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Reconstruction of palaeo air temperature changes from oxygen isotopic records in Lake Zürich: the significance of seasonality

By Guy S. Lister[1])

ABSTRACT

The oxygen isotope composition of precipitation for a region is largely a function of condensation temperature. Thus seasonality changes due to long-term insolation variations may have contributed significantly to the oxygen isotope records for lakes where a seasonal precipitation peak is characteristic. The Lake Zürich catchment experiences a summer precipitation peak, but the reduced winter precipitation in the lowlands is isotopically compensated for by cold precipitation in the Alpine hinterland. Consequently, seasonality change should not have significantly affected the latest Pleistocene-Holocene oxygen isotope record for Lake Zürich. Oxygen isotope ratios derived for past lake waters from sedimented benthic carbonate, corrected for the isotopically heavier atmospheric moisture of the latest Pleistocene, indicate mean annual air temperatures for the last Glacial which were 10 to 15.5 °C colder than at present, depending on the temperature-$\delta^{18}O$ relationship for precipitation. Likewise a mean annual air temperature of 1.5 to 2 °C below that of today is indicated for ca. 12,400 years B.P. (mid Bölling), when meltwaters from stagnant glacial ice masses had permanently ceased to enter Lake Zürich. The post-Glacial climate was marked by temperature fluctuations of less than 1 °C during the early Holocene and an overall warming of up to 2 °C by the mid Holocene.

ZUSAMMENFASSUNG

Die Sauerstoffisotopen-Zusammensetzung für den Niederschlag einer Region ist hauptsächlich eine Funktion der Kondensationstemperatur. Deswegen können Saisonalitätsänderungen, die durch langfristige Änderungen der Sonneneinstrahlung verursacht werden, die Sauerstoffisotopen-Zusammensetzung in Seen, für die eine saisonale Niederschlagspitzenbelastung charakteristisch ist, signifikant beeinflusst haben. Für das Zürichsee-Einzugsgebiet ist eine Sommer-Niederschlagspitzenbelastung charakteristisch, aber die geringen Winterniederschläge in den Niederungen werden durch kalte Niederschläge im alpinen Hinterland isotopisch kompensiert. Daraus resultiert, dass Saisonalitätsänderungen die Sauerstoffisotopen-Zusammensetzung des Zürichsee-Wassers seit dem Spätpleistozän nicht beeinflusst haben. Sauerstoffisotopen-Verhältnisse für damaliges Zürichsee-Wasser, gerechnet anhand der Sauerstoffisotopen-Zusammensetzung bentischer Karbonatschalen, zeigen nach einer Korrektur, die den höheren Anteil an O-18 in der Luftfeuchtigkeit des spätesten Pleistozän berücksichtigt, dass die Jahresdurchschnitt-Lufttemperatur während des letzten Glazials 10 bis 15,5 °C niedriger lag als heute, je nach der verwendeten Temperatur-$\delta^{18}O$ Beziehung für Niederschlag. Vor ca. 12 400 Jahren (mittleres Bölling), als keine Schmelzwässer mehr in den Zürichsee flossen, ergibt sich eine mittlere Jahreslufttemperatur, die 1,5 bis 2 °C niedriger lag als heute. Das postglaziale Klima wurde im frühen Holozän durch Temperaturschwankungen von weniger als 1 °C geprägt. Erwärmung von bis zu 2 °C erfolgte bis zum mittleren Holozän.

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Introduction

A difficult problem in Quaternary geology has been to accurately define palaeo air temperatures for continental regions. This is particularly so in the cases of mid-latitude Ice Age glacial areas, where the ice has long since gone and biological indicators, such as pollen and Coleoptera assemblages, are only sparsely or imperfectly preserved. One approach to this problem in Switzerland has been the measurement of oxygen isotope ratios for carbonates preserved in lacustrine sediment sequences. Those ratios are determined by the oxygen isotope ratios and the temperatures of the ambient lake waters during carbonate precipitation (UREY, 1947; CRAIG, 1965; STUIVER, 1970; GROSSMAN & KU, 1981). The oxygen isotope ratios of the lake waters are in turn dependent on the vapour history and condensation temperatures for meterological precipitation and subsequent modifications by evaporation loss (EPSTEIN & MAYEDA, 1953; DANSGAARD, 1964; YURTSEVER, 1975). Because of uncertainties about the exact relationships between those controls and the oxygen isotope ratios for precipitation under past climatic regimes, lacustrine oxygen isotopic records have usually been interpreted in terms of relative temperatures changes rather than absolute temperature values.

Past studies of oxygen-isotope records from lacustrine carbonate for the latest Pleistocene-Holocene period in Europe have generally concerned small shallow lakes or palaeo-lakes which received drainage from local peri-Alpine catchments rather than Alpine catchments (EICHER & SIEGENTHALER, 1976; EICHER et al. 1981; EICHER & SIEGENTHALER, 1983). Deglaciation meltwater contributions to those isotopic records, which commonly span a period within about 14,000 to 9,000 years B.P., were of little significance.

An oxygen isotope record from Lake Zürich, a deep peri-Alpine lake with a large Alpine catchment, does contain isotopic signals from meltwaters during the last deglaciation (LISTER, 1988). Although the oldest isotopic signals in that record came from carbonate sedimented after ca. 14,500 years B.P., they represent mainly atmospheric precipitation which had been trapped in the ice reservoir for up to thousands of years before, so the record effectively reaches further back into the Pleistocene. In total it spans a period of probably more than 15,000 years.

By the beginning of the Holocene the climate had essentially its present character, however a difference between summer and winter insolation at the top of the atmosphere caused by changes in orbital parameters was at a maximum; 8% more in summer and 8% less in winter than for today in the northern hemisphere. That difference then decreased after about 9,000 years B.P. to the present value, which is again close to the minimum of 18,000 years B.P. (MILANKOVITCH, 1941; KUTZBACH & STREET-PERROT, 1985). KUTZBACH & STREET-PERROT proposed that, as a consequence, northern hemisphere continental interiors should generally have had warmer summers and cooler winters (increased seasonality) at the beginning of the Holocene than at present or at 18,000 years B.P. Presumably for near-coastal regions the effect is less marked, absent or overridden by oceanic influences. For example, the western European climate during the latest Pleistocene was markedly influenced by events in the northern Atlantic (RUDDIMAN, SANCETTA & MacINTYRE, 1977; RUDDIMAN & MacINTYRE, 1981; BROECKER et al., 1988).

The size of the effect that any seasonality change may have had on lacustrine oxygen-isotope records for Switzerland has not been established. Clearly, any differential loading from changing seasonality on net $\delta^{18}O$ values for annual precipitation must be more significant for a lacustrine $\delta^{18}O$ record of 15,000 years duration than in one of 5,000 years duration, because the former would incorporate a full amplitude effect. Thus for a long $\delta^{18}O$ record, the character of that loading should be identified and compensated for if the record is to be interpreted in terms of past mean annual air temperatures. But proxy evidence for the precise magnitude of regional palaeo-seasonality changes is not available.

This paper examines the possible effects that changing seasonality could have had on the oxygen isotope record for palaeo Lake Zürich. An approach is used in which climatic parameters for all altitudes in the modern catchment are integrated to obtain whole-catchment values which correspond to the current $\delta^{18}O$ value for Lake Zürich waters. The modern seasonality amplitude is then arbitrarily altered and those parameters re-integrated in order to observe the size of the effect on the lake-water $\delta^{18}O$ value.

The role of precipitation

The $\delta^{18}O$ value for meteorological precipitation from a given vapour mass is strongly dependent on the air temperature at which the precipitation occurs (Epstein & Mayeda, 1953; Dansgaard, 1964; Yurtsever, 1975; Siegenthaler & Oeschger, 1980). Thus the $\delta^{18}O$ value for precipitation over a catchment is usually more negative during winter than in summer. Lake waters, other than those with a very short residence time, integrate the seasonal isotopic variations into a mean value for catchment runoff. Seasonality changes would have no effect on the mean isotopic value for annual catchment runoff from precipitation which is evenly distributed throughout the year, because the effect of a shift for summer temperature would be cancelled by that for an opposite shift for the corresponding winter temperature. For seasonally biased precipitation, though, the mean temperature for annual precipitation (MTAP) must depart from the mean annual air temperature (MAAT), being lower in the case of a winter precipitation peak and higher in the case of a summer precipitation peak. Increasing or decreasing seasonality would enhance or reduce those departures and the consequent shifts in oxygen-isotope values. Today precipitation for Switzerland is characterised by a summer peak at all altitudes and there is little reason to believe that the pattern has changed during the Holocene. The seasonal precipitation distribution for Switzerland during the last Glacial is not precisely known, but presumably it was characterised by a summer peak, much as for the present circum-polar tundra areas (winter precipitation peaks are today typical of "Mediterranean" and "Marine west coast" climatic types).

Climatic factors for the modern Lake Zürich catchment

Mean monthly precipitation at Zürich ranges between 5.4% and 7.1% of the mean annual total from October through March, and 7.8% to 12.3% from May through September, the peak occurring in July. Mean monthly temperatures range from −0.9 °C in January to 17.6 °C in July, giving an annual temperature amplitude of 18.5 °C (Table 1). The mean air temperature of annual precipitation (MTAP) at Zürich, calculated from

Month	A Mean monthly air temperature (°C)	Mean monthly precipitation (mm)	B Mean monthly precipitation (% annual total)	A x B / 100
J	-0.9	68	6.0	-0.05
F	0.3	61	5.4	0.02
M	4.3	69	6.1	0.26
A	8.1	88	7.8	0.63
M	12.8	107	9.5	1.22
J	15.9	138	12.2	1.94
J	17.6	139	12.3	2.17
A	17.0	132	11.7	2.00
S	13.8	101	9.0	1.24
O	8.6	80	7.1	0.61
N	3.5	72	6.4	0.22
D	0.3	73	6.5	0.02
		1128		10.3

MAAT = 8.4 °C
MTAP, Σ(A x B / 100), = 10.3 °C
(Difference = 1.9 °C)

January-July difference = 18.5 °C

Table 1. Mean monthly air temperature data (1901–60; SCHÜEPP, 1974) and precipitation data (1901–60; UTTINGER, 1966) for the Zürich meteorological station (Zürich MZA, 569 m.a.s.l.) and the calculated mean temperature for annual precipitation (MTAP). The latter is almost 2 °C higher than the mean annual air temperature (MAAT) because of the summer rainfall peak.

Month	A Mean monthly air temperature (°C)	Mean monthly precipitation (mm)	B Mean monthly precipitation (% annual total)	A x B / 100
J	-3.2	112	7.2	-0.23
F	-2.0	98	6.4	-0.13
M	1.8	98	6.4	0.12
A	5.6	115	7.5	0.42
M	10.4	124	8.1	0.84
J	13.3	155	10.1	1.34
J	14.9	183	11.9	1.77
A	14.2	183	11.9	1.69
S	11.3	140	9.1	1.03
O	6.6	120	7.8	0.52
N	1.5	107	6.9	0.10
D	-1.8	105	6.8	-0.12
		1540		7.4

MAAT = 6.1 °C
MTAP, Σ(A x B / 100), = 7.4 °C
(difference = 1.3 °C)

January-July difference = 18.1 °C

Table 2. Mean monthly air temperature data (1901–60; SCHÜEPP, 1967) and precipitation data (1901–60; UTTINGER, 1966) for the Elm meteorological station (962 m.a.s.l.) and the calculated mean temperature for annual precipitation (MTAP). The latter is 1.3 °C higher than the mean annual air temperature (MAAT).

Month	A Mean monthly air temperature (°C)	Mean monthly precipitation (mm)	B Mean monthly precipitation (% annual total)	A x B / 100
J	-8.7	202	8.1	-0.71
F	-8.9	180	7.2	-0.64
M	-6.8	164	6.6	-0.45
A	-4.3	166	6.7	-0.29
M	0.4	197	7.9	0.03
J	3.4	249	10.0	0.34
J	5.5	302	12.1	0.67
A	5.4	278	11.2	0.61
S	3.2	208	8.4	0.27
O	-0.6	183	7.4	-0.04
N	-4.8	190	7.6	-0.37
D	-7.4	168	6.8	-0.50
		2487		-1.1

MAAT = -2.0 °C
MTAP, Σ(A x B / 100), = -1.1 °C
(difference = 0.9 °C)

January-July difference = 14.2 °C

Table 3. Mean monthly air temperature data (1901–60; Schüepp, 1974) and precipitation data (1931–60; Uttinger, 1965) for the Säntis meteorological station (2,500 m.a.s.l.) and the calculated mean temperature for annual precipitation (MTAP). The latter is 0.9 °C higher than the mean annual air temperature (MAAT).

Month	A Mean monthly temperature (°C)	A´ Seasonality reduced by 4 °C. (amount) new value °C	Mean monthly precipitation (mm)	B Mean monthly precipitation (% annual total)	A´ x B / 100
J	-0.9	(+2.0) 1.1	68	6.0	0.07
F	0.3	(+1.3) 1.6	61	5.4	0.09
M	4.3	(+0.7) 5.0	69	6.1	0.31
A	8.1	(+0.0) 8.1	88	7.8	0.63
M	12.8	(-0.7) 12.1	107	9.5	1.15
J	15.9	(-1.3) 14.6	138	12.2	1.78
J	17.6	(-2.0) 15.6	139	12.3	1.92
A	17.0	(-1.3) 15.7	132	11.7	1.84
S	13.8	(-0.7) 13.1	101	9.0	1.18
O	8.6	(-0.0) 8.6	80	7.1	0.61
N	3.5	(+0.7) 4.2	72	6.4	0.27
D	0.3	(+1.3) 1.6	73	6.5	0.10
			1128		10.0

MAAT (A & A´) = 8.4 °C
MTAP, Σ(A´ x B / 100), = 10.0 °C
(Difference = 1.6 °C)

January-July difference = 14.5 °C

Table 4. The effect of reduced seasonality on the mean temperature for annual precipitation (MTAP) at Zürich. Mean monthly air temperature data for Zürich (1901–60; Schüepp, 1974) are here proportionally altered to reduce the annual temperature amplitude by 4 °C (22%). Calculation using corresponding precipitation data results in a MTAP of 10 °C, a reduction of only 0.3 °C with respect to that for observed seasonality. The MAAT remains unchanged.

those data as the sum of the products of the fraction of annual precipitation each month and the corresponding mean monthly temperatures, is 10.3 °C (Table 1). That temperature is 1.9 °C higher than the mean annual air temperature (MAAT) of 8.4 °C recorded at Zürich (Schüepp, 1974).

The lake Zürich catchment however comprises a range of terrains including Alpine mountains, valleys and peri-Alpine lowlands (Fig. 1a). Mean annual precipitation steadily increases with altitude from less than 115 cms at Zürich to more than 300 cms for the highest terrain (Fig. 1b), while mean annual air temperature decreases with increasing altitude from 8.4 °C at Zürich to ca. −5.3 °C at 3,000 m.a.s.l. (Figs. 1c and d). Calculations based on precipitation- and air temperature data from two further stations, Elm (962 m.a.s.l.) and Säntis (2,500 m.a.s.l.; about 15 km to the north of the catchment) indicate that the difference between MAAT and MTAP decreases with alti-

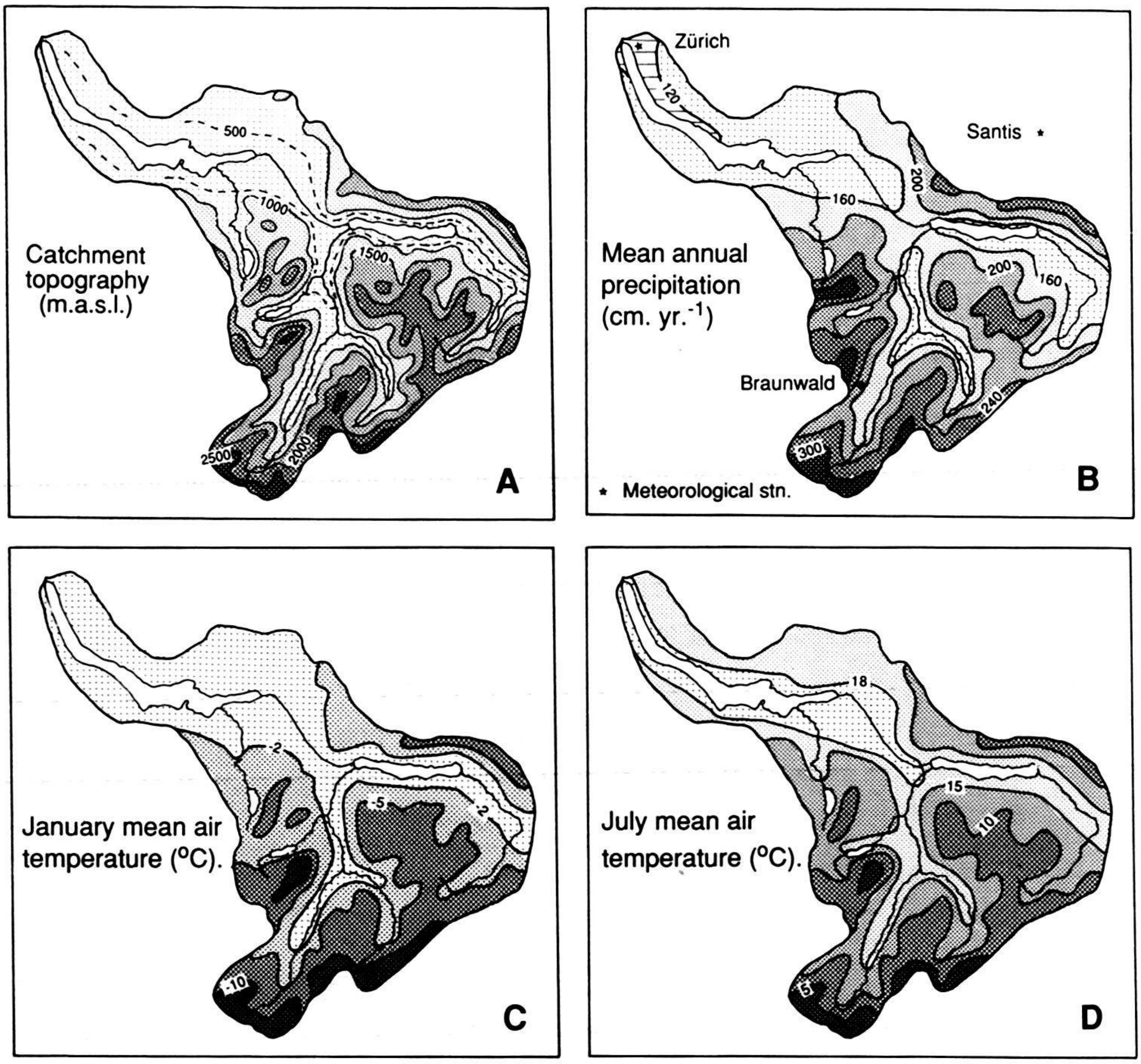

Fig. 1. Present distribution and relationship to topography of mean annual precipitation and mean air temperatures for January and July for the Lake Zürich catchment.

tude (1.3 and 0.9 °C respectively; Tables 2 and 3). That decreasing difference is due to the slight reduction in summer precipitation peak and the reduction in seasonality at higher altitudes. Annual precipitation distribution must be the dominant factor, since a test calculation using the Zürich station data altered to decrease seasonality by 4 °C (22%) results in a reduction of the temperature difference between MAAT and MTAP of only 0.3 °C (Table 4).

Altitude interval (m.a.s.l.)	3000–2500	2500–2000	2000–1500	1500–1000	1000–500	500–L. Zürich (406)
MAAT for 500 m. interval (°C)	**-3.6**	**-0.5**	**2.4**	**5.0**	**7.1**	**8.2**
MTAP - MAAT difference (°C).	+0.9	+1.0	+1.1	+1.2	+1.4	+1.6
MTAP for 500 m interval(°C)	**-2.5**	**-0.5**	**3.5**	**6.2**	**8.5**	**10.0**

Table 5. Mean annual air temperatures and mean temperatures for annual precipitation calculated for 500 m altitude intervals in the Lake Zürich catchment (based on data for stations at Zürich, Elm and Säntis, and the observed air temperature decrease with altitude for the Alpine region).

Terrain	**Altitude** (m.a.s.l.)	**A** Fraction of total catch- -ment area	**B** MAAT for 500 m. interval	**C** Product (A x B)	**D** Precip. (cm / yr)	**E** Fraction of total precip. $\frac{A \times D}{\Sigma (A \times D)}$	**F** MTAP (°C)	Product (E x F)
South peaks	> 2500	0.025	-3.6	**-0.09**	300	0.039	-2.5	**-0.10**
Mountain tops	2500–2000	0.131	-0.5	**-0.07**	270	0.183	0.5	**0.10**
Upper slopes	2000–1500	0.204	2.4	**0.49**	220	0.232	3.5	**0.81**
Lower slopes	1500–1000	0.210	5.0	**1.05**	190	0.206	6.2	**1.28**
Upper valley floors + peri-Alpine hills	1000–500	0.200	7.1	**1.42**	170	0.176	8.5	**1.49**
Lower valley floors + peri-Alpine flats + lake	< 500	0.230	8.2	<u>**1.88**</u>	140	0.165	10.0	<u>**1.66**</u>

MAAT for whole catchment = 4.7 **MTAP for whole catchment = 5.2 °C**

Table 6. Mean annual air temperature (MAAT) and mean temperature for annual precipitation (MTAP) values calculated for the whole Lake Zürich catchment by integrations of the respective data values for successive 500 m altitude intervals (cf. Table 5).

Air temperature isotherms and precipitation isohyets closely follow catchment topographic contours. The air temperature-altitude gradient, except for the lower altitudes, is close to linear at ca. 0.6 °C per 100 m (Schüepp et al. 1978). Thus the MAAT and MTAP averages can be calculated for each 500 m altitude interval (Table 5). The MAAT value for the whole catchment is obtained by integration of the products of the 500 m interval values and the vertically projected areas of the corresponding intervals as a fraction of the total catchment area (Table 6). The MTAP for the whole catchment, which will be taken as that for Lake Zürich water, is obtained as the sum of the products of the mean annual precipitation for each 500 m altitude interval (mean annual precipitation for each interval by its vertically projected area) as a fraction of the total catchment runoff and the MTAP for the corresponding intervals (Table 6).

The MAAT and MTAP values for the whole catchment are 4.7 °C and 5.2 °C respectively. The unexpected difference of only 0.5 °C between those values is considerably less than exists within each of the 500 m intervals. This is due to a temperature compensation effect for the reduced winter precipitation in the lowlands by annual precipitation in the colder Alpine hinterland in the integrated MTAP value.

(NB. These calculations are based on a more comprehensive data set for local climatic conditions than that used by Lister (1988) and some earlier values are revised.)

Summarizing for the Lake Zürich catchment:

(i) Seasonality decreases with increasing altitude by 4 °C, or 22%.
(ii) The summer precipitation peak results in an MTAP which is higher than the MAAT at a given station.
(iii) The difference between MTAP and MAAT decreases with increasing altitude at a rate of ca. 0.5 °C per 1,000 m as a result of a decreasing summer precipitation peak and decreasing seasonality. The latter has the least influence.
(iv) The difference between the whole-catchment MAAT and MTAP values is only 0.5 °C because of a compensation effect in the MTAP value due to integration of both seasonal and altitudinal precipitation-temperature components.
(v) Changes in the total amount of precipitation have no effect on the MAAT–MTAP difference.
(vi) Seasonal and spatial distributions of precipitation would have the most significant influences on the MAAT–MTAP differences.

The oxygen-isotope ratio for the lake waters at a given moment depends on the net product of temporally and spatially variable runoff from a range of sub-environments. In spite of this variability, the $\delta^{18}O$ value for Lake Zürich waters shows no seasonal fluctuations. The modern $\delta^{18}O$ value of −11.4‰ (Pika, 1983) thus corresponds to the whole-catchment MAAT and MTAP values of 4.7 and 5.2 °C respectively.

Seasonality at the Pleistocene/Holocene boundary

In order to test whether or not a seasonality maximum in the earliest Holocene would have significantly enhanced the difference between MAAT and MTAP (and thus the deviation of the temperature-dependent oxygen isotope values for precipitation), the amplitudes of modern mean monthly air temperature data for the three stations Zürich, Elm and Säntis were arbitrarily enlarged by 4 °C (equivalent to the seasonality change between altitude extremes for the modern catchment; cf. Table 4) and the

MTAP's recalculated. The resultant MTAP values of 10.6 (Zürich), 7.6 (Elm) and −0.9 °C (Säntis) are only slightly higher than the modern MTAP values of 10.3, 7.4 and −1.1 °C respectively. The effect on the integrated whole-catchment MAAT−MTAP difference is negligible. This implies that a seasonality maximum during the earliest Holocene should have had little effect on the oxygen-isotope composition of Lake Zürich waters. The late Pleistocene-Holocene oxygen-isotope record for Lake Zürich waters may thus be used, without adjustments for changing seasonality, as a proxy for mean annual air temperature changes for the latest Pleistocene and Holocene, although the possible effects of several conditions need to be kept in mind (see discussion below).

The Lake Zürich isotopic record

In 1980 a long core containing basinal sediments and bedrock was recovered from the deepest part of Lake Zürich during the Zübo Deep Lake Drilling Project (Hsü, Giovanoli & Kelts, 1984; Giovanoli, 1984; Lister, 1984; Fig. 2). Ostracod and

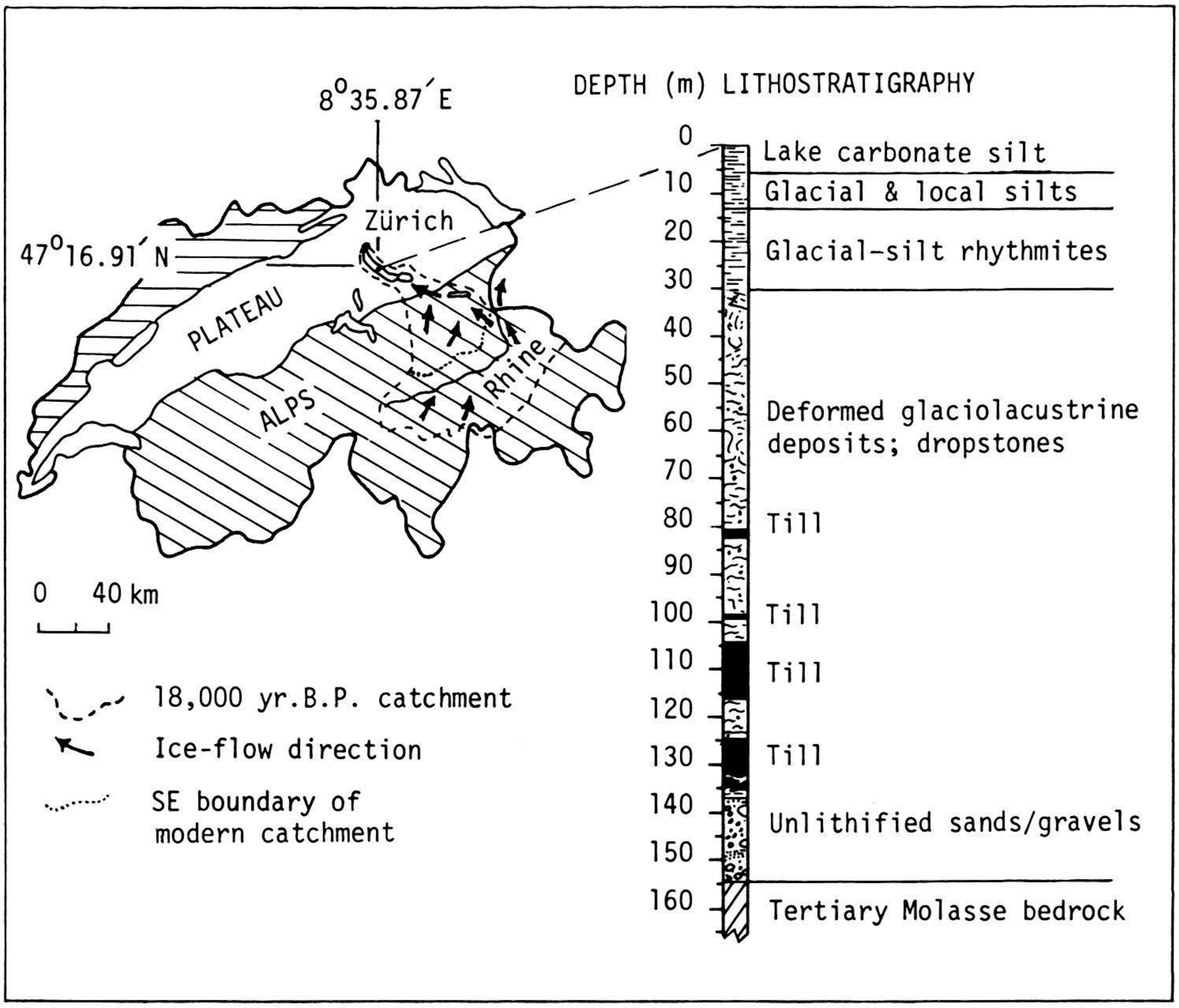

Fig. 2. Location of the Zübo 80 drill site in Lake Zürich, Switzerland, and the gross lithostratigraphy for cored basinal sediments (drill-site co-ordinates: 47°16.91′N, 8°35.87′E; water depth 137 m).

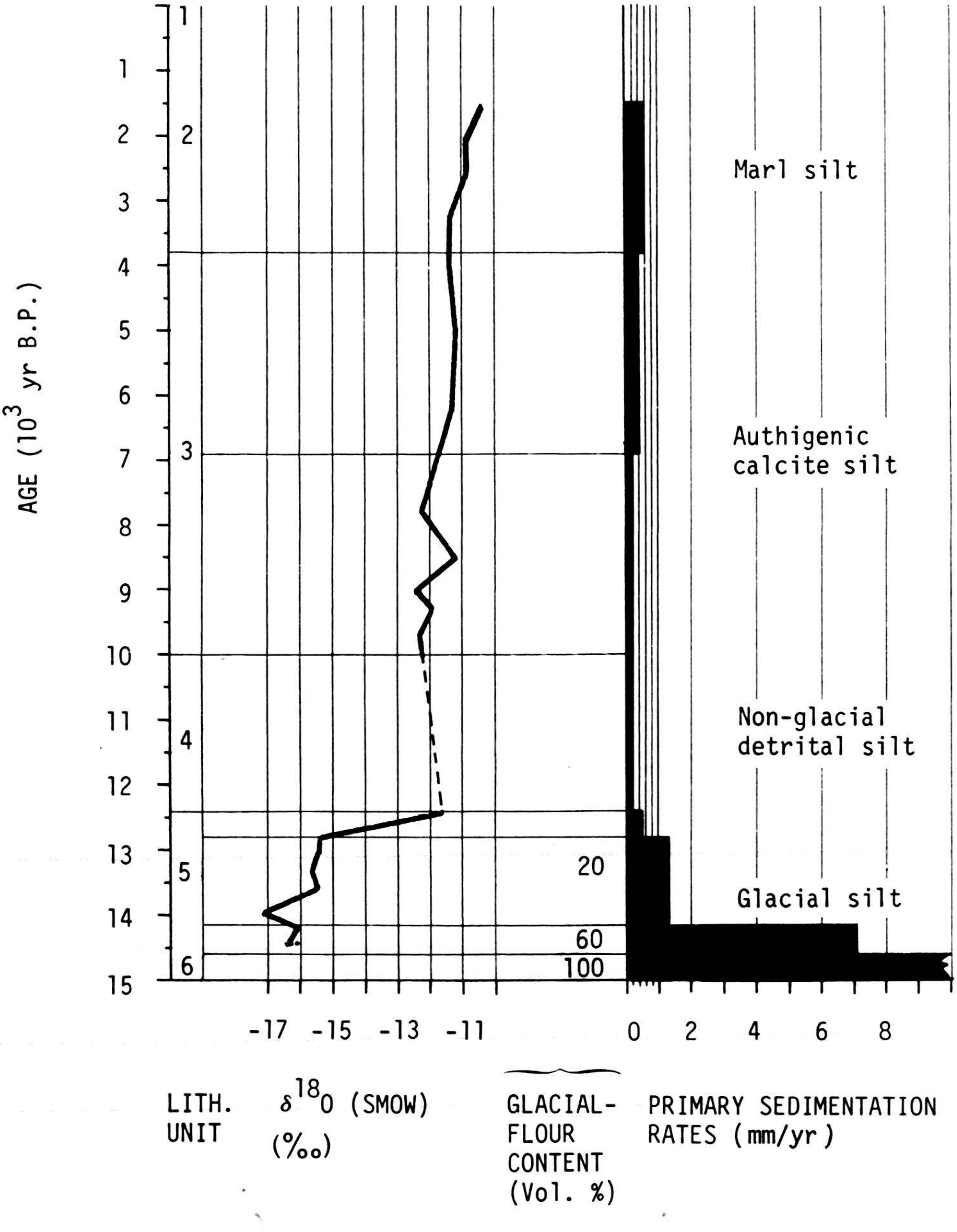

Fig. 3. $\delta^{18}O_{SMOW}$ values for palaeo Lake Zürich calculated from benthic biogenic carbonate $\delta^{18}O_{PDB}$ ratios, mean sedimentation rates (C-14 dated intervals) and glacial-silt content (volume percent of sediment) versus time (after LISTER, 1988).

pelecypod carbonate and terrigenous organic material preserved throughout the upper 11 m of those sediments have provided a C-14 dated isotopic record of hydrologic and climatic changes affecting the catchment during the last 14,500 years (LISTER, 1988). $\delta^{18}O_{SMOW}$ values (CRAIG, 1961) were calculated from $\delta^{18}O_{PDB}$ ratios (CRAIG, 1965) measured for the benthic Ostracoda and Pelecypoda tests (each measurement representing an average value for decades of deposition so that short-term isotopic variations are smoothed (Fig. 3). LISTER (1988) interpreted that isotopic record primarily in terms of rates and timing for deglaciation of the Alpine catchment. Briefly, isotopically-light glacial meltwaters provided the main source of lake waters prior to ca. 12,800 years B.P., rapid melting of stagnant glacial ice ended by ca 12,400 years B.P. and direct catchment runoff provided the lake inflow thereafter. Mean annual air temperature changes initially calculated by LISTER (1988) from those $\delta^{18}O_{SMOW}$ values did not include compensation for the more positive $\delta^{18}O$ ratio of Glacial mean atmospheric moisture (BENDER et al. 1985).

Latest Pleistocene

The meltwaters may have previously been held in the Alpine glacial ice reservoir for thousands of years prior to their final release, and thus represent precipitation from the atmosphere at a time when seasonality was close to that of today. The exact temporal and spatial patterns for precipitation during the last Glacial maximum for the Lake Zürich catchment remain uncertain, however several conditions can be applied for the catchment:

(i) The annual precipitation was considerably reduced with respect to modern precipitation. This alone could not have affected the MAAT–MTAP difference.

(ii) Alpine valleys were filled with ice to depths of up to 1,300 m and the peri-Alpine area was largely covered by piedmont ice lobes to depths of up to several hundred metres. Thus the effective mean altitude for catchment precipitation must have been higher than for the ice-free catchment. This adds an additional cold bias in the whole-catchment MTAP value.

(iii) There was a glacial ice contribution from a divergence of the Rhine glacier at the junction of the Seez and Rhine Valleys. This probably did not have a significant effect on the MAAT-MTAP difference since topography and altitudes are quite similar for the Rhine and Linth catchments.

(iv) The glacial ice reservoir melted at a rate which on average exceeded precipitation additions, so the ratio of high-altitude to low-altitude waters entering the lake should have been larger during the glacial retreat than afterwards. This adds an additional cold bias to the effective MTAP value for meltwaters entering the lake during deglaciation.

(v) Soils and vegetation were less developed than during the Holocene, thus runoff was probably faster and evapotranspiration less, especially for lower catchment areas, than during the Holocene. This would imply less preferential loss of O-16 and consequently a relatively more negative $\delta^{18}O$ value.

The net combined effect of several of those factors should have added a cold bias to the apparent MTAP value for the lake waters and a consequent reduction in the

MAAT–MTAP difference (with respect to that for waters from an ice-free catchment under the same climatic conditions). Although those factors cannot be accurately quantified, their combined effect cannot have been large; despite decreasing contribution of meltwaters to Lake Zürich from a 14,400 to ca. 12,800 years B.P., indicated by a sharp reduction in the percentage of glacial silt in the sediments, $\delta^{18}O_{SMOW}$ values for the lake remained in the −15 to −17‰ range. Unless a winter peak or an even seasonal distribution characterised precipitation during the Glacial maximum, the MAAT–MTAP difference at that time must have been close to the modern value of 0.5 °C. Consequently, the temporal variations recorded for the palaeo-lake water $\delta^{18}O$ values may have closely paralleled variations for past whole-catchment mean annual air temperatures.

Mean annual air temperatures

Latest Pleistocene

Climatic patterns governing precipitation in the Alps during the last glaciation were not the same as they are today (Frenzel, 1980; Manabe & Broccoli, 1984), however the local geographic influences were quite similar. Alpine glaciers which flowed out onto the peri-Alpine lowlands, commonly as piedmont forms, were characteristic in Switzerland, rather than a vertically accumulating ice cap in which $\delta^{18}O$ values would have reflected its geometry (Dansgaard et al. 1971). Alpine precipitation was occurring at nearly the same altitudes as it does today. $\delta^{18}O$ values recorded in the bottom waters of Lake Zürich during the latest Pleistocene might be compared with those for modern waters from the Alpine and peri-Alpine regions in order to estimate past relative mean annual air temperatures. Several factors remain, however, which make absolute mean annual air temperatures calculated directly from those $\delta^{18}O$ values liable to possible error: (i) the exact relationship for moisture condensation temperature versus $\delta^{18}O$ value for palaeo precipitation has not been established, and (ii), the vapour history for palaeo precipitation over the catchment for that time is not precisely known.

The most negative $\delta^{18}O_{SMOW}$ value of −17‰ derived for the lake waters from carbonate sedimented at about 14,000 years B.P., if back-calculated from the modern $\delta^{18}O_{SMOW}$ value, corresponds to a whole-catchment mean annual air temperature of −3.3 °C or −7.7 °C, depending respectively on whether the calculation is made according to the global temperature-$\delta^{18}O$ relationship for precipitation (Dansgaard, 1964), or the seasonal temperature-$\delta^{18}O$ relationship observed for modern precipitation in Switzerland (Siegenthaler & Oeschger, 1980). Neither of those relationships are necessarily valid for long-term climatic change, but provide end points for a probable range. If those values are adjusted to account for the 1.3‰ more positive $\delta^{18}O$ value for mean atmospheric moisture during the Glacial (Bender et al. 1985), the corrected value for the whole-catchment mean annual temperature is −5.2 or −10.6 respectively. The mean annual air temperature difference between the Glacial maximum and present is consequently calculated at 9.9 and 15.3 °C respectively. Häberli (1983) proposed a temperature difference for the region of 15 °C on the basis of past and present permafrost levels. The result suggests that the seasonal temperature-$\delta^{18}O$ relationship observed for modern precipitation in Switzerland (SIEGENTHALER & OESCHGER, 1980) may have also existed during the latest Pleistocene.

The $\delta^{18}O_{SMOW}$ positive shift of 3.7‰ in the waters after around 12,800 years B.P. could represent a climatic warming of 5.3 or 8.2 °C (global or local temperature-$\delta^{18}O$ relationship respectively). $\delta^{18}O$ shifts of about the same size as that for Lake Zürich have been reported for authigenic carbonate silts deposited after about 13,000 years B.P. in small lakes on the Swiss Plateau (EICHER & SIEGENTHALER, 1976; LOTTER & BOUCHERLE, 1984) and in southwestern France (EICHER, SIEGENTHALER & WEGMÜLLER, 1981) which did not receive deglaciation meltwaters, indicating that the magnitude of the oxygen-isotope shift in Lake Zürich probably represents the magnitude of the rise in mean annual air temperature. However the Lake Zürich isotopic shift may not represent the timing of the warming, the isotopic effect of which could have been delayed for several centuries by meltwaters from the last stagnant Glacial ice.

The $\delta^{18}O_{SMOW}$ value for Lake Zürich waters of −11.7‰ at about 12,400 years B.P. is close to the modern value of −11.4‰. If corrected for the more positive $\delta^{18}O$ value of mean atmospheric moisture at that time, a mean annual air temperature of 1.4 or 2.2°C (global or local temperature-$\delta^{18}O$ relationship respectively) lower than that of today is indicated. That is in agreement with evidence from Coleoptera and Trichoptera faunas and pollen assemblages for the Bölling from the Swiss Plateau, which indicate mean July air temperatures of 14 to 16 °C (today 17 °C) and little if any increased aridity at that time (AMMAN & TOBOLSKI, 1983).

Carbonate dissolution in the sediments of deep Lake Zürich removed the isotopic record for the Alleröd and Younger Dryas periods. That dissolution may be explained by a combination of factors contributing to slightly lower pH values for the lake bottom waters including: (i) the sudden absence of very fine grained detrital carbonate (high surface area and low sedimentation rates) provided earlier by the glacial meltwaters, (ii) the absence and/or poor development of soils and vegetation in the catchment (rapid runoff, low dissolution of catchment carbonates), (iii) the absence of a significant rainout of authigenic calcite silt from warm productive surface waters, as is recorded for the Holecene.

Holocene

The sediments of Lake Zürich show no evidence for a glacial meltwater inflow during the Holocene and there is no evidence for any other significant change in the catchment hydrology or lake hydrography. Yet $\delta^{18}O$ excursions of up to 1‰ over about 500 to 1,000 year intervals during the early Holocene and a positive $\delta^{18}O$ shift of 1‰ by the mid Holocene are recorded. Assuming that patterns of seasonal and spatial precipitation distribution have remained essentially constant and the hydrologic and hydrographic regimes stable for the Lake Zürich catchment throughout the Holocene, those shifts must reflect changes in either vapour history or mean annual air temperature. The $\delta^{18}O$ value for mean atmospheric moisture had reached its modern value by about 9,000 years B.P. (BENDER et al. 1985) and climatic conditions were close to those of today. Thus if those $\delta^{18}O$ shifts were caused by changing mean annual air temperatures, they indicate slightly cooler (<1 °C) than average intervals at around 9,000 and 8,000 years B.P., separated by a slightly warmer (<1 °C) than average interval at ca.

8,500 yr. B.P. Quite similar $\delta^{18}O$ fluctuations are recorded in the marl sediments of Lake Amsoldingen, about 100 kilometres to the south west of Lake Zürich, for the early Holocene (LOTTER & BOUCHERLE, 1984). Similarly, the overall shift in the $\delta^{18}O_{SMOW}$ values for Lake Zürich during the first half of the Holocene of would indicate a climatic warming of up to 2 °C, depending on the temperature-$\delta^{18}O$ relationship for precipitation. There is little indication in the $\delta^{18}O$ record for a significant lowering of mean annual air temperature after the commonly reported mid-Holocene climatic optimum or hypsithermal (NILSSON, 1983).

Conclusions

Calculations based on annual precipitation data and mean monthly air temperature data for the modern Lake Zürich catchment indicate that:

(i) The mean temperature for annual precipitation (MTAP) is higher than the mean annual air temperature (MAAT) by 1.9 °C at Zürich, decreasing to less than 1 °C for the mountain tops, because of a ubiquitous summer peak for annual precipitation.

(ii) The integrated whole-catchment mean annual air temperature is 4.7 °C, 0.5 °C less than the corresponding mean temperature for annual precipitation.

(iii) Seasonality reduces by 22% from the lowest to highest catchment altitudes. The effect on the MAAT–MTAP difference is subordinate to that from even small changes for precipitation patterns.

(iv) An arbitrary increase in modern catchment seasonality of 22% has little effect on the whole-catchment MAAT and MTAP values or on the difference between those values

Changing seasonality due to insolation variations at the top of the atmosphere for the northern hemisphere during the last 18,000 years could have had little effect on the net $\delta^{18}O$ value for Lake Zürich waters during the latest Pleistocene and Holocene. This is because a compensation effect in the whole-catchment MTAP value, due to integration of both seasonal and altitudinal precipitation-temperature components, suppresses the effect of seasonality change.

$\delta^{18}O$ values for palaeo waters calculated from the $\delta^{18}O$ ratios of benthic carbonates preserved in Lake Zürich basinal sediments and corrected for the heavier $\delta^{18}O$ value of mean atmospheric moisture during the latest Pleistocene, indicate that mean annual air temperature during the last Glacial maximum was some 10 to 15.5 °C lower than today, depending on the temperature-$\delta^{18}O$ relationship for precipitation. The mean annual air temperature indicated for the mid Bölling, when Glacial meltwaters had permanently stopped flowing into Lake Zürich, is 1.5 to 2 °C lower than that of today. Minor short-term temperature fluctuations ($\pm<1$ °C) from about 10,000 to 7,500 years B.P. and a climatic warming of up to 2 °C by the mid Holocene are indicated.

The suppression of seasonality-change effects that the integration of both seasonal and altitudinal precipitation-temperature distributions has on the isotopic values for Lake Zürich waters was unexpected and possibly unique to this catchment. This whole-catchment model should be tested for other lacustrine systems, particularly those where long-term seasonality changes may have contributed a significant signal to oxygen-isotope records.

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