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Variations in Lake Levels during the Holocene in North America: An Indicator of Changes in Atmospheric Circulation Patterns

Les variations de niveaux lacustres au cours de l'Holocene, en Amérique du Nord : un indicateur de changement dans la circulation atmosphérique

Variationen in der Höhe der Seen-Wasserspiegel während des Holozän in Nordamerika: ein Indikator für Veränderungen in der atmosphärischen Bewegung

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Article abstract

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VARIATIONS IN LAKE LEVELS DURING THE HOLOCENE IN NORTH AMERICA: AN INDICATOR OF CHANGES IN ATMOSPHERIC CIRCULATION PATTERNS

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ABSTRACT Fluctuations in the extent of closed lakes provide a detailed record of regional and continental variations in mean annual water budget. The temporal sequence of hydrological fluctuations during the Holocene in North America has been reconstructed using information from the Oxford Lake-Level Data Bank. This data base includes 67 basins from the Americas north of the equator. Maps of lake status, an index of relative depth, are presented for the period 10,000 to 0 yr BP. The early Holocene was characterised by increasingly arid conditions, which led to widespread low lake levels in the mid-latitudes by 9,000 yr BP. By 6,000 yr BP this zone of low lakes extended from 32° to 51°N. Many of the features of the present day lake-level pattern, particularly high lake levels north of 46°N and along the eastern seaboard, were established by 3,000 yr BP. Four distinctive regional patterns of lake behaviour through time are apparent. Histograms of lake status from 20,000 to 0 yr BP are presented for each of these regions. They illustrate the temporal patterns of lake-level fluctuations on a time scale of $10^3 - 10^4$ yr. Changes in lake status over North America are interpreted as indicating displacements in major features of the general circulation, specifically the zonal Westerlies and the Equatorial Trough, as reflected by changes in air mass trajectories and hence the position of air mass boundaries over the continent.

RÉSUMÉ *Les variations de niveaux lacustres au cours de l'Holocène, en Amérique du Nord: un indicateur de changement dans la circulation atmosphérique*. Les fluctuations de superficie enregistrées dans les lacs fermés fournissent des données détaillées quant aux variations, aux échelles régionale et continentale, du bilan annuel moyen de l'eau. On a reconstitué, en Amérique du Nord, la chronologie des fluctuations survenues à l'Holocène, en se fondant sur les données fournies par le Oxford Lake-Level Data Bank. Cette banque de données renseigne sur 67 bassins lacustres, situés en Amérique au nord de l'équateur. On présente ici des cartes illustrant les niveaux lacustres entre 10 000 et 0 ans BP. L'Holocène inférieur se caractérisait par une progression de l'aridité qui a entraîné un abaissement général du niveau des lacs situés sous les moyennes latitudes, environ 9000 ans BP. Environ 6000 ans BP, cette zone passait du 32° de latitude nord au 51°. Un grand nombre de particularités qui caractérisent aujourd'hui les niveaux lacustres, notamment les hauts niveaux qu'on observe au nord du 46°N et le long de la côte est, étaient déjà acquises vers 3000 ans BP. Quatre types d'évolution générale se dégagent au cours des millénaires. Par ailleurs, on présente des histogrammes illustrant les niveaux lacustres selon une échelle temporelle de $10^3 - 10^4$ ans. On considère que les changements qu'ont connu, en Amérique du Nord, les niveaux lacustres révèlent qu'il y a eu déplacement des composantes principales de la circulation atmosphérique générale, surtout en ce qui a trait aux vents d'ouest et à la dépression équatoriale. Ils se sont traduits par des modifications de la trajectoire des masses d'air, ce qui explique la position des limites de masses d'air sur le continent.

ZUSAMMENFASSUNG *Variationen in der Höhe der Seen-Wasserspiegel während des Holozän in Nordamerika: ein Indikator für Veränderungen in der atmosphärischen Bewegung*. Schwankungen in der Ausdehnung geschlossener Seen liefern einen detaillierten Nachweis über regionale und kontinentale Variationen im durchschnittlichen jährlichen Wasser-Budget. Man hat die zeitliche Abfolge von Wasserschwankungen während des Holozän in Nordamerika rekonstruiert, gestützt auf Informationen von der Oxford Lake-Level Data Bank. Diese Daten-Bank umfaßt 67 Wasserbecken Amerikas, die nörlich vom Äquator liegen. Für die Zeit von 10 000 bis O v.u.Z. werden Karten vorgelegt, die über die relative Tiefe der Seen informieren. Das frühe Holozän zeichnete sich durch zunehmend trockene Bedingungen aus, was um 9 000 v.u.Z. in den mittleren Breiten zu weit verbreiteten niedrigen Seewasserspiegeln führte. Um 6 000 v.u.Z. dehnte sich diese Zone niedriger Wasserspiegel von 32° bis 51° nördlicher Breite aus. Viele Erscheinungsformen, die die heutigen Seen-Wasserspiegel charakterisieren, insbesondere hohe Seen-Wasserspiegel nördlich von 46° nördlicher Breite und entlang der Ostküste wurden um 3 000 v.u.Z. festgelegt. Durch die Jahrtausende sind vier unterschiedliche regionale Muster des Seen-Verhaltens feststellbar. Für jedes dieser Gebiete werden Histogramme des Seen-Zustandes von 20 000 bis O Jahren v.u.Z. vorgelegt. Sie illustrieren die zeitliche Anordnung der Seen-Wasserspiegelschwankungen auf einer Zeit-Skala von 10^3-10^4 Jahren. Veränderungen im Seenzustand Nord-amerikas werden interpretiert als Hinweis auf eine Verlagerung der Hauptmerkmale der allgemeinen atmosphärischen Strömungen, insbesondere was die Westwinde des Gebiets und die äquatoriale Windstille betrifft. Das spiegelt sich in Veränderungen der Zugrichtung der Luftmassen und folglich der Position der Luftmassengrenzen über dem Kontinent.

INTRODUCTION

Fluctuations in closed lakes, which are particularly sensitive to changes in the balance between precipitation and evaporation, provide a detailed record of variations in regional and continental mean annual water budget (SMITH and STREET-PERROTT, 1983; STREET-PERROTT and HARRISON, 1985). The current spatial distribution and relative extent of such lakes can be directly related to the mean position of major features of the atmospheric circulation (STREET-PERROTT and ROBERTS, 1983). Closed lakes are most widespread today in the arid and subhumid regions, particularly in the tropics and subtropics (SCHUILING, 1977). Many lakes in temperate areas, however, ceased to overflow during drier periods of the Late Quaternary in response to changes in both the strength and mean position of major circulation features. Examination of the patterns of lake-level variations therefore provides a method of reconstructing global atmospheric circulation during the Late Quaternary.

In this paper, we describe the spatial and temporal variations in the patterns of lake levels for the Americas north of the Equator, concentrating on the Holocene period. This time span has been chosen because it yields the best coverage of sites with reliable chronologies and good stratigraphical resolution. Previous attempts at reconstructing the palaeoclimates of North America have often had a narrow disciplinary or regional focus. A better understanding of changes in atmospheric circulation can be achieved by consideration of the palaeorecord at a continental scale (BRYSON and WENDLAND, 1967). With recent improvements in the data coverage for North America, it is now possible to adopt such an approach using lake-level information.

Regional climates of North America can be described in terms of the seasonal distribution of air masses from different sources over the continent (BRYSON, 1966; BRYSON and HARE, 1974; WENDLAND and BRYSON, 1981). Figure 1 shows the distribution of the major air masses during winter (January) and summer (July). In winter, in response to the equatorward displacement of the Equatorial Trough and the zonal Westerlies, the cold, dry Arctic air mass dominates much of North America. Penetration of Pacific air into the continental interior is blocked by the presence of this cold, stable air over the mid-continent. The influence of moist tropical air is also limited. In summer, as the Equatorial Trough and zonal Westerlies move northwards, the influence of the Arctic air mass is reduced and both Pacific and Maritime Tropical air masses penetrate further into the continental interior. There are significant contrasts between the moisture characteristics of these air masses and therefore their distribution can be seen as a major determinant of precipitation over the continent. Since lake behaviour reflects the balance between precipitation and evaporation, the regional patterns of lake levels should be related to air mass distribution. Broadly speaking, high

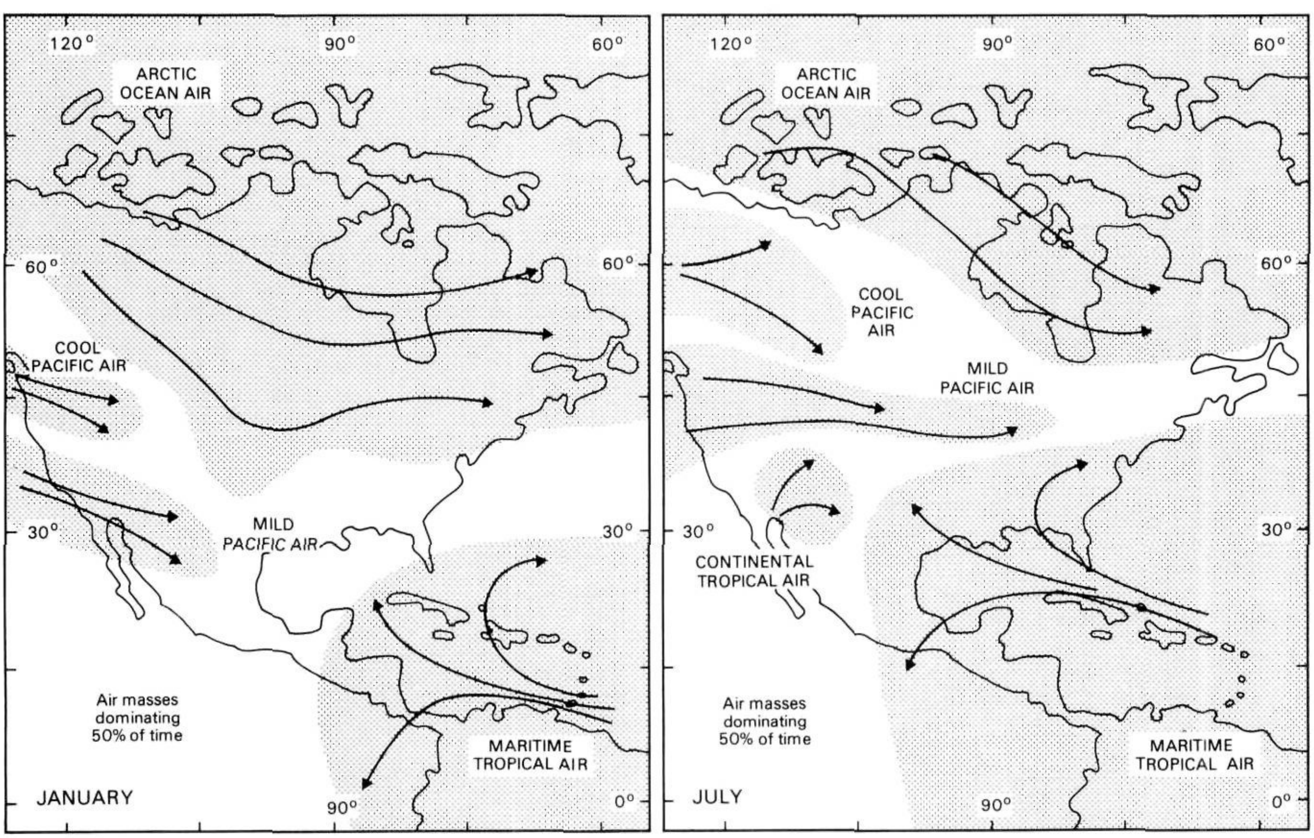

FIGURE 1. Present-day distribution of air masses over North America for January and July. Compiled from data in BRYSON and HARE (1974).

Répartition actuelle des masses d'air au-dessus de l'Amérique du Nord pour janvier et juillet (compilation faite à partir des données contenues dans BRYSON et HARE (1974).

lake levels are characteristic of the frontal zone between Pacific and Arctic air (Arctic Front) and also the region influenced by moist tropical air. Thus high lake levels are found north of 50°N and along the eastern seabord at the present day. The interpretation of spatial patterns of Late Quaternary lake-level fluctuations put forward in this paper is based on this present-day relationship between lake behaviour and major features of the atmospheric circulation as expressed through the distribution of air masses from different sources over the continent.

METHODS

The temporal sequence of hydrological fluctuations in North America has been reconstructed using information from the Oxford Lake-Level Data Bank. This data base, compiled from published material, contains records of fluctuations in lake level from basins that have been closed during part or all of their Late Quaternary history (STREET and GROVE, 1976, 1979). Basins where water depth is primarily controlled by changes in sea level, or responds to glacier fluctuations, have been excluded from the data bank. Only sites with a chronology based on ^{14}C or dated tephra layers are included. Lake-level fluctuations are reconstructed from a wide variety of geomorphological, stratigraphical, palaeoecological and archaeological evidence. The data are therefore standardised (STREET-PERROTT *et al.*, 1985) to yield estimates of lake status, an index of relative depth. The total range of water depth registered within each basin is divided into three status classes (low, intermediate and high), using an arbitrary but consistent set of rules. Status is coded on an ordinal scale at 1000 yr intervals from 30,000 to 0 yr BP (STREET-PERROTT and ROBERTS, 1983; STREET-PERROTT and HARRISON, 1984).

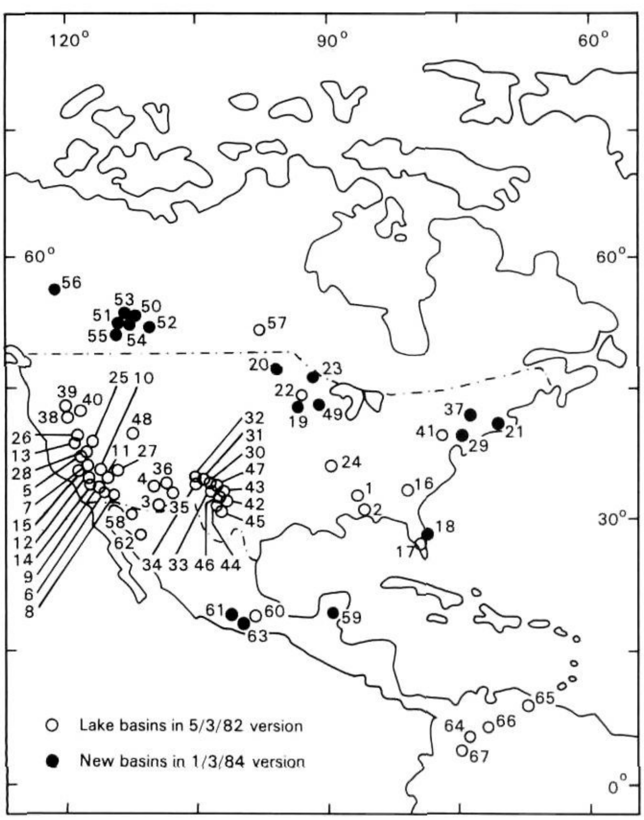

FIGURE 2. The distribution of lake basins used in this study. The numbering system refers to basin numbers in Table I.

Répartition des bassins lacustres traités dans le présent article. La numérotation correspond à celle du tableau I.

The Oxford Data Bank has recently been revised and substantially expanded (Data Bank Version 1/3/84) and now includes a total of 67 basins (Table I and Fig. 2) from North America (HARRISON and METCALFE, 1985). Twenty-one basins have been added in this recompilation, and a number of other lakes have been partially recoded to take into account new evidence or additional dating. This represents a marked improvement in the quality of the data bank coverage, particularly since most of the new basins lie in areas previously poorly represented, such as the northern and eastern parts of the continent (Table I and Fig. 2). Despite this improvement, the temporal and spatial distribution of published lake-level information is still uneven. The basins discussed in this paper cover a latitudinal range extending as far north as 56.25°N. However, approximately 51% occur between the latitudes 30° and 40°N and 31% lie within the Great Basin. This pattern is partly determined by the distribution of closed drainage basins (DE MARTONNE and AUFRÈRE, 1928) but is also influenced by the lack of studies from certain areas, particularly Central America and the eastern U.S.A. (BRADBURY, 1982; MARKGRAF and BRADBURY, 1982; HARRISON and METCALFE, 1985).

SPATIAL STRUCTURE OF LAKE LEVELS

The most distinctive patterns of lake status which occurred during the Holocene over North America are illustrated by Figures 3-6. These patterns and their possible climatological implications are discussed below.

The early Holocene was characterised by increasing aridity in North America, with many lakes falling to intermediate or low levels after the moister conditions characteristic of postglacial times (HARRISON and METCALFE, 1985). This aridity became more pronounced, and by 9,000 yr BP (Fig. 3) widespread low lake levels were registered in both the eastern and western parts of the continent. Conditions remained relatively moist, however, in the central Midwest. Lakes in the American tropics, such as the Basin of Mexico and Lake Pátzcuaro, registered moister conditions at this time. Such conditions could indicate the northward displacement of the Equatorial Trough and increased monsoonal flow into this region. This interpretation is consistent with modelling results which show a significant increase in precipitation associated with enhanced seasonal land-ocean temperature contrasts and stronger monsoonal circulation (KUTZBACH and GUETTER, 1984).

A well-developed arid zone had formed over North America (*ca.* 32°-57°N) by 6,000 yr BP (Fig. 4). This may reflect the further poleward displacement of the frontal zone between the Arctic and Pacific air masses, possibly to north of 56°N. The general trend towards increasing aridity during the early

TABLE I

The Oxford Lake-Level Data Bank

Basin No.	Basin	Latitude (°N)	Longitude (°W)	Elevation (m. asl)	Length of record	No. ¹⁴C dates	Status** 9 6 3 0 ×10 yr BP	Selected references
1	Cahaba Pond, Alabama*	33.50	86.53	210	12,000	13	3 2 2 2	Delcourt *et al.*, 1983
2	Goshen Springs, Alabama*	31.72	86.13	105	26,000	7	2 1 2 2	Delcourt, 1980
3	Cochise, Arizona	32.13	109.85	1260	28,000	33	2 3 3 3	Schreiber *et al.*, 1972
4	Laguna Salada, Arizona	34.35	110.28	1920	7,000	2	– – – 3	Hevly, 1962
5	Adobe, California	37.91	118.60	1951	11,000	7	2 3 2 3	Batchelder, pers. comm.
6	Clark, California	33.33	116.30	169	1,000	2	– – – 3	Hubbs *et al.*, 1960
7	Deep Spring, California	37.28	118.03	1499	10,000	10	3 3 3 3	Jones, 1965
8	Leconte, California	33.33	116.00	–71	13,000	63	3 3 1 3	Van de Kamp, 1973
9	Manix, California	35.05	116.70	130	30,000	5	– – – 3	Berger and Libby, 1967
10	Manly, California	36.00	116.80	–86	26,000	4	– – – 3	Hooke, 1972
11	Mohave, California	35.37	116.13	276	15,000	24	2 – – 3	Ore and Warren, 1971
12	Panamint, California	36.30	117.30	317	30,000 +	10	– – – 3	Smith, 1977
13	Russell, California	38.05	118.77	1951	30,000	4	3 – – 3	Lajoie, 1968
14	Searles, California	35.60	117.70	493	30,000 +	110	3 2 2 3	Smith, 1977
15	Tulare, California	36.00	119.67	57	27,000	8	1 – – 3	Croft, 1968
16	White Pond, Carolina	34.16	80.76	90	19,000	3	3 3 3 2	Watts, 1980
17	Annie, Florida	27.30	81.40	36	27,000	8	2 2 1 1	Watts, 1980
18	Little Salt Spring, Florida*	27.00	82.17	5	12,000	18	2 2 1 1	Clausen *et al.*, 1979
19	Kettle Hole Lake, Iowa*	43.00	95.00	350	12,000	4	3 2 3 3	Collins, 1968
20	Okoboji, Iowa*	46.33	95.20	425	14,000	14	1 3 1 2	Van Zant, 1979
21	Duck Pond, Massachusetts*	41.93	70.00	3	12,000	8	1 3 2 2	Winkler, 1982
22	Kirchner Marsh, Minnesota	44.83	92.77	275	13,000	0	2 3 – 3	Brugam, 1980
23	Weber, Minnesota*	47.47	91.65	559	11,000	4	3 1 – 1	Fries, 1962
24	Old Field Swamp, Missouri	37.12	89.83	97	9,000	4	1 3 – 3	King and Allen, 1977
25	Dixie, Nevada	39.91	118.00	1027	12,000	2	– – – 3	Buckley and Willis, 1970
26	Lahontan, Nevada	40.00	119.50	1054	30,000 +	169	2 3 2 2	Benson, 1978
27	Las Vegas, Nevada	36.32	115.18	–	30,000 +	12	– – – 3	Haynes, 1967
28	Teel, Nevada	38.21	118.34	1495	11,000	1	– – – 3	Hay, 1966
29	Szabo Pond, New Jersey*	40.40	74.48	152	12,000	2	– – – 1	Watts, 1979
30	Arch, New Mexico	34.08	103.13	1174	14,000	5	– – – 3	Wendorf and Hester, 1975
31	Blackwater Draw, New Mexico	34.25	103.33	1250	16,000	17	3 2 3 3	Wendorf and Hester, 1975
32	Estancia, New Mexico	34.60	105.60	1842	12,000	4	3 2 – 3	Bachhuber and McLellan, 1977
33	Lea County, New Mexico	33.45	103.16	1189	14,000	2	– – – 3	Leonard and Frye, 1975
34	Portales Valley, New Mexico	34.44	103.83	1177	15,000	1	– – – 3	Leonard and Frye, 1975
35	San Agustin, New Mexico	33.83	108.17	2065	23,000	17	1 2 3 3	Markgraf *et al.*, 1983
36	Zuni, New Mexico	34.45	108.77	1935	23,000	1	– – – 3	Darton, 1905
37	George, New York*	43.52	73.65	96	12,000	2	3 2 1 1	Hutchinson *et al.*, 1981
38	Chewaucan, Oregon	42.67	120.50	1296	30,000 +	6	– 3 3 3	Van Denburgh, 1975
39	Fort Rock, Oregon	43.17	120.75	1311	29,000	4	2 3 2 2	Bedwell, 1973
40	Harney, Oregon	43.20	119.10	1246	30,000 +	3	1 – – 3	Gehr and Newman, 1978
41	Longswamp, Pennsylvania	40.48	75.67	192	13,000	6	3 – – –	Wendorf and Hester, 1975
42	Guthrie, Texas	33.09	101.80	914	30,000 +	2	– – – 3	Reeves, 1966
43	Lubbock, Texas	33.63	101.90	975	10,000	3	– – – 3	Wendorf and Hester, 1975
44	Monahans Dunes, Texas	31.62	102.77	823	13,000	2	– – – 3	Haynes, 1975
45	Mound, Texas	33.08	102.08	960	21,000	8	– – – 3	Wendorf and Hester, 1975
46	Rich, Texas	33.28	102.20	1006	30,000 +	4	– – – 3	Wendorf and Hester, 1975
47	White, Texas	33.97	102.73	1158	19,000	1	– – – 3	Wendorf and Hester, 1975
48	Bonneville, Utah	40.50	113.00	1280	30,000 +	114	3 3 3 3	Broecker and Kaufman, 1965
49	Mendota, Wisconsin*	43.10	89.42	259	13,000	14	2 3 2 2	Winkler and Swain, pers. com
50	Hastings, Alberta*	53.42	112.88	739	5,000	6	– – 1 1	Vance *et al.*, 1983
51	Isle, Alberta*	52.62	114.43	700	10,000	3	2 3 2 1	Hickman and Klarer, 1981
52	Moore, Alberta*	53.00	110.50	500	10,000	6	3 3 1 1	Schweger *et al.*, 1983
53	Smallboy, Alberta*	53.58	114.13	762	7,000	5	– 3 1 1	Vance *et al.*, 1983
54	Wabamun, Alberta*	53.50	114.25	732	8,000	11	– 3 – 2	Holloway *et al.*, 1981
55	Wedge, Alberta*	50.87	115.17	1500	10,000	2	3 1 1 1	MacDonald, 1982
56	Fiddlers Pond, Brit. Columbia*	56.25	120.75	630	8,000	3	– 3 2 –	White and Mathewes, 1982

Basin No.	Basin	Latitude (°N)	Longitude (°W)	Elevation (m. asl)	Length of record	No. ^{14}C dates	Status** 9 6 3 0 × 10 yr BP	Selected references
57	Manitoba, Manitoba	51.00	98.00	248	12,000	9	3 3 2 2	Teller and Last, 1981
58	Elegante Crater, Mexico	31.80	113.52	1190	17,000	2	– – – 3	Damon *et al.*, 1963
59	Chichancanab, Mexico*	19.50	88.75	38	21,000	4	3 3 1 3	Covich and Stuiver, 1974
60	México, Mexico	19.50	99.00	2240	30,000 +	26	1 2 – 1	Bradbury, 1971
61	Pátzcuaro, Mexico*	19.58	101.58	2044	18,000	6	1 2 2 2	Watts and Bradbury, 1982
62	San Bartolo Playa, Mexico	29.05	111.95	5	8,000	1	– – – 3	Petit-Maire and Casta, 1977
63	Upper Lerma, Mexico*	19.13	99.67	2575	6,000	4	– 3 1 3	Metcalfe *et al.*, In press
64	Fuquene, Colombia	5.50	73.75	2580	30,000 +	0	1 1 1 1	Van Geel and Van der Hammen, 1973
65	Valencia, Venezuela	10.10	67.75	402	13,000	13	2 2 1 2	Bradbury *et al.*, 1981
66	Laguna Ciega, Colombia	6.50	72.30	4000	25,000	0	– – – –	Van der Hammen *et al.*, 1981
67	El Abra, Colombia	5.00	74.00	2570	30,000 +	8	3 3 3 3	Schreve-Brinkman, 1978

* Basins added in the 1.3.84 revision of the data bank: ** Status classes: 1 = High, 2 = Intermediate, 3 = Low

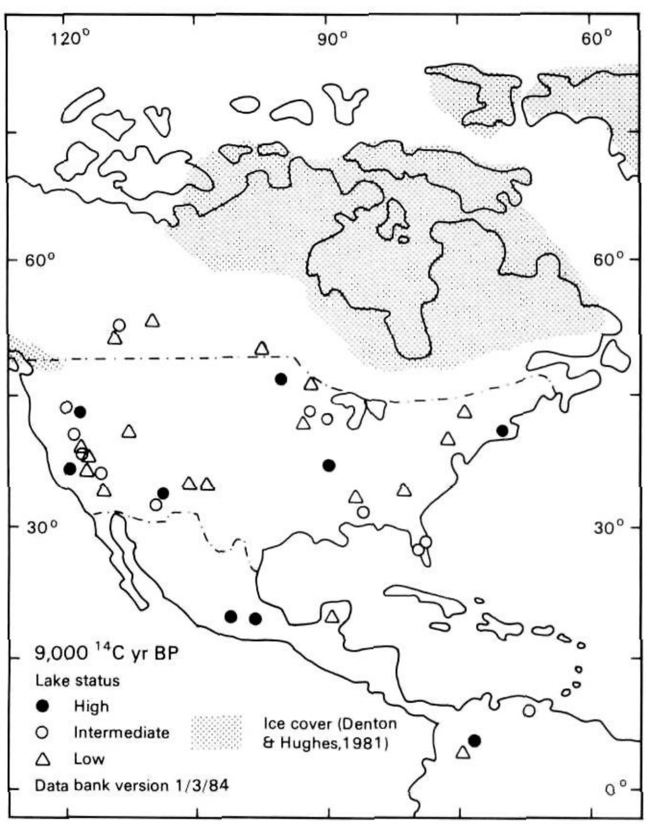

FIGURE 3. Lake status at 9,000 yr BP.
Niveaux lacustres, 9000 ans BP.

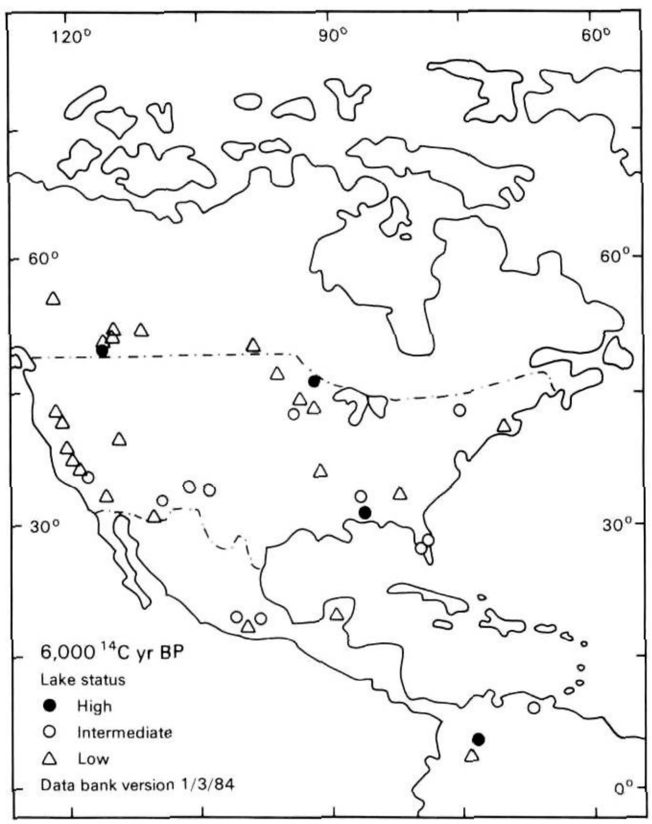

FIGURE 4. Lake status at 6,000 yr BP.
Niveaux lacustres, 6000 ans BP.

and mid-Holocene is consistent with independent evidence for eastward expansion of the prairie across the Midwest between 9,000 and 7,000 yr BP (WEBB *et al.*, 1983), which has been interpreted (BARTLEIN *et al.*, 1984) as resulting from the replacement of Arctic air masses over the region by warm, dry Pacific air. The predominance of Pacific air masses over the mid-Continent may have blocked the penetration of moist, tropical maritime air into the interior at this time. Maritime air mass penetration appears to have been confined to the southeast, where four lakes registered intermediate/high levels. Compared with conditions at present, however, the lakes suggest that flow from the tropics was relatively weak. There are some indications (WEBB *et al.*, 1983; METCALFE and HARRISON, in press; BRADBURY, 1971) that the early Holocene drying phase, illustrated by the pattern at 6,000 yr BP, was in fact most widespread at 7,000 yr BP.

The present day patterns of both air mass and lake-level distributions were established between 6,000 yr BP and today. By 3,000 yr BP (Fig. 5) a band of high and intermediate lakes had developed between 46° and 56°N. This probably reflected the southward displacement of the Arctic Front, at least to around 51°N but more probably to its present-day mean position. The Great Basin was still relatively dry, although some lakes adjacent to the Sierra Nevada registered intermediate levels, and hence moister conditions, at this time. Wetter conditions were also experienced along the eastern seaboard, indicating increased penetration of moist tropical air as far north as 45°N. High lake levels were registered throughout the American tropics and in Florida, which could indicate a stronger trade wind circulation at this time (JAUREGUI, 1979). This more meridional flow would have been encouraged by the establishment of a semi-permanent ridge in the Westerlies over the western part of the Continent and of a trough east of the Rockies (BARTLEIN *et al.*, 1984) typical of the present-day atmospheric circulation. After 3,000 yr BP conditions became more arid within the Great Basin and the American tropics. Thus, the present-day status map (Fig. 6) is characterised by high lake levels along the eastern seaboard and north of 46°N and drier conditions in the mid-Continent, the Great Basin and, generally speaking, within the tropics.

TEMPORAL STRUCTURE OF LAKE LEVELS

Consideration of the lake status maps suggests that there are at least four distinctive regional patterns of lake behaviour through time: tropical (0-23.5°N); eastern midlatitude (23.5°-50°N, east of 100°W); western midlatitude (23.5°-50°N, west of 100°W); and northern midlatitude (50°-60°N). Figure 7 illustrates the temporal sequence of lake-level fluctuations in each of these regions between 20,000 yr BP and the present. There is a broad similarity between the eastern midlatitude (Fig. 7c) and tropical (Fig. 7d) patterns, with both experiencing drier conditions around the Glacial Maximum (20,000 to 15,000 yr BP). In the eastern midlatitudes two distinct phases of high lake levels were recorded, between 14,000 and 9,000 yr BP and from 4,000 yr BP to the present. These were both registered in the tropics but the pattern there is more complex. The similarity between the two histograms may reflect the importance of Tropical Maritime air as a moisture source in both regions. Thus the earlier phase of high lake levels (14,000 – 9,000 yr BP) may reflect increased penetration of moist air from the Gulf of Mexico, as a result of the weakening of zonal circulation and northward displacement of the Arctic Front following the period of rapid recession of the Laurentide Ice Sheet shortly after 14,000 yr BP (BRYSON *et al.*, 1969; PREST, 1969; MAYEWSKI *et al.*, 1981). It is more difficult to interpret the eventful record of the tropical lakes during the early Holocene, but it probably reflects the influence of other air masses on the climate of this region.

The western midlatitude histogram (Fig. 7b) shows a dramatically different pattern from that registered by lakes in the eastern midlatitudes and the tropics, with high lake levels characteristic of the Glacial Maximum and late Glacial, and

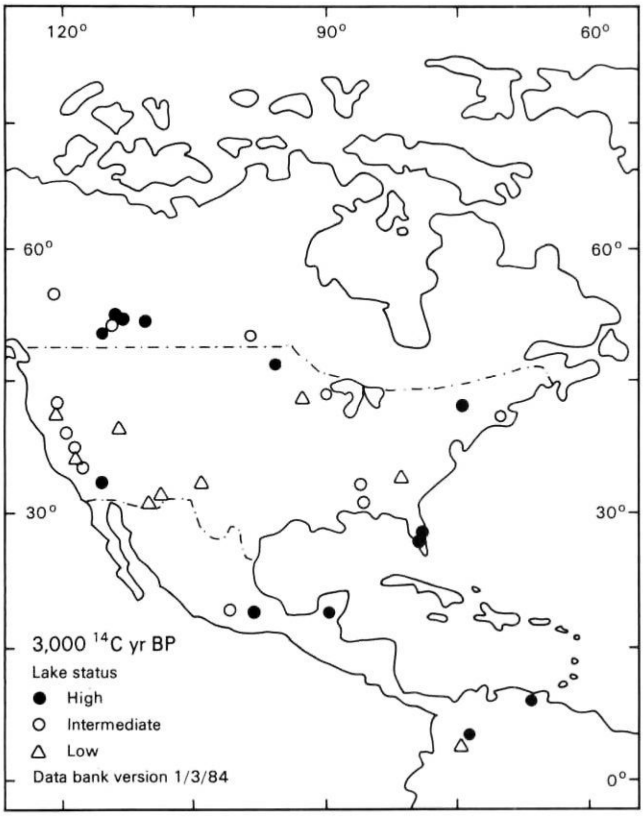

FIGURE 5. Lake status at 3,000 yr BP.
Niveaux lacustres, 3000 ans BP.

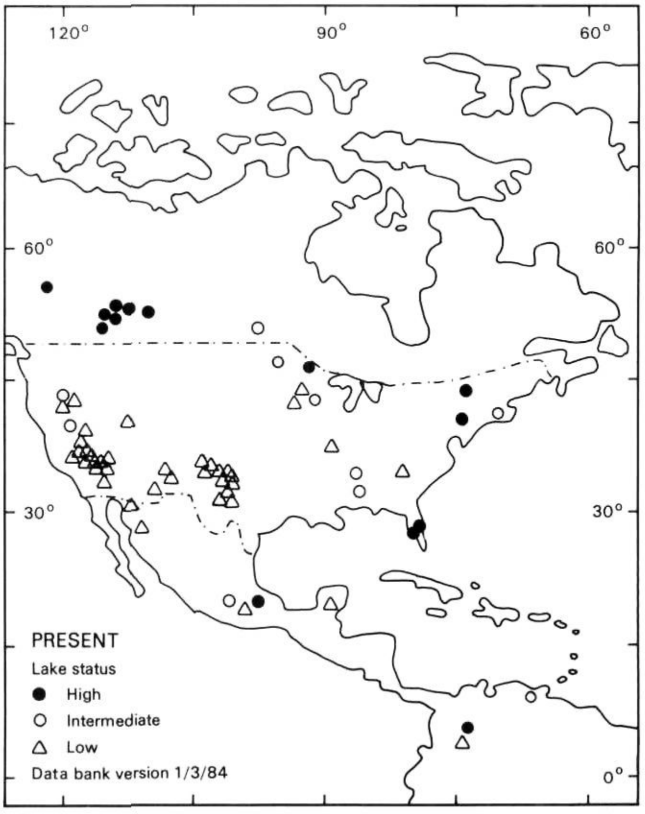

FIGURE 6. Lake status at the present day.
Niveaux lacustres actuels.

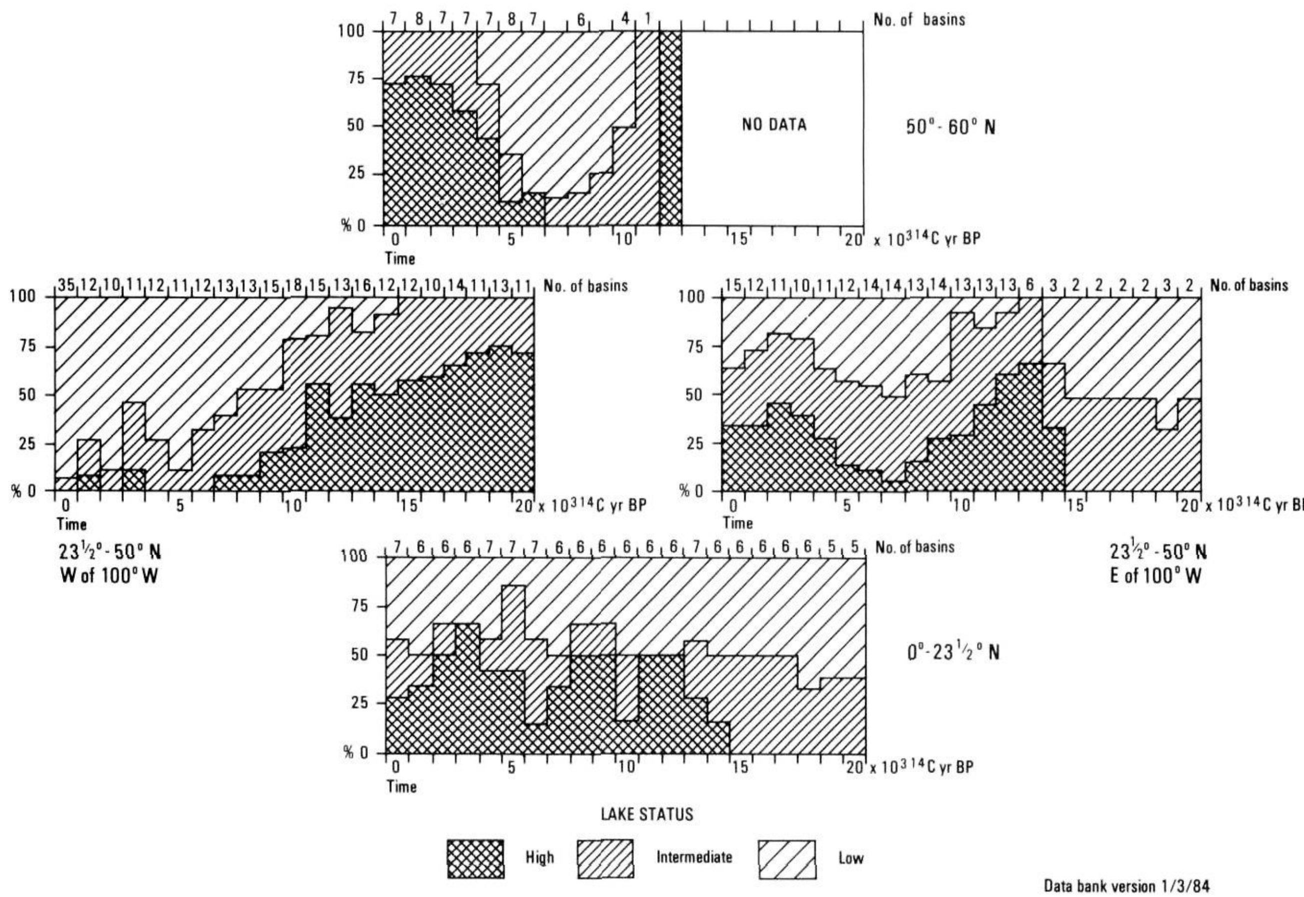

FIGURE 7. Histograms showing temporal variations in lake status for tropical, eastern midlatitude, western midlatitude and northern midlatitude subsets of the Oxford Lake-Level Data Bank.

Histogrammes illustrant les variations dans le temps des niveaux lacustres pour les sous-ensembles des latitudes tropicales et des moyennes latitudes est, ouest et nord déterminés à partir du Oxford Lake-Level Data Bank.

essentially drier conditions during the early Holocene. A return to moister conditions around 4,000 to 3,000 yr BP and again at 1,000 yr BP may be indicated by an increase in the number of lakes of intermediate status. The maximum of arid conditions in the western midlatitudes around 6,000 to 5,000 yr BP, occurs slightly after the period of marked low lake levels registered in the northern midlatitudes (Fig. 7a) during the early Holocene (10,000 – 7,000 yr BP). It is possible to interpret these temporal patterns as a reflection of the latitudinal migration of the frontal zone between the Arctic and Pacific air masses during the Holocene. Low lake levels after 10,000 yr BP may indicate the poleward migration of this belt, culminating around 6,000 yr BP when the Arctic Front appears to have reached its most northerly position. High lake levels in the northern midlatitudes from 4,000 yr BP to the present probably reflect the southward migration of this zone to its present position.

CONCLUSIONS

Lake-level data for North America reveal large fluctuations in water balance over the continent on the time scale of 10^3 yr. Lake-level behaviour exhibits a degree of spatial coherence, which enables regional patterns of lake status to be identified. There are distinctive differences, for example, between the temporal sequences of lake-level fluctuations in the eastern midlatitudes (23.5°-50°N, east of 100°W) and the western midlatitudes (23.5°-50°N, west of 100°W). The observed fluctuations in lake behaviour can be seen as a response to changes in the location and intensity of major features of the general circulation and the resultant changes in air mass trajectories over the continent.

The lake-level data provide some support for latitudinal migrations of major features of the general circulation, specifically the Arctic Front and the Equatorial Trough. Around 18,000 yr BP the mean westerly storm track appears to have been centred further south than present at around 35°-36°N (HARRISON and METCALFE, 1985). Subsequently, the Westerlies migrated northwards reaching their maximum poleward displacement, possibly north of 56°N, at around 6,000 yr BP. The present day air mass configuration was probably established about 3,000 yr BP. It is more difficult to reconstruct the latitudinal migration of the Equatorial Trough in detail. At 18,000 yr BP, it appears to have been further south than at present, while rising lake levels at 13,000 yr BP in the tropics probably reflect its migration northward. The limited and sometimes contradictory data for the American tropics, however, make it impossible to evaluate the degree to which displacements of the Equatorial Trough were in phase with, and of similar magnitude to, those in midlatitudes.

Superimposed on this pattern of latitudinal migrations, lake levels appear to have responded to changes in the strength and zonality of the atmospheric circulation. Such changes are particularly important through their influence on the behaviour of Tropical Maritime air masses from the Gulf of Mexico. Periods of markedly zonal circulation, for example between 18,000 and 14,000 yr BP, appear to be characterised by reduced penetration of moist tropical air into the continent, leading to low lake levels in both the circum-Gulf tropics and subtropics and along the eastern seaboard of the U.S.A. In contrast, the lake-level pattern at 9,000 yr BP suggests a much less zonal circulation pattern associated with increased monsoonality. Variations in the importance of tropical air masses as a moisture source over the continent,, however, may also reflect changes in the strength of the tropical circulation. These may be the result of variations in land and sea-surface temperature, and pressure gradients.

An understanding of the regional patterns of lake-level behaviour over North America requires an appreciation that the palaeo-atmospheric circulation was at least as inherently complex as that of the present day. Although a reasonable level of explanation of the observed patterns has been achieved by consideration of air mass trajectories, we feel that a more detailed analysis of the associated weather systems is necessary to understand fully the observed changes in the circulation.

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