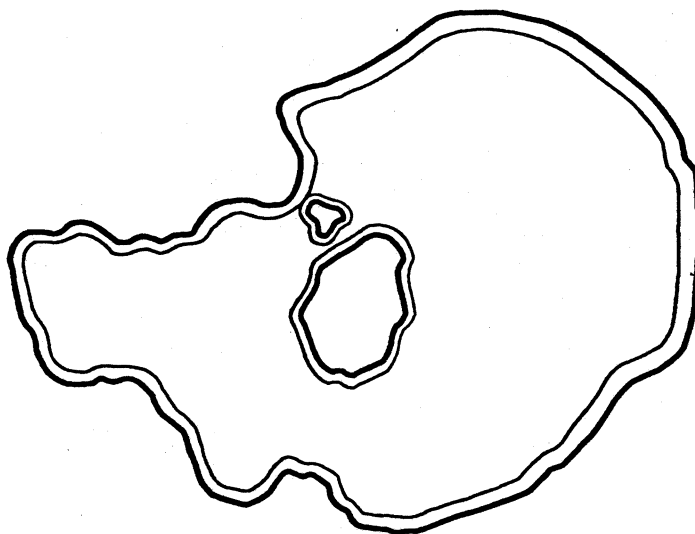An Auxiliary Report
Prepared for the

MONO BASIN WATER RIGHTS EIR

Meromixis in Hypersaline Mono Lake, California
(1: Stratification and Vertical Mixing
during the Onset, Persistence, and
Breakdown of Meromixis)

An Auxiliary Report
Prepared for the
Mono Basin Water Rights EIR Project

This auxiliary report was prepared to support the environmental impact report (EIR) on the amendment of appropriative water rights for water diversions by the City of Los Angeles Department of Water and Power (LADWP) in the Mono Lake Basin. Jones & Stokes Associates is preparing the EIR under the technical direction of the California State Water Resources Control Board (SWRCB). EIR preparation is funded by LADWP.

SWRCB is considering revisions to LADWP's appropriative water rights on four streams tributary to Mono Lake, Lee Vining Creek, Rush Creek, Parker Creek, and Walker Creek. LADWP has diverted water from these creeks since 1941 for power generation and municipal water supply. Since the diversions began, the water level in Mono Lake has fallen by 40 feet.

The Mono Basin water rights EIR examines the environmental effects of maintaining Mono Lake at various elevations and the effects of possible reduced diversions of water from Mono Basin to Owens Valley and the City of Los Angeles. Flows in the four tributary creeks to Mono Lake and water levels in Mono Lake are interrelated. SWRCB's decision on amendments to LADWP's water rights will consider both minimum streamflows to maintain fish populations in good condition and minimum lake levels to protect public trust values.

This report is one of a series of auxiliary reports for the EIR prepared by subcontractors to Jones & Stokes Associates, the EIR consultant, and contractors to LADWP. Information and data presented in these auxiliary reports are used by Jones & Stokes Associates and SWRCB, the EIR lead agency, in describing environmental conditions and conducting the impact analyses for the EIR. Information from these reports used in the EIR is subject to interpretation and integration with other information by Jones & Stokes Associates and SWRCB in preparing the EIR.

The information and conclusions presented in this auxiliary report are solely the responsibility of the author.

Copies of this auxiliary report may be obtained at the cost of reproduction by writing to Jim Canaday, Environmental Specialist, State Water Resources Control Board, Division of Water Rights, P.O. Box 2000, Sacramento, CA 95810.

Acknowledgments

Meromixis in hypersaline Mono Lake, California. 1: Stratification and vertical mixing during the onset, persistence, and breakdown of meromixis.

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Acknowledgments

Abstract

Changes in vertical mixing in hypersaline Mono Lake, California, are described for the onset, persistence, and breakdown of meromixis, 1982 through 1990. In 1982 and 1983 exceptionally large runoff led to a 2.6 m rise in surface elevation and the onset of meromixis. Chemical stratification accounted for a density difference between 2 and 28 m of $1.2–1.5 \times 10^{-2}$ g cm^{-3} during 1984; the midsummer density difference between 2 and 28 m due to temperature was ca. 0.5×10^{-2} g cm^{-3}. During the period of study, salinities ranged from 77 to 98 g liter^{-1}; sodium, chloride, sulfate, and carbonate are the major ions. The flux-gradient heat method corrected for solar heating was used to calculate vertical mixing during the period from April to October. The eddy diffusivity at the thermocline ranged from molecular to 26×10^{-6} m^2 s^{-1} and averaged 3.4×10^{-6} m^2 s^{-1}. Eddy diffusivity was found to regress on N^2, the Brunt-Väisälä frequency squared, to the -0.58 power, suggesting turbulence is generated by local shear rather than large scale processes.

Saline lakes occur on every continent, are often the only natural lakes in endorheic basins, and are especially responsive to climatic variations (Hammer 1986). The volume of saline water in large, deep lakes and land-locked seas is almost as large as the volume of the world's freshwater lakes and rivers. However, long-term limnological examination of saline lakes is rare.

Mono Lake, a large, moderately deep, saline lake, is renowned for its biological and geochemical features (Patten et al. 1987). Mono Lake covers 160 km^2 and has a mean depth of 17 m at an elevation of 1943 m. It occupies a tectonic basin on the western edge of the North American Great Basin just east of the Sierra Nevada, California (38°N, 119°W).

An El Niño – Southern Oscillation during 1982 and 1983 resulted in exceptional runoff into Mono Lake and caused the lake to become meromictic. With frequent measurements spanning the period from 1982 to 1990, we document the onset, persistence, and breakdown of the meromixis and associated changes in vertical mixing. We characterize vertical mixing by eddy diffusivities derived using the flux-gradient heat method corrected for solar heating. In other papers (Jellison and Melack in press(a); Jellison et al. in press(b), Miller et al. in press) we utilize these estimates of vertical mixing and associated changes in chemical stratification to examine biogeochemical and ecological responses to meromixis.

Methods

Field sampling and laboratory measurements – Measurements of Mono Lake were conducted biweekly from March to August and monthly during the rest of the year from 1982 through 1990, except that winter months (October through February) were not sampled from 1982 to 1984. Temperature was measured at one meter depth intervals at three stations (6, 11, S-30; Fig. 1) using a thermistor (Yellow Springs Instruments 701) and Wheatstone bridge circuit (Cole-Parmer model 8502-25) readable to 0.01°C.

Calibrations, at about one degree increments from ca. 0 to 25°C, were made several times each year against a certified thermometer and indicated a measurement accuracy of 0.05°C. Lake surface elevations were recorded weekly from staff gauges by the Los Angeles Department of Water and Power (LADWP).

Samples for conductivity were collected at stations 6 and 11 (Fig. 1) at monthly intervals. The stations were sampled at 7–10 depths with a Van Dorn water sampler. While some depths were consistently sampled (2, 8, 12, 20 and 28 m), others depended on the previous thermal and conductivity profiles and were chosen at smaller intervals across major gradients. Conductivity samples were filtered immediately upon collection through 25 mm Gelman A/E glass-fiber filters (pore size ca. 1 µm) into high density polyethylene bottles and stored at ca. 4°C.

Conductivity of samples was measured in the laboratory in a 1-cm cell between 24 and 26°C and corrected to 25°C. The instrument (Yellow Springs Instruments model 32) and cell (Labline) were calibrated against KCl solutions (1.0 M, 0.5 M, and 0.2 M) of known conductivity. All samples were measured at one time to increase the accuracy and precision of the measurements. Replicate readings indicated a measurement uncertainty of 0.4 mS cm^{-1}, or ca. 0.5%. An expression to correct the measured conductivity to conductivity at 25°C was determined in a water bath at temperatures ranging from 7–25°C, using Seabird Electronics conductivity and temperature sensors (Seacat model SBE 19).

Major solutes were measured in a sample of Mono Lake water collected at 2 m at station 6 on 14 October 1987. All analyses required dilutions which were performed with pipettes calibrated by weighing, volumetric flasks and deionized water (conductance < 1 µS cm^{-1} at 25°C). Sulfate and chloride were measured with a Dionex 2010i ion chromatograph equipped with an AS4A ion exchange column and conductivity detector. Acid neutralizing capacity (ANC) was determined by Gran titration with 1.0 N HCl. Analyses of calcium, magnesium, potassium and sodium were performed on a Varian

400-P atomic absorption spectrophotometer. Salinity, as total dissolved solids (TDS), was measured gravimetrically by drying 5 ml of lake water to a constant weight (> 72 h) at 180°C. Over the range of conductivities from 74 to 92 mS cm^{-1} at 25°C, TDS (g liter^{-1}) = $(1.421 \times Cond_{25})$ - 35.64; n = 22, r^2 = 0.978. The standard error of the estimate for the regression was 1.23 g liter^{-1}. The non-zero intercept arises from the nonlinearity of the relation which was not significant over the range of conductivities considered here. A second order regression yielded a smaller r^2.

Density of Mono Lake water was measured with a vibrating flow densimeter (Anton Paar model DMA60 with DMA602 cell; Picker et al. 1974) calibrated with standard seawater (Inst. of Oceanographic Sciences, Godaming, U.K., P94) and distilled water. Densities of standards were calculated using algorithms in Fofonoff and Millard (1983). Temperatures in the densimeter were recorded with a fast response thermometer (Thermometrics FP07 thermistor and Hewlet Packard 34740A multimeter) calibrated against a quartz thermometer (Hewlett Packard model 2804A) accurate to 0.005°C. Density measurements of duplicate samples yielded a mean uncertainty of 3×10^{-5} g cm^{-3}.

Incident photosynthetically available irradiance (PAR, 400–700 nm) was recorded continuously with a cosine-corrected, quantum sensor and integrated over hourly intervals at a site seven kilometers from the lake's southwestern shore. Attenuation of PAR within the water column was measured at 0.5 m intervals with a submersible quantum sensor at stations 6 and 11.

Numerical procedures – Vertical mixing is often characterized by eddy diffusivities which assume a Fickian diffusion equation to describe the complex vertical mixing processes which occur over a variety of spatial and temporal scales (cf. Spigel and Imberger 1987). This description has been applied to a variety of lakes using different tracers, including heat (Jassby and Powell 1975), tritium (Quay et al. 1980) and SF_6 (Wanninkhof 1986). Although their empirical nature and accompanying limitations must be recognized, eddy diffusivities provide a useful characterization of vertical mixing for

year to year comparisons.

Eddy conductivities were calculated using the flux-gradient heat method modified for solar heating (Jassby and Powell 1975).

$$K_z = -\frac{1}{\dfrac{\delta\theta}{\delta z}}\left[\frac{1}{A_z}\frac{d}{dt}\int_z^{z_m} A_u\theta_u\,du - \frac{1}{\rho c}R_z\right]$$

where K_z is the coefficient of vertical eddy conductivity at depth z, z_m is the maximum depth of the lake, A_z is area at depth z, u and z are depths positive downwards, R_z is irradiance at depth z, θ is temperature, ρ is density, c is thermal capacity, and t is time. The temperature gradients were estimated as 2 m central differences. Depths, areas, and volumes were changed to correspond to changes in the lake level. The heat integral was evaluated at 1 m intervals using lakewide mean temperatures and area-capacity curves (Pelagos Corp., unpubl.). While the thermal capacity of Mono Lake water is lower than fresh water, when combined with the density effect of dissolved salts, the volumetric thermal capacity is near unity (0.99 cal cm^{-3} °C; Mason 1967). Eddy diffusivities were assumed equal to eddy conductivities after being corrected for molecular conductivity (0.13 × 10^{-6} m^{-2} s^{-1}; Chemistry and physics handbook 1977, Table E-11).

In moderately sized lakes, internal waves and other water movements make estimating lakewide mean temperature profiles difficult, hence sampling of multiple stations is often required to minimize errors. Given the lake's size, diel or cyclonic variations in wind are likely to cause internal seiches in Mono Lake. The calculated period of the unimodal internal seiche in Mono Lake ranges from ca. 8 to 18 hours assuming a rectangular basin (Hutchinson 1957, p. 336, eq. 92) and August density profiles. Typical summer conditions include morning calm followed by winds that begin in early afternoon and reach 5–10 m s^{-1} before diminishing near sunset. Although sampling was most often done during calm to low wind conditions from early to midday, internal seiches from the preceding day are likely to be present. On a number of sampling dates, thermocline

profiles at different stations were vertically displaced up to 2 m relative to each other suggesting either thermocline tilting or internal seiche activity.

In estimating lakewide mean profiles, the conventional mean is biased when station to station variance is due to isotherm tilting under wind stress or internal seiche activity (Sweers 1968). Also, when sigmoidal temperature profiles taken from various stations are displaced relative to each other due to internal seiches, the conventional sample mean will smear the vertical temperature gradient over the range of isotherm displacement. For this reason, the Sweers' "inverse algorithm", in which the depths of a number of isotherms are averaged and used to construct a mean temperature profile, was employed whenever possible in determining lakewide mean profiles. From late autumn to spring, temperature profiles were often non-monotonically decreasing with depth due to density gradients arising from salinity stratification during meromixis. The conventional average was used in these cases, since the Sweers' "inverse algorithm" can yield non-unique solutions under these circumstances. The lakewide average of temperatures from three stations was used throughout the analysis.

The errors in the estimates of heat content arising from internal water movements are potentially much larger than those due instrumental errors alone (c.f. Stauffer 1992). Stauffer (1992) presents a technique in which stations are resampled following a suitable time interval and then changes in the heat content are made between corresponding pairs of sampling visits. This "revisit" technique provides a method for accurate error estimation. Although our data were not collected in a fashion to enable this type of analysis, we employed an approximate analog with data collected in 1984 when six stations were sampled. For each sampling date, two lakewide mean temperature profiles were estimated based on two different sets of three stations (6, 8, 11 versus 4, 9, S-30; Fig. 1). The two lakewide means are assumed to approximate identically distributed independent estimates of heat content for the purposes of error estimation.

Solar heating was estimated from continuous measurements of incident PAR,

calculated albedoes, and light attenuation within the water column. Comparison of measurements with an Eppley pyranometer (285–2,800 nm) and PAR (400–700 nm) collected at a similar elevation 45 km south of Mono Lake, indicated PAR comprised 44.6% of the total solar irradiance assuming a conversion of 4.57 μEinst = 1 joule (McCree 1972). This is close to findings in other studies (45%, Gates 1966; 41%, Jassby and Powell 1975). The PAR data were converted to total solar input using this ratio. Albedoes were calculated assuming all radiation was direct; this assumption introduces only a small error (Jassby and Powell 1975). Attenuation within the water column was divided into seven wavelength bands. Visible light attenuation was measured as PAR attenuation. The attenuation of infra-red light for five intervals was obtained from Hale and Querry (1973): 1.1 m^{-1}, 700–800 nm; 3.4 m^{-1}, 825–900 nm; 26 m^{-1}, 925–1,000 nm; 870 m^{-1}, 1,200–1,800 nm; and 7,800 m^{-1} from 2,000–2,400 nm. The attenuation of ultraviolet light (300–400 nm) measured in lake water filtered through a 0.45 Millipore filter was 1.5 m^{-1}.

Results

Meromixis and vertical structure – The surface elevation of Mono Lake declined at a mean rate of 0.43 m yr^{-1} from 1971 to 1982 (LADWP 1984). This trend was reversed in early 1982, as the surface elevation of Mono Lake rose 2.6 m during 1982, 1983, and early 1984 due to exceptionally high runoff and reduced diversions of inflowing streams (Fig. 2). More typical conditions in 1984 and 1985 and resumed diversions of inflowing streams resulted in a subsequent 0.7 m decline. This decline was temporarily reversed in 1986 following another year of large runoff. During the next three years, 1987 through 1989, surface levels declined 1.6 m during a period of sustained drought. During 1990 the lake level was relatively stable as LADWP maintained flows in inflowing streams.

The large volume of freshwater inflows beginning in 1982 and continuing through 1983 created strong, vertical chemical gradients and the onset of meromixis. The lake

remained chemically stratified until November 1988 (Fig. 3). The difference in conductivity between 2 and 28 m increased from 5 mS cm^{-1} in April 1983 to 12 mS cm^{-1} in March 1984. Evaporative concentration of the mixolimnion and reduced inflows decreased this difference to 4–5 mS cm^{-1} by late 1985. However, higher runoff in 1986 initiated a second chemocline located several meters above the initial one, and the difference in conductivity between 2 and 28 m was 10 mS cm^{-1} in July 1986. Evaporative concentration from 1986 through 1988 increased the salinity of the mixolimnion until it exceeded that of the monimolimnion by August 1988. Holomixis occurred in late November when seasonal thermal stratification weakened. In 1989, as evaporation led to a 0.4 m drop in lake level and concentration of epilimnetic water, a small inverse conductivity gradient developed at 2 m with values ca. 1 mS cm^{-1} higher than those at 28 m. Holomixis in November 1989 eliminated this gradient. A similar small inverse gradient was observed during the stratified period in 1990 as the lake level dropped 0.24 m from April through September. Monimolimnetic conductivities decreased slightly during meromixis and can be attributed to gradual mixing with mixolimnetic water and perhaps groundwater inflows beneath the chemocline. A linear regression of conductivity during meromixis at 28 m against time indicated a significant trend of decreasing conductivities (slope = 0.66 mS cm^{-1} y^{-1}, r^2 = 0.35 and n = 80).

The chemocline, the depth of maximum conductivity gradient, was located between 15 and 20 m during mid-1983 (Fig. 4). On account of freshwater inflows it migrated to 11 m at the beginning of 1984. This chemocline progressively deepened each subsequent year and was located at 20–23 m just before meromixis was terminated in late 1988. The maximum gradient at the chemocline was 4 mS cm^{-1} m^{-1} in 1985. The slight apparent gradient, 0.2 mS cm^{-1} m^{-1}, in late 1988 during holomixis most likely reflects analytical errors. A second chemocline was formed above the initial one in 1986 as another above average runoff year resulted in freshwater inputs above the seasonal thermocline. This secondary chemocline coincided with the thermocline and reached 3 mS

$cm^{-1} m^{-1}$ by late summer. It was eliminated during the same year as autumn cooling resulted in mixing down to the deeper chemocline.

During the period from 1983 through 1990 the salinity expressed as total dissolved solids ranged from 77 to 94 g liter^{-1} at 2 m and from 88 to 98 at 28 m. The major solutes in Mono Lake are Na^+, CO_3^{2-} plus HCO_3^-, Cl^- and SO_4^{2-} (Table 1). Our analyses yield an equivalence ratio of sum of cations to sum of anions of 1.01. Our solute concentrations and ionic ratios are similar to those reported by Mason (1967). Borate contributes about 5% of the ANC (Mason 1967), and essentially all the remainder is carbonate and bicarbonate. Based on the proportions of carbonate to bicarbonate measured by Simpson and Takahashi (1973) in Mono Lake, carbonate contributed about 433 meq liter^{-1} and bicarbonate about 130 meq liter^{-1} in our sample.

Near surface temperatures (2 m) were lowest in February (1–4°C) and highest in July and August (19–23°C)(Fig. 5). Superimposed on this general pattern were several significant differences due to the onset of meromixis and changes in vertical density stratification. During early 1982 the temperature near the bottom (28 m) was 1–2°C and warmed to near 5°C by late autumn. Thereafter, near bottom temperature remained nearly constant for the entire 6-yr period of meromixis. In late 1988, temperature at 28 m rose 4°C at the beginning of holomixis and then dropped 8°C during winter mixing. During 1989 the first year after the breakdown of meromixis, hypolimnetic temperatures rose throughout the thermally stratified period and increased 9°C during the year. During meromixis, mixolimnetic temperatures were 1 to 3°C colder than those in the monimolimnion during the period of minimum lakewide temperatures. This inverse thermal stratification was probably also present in 1983 and 1984, but was not detected because surveys were not conducted in January and February of those years.

The thermocline, represented by the maximum temperature gradient, showed consistent seasonal patterns, in which variations due to meromixis were imposed (Fig. 6). When lake levels were rising during meromixis, 1982, 1983, and 1986, the midsummer

thermocline was located higher in the water column relative to other years, 1984, 1985, 1987, and 1988. The maximum temperature gradient varied from near zero to 4°C m^{-1} on a seasonal basis.

The densities of a sample collected on 14 October 1987 at station 6 (conductivity at 25°C, 83.8 mS cm^{-1}) were measured at temperatures ranging from 4 to 25°C (Fig. 7A). Densities were also measured at 20°C for 24 samples collected from 1983 to 1987 whose conductivities ranged from 79 to 92 mS cm^{-1} at 25°C (Fig. 7B). The dependence of density on conductivity and temperature were determined separately using quadratic regressions:

$$\rho_1 = 1.07486 - 2.164 \times 10^{-4}\theta - 3.26 \times 10^{-6}\theta^2, \; n = 12$$

standard deviation of the residuals $= 3.22 \times 10^{-5}$ g cm^{-3}

$$\rho_2 = 1.20441 - 4.265 \times 10^{-3}Cond_{25} + 3.166 \times 10^{-5}Cond_{25}^2, \; n = 24$$

standard deviation of the residuals $= 1.10 \times 10^{-3}$ g cm^{-3}

where ρ_1 and ρ_2 are densities (g cm^{-3}), θ is temperature (°C), and $Cond_{25}$ is conductivity at 25°C (mS cm^{-1}). These regressions ignore second order effects between conductivity, temperature, and density.

The overall density structure from 1983 to 1990 (Fig. 8) was calculated using these regression equations. A maximum density difference between the mixolimnion (2 m) and the monimolimnion (28 m) of 0.020 g cm^{-3} occurred in August 1983. Overall stratification decreased to 0.007 g cm^{-3} by late 1985 due to evaporative concentration and winter cooling. An above normal runoff led to a subsequent increase to 0.017 g cm^{-3} in July 1986 after which stratification decreased until meromixis was terminated in November 1988.

During most of meromixis chemical stratification was greater (up to 3x) than seasonal temperature stratification (Fig. 9). During the two monomictic years, 1989 and 1990, inverse chemical density gradients, caused by evaporative concentration of surface waters, were sustained by strong thermal stratification.

Eddy diffusivities – The comparison of lakewide heat content based on two different sets of three stations (6, 8, 11 versus 4, 9, S-30) in 1984 yielded a mean standard deviation in the estimated heat content at the thermocline of 246 cal cm^{-2}. To reduce this, we used a three point moving average of lakewide mean temperature profiles. The Sweers' algorithm was used to calculate the moving temporal average in the same fashion as lakewide averages were done. The mean standard deviation in the temporally averaged heat content was 209 cal cm^{-2}. The effect of using a three point temporal moving average on biweekly sampling data is to smooth the estimate of eddy diffusivities over approximately monthly intervals. The mean relative standard error of the estimate of the change in the heat content at the thermocline in 1984 was 48%. The mean relative standard error for eddy diffusivity at the thermocline calculated by comparing estimates based on the two different sets of lakewide means was 44%.

Both solar heating and geothermal heat flux can contribute to hypolimnetic heating. The derived eddy conductivities were corrected for solar heating. Insolation accounted for an average of 19% of the heating beneath the thermocline for the period over which diffusivities were calculated. Measurements of geothermal and sediment heat flux are not available for Mono Lake. However, an estimate of the sediment heat flux was derived assuming a simple harmonic temperature change over a solid:

$$T_{zt} = T_0 + B_z + Ae^{-z\gamma}\cos(\omega t - z\gamma)$$

where T_{zt} is temperature at time, t, and depth, z, in the sediments; T_0 is mean annual temperature at $z = 0$; B_z is the steady-state temperature gradient at depth z, for $z > 0$; A is the amplitude of the temperature variation; ω is the angular velocity of the temperature variation; and $\gamma = (\omega/2\alpha)^{1/2}$ where α is the thermal diffusivity of the sediments. The thermal diffusivity and steady-state temperature gradient were assumed equal to those found in two small Wisconsin Lakes (Likens and Johnson 1969). Applying the hypsographic data and temperature profiles of Mono Lake to this equation yielded a sediment heat flux which was always less than 5% of the observed heat flux at depths

within the metalimnion.

An upper limit on geothermal heat flux beneath the chemocline was estimated from heat changes and decreases in conductivity beneath the chemocline from 1985 to 1987. The heat content beneath the persistent chemocline was nearly constant (Fig. 5), decreasing only 2.3% from 1985 to 1987. The monimolimnetic conductivity decreased 4.3% from 1985 to 1987 (Fig. 3). Assuming that the water mixed into the monimolimnion had a conductivity equal to the mixolimnetic average, the volume exchange was 77%. A maximum estimate of geothermal heat flux was then obtained by assuming that the temperature of the more dilute surface water mixed into the monimolimnion was at the annual minimum (cf. Fig. 5). Even though maximal, the derived estimate, 0.8 cal cm^{-2} d^{-1}, is still only 2 to 8% of the heat flux observed at the thermocline.

Eddy diffusivities usually decreased with depth to a minimum at or just below the thermocline, followed by an increase deeper in the water column (Fig. 10). The overall mean from 1982 to 1990 for all 1 m intervals within the metalimnion (thermal gradient $>$ 1°C m^{-1}) was 1.3×10^{-6} m^2 s^{-1}, which is ca. 10 times the molecular conductivity. Because sampling errors led to large uncertainties in the calculated diffusivities outside the strongly stratified portion of the water column, a more detailed analysis of vertical profiles of diffusivities is not warranted, and we restrict further consideration to diffusivities at the thermocline. Eddy diffusivity at the thermocline ranged from molecular to 26×10^{-6} m^2 s^{-1} (Fig. 11) and had a mean of 3.4×10^{-6} m^2 s^{-1}. Diffusivities were maximal early in the year when stratification was weak and decreased as stratification increased and the thermocline deepened.

A year-to-year comparison of mean summer diffusivities (June through September) indicated significant trends (Fig. 12). The mean diffusivity was lowest during periods of greatest chemical stratification in 1984 and 1986. From 1986 to 1989 diffusivities increased as chemical stratification decreased. The pronounced increase in 1989 was accompanied by inverse chemical stratification resulting from continued concentration of

mixolimnetic water due to evaporation (Fig. 9). Values in 1990 were low compared to 1989, but similar to 1988. The power of statistical comparisons between years is low because the number of sampling intervals was low, differences in the number and time of sampling dates precluded using paired comparisons, and diffusivities varied widely over the stratified period. The mean diffusivities during the strongly stratified period (June–September) or 'summer' were compared across years using t-test's because the Kolmogorov-Smirnov test detected no departures from normality within individual 'summers'. During this 'summer' season, mean thermocline diffusivity in 1989 was significantly ($p<0.05$) higher than in all other years. The mean for 'summer' 1988 was greater than for all other meromictic years (1983, 1984, 1986, 1987) except 1985 when vertical salinity gradients were low. The 'summer' mean for 1985 was also significantly higher than that in 1986 and 1987.

Eddy diffusivities were compared to the local buoyancy computed as the Brunt-Väisälä frequency N, where $N^2 = (g\ \rho^{-1})(\delta\rho\ \delta z^{-1})$. Because conductivity measurements were routinely collected at only 2, 8, 12, 20 and 28 m, we calculated eddy diffusivities over the interval 12 to 20 m for comparison with Brunt-Väisälä frequencies based on temperature and conductivity measurements. N^2 values at 12 to 20 m ranged from 7×10^{-5} s^{-2} to 1.5×10^{-2} s^{-2} with a mean of 5.5×10^{-3} s^{-2}. The log-log regression of diffusivities on the Brunt-Väisälä frequency squared was:

$$K_z = 4.86 \times 10^{-8}\ (N^2)^{-0.58}, \quad r^2 = 0.18,\ p < 0.0001\ \text{and}\ n = 82.$$

The explained variance is small, but the regression coefficients are both highly significant. The range of the intercept given by one standard error of the estimate is 2.18×10^{-8} to 1.09×10^{-7} while that for the slope, -0.44 to -0.72.

Discussion

Mono Lake was monomictic during the mid-60s (Mason 1967) and from 1976 to 1982 (Winkler 1977; Lenz 1982; Melack 1983). The abrupt 2.6 m change in its surface

elevation observed from 1982 to 1984 is unprecedented in historical records. The largest two year rise in surface elevation since accurate records began in 1912 had been 1.55 m between 1912 and 1915 (LADWP 1984). Based on shorelines and other evidence, Stine (1981) showed a possible increase in surface elevation of 2 m from 1861 to 1863. The relative volume changes accompanying these past surface level changes were smaller than the current one: 10.4% in 1861–1863 and 8.1% in 1913–1915 versus 15.1% in 1982–1984. Also, the salinity differences between stream discharge and lake water were less at the previous surface elevations. The recent onset of ectogenic meromixis in Mono Lake appears to be a rare event.

Meromixis in other saline lakes has also set in when a change in surface runoff was large relative to the volume of the lake. Examples include Big Soda Lake, Nevada, where the surface elevation rose 18 m on account of irrigation (Hutchinson 1937), and small hypersaline lakes in Western Australia made seasonally meromictic by high winter runoff (Bunn and Edward 1984). Also, MacIntyre and Melack (1982) described the effect of variation in rainfall on chemical stability and meromixis in an equatorial saline lake.

Several factors contributed to the gradual breakdown and final elimination of meromixis in Mono Lake in late 1988. First, freshwater inputs decreased as diversions to the Los Angeles Aqueduct were resumed and high evaporation rates (116 cm yr^{-1}, Vorster 1985) then concentrated the mixolimnetic water. Second, as the salinity of the mixolimnion increased, deeper mixing entrained hypersaline monimolimnetic water, thereby further increasing mixolimnetic salinities. The rate of salinity increase in the mixolimnetic water observed during 1984 and 1985 made termination of meromixis likely during 1986. However, another heavy runoff year in 1986 diluted the mixolimnion and re-established the large difference in salinity between surface and monimolimnetic waters. Following further deep mixing and more importantly evaporative concentration, total dissolved solids in the mixolimnion finally exceeded those in the monimolimnion by August 1988. Thus, when thermal stratification weakened in November 1988, meromixis

ended.

Although they occur over different time scales, the same processes destroy meromixis in other lakes. Seasonal meromixis in small basins usually breaks down during late summer as surface water is concentrated by evaporation (Bunn and Edward 1984). Over 100 years of ectogenic meromixis in the Dead Sea ended in 1979 after evaporative concentration of the mixolimnion and decreased freshwater inputs resulted in gradual weakening of Schmidt stability and deeper mixing (Steinhorn 1985).

The onset, persistence, and breakdown of meromixis in Mono Lake had significant affects on temperature and vertical mixing. Monimolimnetic temperatures were nearly constant for six years. This contrasts with monomictic conditions, as represented by 1989 and 1990, in which hypolimnetic temperatures warmed throughout the stratified period increasing by 9°C and 2.5°C over the season, respectively. Also, the depth of the summer mixed layer was inversely correlated with changes in surface elevation and freshwater inputs. During meromixis and periods of rising lake levels, minimum heat content was higher, maximum heat content lower, and thus the Birgean heat budget (annual difference) lower than under monomictic conditions or periods of declining lake levels. Anderson (1958) noted a similar effect of meromixis on the Birgean heat budget when comparing meromictic Soap Lake, Washington, to shallower nearby holomictic, Lake Lenore. During an earlier monomictic period at Mono Lake, 1963 and 1964, Mason (1967) calculated Birgean heat budgets which were similar to that found under monomictic conditions and declining lake levels in 1989.

The density-temperature relationship in hypersaline Mono Lake water differs slightly from seawater. The change in density with temperature at 20°C is 3.43×10^{-4} g cm^{-3} $°C^{-1}$ for Mono Lake at a salinity of 83.5 g liter^{-1} and is 2.63×10^{-4} g cm^{-3} $°C^{-1}$ for seawater (Fofonoff and Millard 1983). Mason (1967) found a slightly lower value 3.39×10^{-4} g cm^{-3} $°C^{-1}$ in 1964 when Mono Lake's salinity was ca. 73 g liter^{-1}. The steeper slope for Mono Lake water compared to seawater is likely owed to the relatively large

temperature effect on the partial molal expansibility of carbonate (see Table 2, MacIntyre and Melack 1982), a solute about one thousand times more abundant in Mono Lake then in seawater.

In moderately sized lakes, the accurate determination of the downward flux of heat is made difficult by internal seiches and other water motions. In Mono Lake relatively large errors in estimates of the change in heat content at the thermocline (249 cal cm^{-2}) resulted using a three station sampling design (station density, 0.02 km^{-2}). By employing multiple visits to stations, Stauffer (1992) determined an error in the estimate of heat content for two medium-sized Wisconsin lakes of ca. 100 cal cm^{-2}, given a station sampling density of ca. 0.2 km^{-2}. In a detailed analysis of variance components associated with estimates of heat content and eddy diffusivities, Stauffer (1992) concluded that errors due to internal water motions were much greater than those which arise from the propagation of instrumental error. We concur. To assess the relative importance of instrumental error, we performed a Monte Carlo analysis in which synthetic data sets were generated by adding normally distributed random variates to the observed mean temperature profiles in 1984 and eddy diffusivities calculated after lakewide and temporal averaging. An instrumental error of $0.05°C$ yielded a mean relative error of only 9% when profiles were treated in the same fashion as the actual data were. This is much less than the error of 44% that we observed.

Diffusivities increase as a function of wind energy and surface area (Spigel and Imberger 1987). In Mono Lake, the mean eddy diffusivity at the thermocline during the strongly stratified period (June–September) was 2.7×10^{-6} m^2 s^{-1}. The values for Mono Lake are similar to those in other moderately sized lakes (e.g. L. Kinneret, Lerman and Stiller 1969; L. Mendota, Stauffer 1986; Überlinger See of Lake Constance, Heinz et al. 1990). The annual variation in diffusivities reflected an inverse correlation with the degree of stratification, with high values early and late in the stratified period. Year-to-year differences were also observed with values in rough inverse correlation with the degree of

chemical stratification.

A criticism of using the flux-gradient heat method to characterize vertical mixing is the potential difference between heat and solute diffusivities. In small lakes under highly stratified conditions eddy diffusivities may approach molecular conductivity. Because molecular conductivities are 1 or 2 orders of magnitude higher than molecular diffusivities of most solutes, calculations based on heat may overestimate vertical mixing of solutes. Quay et al. (1980) found heat diffused much faster in the thermocline than tritium in a highly stratified small lake. In larger lakes where vertical mixing is more active most researchers have assumed heat and solutes have the same effective diffusivity. Mean eddy diffusivities at the thermocline from April to October were 3.43×10^{-6} m^2 s^{-1} or ca. 26 times molecular conductivities. However, during some sampling intervals calculated diffusivities approached molecular conductivities. Wanninkhof (1986) estimated metalimnetic eddy diffusivities in Mono Lake during July and August 1985 to be 6.0×10^{-7} m^2 s^{-1} using sulfur hexafluoride (SF_6) injected into the epilimnion as a tracer. Our estimate using heat over the same period within the metalimnion (15 m) was similar, 8.7×10^{-7} m^2 s^{-1}.

Theoretical analyses suggest a relationship between eddy diffusivity and the Brunt-Väisälä frequency of the form: $K_z = a(N^2)^m$, where a is a measure of the general magnitude of turbulence and m depends on the mode of turbulence generation. The range of stabilities (N^2) and eddy diffusivities measured in Mono Lake overlapped with those observed in other moderate to large lakes (e.g. Lake Washington, Lake Zurich, Lake Mendota) as illustrated in Quay et al. (1980, Fig. 11). The intercept (a) in the N^2 versus Kz regression is 4.86×10^{-8} m^2 s^{-1} for Mono Lake. Care is required when comparing these data because different regions of the lakes are represented for some lakes; only thermocline values are used for Mono Lake.

Welander (1963) suggested from dimensional arguments that m = -1 when turbulence is generated by large scale horizontal eddies cascading down to smaller eddies

and m = -0.5 when turbulence is generated from local shear. In lakes, researchers have in general found the exponential coefficient to lie closer to -0.5 than -1, suggesting local shear is the dominant mode of turbulence generation (Quay et al. 1980; Jassby and Powell 1975; Stauffer and Armstrong 1984; Effler and Field 1983; Heinz et al. 1990). Results from Mono Lake support this general conclusion as the exponential coefficient was -0.58±0.14.

Although this result agrees with Welander's conditions for the importance local shear, many of Welander's assumptions are not met in lakes and additional mixing mechanisms are know to be important (Imberger and Patterson 1990). To examine further the likelihood that local shear is a major mechanism in Mono Lake we calculated Wedderburn and Lake numbers (Imberger and Patterson 1990) and compared simulations of vertical mixing with and without shear production in the metalimnion.

Application of DYRESM, a one-dimensional vertical mixing model (Imberger and Patterson 1981) to Mono Lake successfully simulates seasonal changes in thermal structure (J. Romero pers. comm.). DYRESM includes shear production as an explicit mixing mechanism. If shear production in the metalimnion is excluded, thermocline deepening is stopped and thermal structure is no longer simulated correctly (J. Romero and J. Patterson pers. comm.).

The Wedderburn number (W), defined by the relation

$$W = \frac{g' h^2}{u_*^2 L'}$$

where g' is the effective gravity based on the density change across the base of the mixed layer, h is the thickness of the surface layer, u_* is the water friction velocity due to wind stress and L' is the fetch (Imberger and Patterson 1990, Monismith 1985, Patterson et al. 1984), can be used to characterize the dynamics of mixed layers in lakes. W is dimensionless and represents the ratio of pressure force $(g'h^2)$ at the location of upwelling to the surface force $(u_*^2 L')$ imposed by the wind stress. Field and laboratory

measurements and scaling arguments suggest the values of W from about 1 to 30 are evidence for thermocline tilting and local shear production (Patterson et al. 1984, Monismith 1986). Such interpretation applies to the region at the base of the mixed layer and the top of the metalimnion. W was calculated for Mono Lake during periods of stratification when eddy diffusivities were determined; a two layer approximation was used to estimate g', h was obtained from representative density profiles, and a range of wind speeds, air temperatures and humidities measured in the center of the lake were used to calculate u_*. For hourly mean wind speeds in the range of 5 to 10 m s^{-1}, which occur for several hours on most days, W ranged from about 0.4 to 60. Many of these values of W are indicative of thermocline tilting and shear production.

Imberger and Patterson (1990) generalized W to describe the behavior of a lake as a whole and formulated the Lake number, L_N. Their analysis of L_N suggests that the behavior of the seasonal thermocline, which affects mixing below the thermocline, is related to the value of L_N, where large L_N (> 200) means most of the mixing occurs in the surface layer and small L_N (<1) means the main thermocline tilts with stronger mixing in the hypolimnion. Values of L_N for Mono Lake calculated with the same conditions used to calculate W ranged from 0.5 to 9. These values of L_N provide further support for the importance of shear production in the metalimnion in Mono Lake.

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Table 1. Chemical composition of Mono lake water; 2 m, 14 October 1987, Station 6. Acid neutralizing capacity (ANC) is about 73% carbonate, 22% bicarbonate, and 5% borate (see text).

Solute	Concn (meq liter^{-1})
Na	1340
K	58
Ca	0.3
Mg	3.3
Cl	562
SO_4	236
ANC	593

Figure captions

Fig. 1. Bathymetry of Mono Lake and sampling stations.

Fig. 2. Surface elevation of Mono Lake.

Fig. 3. Conductivity in Mono Lake at 2 (o) and 28 (•) m.

Fig. 4. Depth of chemocline and conductivity gradient at the chemocline.

Fig. 5. Temperature in the mixolimnion (•, 2 m) versus the monimolimnion (single line, 28 m). Monimolimnion samples on same dates indicated for mixolimnion.

Fig. 6. Depth (•) and temperature gradient of the thermocline as defined by the depth maximum temperature gradient during strong thermal stratification (gradient > 1°C m⁻¹).

Fig. 7. Density of Mono Lake water versus temperature (A) and conductivity at 20°C (B) for a sample collected from 2 m at Station 6 on 10 October 1987.

Fig. 8. Excess density profiles ((ρ-1) $\times$ 10^5 g cm^{-3}) based on in situ temperatures and laboratory measurements of conductivity.

Fig. 9. Thermal (•) versus chemical (o) contribution to overall density stratification. Density difference is that between 2 and 28 m.

Fig. 10. Vertical profiles of eddy diffusivity under meromictic (1984, open symbols) and monomictic (1989, closed symbols) during June (squares) and August (diamonds). Arrows indicate depth of maximum temperature gradient.

Fig. 11. Eddy diffusivities at the thermocline defined as the depth of the maximum temperature gradient. Stars indicate three dates on which calculated diffusivities were less than zero, presumably due to measurement error of heat content.

Fig. 12. Mean thermocline eddy diffusivities (±1 SE) during the period of strong thermal stratification, June–September.
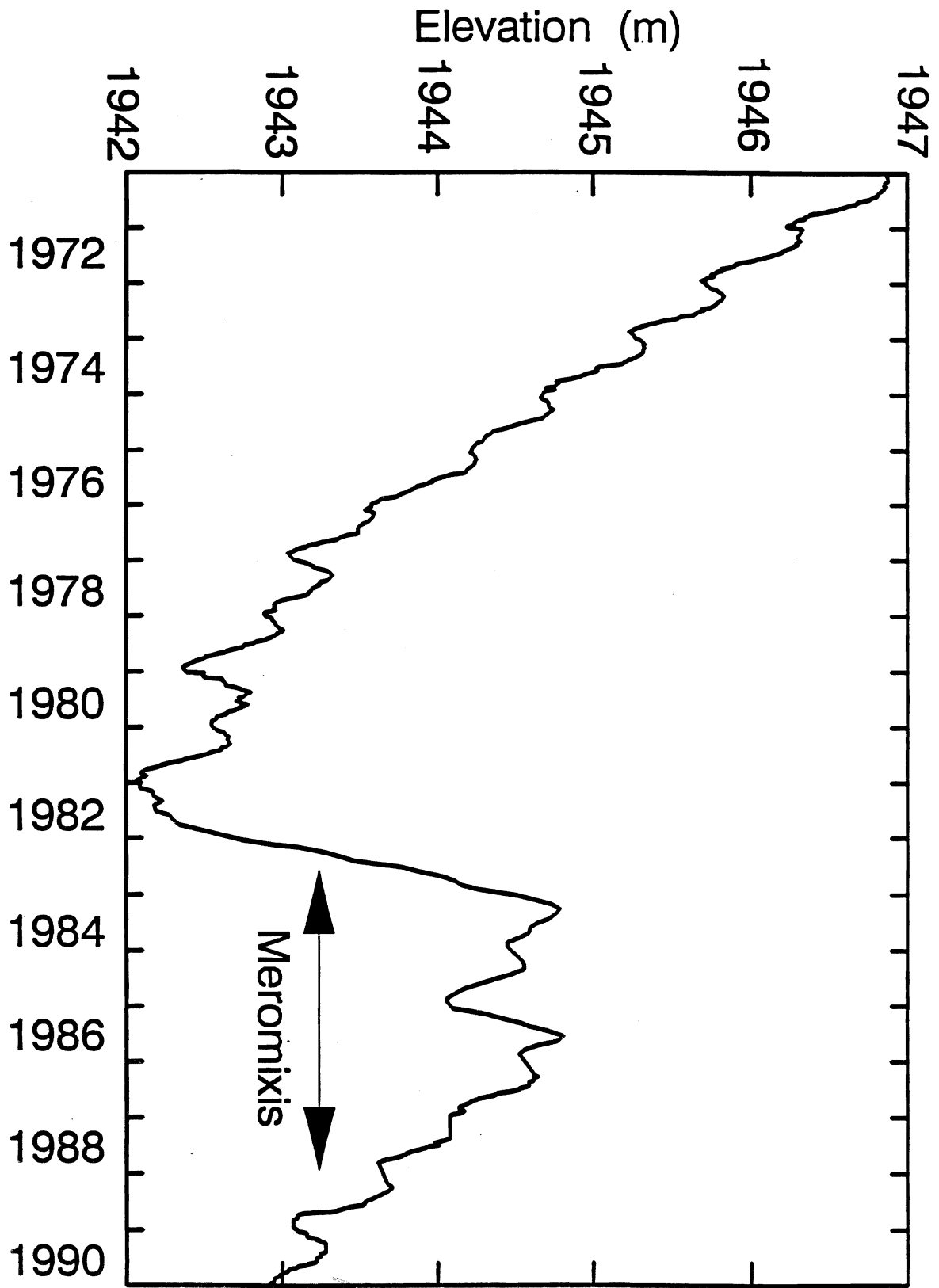
Mono Lake

N

Paoha
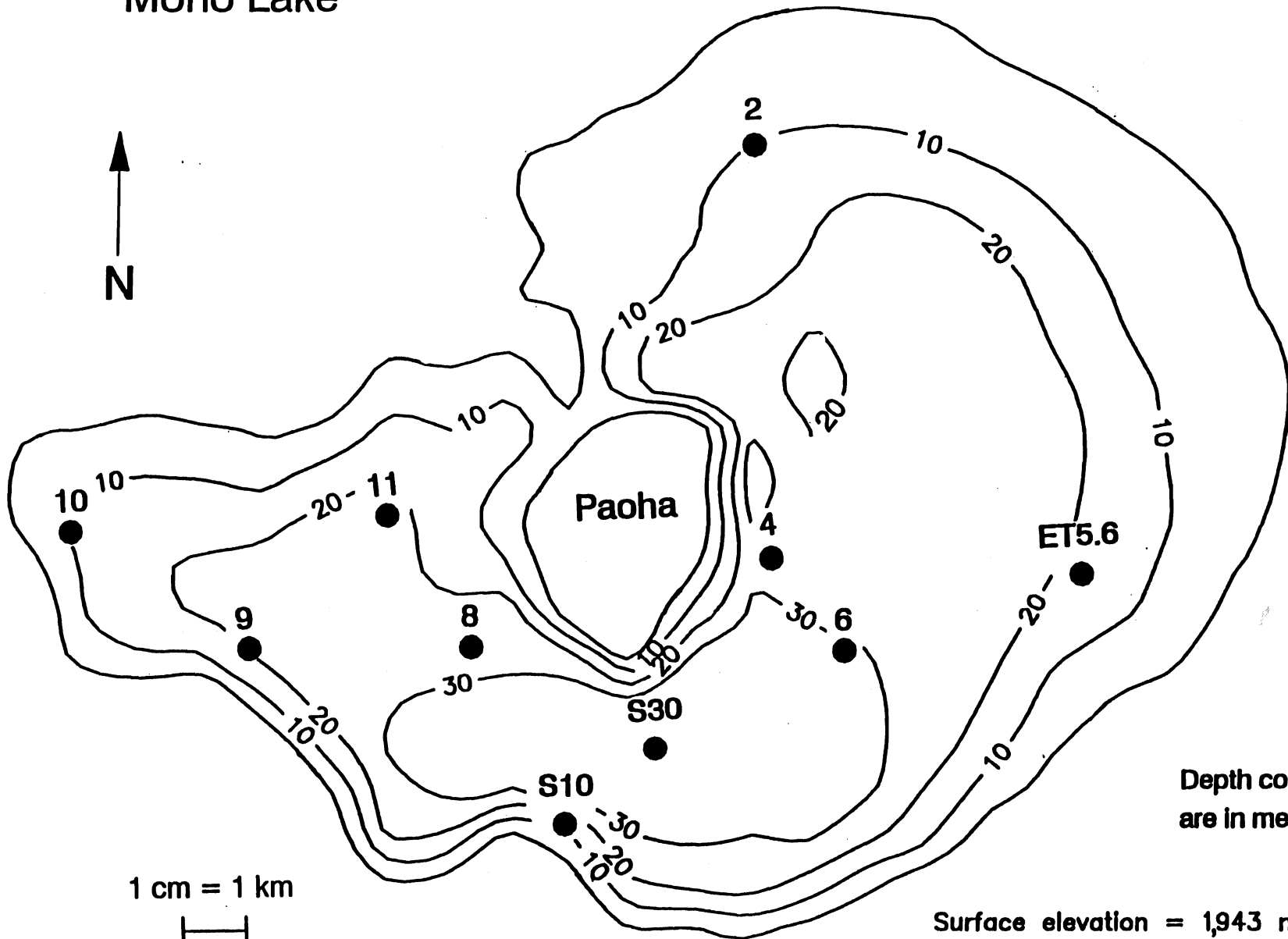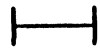
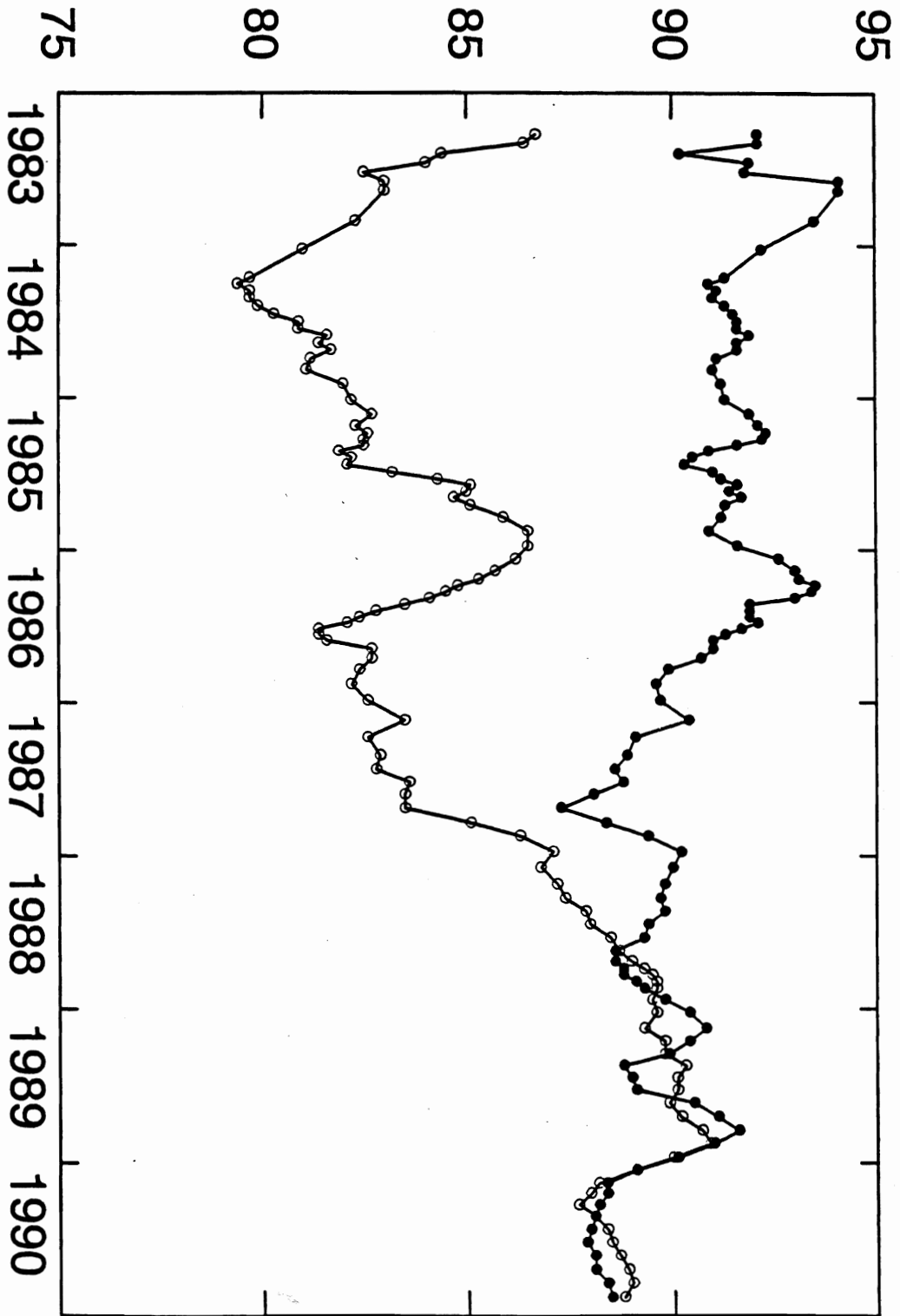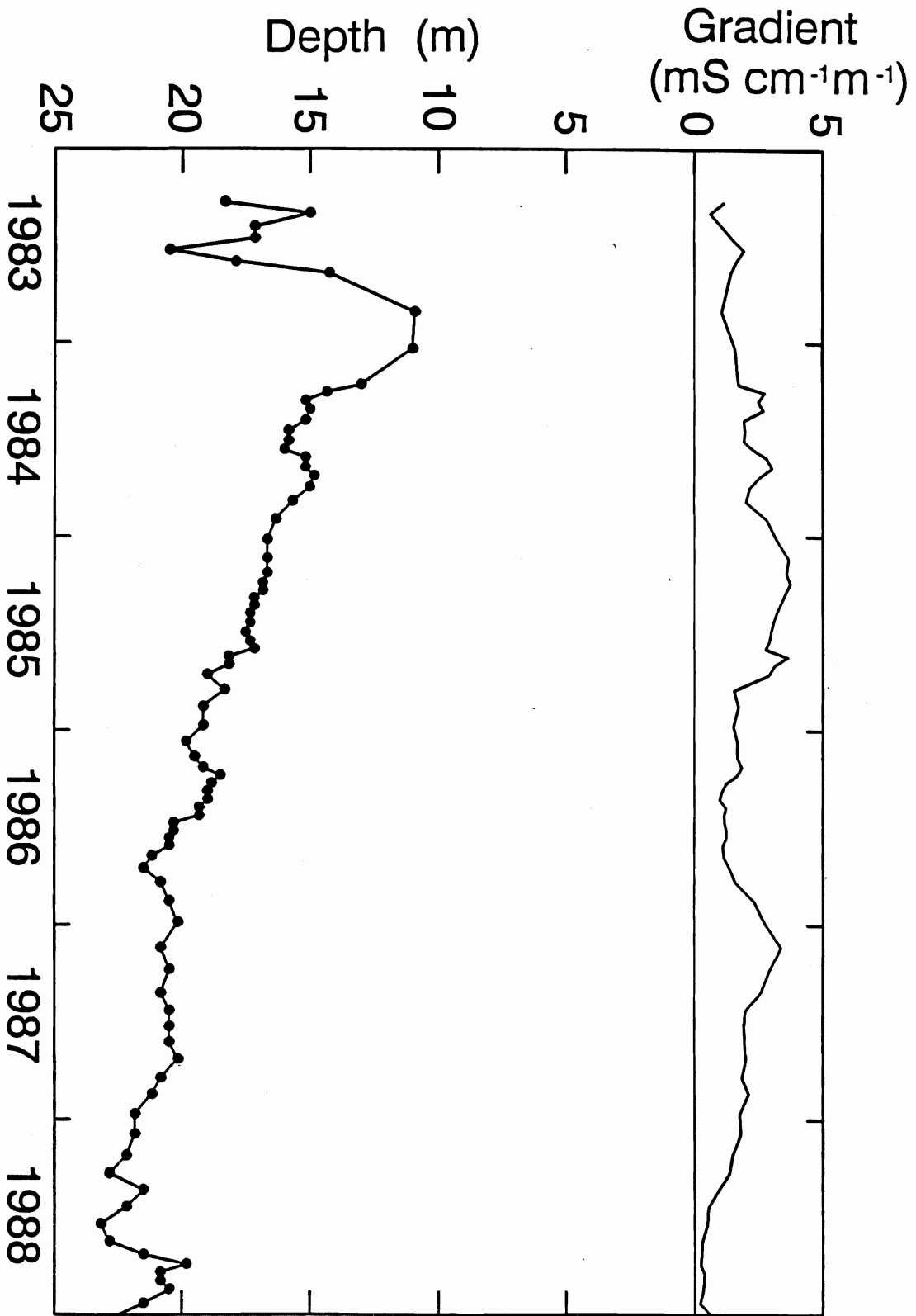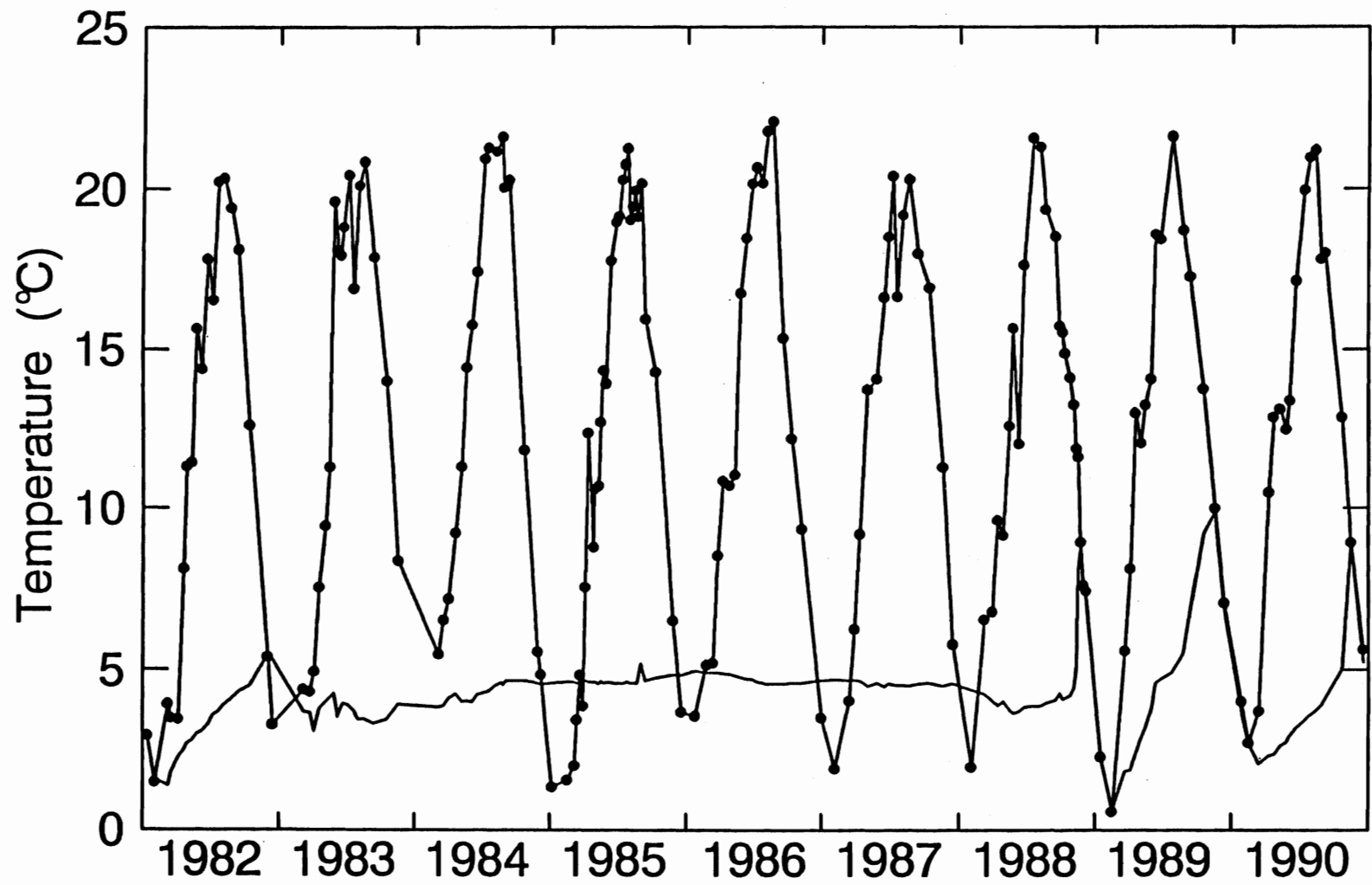Depth contours are in meters

1 cm = 1 km

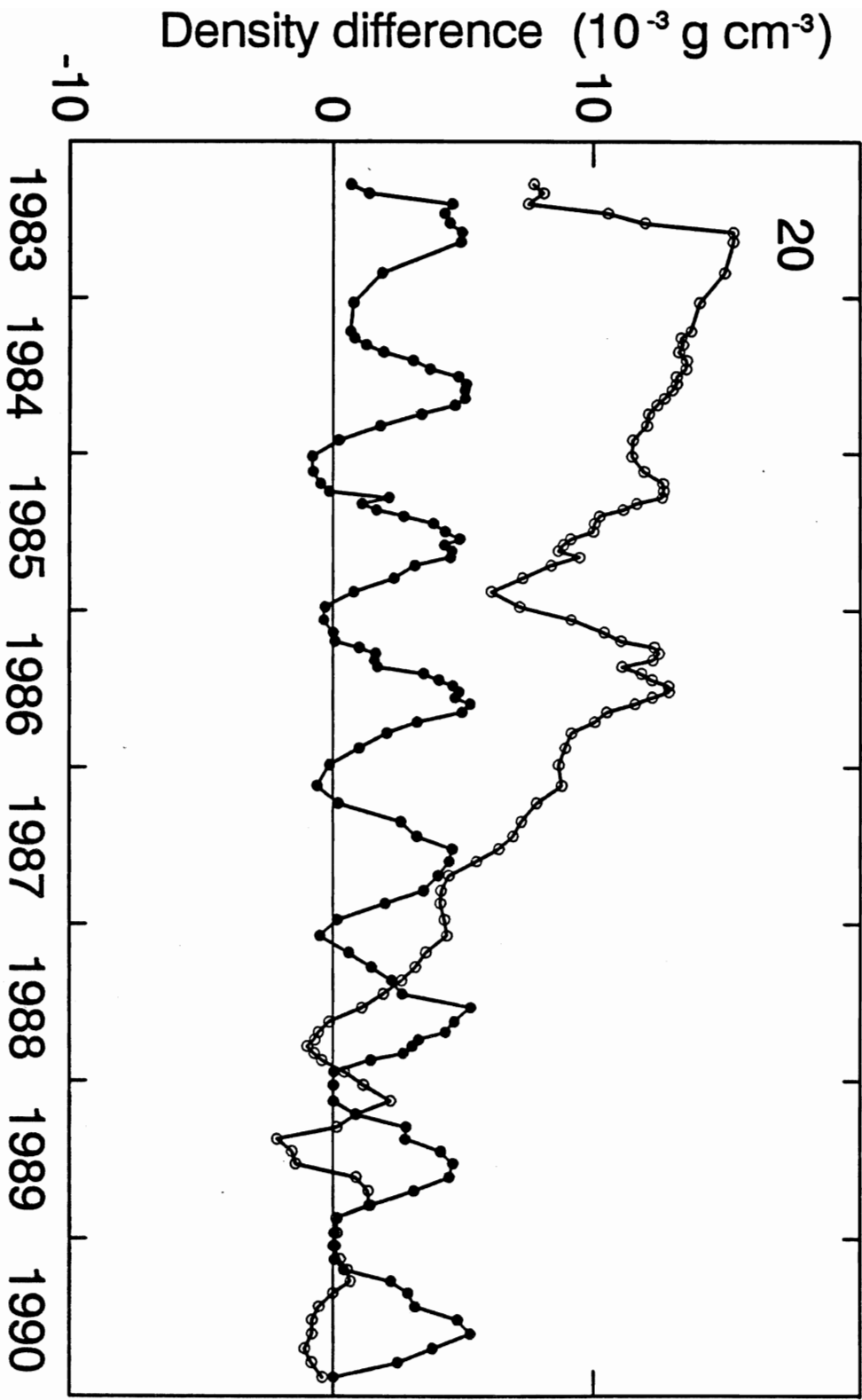Surface elevation = 1,943 m

Conductivity (mS cm⁻¹ at 25℃)