Stable Isotope Geochemistry: A Tribute to Samuel Epstein
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The elusive climate signal in the isotopic composition of precipitation

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Abstract—The hydrogen and oxygen isotopic compositions of precipitation contain a climate signal. Two climate signals that are present in precipitation show up as a correlation between isotopic composition and temperature and a correlation between isotopic composition and the amount of precipitation. The temperature signal is strongest in polar continental regions and the amount signal is strongest in tropical regions. In temperate regions both signals are present, making retrieval of climate information more difficult.

An investigation of eight locations where long-term collections of isotopic data exist has revealed that correlations between climate parameters and isotopic values are usually limited to certain seasons of the year. Only parts of a year may show a good amount-isotope or temperature-isotope signal from one seasonal period in a year to the same seasonal period in other years. The result is that most locations yield poor correlations for whole-year periods on a year-to-year basis.

A detailed study of a seven-year collection of individual precipitation events in southeastern New York state has shown that year-to-year correlations between the isotopic composition of precipitation and both temperature and the amount of precipitation exist. These year-to-year correlations are limited to specific seasons of the year. The temperature signal is strongest in the months January to April. The amount signal is strongest in the months May to August. No simple climate signal was detected in September to December precipitation. The temperature signal in the January to April precipitation is best understood in the context of changes of atmospheric circulation patterns that changed the loci of storm tracks. The amount signal in the May to August precipitation is best understood in the context of changes in atmospheric circulation patterns that determined frontal positioning during rainfall events.

INTRODUCTION

EVER SINCE UREY (1947) recognized that light elements partition their isotopes as a function of temperature the utilization of isotope data to unravel past climates has led to numerous discoveries. For example, EMILIANI (1955) demonstrated that shifts in the isotopic composition of oxygen in microfossil shells in deep-sea cores are a result of changes in ocean temperature and changes in the volume of the polar ice caps. The sawtoothed profile of the Pleistocene isotope record reflects several cycles of slow growth and then rapid melting of the ice caps. A review by SAVIN (1977) outlines the history and major discoveries in this subfield for the Cenozoic Era.

A detailed record of climate change during the lastest ice age was discovered in the oxygen and hydrogen isotopic compositions of ice cores in both Greenland (DANSGAARD and TAUBER, 1969; DANSGAARD *et al.*, 1969) and Antartica (EPSTEIN *et al.*, 1970). The isotope ratios were lower when the climate was colder. This effect is primarily a reflection of the capacity of air to hold H_2O. An air mass moving from a warm ocean to the polar regions progressively loses H_2O, and the condensate has both a higher $^{18}O/^{16}O$ and a higher D/H ratio than the vapor that remains. This process, which can be modelled as a Rayleigh distillation, ultimately yields very low isotope ratios that are lowest when the ambient temperature is lowest.

A detailed evaluation of the equilibrium and non-equilibrium factors that determine the isotopic composition of precipitation is given by DANSGAARD (1964). Two major factors correlate with the isotopic ratios: temperature and the amount of precipitation. The best temperature correlation is observed in continental regions nearer to the poles, whereas the correlation with amount of rainfall is best in tropical regions. In temperate latitudes both factors are important.

The search for a climate-isotope signal in temperate regions has focused predominately on stable isotope studies of tree rings. EPSTEIN *et al.* (1976) discovered a correlation between the isotopic com-

position of ground water and the isotopic composition of tree ring cellulose. Because the former reflects local climate (*e.g.,* FRIEDMAN *et al.,* 1964) tree rings theoretically should provide a record of local climate changes. A study by EPSTEIN and YAPP (1976) of tree rings from a Bristle Cone Pine in eastern California uncovered a major isotopic shift that could be correlated with the Little Ice Age in Europe. Several other investigators (SCHIEGEL, 1974; WILSON and GRINSTED, 1975; GRAY and THOMPSON, 1976) have also shown correlations between local climate changes and the isotopic ratios of tree rings.

WHITE (1983) and WHITE *et al.* (1985) have attempted to understand how the isotopic signal is recorded in tree rings. They discovered that the isotopic ratios of the tree rings reflect the ratios in the sap present in the tree during the growing season, and this led to the classification of trees into three categories: dry site, wet site, and intermediate site. Dry-site trees get their water only from rain. Wet-site trees get their water predominantly from ground waters. Intermediate-site trees get their water from both, the proportions depending on the depth of the water table. Most trees are in the intermediate category. These studies revealed that care must be taken in interpreting the isotopic signal found in tree rings.

With the above restrictions in mind, WHITE (1983) and LAWRENCE and WHITE (1984) reported a correlation between the isotopic composition of May to August rain over a four-year period and the isotopic composition of two dry-site trees. They further showed that for a time period of six years, the isotopic ratio of May to August rain correlated with the amount of May to August rain. Finally, they showed that for time periods of 11 and 21 years, the isotopic ratios of tree rings in two dry-site trees correlated with the amount of May to August rain (LAWRENCE and WHITE, 1984). Unfortunately, studies carried back 80 years on one of the dry-site trees did not show a continued good correlation, and the correlation was particularly poor in the middle part of the 80-year interval (J. W. C. WHITE, unpubl. data). This period of poor correlation with isotope studies was also the same interval over which standard tree rings width studies also yielded a poor correlation with rainfall amount.

Paleoclimates can also be studied using $^{18}O/^{16}O$ ratios of fresh-water fossils (BUCHARDT and FRITZ, 1980; FRITZ and POPLAWSKI, 1974; ABELL, 1986; YAPP, 1979; MAGARITZ and HELLER, 1980). The main problem with fresh-water fossils is that the $^{18}O/^{16}O$ shifts in such fossils are mainly determined by two counteracting effects. A shift to colder climates usually means lower $\delta^{18}O$ values in the fresh waters in which the organisms live and thereby in their shells. But this same shift in climate increases the $^{18}O/^{16}O$ fractionation between the water and the carbonate shell. An additional problem is that in dry areas evaporation tends to raise the $^{18}O/^{16}O$ ratio of surface waters.

It is essential to discover in detail how climatic changes and meteorological factors induce changes in the isotopic composition of precipitation. Success in unraveling past climate changes may depend on locating places on the Earth's surface that display a simple isotope-climate relationship. The report that follows focuses on identifying and evaluating these factors in a variety of localities. The data base consists of the data set of the International Atomic Energy Agency (IAEA, 1969, 1970, 1971, 1973, 1975, 1979, 1983, 1986) and a collection of isotopic analyses of precipitation from storms collected over a seven-year period in southeastern New York state.

GLOBAL RELATIONSHIPS IN THE ISOTOPIC RATIOS OF PRECIPITATION

Because the objective of this report is in part to identify places on Earth where the climate-isotope relationship in precipitation is simple, we first look at isotope data on a global scale. The only global set of data that exists is that compiled by the International Atomic Energy Agency (IAEA), first evaluated in detail by DANSGAARD (1964). Subsequently, the data have been available both on magnetic tape and in IAEA technical reports. It can be seen that the isotopic composition of precipitation is strongly dependent on climate by looking at the average distribution of oxygen isotopes in precipitation on a global scale in January and July. Figures 1 and 2 show contour maps of oxygen isotope values based on average values for January and July, respectively. Over 80 stations involving a few to several years of samples were used to construct the contours. The data of FRIEDMAN *et al.* (1964) and LAWRENCE (1970) for North America were helpful in estimating contours in mountainous areas.

The most noticeable isotopic shift occurs in the continental regions, particularly at high latitudes. The isotope values are much lower in the northern hemisphere in January than in July. The gradients in $^{18}O/^{16}O$ ratios on the northern continents are also very steep in January, particularly near ocean-continent boundaries. These low isotope values reflect the extremely cold temperatures over the northern continents in January, and the steep isotopic gradients reflect large temperature gradients.

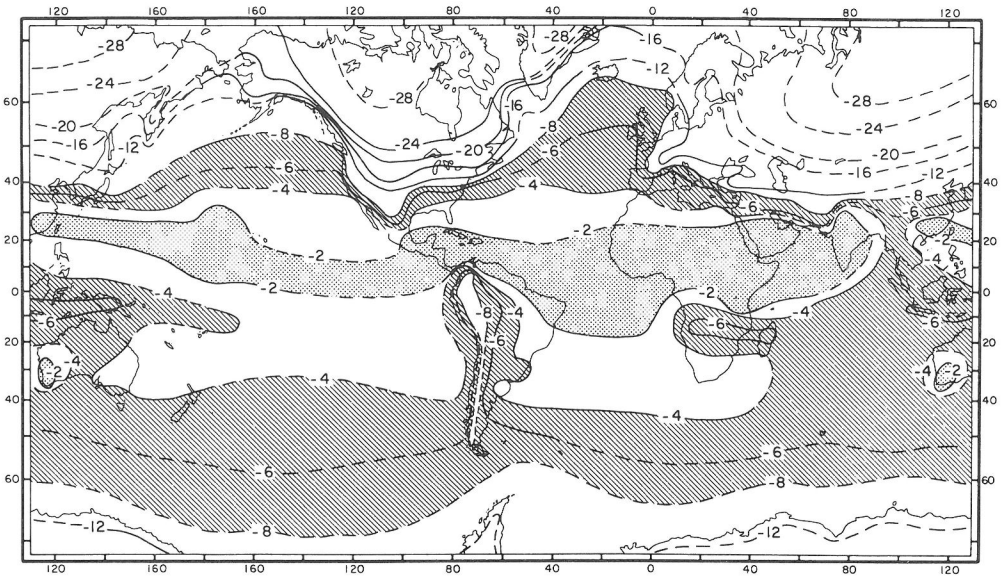

FIG. 1. Contours of $\delta^{18}O$ values relative to Standard Mean Ocean Water (SMOW) of the average precipitation in the month of January. Data obtained from the International Atomic Energy Agency (IAEA).

Low isotope ratios and steep gradients undoubtedly exist over the Antarctic continent in July, but there are insufficient data to draw contours with confidence.

The areas on Earth that exhibit the smallest changes in oxygen isotope ratios are the oceans. This is expected because temperature changes are minimal over the oceans. In both January to July oxygen isotopic gradients are somewhat steeper over tropical and subtropical continental regions than over the oceans (Figs. 1 and 2).

Simple geographic relationships between climate and the isotopic composition of precipitation can be seen. Temperature-isotope relationships for northern continental locations ($\delta^{18}O = 0.69T - 13.6$, $\delta D = 5.6T - 100$) are determined by plot-

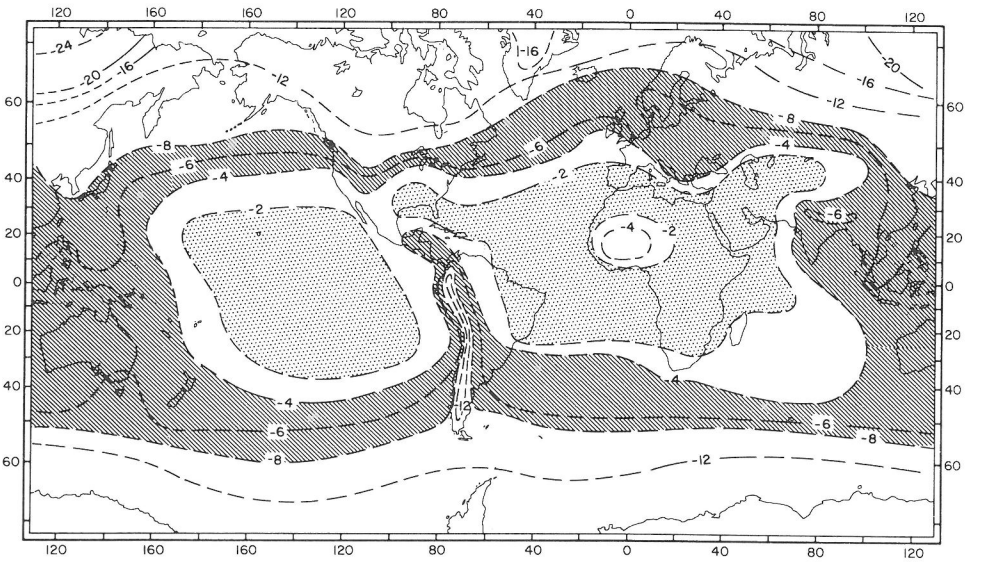

FIG. 2. Contours of $\delta^{18}O$ values relative to SMOW of the average precipitation in the month of July. Data obtained from the IAEA.

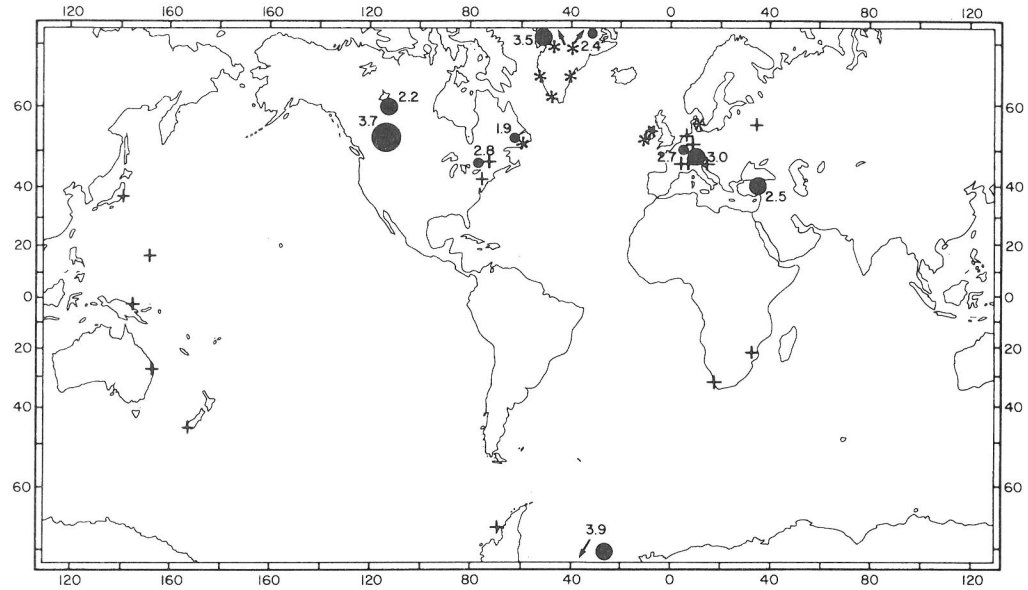

FIG. 3. Locations of IAEA weather stations where significant correlations exist between the hydrogen isotopic composition of monthly precipitation and the average monthly temperature. The numbers next to the dots give the slope, A, in the relationship, $\delta D = AT + B$ where T is temperature in degrees Celcius and δD is the hydrogen isotopic composition of precipitation expressed in per mil deviations from SMOW. The size of the dots is related to the coefficient of determination, r^2, of the relationship. The smallest dots indicate an r^2 value between 0.5 and 0.6, the middle sized dots r^2 between 0.6 and 0.7, and the large dot r^2 greater than 0.7. The * marks show the locations of IAEA precipitation collection stations used by DANSGAARD (1964) to determine temperature-isotope relationships. The + marks show the location of IAEA precipitation collection stations with long records.

ting the mean annual temperature of a locality against the mean annual isotopic composition of its precipitation (DANSGAARD, 1964). Many of the locations used by DANSGAARD (1964) are shown in Figs. 3 and 4. Additional locations in northern Greenland off these maps were also used. Locations in Antarctica also fit this relationship. Over other areas of the Earth temperature-isotope correlations are much worse and no meaningful relationships were found.

An amount-isotope relationship was also noted by DANSGAARD (1964) in the tropics, particularly in the Pacific Ocean. He noted that the farther east the samples were taken, the lower was the precipitation and the higher the isotope ratio. He attributed these differences mainly to differing condensation temperatures, differing degrees of evaporation on falling rain drops, and differing stages of condensation. All of these factors can be related to the positioning of the rain collection stations in the subtropical high pressure area in the Pacific. The air on the eastern flank of the subtropical high has cooler and dryer air than air on the southern and western flanks. Figure 5 displays the average hydrogen isotopic composition of precipitation as a function of the average amount of annual precipitation for tropical island stations. The locations of these stations are given in Fig. 4.

TEMPORAL RELATIONSHIPS IN THE ISOTOPIC RATIOS OF PRECIPITATION

The goal of this report is to stimulate interest in searching for locations on the Earth's surface where temporal changes in the isotopic composition of precipitation can be simply related to temporal climatic changes. The analysis of the isotopic values of precipitation has now been going on long enough so that year-to-year relationships can be investigated. Following a review of the climate-isotope relationships within a year we will evaluate year-to-year relationships.

Temporal relationships within annual periods

By evaluating monthly precipitation samples analyzed by the IAEA, LAWRENCE (1980) discovered temporal relationships between the isotopic composition of precipitation and temperature within a single year. Pearson's product-moment correlation coefficient is utilized, and Fig. 3 displays the locations on the Earth's surface where there are good

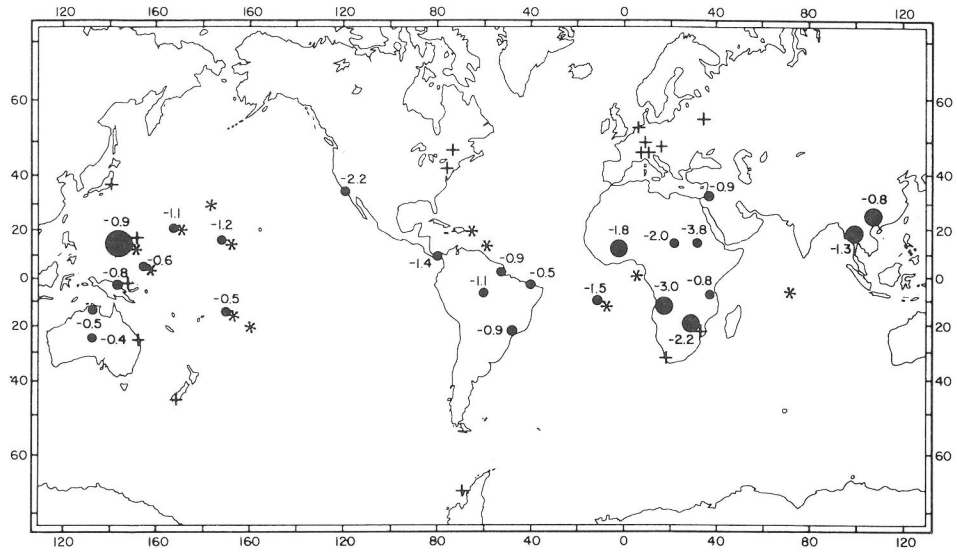

FIG. 4. Locations of IAEA weather stations where significant correlations exist between the hydrogen isotopic composition of monthly precipitation and the amount of monthly precipitation. The numbers next to the dots give the slope, A, in the relationship, $\delta D = AX + B$ where X is the amount of monthly precipitation in centimeters and δD is the hydrogen isotopic composition of precipitation expressed in per mil deviations from SMOW. The size of the dots is related to the coefficient of determination, r^2, of the relationship. The smallest dots indicate an r^2 value between 0.3 and 0.4, the middle size dots r^2 between 0.4 and 0.5, and the large dot r^2 greater than 0.5. The * marks show the locations of IAEA precipitation collection stations used to develop the amount-isotope relationship shown in Fig. 5. The + marks show the location of IAEA precipitation collection stations with long records.

correlations between monthly temperatures and the isotopic composition of monthly precipitation. The larger dots indicate the better correlations and the number gives the slope of the relationship. All IAEA stations not represented by a dot had r^2 values less than 0.5. As can be seen, the good temporal correlations are found only in northern continental regions and one Antarctic station. Note that the slopes in these temporal relationships are lower than the slope of the geographic relationship (5.6) given by DANSGAARD (1964). This difference exists mostly because at any of the given locations winter storms tend to be warmer than the average temperature, and summer storms tend to be colder than the average temperature.

Correlations were also found within a year between the amount of precipitation and its hydrogen isotopic composition (LAWRENCE, 1980; IAEA, 1981; see Fig. 4). IAEA stations with r^2 values greater than 0.3 are shown. Once again, larger dots indicate better correlations and the numbers indicate the slope of the correlation with amounts expressed in centimeters of precipitation. Good correlations between the amount of precipitation and hydrogen isotope values are found only in the tropics. DANSGAARD (1964) first noted and evaluated this relationship and labelled it the "amount" effect.

Temporal relationships from year to year

The recording of an isotope-climate signal at a single location over time periods ranging from years to centuries is the ultimate goal of stable-isotope paleoclimatologists. The climate signal may be limited to a tree's growing season for dry-site trees (WHITE, 1983; LAWRENCE and WHITE, 1984; WHITE *et al.*, 1985) or to periods of several years as represented by ground waters. Trees which utilize

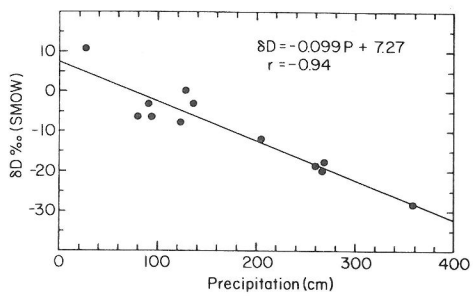

FIG. 5. The average δD value of the annual precipitation from oceanic islands plotted as a function of the average amount of annual rainfall. The island stations are distant from continents, within 30° of the equator, and at elevations less than 120 meters.

ground waters, fresh-water fossils, and dripstone deposits in caves are all sensitive to the isotope-climate signal of local ground waters. With this in mind, below we investigate year-to-year variations in the isotopic composition of precipitation.

There are only a few locations where precipitation samples have been gathered for long enough time periods that we can look for correlations between climate and isotope values. These locations are IAEA precipitation collection stations and one station maintained by us at Mohonk Lake, New York, U.S.A. The locations of these stations are shown on Figs. 3 and 4. Eight of these stations will be investigated here.

We illustrate a simple method of looking for a climate-isotope relationship. Time periods of two to twelve months from one year to another will be investigated, and time periods of two to six months will give us seasonal comparisons from year to year. Average isotope values for these seasonal periods

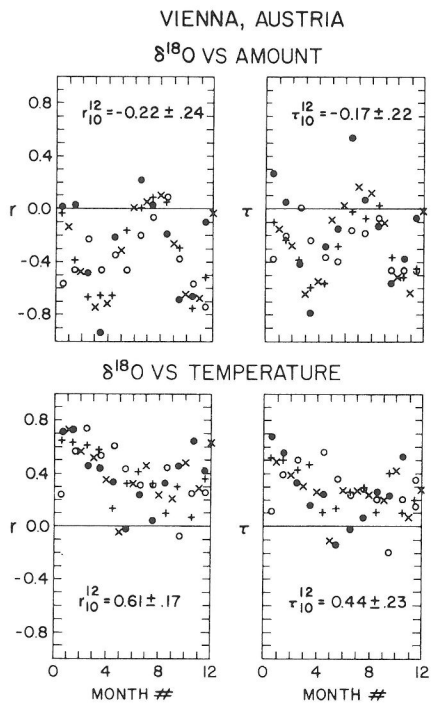

FIG. 6. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Vienna, Austria. The correlation coefficients plotted are the familiar Pearson product-moment correlation coefficient (r) and Kendall's rank correlation coefficient (Tau) (DEMIRMEN, 1976). Comparisons are for seasonal values from year to year. The symbols for the seasons are as follows: closed circles = two months, × = three months, + = four months, open circles = six months. The r and Tau values listed separately are the mean and standard deviation of annual comparisons.

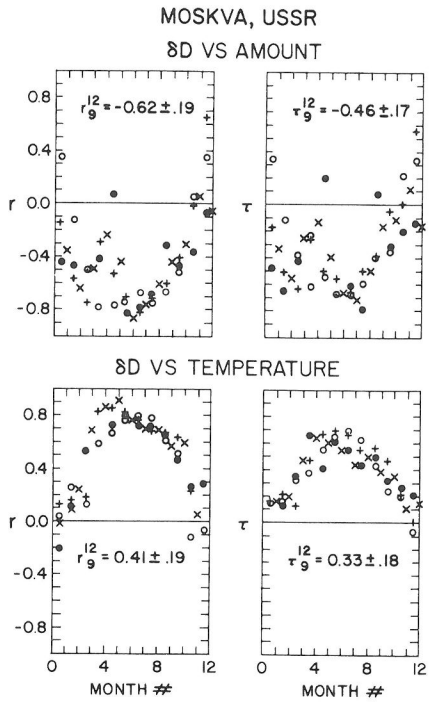

FIG. 7. The correlations of hydrogen isotope values of precipitation with precipitation amounts and temperatures for Moskva, U.S.S.R. See Fig. 6 caption for more detail.

will be compared to either the average temperatures or the total amount of precipitation for these seasonal periods. Correlations will be determined using statistical methods that derive the familiar Pearson product-moment correlation coefficient, as well as Kendall's rank correlation coefficient. The Kendall coefficient is being used because proper use of the Pearson coefficient requires an assumption of bivariate normality of compared data sets (DEMIRMEN, 1976) which climatic and isotope data usually do not have.

Correlation coefficients for seasonal isotope values versus total seasonal precipitation or average seasonal temperature from year to year for eight locations around the world are shown in Figs. 6 to 13. Pearson's coefficients are shown on the left-hand side of the figures and Kendall's on the right-hand side. Correlation coefficients range from 1.0 to −1.0, respectively, with these limits representing perfect positive correlation and perfect negative correlation of the variables (0.0 represents no correlation). For most locations correlations were determined for all seasons of the year. This was possible when continuous records were available for several years. In instances where records were fragmented, only seasons in the range 1 to 12 could be correlated. In other

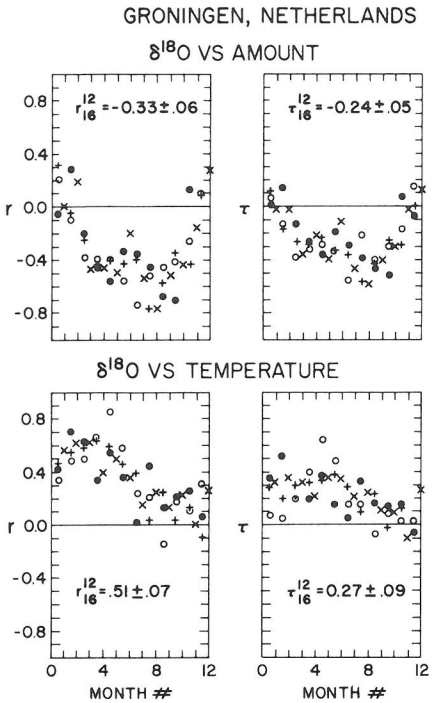

FIG. 8. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Groningen, Netherlands. See Fig. 6 caption for more detail.

words, it was not possible to compare seasons going from the end of one year into the next. The position of a season on the time axis in the diagrams is the month number of the mid period of the season. For example, the January to February season is plotted at 1.5 on a given diagram and the September to December season is plotted at 10.5 on the same diagram.

The numerical r (Pearson) and Tau (Kendall) correlation coefficient values given in each diagram represent 12-month year-to-year correlations. The subscript gives the number of years used in determining the correlation. The superscript gives the number of 12-month periods averaged. For example, January to December is one twelve-month period, whereas February to January is another, and so on. The plus or minus value after the numerical average r or Tau value is the standard deviation of the average. For locations where isotope records are fragmented, only the 12-month period from January to December could be compared from year to year. In that instance the superscript has a value of unity.

The most outstanding feature of the correlations shown in Figs. 6 to 13 is the variability of correlation between isotope values and amount or temperature from one part of a year to another. Some seasons show good correlations from one year to the next while other seasons show very little correlation, or in a few instances the opposite correlation. The net effect of this variability is that year-to-year correlations of 12-month periods are weak for most locations.

Examination of Figs. 6 to 13 shows that each location displays a unique pattern of correlations. At Vienna, Austria (Fig. 6), correlations of amount and $^{18}O/^{16}O$ ratios are highly seasonal, with the strongest correlations occurring around the equinoxes. Temperature-isotope correlations are good in cold months and weaker the rest of the year. At Moskva (Moscow), U.S.S.R. (Fig. 7), a very different pattern is seen. Both amount-isotope and temperature-isotope correlations are strongest in the warm months of the year. At Groningen, Netherlands (Fig. 8), the amount-isotope pattern of correlations is similar to that at Moskva, with generally weaker correlations; the temperature-isotope pattern at Groningen is similar to that of Vienna, but with generally weaker correlations.

At Mohonk, New York, U.S.A., a location that

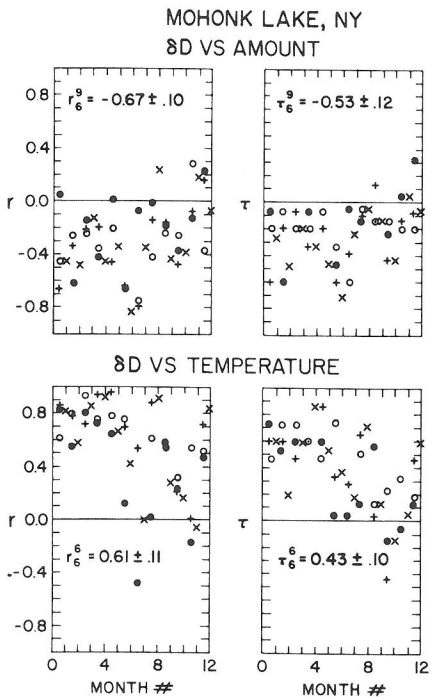

FIG. 9. The correlations of hydrogen isotope values of precipitation with precipitation amounts and temperatures for Mohonk Lake, New York, U.S.A. See Fig. 6 caption for more detail.

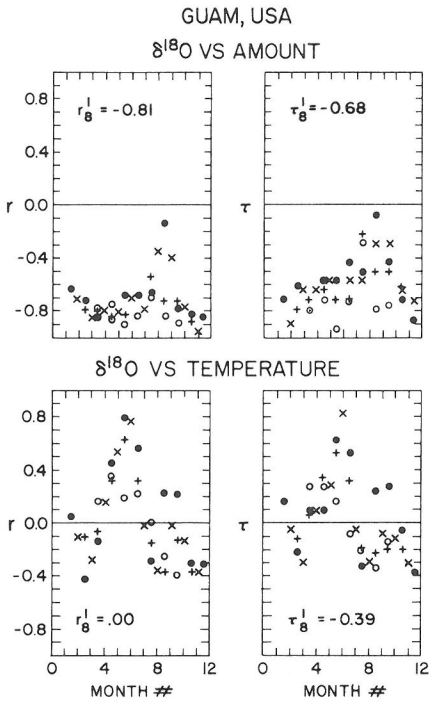

FIG. 10. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Guam. See Fig. 6 caption for more detail.

will be examined in detail below, the amount-isotope correlation (Fig. 9) shows considerable scatter, although the correlation is generally negative and best near the summer soltice. Overall, the correlation for 12-month comparisons at Mohonk is the best of all eight stations with the exception of Guam (Fig. 10). The temperature-isotope correlation at Mohonk is particularly good in the winter months but weakens in other seasons, especially autumn. At a nearby location, Ottawa, Canada (Fig. 11), correlations between amount and isotope values are weaker than at Mohonk. Temperature-isotope correlations at Ottawa as at Mohonk are stronger in the colder months, although the winter seasons crossing from one year to another are not represented.

The best year-to-year correlations are at Guam (Fig. 10). The correlation between amount and oxygen isotope values is strong for all months of the year, with the possible exception of August-September. This high degree of correlation shows up in the 12-month year-to-year correlation coefficient. The temperature-isotope correlations, however, are generally weak and opposite for different seasons of the year. Considerably weaker correlations between $\delta^{18}O$ values and amount are observed at Tokyo, Japan, which is a nearby location at a higher latitude (Fig. 12). These correlations at Tokyo are strongest in the summer. The temperature-isotope correlations are better in the summer and autumn.

The last station to be examined, Argentine Island, U.K., lies in the southern hemisphere on the edge of the Antarctic continent. Here, the amount-isotope and temperature-isotope correlations display sinusoidal patterns that tend to mirror each other. Although moderately weak, the best correlations occur around the equinoxes. The amount-isotope correlation changes from positive around the fall equinox to negative around the spring equinox. The temperature-isotope correlations are best during the spring.

One final observation concerning the eight locations is that the scatter in correlation coefficients appears in part to be related to the number of years of observations. Those locations with a large number of years of isotope data such as Groningen, Netherlands (Fig. 8), Tokyo, Japan (Fig. 12), and Argentine Island, U.K. (Fig. 13), exhibit much less scatter in correlation coefficients for any given season than the other locations examined. Continued collection of isotope data by the IAEA is therefore

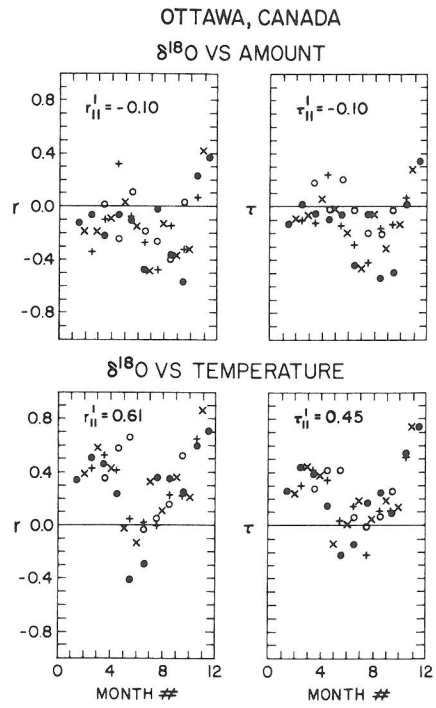

FIG. 11. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Ottawa, Canada. See Fig. 6 caption for more detail.

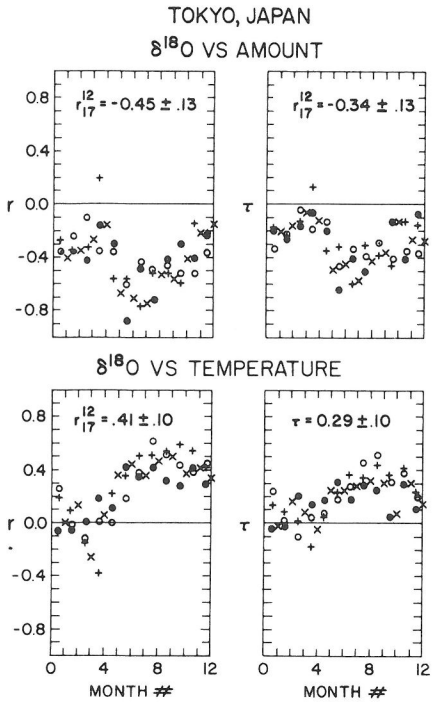

FIG. 12. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Tokyo, Japan. See Fig. 6 caption for more detail.

very important. Unfortunately, a large number of IAEA stations have very fragmented records.

The unique patterns of correlation seen at the different locations are almost certainly related to atmospheric circulation patterns that are characteristic of that location on the Earth's surface. Positioning with respect to continental land masses and oceans must be very important, because the heat budget of the atmosphere is strongly influenced by the distribution of land and ocean masses. Atmospheric circulation patterns respond seasonally to changes in this heat budget. Local orographic or ocean circulation effects may also be important. Because of this, it is important that we examine changes in isotopic values at any given location with respect to changes in meteorological conditions at that location. In the next section we take a closer look at changes in atmospheric circulation patterns at one location from one year to the next and relate them to isotopic changes in precipitation.

Detailed relationships at Mohonk Lake, New York

A more detailed examination of climate-isotope relationships is possible at Mohonk Lake, New York, than at the other sites examined, because precipitation from individual storms was collected over a seven-year period. Mohonk Lake is located near New Paltz in southeastern New York state. A set of precipitation samples was collected there from May 1977 to December 1983. The isotopic analyses from this sample collection are listed in Table 1.

The objective here is to demonstrate that changes in the isotopic composition of precipitation are related to changes in atmospheric circulation patterns. This can only be achieved by examining the meteorological conditions existing at the time the precipitation fell. Such an examination of isotopic data was undertaken by LAWRENCE *et al.* (1982) for precipitation samples collected in Mohonk Lake from storms from July 1977 to June 1979. It was shown that the track taken by a storm relative to the collection station had a very important effect on the isotopic composition of the precipitation. The more seaward and southerly the paths, and the colder the temperatures at Mohonk, the lower were the D/H ratios.

Examination of the seven-year data set in Table 1 reveals some year-to-year isotopic variations that can be directly related to changes in atmospheric

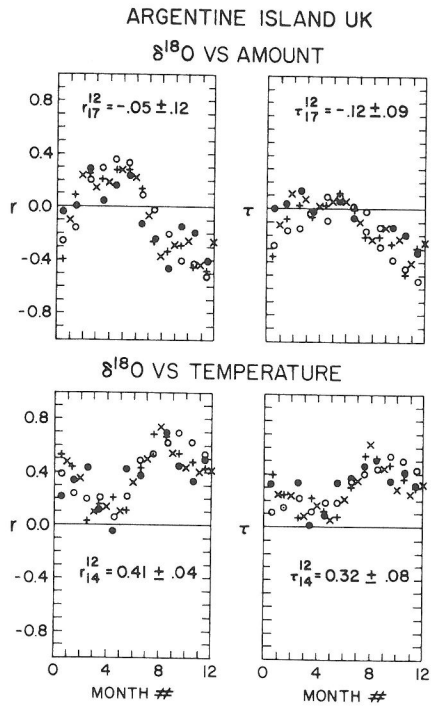

FIG. 13. The correlations of oxygen isotope values of precipitation with precipitation amounts and temperatures for Argentine Island, U.K. See Fig. 6 caption for more detail.

Table 1. Hydrogen isotopic composition of precipitation

Date	Amount (cm)	δD (per mil)	Date	Amount (cm)	δD (per mil)
		1977			
5/4–5	2.3	−38 ± 3	8/31	0.4	−29
5/9–10	3.4	−64 ± 1	9/13–14	1.3	−18
5/18	0.5	−16 ± 3	9/16–17	3.2	−46
6/6–10	6.3	−53	9/20–21	4.5	−50
6/18	1.6	−37 ± 2	9/23–26	10.4	−65
6/25	1.1	−29 ± 3	10/1–2	5.7	−43
6/29	0.7	−39 ± 1	10/8–9	3.4	−11
7/6	0.7	−35 ± 2	10/14–15	1.5	−21
7/8	0.4	−21 ± 2	10/16–17	2.5	−14
7/17	0.4	−12 ± 1	10/19–20	1.3	−47
7/19	0.5	−25 ± 1	11/7–9	13.2	−44
7/25	1.8	−33 ± 1	11/25–26	3.1	−88
8/1–2	0.3	−22	11/29–12/1	2.6	−62
8/3	0.4	−44	12/9	0.5	−66
8/5	0.5	−35	12/12–15	3.8	−40
8/12	0.7	−14	12/18–19	1.3	−146
8/17	1.0	−26	12/20–21	2.3	−58
8/22	0.4	−39	12/25	0.8	−73
		1978			
1/1–2	0.8	−113	7/10	0.8	−40 ± 2
1/6–9	6.4	−48	7/17–18	0.8	−38 ± 1
1/13–14	3.0	−116	7/23	0.6	−28 ± 1
1/17–18	3.5	−96	7/28–29	0.7	−20 ± 1
1/19–20	2.3	−145	7/31–8/1	1.0	−56 ± 3
1/25–26	4.0	−75 ± 1	8/4	0.5	−45 ± 2
2/6–7	1.9	−138	8/6–7	3.4	−38 ± 2
3/3	0.8	−123	8/11–12	0.9	−44 ± 2
3/14	3.3	−30	8/24–25	1.9	−7 ± 1
3/16	0.4	−130	8/28	0.5	−17 ± 2
3/25–27	6.0	−55	8/31	4.1	−45 ± 1
4/19–20	3.2	−55 ± 2	9/12	0.8	−24 ± 2
5/4–5	2.0	−134 ± 2	9/18–19	5.9	−35 ± 1
5/8	2.0	−50 ± 2	9/22–23	0.6	−12
5/9	1.9	−34 ± 1	10/4	0.6	−25
5/14–15	5.0	−31 ± 2	10/6	1.8	−29
5/16–18	4.9	−67 ± 2	10/25–27	1.0	−22
5/24–25	5.9	−57 ± 2	11/7–8	0.4	−37
5/31	1.0	−22 ± 1	11/17–18	2.8	−31
6/3	1.8	−51 ± 4	11/23–24	1.7	−67
6/7–8	2.3	−21 ± 4	11/29–30	0.8	−161
6/9	1.1	−62 ± 2	12/3–4	1.1	−83
6/13	0.4	−38 ± 2	12/8–10	3.6	−84
6/21	1.8	−21 ± 4	12/21–22	2.4	−92
7/3–4	2.8	−84 ± 5	12/24–25	3.8	−112
		1979			
1/1–4	7.1	−62	3/29	0.6	−55
1/5–6	0.5	−165 ± 5	4/2–3	0.7	−30
1/7–8	5.8	−84 ± 5	4/4–5	0.6	−66
1/12–14	1.5	−76 ± 5	4/8–10	3.2	−64
1/17–18	0.6	−99	4/14–15	2.8	−63
1/20–21	7.4	−87	4/26–28	4.4	−37
1/24–26	5.5	−86	5/3–4	0.6	−24 ± 4
2/7–8	0.8	−127	5/12–14	1.5	−42 ± 2
2/19	0.6	−170	5/18–20	0.9	−37
2/23–25	4.3	−69	5/23–25	10.2	−43 ± 2
2/25–27	2.5	−109	5/26	0.7	−48
3/2	0.5	−72	6/5	2.6	−42 ± 4
3/6–7	3.4	−45	6/11	4.4	−43 ± 2
3/10–11	1.5	−110	6/18	0.9	−19 ± 2
3/14	0.3	−39	6/30	0.5	−25 ± 4
3/24–25	2.1	−46	7/1	1.2	−21

Table 1. (Continued)

Date	Amount (cm)	δD (per mil)	Date	Amount (cm)	δD (per mil)
		1979			
7/16	2.8	−60	10/1	4.6	−81
7/18	0.7	−58	10/3	2.3	−46
7/24	0.3	−34	10/5	4.0	−28
8/2	1.1	−34	10/10	0.8	−185
8/10	1.9	−25	10/12	0.7	−86
8/11	1.5	−55	10/28	0.5	−83
8/12–13	4.3	−54	11/2–3	3.9	−35
8/18–19	1.8	−30	11/9–10	1.2	−23
8/24–25	2.2	−21	11/11–12	0.6	−112
8/29	0.6	−27	11/25–26	3.2	−30
9/6	10.1	−47	12/6	0.8	−120
9/14	1.5	−38	12/13	0.8	−130
9/21–22	4.3	−49	12/24–25	2.8	−37
9/28–29	1.6	−30			
		1980			
1/11	1.8	−31	7/2	1.2	−36
2/16	1.9	−134	7/5	3.5	−36
2/22	0.8	−98 ± 5	7/21	3.8	−14 ± 3
3/8	1.2	−40	7/22–23	1.1	−50
3/9–10	1.1	−75	7/29	0.4	−16
3/13–14	2.9	−86	8/1	0.9	−16 ± 2
3/17–18	2.3	−10	8/2–3	2.0	−41 ± 3
3/21–22	8.1	−70	8/5	1.9	−12 ± 1
3/24–25	1.9	−28	8/15	0.8	−27 ± 1
3/29–30	1.5	−98	9/5	0.6	−22
4/4	1.5	−66	9/6	0.8	−37
4/9	6.9	−28	9/17–18	3.7	−27
4/14–15	1.3	−45	9/25–26	0.7	−34
4/27–30	6.7	−45	10/2–3	1.3	−37
5/11–12	1.4	−27	10/3	1.6	−94
5/13	0.7	−46	10/10–11	1.1	−25
5/18–19	1.0	−27	10/25	4.9	−73 ± 5
5/21	0.9	−70	11/9	0.6	−56
6/7	1.4	−16 ± 2	11/17–18	3.6	−92
6/15	0.6	−5 ± 2	11/24	3.7	−54
6/20	0.4	−35 ± 2	11/27–28	2.2	−54
6/29–30	5.7	−48 ± 2	12/15–17	1.4	−105
		1981			
1/6–7	0.8	−149	6/21–22	2.0	−40
2/1–2	4.6	−29	6/25	0.7	−40
2/8–9	0.8	−114	7/1–3	3.5	−24
2/10–11	2.9	−34	7/4–5	4.3	−54
2/19–21	3.8	−63	7/20–21	3.4	−19 ± 1
2/23–24	3.0	−47	7/28–29	0.9	−33
3/30	0.8	−25	8/11–12	0.8	−43 ± 3
4/1–2	2.1	−57	8/30	2.0	−14 ± 6
4/5–6	0.6	0	9/1	1.3	−13 ± 1
4/9	0.6	−16	9/8	4.5	−63
4/14	2.0	−36	9/14–15	0.7	−31
4/23–24	1.1	−15	9/15–16	0.8	−53
4/28–29	1.2	−36	9/22–23	1.2	−22
4/29	1.1	−45	10/1–2	1.6	−20
5/2	0.5	−82	10/6–7	0.7	−26 ± 1
5/10–12	10.7	−54	10/18–19	1.0	−27
5/15–16	1.2	−42	10/23–24	2.7	−50
5/29	1.5	−18	10/26–28	3.8	−52 ± 1
6/3–4	0.5	−30	11/6	1.0	−41
6/12–13	0.8	−56	11/15–18	1.2	−65
6/14	1.7	−71	11/19–20	1.5	−40
6/15	1.1	−58	12/1–2	3.2	−53
6/20	0.9	−30	12/14	1.7	−170

Table 1. (Continued)

Date	Amount (cm)	δD (per mil)	Date	Amount (cm)	δD (per mil)
		1981			
12/15	2.1	−160	12/23	1.4	−29
12/17–18	0.7	−105	12/27	0.9	−60
		1982			
1/1	1.7	−105	6/17	1.1	−28
1/4	6.1	−60	6/22–23	1.4	−81
1/13–14	1.3	−155	6/29	2.3	−49
1/23	1.9	−74	7/20	3.5	−35
1/30–2/1	2.9	−11	7/28	3.3	−37
2/3–4	4.3	−49	7/29	0.5	−25
2/9	1.4	−126	7/31	0.7	−32
2/19–20	1.0	−106	8/9	1.9	−46
3/4–5	1.1	−56	8/9	0.9	−26
3/6–8	2.2	−105	8/17	0.4	−49
3/9	0.5	−75	8/25	2.1	−42
3/17	1.3	−26	9/2	0.5	−46
3/26	0.8	−48	9/2–3	0.5	−25
3/31	1.7	−24	9/15–16	3.9	−20
4/3	3.3	−28	9/22	0.6	−75
4/6	2.0	−129	9/22–23	2.9	−68
4/17–18	2.0	−43	9/27	1.9	−50
4/26	3.6	−70	10/7–9	1.3	−43
5/19	0.7	−30	10/13–14	0.9	−44
5/20	0.6	−43	11/4–5	3.7	−57
5/22–24	2.1	−30	11/12–13	3.0	−42
5/29	3.9	−64	11/28–29	1.1	−58
5/31	1.1	−50	12/16	2.9	−32
6/2	1.1	−56	12/19–20	0.4	−84
6/5–7	10.0	−65	12/23–24	0.9	−48
6/13–14	3.7	−54			
		1983			
1/5–6	0.9	−29	5/29–30	2.0	−22
1/10–11	3.5	−42	5/30	1.6	−21
1/15	1.8	−72	6/4	3.5	−41
1/23	3.6	−53	6/6–7	3.5	−29
1/30	0.7	−96	6/27–29	3.9	−46
2/2–3	4.0	−62	7/24	2.3	−63
2/6–8	2.7	−105	8/11–12	3.8	−32
2/11–12	2.5	−170	8/18	0.6	−7
3/1–2	1.4	−78	8/28	1.3	−40
3/5	0.5	−65	8/29	0.5	−43
3/7–9	4.7	−56	8/29	0.6	−34
3/10–11	1.8	−90	8/30–31	0.5	−51
3/12	0.7	−148	9/21	5.9	−58
3/18–20	6.3	−42	9/22	0.6	−28
3/21	2.9	−63	9/30	0.9	−89
3/27–28	2.9	−73	10/5	1.0	−20
4/3	3.1	−55	10/12	2.7	−27
4/7–8	0.5	−32	10/13–14	0.6	−21
4/8	0.6	−49	10/18–19	1.4	−95
4/10–11	4.7	−68	10/23–24	2.8	−47
4/15–16	7.8	−67	11/10–11	2.9	−54
4/19–20	3.4	−137	11/15–16	1.9	−62
4/24–26	6.1	−71	11/21	1.9	−37
4/30	0.4	−10	11/23–25	4.6	−82
5/1–2	0.7	−61	11/28–29	2.5	−41
5/8–9	1.2	−44	12/4	1.8	−98
5/15	3.4	−18	12/6–7	2.7	−70
5/16	0.5	−86	12/12–14	8.3	−35
5/19–20	1.2	+2	12/22	2.3	−97
5/26–27	4.4	−46	12/28–29	2.6	−58

circulation patterns. These year-to-year relationships are best revealed when one season of a year is compared to the same season of another year. In the discussions that follow each year is broken up into three seasons: January to April, May to August, and September to December. In part, the justification for this breakdown can be seen by examining Fig. 9. The January to April time period shows the best correlations between temperature and isotope values. The May to August time period was chosen for a combination of reasons. Firstly, this time period is when trees form most of the cellulose that goes into tree rings. Dry-site trees use only hydrogen from growing season precipitation to form these tree rings (WHITE, 1983; WHITE *et al.*, 1985). Therefore, any climate signal present in May to August precipitation will be recorded in the tree-ring cellulose (LAWRENCE and WHITE, 1984). Secondly, the best correlations between amount and isotopic values are for this time period, although considerable scatter is observed (Fig. 9).

Changes in storm tracks are most easily correlated with the isotopic composition of precipitation from one year to the next in the January to April time period. In Fig. 14 the storm tracks for January to April for the years 1978 to 1983 are shown along with the average isotopic composition of the storms. The numbers on each of the storm tracks give the time sequence of the storms. As can be seen, the year with the most coastal storm track positioning (1978) gives the lowest isotope values, whereas the most inland storm positioning (1981) gives the highest isotope values. Other years have intermediate positioning and intermediate isotope values (see Fig. 14). In 1982 and 1983, however, the average storm positions were different yet the average isotope values are the same. A temperature difference between 1982 and 1983 accounts for this apparent discrepancy. In 1982 the average temperature was lower than in 1983.

Although storms were more coastal in 1983 than in 1982, it was warmer at Mohonk Lake and storms were weaker. The greater number of dashed lines shown in the 1983 map indicates that storms were weak and difficult to track. In a detailed analysis of winter storms GEDZELMAN and LAWRENCE (1982) describe how isotopic changes in storms are related to storm structure. The farther up a warm frontal surface moist air has to move before reaching the precipitation site, the lower the isotope values at the precipitation site. Therefore, on average, colder winters have better developed warm frontal surfaces and thus exhibit lower isotope values.

Year-to-year variations of isotopic composition in the May to August time period relate best to the average position of fronts during the precipitation event. In Fig. 15 the average positions of fronts at the midpoint of all precipitation events for the years 1977 to 1983 are shown. The error bars represent the standard error of the mean position of the fronts. For six of the seven years a clear relationship between frontal position and the average hydrogen isotopic composition of the precipitation is evident. When Mohonk was located south of the mean frontal position, 1977 and 1980, δD values were high. When Mohonk was located north of the mean frontal position, 1978 and 1982, δD values were low. When Mohonk was located near the average position of the fronts, 1979 and 1980, δD values were intermediate. GAMBELL and FRIEDMAN (1965) observed such a relationship for a single storm in which precipitation formed along a cold front.

The year 1981 is anomalous. A greater number of warm fronts produced precipitation than in other years. This is partly reflected in the more east-west positioning of the average frontal positions compared with the other years. The abundance of warm fronts in 1981 suggests better development of extratropical cyclones. The summer rain patterns can be classified as cyclonic or convective; the cyclonic patterns display the lower isotopic values (GEDZELMAN *et al.*, 1987). Finally, the September to December time periods for the years 1977 to 1982 were investigated in an attempt to find correlations between isotopic composition of precipitation and atmospheric circulation patterns, but no good correlations were found. This time period also showed weaker correlations with amount or temperature than did the other seasons (Fig. 9).

CONCLUSIONS

The aim of this paper was to focus attention on finding locations where the climate-isotope relationship in precipitation is simple. Under such conditions proxy recorders of climate such as tree rings, dripstone deposits in caves, and fresh-water fossils might be utilized to give past climatic information. To date, it can be seen from the examination of IAEA isotope data that year-to-year correlations of isotope values with precipitation amount and temperature are generally poor if whole-year time periods are considered. The exceptions are amount-isotope correlations at Guam and possibly at Mohonk Lake, New York. The conclusion that can be drawn is that proxy recorders of climate that obtain their isotopic imprint from ground waters may only be used successfully in certain specific locations. If the "good" sites are to be discovered, long-term precipitation collections will have to be carried out at many more localities in the future.

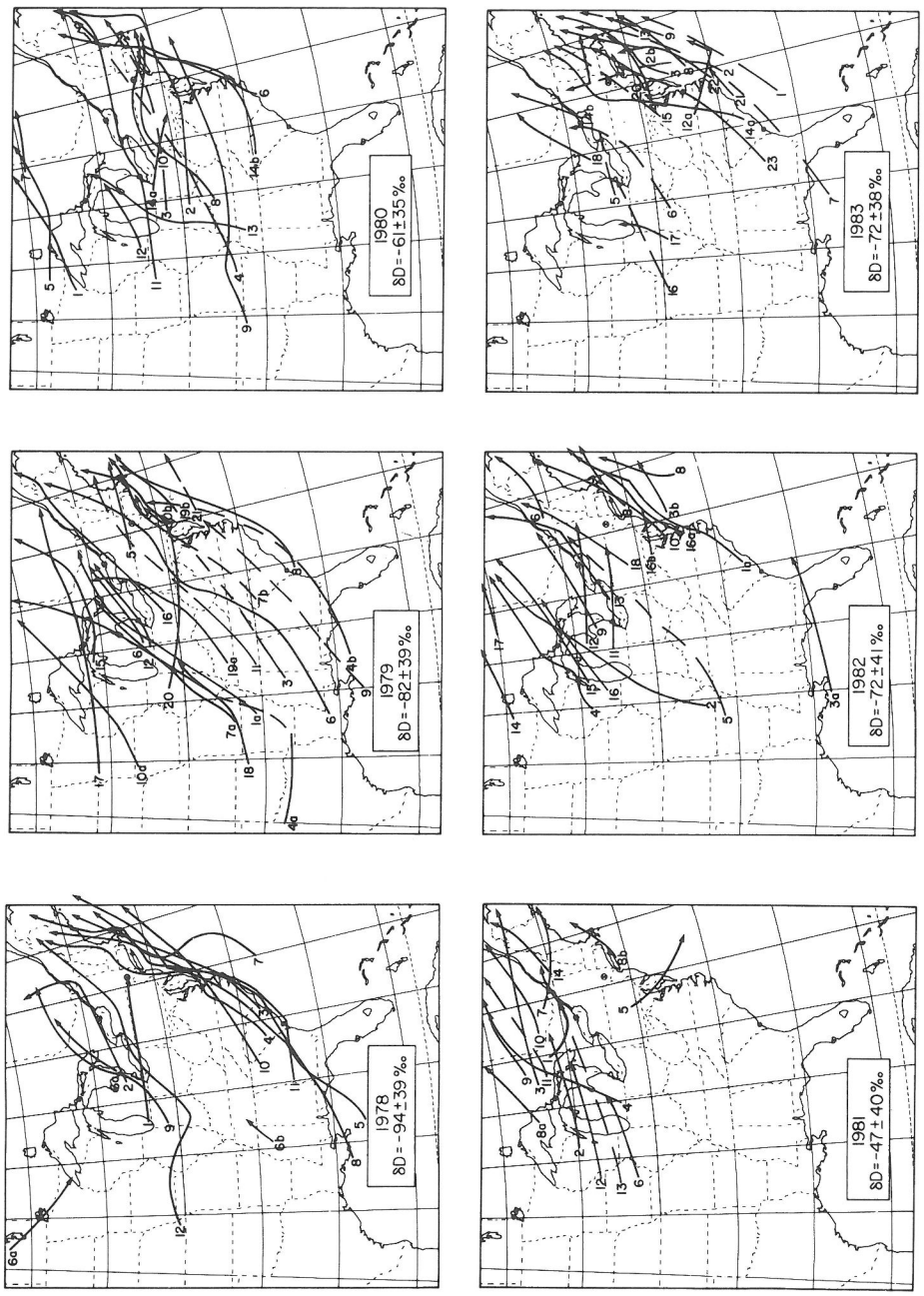

FIG. 14. Storm tracks, showing loci of the low pressure centers of extratropical cyclones occurring between January and April for the years 1978 to 1983. The numbers at the beginning of the tracks give the time sequence of storms for each year. Dashed storm tracks indicate weaker storms which were more difficult to plot. The average hydrogen isotopic composition (unweighted) and standard deviation of all of the storms for each year are also given expressed in δD. The location of Mohonk Lake, New York is shown by an × within a circle.

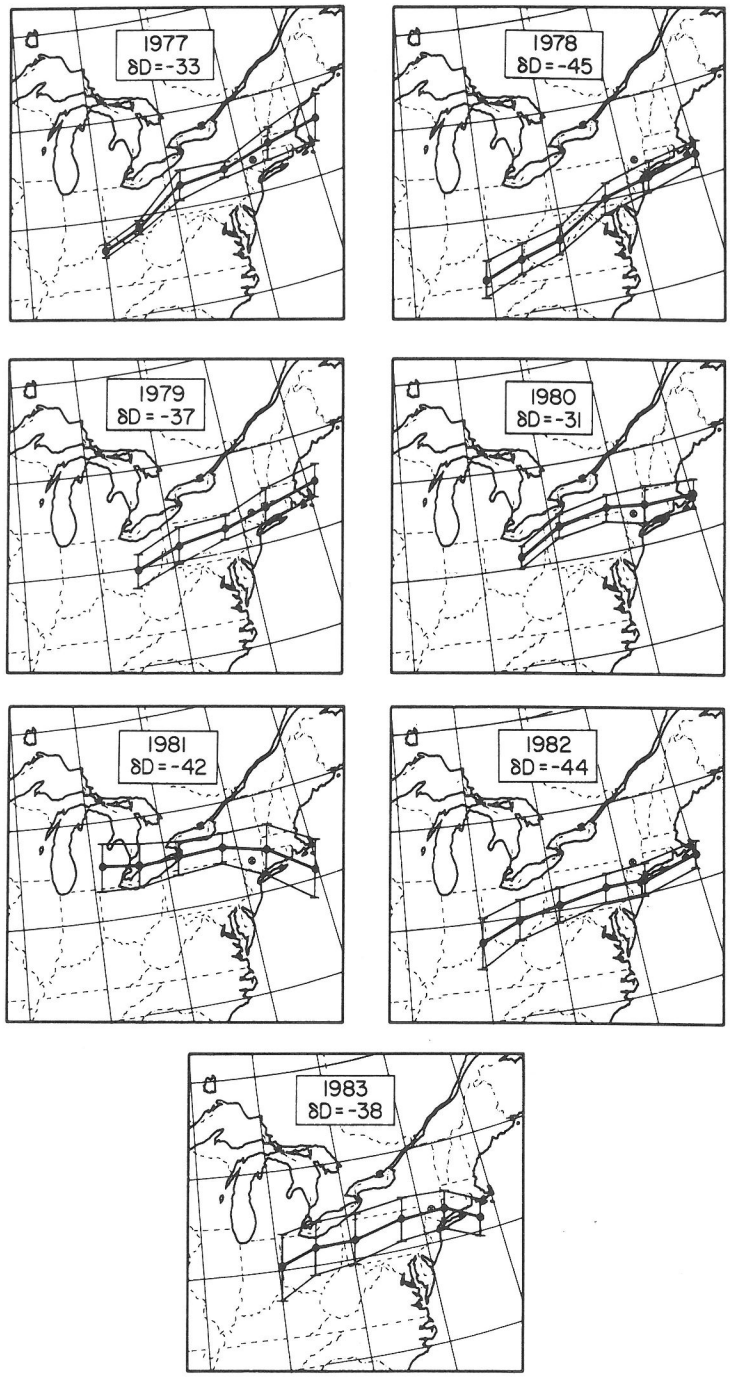

FIG. 15. Average frontal position at the mid point of all precipitation events occurring at Mohonk Lake, New York for the time period May to August for the years 1977 to 1983. The error bars give standard error of the mean position of the fronts. The location of Mohonk Lake is indicated by an × within a circle. The average δD value (unweighted) of all storms for each year is also given.

In order to further demonstrate the potential of Guam and Mohonk Lake as locations to make further paleoclimate studies, the isotope data from these locations were modelled to simulate a ground water isotope-climate signal (Figs. 16 and 17). Twelve-month totals of precipitation are plotted as a function of time for both Guam and Mohonk Lake, and these rolling totals exhibit considerable change over time. Plotted above these values in each figure are twelve-month rolling means of the annual isotope values. Visually, it can be seen that a good correlation exists between the two rolling parameters. The Pearson, Kendall, and Spearman correlation coefficients (DEMIRMEN, 1976) for each data set are given, and the values of the correlation coefficients are typically high. This suggests that proxy recorders of climate that utilize ground waters in these areas may provide climatic information about past precipitation patterns.

Another possibility for retrieving climatic information from proxy recorders of isotopic signals in precipitation is to find proxy recorders that only utilize part of a year's precipitation. Tree rings from trees that grow on dry sites offer such a possibility (WHITE, 1983; LAWRENCE and WHITE, 1984; WHITE *et al.*, 1985). Of the stations examined in this report, Moskva, U.S.S.R., seems to offer the best prospect for isotopic studies of dry-site trees. Both temperature and precipitation amounts show good correlations with the isotopic composition of summer rain. During cooler and wetter summers in Moskva, isotope values are lower than in warmer and drier summers (Fig. 7). If other proxy recorders utilize only one season's precipitation, several other locations may also offer good prospects.

Isotopic studies of precipitation from individual storms collected over long periods should be undertaken at more locations. In this way whole-year comparisons from year to year may be discovered to yield good correlations with climatic variables. The polar regions are particularly promising. If individual storms are studied and isotope changes can be related to changes in meteorological parameters, the isotope data already produced from ice cores might yield a much better understanding of polar climate change. The tropical regions of the Earth are another promising area because a strong amount-isotope correlation may be present at some locations. Such an isotopic relationship may be related to changes in atmospheric circulation patterns, which in turn may be related to changes in the temperatures of the oceans' surface waters. The possibility of discovering a historical record of the El Niño in the Pacific Ocean is exciting. Isotopic studies of fresh-water fossils may offer good prospects because seasonal temperature variations are minimal in the tropics.

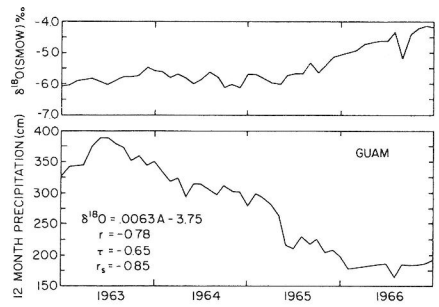

FIG. 16. The rolling twelve-month weighted mean of oxygen isotopic composition of precipitation from Guam, plotted as a function of time. The rolling twelve-month precipitation amounts are also plotted. The Pearson, Kendall, and Spearman correlation coefficients (DEMIRMEN, 1976) of the compared parameters are also given.

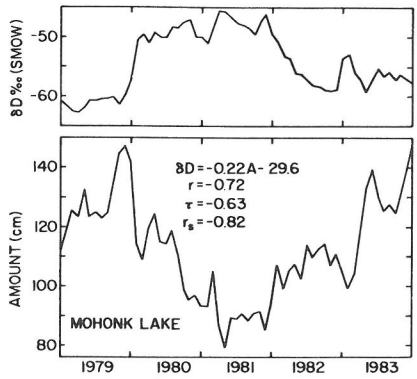

FIG. 17. The rolling twelve-month weighted mean of hydrogen isotopic composition of precipitation from Mohonk Lake, New York plotted as a function of time. The rolling twelve-month precipitation amounts are also plotted. The Pearson, Kendall, and Spearman correlation coefficients (DEMIRMEN, 1976) of the compared parameters are also given.

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