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Stable isotopic composition of precipitation in the semi-arid north-central portion of the US Great Plains

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Stable isotopic composition of precipitation in the semi-arid north-central portion of the US Great Plains

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Abstract

Where data are available, hydrologic studies may use stable oxygen and hydrogen isotopes to investigate, groundwater/surface water interaction, groundwater recharge and advective/diffusive transport, to estimate groundwater ages or to unravel paleohydrology. Such studies require that the isotopic composition of precipitation be known, as precipitation is a major input to groundwater and surface water systems. Oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) data for precipitation are lacking for the semi-arid portion of the north-central Great Plains of the US, and thus there is need to establish additional meteoric water lines as isotope input functions across the region, as well as to develop better understanding of the isotopic climate linkages that control oxygen and hydrogen isotope ratios in precipitation. This study examines the $\delta^{18}O$ and δ^2H composition of precipitation for a representative site near North Platte, Nebraska in the semi-arid north-central Great Plains during the years 1989 through 1994. Oxygen-18 values range from −30.5 to +1.7‰. Deuterium values range from −228 to +11‰. Yearly arithmetic mean values for the North Platte station are −9.8 and −71‰, respectively. Weighted yearly means for $\delta^{18}O$ and δ^2H over the 6-year period were −9.6 and −69‰, respectively. North Platte values show a strong isotopic enrichment between winter and summer precipitation, and a strong $\delta^{18}O$–T correlation $r^2 = 0.845$ for mean monthly values of 0.54‰ per degree Celsius. The local meteoric water line for the site is $\delta^2H = 7.66\delta^{18}O + 4.96$. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Precipitation; Isotopes; Climate; NADP; Groundwater; Great Plains

1. Introduction

1.1. Purpose

It is well established that stable oxygen (^{18}O and ^{16}O) and hydrogen (^1H and ^2H) isotopes are useful in hydrologic studies (Clark and Fritz, 1997; Mazor, 1991; Fontes, 1980). Oxygen and hydrogen isotopes have been utilized in surface water studies to examine the dynamics of river mixing (Yang et al., 1996; Krouse and Mackay, 1971), irrigation canal leakage (Sibray et al., 1997; Harvey and Sibray, 2000) and in hydrograph separation (Buttle, 1994). Oxygen and hydrogen isotopes have also been used to investigate groundwater recharge (Mathieu and Bariac, 1996; Stimson et al., 1993), determine the effects of evaporation on groundwater systems (Hendry, 1988; Clark, 1987), estimate advection/diffusion rates in fine-grained terrestrial (Desaulniers and Cherry, 1989) and lake sediments (Harvey, 1996), examine groundwater and surface

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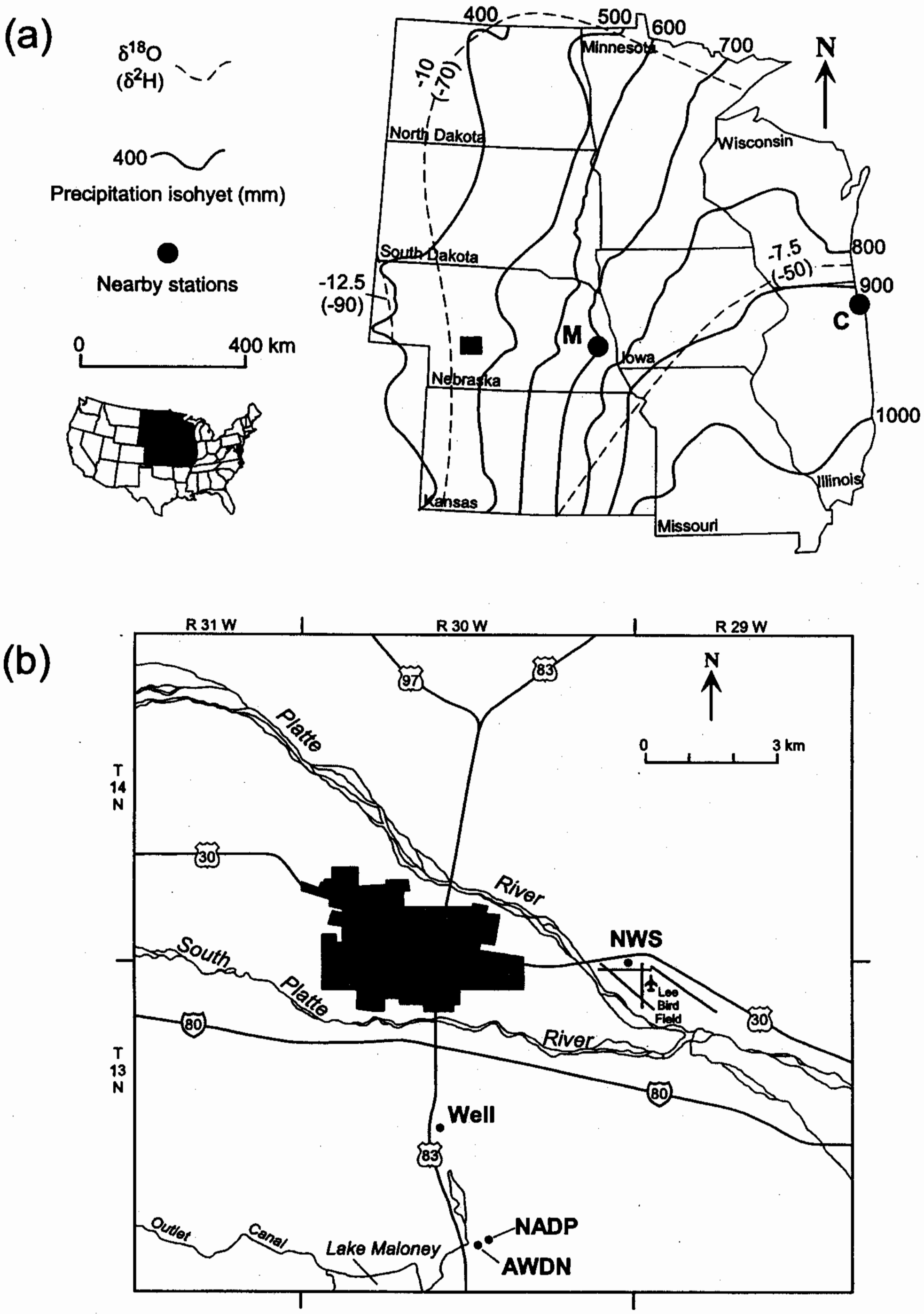

Fig. 1. (a) Locations of the IAEA station at Chicago (C) and the Mead (M), Nebraska station of Harvey (2000). Isohyets for precipitation were taken from Simpkins (1995). Predicted oxygen and deuterium (in parentheses) contours of Nebraska meteoric waters expressed as ‰ V-SMOW are from Sheppard et al. (1969). (b) Expansion of the shaded square area in (a) showing the location of precipitation and meteorological monitoring stations in North Platte, Nebraska.

water interaction (Krabbenhoft et al., 1990) and as a relative age dating tool to identify groundwaters that were recharged under colder climates during the Pleistocene (Siegel and Mandle, 1984; Matheney and Gerla, 1996).

However, these studies require that the oxygen and hydrogen isotope composition of precipitation be known, as precipitation is a major input to hydrologic systems. Since 1953, isotope ratios in precipitation have been measured at numerous monitoring stations worldwide by the International Atomic Energy Agency (IAEA), but few IAEA stations in the US recorded $\delta^{18}O$ and $\delta^{2}H$ data, and many IAEA stations that did are no longer in operation. Thus, modern analyses are lacking, and the distribution of data sets across the continental US is sparse.

Hydrologic studies in the semi-arid portions of the north-central Great Plains region must use data from the closest IAEA station in Chicago, Illinois (≈ 1275 km), or from a recent study by Harvey (2000) in eastern Nebraska (≈ 350 km), both of which are located in more humid climates. While data have been successfully extrapolated to nearby locations with a similar climate and precipitation pattern (Harvey et al., 1997; Harvey, 1996), the north-central region has climate and precipitation patterns greatly different from those present at Chicago and, although more similar, eastern Nebraska as well. Recent studies have attempted to define a long-term isotopic trend for the central US (see Rozanski et al., 1993); but these data sets are too widely spaced to be beneficial to the Great Plains, where the climate varies from semi-arid in the western portion to sub-humid in the eastern portion. Thus, there is a need for more localized data that are representative of the various climatic zones.

In the absence of long-term monitoring stations (as is the case in the north-central Great Plains region), Harvey (2000) and Welker (2000) suggest that the $\delta^{18}O$ and $\delta^{2}H$ values of precipitation can be determined using archive precipitation samples collected at monitoring stations managed by the National Atmospheric Deposition Program (NADP) as part of their weekly precipitation chemistry monitoring program (NADP, 1998; Bigelow, 1991). Harvey (2000) cautions however, that before using NADP data for hydrological investigations, two conditions must be met in order to insure that the data are truly representative of the monthly and yearly meteoric input functions at the given location: (1) the samples analyzed must be representative of the yearly distribution of precipitation at the station, such that each of the four seasons are represented, and that a majority of the samples represent that portion of the year with the largest and most frequent precipitation events; and (2) the precipitation samples must not have been impacted significantly by post-depositional modification effects (primarily evaporation), insuring that the isotope values obtained are representative of meteoric water at the monitoring site at the time of collection.

This study determined the $\delta^{18}O$ and $\delta^{2}H$ values of archived precipitation samples from the NADP monitoring station in North Platte, Nebraska, for years 1989–1994. North Platte lies near the center of the Great Plains, and is representative of the semi-arid portion of the region. Thus, while much of the discussion in this paper will focus on Nebraska, the data are also representative of the larger arid portions of the north-central Great Plains. The results of this study augment the more global work of Craig (1961), Gat (1980) and Gat and Gonfiantini (1981), the more regional work of Welker (2000, 1997) and Fritz et al. (1987) and the local work of Harvey (2000) and Simpkins (1995), but are unique in that they can be used in hydrologic and climate studies across the central Great Plains.

1.2. Study area

The northern Great Plains of the central US extend north from Kansas to the Canadian border, and east from the Rocky Mountains to the Missouri River. The plains are dominated by native grasslands, dryland and irrigated agriculture. This mid-continental region is typical of other such areas globally including central Eurasia and portions of Africa and South America that have similar vegetation type, climate and human development patterns (Walter, 1979).

The state of Nebraska is located in the center of the northern Great Plains, between latitude 40° to 43°N and longitude 96° to 104°W (Fig. 1). Nebraska's inner-continental location is 1368 km from the Gulf of Mexico and 1810 and 1979 km from the Pacific and Atlantic Oceans, respectively (Fig. 1). Nebraska's rolling prairie landscape is a complex mosaic of glaciated hills in the east, non-glaciated loess-covered

Table 1
Stable isotope data for precipitation in North Platte, Nebraska (years 1989–1994). Temperature data are taken from the AWDN station. Precipitation data are taken from the NADP station except where noted (*). The deuterium excess (*d*) is calculated as $d = \delta^2H - 8\delta^{18}O$. Analytical precision for $\delta^{18}O$ and δ^2H are 0.2 and 2.0‰, respectively

Week sampled	Ave. weekly temp. (°C)	Weekly precip. (mm)	$\delta^{18}O$ (‰ V-SMOW)	δ^2H (‰V-SMOW)	*d* (‰V-SMOW)
Year 1989					
05-16 to 05-23	16.4	31	−6.3	−42	8.3
07-25 to 08-01	24.2	18	−3.6	−29	−0.2[a]
08-01 to 08-08	21.5	19	−9.6	−76	1.1[a]
08-22 to 08-29	20.6	42	−3.8	−24	7
08-29 to 09-05	19.9	2	−5.4	−37	6
09-05 to 09-12	14.9	24*	−13.1	−95	9.7
Year 1990					
02-27 to 03-06	3.1	7	−12.4	−91	7.9
03-20 to 03-27	2.1	7	−10.7	−85	0.5[a]
04-03 to 04-10	6.5	4	−10.8	−83	3.8
04-10 to 04-17	5.4	3	−9.1	−86	−13.2[a]
05-01 to 05-08	10.8	10	−7.7	−67	−5.4[a]
05-08 to 05-15	9.5	26	−8.8	−60	10.3
05-22 to 05-29	16.4	6	−4.6	−33	3.6
06-12 to 06-19	20.6	14	−4.5	−35	1.5[a]
07-10 to 07-17	19.3	3	−9.5	−76	0.1[a]
07-17 to 07-24	20.1	48	−6.1	−45	3.9
08-07 to 08-14	20.9	27	−6.4	−46	5.2
10-16 to 10-23	8	8	−18.1	−139	6.2
Year 1991					
03-26 to 04-02	6.5	9*	−12.4	−100	−1.3[a]
04-30 to 05-07	8.3	47	−5.5	−36	7.6
07-09 to 07-16	22.7	6	−4.9	NA	NA
09-03 to 09-10	22.5	3	−6.8	−57	−3.0[a]
09-10 to 09-17	18.7	44	−8.1	−59	5.8
10-01 to 10-08	11.2	12	−14.3	−105	9.6
10-22 to 10-29	6.7	30*	−12.4	−92	7.1
11-05 to 11-12	1.6	5	−17.4	−140	−0.9[a]
11-12 to 11-19	4.4	16	−13.3	−98	8.4
12-10 to 12-17	2.3	9	−24.1	−190	2.5[a]
12-31 to 01-07-92	−0.5	23	−17.6	−134	7.4
Year 1992					
06-23 to 06-30	20.9	13	−8.4	−58	9.7
06-30 to 07-07	19.7	5	−7.5	−51	9.3
07-07 to 07-14	21.1	20	−8.3	−56	10.2
07-14 to 07-21	18.9	16	−12.9	−97	6.9
07-21 to 07-28	20.1	43	−8.3	−58	8.2
07-28 to 08-04	19.5	44	−7.5	−52	7.7
08-04 to 08-11	21.8	20	−7.9	−49	14.1
Year 1993					
02-09 to 02-16	−9.7	32	−11.5	−77	14.8
02-16 to 02-23	−13.7	8	−21.2	−158	12.1
03-16 to 03-23	2.1	5	−15.8	−126	−0.1[a]
03-23 to 03-30	9.7	3	−9.5	−75	1.2[a]
04-06 to 04-13	7.2	23	−11.3	−76	14.4
04-13 to 04-20	6.1	6	−16.5	−129	3.4
04-27 to 05-04	10.5	18	−10.8	−82	4.8

Table 1 (*continued*)

Week sampled	Ave. weekly temp. (°C)	Weekly precip. (mm)	δ^{18}O (‰ V-SMOW)	δ^{2}H (‰V-SMOW)	*d* (‰V-SMOW)
05-04 to 05-11	13.9	20	−8.3	−60	6
05-11 to 05-18	15.7	6	−4.2	−33	0.5[a]
05-18 to 05-25	15.2	24	−7.2	−51	6.2
05-25 to 06-01	17.2	31	−7.5	−57	3.4
06-01 to 06-08	14.2	33	−10.8	−68	18.4
06-08 to 06-15	19	16	−7.1	−49	7.7
06-15 to 06-22	20.2	91	−10.5	−71	13
06-22 to 06-29	20.1	31	−6.2	−41	8.6
06-29 to 07-06	21.4	6	−6.4	−55	−4.3[a]
07-06 to 07-13	20.9	28	−5.6	−39	5.4
07-13 to 07-20	20.9	10	−8.9	−53	18.2
07-20 to 07-27	21.1	46	−8.2	−58	7.5
07-27 to 08-03	21.1	14	−10.5	−78	6.4
08-03 to 08-10	20.6	21	−7.6	−57	3.8
08-10 to 08-17	23.1	3	−3.8	−36	−5.4[a]
08-17 to 08-24	22	50	−5.2	−28	14.4
08-24 to 08-31	18.5	9	−7	−44	11.8
08-31 to 09-07	18.8	14	−10.6	−69	15.7
09-07 to 09-14	15.7	4	−12.7	−87	14.7
09-14 to 09-21	14.8	5	−6.2	−39	10.7
10-12 to 10-19	10.7	6	−13.2	−99	6.7
10-19 to 10-26	8.8	4	−17.5	−127	12.8
12-14 to 12-21	−3.1	5	−16.5	−116	16.2
Year 1994					
01-11 to 01-18	−7.2	6	−19.4	−143	12.6
01-25 to 02-01	−8	12	−15.9	−115	12.3
02-15 to 02-22	0.6	6	−23.1	−165	20.2
04-05 to 04-12	5.6	17	−16.5	−124	7.9
04-19 to 04-26	13.9	9	−8.8	−56	14.5
04-26 to 05-03	4.9	20	−12.8	−86	16.6
05-03 to 05-10	13.5	7	−10.6	−73	11.9
05-17 to 05-24	20.2	9	−2.5	−9	11.2
05-24 to 05-31	18.9	5	−9.3	−60	14.4
05-31 to 06-07	21.2	29	−6.7	−37	16.8
06-07 to 06-14	22.6	27	−8.2	−51	14.5
06-14 to 06-21	23.1	10	−1.6	−9	3.8
06-21 to 06-28	21.6	7	−6	−33	14.8
06-28 to 07-05	22.6	8	−7	−38	18.3
07-05 to 07-12	21.5	50	−4.4	−21	14
07-12 to 07-19	20.7	53	−8.8	−50	20.3
07-19 to 07-26	20.5	11	−6.5	−45	7.4
08-02 to 08-09	22.6	19	−6.1	−28	21
08-16 to 08-23	21.8	2	−0.6	−9	−4.3[a]
08-23 to 08-30	22.8	4	1.7	11	−2.5[a]
08-30 to 09-06	18.4	6	−4.5	−27	8.8
09-20 to 09-27	12.7	9	−12.4	−92	6.7
10-04 to 10-11	12.4	29	−9.7	−65	12.4
10-11 to 10-18	12.2	34	−12.2	−77	20.3
11-01 to 11-08	4.8	6	−15.1	−101	20.4
11-15 to 11-22	1.3	10	−11	−65	23
12-06 to 12-13	−7.3	8	−30.5	−228	16.5

[a] Samples have been impacted by evaporated as their *d*-excess values are <3‰.

dissected plains and extensive sand dune fields (covering nearly 1/4 of the state, the Sand Hills, an area of grass-stabilized dunes is the largest sand dune area in the Western Hemisphere) across its central region, and flat lying table lands cut by deeply eroded river valleys in the west.

The data presented in this paper were collected from three different meteorological stations at North Platte, Nebraska. Stable isotope ratios were determined on NADP precipitation samples collected at the West Central Research and Extension Center (WCREC) in North Platte, Nebraska (Fig. 1). The reported precipitation values (except where noted in Table 1) were collected at this site. For the three dates when the NADP station failed to report a precipitation value, the reported value comes from the nearby Automated Weather Data Network (AWDN) station. The NADP station is located in west-central Nebraska at latitude 41 03 33 N, longitude 100 44 47 W, at an elevation of 919 m above sea level. The NADP site is operated by the University of Nebraska Conservation and Survey Division.

Climate data were compiled from two stations at North Platte (Fig. 1). The primary station used in this study is an AWDN station operated by the High Plains Climate Center that is located 358 m from the NADP station on the western boundary of the WCREC site at latitude 41 05 N, longitude 100 46 W, and an elevation of 922 m above sea level. The second station is a National Weather Service (NWS) meteorological site, located at Lee Bird Field, approximately 9 km from the NADP site at latitude 41 08 N, longitude 100 42 W, and an elevation of 847 m above sea level (Fig. 1).

1.3. Climate and precipitation sources

The climate varies across the northern Great Plains ranging from moist sub-humid climate in the east to dry, semi-arid climate in the west. Nebraska, located

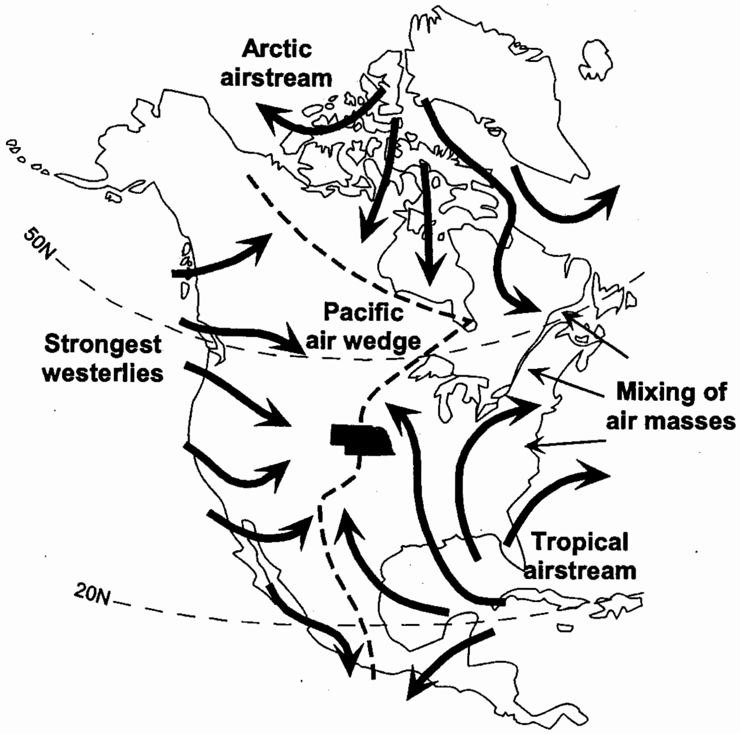

Fig. 2. Map of North America showing location of competing airstreams and their relation to Nebraska's two major moisture sources (Pacific Ocean and Gulf of Mexico). Shaded area shows the location of Nebraska in the US (modified from Bryson and Hare, 1974).

at the center of the region, also experiences this east to west variation. The state experiences a wide range of annual temperatures as a result of its continental position, and relatively clear skies throughout the year (Lawson et al., 1977). Average yearly temperatures across the state range from 6.9°C in the northwestern portion of the panhandle to 11.0°C in the southeast (Owenby and Ezell, 1990). Nebraska also lies in a zone of the northern plains where the precipitation increases rapidly from west to east. Values across the state range annually from 370 mm in the western panhandle near the Wyoming border to 922 mm in the southeast corner, along the Missouri River (Lawson et al., 1977).

Northern Great Plains climate is largely influenced by four factors: altitude, proximity to the Rocky Mountains that block the eastward movement of Pacific Ocean moisture, distance and direction from the Gulf of Mexico — the main moisture source for the region's precipitation and distance from the equator (Colville and Meyers, 1965). The climatology of Nebraska and the northern Great Plains, reflects the competing influences of the Arctic airstream, the Tropical airstream and the Pacific air wedge (Fig. 2). Strong seasonal contrasts are produced by the alternation of moist, warm air from the Gulf of Mexico and Pacific Ocean, cold, dry Arctic air, and mild, dry westerly winds (Court, 1974; Bryson and Hare, 1974; Lawson et al., 1977). In summer, tropical air may be displaced by dry, cooler air from Canada. In winter, Arctic air dominates the northern Great Plains weather, but with the lack of a land barrier to the south, unseasonably warm southern air frequently flows into the region. Lawson et al. (1977) state that no other continental area experiences such severe contrasts in air mass conditions.

These relationships are important because the various airstreams entrain and deliver moisture from different sources, which, in addition to temperature and altitude cause variations in the stable isotopic signature of precipitation. Nebraska's precipitation comes primarily from two moisture sources, the Gulf of Mexico and the Pacific Ocean or some mixture of both, with nearly 80% of the moisture having a Gulf source (Allen Dutcher, Nebraska State Climatologist, High Plains Climate Center, personal communication).

2. Methodology

2.1. Precipitation collection

Weekly precipitation samples were collected every Tuesday at the North Platte station by the NADP/NTN network with the aid of site operators for years 1989–1994, using a modified Aerochem Metrics wet/dry precipitation collector (Bigelow, 1991). The precipitation falls into a collector that is covered by a mechanical lid assembly having a semi-gas tight seal on the bucket to prevent evaporation. During precipitation events, a 75 Ω sensor is activated and the lid opens. The lid closes after the precipitation event. Precipitation amounts are measured at the station using a Belfort Model 5-780 weighing bucket recording gage.

After collection, the weekly composited precipitation sample was shipped to the Illinois State Water Survey (ISWS) in the sealed 13.25 l plastic bucket taken from the collector. If sufficient water was present in the collector, pH and conductivity were measured on the sample by the field technician at the collection site. At the ISWS lab, the sample was transferred from the collector to 1000 ml plastic bottles for processing, and the amount of sample was recorded. Samples were then filtered and split into two 60 ml subsamples. The subsamples were placed in plastic bottles. Cation and anion analyses were conducted on one subsample (Lynch et al., 1995) at the ISWS Central Analytical Laboratory. The second subsample was placed in storage (archived) on site, in a cold room at 4°C.

2.2. Archive sample QA/QC

Several unpublished internal studies (available on the NADP web site at http://nadp.sws.uiuc.edu/) have been conducted by the NADP to determine if samples have evaporated during collection and/or storage. Collector efficiency studies compared precipitation amounts recorded by the Belfort collectors to amounts captured in the Aerochem Metrics collector, to evaluate the potential for evaporation during collection. NADP also periodically removes random archive samples from storage and performs a repeat chemical analysis to determine if ion concentrations match those of the initial analyses done on the original sample at the time of collection. These comparative tests indicate that the majority of precipitation samples collected have not undergone evaporation during collection and/or storage, and in the small number of cases where evaporation was detected, the total amount of evaporation did not exceed 1% of the total volume of sample collected (Van Bowersox, NADP, personal communication).

Another way to evaluate the integrity of the archive samples is to examine their *d*-excess values (defined by Dansgaard (1964) as $d = \delta^2\mathrm{H} - 8\delta^{18}\mathrm{O}$) as an indicator of potential sample evaporation. The *d*-excess in precipitation is defined by the air–sea interaction processes over the ocean surface as described by Craig and Gordan (1965), Merlivat and Jouzel (1979) and Gat (1996). These processes fix the *d*-excess value, which remains unchanged as air masses move across the continents and lose moisture by rainout. If, however, the air masses are impacted by secondary processes that return moisture to the air, such as evaporation from an open surface water body (i.e. recycling of water) (Gat et al., 1994; Machavaram and Krishnamurthy, 1995), the inherited *d*-excess value can be altered as the air mass moves inland.

The *d*-excess value may also be impacted by evaporation of the precipitation, either as it falls through the air (Gat, 1996) or as it sits in the rain collector. It can be shown using the moisture exchange model of Merlivat and Jouzel (1979) that for reasonable ranges of temperature (20–30°C) and relative humidity (70–95%) over the ocean, the initial *d*-excess value of transported moisture should be between 3 and 15‰. Thus, NADP archive samples (or any samples) with *d*-excess values less than 3‰ should be used with caution, unless the source of their evaporative enrichment can be determined with certainty, as they may have been impacted by evaporation in the collector.

Examining this data set (Table 1) shows that 18 of the 93 samples were likely impacted by evaporation. These samples were typically collected during weeks when very small precipitation amounts were recorded (Table 1) in the collector. Several samples were collected in winter or early spring and may have fallen in the form of snow. Most, however, were collected in summer or early fall, and it may be that the warmer air temperatures, coupled with the low collector volumes resulted in partial evaporation of the sample while it was sitting in the collector. Evaporation observed in the summer *d*-excess values could also have occurred beneath the cloud base as the precipitation fell through the air column, and not on the ground in the collector. The hot, dry conditions present in North Platte during the summer months could easily give rise to this effect.

The reader is cautioned that if it can be determined that the depleted *d*-excess samples have been evaporated while sitting in the collector, then those individual samples are not representative, and should not be included in the final data analysis. However, if it is determined that the samples have not been compromised, but rather that their low *d*-excess values record a natural meteorological occurrence, they should be included in the data analysis. Since we could not determine with certainty which of these two phenomena produced the evaporation that resulted in the low *d*-excess values, we have opted to include all of the samples collected in this study in our analyses.

2.3. Stable isotopic analysis

Archived precipitation samples from the North Platte NADP/NTN site for the years 1989–1994 were analyzed in 1998 and 1999 for ^{18}O and ^{2}H composition. Oxygen-18 determinations were performed at the Colorado State University facility for Mass Spectrometry using a dual inlet, stable isotope ratio mass spectrometer (VG-Optima) calibrated with Vienna Standard Mean Ocean Water (V-SMOW), Greenland Ice Sheet Precipitation (GISP) and Standard Light Antarctic Precipitation (SLAP) obtained from IAEA, Vienna (Gonfiantini, 1978; Gat and Gonfiantini, 1981). Two working standards were used, one depleted in ^{18}O (snowmelt water from Cammron Pass, Colorado) and the second being enriched tapwater. The CO_2-headspace equilibrium technique was used to measure the ^{18}O abundance in the samples (Yurtsever and Gat, 1981). Deuterium analyses were performed at the University of Waterloo's Environmental Isotope Laboratory. Deuterium determinations were made on a Micromass 602C mass spectrometer following the zinc reduction preparation method of Coleman et al. (1982).

Oxygen and hydrogen results are reported as parts per thousand (‰) with respect to V-SMOW using the

(δ) notation:

$$\delta_{\mathrm{sample}} = \frac{(R_{\mathrm{sample}} - R_{\mathrm{standard}})}{(R_{\mathrm{standard}})} \times 1000$$

where R_{sample} is the ratio of $^{18}\mathrm{O}/^{16}\mathrm{O}$ or $^{2}\mathrm{H}/^{1}\mathrm{H}$ in the sample and R_{standard} is the ratio of the international standard. The analytical precision for $\delta^{18}\mathrm{O}$ and $\delta^{2}\mathrm{H}$ are 0.2 and 2.0‰, respectively.

Yearly weighted mean values of $\delta^{18}\mathrm{O}$ and $\delta^{2}\mathrm{H}$ were calculated by the equation

$$\overline{\delta_{\mathrm{w}}} = \left(\frac{\sum_{i=1}^{n} P_i \delta_i}{\sum_{i=1}^{n} P_i} \right).$$

where δ_i is the $\delta^{18}\mathrm{O}$ and $\delta^{2}\mathrm{H}$ (‰) weekly composite sample, P_i is the recorded total weekly precipitation of the ith week and n is the number of weekly samples (93). Monthly weighted means were calculated in a similar fashion where δ_i is the monthly average $\delta^{18}\mathrm{O}$ and $\delta^{2}\mathrm{H}$ (‰) value over the 6-year period (1989–1994), P_i is the average monthly precipitation of the ith month over the 6-year period (1989–1994) and n is the number of months (12)

2.4. Meteorological data

AWDN meteorological data and NWS data for 1989–1994 were provided by the High Plains Climate Center at the University of Nebraska-Lincoln. The AWDN station monitors hourly and daily temperature, precipitation, relative humidity, solar radiation, soil temperature, wind speed and wind direction. AWDN daily temperature is recorded using a Vaisalla HMP 45 temperature/relative humidity sensor. Daily precipitation is collected using a Sierra tipping bucket (1 mm/tip). The precipitation gauge does not contain a heating element to convert frozen precipitation to liquid equivalent precipitation. The NWS meteorological site is equipped with Automated Surface Observation System instrumentation. NWS data were used for comparison with the AWDN data and to fill existing gaps in the AWDN data set caused by instrument failure.

3. Results and discussion

3.1. Meteorology of North Platte, Nebraska

Monthly precipitation and temperature data for the North Platte station are shown in Fig. 3 for 1989–1994. The 1961–1990, "30-year normal" values for precipitation and temperature (Owenby and Ezell, 1990) are also shown. The normal yearly temperature is 8.9°C and normal precipitation is 490 mm for a given year.

With the exception of February, when considerable variation occurred, temperatures were near monthly normals having yearly averages of 8.8, 9.9, 10.4, 9.4, 7.9 and 9.8°C, respectively. The slight warming trend observed from 1990 to 1991 is somewhat unrepresentative as it results from elevated temperatures in the months of January and February in 1990, and higher than normal temperatures in February and December in 1991, and not a rise in the overall monthly temperatures of the region (Fig. 3). As monthly deviations from their respective norms are small, and since the yearly average values are close to normal, isotopic values of precipitation collected from 1989 through 1994 should be representative of normal precipitation at North Platte with respect to temperature effects (see discussion below).

Monthly and yearly precipitation values were quite variable over the 6-year study period and were below normal. The total yearly precipitation for 1989–1994 were 318, 337, 438, 490, 621 and 454 mm, respectively. The driest years, 1989 and 1990, received over one-third less precipitation than normal.

The reasons for these anomalous weather patterns can be found by examining Daily Weather Maps for the 6-year period. The year 1989 was Nebraska's last significant "La Niña" event (the opposite of "El Niño"), and was considered a drought year. Generally, La Niña events amplify the jet stream's mean position and produce more ridging across the central US than is experienced during a normal year. During 1989, high pressure, present over the western US, and low pressure over Hudson Bay in northern Canada, forced cold, dry polar air down into the Great Plains. This resulted in a decrease in precipitation, since Gulf moisture could not be carried north. In 1990, drought conditions began to subside somewhat, but high pressure over the western and south-central US again

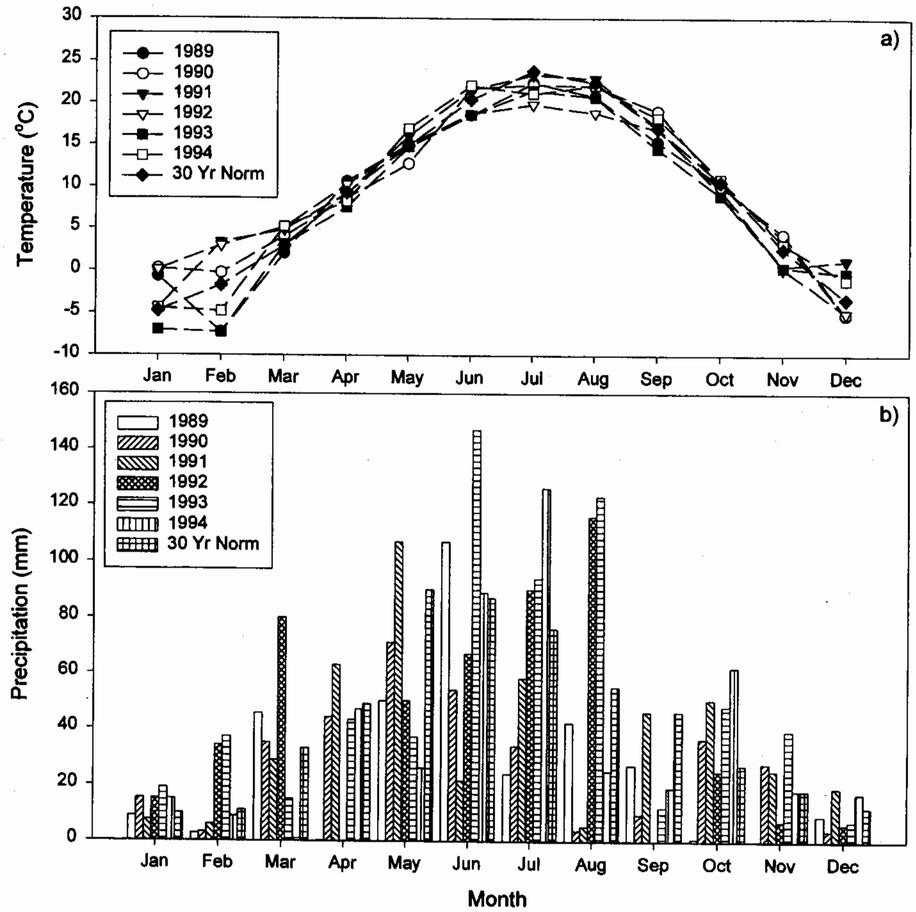

Fig. 3. Precipitation (bars) and temperature (symbols) record for North Platte, Nebraska (1989–1994). Also shown are the 1961–1990 normal values taken from Owenby and Ezell (1990).

prevented Gulf moisture from penetrating north for much of the summer and fall months. In 1991, low pressure off the west coast kept the jet stream to the north in Canada, resulting in mean zonal flow, preventing cold arctic air from penetrating down into the Great Plains. The result was warmer temperatures in January, February and December and increased precipitation across the region including two major snow storms in April and October.

The Mount Pinatubo volcano erupted in the Philippines in June of 1991 blasting millions of tons of volcanic debris into the atmosphere creating a massive sun-blocking aerosol cloud (Kerr, 1993). The eruption continued into 1992 and caused significant hemispheric cooling which resulted in lower than normal temperatures, and with these cooler temperatures, increased precipitation (Fig. 3). Residual effects of the eruption were also seen in the climate patterns of early 1993 (Allen Dutcher, personal communication).

In 1993, flooding decimated the upper Mississippi River Basin. The same climatic patterns that delivered unprecedented heavy rainfall to the basin also caused above-normal levels of summer rainfall in western Nebraska. During June and July, the mean position of the polar jet stream extended from the northern Rocky Mountains to the upper Mississippi River Basin and a strong pressure height gradient occurred in the region (Kunkel et al., 1994). In June, below-normal heights occurred over the Rockies and eastern

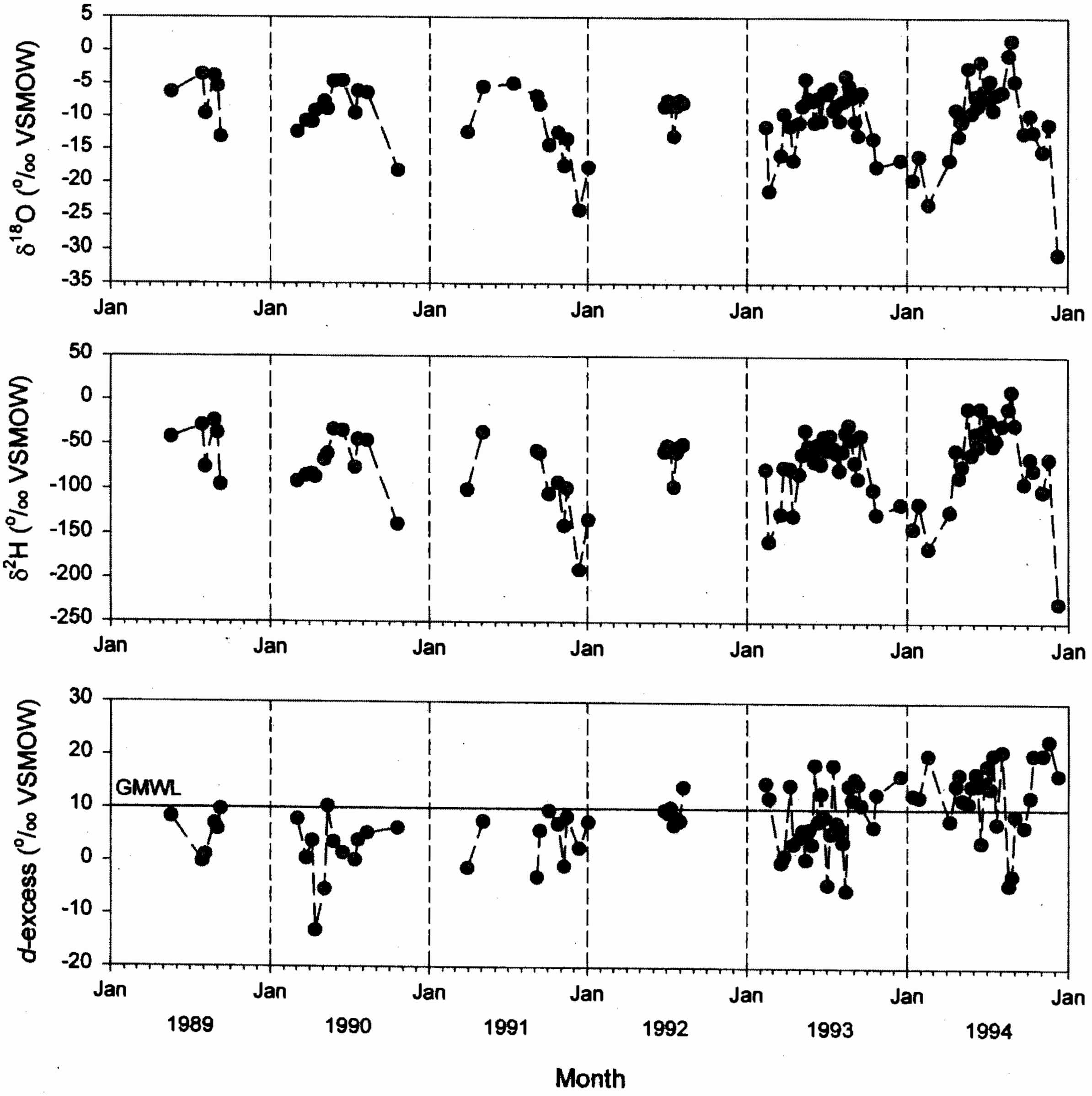

Fig. 4. Six-year weekly time series plot of $\delta^{18}O$, $\delta^{2}H$ and deuterium excess values *d* for North Platte, Nebraska.

Pacific, and off the coast of Newfoundland, while above-normal heights were present over the eastern United States. The July pattern was similar except that an additional area of above-normal heights was seen over the eastern Pacific. This pattern was accompanied by a frontal boundary located over the basin on at least 40 days in June and July. This anomalous pattern reoccurred briefly over the western US and the eastern Pacific in August (Kunkel et al., 1994). Frequent low-pressure waves developed in this region of horizontal surface temperature gradients and enhanced upper-air winds, bringing heavy rainfall to the area, including North Platte which recorded

Table 2
Coefficients for meteoric water lines and arithmetic mean values from stations in the northern US Great Plains region. The water line equation is $\delta^2\text{H} = A\delta^{18}\text{O} + B$

Station	Slope (A)	Intercept (B)	Weighted mean δ^{18}O (‰)	Arithmetic mean δ^{18}O (‰)	Weighted mean δ^2H (‰)	Arithmetic mean δ^2H (‰)
Chicago, IL[a]	6.98	0.08	−6.0	−6.9	−43	−50
Mead, NE[b]	7.40	7.32	−7.4	−8.1	−48	−53
North Platte, NE[c]	7.66	4.96	−9.6	−9.8	−69	−71

[a] IAEA, (1992).
[b] Harvey, (2000).
[c] This study.

approximately twice the average monthly precipitation during June and August (Fig. 3).

Statewide, 1994 was, on average, a normal year with respect to precipitation. However, several areas, including the area surrounding the North Platte station experienced drought-like conditions during several months resulting in below-normal yearly precipitation values. This likely resulted from a weaker, nocturnal low-level jet stream across the southern High Plains which produced fewer mesoscale convective complexes across eastern Nebraska, and thus less moisture (Allen Dutcher, personal communication). During 1994, a greater percentage of the rainfall activity across eastern Nebraska was from air mass thunderstorms. Under these conditions, it is not uncommon for some locations to receive above-normal precipitation, while other areas experience drier than normal conditions.

Despite the short-term variations in precipitation created by these weather patterns, averaging the isotopic content of precipitation over the 6-year period should provide values that are representative of the long-term average values (i.e. the local meteoric water line) for North Platte and central Nebraska. The poor recovery of winter precipitation also has little effect, due to lower precipitation rates across the region during the winter months.

3.2. Stable isotopic composition of precipitation

Values for weekly precipitation and corresponding δ^{18}O and δ^2H values and deuterium excess-*d* are presented in Table 1 and plotted in Fig. 4. Values for δ^{18}O ranged from +1.7 to −30.5‰, and δ^2H values ranged from +11 to −228‰. These ranges are typical of mid-continental stations globally (Gat and Gonfiantini, 1981). Arithmetic mean values for the North Platte station were −9.8 and −71‰, respectively. The standard deviations around the arithmetic mean are 5.3 and 41‰, respectively. Weighted yearly mean values over the 6-year monitoring period were −9.6‰ for δ^{18}O and −69‰ for δ^2H. These values were consistent with those interpolated for Nebraska (Fig. 1) from a regional scale map of meteoric waters across the US constructed by Sheppard et al. (1969).

Arithmetic and weighted mean values for nearby stations are presented in Table 2. The annual means

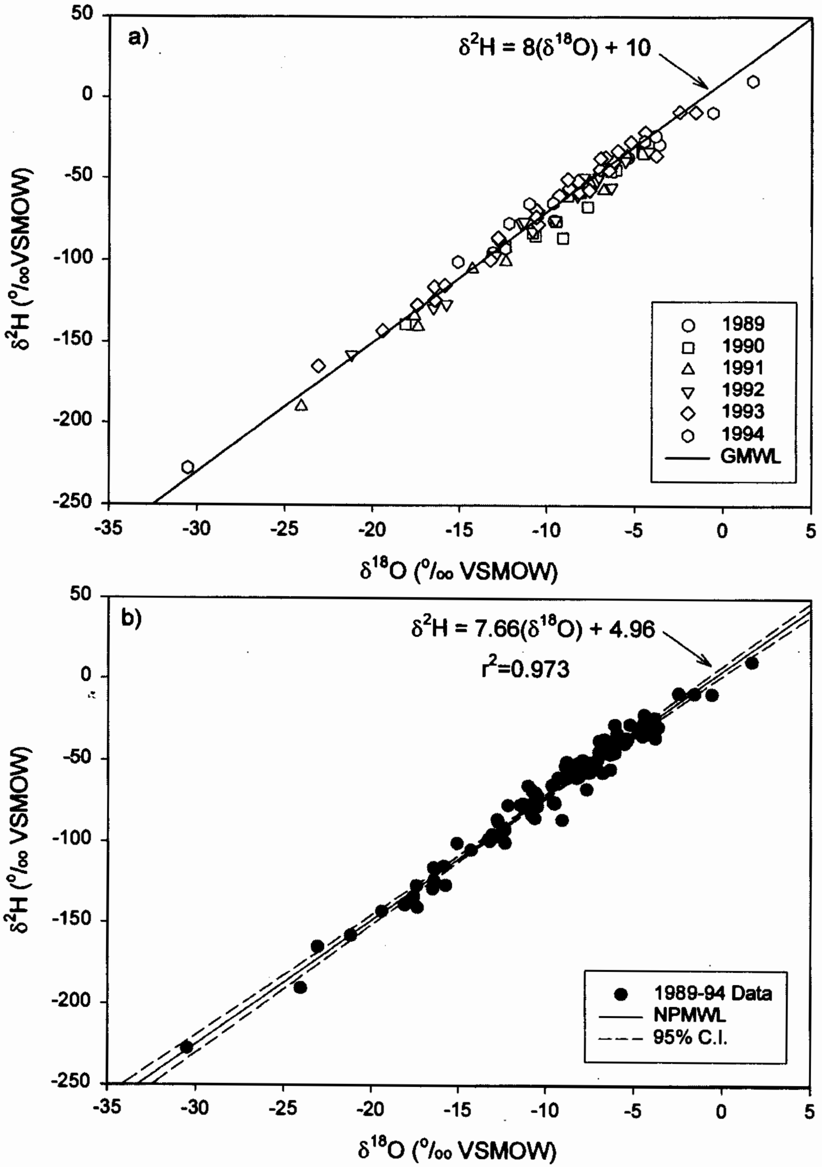

Fig. 5. (a) Oxygen-18 vs deuterium plot showing North Platte Meteoric Water Line (NPMWL) for the 1989–1994 precipitation samples plotted by collection year. The Global Meteoric Water Line (GMWL) of Craig (1961) is also plotted. (b) Linear regression analysis of the total 1989–1994 data set.

were more depleted than values reported for eastern Nebraska collected from 1992 through 1994 (Harvey, 2000), and even more depleted in comparison to the $\delta^{18}O$ and $\delta^{2}H$ mean values from Chicago precipitation collected from 1962 to 1979 (IAEA, 1992). While a comparison between the three stations documents the isotopic variations across the north-central Great Plains region, without more detailed sampling for determining the source of moisture for a given precipitation event, it is not possible to determine whether the differences between the three stations reflects different meteorological

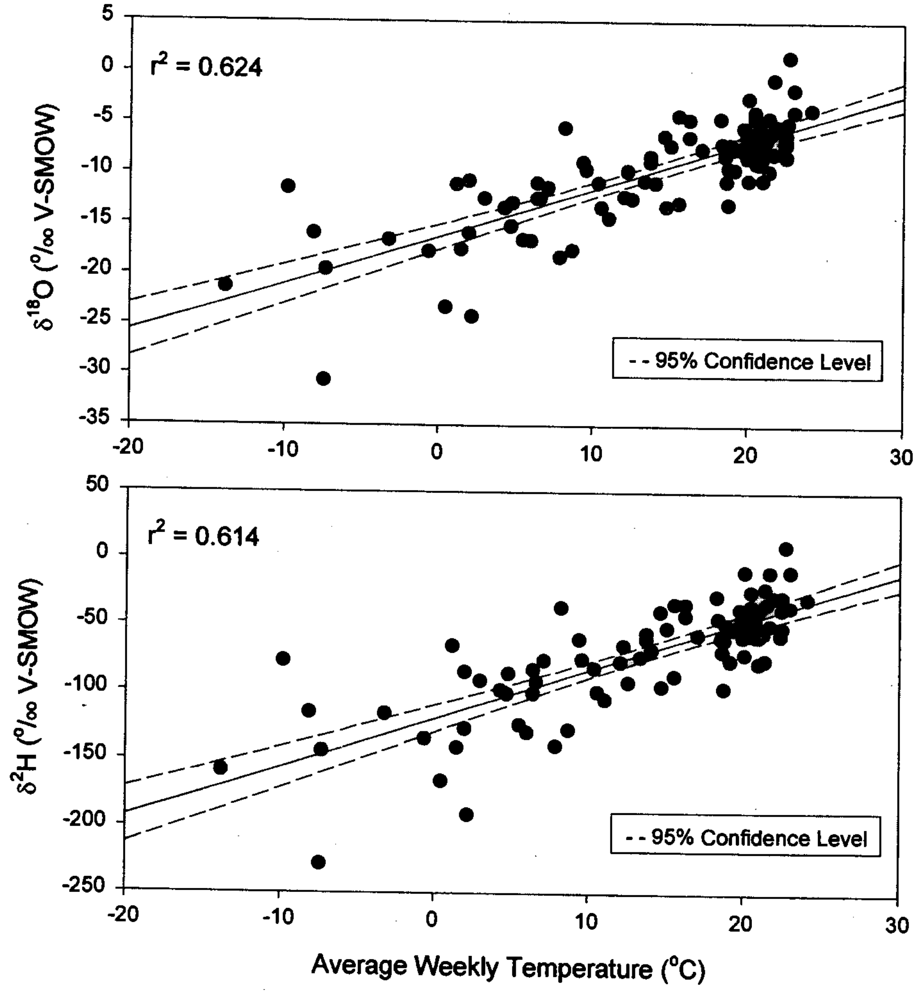

Fig. 6. Temperature effects on weekly $\delta^{18}O$ and $\delta^{2}H$ values for years 1989–1994.

regimes, or whether they are due to local processes that modify the isotopic composition of local precipitation (the Chicago station for example, is located near Lake Michigan, where precipitation may have been affected by evaporation of nearby lake water; Machavaram and Krishnamurthy, 1995).

The North Platte data can be validated using a linear plot of $\delta^{18}O$ vs $\delta^{2}H$ values (Fig. 5). The relationship between $\delta^{18}O$ and $\delta^{2}H$ in precipitation is controlled primarily by condensation processes related to Rayleigh distillation. Precipitation $\delta^{18}O$ and $\delta^{2}H$ values globally generally plot along the Global Meteoric Water Line (GMWL), defined by Craig (1961) as

$$\delta^{2}H = 8\delta^{18}O + 10$$

A local North Platte Meteoric Water Line (NPMWL) for the north-central Great Plains was constructed from the North Platte precipitation data by using the linear least-squares regression technique (Lapin, 1980). The equation of the line was

$$\delta^{2}H = 7.66\delta^{18}O + 4.96 \qquad (r^2 = 0.97)$$

The North Platte meteoric water line plots slightly below the global water line (i.e. lower *d*-excess). Such deviations result from differences in climatic factors,

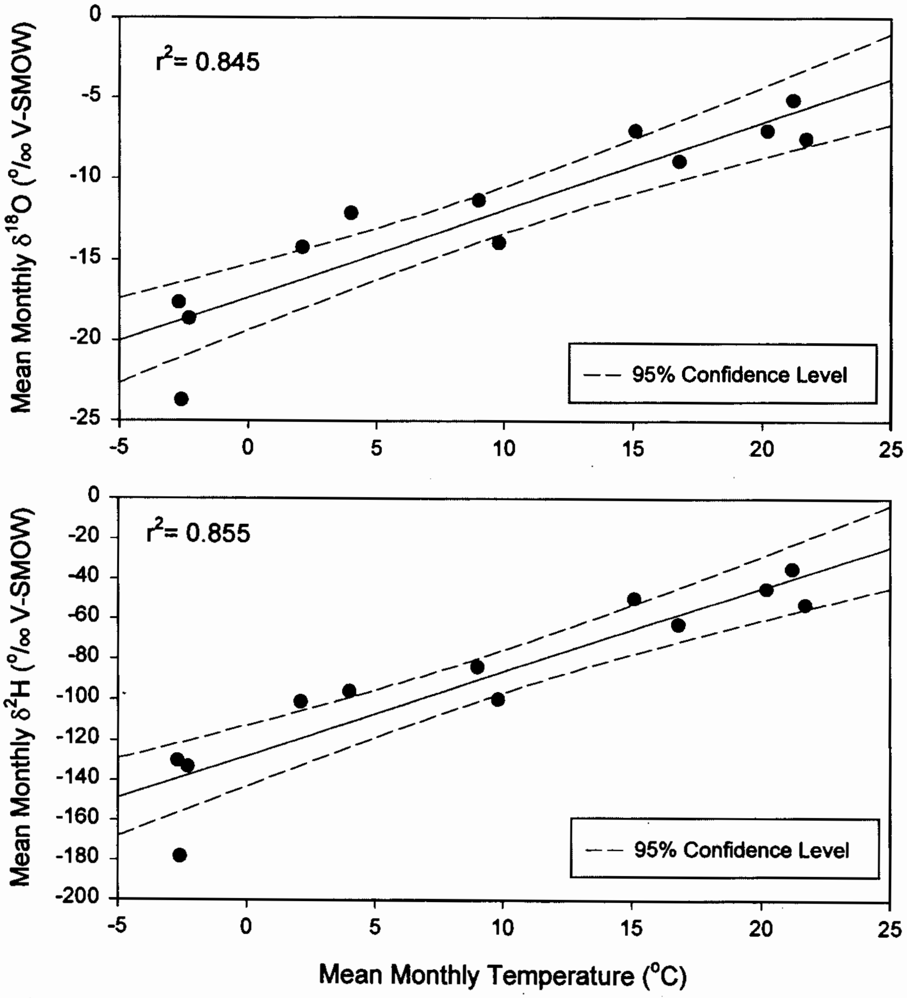

Fig. 7. Temperature effects on monthly $\delta^{18}O$ and $\delta^{2}H$ values for years 1989–1994. Isotope and temperature values are plotted as arithmetic mean monthly values.

such as air temperature, secondary evaporation, seasonality of precipitation and moisture source (Clark and Fritz, 1997), and occur in precipitation globally (Simpkins, 1995; Rozanski et al., 1993; Fritz et al., 1987).

Studies suggest that the isotopic composition of precipitation may be more related to air mass trajectories than to temperature relationships alone (Fritz et al., 1987; Lawrence and White, 1991; Rozanski et al., 1993). However, temperature appears to be the controlling factor in central Nebraska. A reasonably strong correlation can be seen between weekly $\delta^{18}O$ and $\delta^{2}H$ values and weekly temperature; however, there is scatter within the data (Fig. 6). This scatter likely results from errors in assigning a weekly average temperature to the weekly precipitation samples. If the exact temperature at the time of the storm event could be determined, the $\delta - T$ correlation might be stronger. However, the time and actual temperature of a specific storm event could not be determined with certainty because the precipitation sample represents a composite of all of the storm events in a given week. The regression equations relating the weekly North Platte oxygen and deuterium

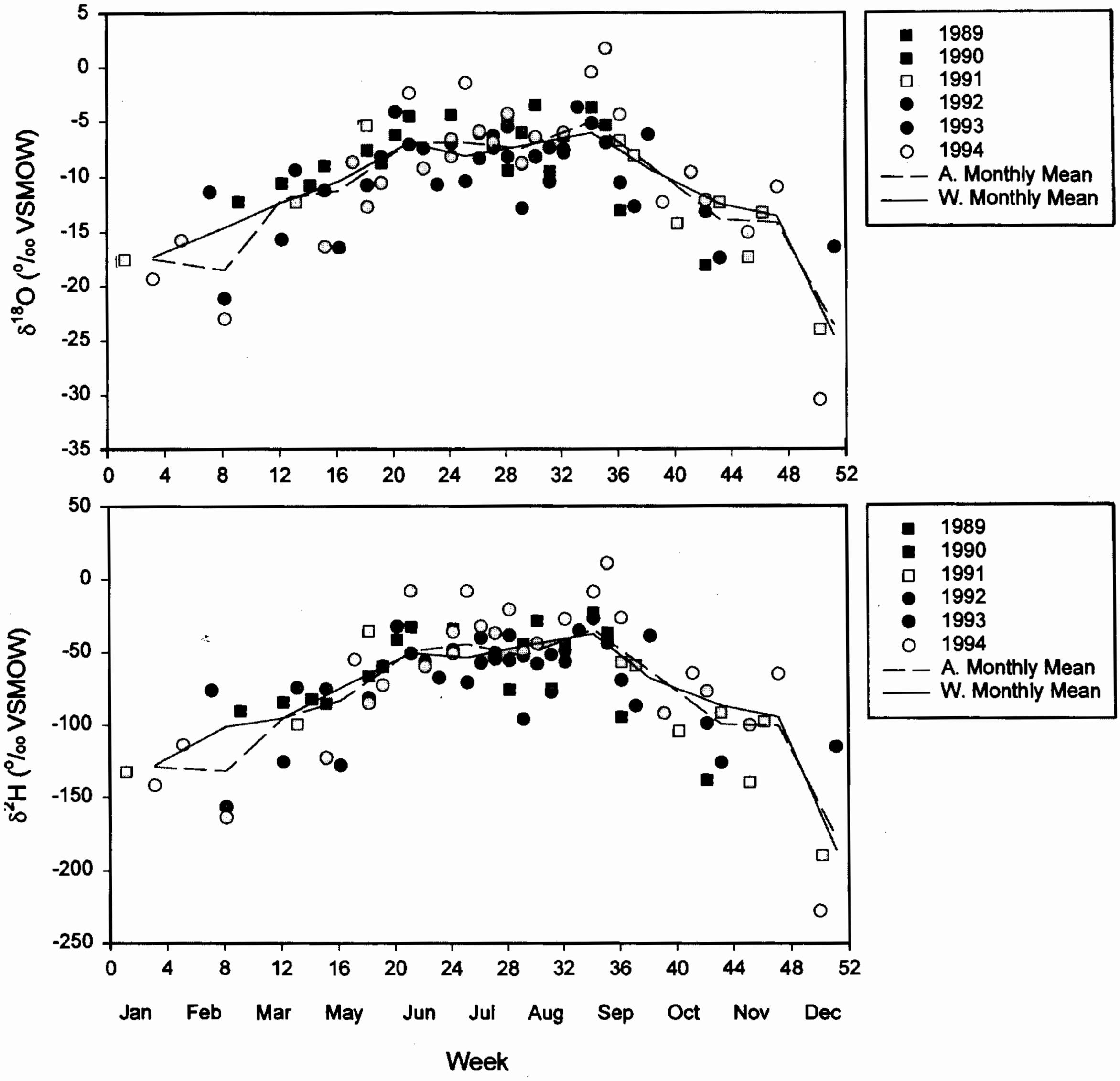

Fig. 8. Weekly $\delta^{18}O$ and δ^2H values for years 1989–1994 for North Platte showing seasonal changes in precipitation. Also plotted are the monthly average curves for each isotope.

values to weekly temperature are

$$\delta^{18}O = 0.467T\ (°C) - 16.3 \qquad (r^2 = 0.62)$$

$$\delta^2H = 3.60T\ (°C) - 120 \qquad (r^2 = 0.61)$$

A much stronger correlation exists between monthly mean $\delta^{18}O$ and δ^2H values and monthly mean temperatures (Fig. 7). The regression equations for the North Platte data are

$$\delta^{18}O_{\text{monthly}} = 0.541T\ (°C) - 17.3 \qquad (r^2 = 0.84)$$

$$\delta^2H_{\text{monthly}} = 4.15T\ (°C) - 128 \qquad (r^2 = 0.85)$$

A plot of weekly $\delta^{18}O$ and δ^2H values (Fig. 8) for

1989–1994 shows the seasonal effect on precipitation resulting from increasing precipitation events and amounts and higher temperatures over the summer months (April–September). Winter precipitation (October–March) has a more depleted signature while summer precipitation is enriched relative to the yearly δ^{18}O and δ^{2}H averages (−9.8 and −71‰, respectively).

The stable isotope values of individual storm events could not be evaluated since the precipitation samples were collected over a 1-week monitoring period and may have contained precipitation from multiple events having different moisture sources. As a result, the isotopic signatures of the two primary precipitation sources (Gulf and Pacific Ocean) could not be identified. Nor was it possible to determine if samples having deviations from the $\delta - T$ averages (Figs. 6 and 7) resulted from anomalous δ or T values.

The deuterium excess values for the North Platte station for 1989–1994 ranged from a high of 23‰ to a low of −13.2‰ (Table 1) with an arithmetic mean of 8.3‰ and a weighted mean of 9.5‰ (if the 18 *d*-excess values <3‰ are omitted, the means become 10.8 and 9.7‰, respectively). With the exception of the negative values (for the reasons discussed previously) these values were generally within the range of the *d*-excess values reported for other sites in North America (Harvey, 2000; Simpkins, 1995; Rozanski et al., 1993; Gat et al., 1994), and elsewhere globally (IAEA, 1992; Dansgaard, 1964; Rozanski et al., 1993). All *d*-excess values in this study were within the ranges reported at IAEA stations globally (IAEA/WMO, 1998; IAEA, 1992). In general, the North Platte *d*-excess values were near the global average of 10‰. The North Platte yearly means are also consistent with the arithmetic and weighted means reported for the IAEA station located at Waco, Texas (10.1 and 9.9‰) which are taken to represent the composition of moisture derived over the Gulf of Mexico (Harvey, 2000; Gat et al., 1994), the main moisture source for Nebraska.

3.3. Comparison to local groundwater

The mean weighted annual composition of precipitation over a given region is typically reflected in the isotopic composition of shallow groundwater in that region (Clark and Fritz, 1997). A groundwater sample collected from a shallow well approximately 3 km from the weather station (Fig. 1) had δ^{18}O and δ^{2}H values of −10.8 and −80‰, respectively. Shallow groundwaters collected as part of several other ongoing studies in the nearby area also have δ^{18}O and δ^{2}H values between −9 to −10‰ and −63 to −70‰, respectively. This general agreement between precipitation and groundwater isotope values provides further validation of the use of the archive data to determine the isotopic composition of precipitation.

4. Summary and applications

The isotopic attributes of precipitation collected in the U.S. north-central Great Plains at North Platte, Nebraska are similar to the findings from other mid-continental regions across the globe, including a strong isotopic enrichment between winter and summer precipitation and a strong $\delta^{18}\text{O}-T$ correlation ($r^2 = 0.845$) of 0.54‰ per degree Celsius. The results differ, however, in that the local meteoric water line is slightly below the Global Meteoric water line, and that yearly δ^{18}O and δ^{2}H means are more depleted than means from nearby stations in Mead, Nebraska and Chicago, Illinois.

The data compiled by this research will be used in ongoing investigations whose preliminary results have been reported at conferences and in the literature. These studies examine regional groundwater recharge (Harvey, 1999; Gosselin et al., 1998), wetland hydrology (Kurtz et al., 1998), groundwater/surface water interaction (Schellpeper and Harvey, 1998) and regional paleo-hydrology (Swinehart et al., 1997). The strong seasonal variation in the isotopic abundance of precipitation will allow us to ascertain whether plants are using winter or summer precipitation during growth periods (Dodd et al., 1998; Alstad et al., 1999). In addition, the $\delta - T$ correlation can be applied to the reconstruction of climates in the central Great Plains, a location of great interest to paleo-climatologists (Yu et al., 1997) as it is a region where divergent air mass converge.

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References

Alstad, K.P., Welker, J.M., Williams, S., Trlica, M.J., 1999. Carbon and water relations of *Salix monticola* in response to winter browsing and changes in surface water hydrology: An isotopic study using $\delta^{13}C$ and $\delta^{18}O$. Oecologia 120, 375–385.

Bigelow, D.S., 1991. Comparability of wet-only precipitation chemistry measurements from the United States National Atmospheric Deposition Program (NADP) to those of the Canadian network for sampling acid precipitation (CANSAP). Environ. Sci. Technol. 25, 1867–1875.

Bryson, R.A., Hare, F.K., 1974. The climates of North America. In: Bryson, R.A., Hare, F.K. (Eds.). Climates of North America. World Survey of Climatology, vol. 11. Elsevier, Oxford, pp. 1–47.

Buttle, J.M., 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. Progress in Physical Geography 18, 16–41.

Clark, I.D., 1987. Groundwater resources in the Sultanate of Oman: Origin, circulation times, recharge processes and paleoclimatology, Isotopic and geochemical approaches. Unpublished Doctoral thesis, Université de Paris-Sud, Orsay, France, 264pp.

Clark, I.D., Fritz, P., 1997. Environmental Isotopes in Hydrogeology. Lewis Publishers, New York (328pp.).

Coleman, M.L., Shepherd, T.J., Durham, J.J., Rouse, J.E., Moore, G.R., 1982. Reduction of water with zinc for hydrogen isotope analysis. Anal. Chem. 54, 993–995.

Colville, W.L., Meyers, R.E., 1965. Nebraska's Precipitation: Its patterns and Probabilities, Misc. Pub. 10, University of Nebraska College of Agriculture and Home Economics, The Agricultural Experiment Station, 59pp.

Court, A., 1974. The climate of the coterminous United States. In: Bryson, R.A., Hare, F.K. (Eds.). Climates of North America. World Survey of Climatology, vol. 11. Elsevier, Oxford, pp. 193–343.

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702.

Craig, H., Gordan, L., 1965. Deuterium and Oxygen-18 variations in the ocean and the marine atmosphere. In: Tongiorgi, E. (Ed.), Stable Isotopes in Oceanographic Studies and Paleotemperatures, Spoleto, pp. 9–130.

Dansgaard, W., 1964. Stable isotopes in precipitation. Tellus XVI (4), 436–468.

Desaulniers, D.E., Cherry, J.A., 1989. Origin and movement of groundwater and major ions in a thick deposit of Champlain Sea clay near Montréal. Can. Geotechnol. J. 26, 80–89.

Dodd, M.B., Lauenroth, W.K., Welker, J.M., 1998. Differential water resource use by herbaceous and woody plant life-form in a shortgrass steppe community. Oecologia 117, 504–512.

Fontes, J.Ch., 1980. Environmental isotopes in groundwater hydrology. In: Fritz, P., Fontes, J.Ch. (Eds.). The Terrestrial Environment. Handbook of Environmental Isotope Geochemistry, vol. 1. Elsevier, Amsterdam, pp. 75–140.

Fritz, P., Drimmie, R.J., Frape, S.K., O'Shea, K., 1987. The isotopic composition of precipitation and groundwater in Canada, IAEA-SM-299/17. International Symposium on the Use of Isotope Techniques in Water Resources Development, Vienna, Austria, March 30–April 3.

Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. Annu. Rev. Earth Planetary Sci. 24, 225–262.

Gat, J.R., 1980. The isotopes of hydrogen and oxygen in precipitation. In: Fritz, P., Fontes, J.Ch. (Eds.). Handbook of Environmental Isotope Geochemistry. The Terrestrial Environment A, vol. 1. Elsevier, Amsterdam, pp. 21–47.

Gat, J.R., Gonfiantini, R., 1981. Stable isotope hydrology: Deuterium and oxygen-18 in the water cycle. IAEA Technical Report Series No. 210, International Atomic Energy Agency, Vienna, 339pp.

Gat, J.R., Bowser, C.J., Kendall, C., 1994. The contribution of evaporation from the Great Lakes to the continental atmosphere: estimate based on stable isotope data. Geophys. Res. Lett. 21, 557–560.

Gonfiantini, R., 1978. Standards for stable isotope measurements in natural compounds. Nature 271, 534–536.

Gosselin, D.C., Harvey, F.E., Strickland, D.B., Stotler, R., 1998. Major Ion, O-18, and D variations in groundwater from the Dakota aquifer of Nebraska. Geological Society of America Annual Meeting, Toronto, Ontario, Canada, October 26–29, Abstracts with Programs, 30(7), A-86.

Harvey, F.E., 2000. Use of NADP archive samples to determine the isotope composition of precipitation: characterizing the meteoric input function for use in ground water studies. Ground Water (submitted for publication).

Harvey, F.E., 1999. Evaluating groundwater recharge models in Nebraska using stable oxygen and hydrogen isotopes. Geological Society of America Annual Meeting, Denver, CO, October 25–28, Abstracts with Programs, 31(7), A-349.

Harvey, F.E., 1996. Evaluation and Development of Methods for Hydrogeologic Studies in Deep Lakes: Applications in the Hamilton Harbour, Western Lake Ontario. PhD thesis, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, Canada, 237pp.

Harvey, F.E., Sibray, S.S., 2000. Delineating ground water recharge from leaking irrigation canals using water chemistry and isotopes. Submitted for publication.

Harvey, F.E., Frape, S.K., Drimmie, R.J., 1997. Isotopic variations in the Hamilton Harbour as indicators of Lake Ontario inflow. J. Great Lakes Res. 23, 169–176.

Hendry, M.J., 1988. Hydrogeology of clay till in a prairie region in Canada. Ground Water 26, 607–614.

International Atomic Energy Agency/World Meteorological Organization (IAEA/WMO), 1998. Global Network for Isotopes in Precipitation (GNIP). The GNIP Database, Release 2, May 1998, URL: http://www.iaea.org/programs/ri/gnip/gnipmain.htm

International Atomic Energy Agency (IAEA), 1992. Statistical treatment of data on environmental isotopes in precipitation. Technical Report Series No. 331, IAEA, Vienna, 781pp.

Kerr, R.A., 1993. Pinatubo global cooling on target. Science 259, 594.

Krabbenhoft, D.P., Bowser, Č.J., Anderson, M.P., Valley, J.W., 1990. Estimating groundwater exchange with lakes: 1. The stable isotope mass balance method. Water Resour. Res. 26 (10), 2445–2453.

Krouse, H.R., Mackay, J.R., 1971. Application of $H_2{}^{18}O/H_2{}^{16}O$ abundances to the problem of lateral mixing in the Liard-Mackenzie River system. Can. J. Earth Sci. 8, 1107–1109.

Kunkel, K.E., Changnon, S.A., Angel, J.R., 1994. Climatic aspects of the 1993 Upper Mississippi River Basin flood. Bull. Am. Meteorol. Soc. 75 (5), 811–822.

Kurtz, T.M., Harvey, F.E., Swinehart, J.B., 1998. Hydrogeology of Peatland Fens in the Nebraska Sand Hills: the role of groundwater in the development of glacial relict wetland ecosystems. Geological Society of America Annual Meeting, Toronto, Ontario, Canada, October 26–29, Abstracts with Programs, 30(7), A-119.

Lapin, L.L., 1980. Statistics: Meaning and Method. Harcourt Brace Jovanovich, New York (543pp.).

Lawrence, J.R., White, J.W.C., 1991. The elusive climate signal in the isotopic composition of precipitation. Geochem. Soc. Spec. Publ. 3, 169–185.

Lawson, M.P., Dewey, K.F., Nield, R.E., 1977. Climatic Atlas of Nebraska. University of Nebraska Press, Lincoln, NE (88pp.).

Lynch, J.A., Grimm, J.W., Bowersox, V.C., 1995. Trends in precipitation chemistry in the United State: a national perspective, 1980–1992. Atmos. Environ. 29, 1231–1246.

Machavaram, M.V., Krishnamurthy, R.V., 1995. Earth surface evaporative process: a case study from the Great Lakes region of the United States based on deuterium excess in precipitation. Geochim. Cosmochim. Acta 59 (20), 4279–4283.

Matheney, R.K., Gerla, P.J., 1996. Environmental isotopic evidence for the origins of ground and surface water in a prarie discharge wetland. Wetlands 16 (2), 109–120.

Mathieu, R., Bariac, T., 1996. An isotopic study (^2H and ^{18}O) on water movements in clayey soils under a semiarid climate. Water Resour. Res. 32, 779–789.

Mazor, E., 1991. Chemical and Isotopic Groundwater Hydrology. Marcel Dekker, New York (413pp.).

Merlivat, L., Jouzel, J., 1979. Global climate interpretation of the deuterium-oxygen 18 relationship for precipitation. J. Geophys. Res. 84 (C8), 5029–5033.

National Atmospheric Deposition Program (NADP), 1998. National Atmospheric Deposition Program 1997 Wet Deposition. Illinois Water Survey Report, IWS, Champaign, IL, 16pp.

Owenby, J.R., Ezell, D.S., 1992. Monthly station normals of temperature, precipitation and heating and cooling degree days 1961–1990, Climatography of the United States, No. 81. US Department of Commerce, National Oceanic and Atmospheric Administration.

Rozanski, K., Araguás-Araguás, L., Gonfiantini, R., 1993. Isotopic patterns in modern global precipitation. Geophys. Monogr. Am. Geophys. Union 78, 1–36.

Schellpeper, J.J., Harvey, F.E., 1998. Chemical and isotopic characterization of ground and surface waters in the republican river basin of Nebraska as a means to assess the impact of irrigation practices. Geological Society of America Annual Meeting, Toronto, Ontario, Canada, October 26–29, Abstracts with Programs, 30(7), A-76.

Sheppard, S.F.M., Nielsen, R.L., Taylor, H.P., 1969. Oxygen and hydrogen isotope ratios of clay minerals from porphyry copper deposits. Econ. Geol. 64, 755–777.

Sibray, S.S., Harvey, F.E., Heinen, D.E., 1997. Determining recharge sources and the impact of unlined irrigation canals in Western Nebraska, using stable isotope and major ion chemistry and tritium and carbon-14 dating. Geological Society of America Annual Meeting, Salt Lake City, Utah, October 20–23, Abstracts with Programs, 29(6), A-382.

Siegel, D.I., Mandle, R.J., 1984. Isotopic evidence for glacial meltwater recharge to the Cambrian–Ordovician aquifer, North-Central United States. Quat. Res. 22, 328–335.

Simpkins, W.W., 1995. Isotopic composition of precipitation in central Iowa. J. Hydrol. 172, 185–207.

Stimson, J., Rudolph, D., Farvolden, F., Frape, S., Drimmie, R., 1993. Causes of groundwater salinization in a low lying area of Cochabamba Valley, Bolivia. Isotope techniques in the study of past and current environmental changes in the hydrosphere and the atmosphere, IAEA-SM-329/26, pp. 185–198.

Swinehart, J.S., Harvey, F.E., Loope, D.B., Steinauer, G., 1997. Holocene history and hydrology of Nebraska Sand Hills Fens. Society of Wetland Scientists, 18th Annual Meeting, Symposium on Peatlands of Western North America, Bozeman, MO, June 1–7.

Walter, H., 1979. Vegetation of the World. Springer, Berlin (101pp.).

Welker, J.M., 1997. Isotopic ($\delta^{18}O$) characteristics of weekly precipitation collected across the US: An initial analysis with application to water source studies. ISOBALANCE Workshop, Saskatoon, Canada, Oral presentation, April 1997.

Welker, J.M., 2000. Isotopic ($\delta^{18}O$) characteristics of weekly precipitation collected across the USA: an initial analysis with application to water source studies. Hydrol. Process. 14 (8), 1449–1464.

Yang, C., Telmer, K., Veizer, J., 1996. Chemical dynamics of the St. Lawrence riverine system: δD_{H2O}, $\delta^{18}O_{H2O}$, $\delta^{13}C_{DIC}$, $\delta^{34}S_{sulfate}$, and dissolved $^{87}Sr/^{86}Sr$. Geochim. Cosmochim. Acta 60 (5), 851–866.

Yu, Z., McAndrews, J.H., Eicher, U., 1997. Middle Holocene dry climate caused by change in atmospheric circulation patterns: evidence from lake levels and stable isotopes. Geology 25, 251–254.

Yurtsever, Y., Gat, J.R., 1981. Atmospheric waters. In: Gat, J.R., Gonfiantini, R. (Eds.), Stable isotope hydrology: deuterium and oxygen-18 in the water cycle. International Atomic Energy Agency, Vienna.

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