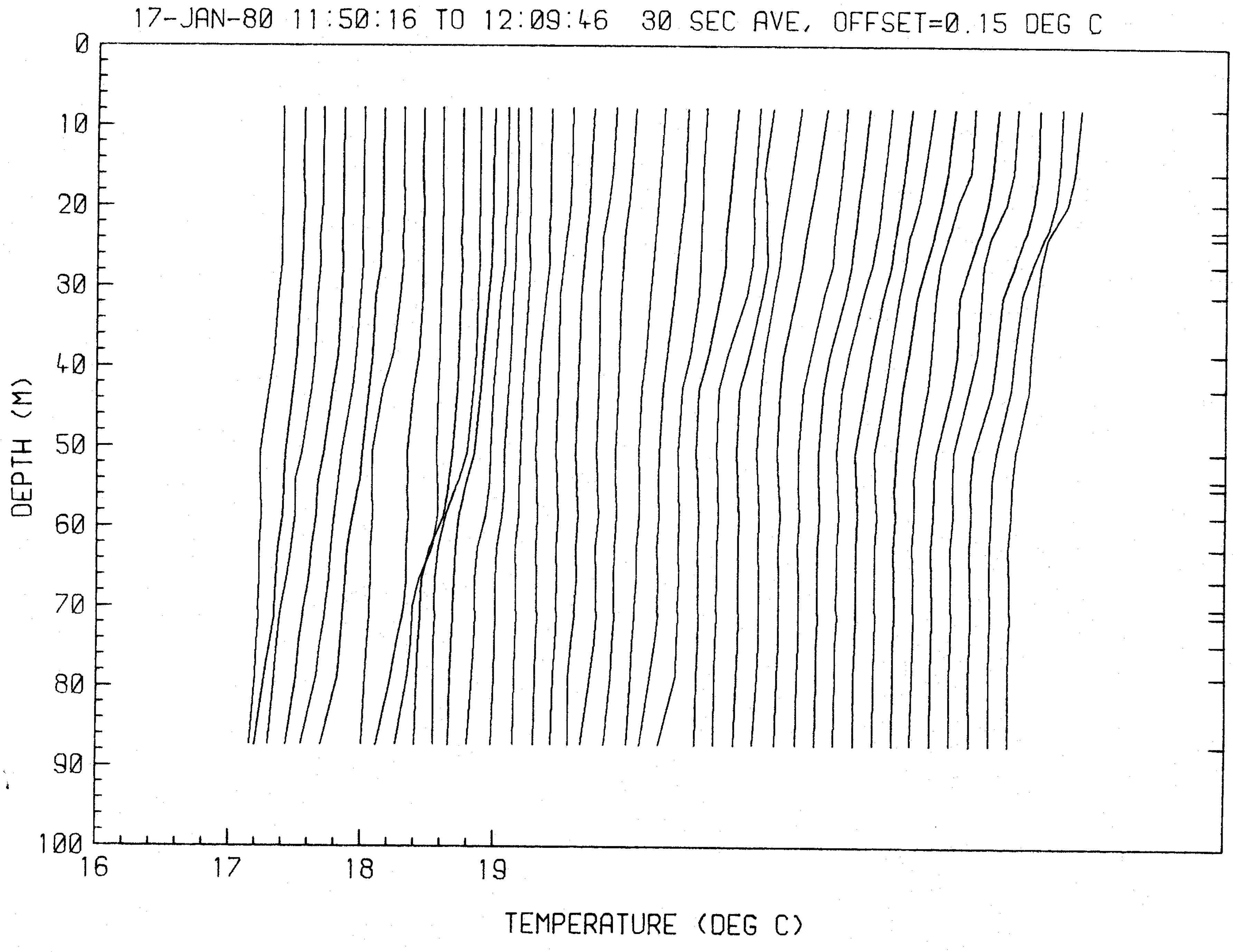
TEMPERATURE (DEG C)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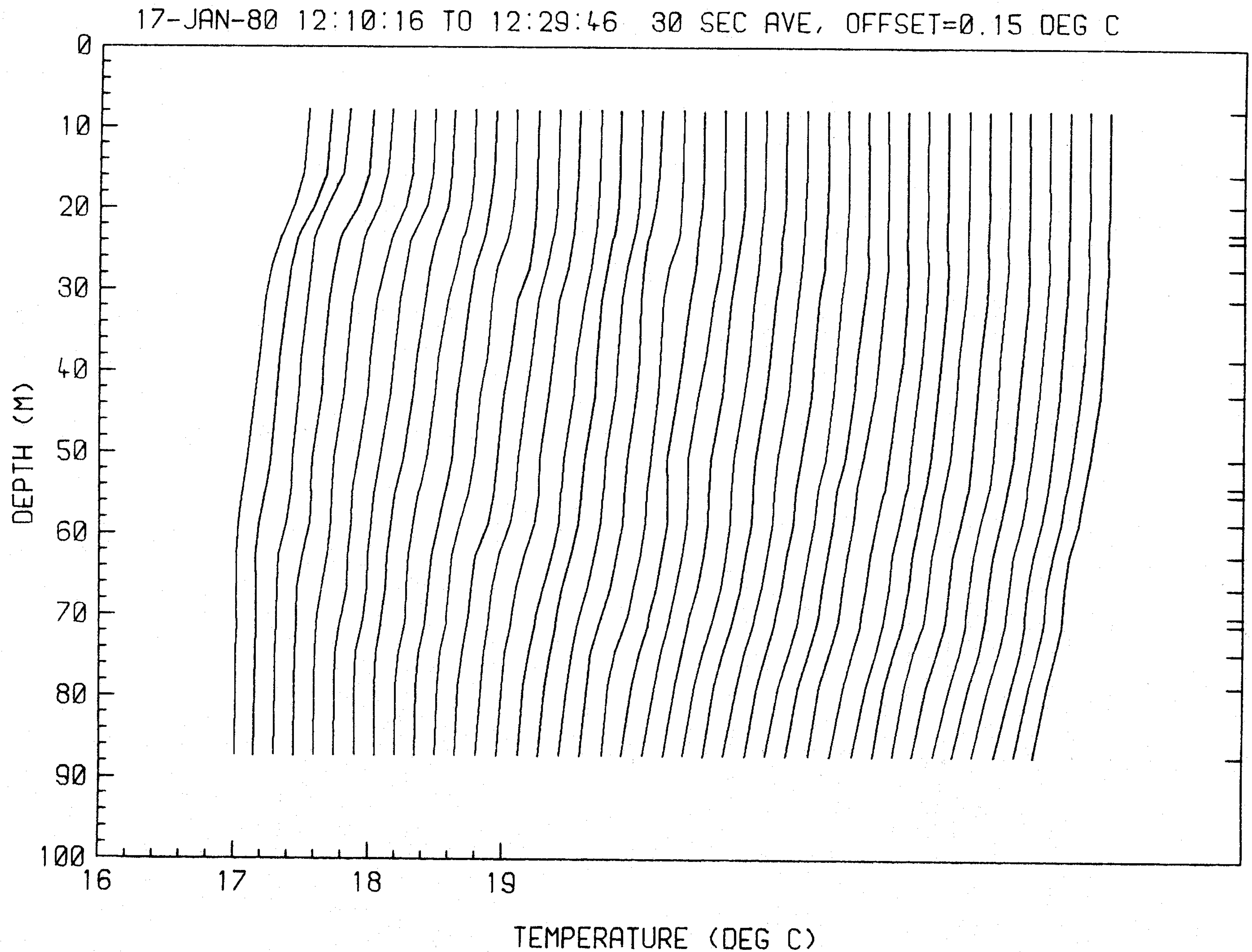
TEMPERATURE (DEG C)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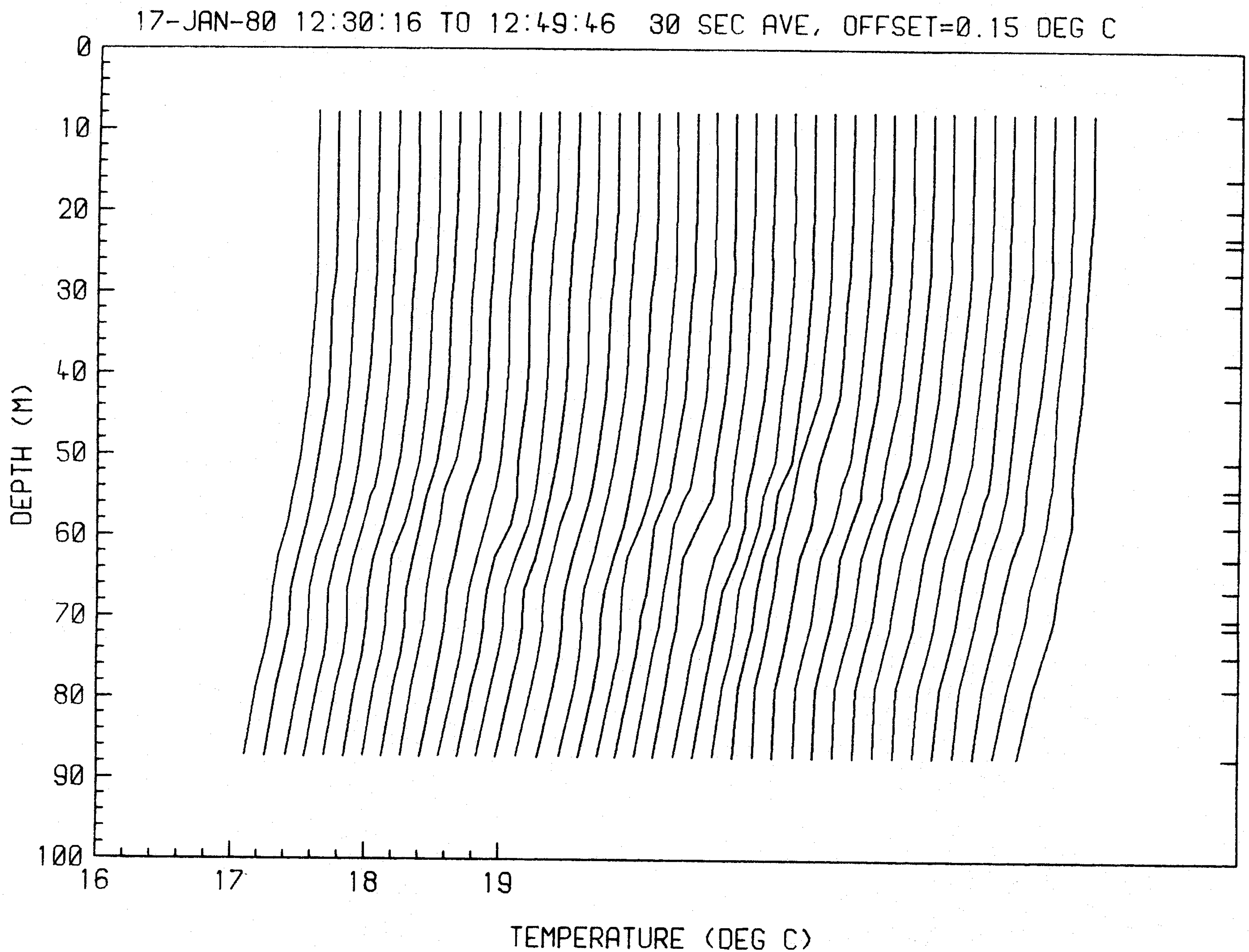
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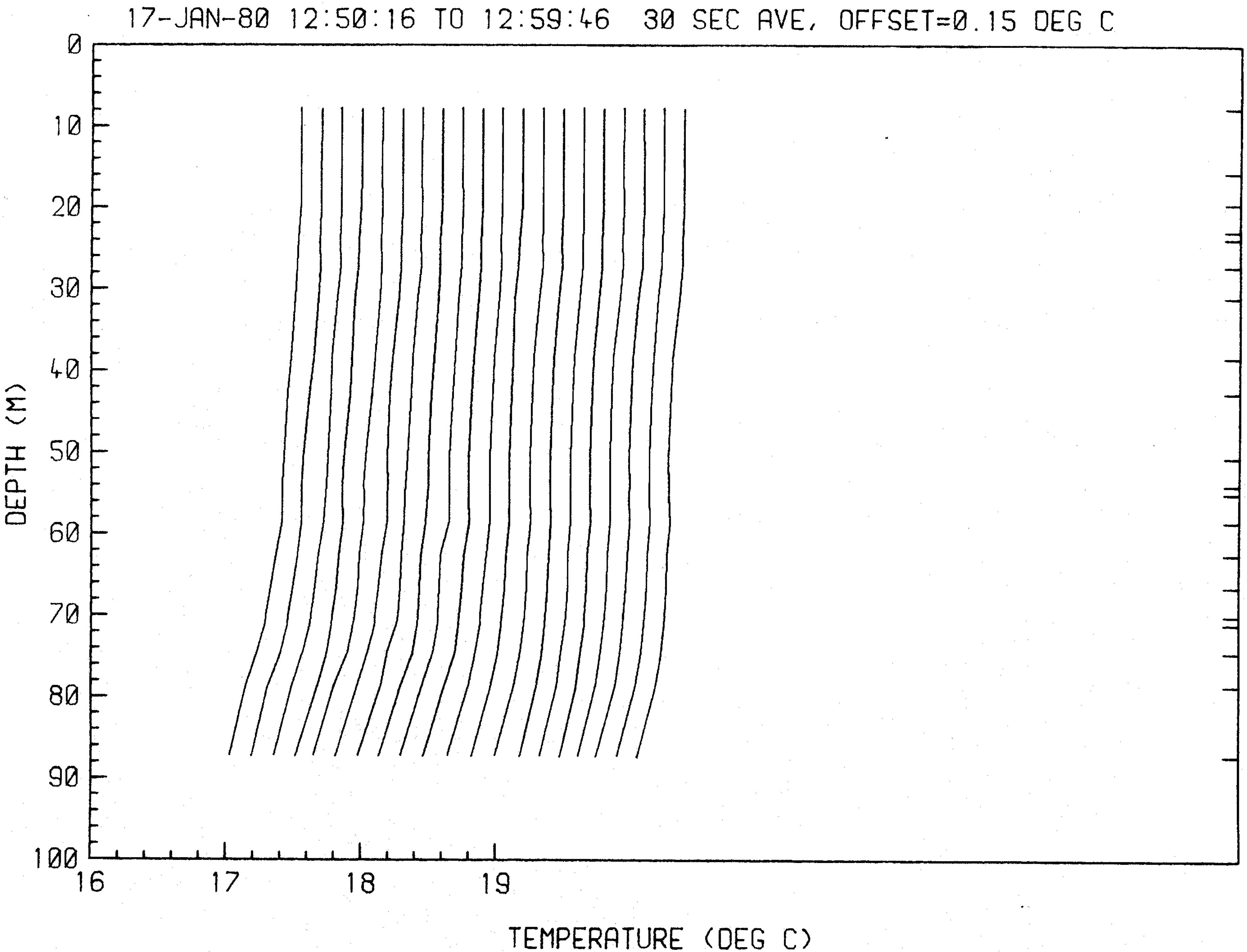
TEMPERATURE (DEG C)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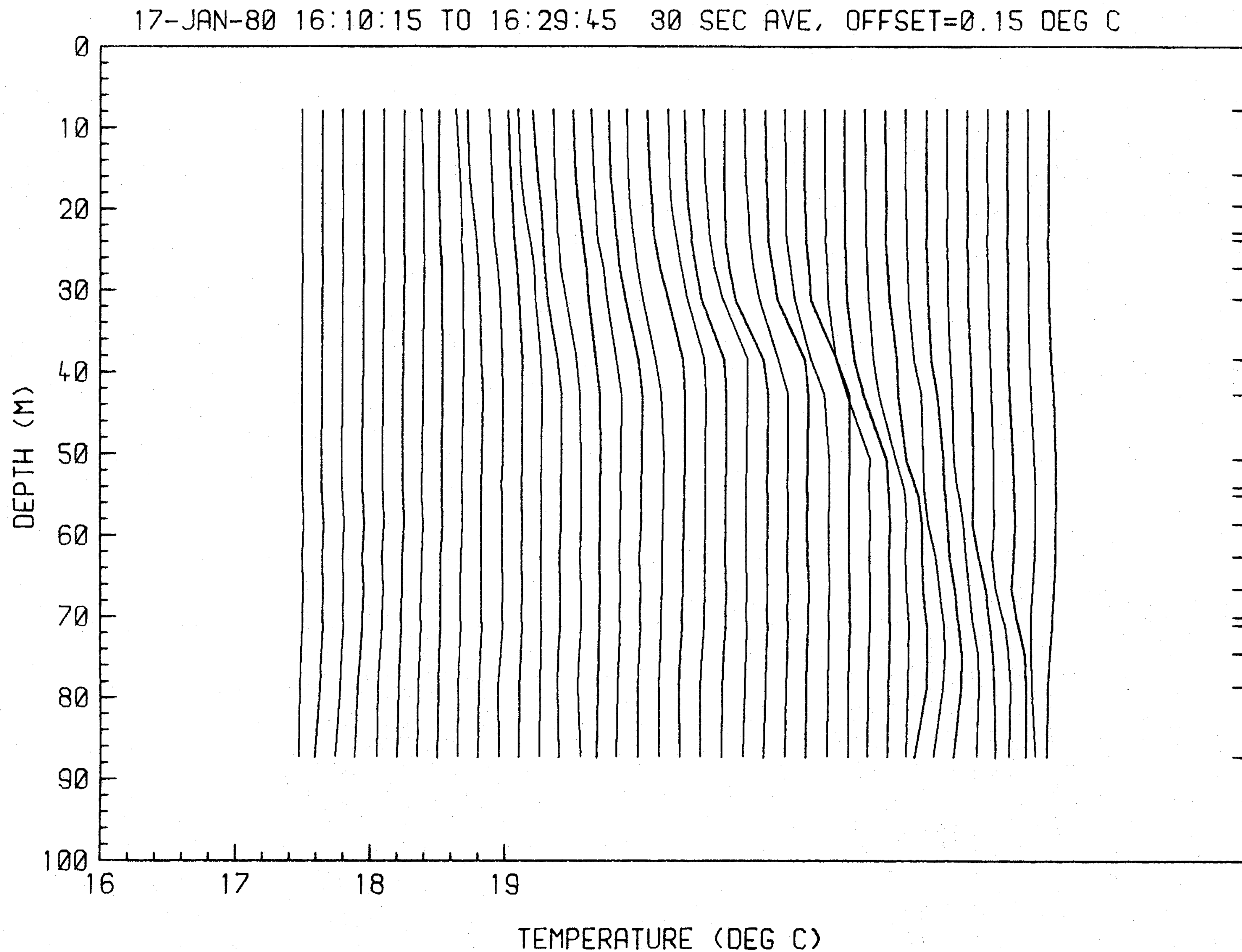

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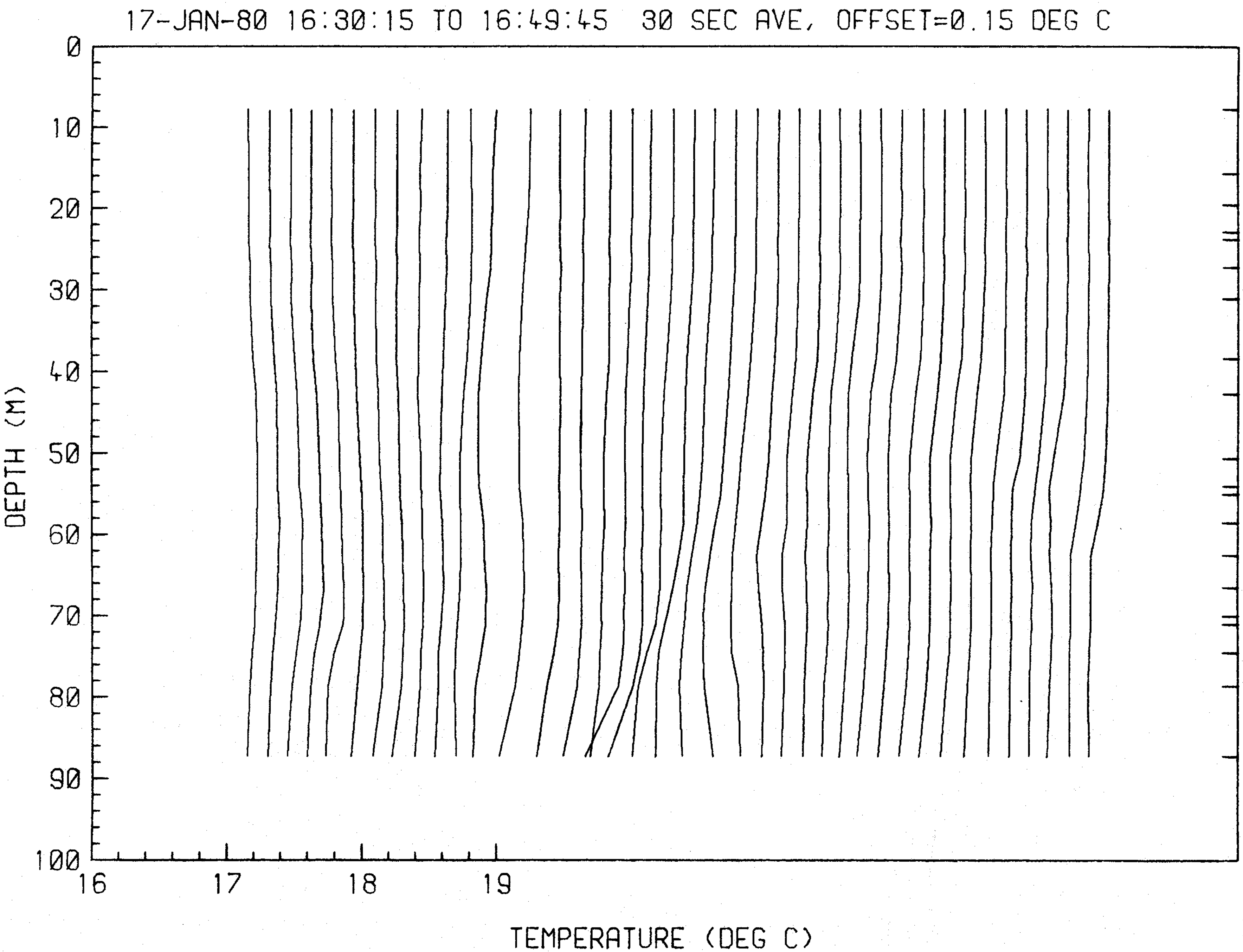
TEMPERATURE (DEG C)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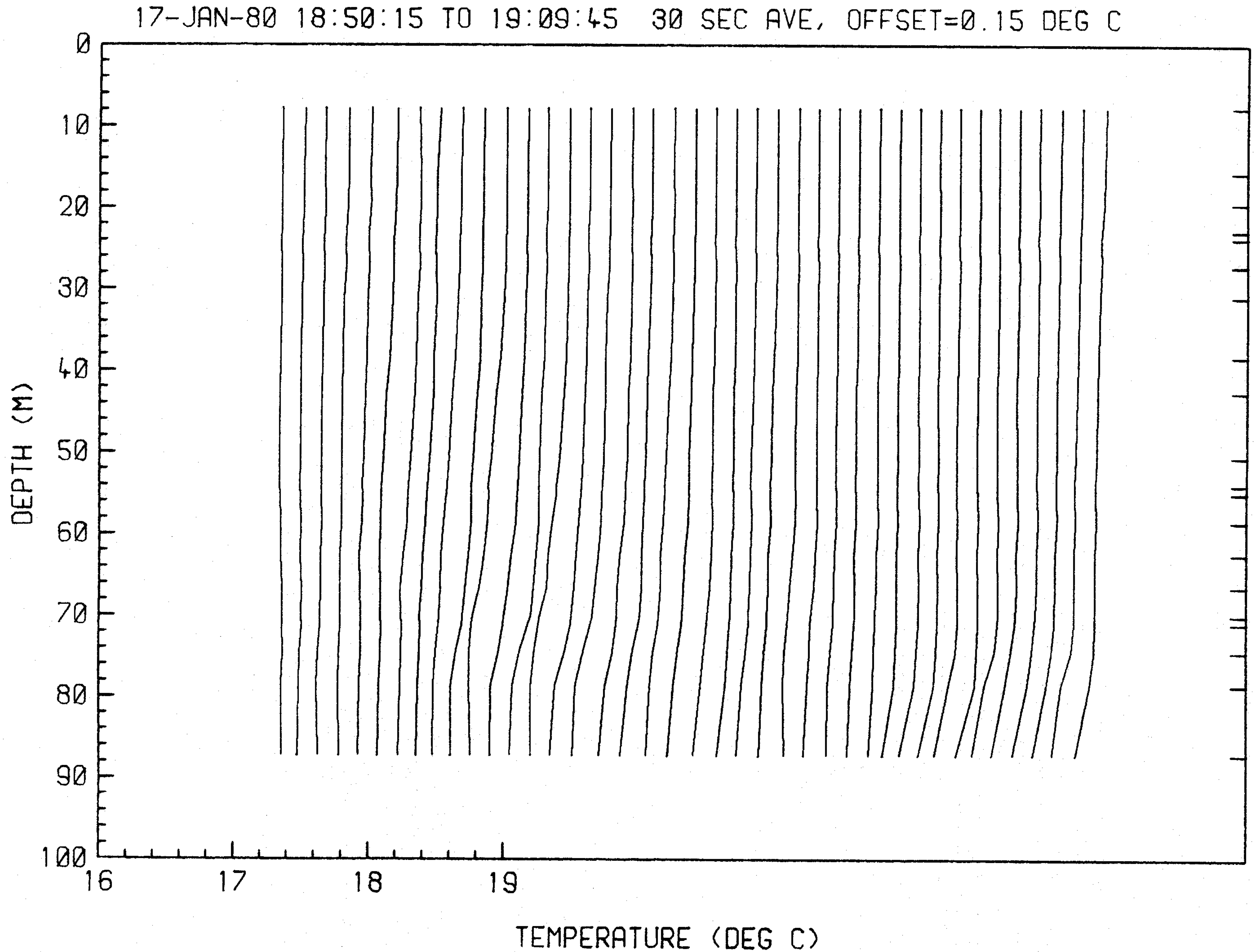
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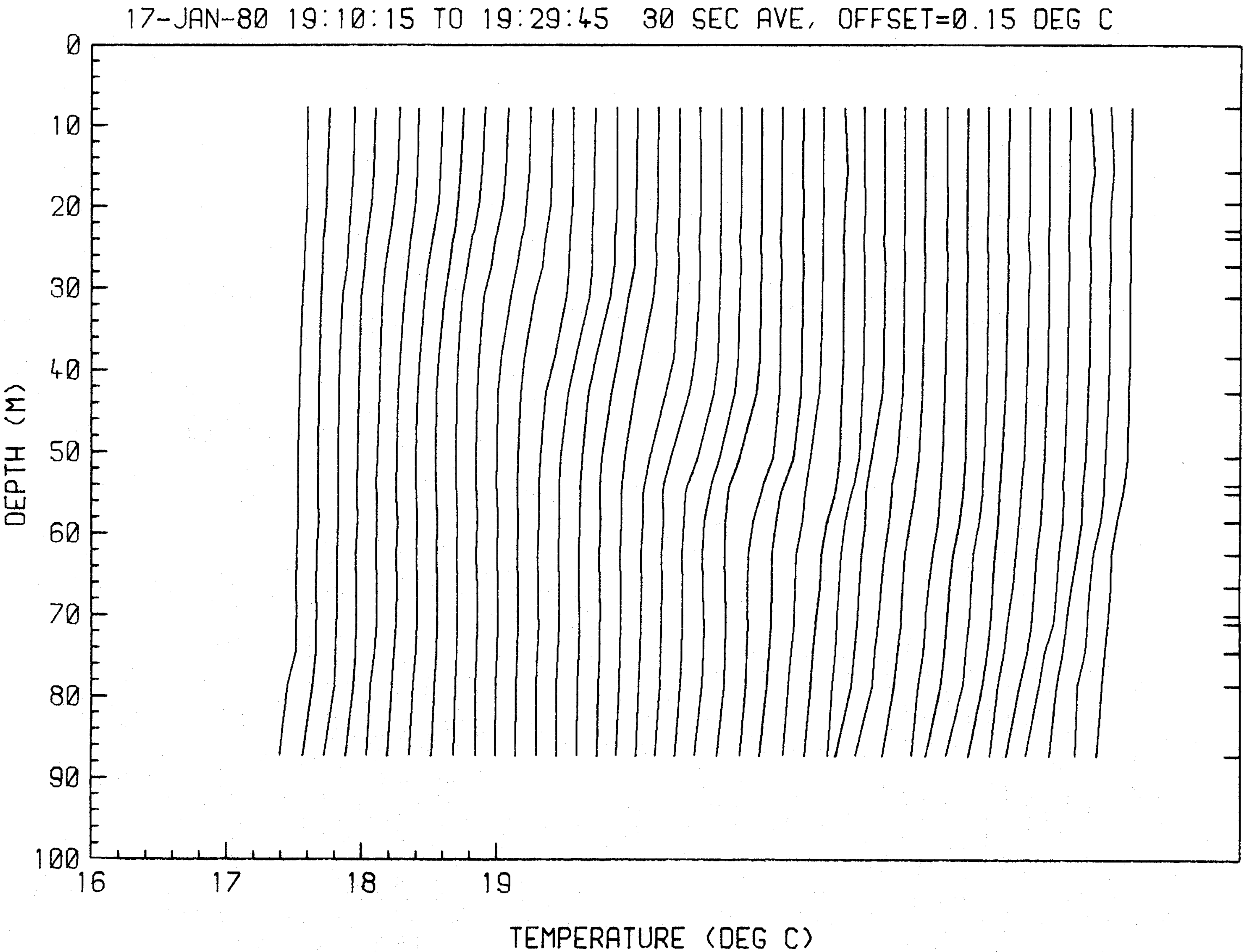
TEMPERATURE (DEG C)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TEMPERATURE (DEG C)

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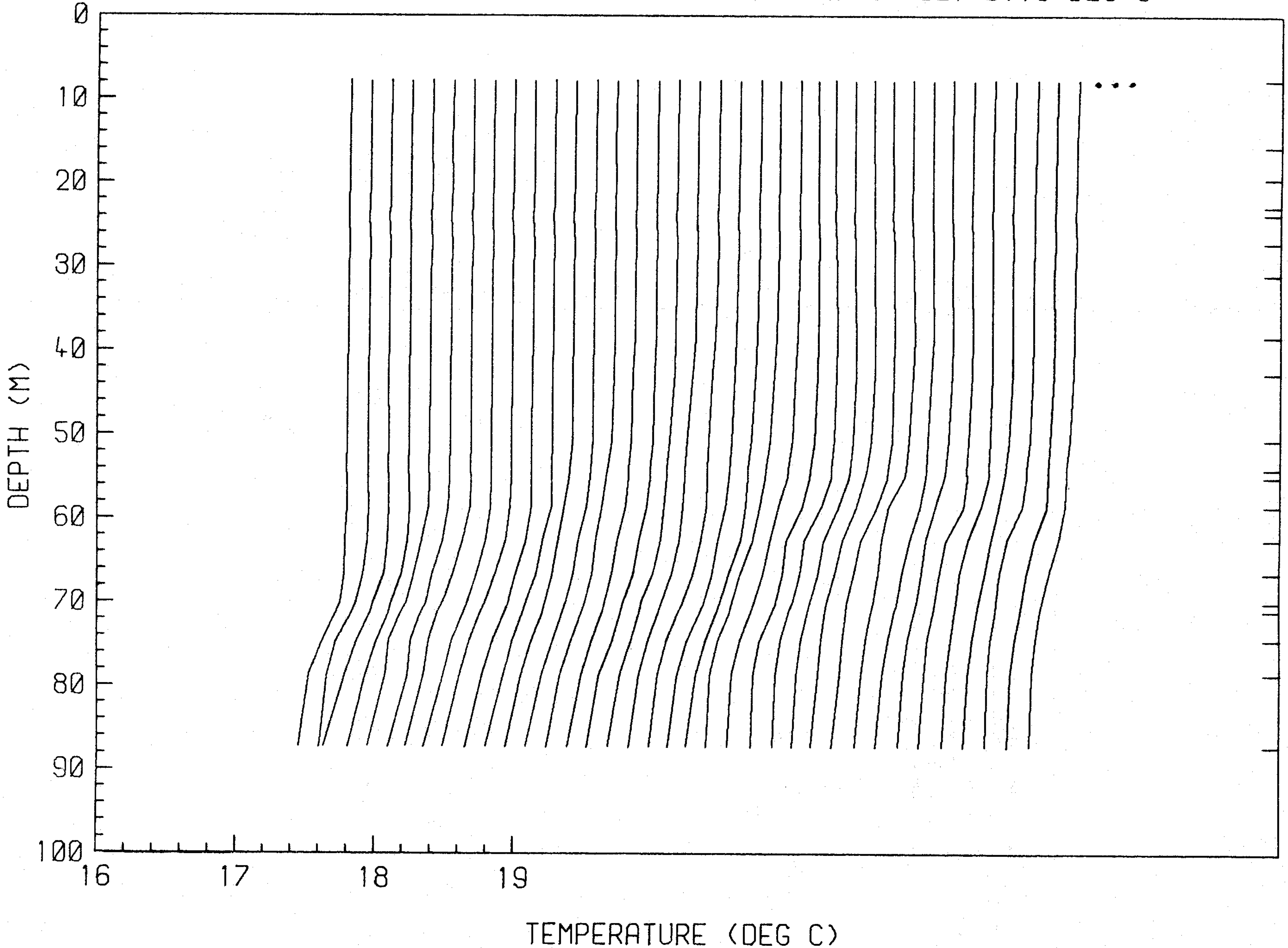

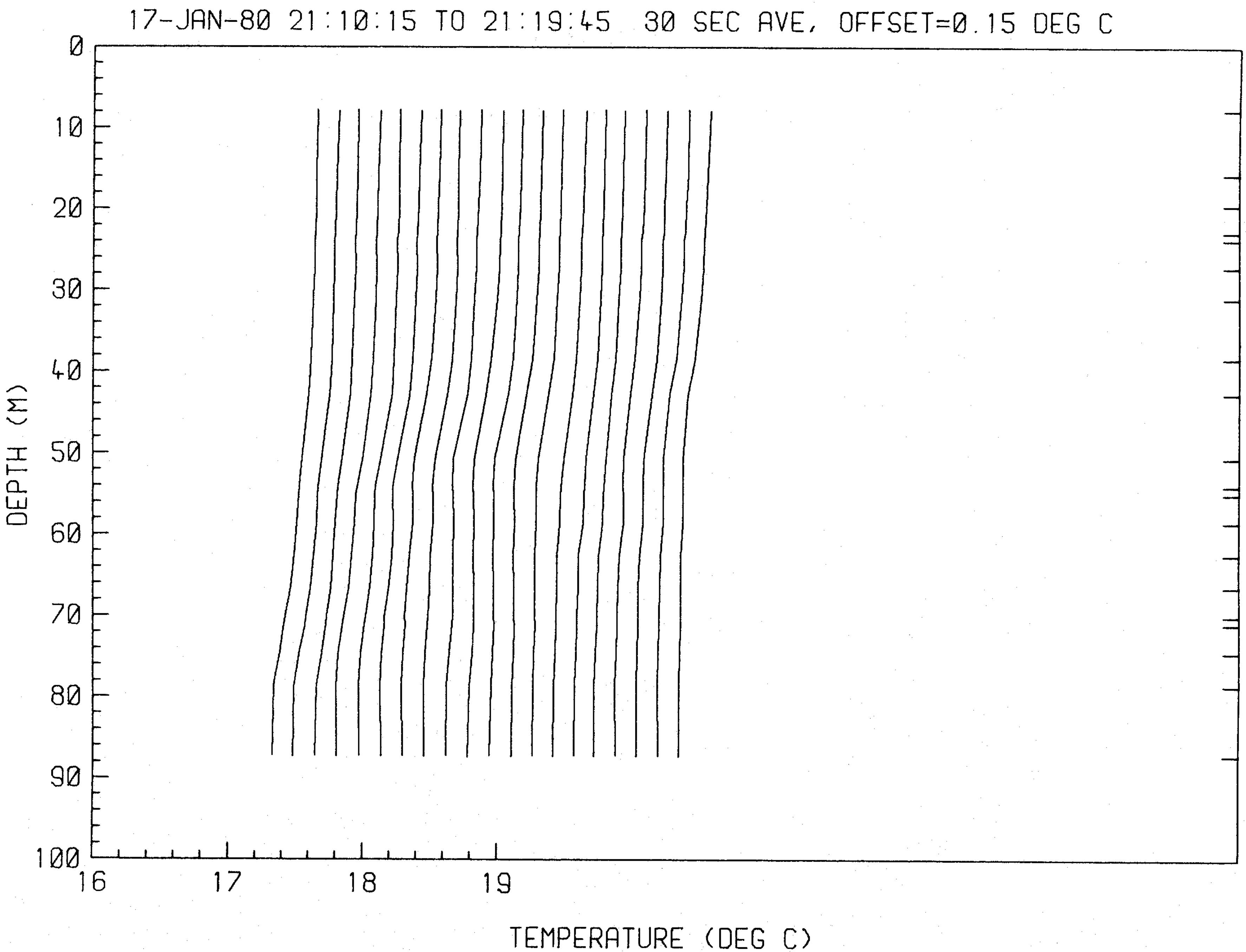
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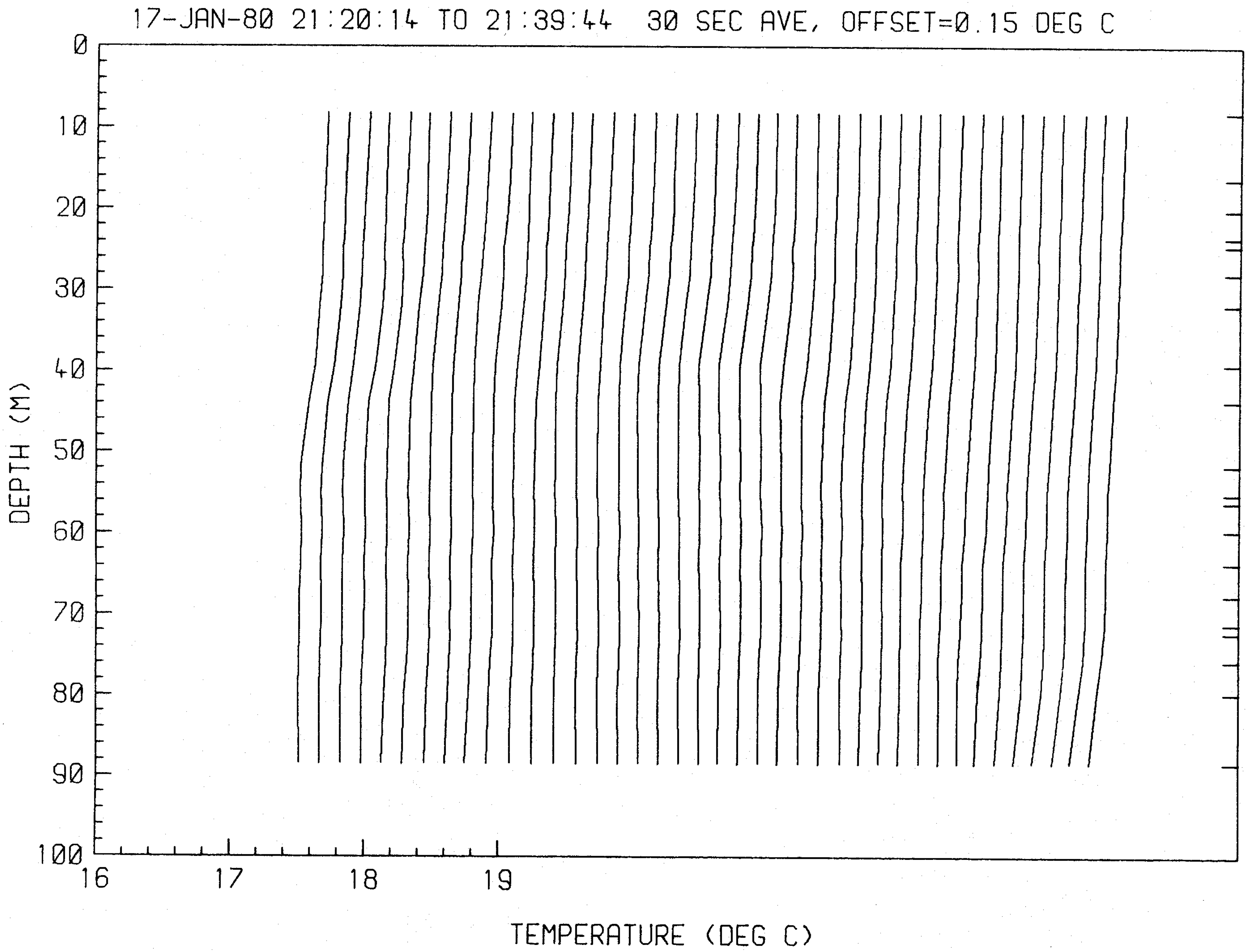
TEMPERATURE (DEG C)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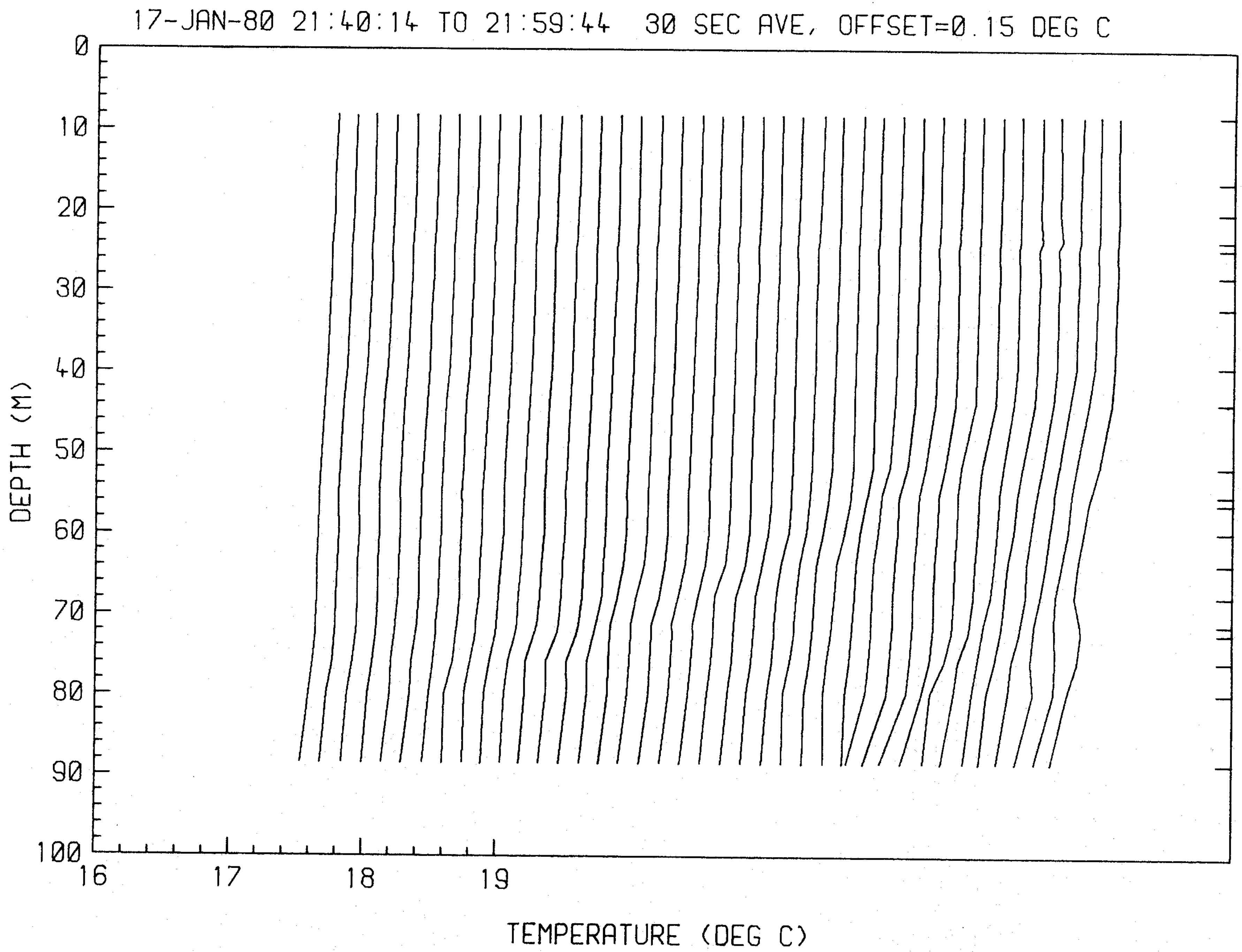
TEMPERATURE (DEG C)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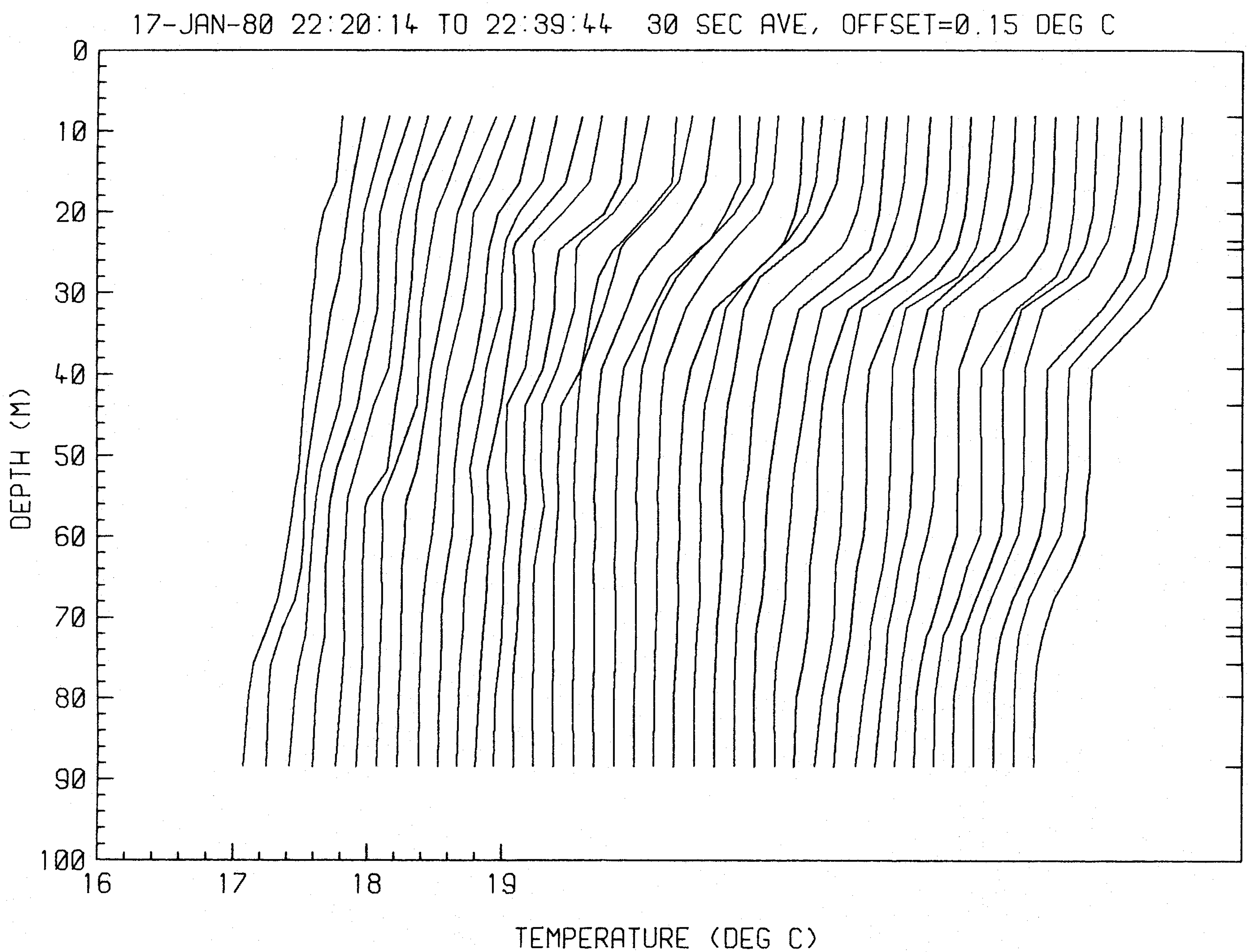
TEMPERATURE (DEG C)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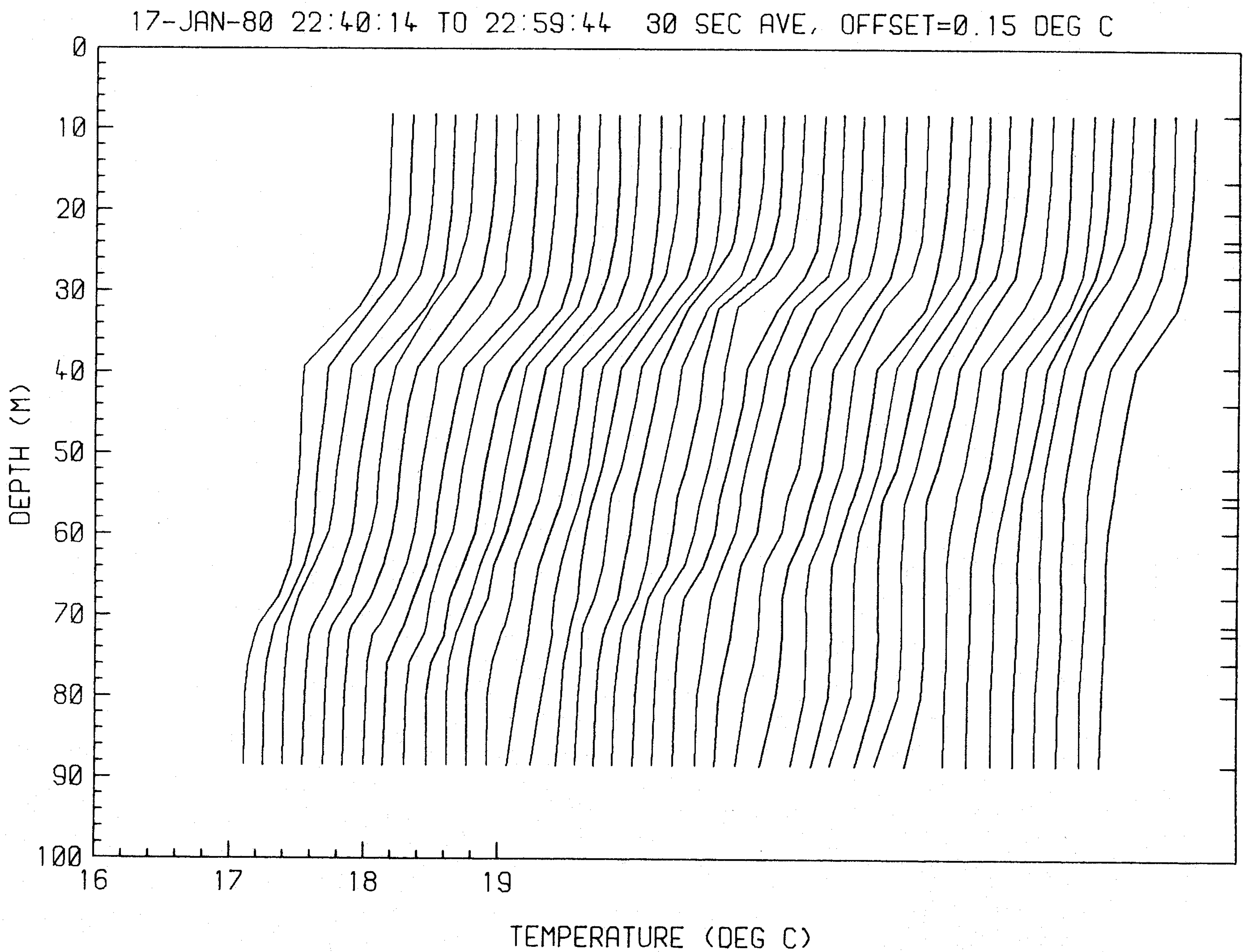
TEMPERATURE (DEG C)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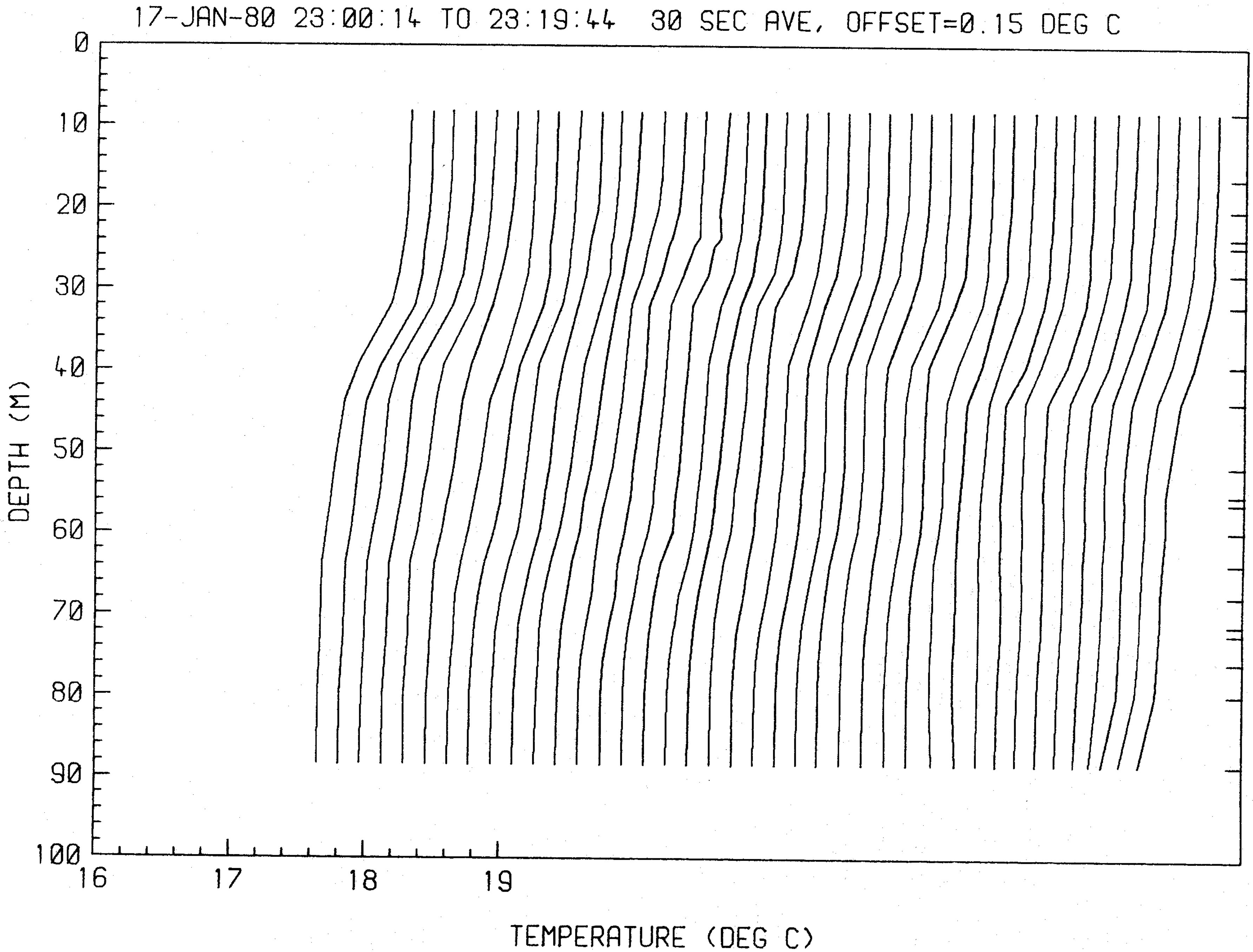
TEMPERATURE (DEG C)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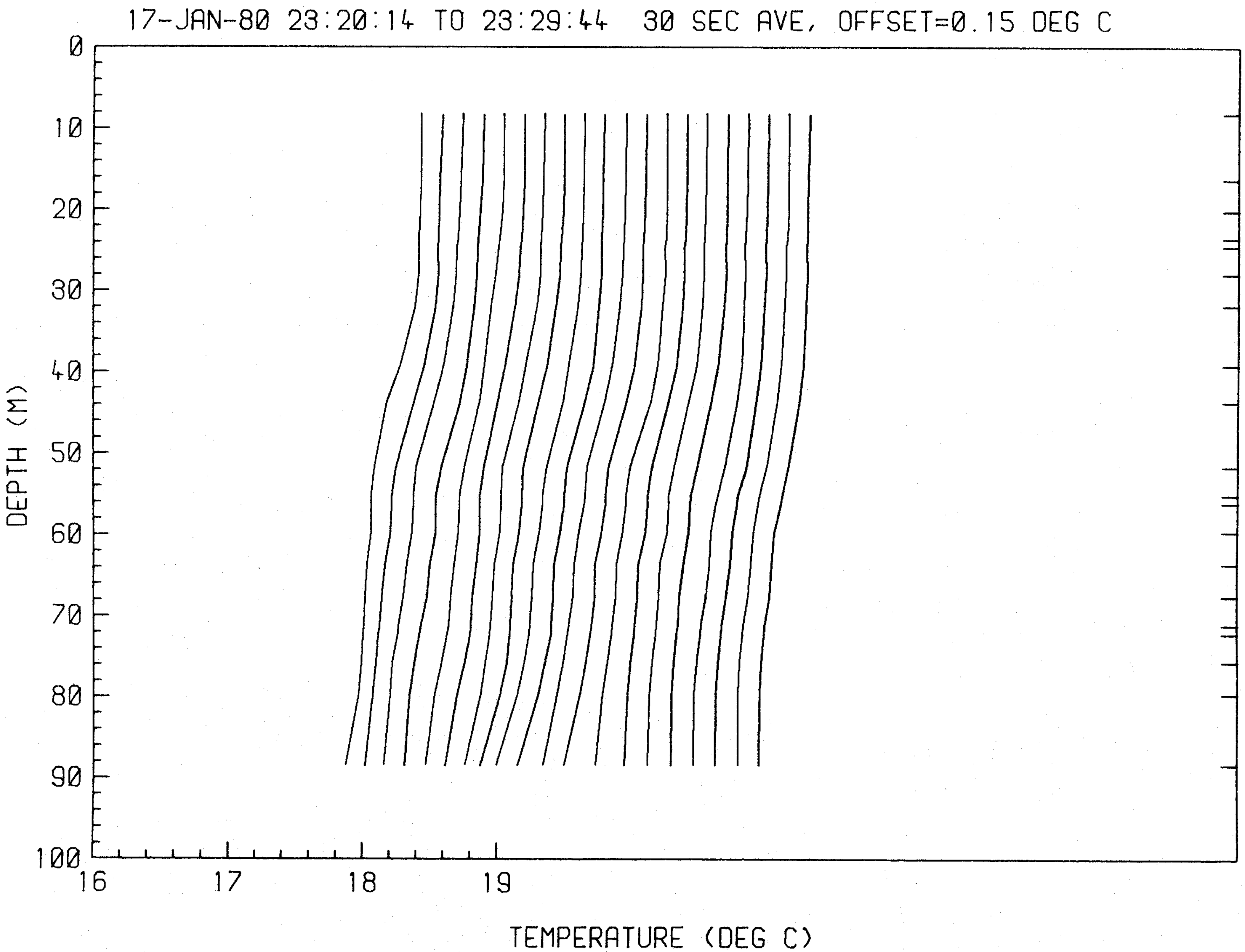
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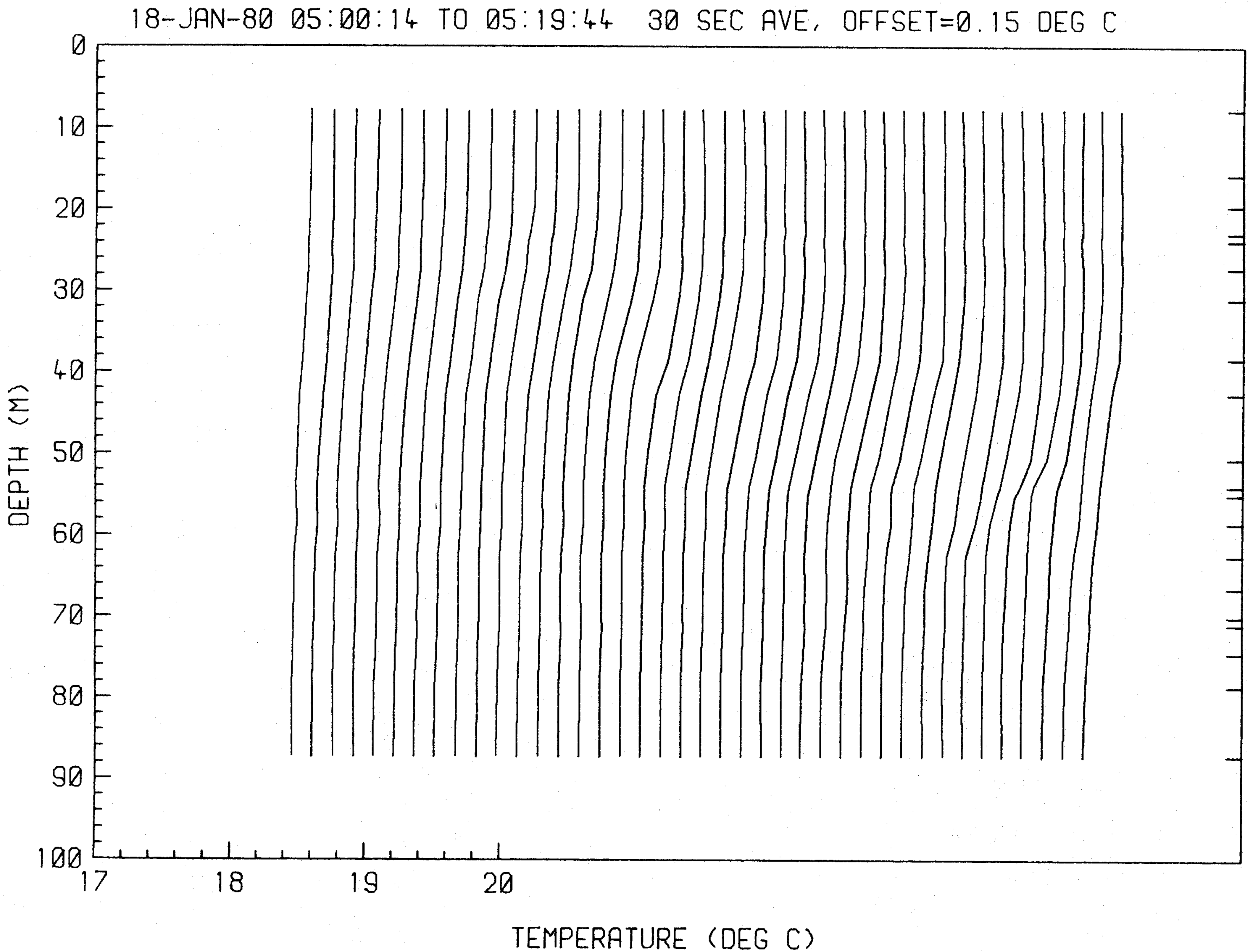
TEMPERATURE (DEG C)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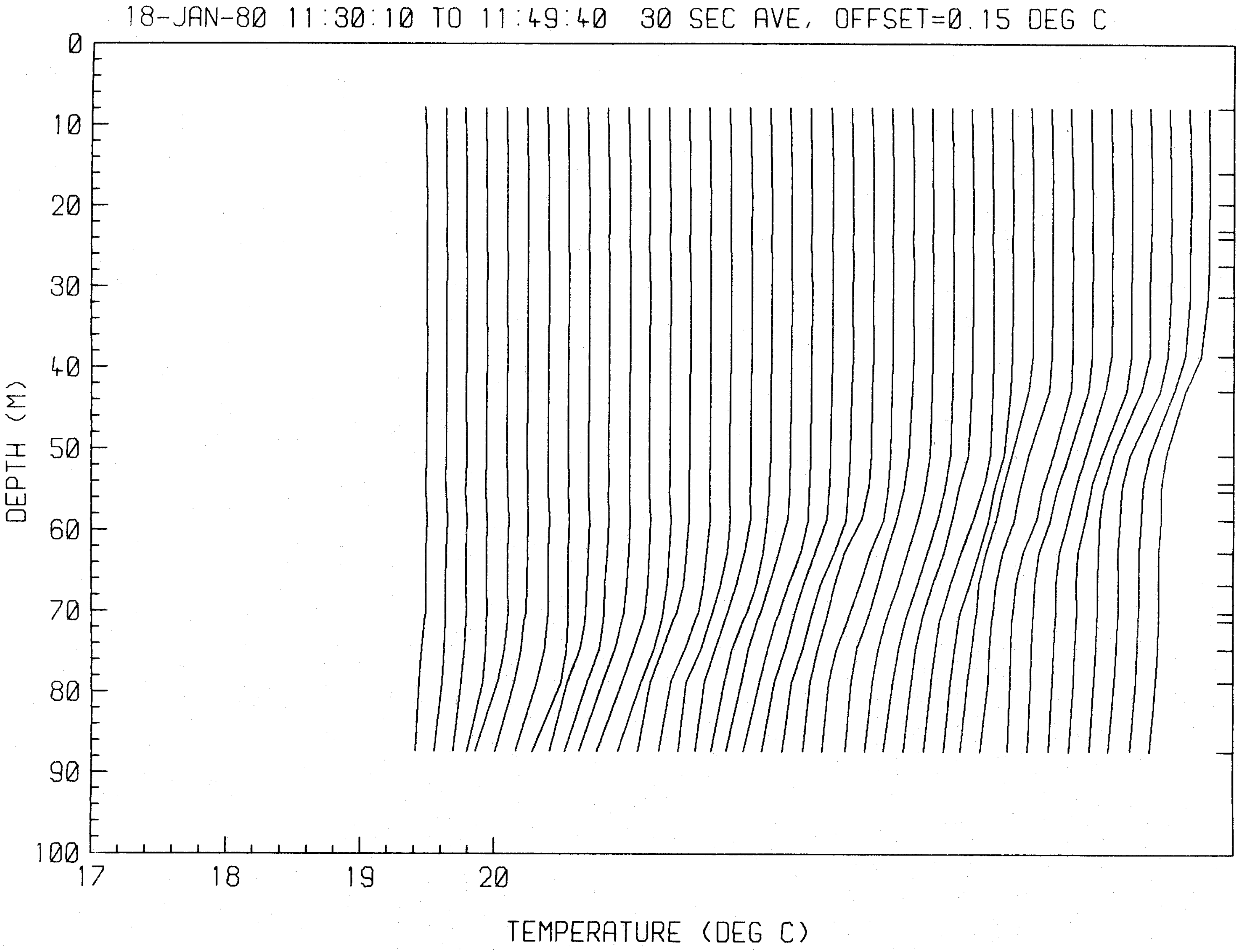
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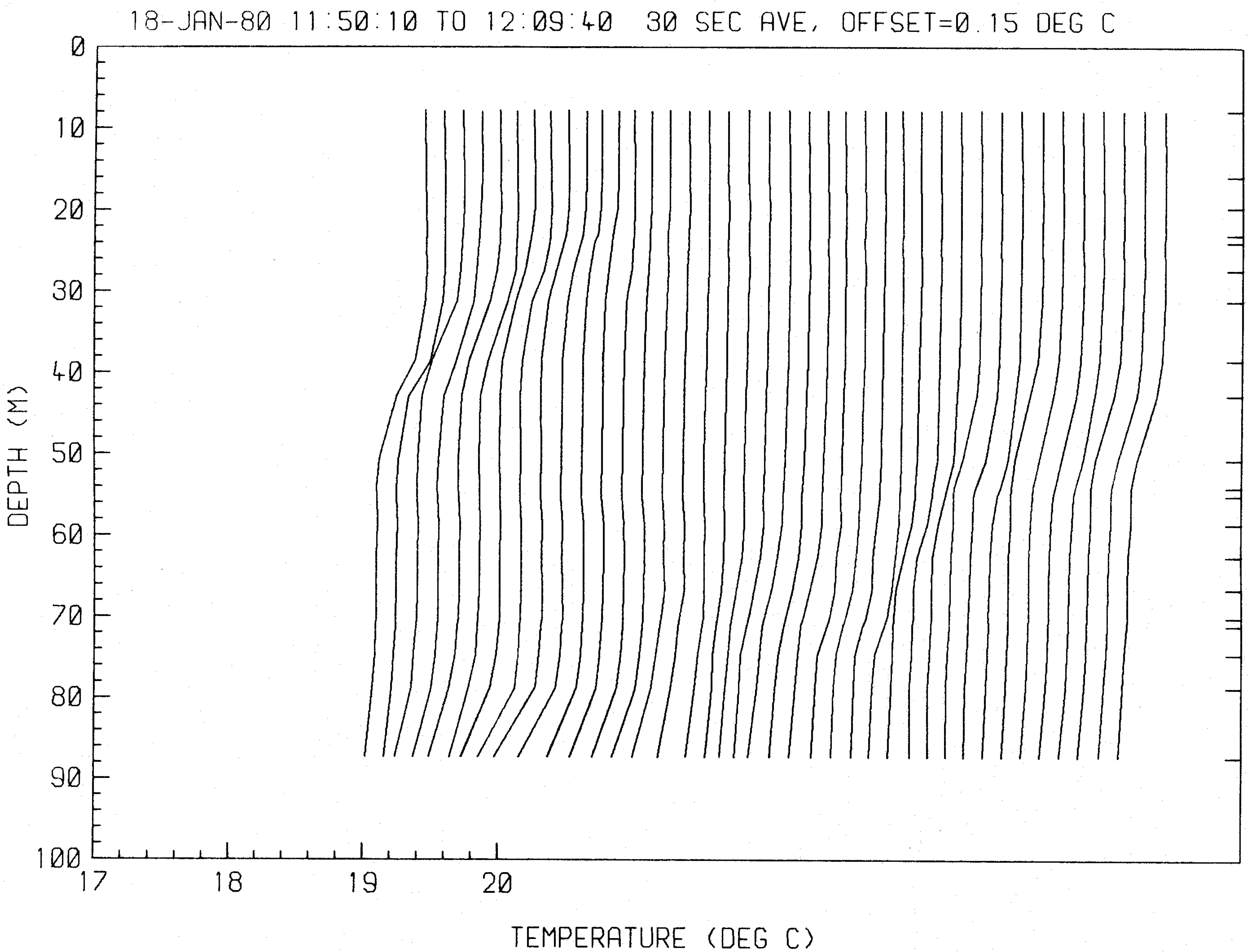
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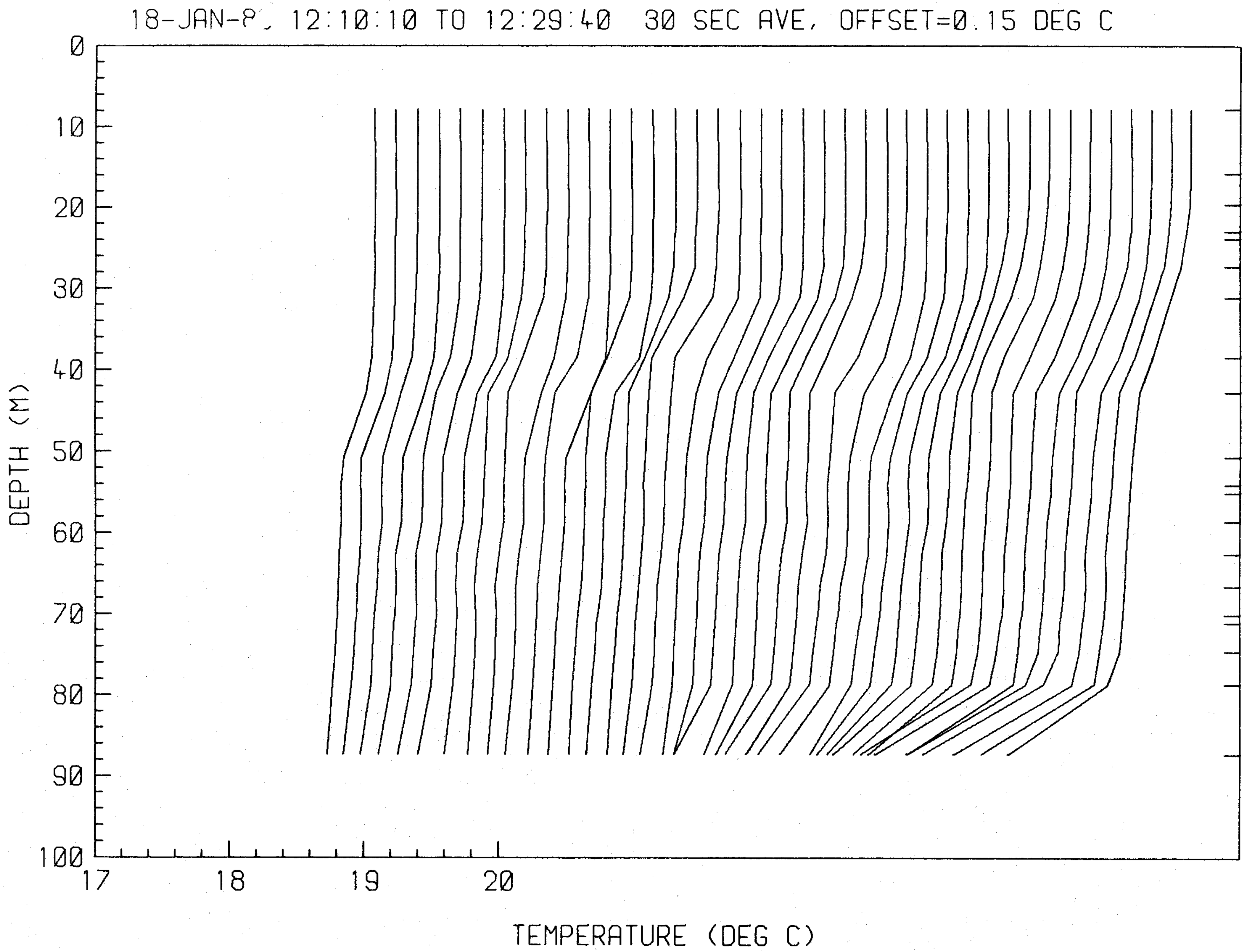
TEMPERATURE (DEG C)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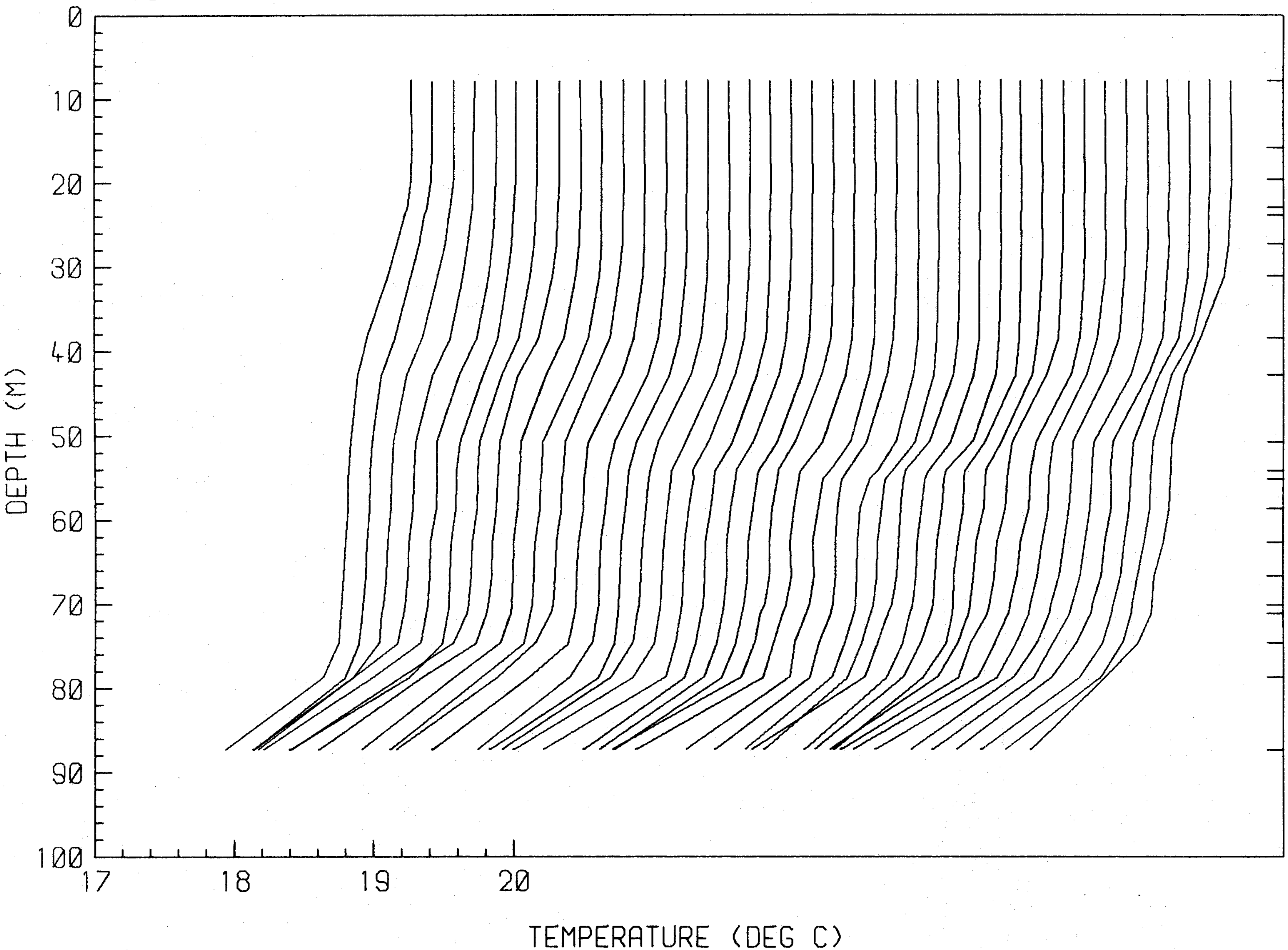
TEMPERATURE (DEG C)

18-JAN-80 12:30:10 TO 12:49:40 30 SEC AVE, OFFSET=0.15 DEG C



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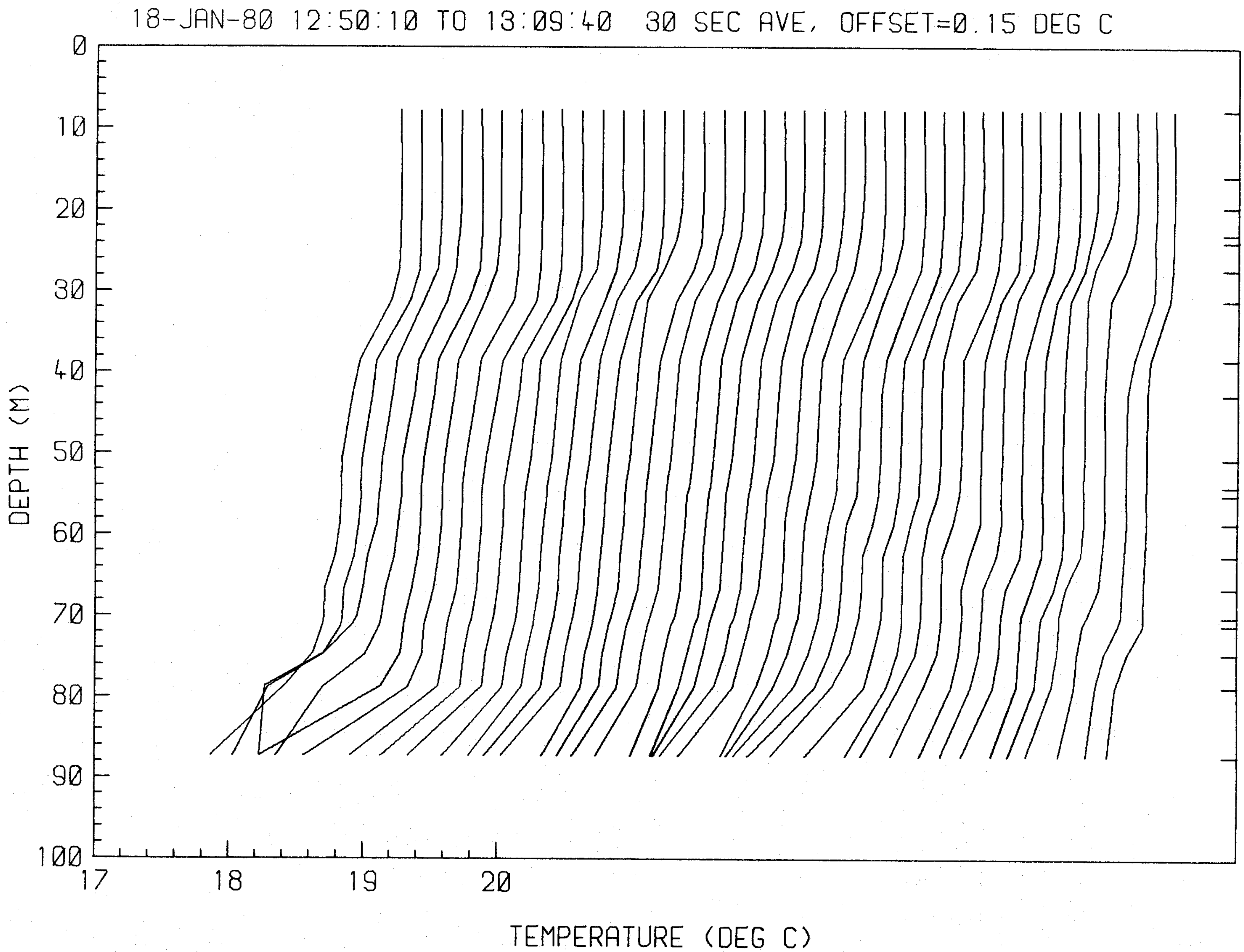
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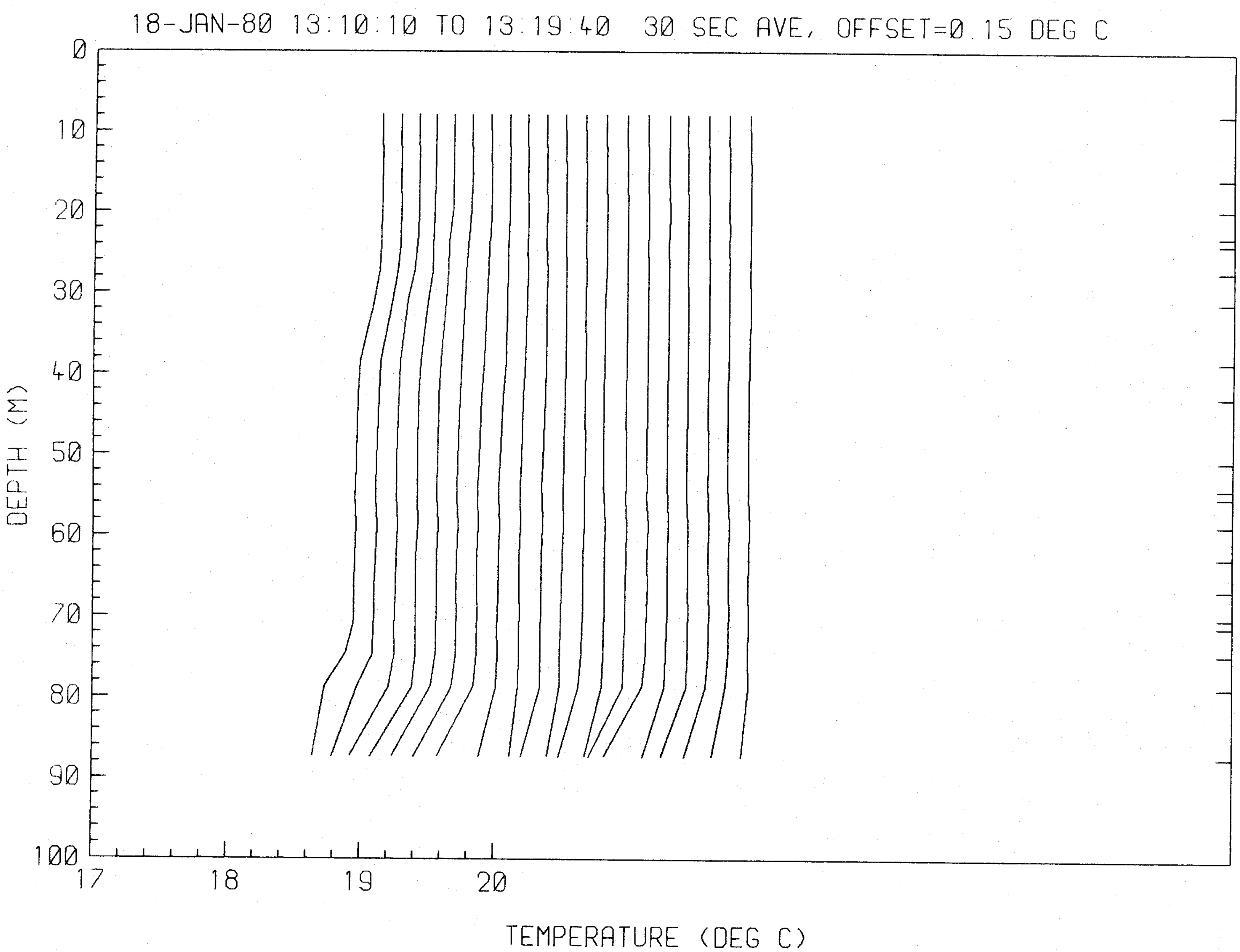
TEMPERATURE (DEG C)


18-JAN-80 13:10:10 TO 13:19:40 30 SEC AVE, OFFSET=0.15 DEG C
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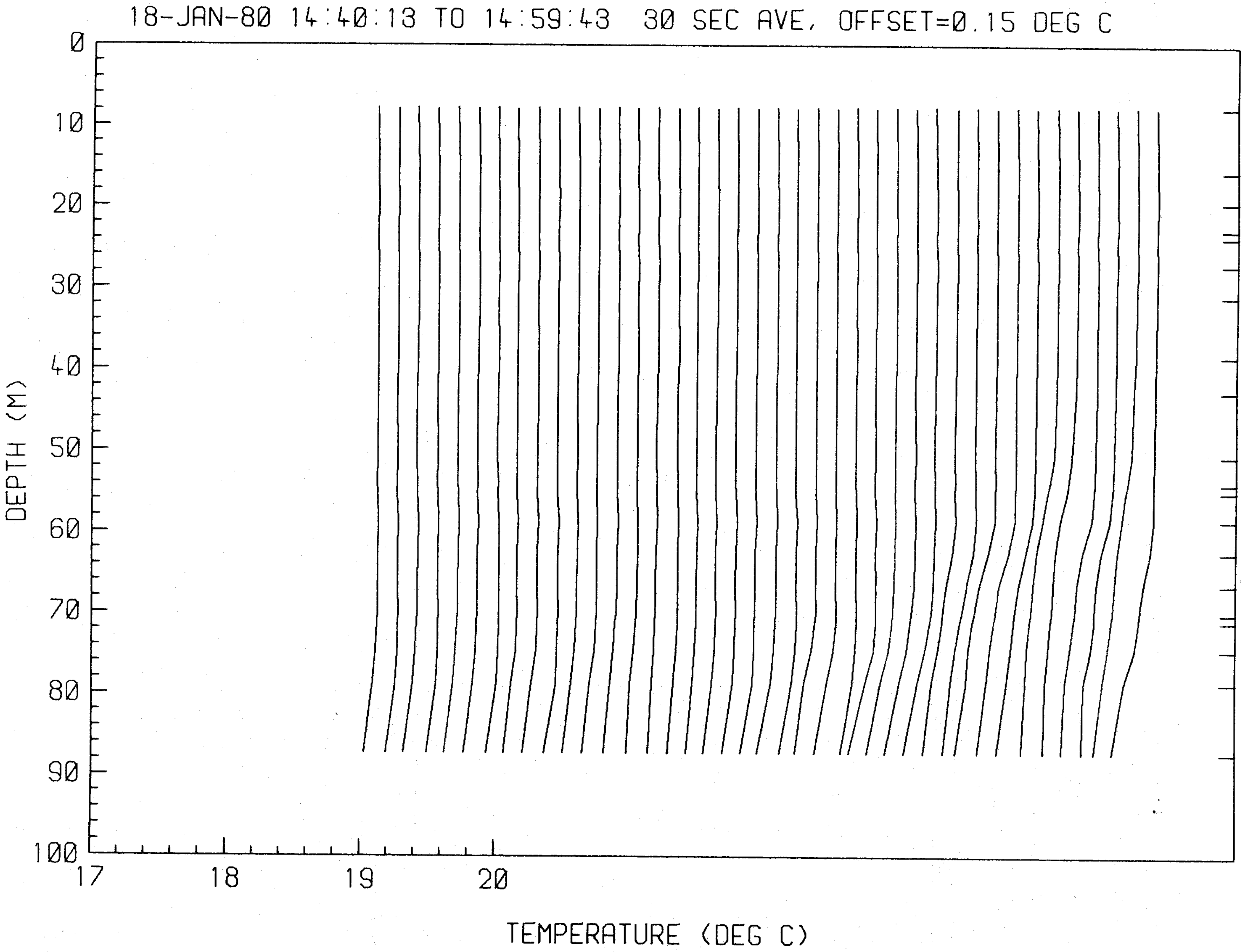
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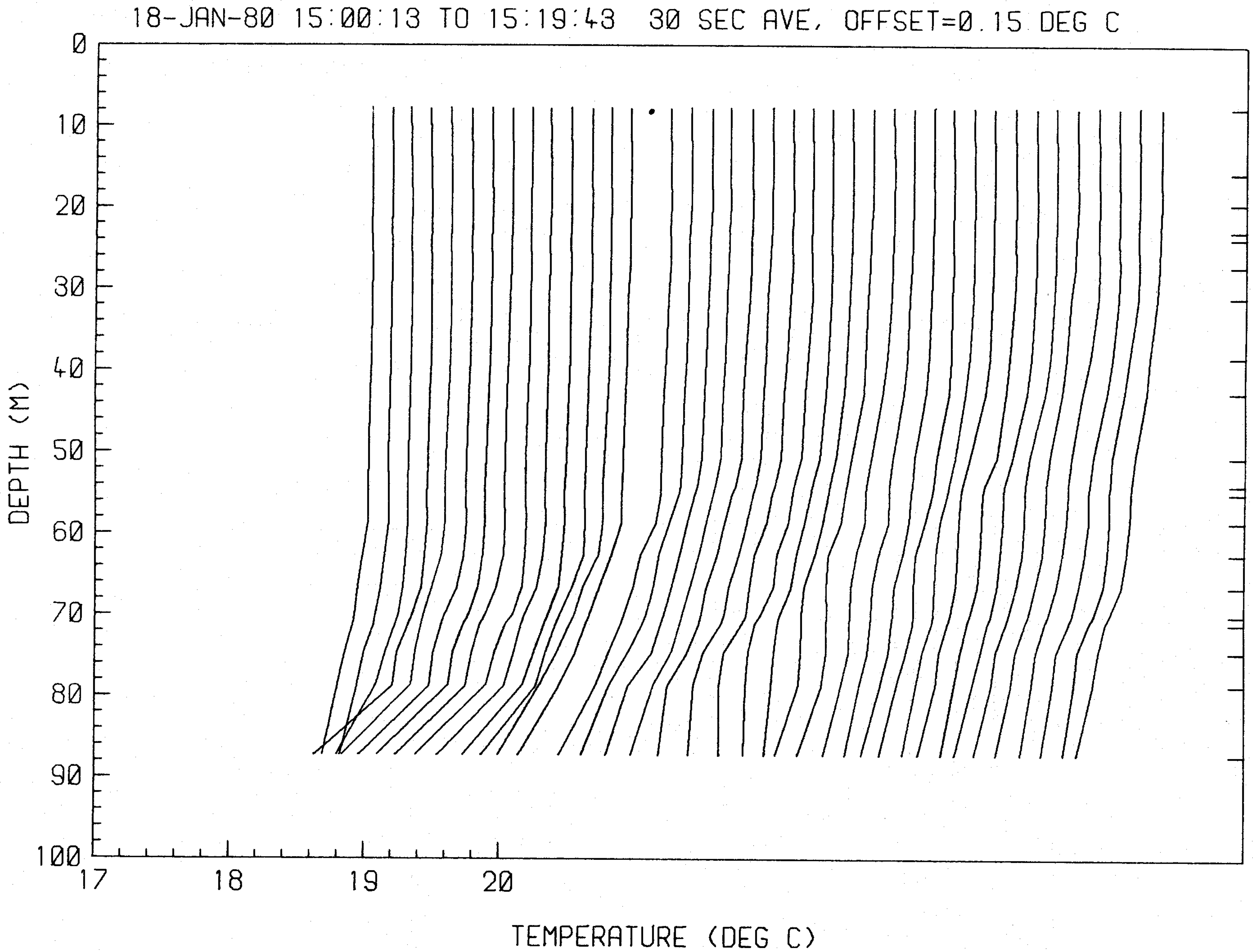
TEMPERATURE (DEG C)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DEPTH (M)
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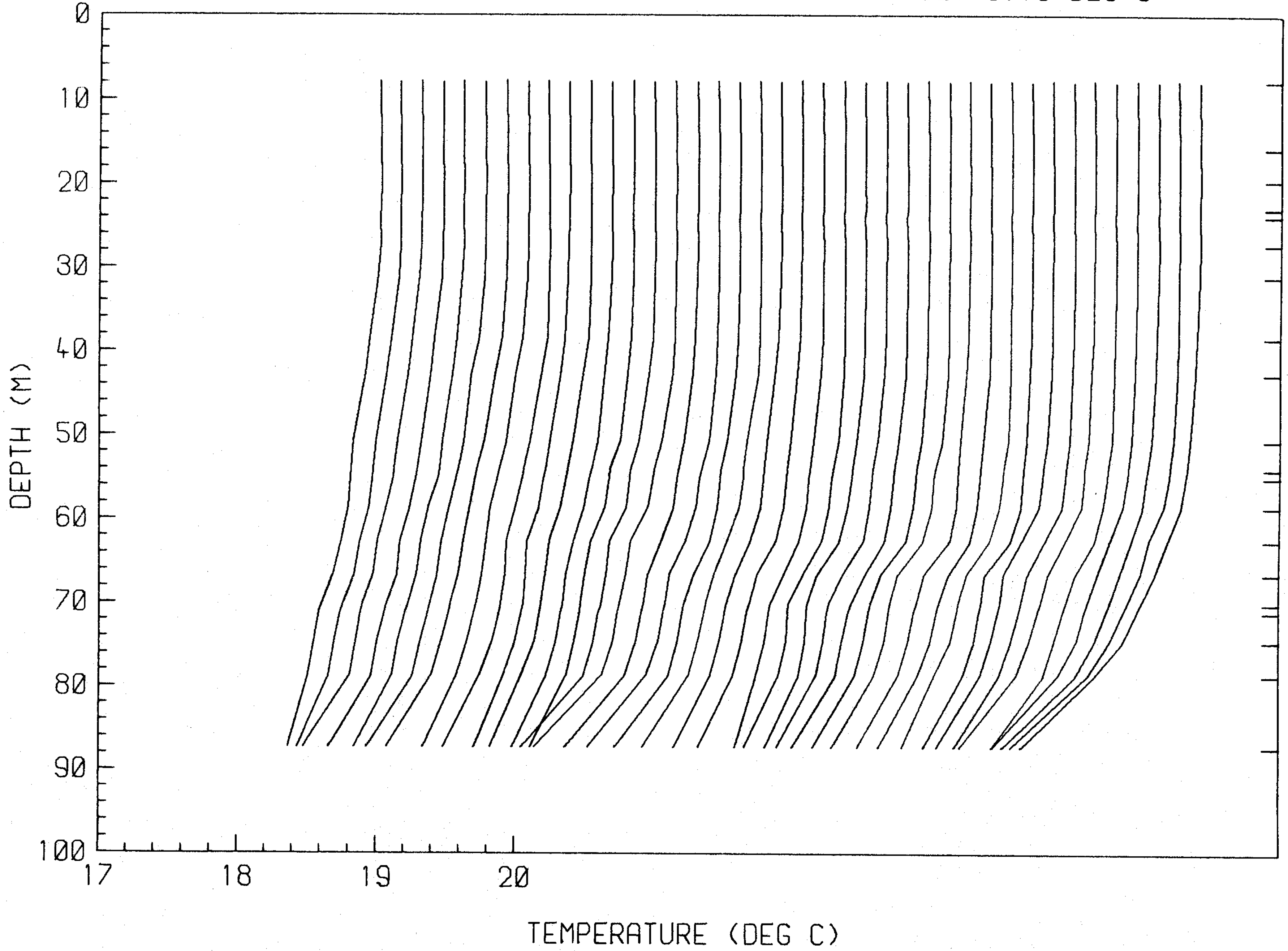
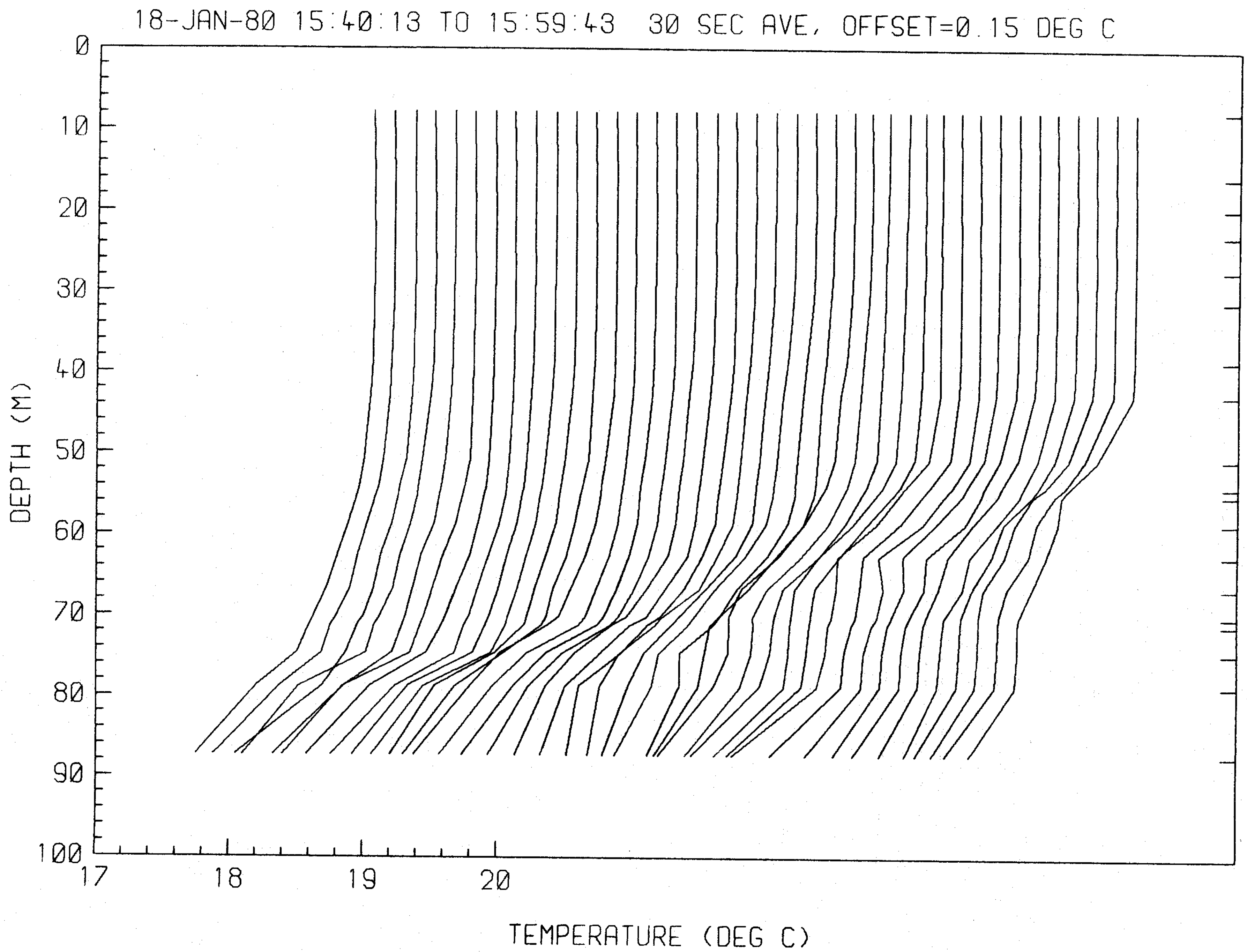
TEMPERATURE (DEG C)

18-JAN-80 15:20:13 TO 15:39:43 30 SEC AVE, OFFSET=0.15 DEG C

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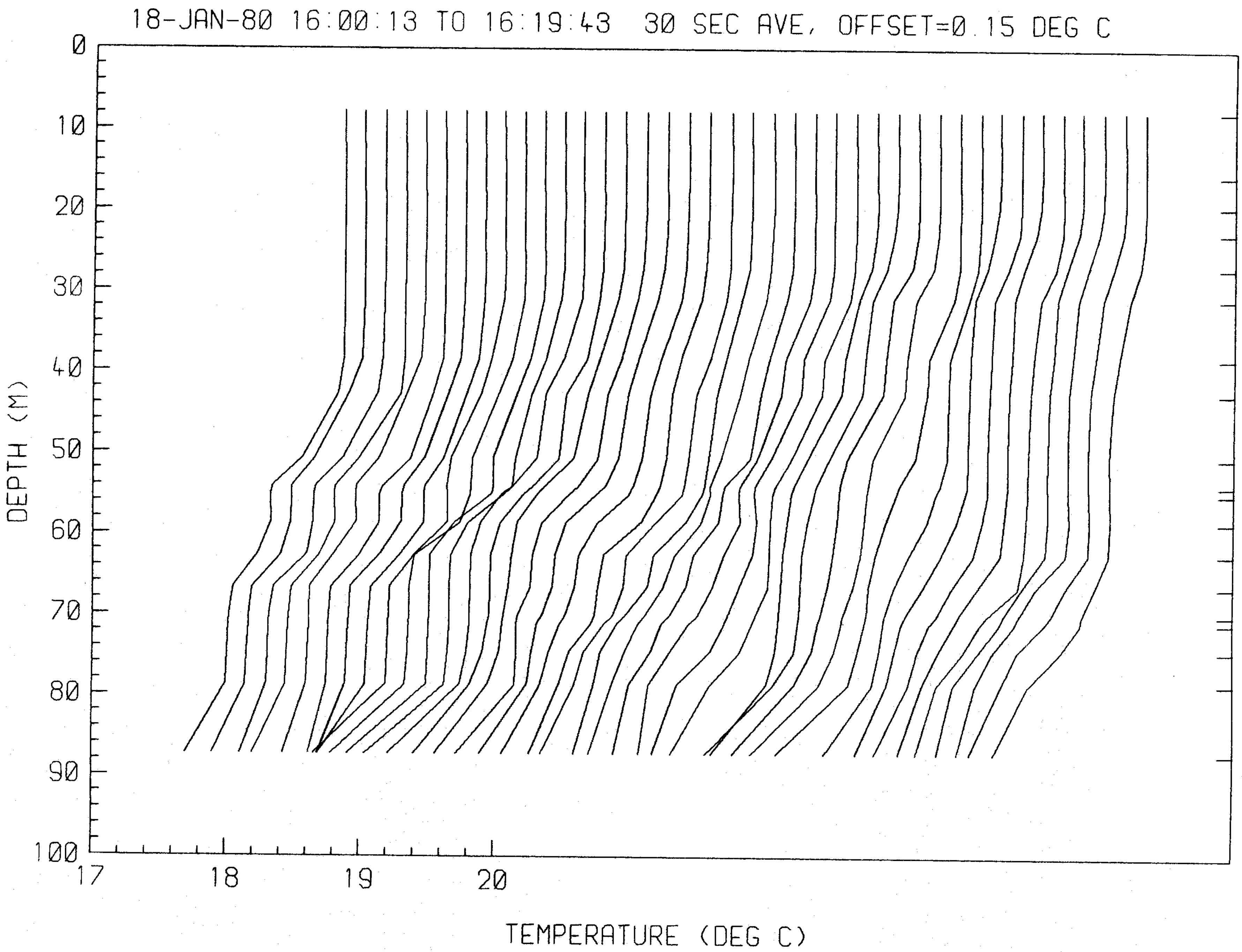
TEMPERATURE (DEG C)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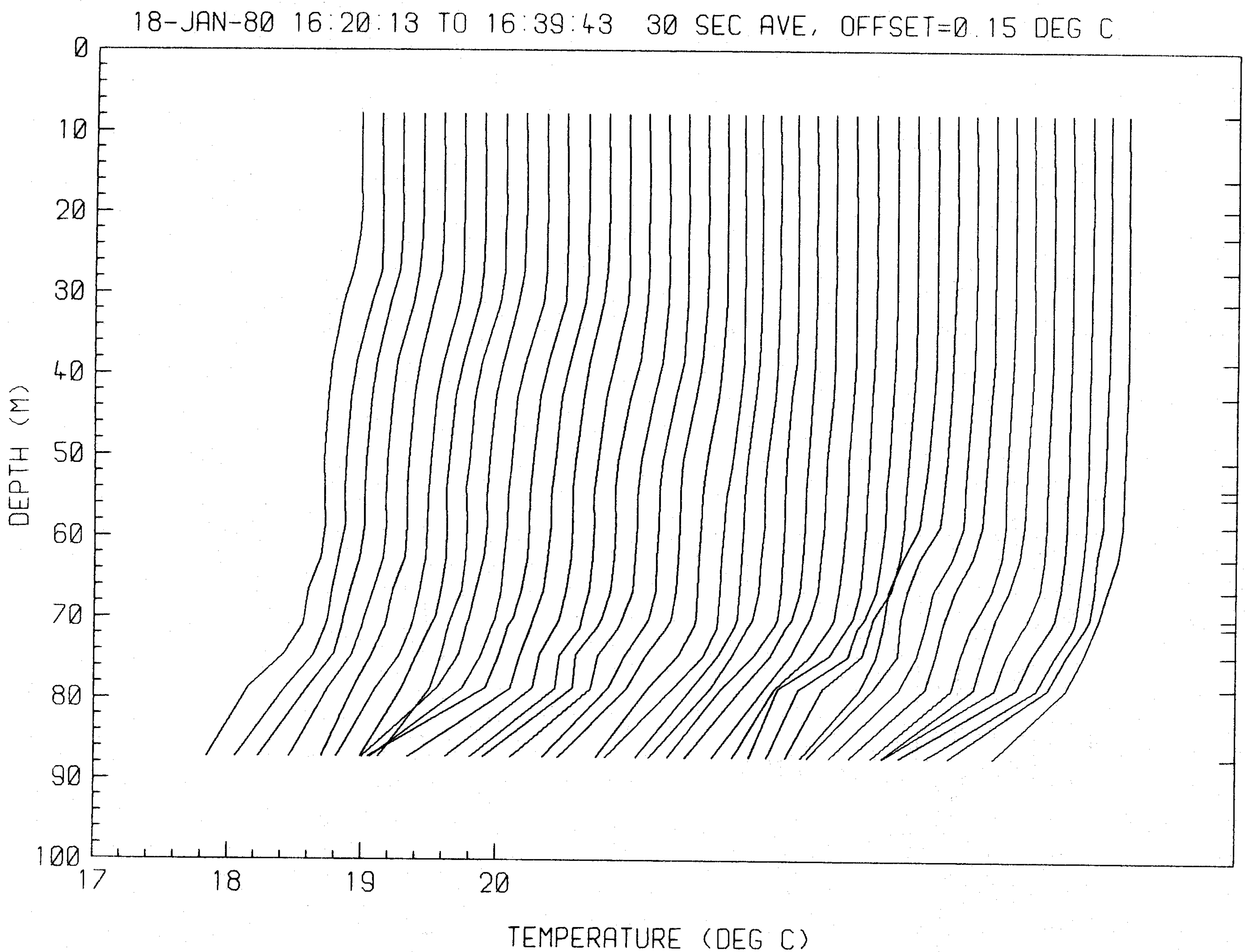
TEMPERATURE (DEG C)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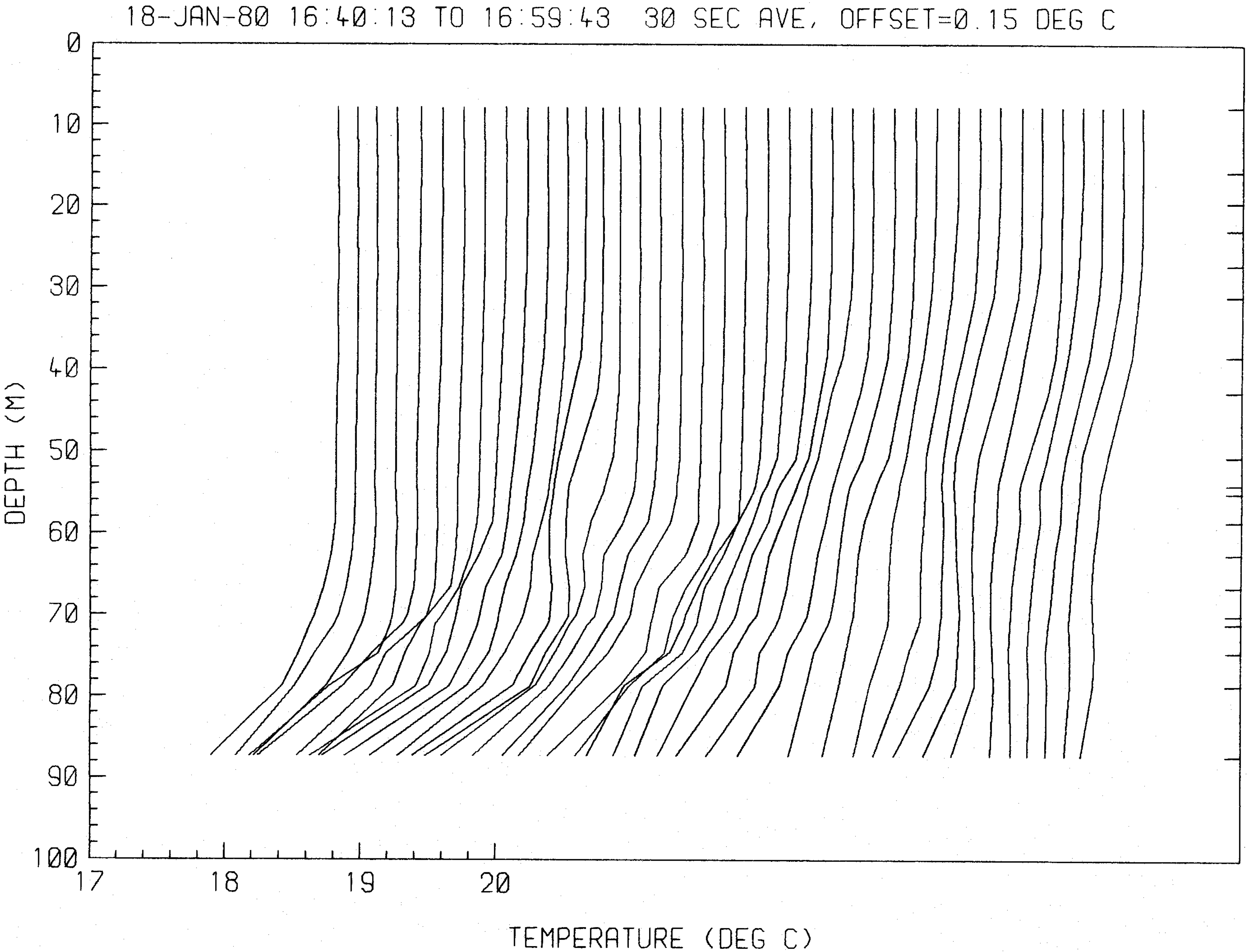
TEMPERATURE (DEG C)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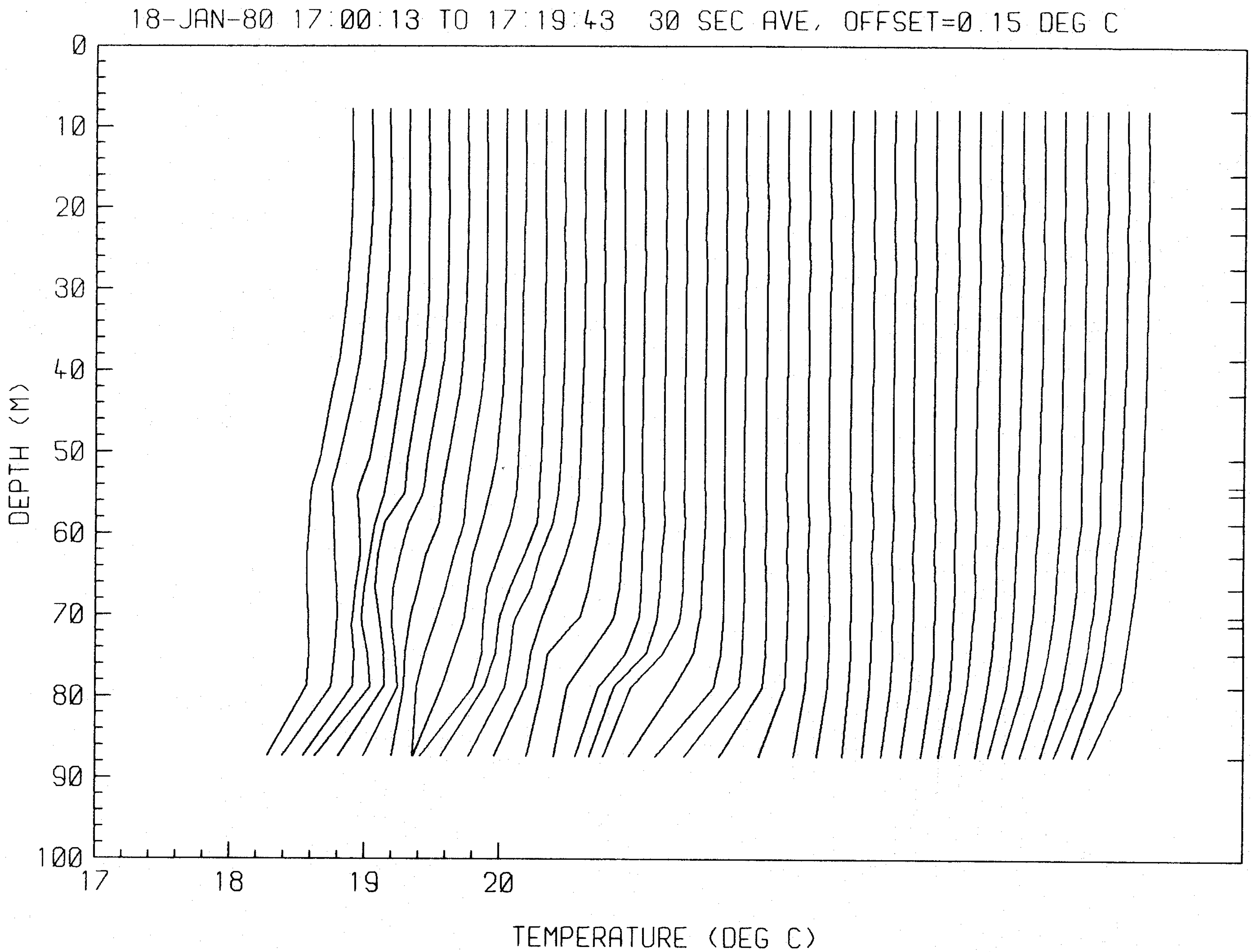
TEMPERATURE (DEG C)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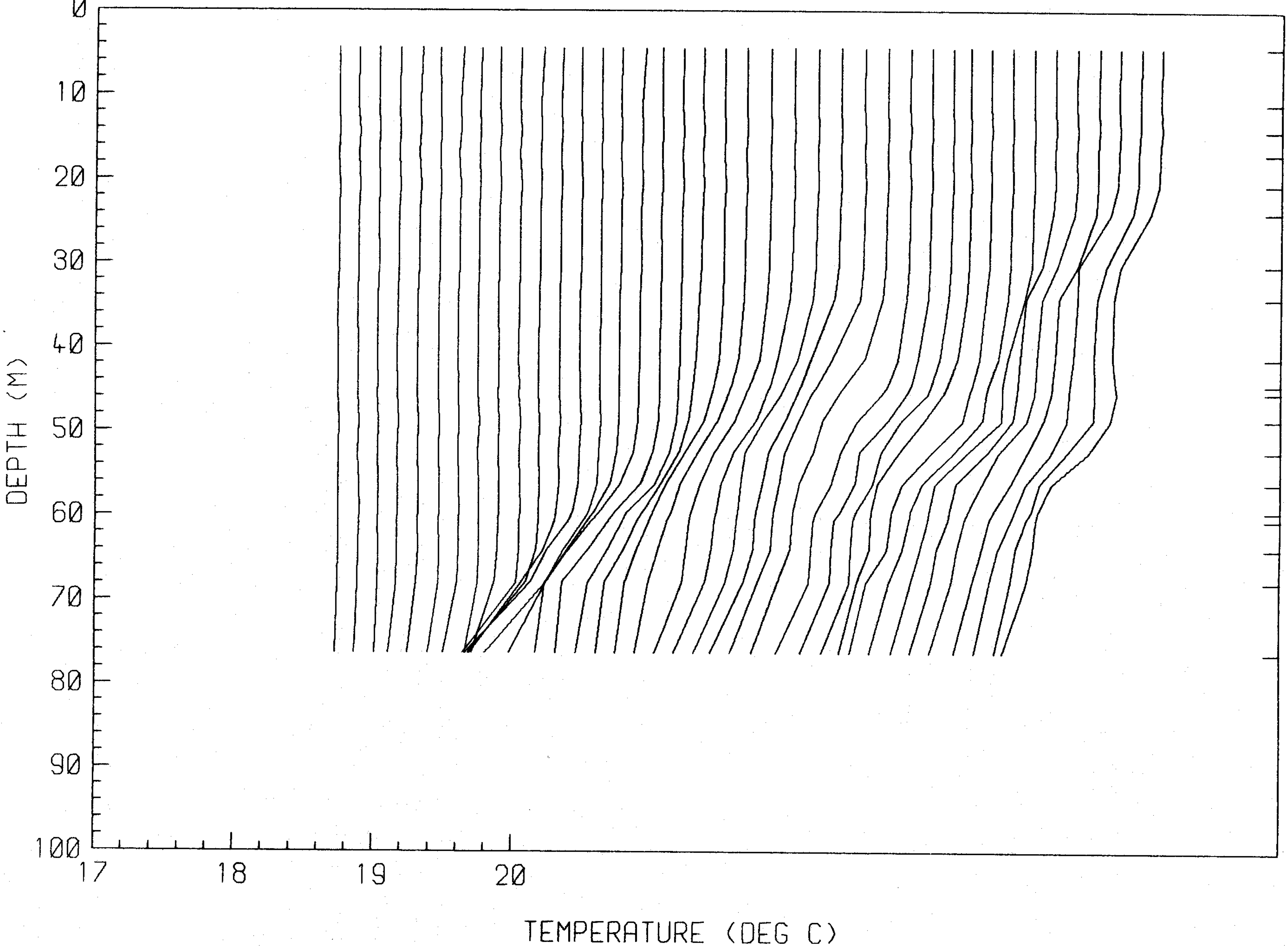
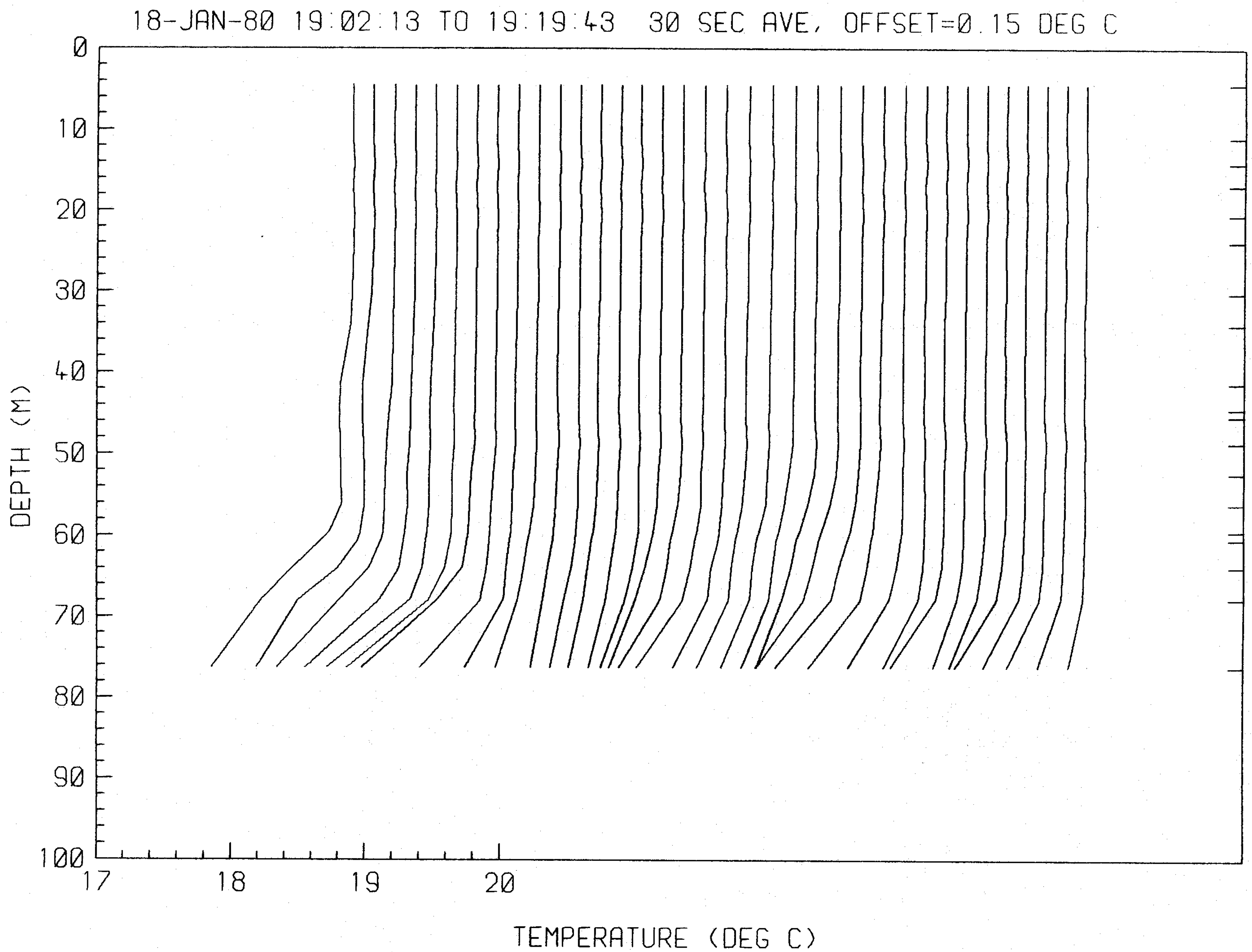
TEMPERATURE (DEG C)

18-JAN-80 18:20:13 TO 18:39:43 30 SEC AVE, OFFSET=0.15 DEG C

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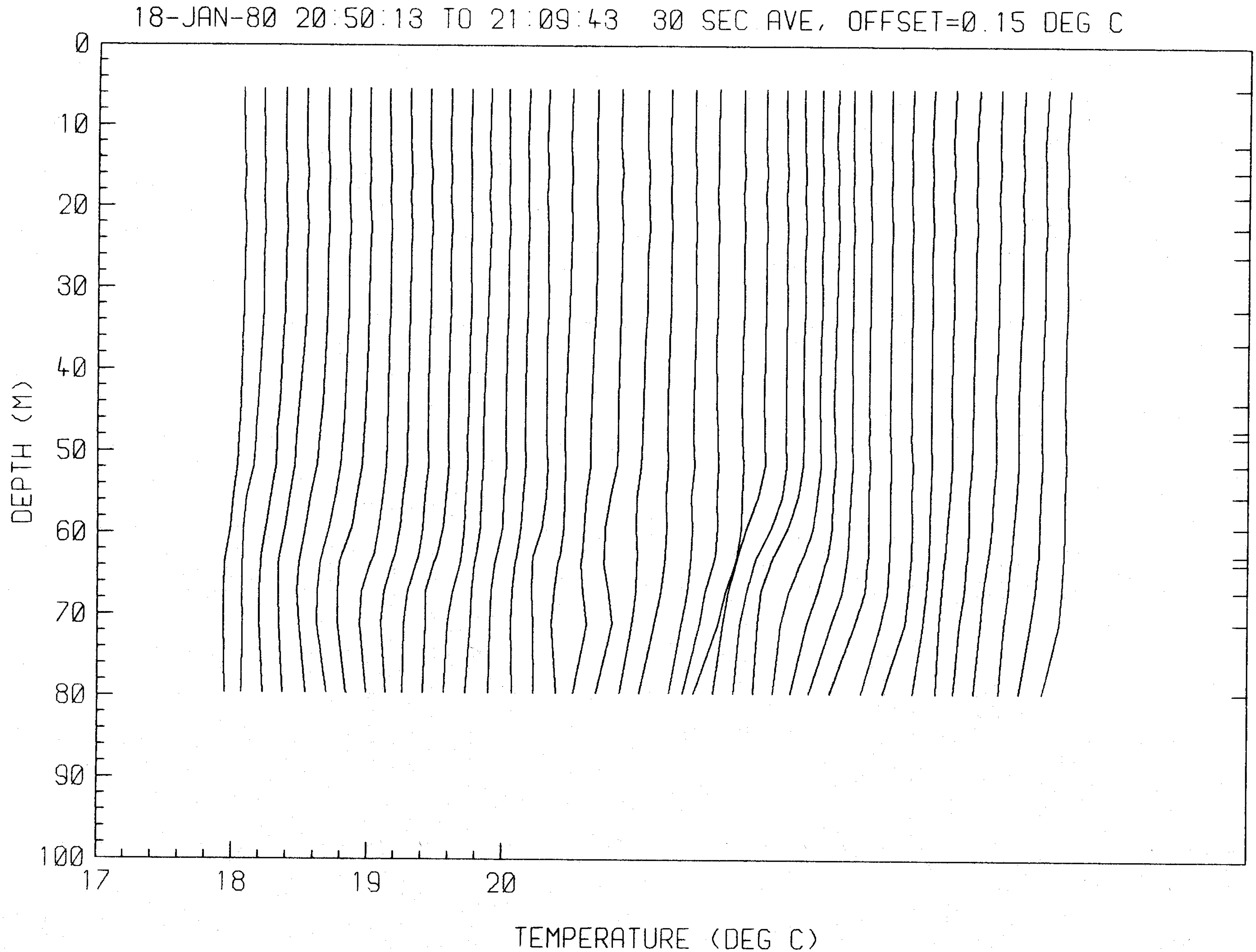
TEMPERATURE (DEG C)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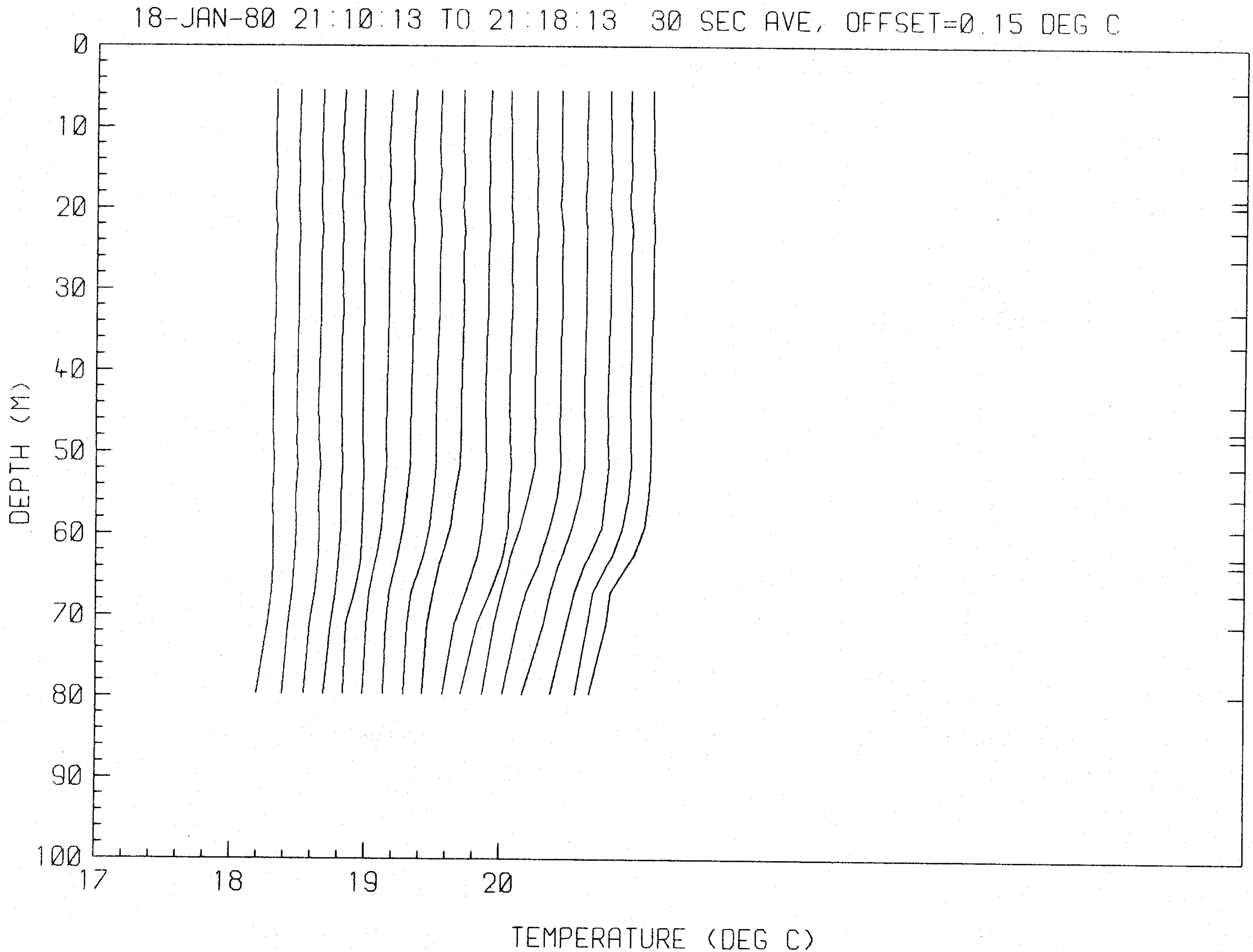
TEMPERATURE (DEG C)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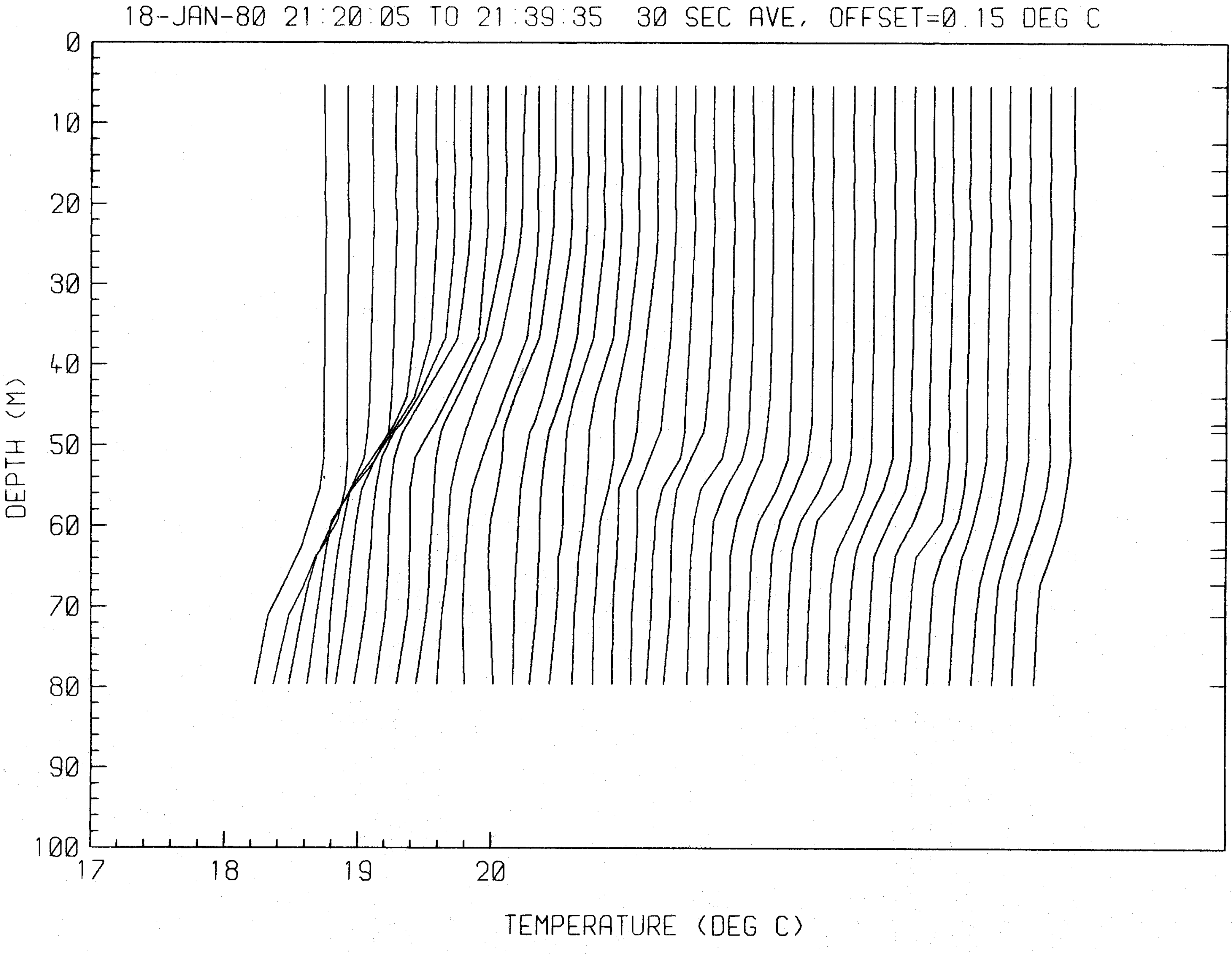
TEMPERATURE (DEG C)



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TEMPERATURE (DEG C)

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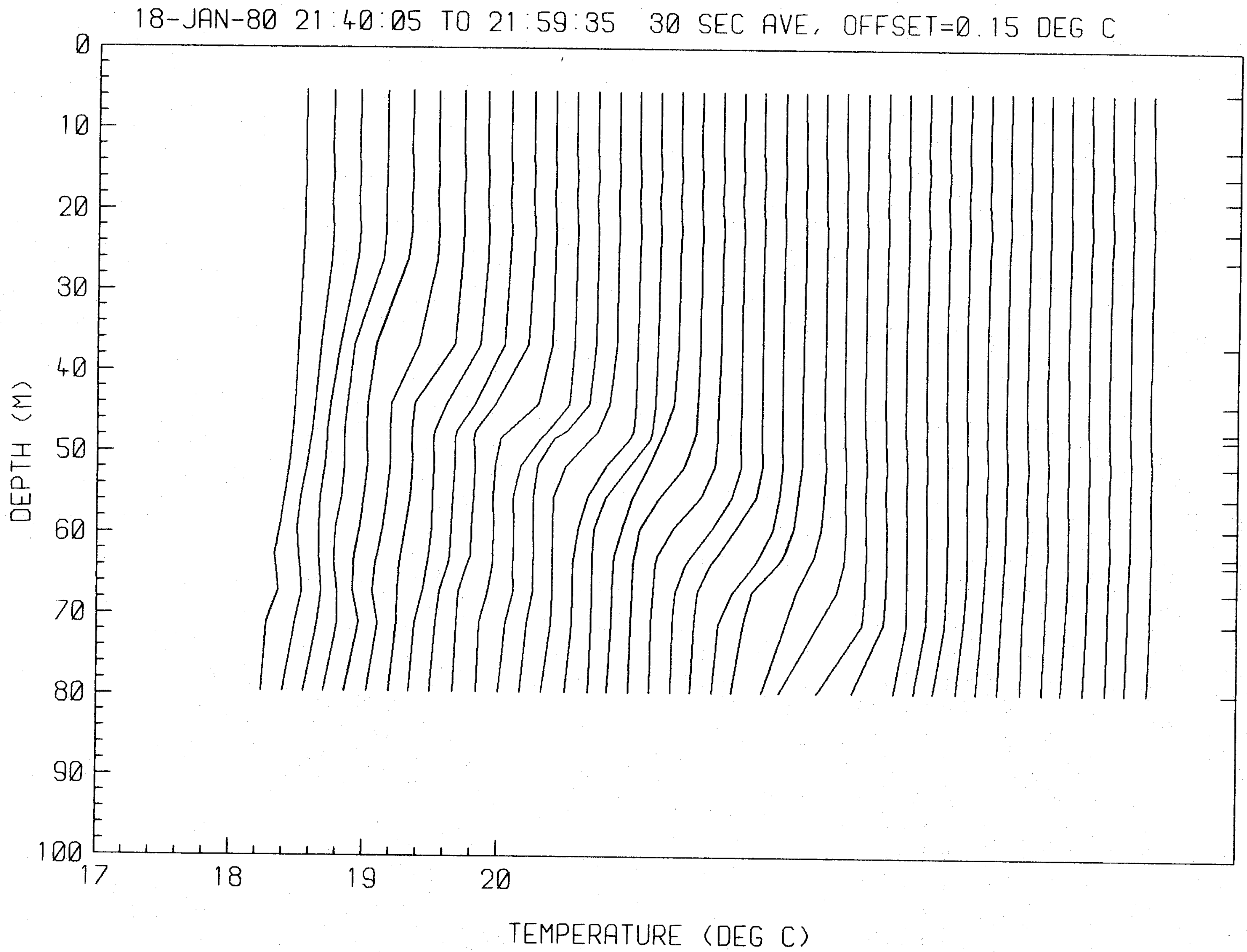
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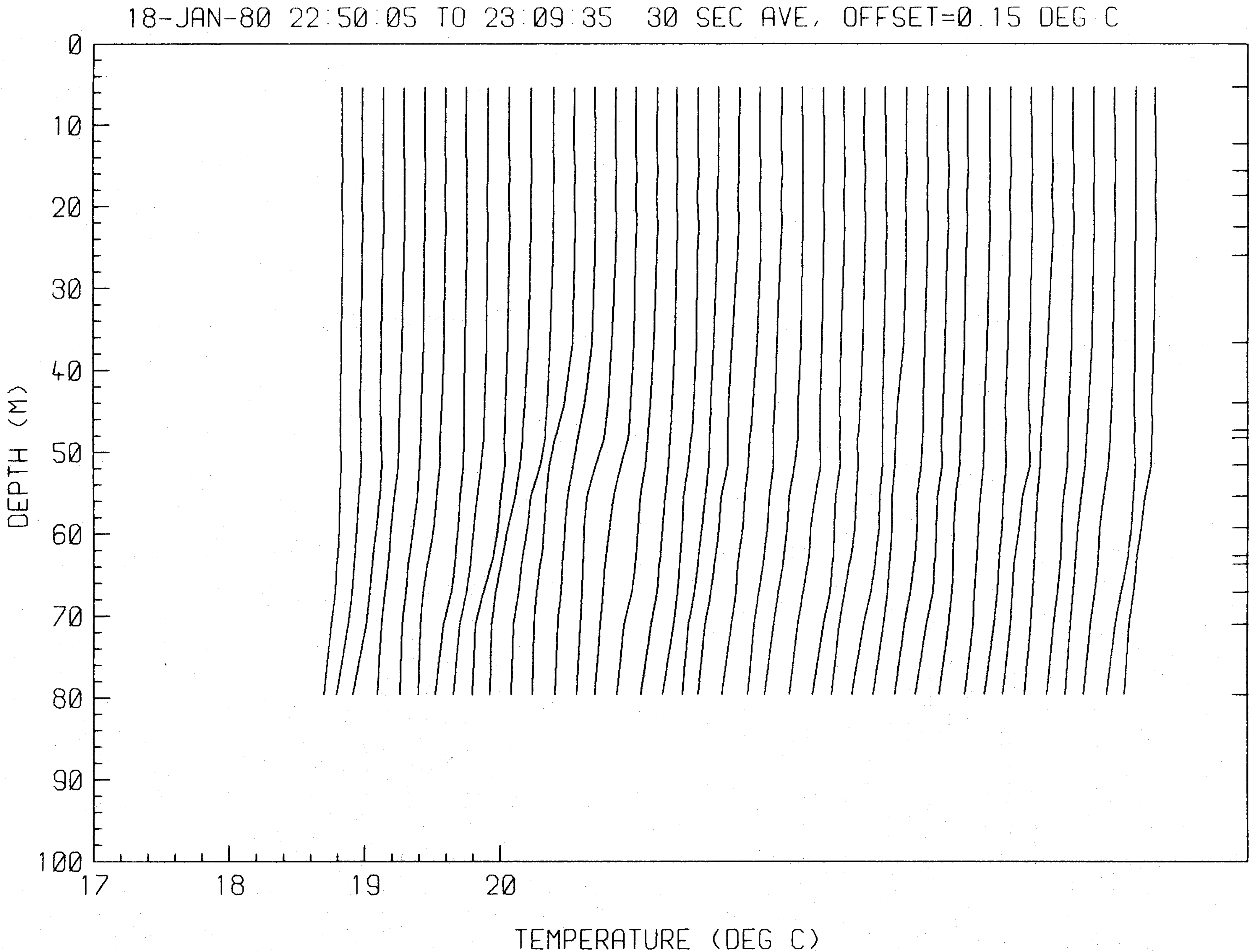
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TEMPERATURE (DEG C)

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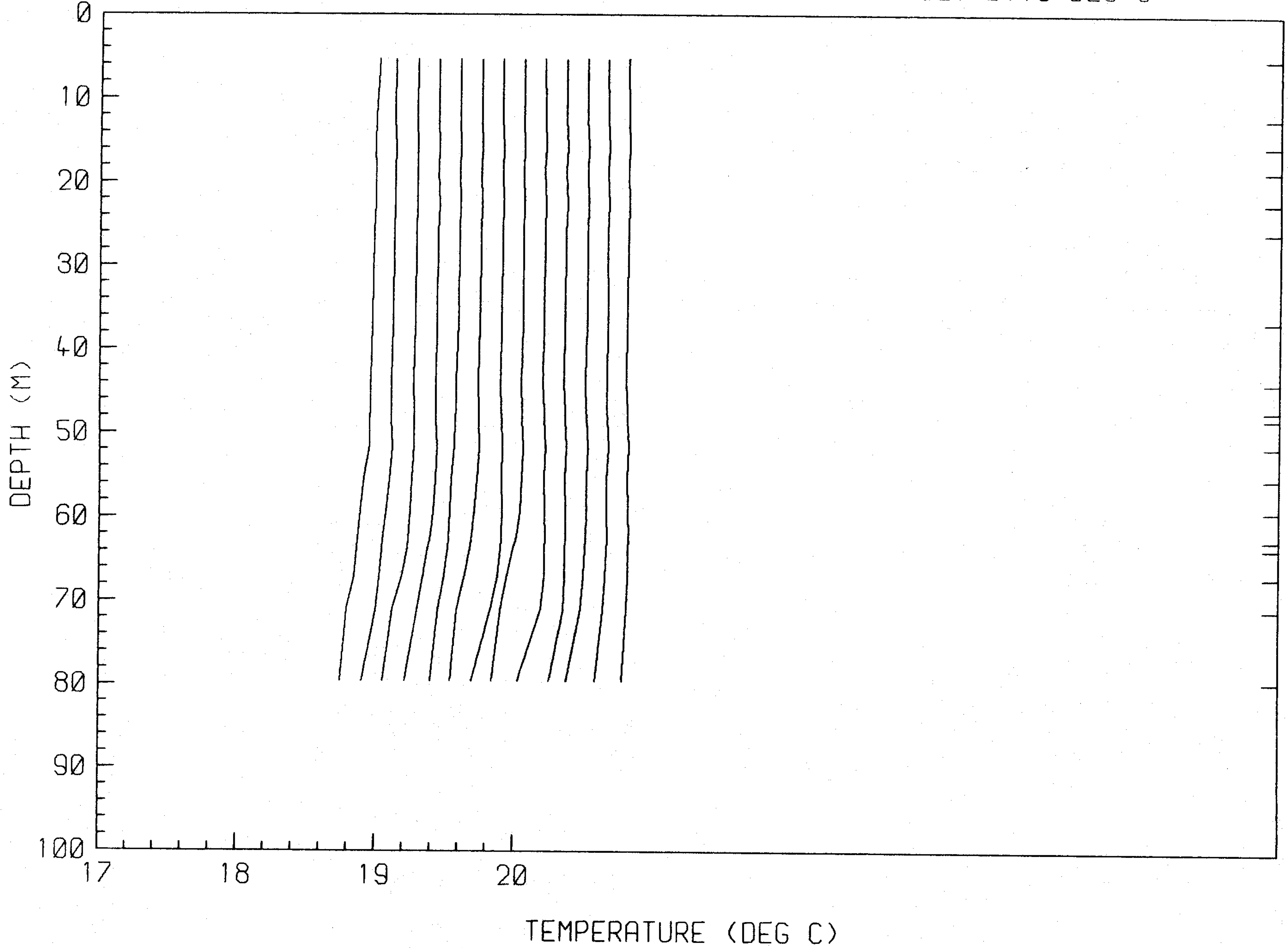

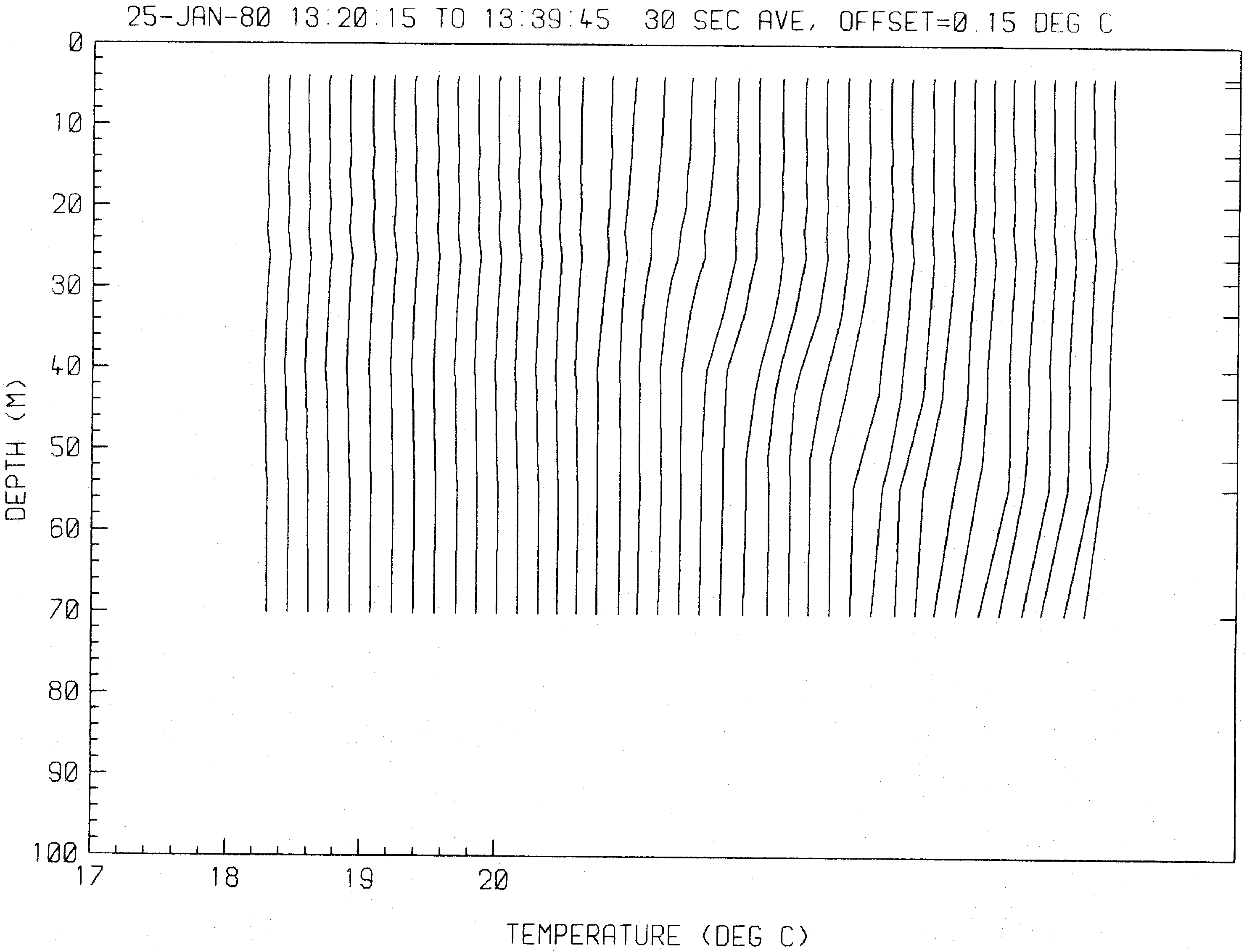
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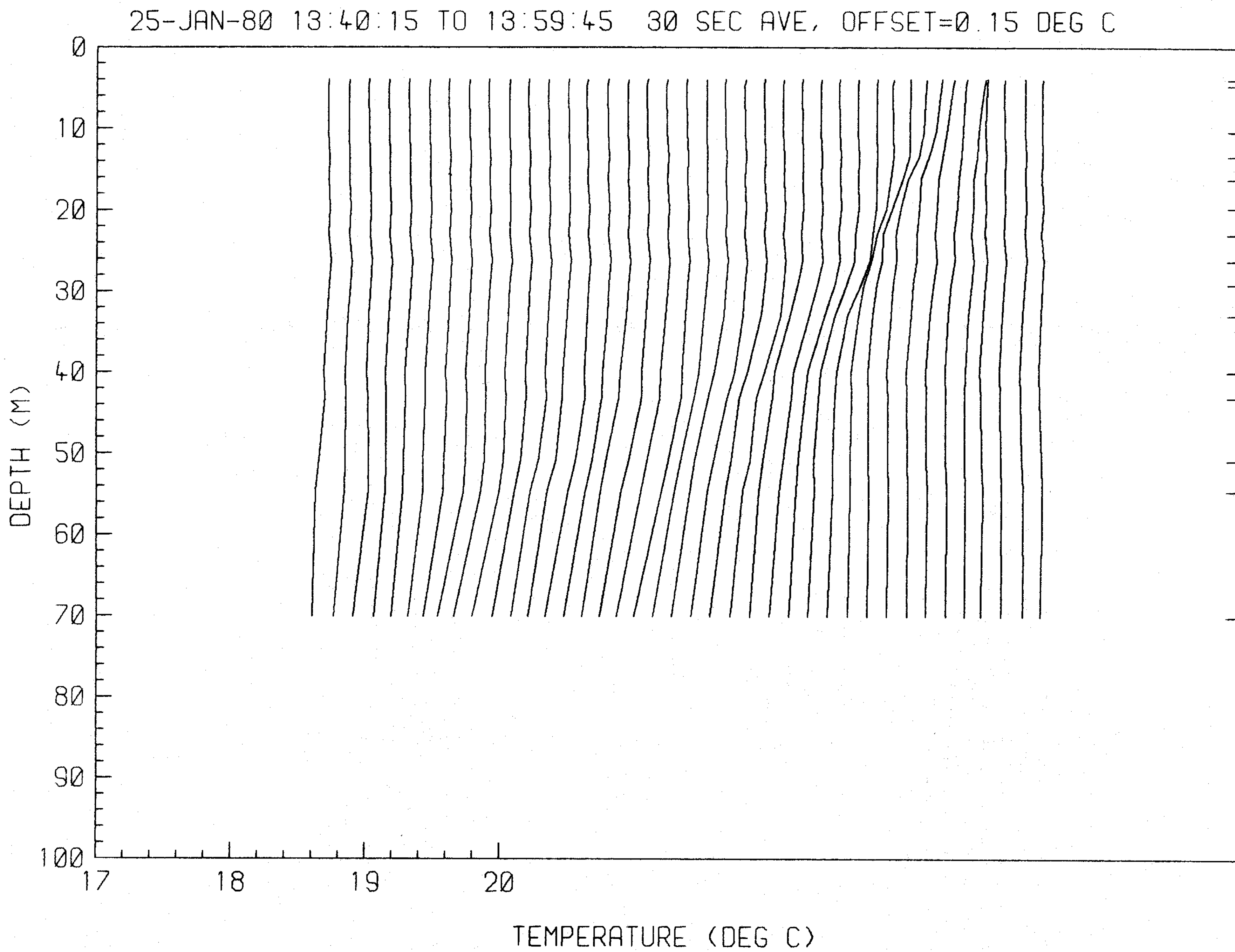
TEMPERATURE (DEG C)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DEPTH (M)
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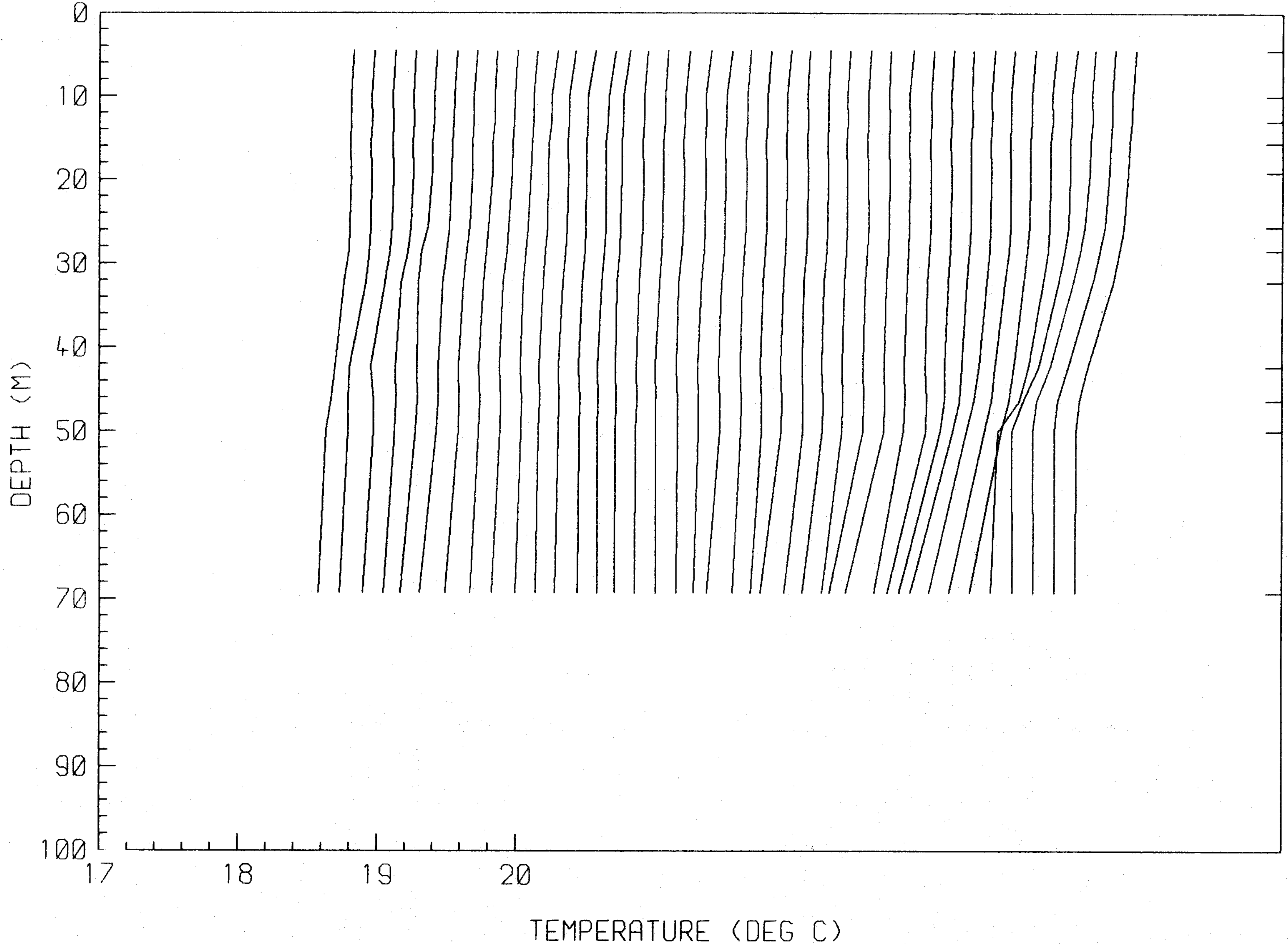
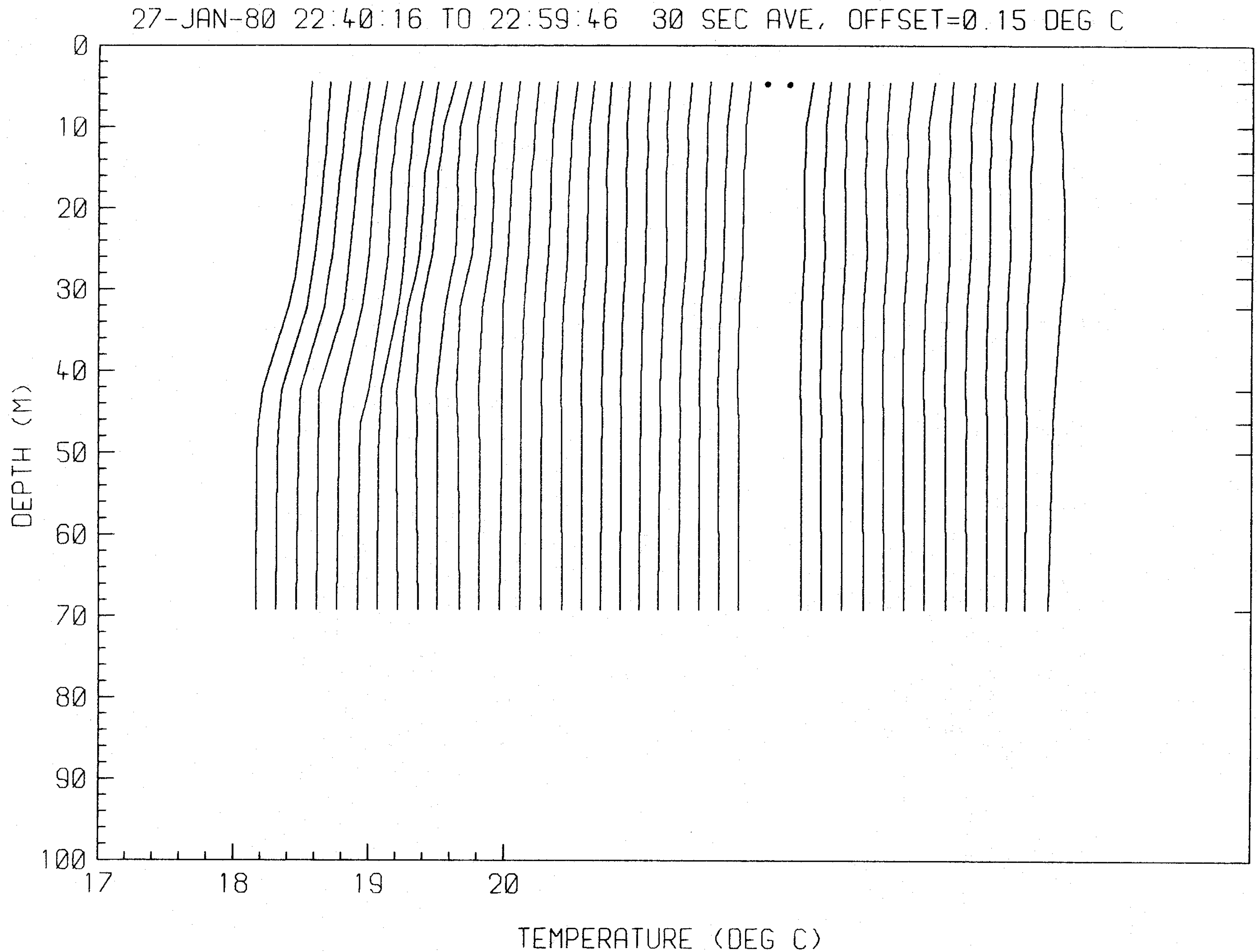
TEMPERATURE (DEG C)

27-JAN-80 22:20:16 TO 22:39:46 30 SEC AVE, OFFSET=0.15 DEG C

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DEPTH (M)
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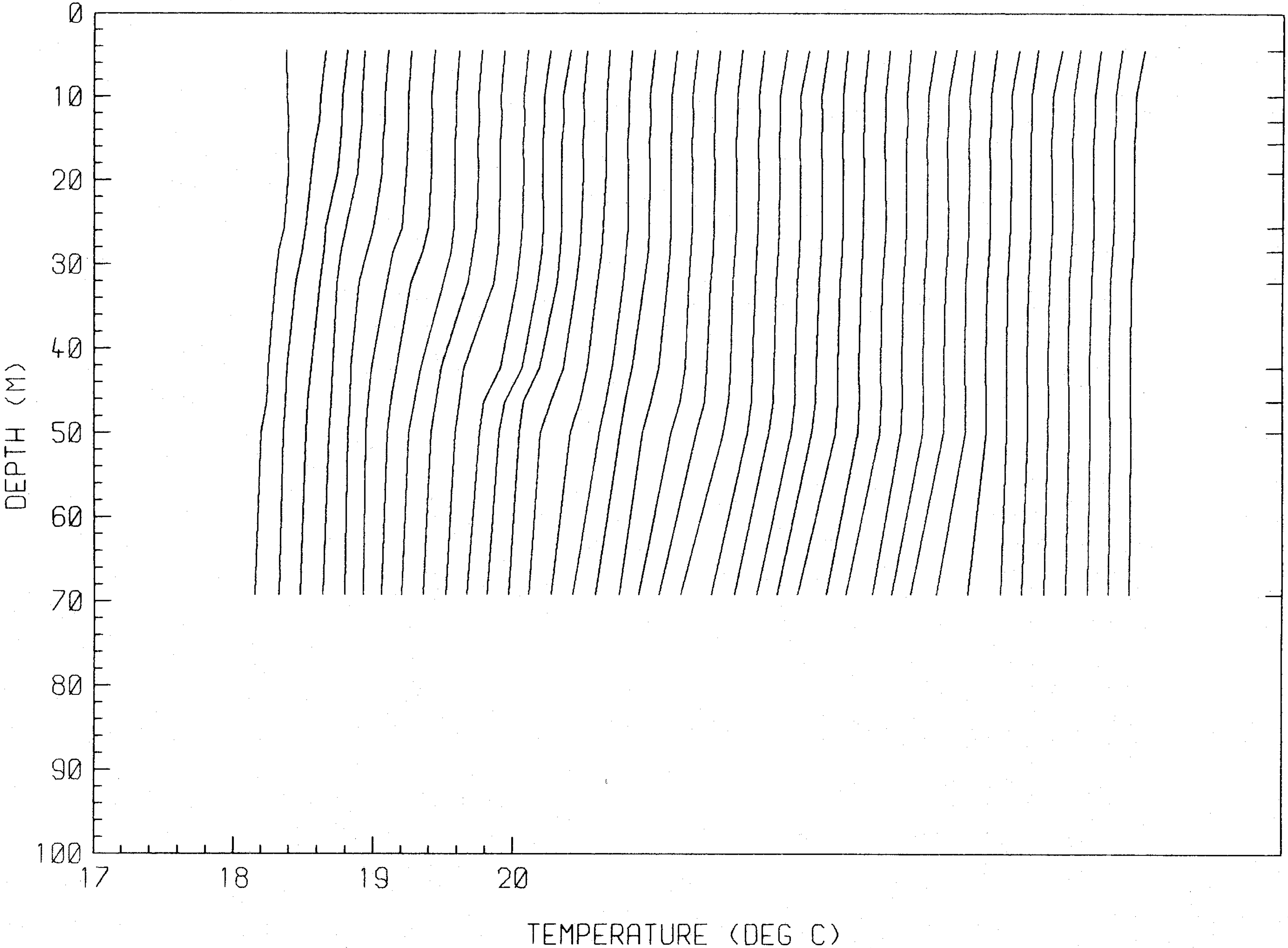
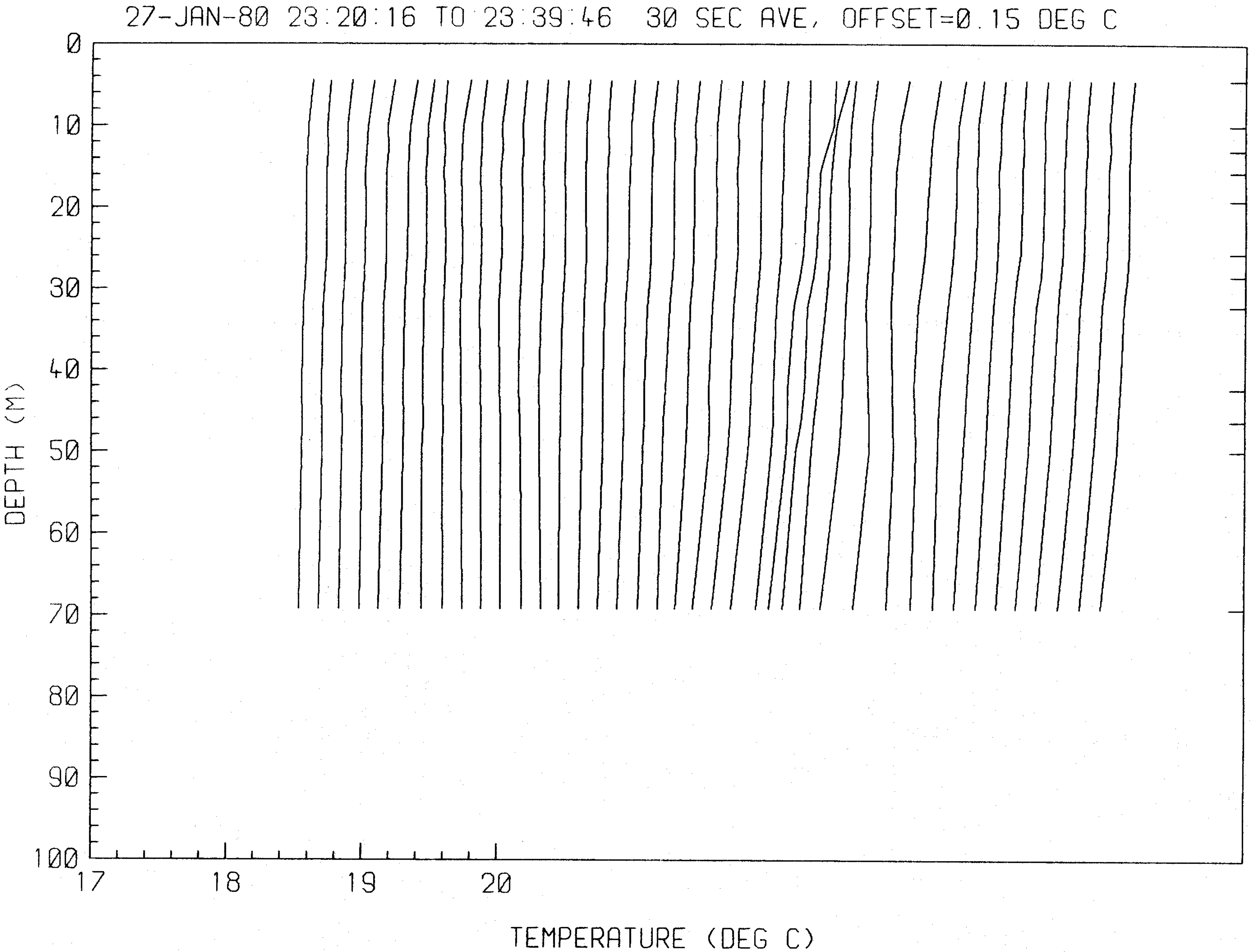
TEMPERATURE (DEG C)

27-JAN-80 23:00:16 TO 23:19:46 30 SEC AVE, OFFSET=0.15 DEG C

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DEPTH (M)
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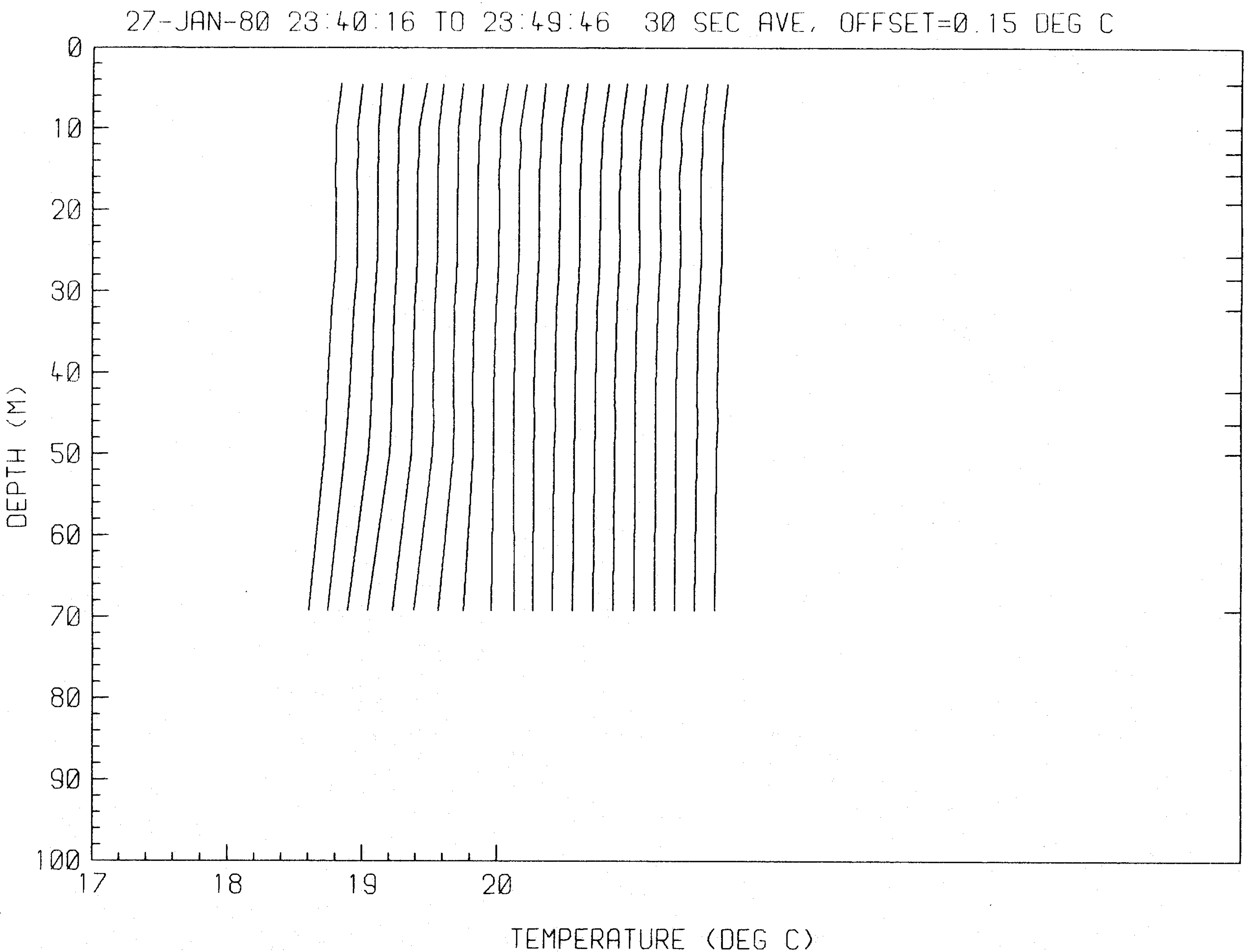
TEMPERATURE (DEG C)



27-JAN-80 23:40:16 TO 23:49:46 30 SEC AVE, OFFSET=0.15 DEG C
DEPTH (M)
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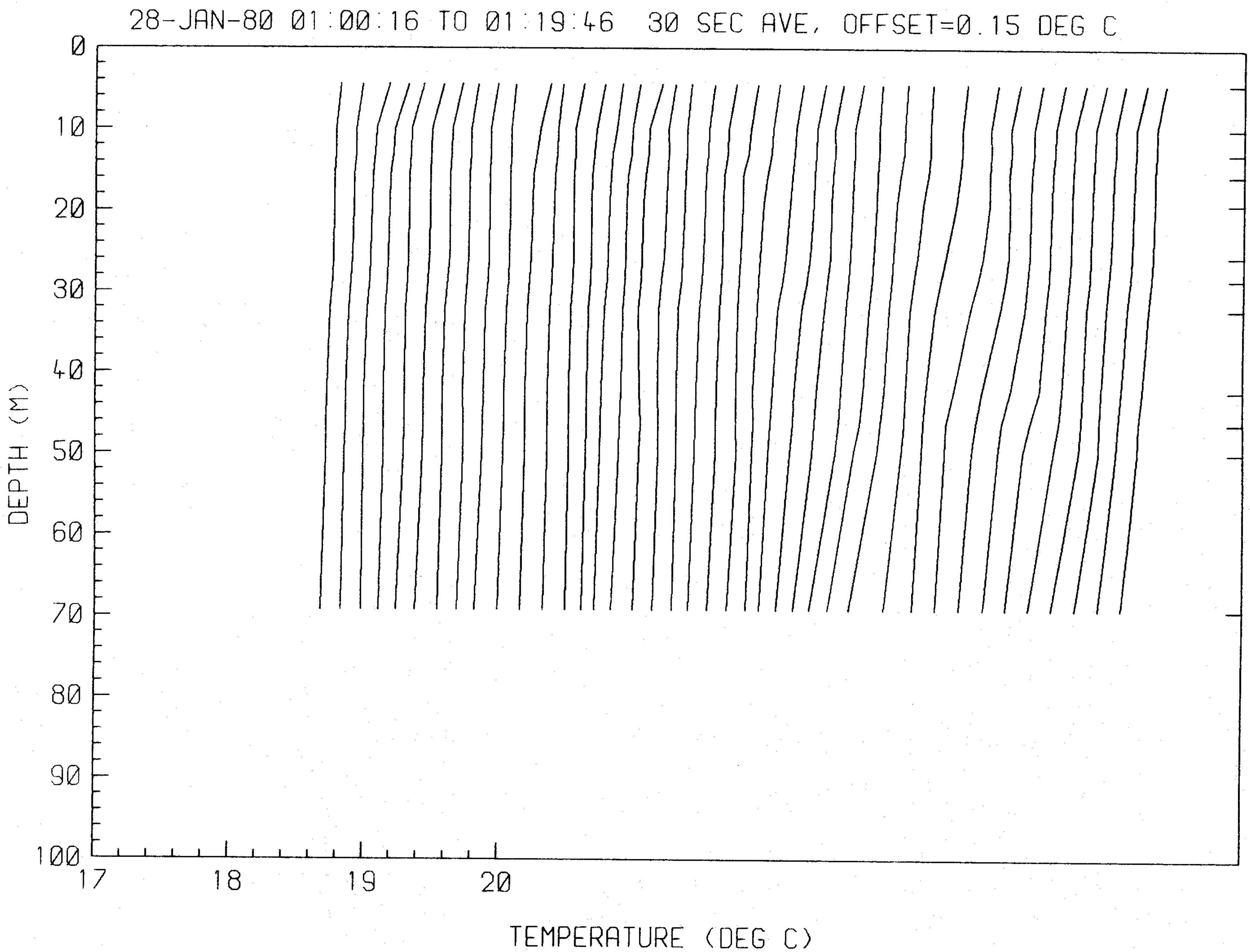
TEMPERATURE (DEG C)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DEPTH (M)
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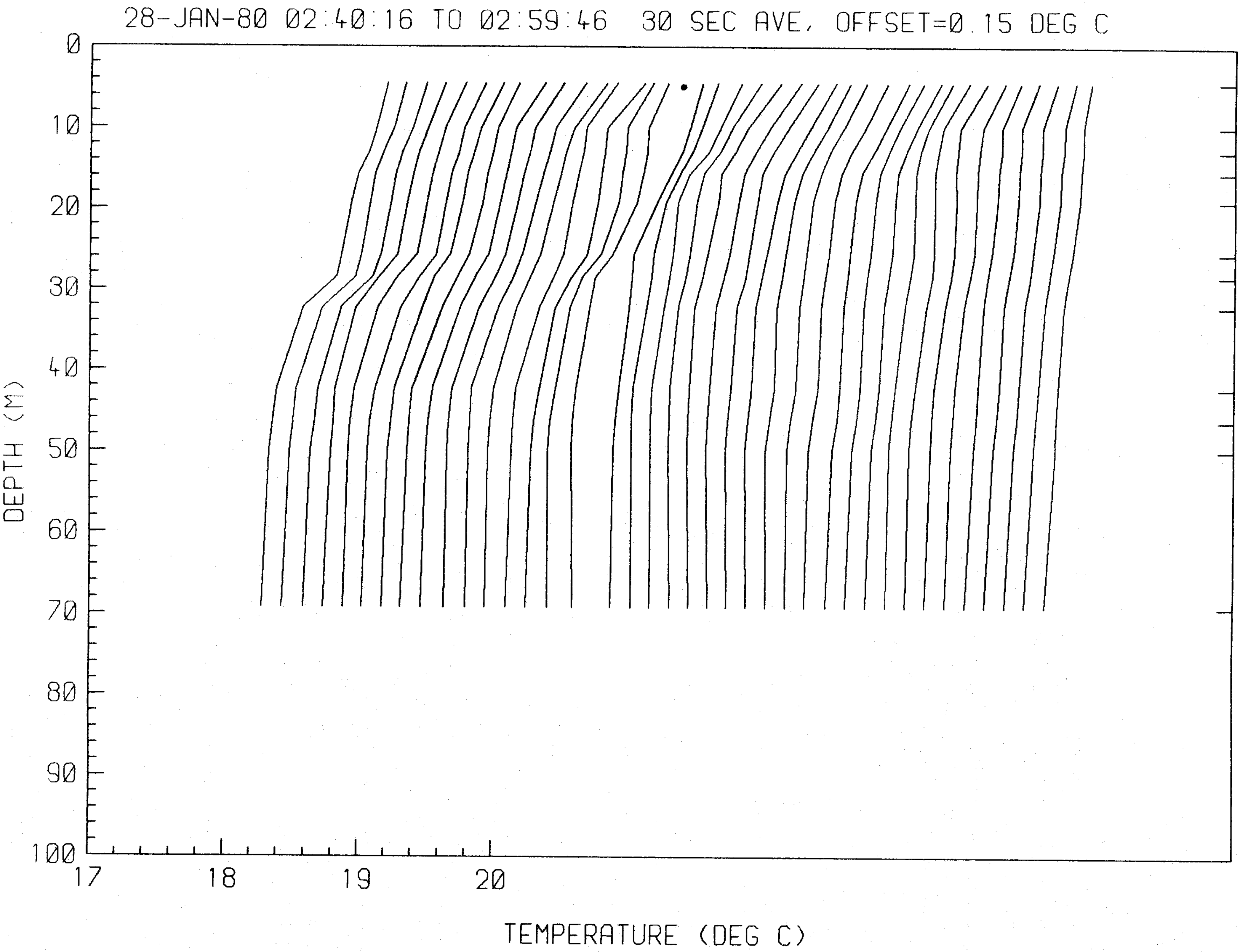
TEMPERATURE (DEG C)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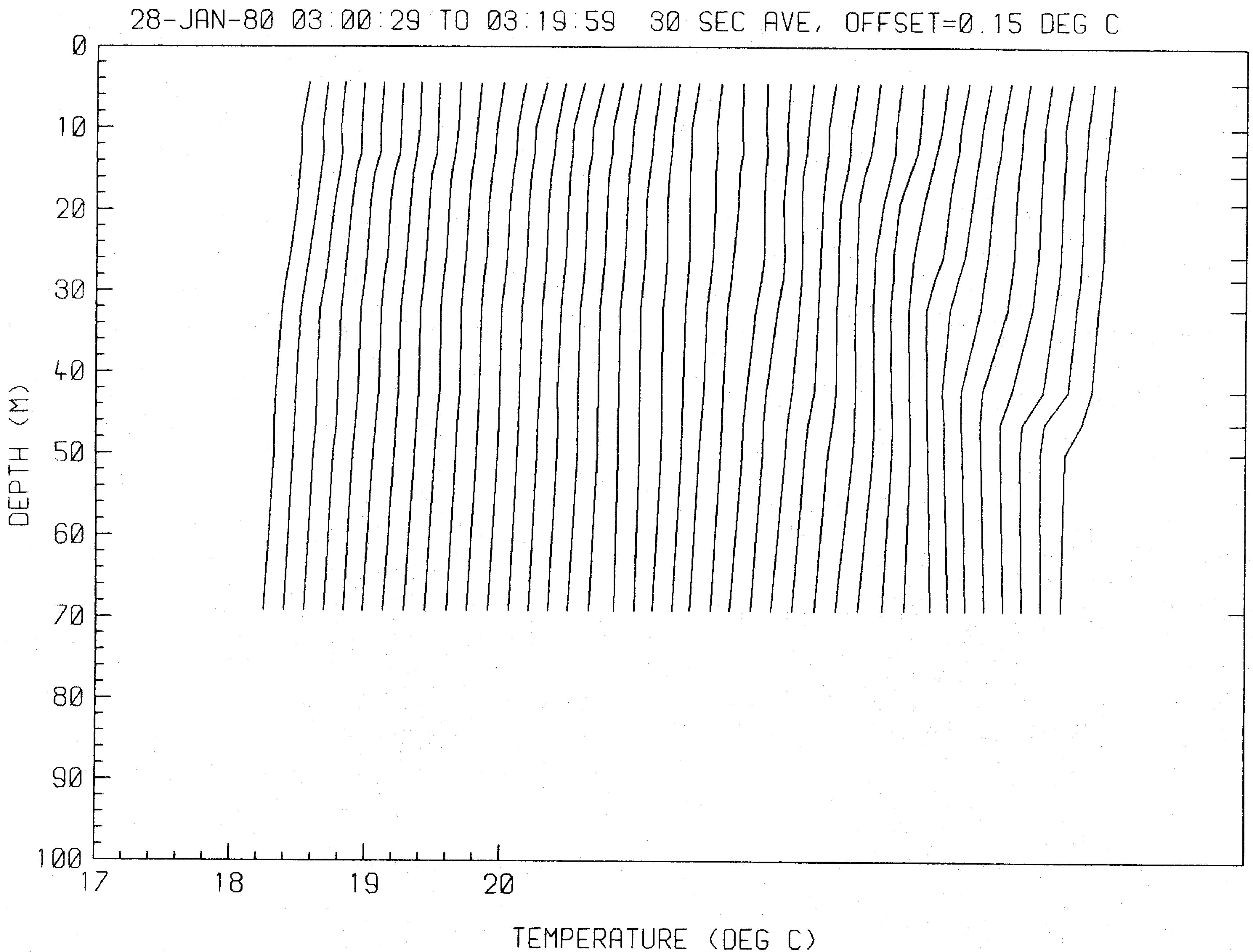
TEMPERATURE (DEG C)



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DEPTH (M)
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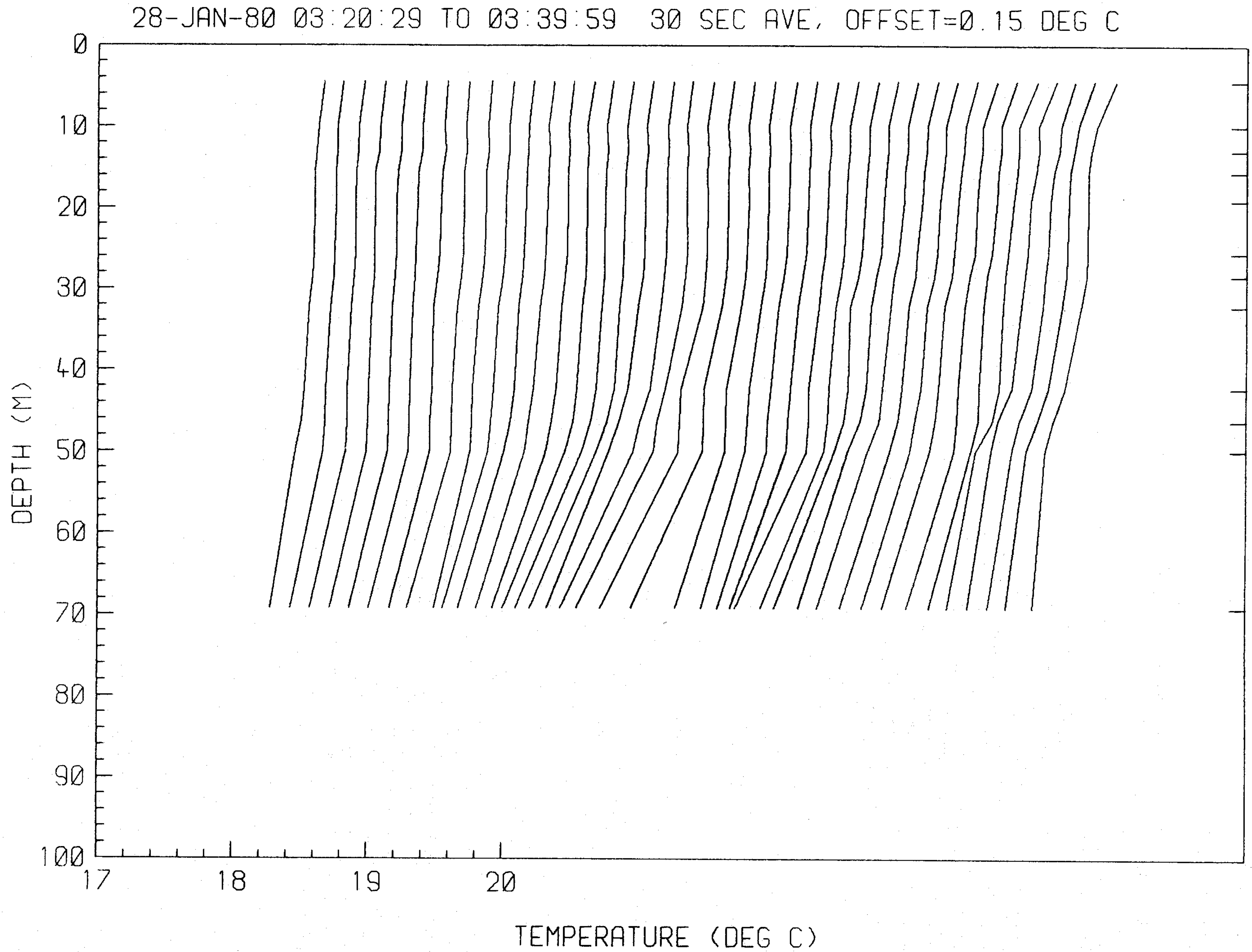
TEMPERATURE (DEG C)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DEPTH (M)
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TEMPERATURE (DEG C)

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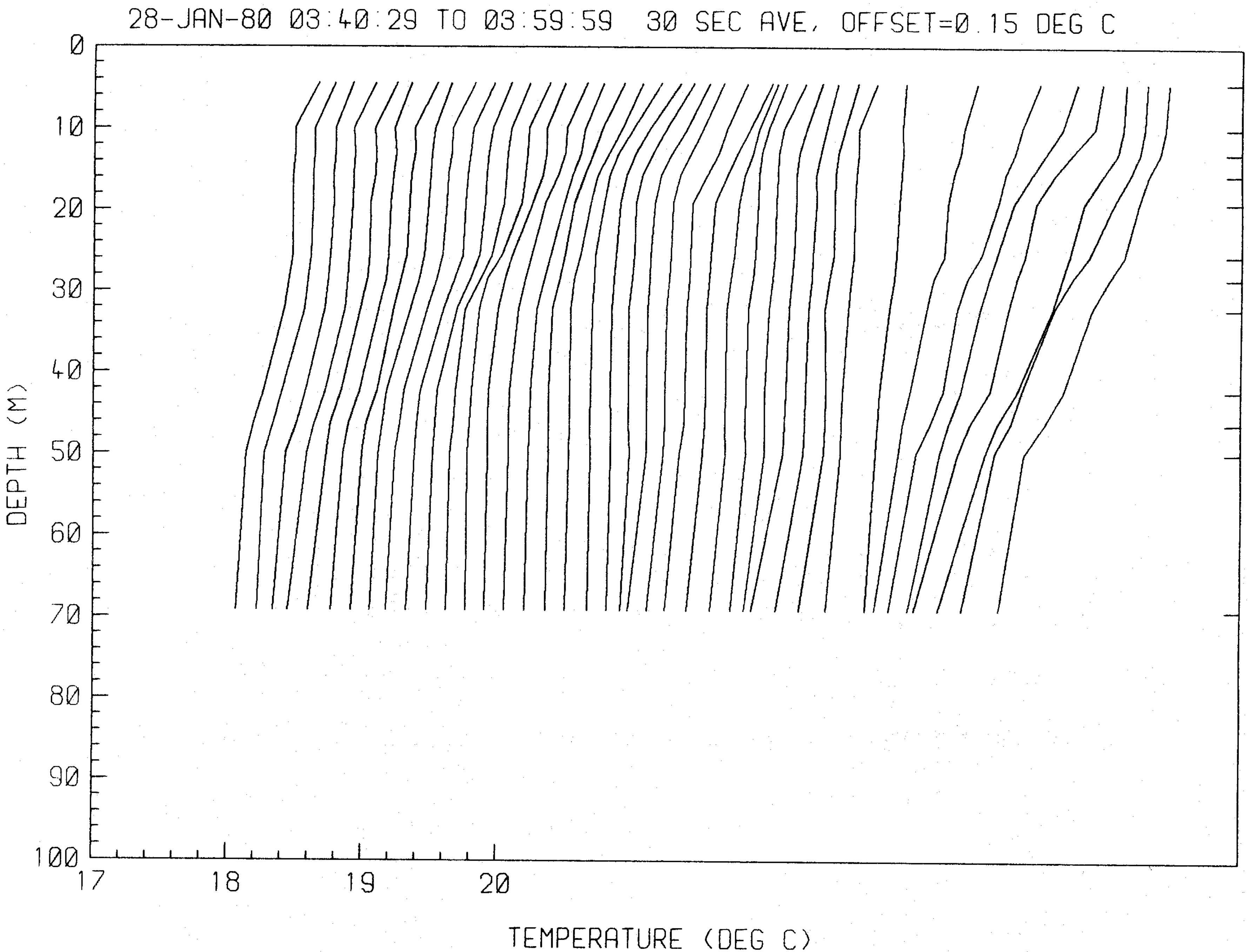
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DEPTH (M)
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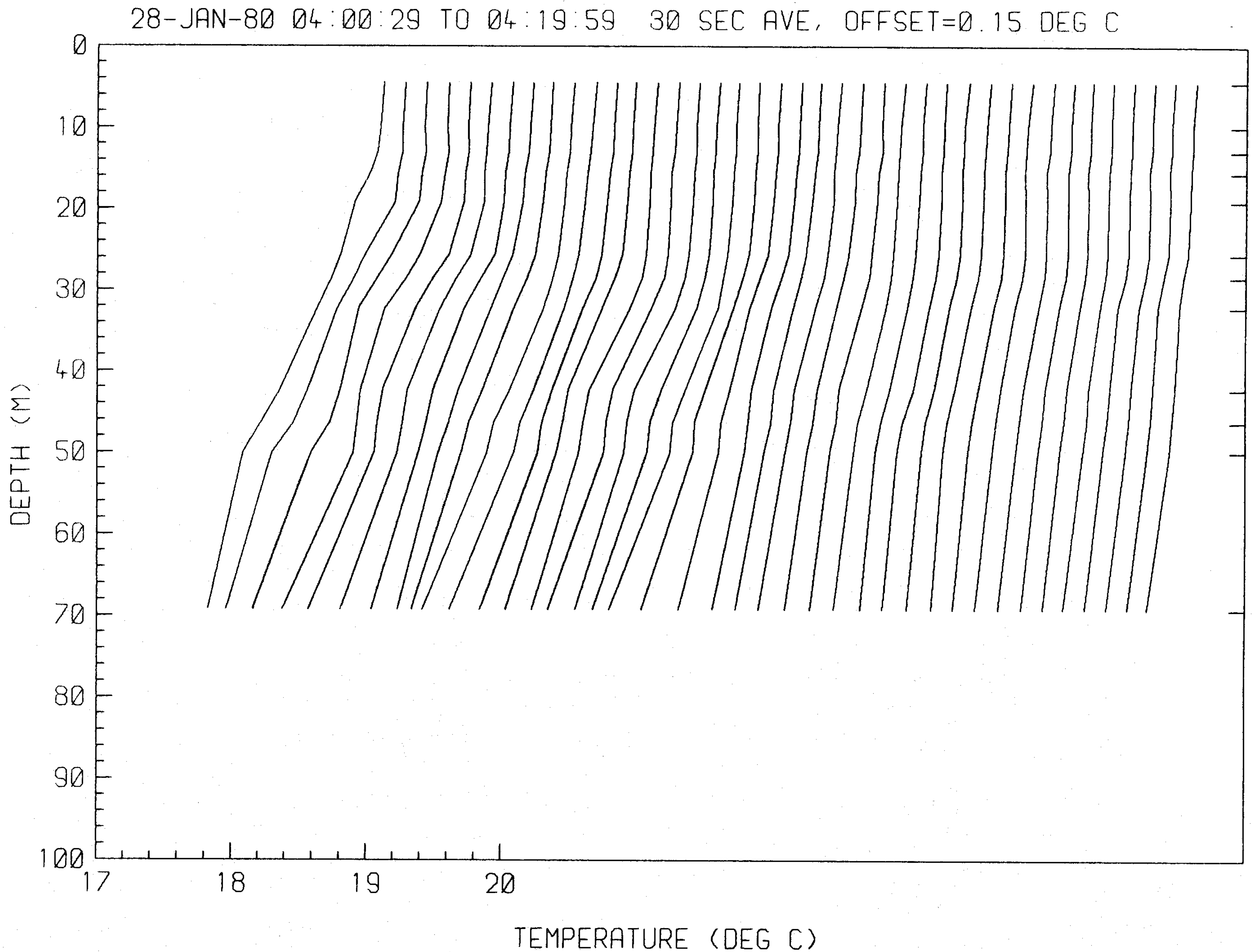
TEMPERATURE (DEG C)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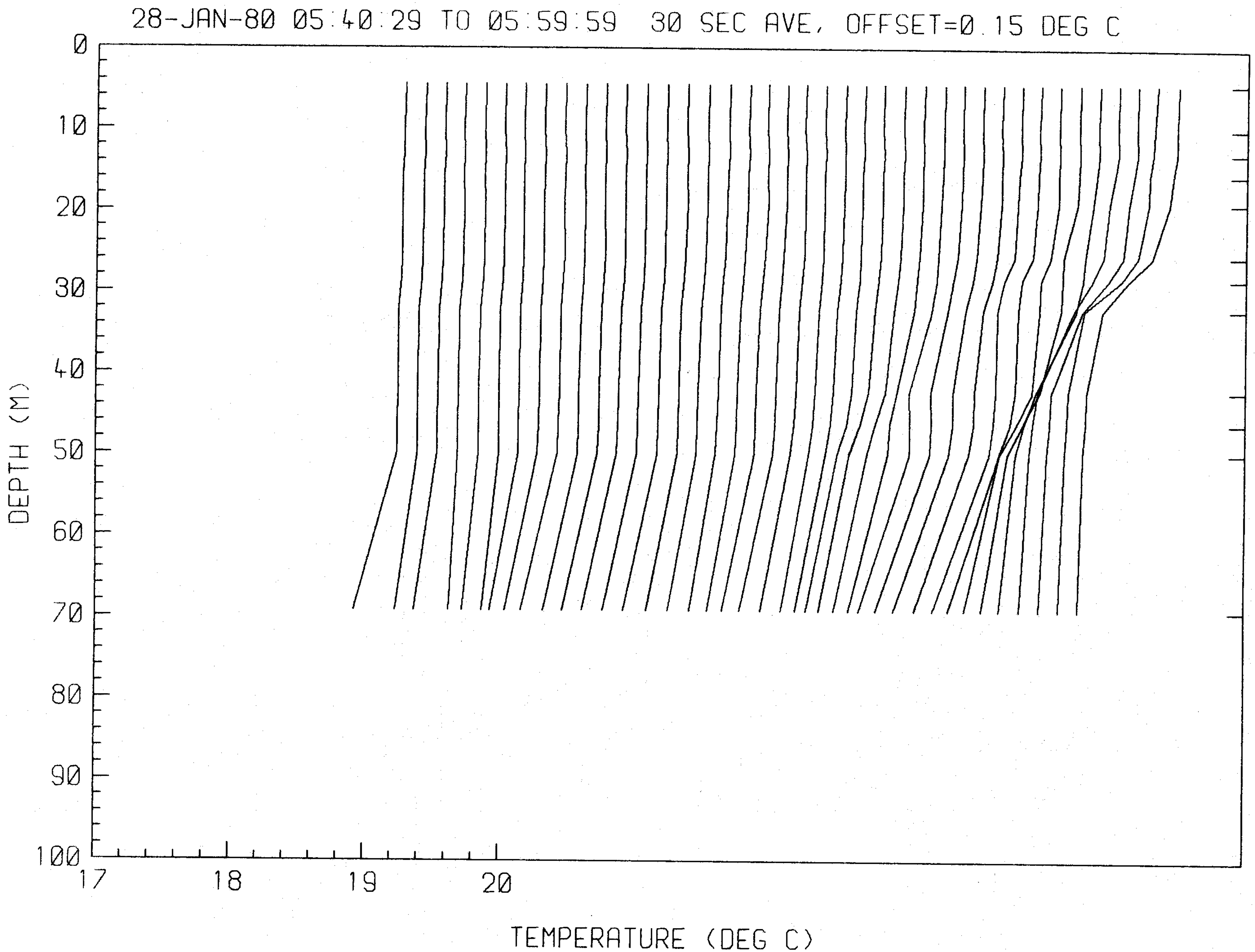
TEMPERATURE (DEG C)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TEMPERATURE (DEG C)

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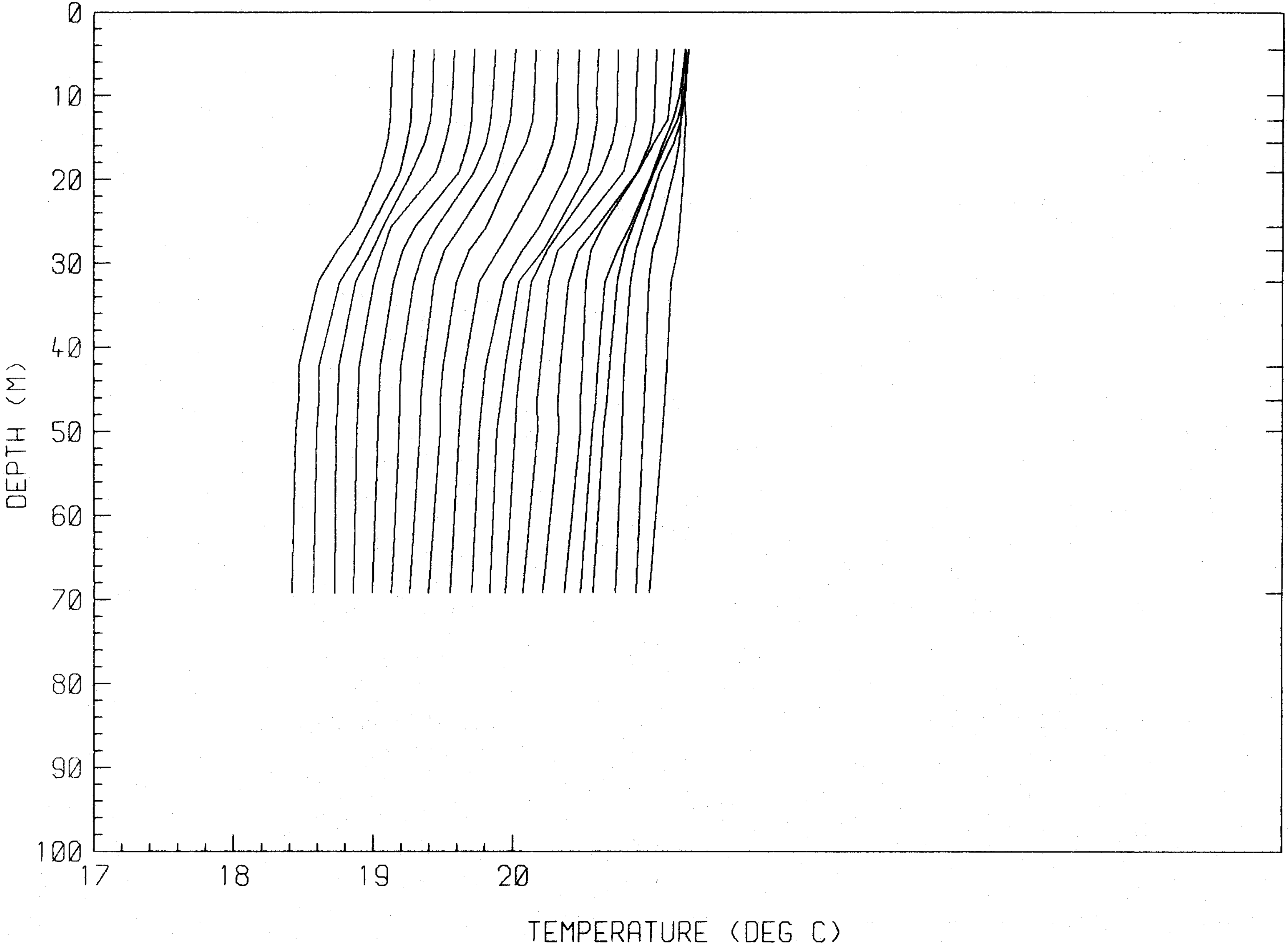

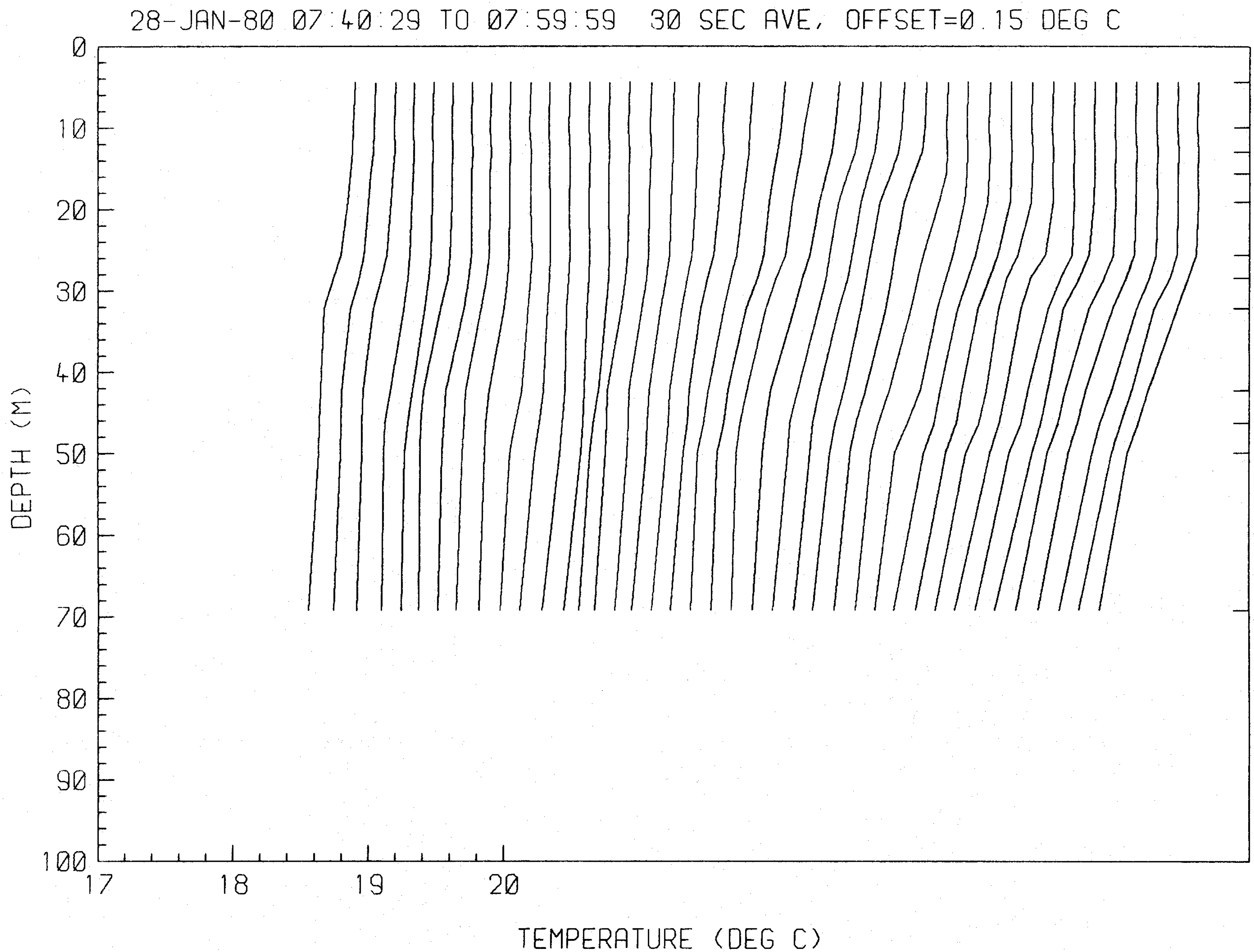
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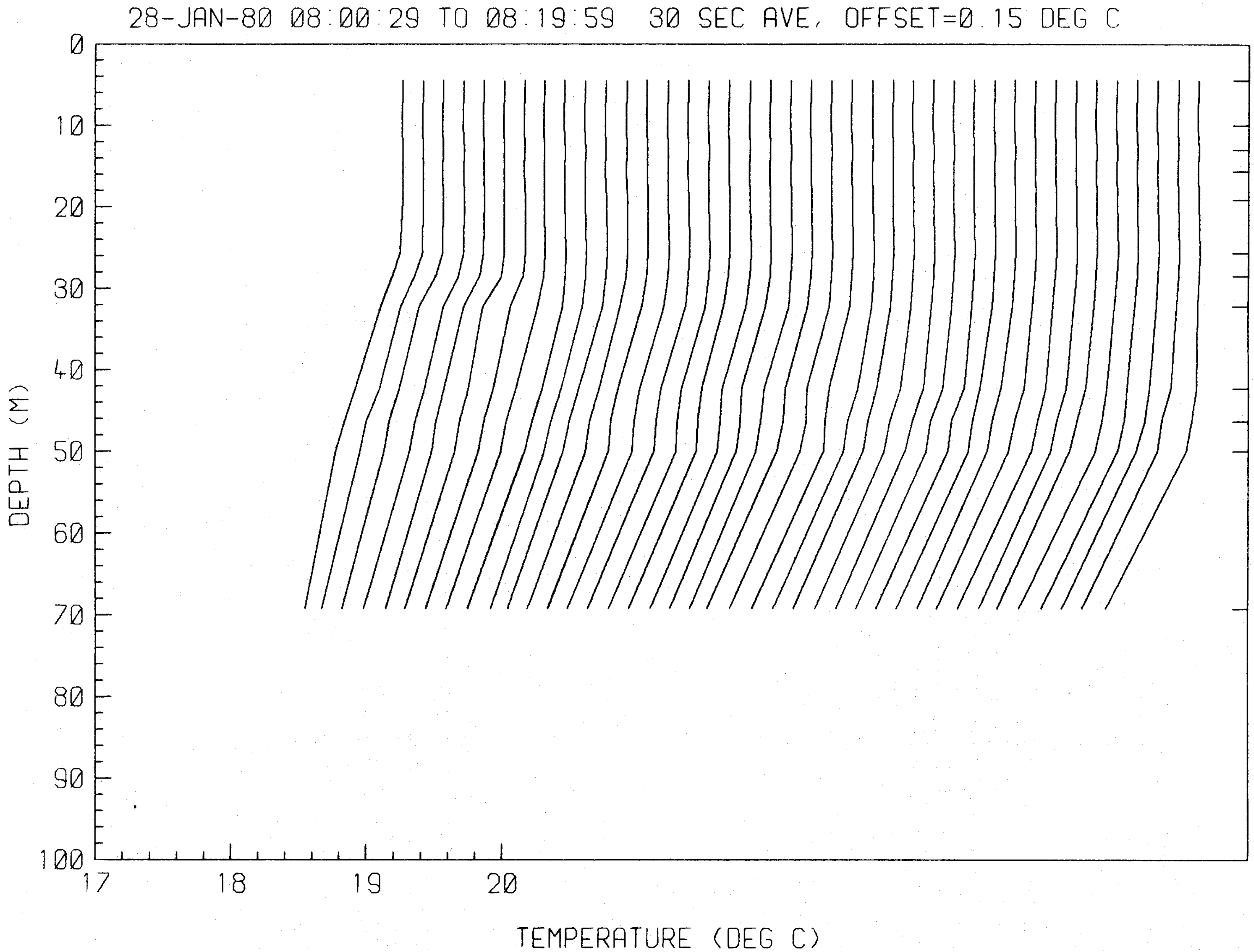
TEMPERATURE (DEG C)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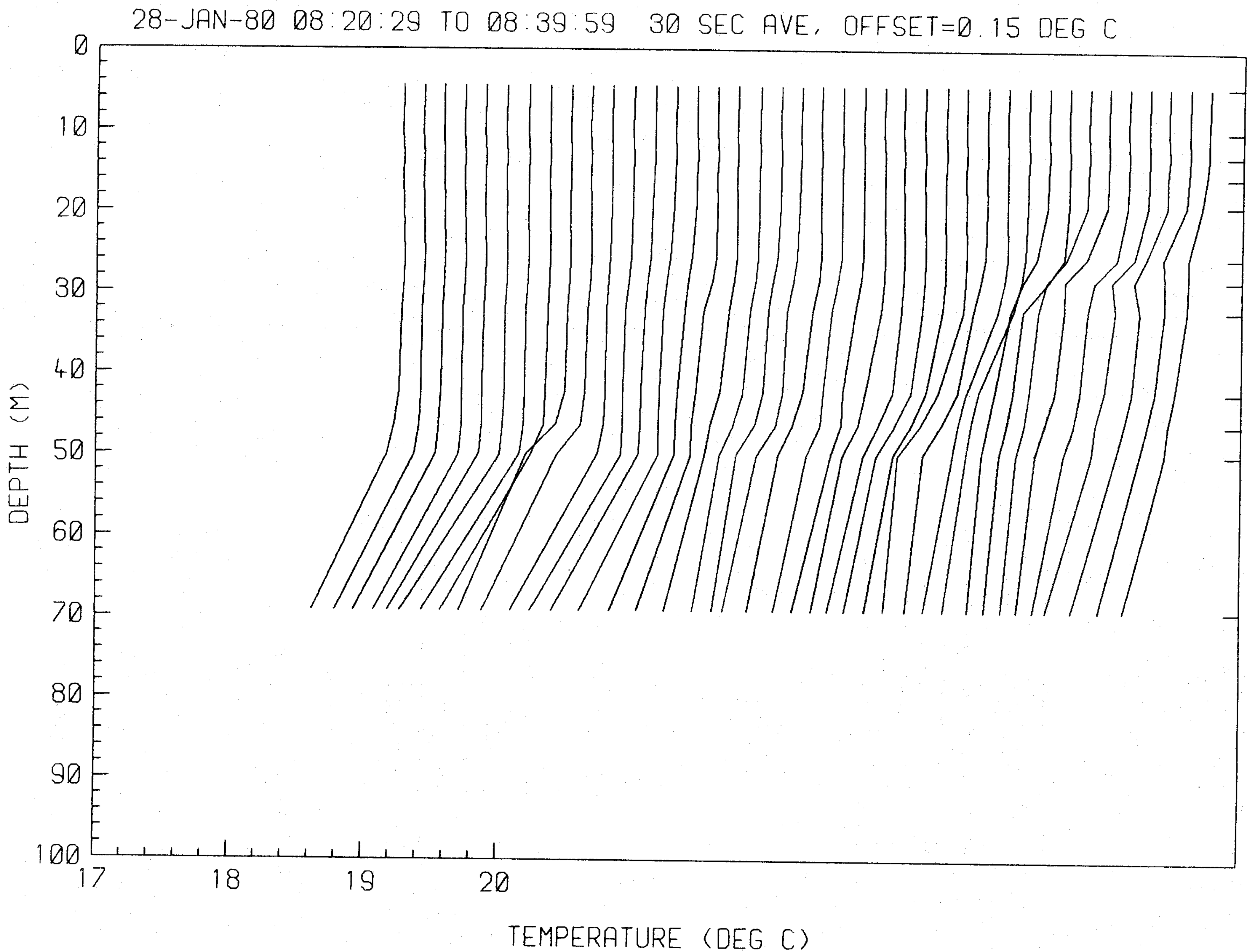
TEMPERATURE (DEG C)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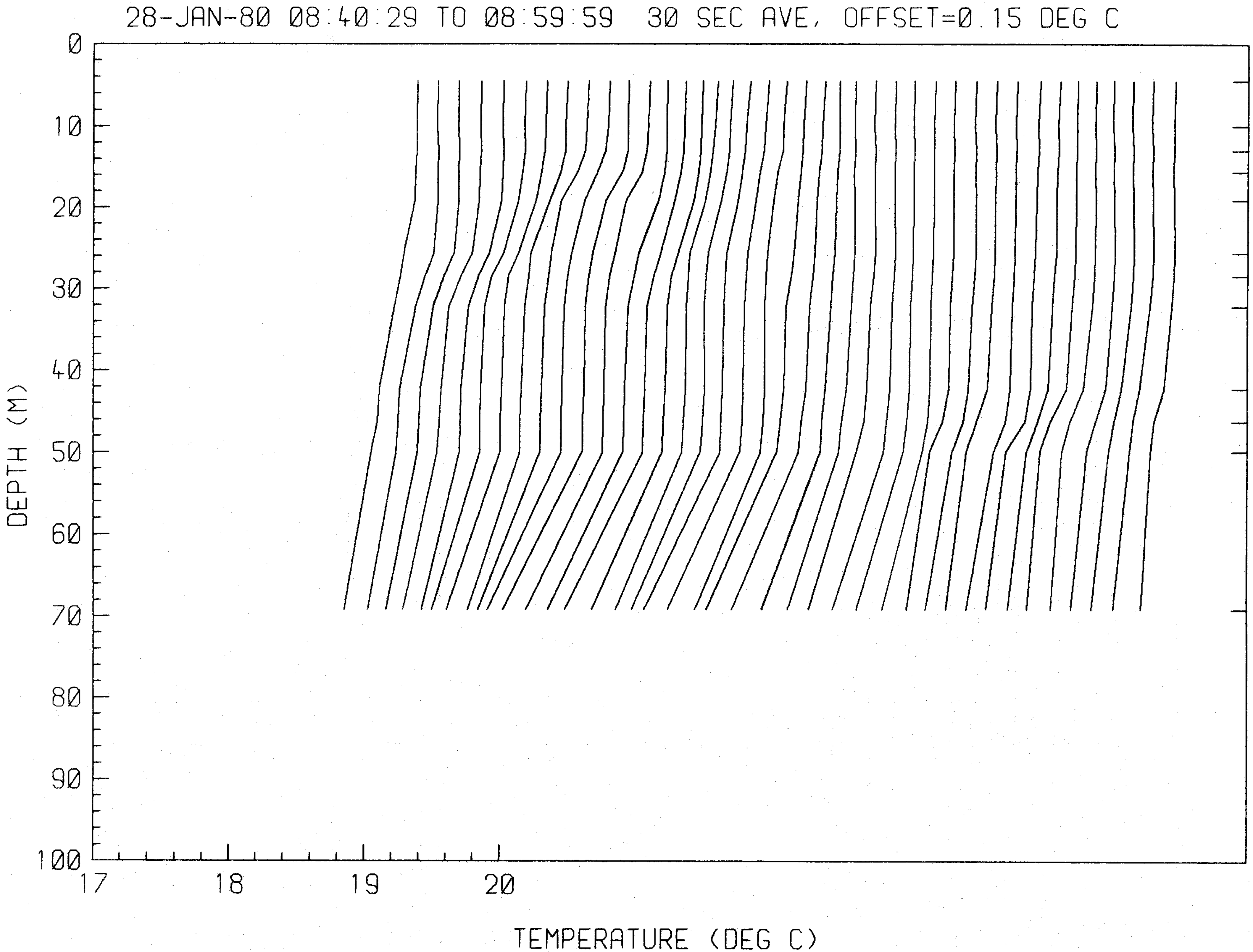
TEMPERATURE (DEG C)



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DEPTH (M)
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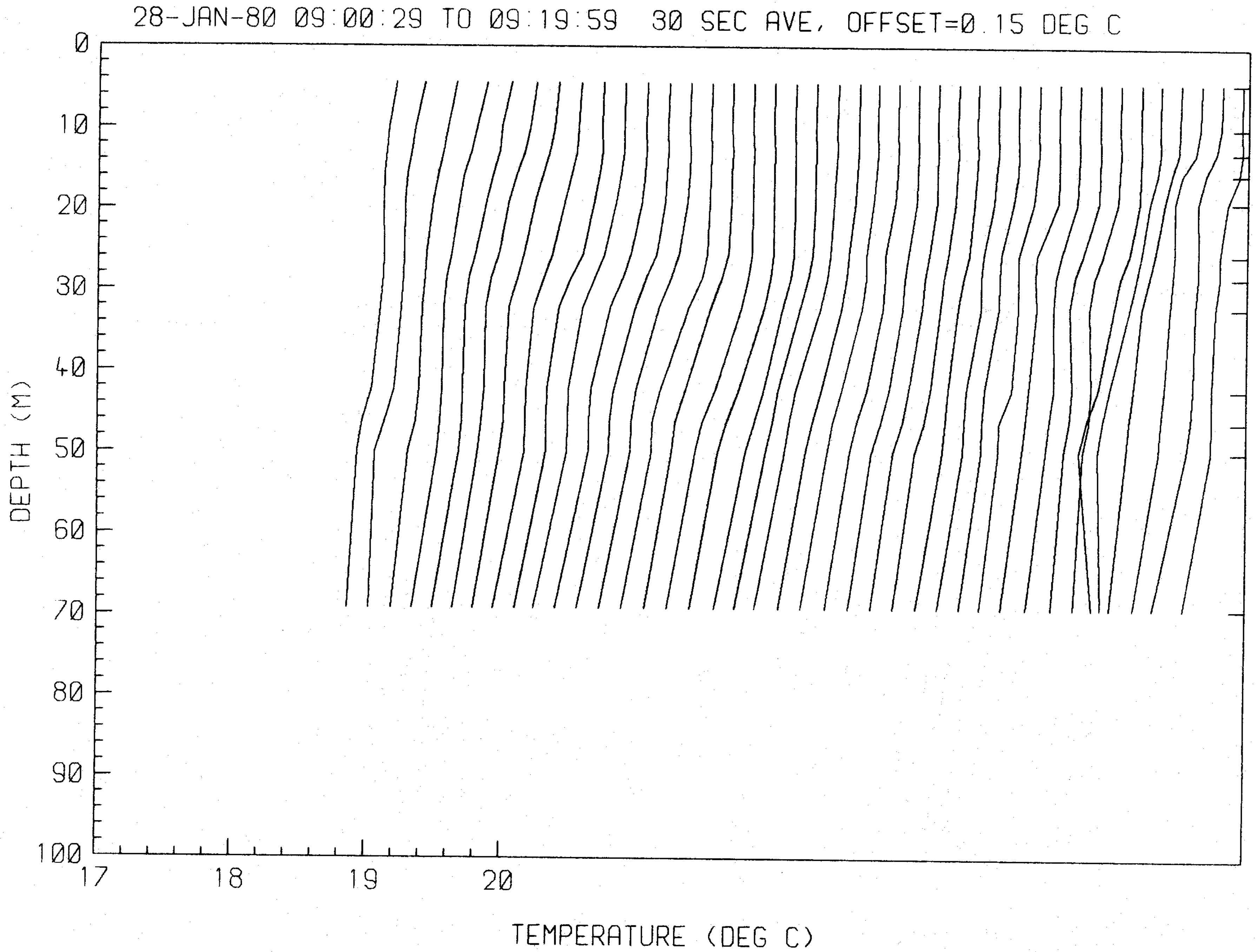
TEMPERATURE (DEG C)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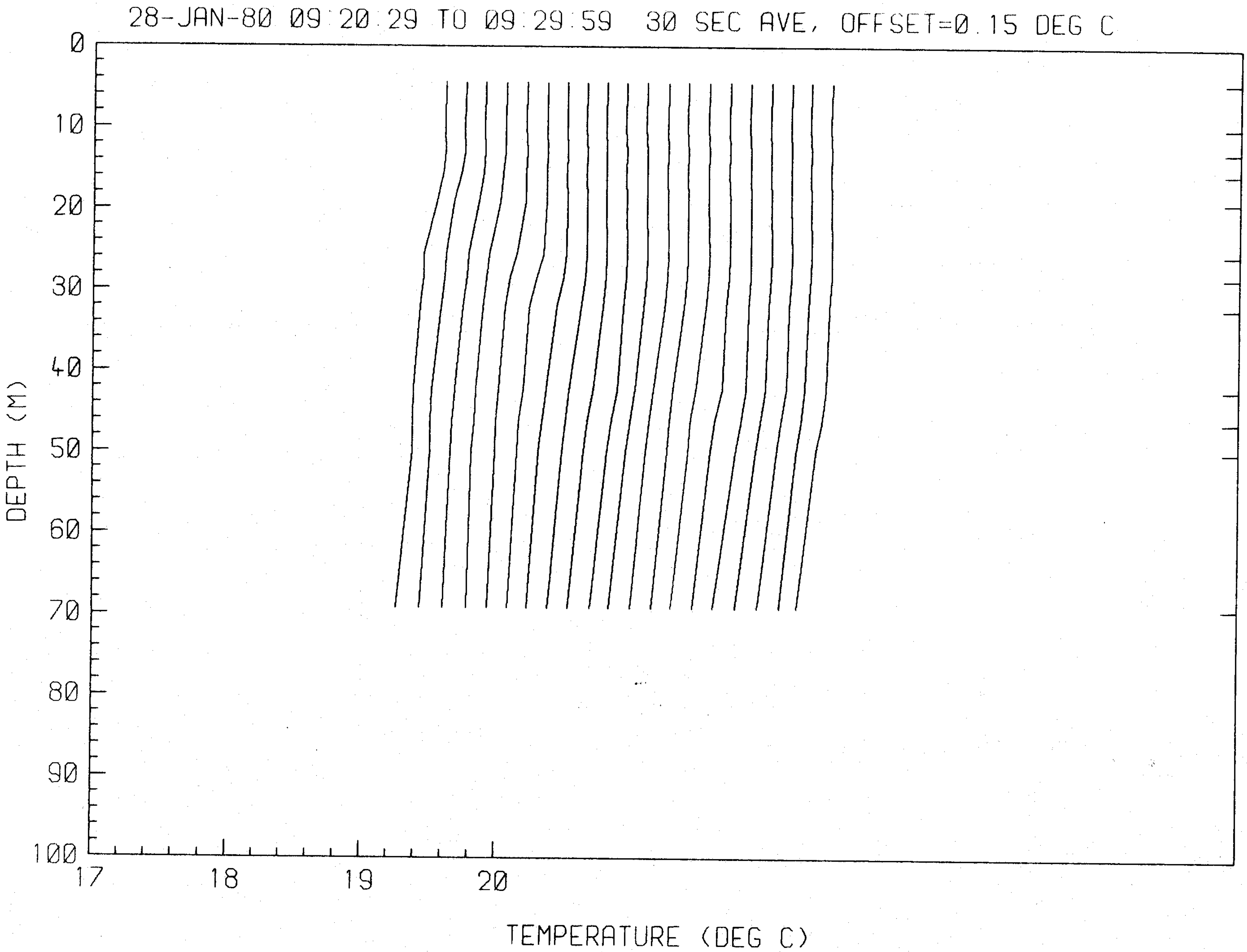
TEMPERATURE (DEG C)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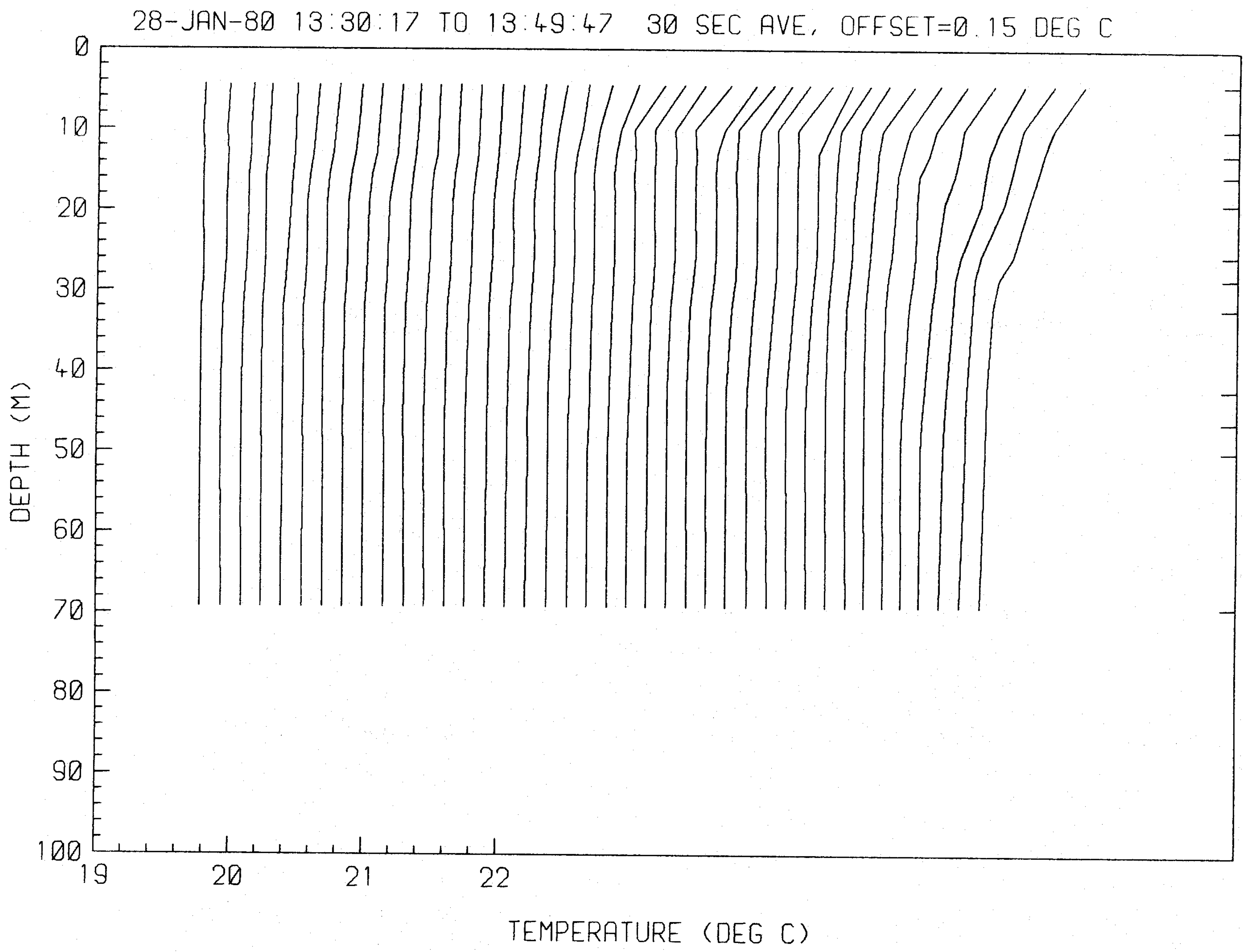
TEMPERATURE (DEG C)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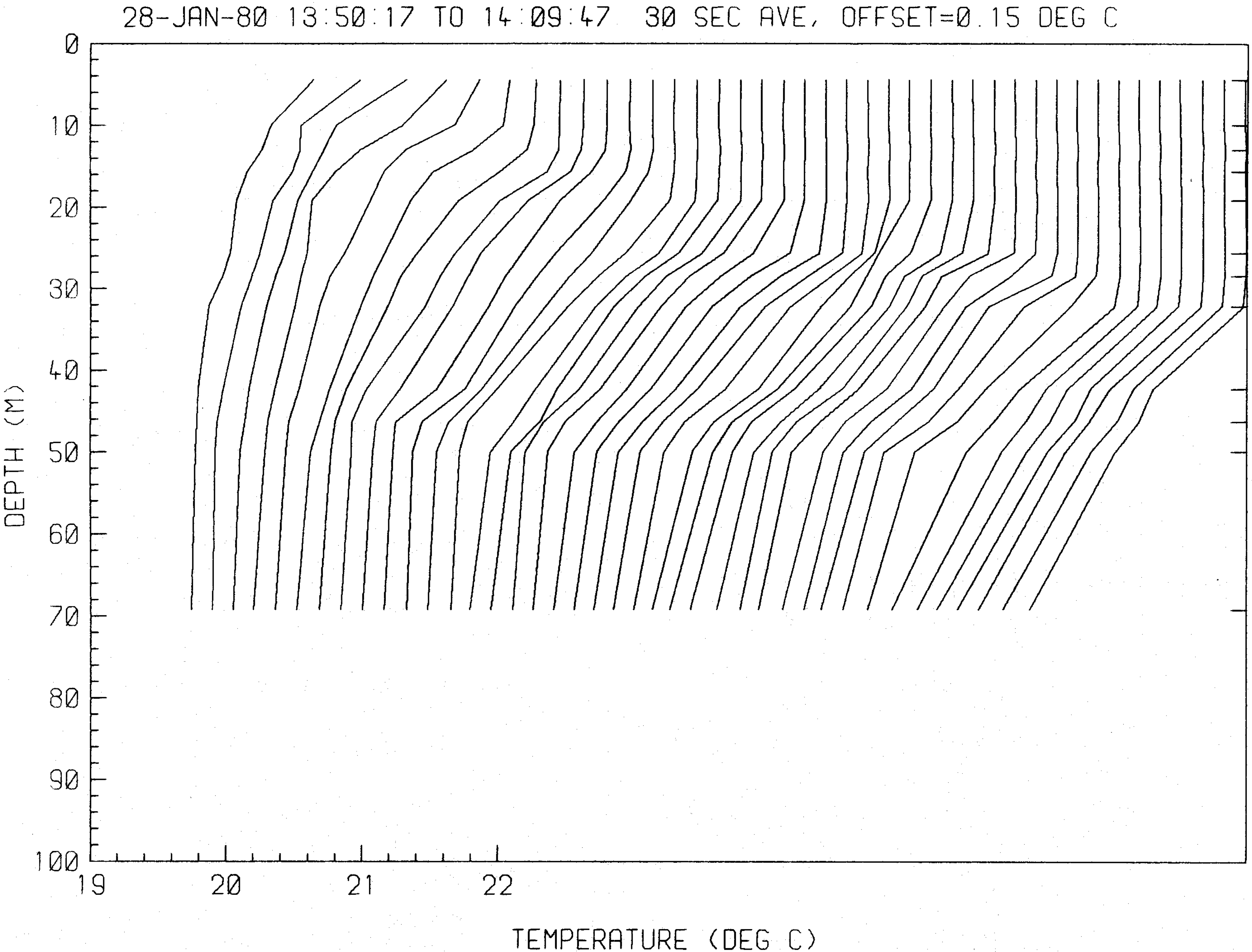
TEMPERATURE (DEG C)

173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DEPTH (M)
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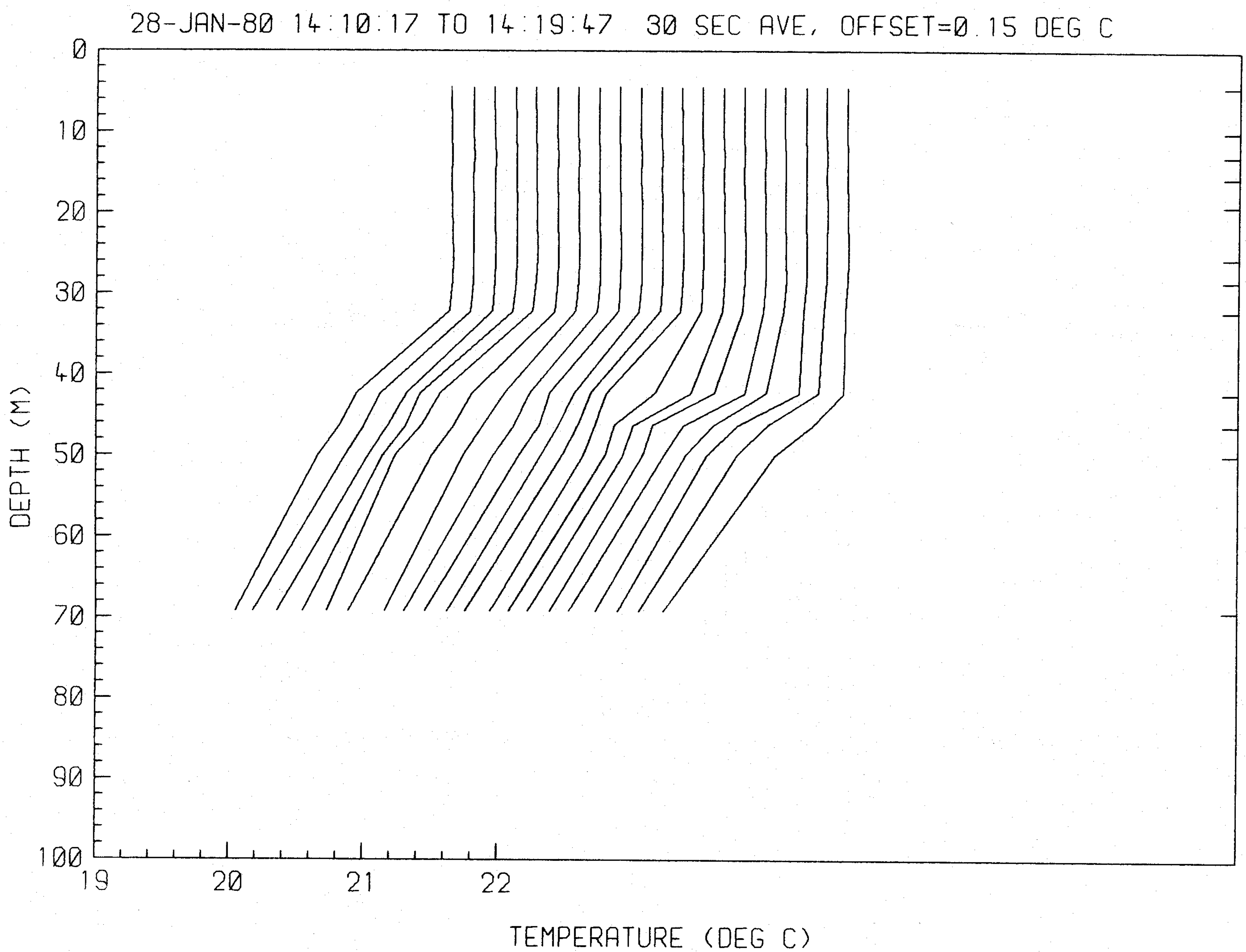
TEMPERATURE (DEG C)


28-JAN-80 14:10:17 TO 14:19:47 30 SEC AVE, OFFSET=0.15 DEG C
DEPTH (M)
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TEMPERATURE (DEG C)

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APPENDIX D

Configuration of the Chain Under Tow

Expressions for the shape of the chain under tow were derived by Baumann _et al_. (1980). The analytical expressions were derived by neglecting accelerations so that the problem reduced to finding a solution to the problem of the hanging chain. A model for the shape of the chain is required for interpolating between measurements of depth on the chain and to predict the depths of sensors for various lengths of submersion and tow speeds.

One of the parameters required by the models is the drag force D per unit length of chain or per unit vertical distance. This force was assumed to be of the form

$$D = C\ A\ \rho U^2$$

where C is the drag coefficient, A the cross-sectional area of the chain per unit length, ρ the density of water and U the tow speed. Baumann _et al_. assumed the value of C = 0.13 as suggested by the manufacturer of the fairing and found reasonable agreement between models and observations for tow speeds up to 3.5 m/s and submerged lengths of 70 m. Given that C = 0.13, $C\ A\ \rho$ equals 2.6 Newtons/m^3 s^{-2} for the chain in question.

During FRONTS-80 we had about 100 m of submerged chain in the water and towed at speeds up to 6 m/s thereby providing a more critical test of models and the drag coefficient C. We found that the value of C suggested by the manufacturer of the fairing was too large. A value of $C A \rho = 1.7$ Newtons/$m^3 s^{-2}$ gives good agreement between observations and predictions of the model. This corresponds to a value of $C = 0.085$. The model chosen assumed drag proportional to s, the distance along the chain.

The difference between observations of depth and predictions of the model is shown for two depths as a function of tow speed in Figure 10. The mean difference is about 1 m which is mostly likely due to uncertainty in the calibration of the pressure sensors. The scatter at tow speeds below 4 m/s is about ± 1 m. At tow speeds greater than 4 m/s, the scatter is ± 2 m/s and shows a systematic difference dependent on sensor.

The observed and predicted difference in depth between the pressure sensors as a function of tow speed is shown in Figure 11. The shapes of the curves are similar although there is a systematic difference ranging from about 0.5 m at low tow speeds to about 1 m at high tow speeds.

We conclude that there is satisfactory agreement between the model and the measurements to within ± 1 m at tow speeds below 3 m/s and to within ± 2 m at speeds between 3 and 6 m/s. The lack of agreement is partly if not substantially caused by uncertainty in the calibrations of the pressure sensors as shown by lack of consistency between the measurements.

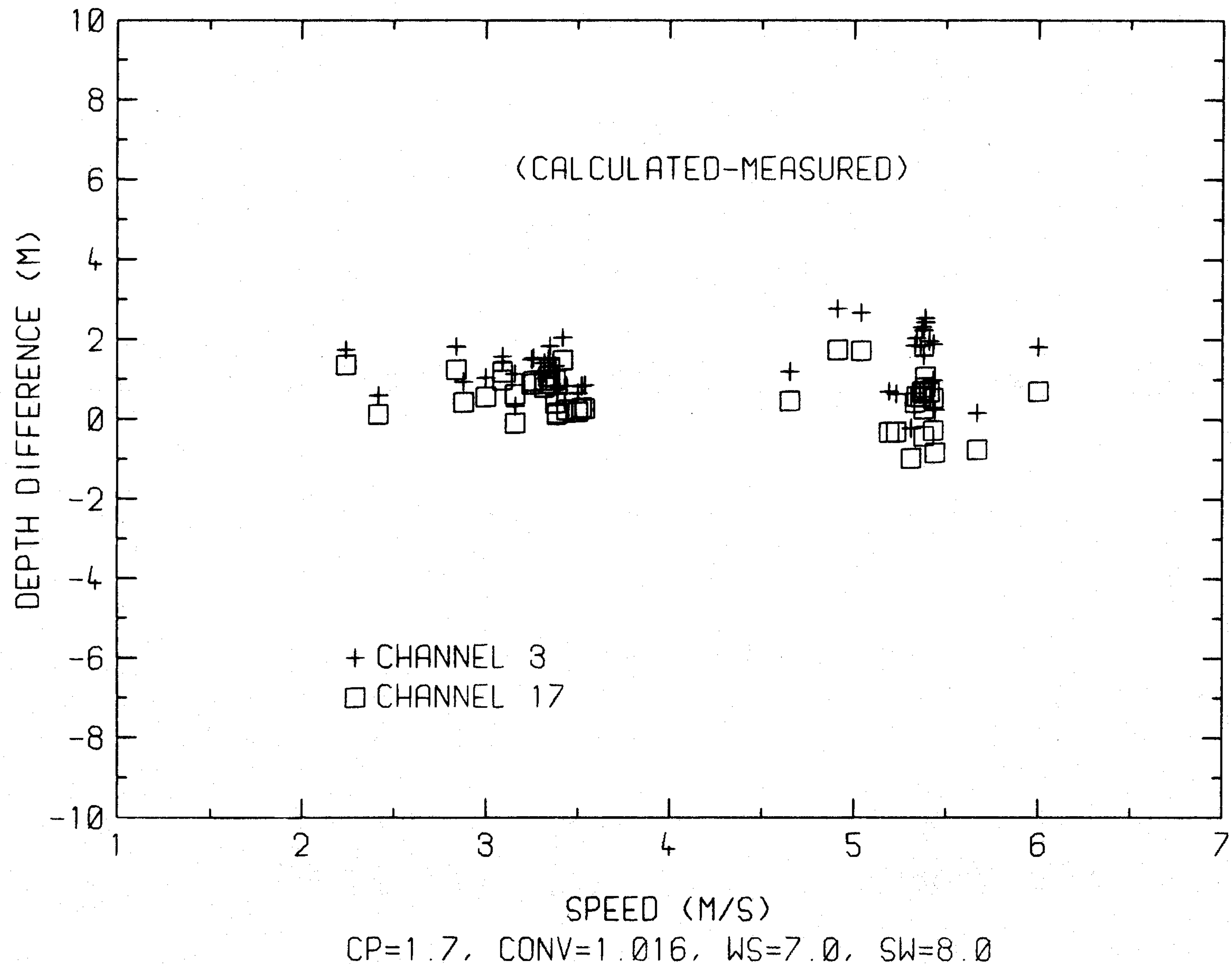

Figure 10. The difference in depths predicted by a model of the shape of the towed chain and depths measured at 11 and 47 m upward along the chain from its bottom. The difference is plotted as a function of tow speed.

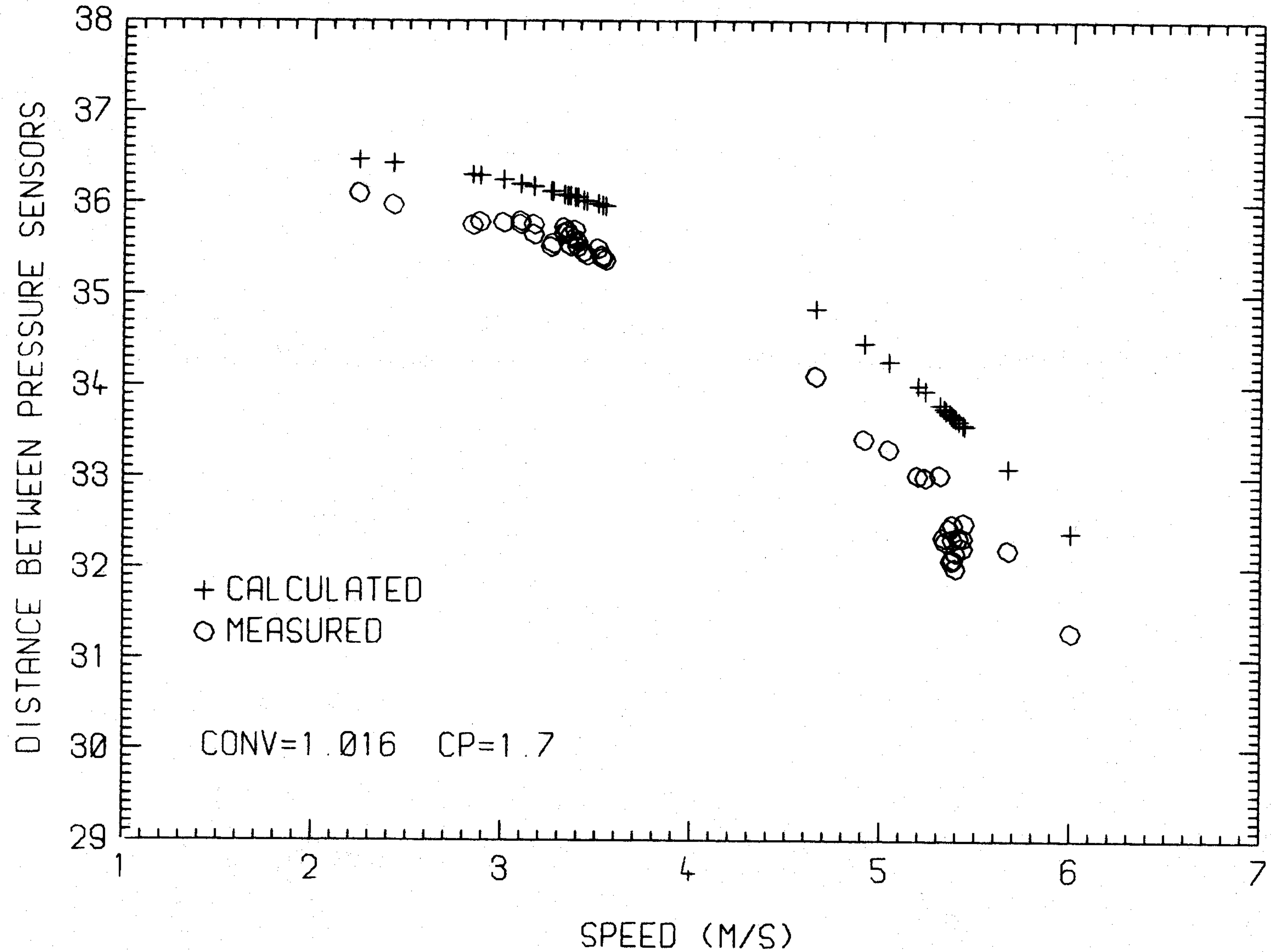

Figure 11. The distance between pressure sensors on the towed chain as calculated from a model and as measured. Both estimates are plotted as a function of tow speed.

In Figures 12, 13 and 14 the shape of the chain is plotted using the new value of the drag coefficient. The origin of the curves ($x = z = 0$) is at the depressor. The curves may be compared with similar curves in Baumann _et al_. which resulted from the old value of C (0.13). All other parameters were assumed to be the same. For tow speeds less than 3 m/s the chain is not far from vertical and predictions of sensor depths from the models depend weakly on choices of parameters or models.

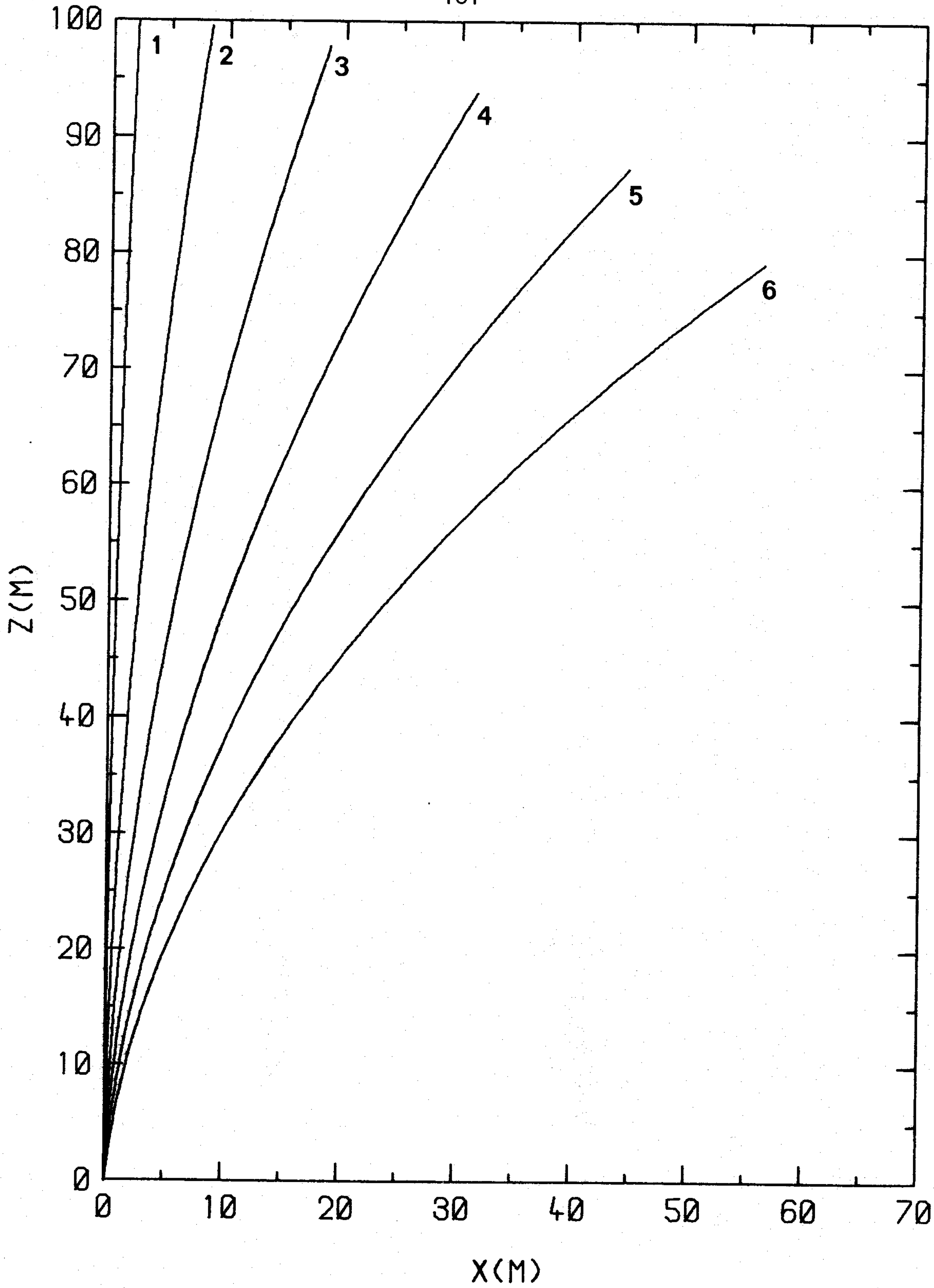

Figure 12. The shape of a towed thermistor chain, 100 m in length, for tow speeds ranging from 1 to 6 m/s. The drag force on the chain is assumed proportional to s, the distance along the chain.

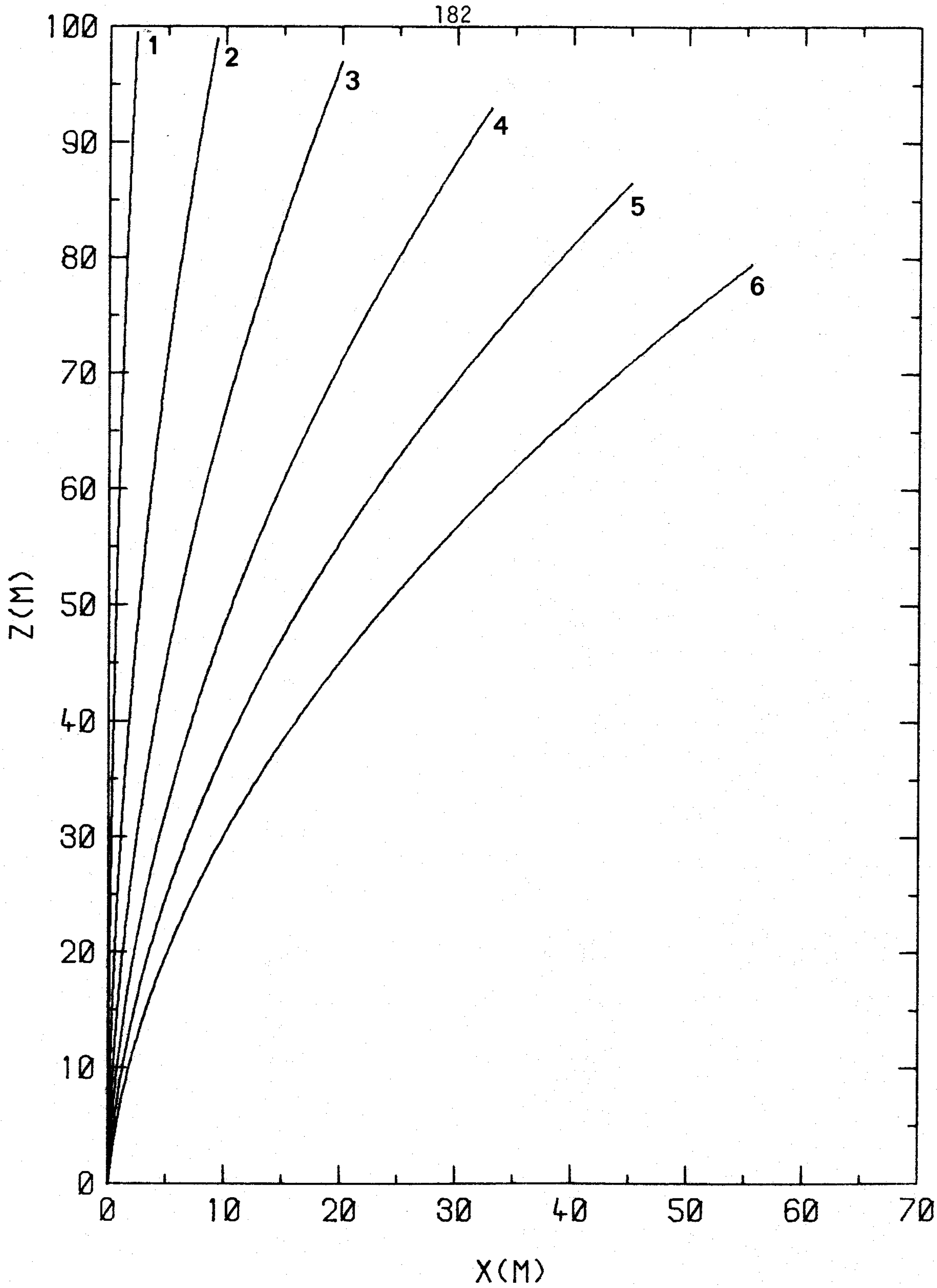

Figure 13. The shape of a towed thermistor chain, 100 m in length, for tow speeds ranging from 1 to 6 m/s. The chain is assumed to be weightless in water and the drag force is assumed proportional to Z.

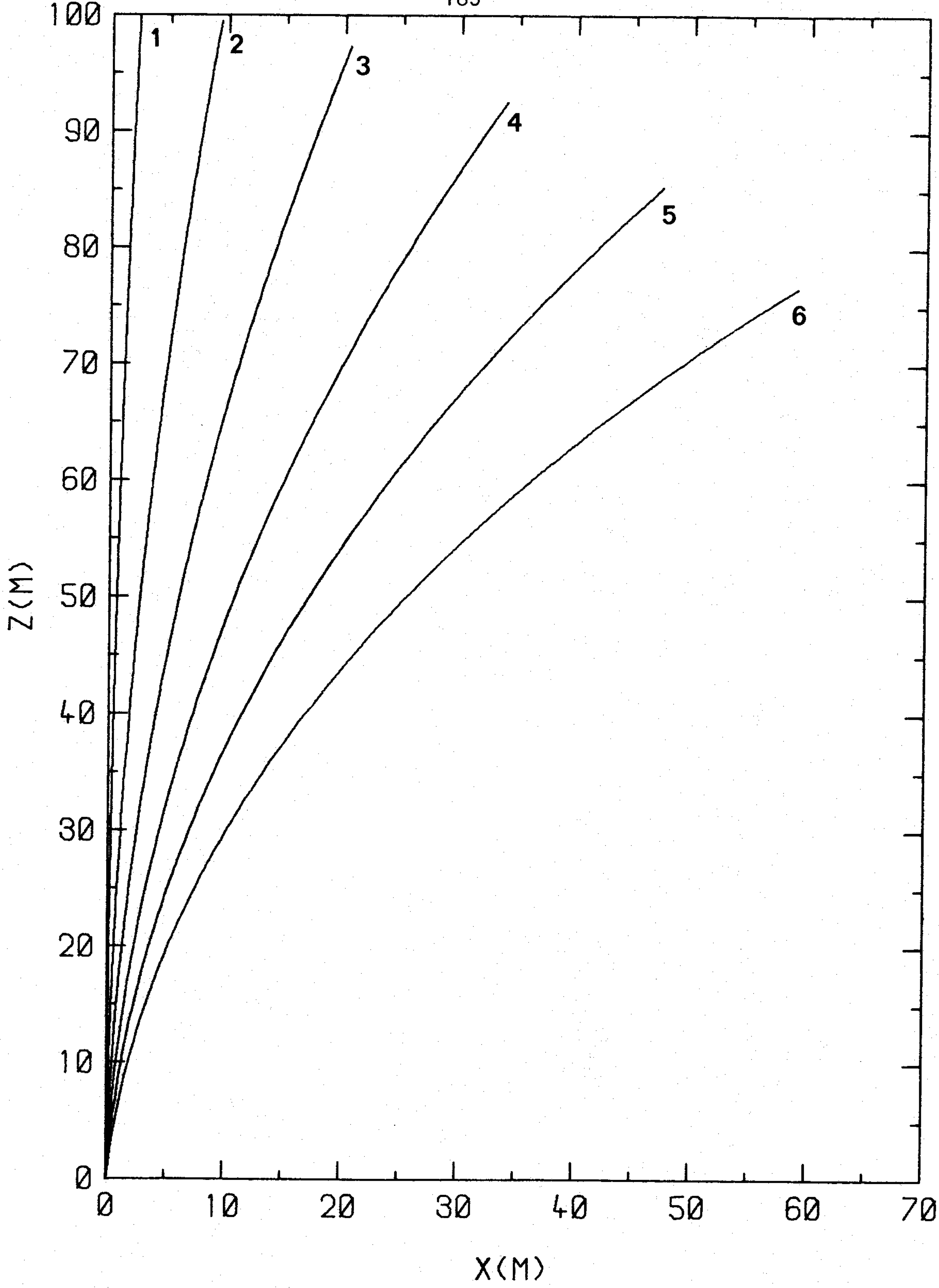

Figure 14. The shape of a towed thermistor chain, 100 m in length, for tow speeds ranging from 1 to 6 m/s. The chain is assumed to be weightless in water and the drag force is assumed proportional to s the distance along the chain.