VII. LONG-TERM CLIMATE VARIABILITY AT THE WASTE ISOLATION PILOT PLANT

Peter N. Swift

Tech Reps, Inc.
5000 Marble Avenue NE
Albuquerque, New Mexico 87110

ABSTRACT

Changes in climate during the next 10,000 years (10 ka), particularly long-term increases in precipitation, may affect performance of the Waste Isolation Pilot Plant (WIPP). Data from deep-sea sediments indicate that fluctuations in global climate corresponding to glaciation and deglaciation of the northern hemisphere have been regular in both frequency and amplitude for at least 780 ka. Field data from the American Southwest and global climate models indicate that the coolest and wettest conditions in the past at the WIPP have occurred during glacial maxima, when the North American ice sheet reached its southern limit roughly 1200 km north of the WIPP and deflected the jet stream southward. Field data indicate that average precipitation in the Southwest during the last glacial maximum 22 to 18 ka BP (before present) was approximately twice that of the present. Mean annual temperatures were probably no lower than 5°C below present. Driest conditions (precipitation approximately 90 percent of present) occurred 6.5 to 4.5 ka BP, after the ice sheet had retreated to its present location. Wet periods of unknown duration have occurred since the retreat of the ice sheet, but none have exceeded glacial limits. Modeling of glacial periodicity suggests that, barring anthropogenic controls, the next glacial maximum may occur in approximately 60 ka. Global climate models suggest that anthropogenic effects (e.g., warming caused by an increased greenhouse effect) will not result in a significant increase in precipitation at the WIPP. The climate of the last glacial maximum is therefore suitable for use as a cooler and wetter limit for variability during the next 10 ka.

Introduction

Changes in the climate of southeastern New Mexico during the next 10,000 years (10 ka) may affect the performance of the Waste Isolation Pilot Plant (WIPP). In particular, changes in the average level of precipitation could affect recharge to the Rustler Formation and the currently unsaturated overlying units. Hydrologic models indicate that an increase in recharge may increase flow through the Culebra Dolomite Member of the Rustler Formation, reduce ground-water travel time from the vicinity of the repository to the accessible environment, and, in the event of an intrusion, increase the cumulative radionuclide release to the accessible environment (Brinster, 1991). Climatic changes may also affect agricultural uses of the area. Data about the nature of expected climatic changes are essential for assessments of repository performance.

MODERN CLIMATE

At present, the climate at the WIPP is arid to semi-arid. Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (Hunter, 1985). At Carlsbad, 38 km west of the WIPP and 100 m lower, 53-year (1931-1983) annual means for precipitation and temperature are 32 cm/yr and 17.1°C (University of New Mexico, 1989). Short-term variation about the annual means can be considerable, and historic weather data cannot be used to predict long-term climatic shifts. For example, the 105-year (1878 to 1982) precipitation record from Roswell, 135 km northwest of the WIPP and 60 m higher, shows an annual mean of 27 cm/yr with a high of 84 cm/yr and a low of 11 cm/yr (Hunter, 1985).

The climate of southeastern New Mexico is monsoonal: most of the precipitation falls in late summer, when solar warming of the continent creates an atmospheric pressure gradient that draws moist air inland from the Gulf of Mexico (Cole, 1975). The coincidence of precipitation and temperature maxima is typical of a monsoonal climate (Figure VII-1). Much of the rain falls during localized and often intense summer thunderstorms, and winters are cool and generally dry. Both temperature and precipitation are dependent on elevation, and climates vary according to local topography. At lower elevations throughout the region, including the vicinity of the WIPP, potential evaporation greatly exceeds precipitation. Freshwater pan evaporation in the region is estimated to exceed 274 cm/yr (Hunter, 1985). Effective moisture, defined by Neilson (1986) as precipitation minus potential losses to evaporation and transpiration by plants, is extremely limited most of the year. Surface runoff and infiltration of rainwater into the subsurface are also limited. Hunter (1985) concluded from a literature review that within the vicinity of the WIPP, on the average, 96 percent of precipitation is lost to evapotranspiration. Evapotranspiration values may be significantly higher or lower locally.

CLIMATIC CHANGE

Because currently available long-term climate models are incapable of resolution on the scales required (e.g., Hansen et al., 1988; Mitchell, 1989), it is not possible to predict the climate of southeastern New Mexico for the

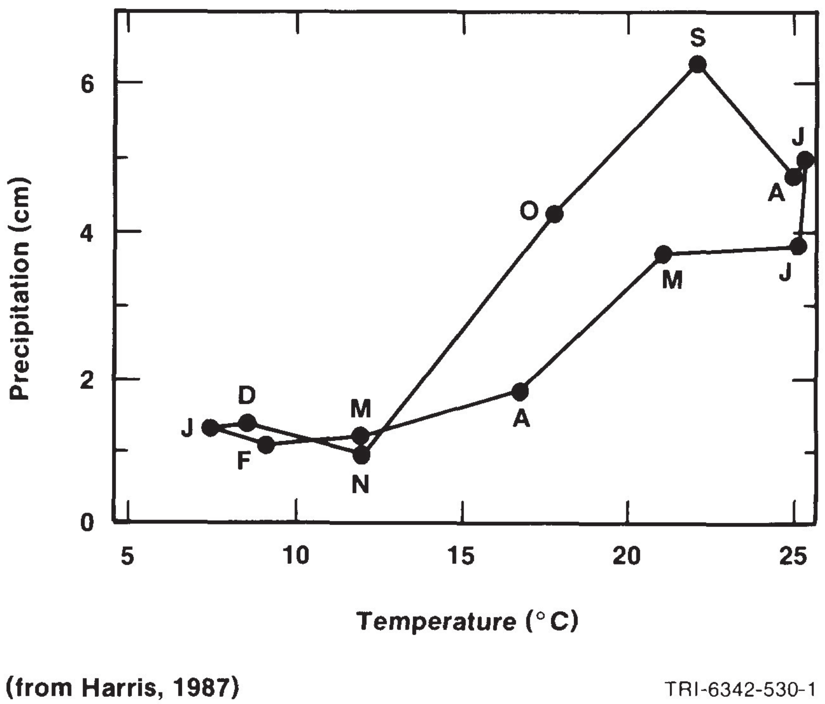

Figure VII-1. Climatograph Showing Thirty-Year (1931-1960) Monthly Precipitation and Temperature Means for Carlsbad Caverns (Harris, 1987). Carlsbad Caverns are approximately 65 km southwest of the WIPP and 300 m higher.

next 10 ka. Instead, this report reviews evidence of past climatic changes in the region, and establishes limits on future precipitation based on known and modeled past extremes. Much of the available paleoclimatic data only record long-term average levels of precipitation, and these limits do not reflect the high variability apparent in the modern short-term data. The precipitation record presented here primarily reflects gradual shifts in long-term mean values, as is appropriate for recharge modeling.

A fundamental assumption, analogous to that made by Spaulding (1985) in his study of climatic variability at the Nevada Test Site, is that the climatic extremes of the next 10 ka will not exceed those associated with the glaciations and deglaciations that have recurred repeatedly in the northern hemisphere since the late Pliocene approximately 2.5 million years ago (2.5 Ma BP). The assumption is based on strong evidence, reviewed briefly in this report, which shows that past glacial cycles have been consistent in both intensity and frequency. The possibility that human-induced changes in the composition of the earth's atmosphere may influence future climates complicates projections of this cyclic pattern into the future, but, as presently modeled, fluctuations during the next 10 ka will remain within past limits.

None of the currently available models of the greenhouse effect predict long-term global climatic changes larger than those during the last 2.5 Ma (e.g., Mitchell, 1989). Furthermore, a short-term increase in the greenhouse effect appears unlikely to degrade predicted repository performance. The highest past precipitation levels in the American Southwest, up to twice those of the present, occurred during full-glacial conditions associated with global cooling (e.g., Van Devender et al., 1987; other sources cited below). Greenhouse models, however, predict average equilibrium global warming of 1.8 to 5.2°C with carbon dioxide concentrations twice present levels (Mitchell, 1989), a condition which could delay the start of renewed glaciation. Model predictions of future precipitation trends accompanying greenhouse warming are less consistent and less reliable than temperature predictions, but none suggest significantly higher levels of precipitation in southern New Mexico than those of the present (Washington and Meehl, 1984; Wilson and Mitchell, 1987; Schlesinger and Mitchell, 1987). Because long-term increases in recharge are improbable without increases in precipitation, the highest risk climatic change that will be considered here is, therefore, a return to the glacial extremes of the past.

Data that can be used to interpret paleoclimates in the American Southwest come from a variety of sources and indicate an alternation of arid and sub-arid to subhumid climates throughout the Pleistocene.[1] Prior to 18 ka BP, radiometric dates are relatively scarce, and the record is incomplete. From 18 ka BP to the present, however, the climatic record is relatively complete and well constrained by radiocarbon dates. This report cites extensive floral, faunal, and lacustrine data from the Southwest that permit reconstructions of precipitation and temperature during the late Pleistocene and Holocene. These data span the transition from the last full-glacial maximum to the present interglacial period, and, given the global consistency of glacial fluctuations as described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

Variability in Global Climate over the Last 2.5 Million Years

Core samples of datable marine sediments provide a continuous record that reveals as many as 50 glaciation/deglaciation events in the last 2.5 Ma. Specifically, correlations have been made between major glacial events and three independent variables: oceanic ratios of $^{18}O/^{16}O$ as measured in the

1 The Pleistocene Epoch began approximately 1.6 Ma BP (Geological Society of America, 1984). Following the usage of Van Devender et al. (1987), I have selected 11 ka BP as the end of the Pleistocene Epoch and the beginning of the present Holocene Epoch. Some authors prefer 10 ka BP for the Pleistocene/Holocene boundary.

remains of calcareous foraminifera, the record of past sea-surface temperatures as determined from planktonic assemblages, and the total percent calcium carbonate ($CaCO_3$) in individual layers of oceanic sediment (Ruddiman and Wright, 1987).

Oxygen isotope ratios provide the most direct evidence because they reflect past volumes of glacial ice (Imbrie et al., 1984). Evaporation fractionates ^{18}O and ^{16}O populations in water, producing a vapor-derived meteoric facies relatively enriched in ^{16}O and an oceanic facies relatively enriched in ^{18}O. Glacial ice sheets store large volumes of meteoric water, preventing the remixing of the isotope fractions and significantly altering $\delta^{18}O$ values in the world's oceans.[2] Foraminifera preserve samples of past $\delta^{18}O$ values when they extract oxygen from sea water and incorporate it into calcareous body parts, and abundant fossil remains permit the construction of detailed records such as that shown in Figure VII-2a, covering the last 780 ka. High positive values of $\delta^{18}O$ reflect glacial maxima, and negative values reflect warm interglacial periods. Because the largest volumes of ice were in the North American sheet, $\delta^{18}O$ fluctuations can be interpreted directly as a first order record of North American glaciation and deglaciation (Mix, 1987; Ruddiman and Wright, 1987). Because the correlation is quantitative, the isotopic record indicates that most glacial events, including the most recent one, have been of roughly equivalent intensity. It also indicates that the present value is at or near that of a glacial minimum.

Sea-surface temperature records, although not as closely tied to glacial events, show the same alternating pattern. Temperatures at the surface of northern hemisphere oceans, as determined from the fossil assemblages of planktonic foraminiferal species, were measurably colder during glaciation and warmer during interglacial periods (Ruddiman, 1987). Plots of total $CaCO_3$ content of deep marine sediments confirm the pattern. Major glacial peaks, as distinguished from the pelagic calcareous background by the high silicic signal from ice-rafted continental debris, coincide with those determined from isotope and temperature data (Ruddiman and Wright, 1987).

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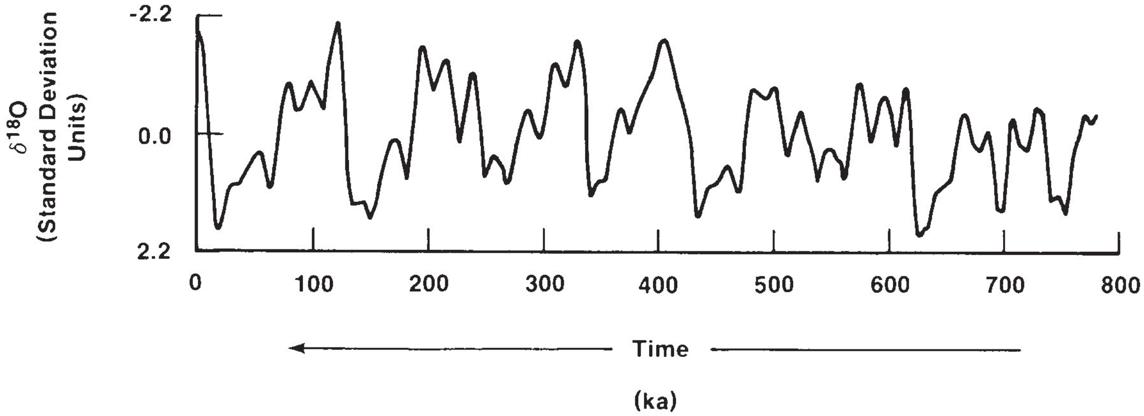
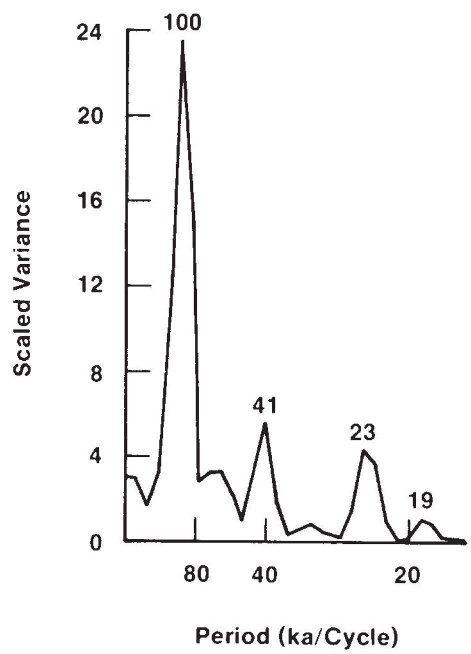
2 By convention, $^{18}O/^{16}O$ ratios are reported as:

$$\delta\,^{18}O \equiv 1000 \times \frac{(^{18}O/^{16}O_{sample} - {}^{18}O/^{16}O_{reference})}{^{18}O/^{16}O_{reference}}$$



a. $\delta^{18}O$ variations from five deep-sea core samples. Data have been normalized, stacked, and smoothed with a 9-point Gaussian filter (Imbrie et al., 1984).



b. Spectral analysis of $\delta^{18}O$ record in Figure a, showing periodicity of glaciation and deglaciation (after Imbrie, 1985).

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Figure VII-2. Foraminiferal $\delta^{18}O$ Record of the Last 780,000 Years.

Complete causes for glaciation and deglaciation are complex and not fully understood (Ruddiman and Wright, 1987), but the strong periodicity of the $\delta^{18}O$ record indicates that climatic alternations have been consistent in the past. Spectral analysis of the $\delta^{18}O$ curve for the last 780 ka shows that within that time the primary control on the periodicity of glacial events has been variation in global insolation (the amount of energy received from the sun) caused by irregularities in the earth's orbit (Figure VII-2b). Glacial intervals of 19, 23, 41, and 100 ka correspond to calculated intervals between northern hemisphere summer insolation minima of 19 and 23 ka related to the precession of the earth's axis, 41 ka related to the tilt of earth's axis, and 94, 125, and 413 ka related to eccentricity of the earth's orbit (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984; Imbrie, 1985). Calculations based on astronomical observations indicate that orbital parameters have not changed significantly in the last 5 Ma (Berger, 1984), and geological evidence suggests they may have been stable for at least 300 Ma (Anderson, 1984; Heckel, 1986).

Longer term global climatic changes, such as the beginning of the present pattern of glaciation and deglaciation 2.5 Ma BP, are in part controlled by changes in the configuration of the earth's continents, which in turn controls both global circulation patterns and the potential distribution of ice sheets (e.g., Crowell and Frakes, 1970; Caputo and Crowell, 1985). Continental masses move at plate-tectonic rates of centimeters per year, several orders of magnitude too low to affect glacial processes within the next 10 ka. Vertical uplift or subsidence of large continental regions may also affect global climate by changing circulation patterns (e.g., Boulton, 1989; Ruddiman and Kutzbach, 1989), but maximum uplift rates are at least an order of magnitude too low to change present circulation patterns within the next 10 ka.

This long-term stability of the cycles of glaciation and deglaciation provides the basis for concluding that climatic extremes of the next 10 ka will remain within past limits. The relative amplitudinal consistency (Figure VII-2a) implies that future glaciations will be comparable in severity to past ones. The periodicity of the pattern indicates that, although glacial minima such as that of the present are relatively brief, glacial advances are slow, and the next maximum will not occur for many tens of thousands of years. Predictions about the precise timing of future glacial events are complicated by uncertainties about feedback processes involved in the growth of ice sheets, but extrapolation of the isotopic curve using a relatively simple model for nonlinear climate response to insolation change suggests that, in the absence of anthropogenic effects, the next glacial maximum will occur in approximately 60 ka (Imbrie and Imbrie, 1980). Combined with the climatic data discussed below, these observations justify the choice of the late-Pleistocene, full-glacial climate as a conservative upper limit for precipitation during the next 10 ka.

Pleistocene and Holocene Climates of the Southwestern United States

Climatic data for the early and middle Pleistocene are incomplete and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum 22 to 18 ka BP. Stratigraphic and pedologic data from several locations (Figure VII-3), however, indicate that cyclical alternation of wetter and drier climates in the Southwest had begun by the early Pleistocene. Fluvial gravels in the Gatuña Formation exposed in the Pecos River Valley of eastern New Mexico indicate wetter conditions 1.4 Ma BP and again 600 ka BP (Bachman, 1987). The Mescalero caliche, exposed locally over much of southeastern New Mexico, suggests drier conditions 510 ka BP, and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions again later in the Pleistocene (Bachman, 1981, 1987). The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas, time correlative to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 Ma BP and continuing to the present (Holliday, 1989a). The duration, frequency, and total number of Pleistocene climatic cycles in the Southwest have not been established.

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from six independent lines of evidence dated using carbon-14 techniques: plant communities preserved in packrat middens throughout the Southwest, including sites in Eddy and Otero Counties, New Mexico (Van Devender, 1980; Van Devender et al., 1984, 1987); pollen assemblages from lacustrine deposits in western New Mexico and other locations in the Southwest (Markgraf et al., 1984; Van Devender et al., 1987); gastropod assemblages from western Texas (Pierce, 1987); ostracode assemblages from western New Mexico (Markgraf et al., 1984); paleo-lake levels throughout the Southwest (Markgraf et al., 1983, 1984; Benson and Thompson, 1987; Holliday and Allen, 1987; Bachhuber, 1989; Waters, 1989; Enzel et al., 1989); and faunal remains from caves in southern New Mexico (Harris, 1987, 1988). Figure VII-3 shows the locations of key sites discussed here and in the references cited.

Because decreases in temperature and increases in precipitation produce similar environmental changes, not all data cited uniquely requires the paleocli-

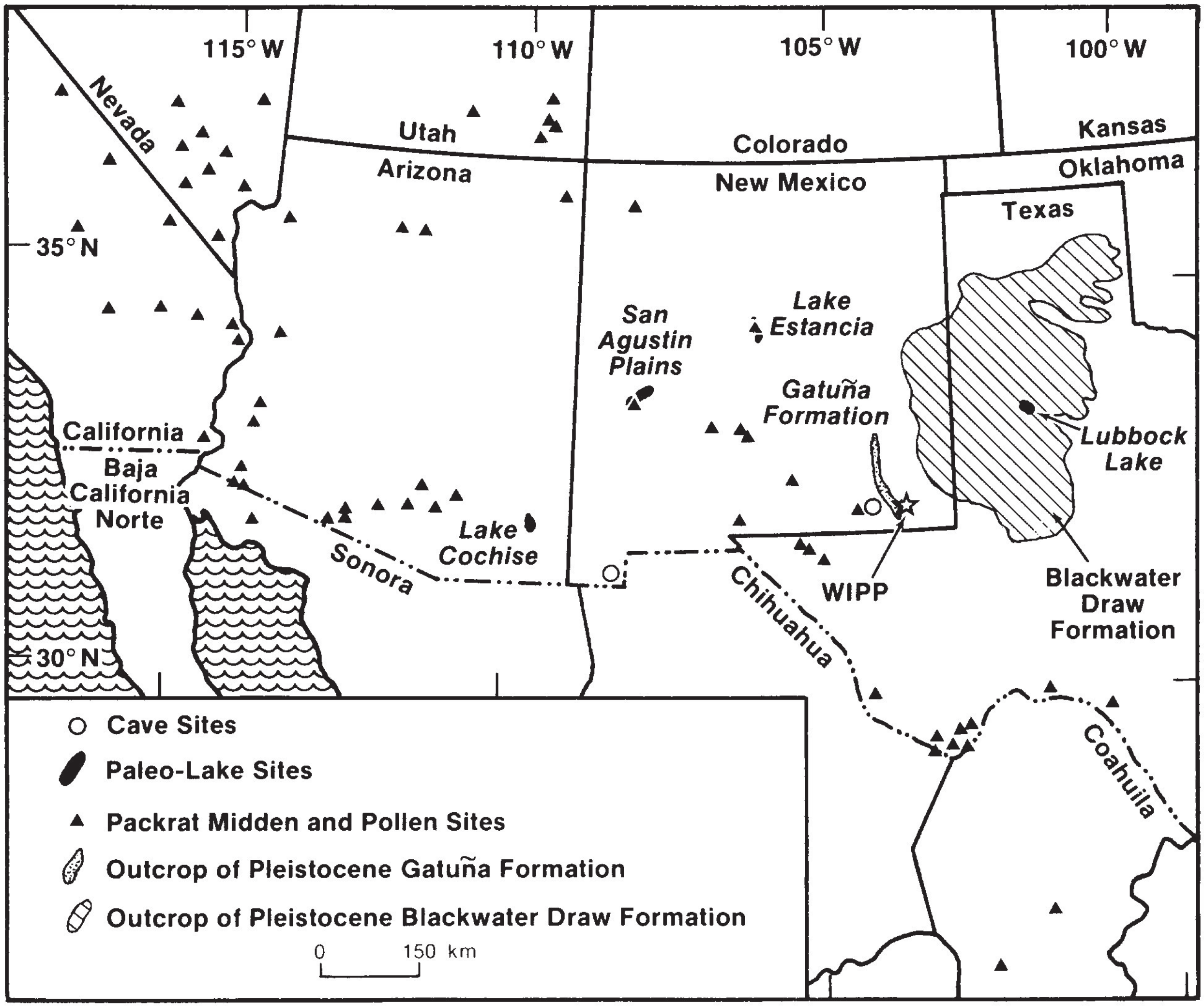

Figure VII-3. Location Map for Paleoclimate Data. Data from Bachman, 1981; Markgraf et al., 1983; Harris, 1987; Pierce, 1987; Van Devender et al., 1987; Waters, 1989; Bachhuber, 1989; Holliday, 1989a.

matic interpretation presented in this report (Figure VII-4). For example, lake-level increases can, in theory, result solely from decreased evaporation at lower temperatures. Interpretations drawn individually from each of the data sets are consistent with the overall trends, however, and the pattern of change is confirmed by global climate models (Spaulding and Graumlich, 1986; Kutzbach and Guetter, 1986; COHMAP Members, 1988). Furthermore, specific floral and faunal assemblages are sufficiently sensitive to precipitation and temperature effects to distinguish between the two (e.g., Van Devender et al., 1987; Pierce, 1987). The paleoclimates described here are those that best explain data from all sources.

Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid-Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise, which are now restricted to warmer climates, suggests hot summers and mild, dry winters (Harris, 1987, 1988). Lacustrine evidence confirms the interpretation of a relatively dry climate prior to and during the glacial advance. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber, 1989), and water depths in lakes at higher elevations in the San Agustin Plains in western New Mexico did not reach a maximum until between 22 and 19 ka BP (Forester, 1987).

Ample floral and lacustrine evidence documents cooler and wetter conditions in the Southwest during the glacial peak (e.g., Benson and Thompson, 1987; Van Devender et al., 1987; Pierce, 1987; Bachhuber, 1989). These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene glaciations advanced farther southwest than northeastern Kansas, and the most recent, late-Wisconsin ice sheet reached its limit in South Dakota, roughly 1200 km from the WIPP (Andrews, 1987). Discontinuous alpine glaciers formed at the highest elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions, and had little influence on regional climate at lower elevations. The closest such glacier to the WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, 220 km to the northwest (Richmond, 1962).

Global climate models indicate that the dominant glacial effect in the Southwest was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north (Figure VII-5) (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986; COHMAP members, 1988). At the glacial peak, major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

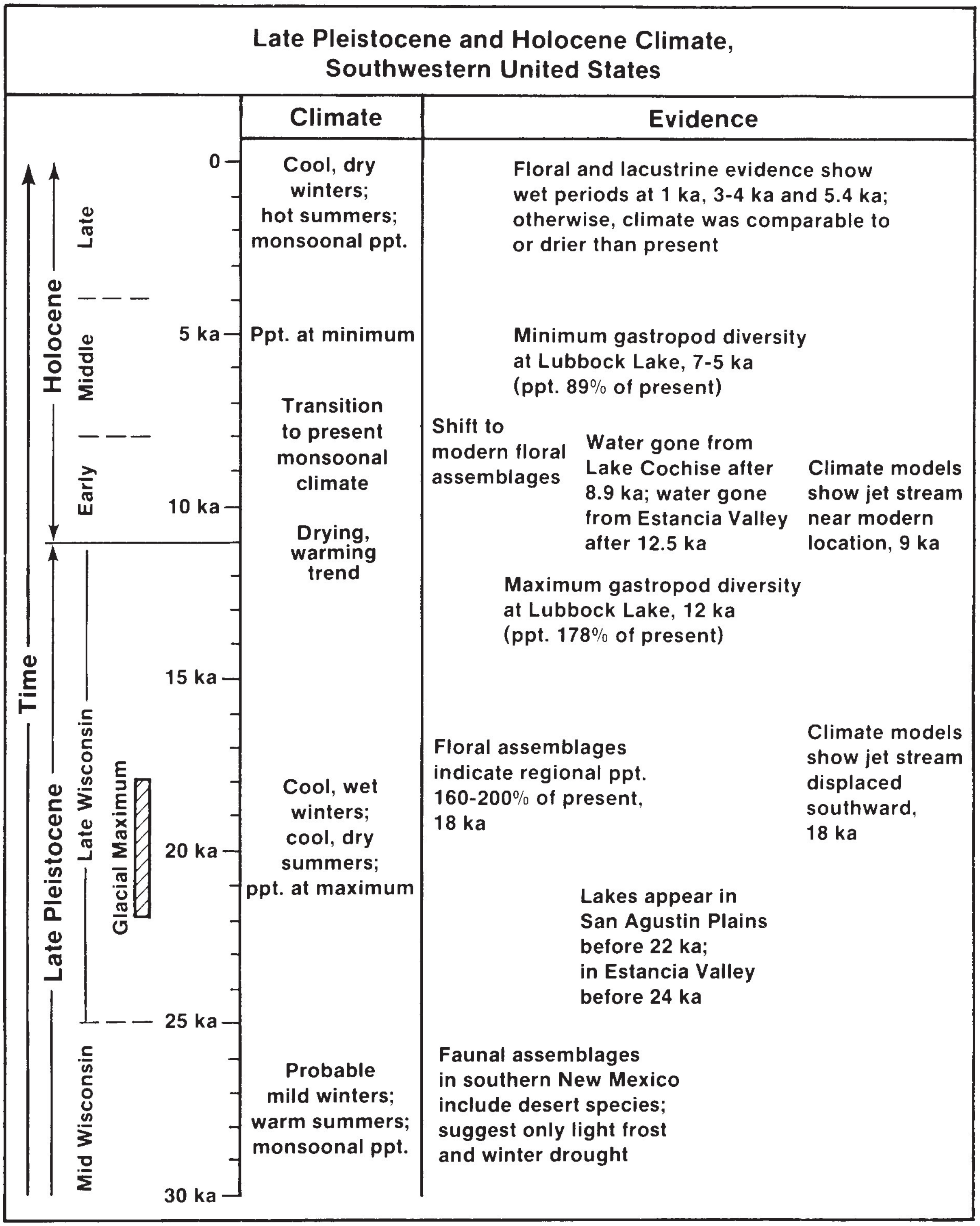

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Figure VII-4. Late Pleistocene and Holocene Climate, Southwestern United States. Time scale after Van Devender et al., 1987. Climate references cited in text.

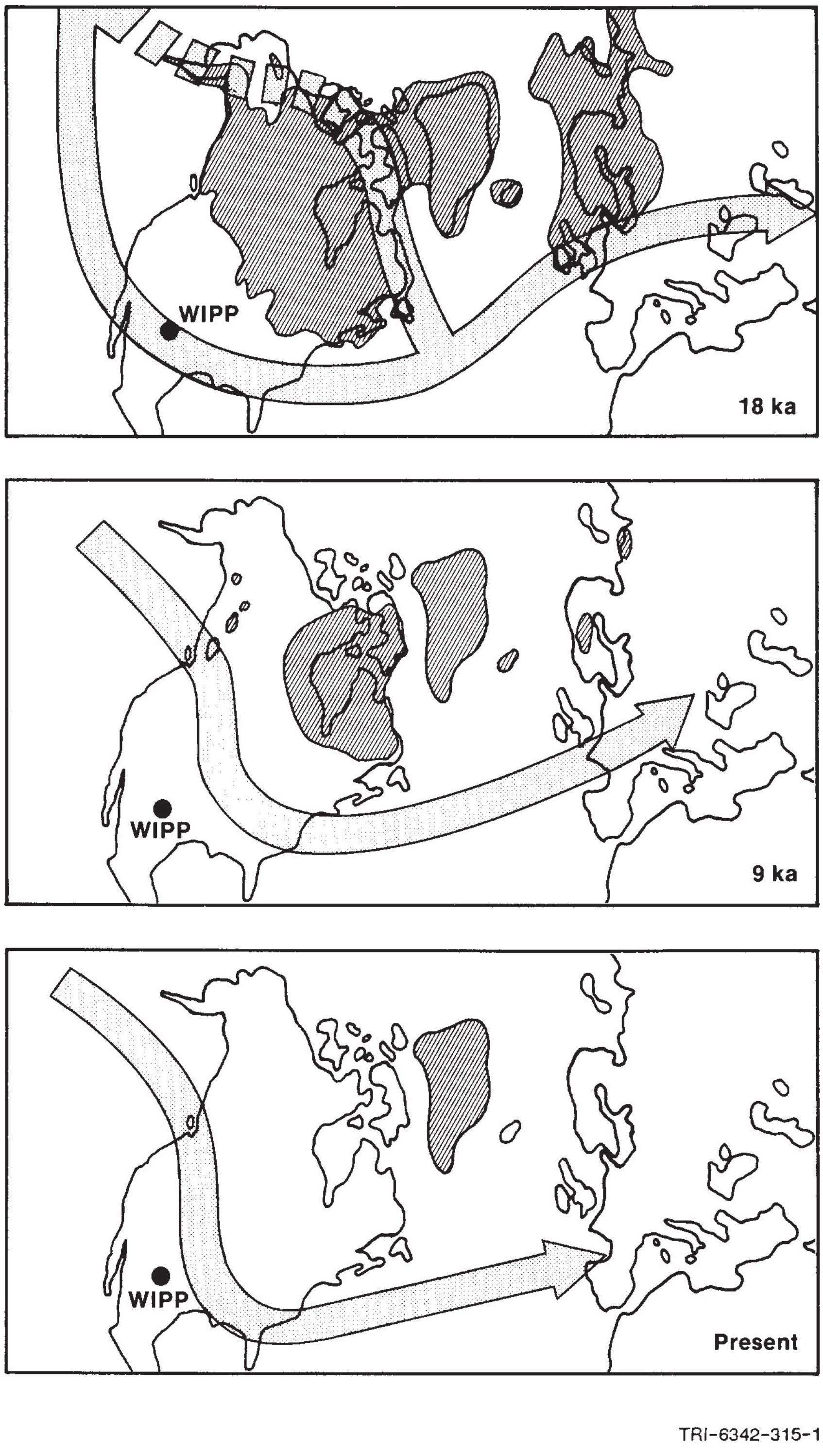

Figure VII-5. Distribution of Northern Hemisphere Ice Sheets and Modeled Average Position of Jet Stream at 18 ka BP, 9 ka BP, and Present (from COHMAP Members, 1988). Ice shown with dark pattern, jet stream shown with arrow (broken where disrupted or weak).

Field evidence does not support the suggestion (Galloway, 1970, 1983; Brakenridge, 1978) that higher lake levels and changed faunal and floral assemblages at the glacial maximum could have resulted solely from lowered temperatures. Plant communities indicate the decrease in mean annual temperatures below present values was significantly less than the 7 to 12°C required by cold and dry climate models (Van Devender et al., 1987). Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5°C below present values (Pierce, 1987). Both floral and faunal evidence indicate annual precipitation throughout the region was 60 to 100 percent more than today (Spaulding and Graumlich, 1986; Pierce, 1987; Van Devender et al., 1987). Floral evidence also suggests winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon. Piñons, oaks, and junipers grew at lower elevations throughout southern New Mexico (Van Devender et al., 1987), probably including the vicinity of the WIPP.

The jet stream shifted northward following the gradual retreat of the ice sheet after 18 ka BP (Figure VII-5), and the climate responded accordingly. By the Pleistocene/Holocene boundary approximately 11 ka BP, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today (Van Devender et al., 1987). Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the ice sheet had retreated into northeastern Canada in the early Holocene.

Evidence for an early Holocene drying trend comes from several sources. Permanent water disappeared from late-Pleistocene lakes in the Estancia Valley after 12.5 ka BP (Bachhuber, 1989), and from Lake Cochise (the modern Willcox Playa) in southeastern Arizona after 8.9 ka BP (Waters, 1989). Water remained in lakes in the higher elevation San Agustin Plains until 5 ka BP, but ostracode assemblages suggest an increase in salinity by 8 ka BP, and the pollen record shows a gradual shift at that location from a spruce-pine forest 18 to 15 ka BP to a juniper-pine forest by 10 ka BP (Markgraf et al., 1984). Packrat middens in Eddy County, New Mexico, indicate that desert-grassland and desert-scrub communities predominated at lower elevations between 10.5 and 10 ka BP (Van Devender, 1980). Soil studies indicate drier conditions at Lubbock Lake after 10 ka BP, although marshes and small lakes persisted at the site until the construction of a dam and reservoir in 1936 (Holliday and Allen, 1987). Based on a decrease in diversity of both terrestrial and aquatic gastropod species, Pierce (1987) estimated a drop in annual precipitation at Lubbock Lake from a high of 80 cm/yr (nearly twice the modern level at that location of 45 cm/yr) at 12 ka BP to 40 cm/yr by 7 ka BP. Coincident with this decrease in precipitation, evidence from vole remains recovered from caves in southern New Mexico (Harris, 1988) and from plant communities throughout the Southwest (Van Devender et al., 1987) indicates a rise in summer temperatures.

By mid-Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show the southern High Plains were drier from 6.5 to 4.5 ka BP (Holliday, 1989b) than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7 to 5 ka BP (precipitation 89 percent of present, mean annual temperature 2.5°C higher than present), with a cooler and wetter period at 1 ka BP (precipitation 145 percent of present, mean annual temperature 2.5°C lower than present) (Pierce, 1987). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period around 990 years ago (Van Devender et al., 1987). Stratigraphic work at Lake Cochise shows two mid-Holocene lake stands, one near or before 5.4 ka BP and one between or before 3 to 4 ka BP, but both were relatively short-lived, and neither reached the maximum depths of the late-Pleistocene high stand that existed before 14 ka BP (Waters, 1989).

Precipitation maxima during these Holocene wet periods were less in both magnitude and duration than those of the late Pleistocene. Enzel et al. (1989) observed comparable Holocene wet periods recorded in playa deposits in the Mojave Desert 3620 ± 70 and 390 ± 90 years ago, and related them to short-term changes in global circulation patterns that resulted in increased winter storm activity in the region. Historical records over the last several hundred years indicate numerous lower intensity climatic fluctuations, some too short in duration to affect floral and faunal assemblages, which may also be the result of temporary changes in global circulation (Neilson, 1986). Sunspot cycles and the related changes in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world (e.g., Lamb, 1972), but the validity of the correlation is uncertain (Robock, 1979). Correlations have also been proposed between volcanic activity and climatic change (Robock, 1979; Bryson, 1989). In general, however, causes for past short-term changes are unknown, and it is difficult at present to accurately predict frequency or amplitude of recurrence. Despite this uncertainty, the past record does support the conclusion that future short-term fluctuations in the Southwest will not be as severe as the long-term climatic changes created by major ice sheets in the northern hemisphere. Full-glacial conditions remain a conservative upper limit for precipitation at the WIPP during the next 10 ka.

Climatic Implications of Data from WIPP Ground-Water Samples

Isotopic data from ground-water samples collected from the Rustler and Dewey Lake Formations in the vicinity of the WIPP are generally consistent with the climatic changes described above. Lambert (1986) and Lambert and Harvey (1987) concluded that although deuterium/hydrogen and $^{18}O/^{16}O$ ratios indicate a meteoric origin for water in the confined aquifers, they are sufficiently distinct from modern surface-water values to suggest that the contribution of modern recharge to the system is slight. Chapman (1986) disagreed with this interpretation, noting similar ratios in the presumably young waters of the Roswell Artesian Basin immediately to the north, and she concluded that stable-isotope data from the WIPP area do not permit interpretations about the age of the ground water. Tritium data are less ambiguous. Low tritium levels in all WIPP-area samples indicate minimal contributions from the atmosphere since 1950 (Lambert, 1987; Lambert and Harvey, 1987). The four internally consistent radiocarbon analyses currently available for water samples from the Rustler and Dewey Lake Formations support this interpretation. Modeled minimum ages in each case are between 12 and 16 ka, suggesting that both units have had little recharge since the period immediately following the late-Pleistocene glacial maximum (Lambert and Harvey, 1987). Lambert and Carter (1987) presented uranium isotope data that also support this interpretation: observed high $^{234}U/^{238}U$ activity ratios require a conservative minimum residence time in the Culebra Dolomite of several thousands of years, and more probably reflect minimum ages of 10 to 30 ka. Chapman (1988) questioned the validity of equating isotope residence times with ground-water age, but agreed that high $^{234}U/^{238}U$ activity ratios occur in regions of low transmissivity, where flow is presumably slower and residence times are longer. Lappin et al. (1989) used ground-water isotope data, along with supporting evidence from $^{87}Sr/^{86}Sr$ ratios in vein fillings, to argue that the Rustler Formation has been essentially a closed hydrologic system for the last 12 ka. In their interpretation, significant recharge last occurred during the late Pleistocene, and the present flow in the Culebra Dolomite reflects the slow draining of the aquifer. If this interpretation is correct, recharge may not occur again until precipitation levels are substantially higher than at present.

Other data suggest that, isotopic evidence notwithstanding, some recharge may be occurring at the present. Anomalous increases in water levels have been observed at 7 WIPP-area wells since hydraulic tests at the H-11 multipad in 1988 (Beauheim, 1989). Vertical recharge from the surface cannot be ruled out as a cause for these rises, although no specific link to precipitation events has been demonstrated. Other possible causes include decreases in discharge from the Culebra Dolomite, changes in reservoir volume related to incomplete recovery from the transient pressure changes associated with the pumping test itself, changes in reservoir volume related to external changes in the regional stress field, or undetected recharge from other aquifers through existing boreholes (Beauheim, 1989). Numerical modeling of ground-water flow in the WIPP area indicates that, although it is hydraulically possible for present flow to reflect late-Pleistocene recharge (Davies, 1989), some component of modern vertical recharge is also compatible with observed conditions (Haug et al., 1987; Davies, 1989). Major ion chemical analyses of Culebra Dolomite water samples support the interpretation of vertical recharge south of the WIPP, where low salinities may be the result of mixing with fresh surface water (Chapman, 1988). Lappin et al. (1989) suggested instead that water chemistry is a function of host rock composition, noting that ground-water salinity correlates well with the distribution of halite in the Rustler Formation.

Questions about vertical recharge to the Culebra Dolomite and the true age of WIPP-area ground water remain unanswered. In the absence of definitive data, this report makes no assumptions about ground-water age, and conservatively allows the possibility of recharge under present climatic conditions.

Summary of Climate Variability

Speculation about future climate variability must be based on observed past fluctuations. The largest global climatic changes in the last 2.5 Ma have been those associated with glaciation and deglaciation in the northern hemisphere. The high degree of consistency in both frequency and intensity displayed in the glacial record indicates that an accurate interpretation of past climatic cycles does provide a useful guide for estimating future changes.

Geologic data from the American Southwest show repeated alternations of wetter and drier climates throughout the Pleistocene. Floral, faunal, and lacustrine data permit detailed and quantitative reconstructions of precipitation that can be linked directly to glacial events of the late Pleistocene and Holocene. Figure VII-6 shows estimated mean annual precipitation for the WIPP for the last 30 ka, interpolated from the composite regional data cited above and based on present average precipitation at the site of 30 cm/yr (Brinster, 1991). This plot should be interpreted with caution because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages change gradually, and show only a limited response to climatic fluctuations that occur at frequencies higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years (Neilson, 1986). Sedimentation in lakes and playas has

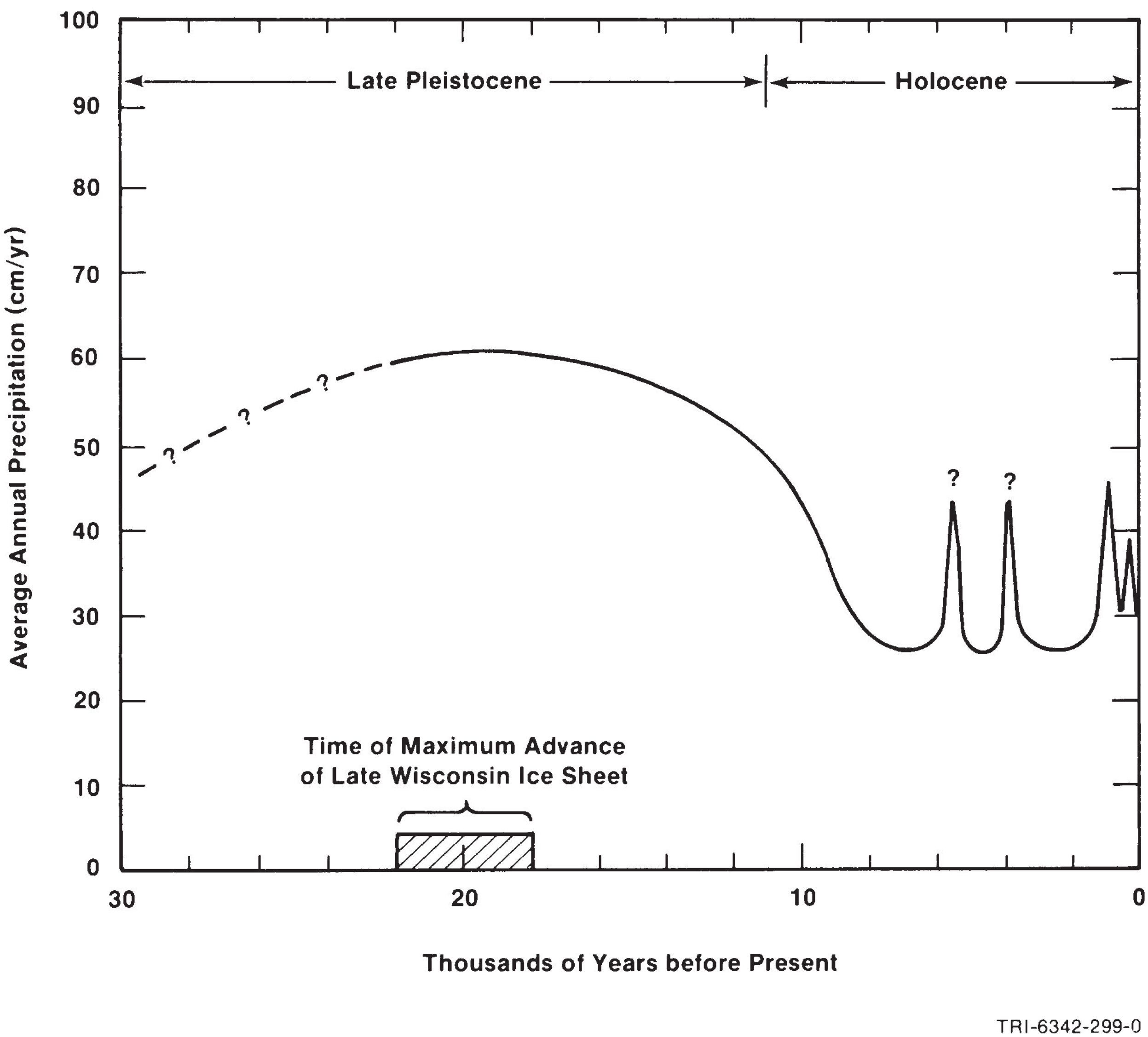

Figure VII-6. Estimated Mean Annual Precipitation at the WIPP during the Late Pleistocene and Holocene. Data from Van Devender et al., 1987; Pierce, 1987; Waters, 1989; and other sources cited in text.

the potential to record higher frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation. Dry playas generally show little response to decreases in precipitation. A more complete record of precipitation would almost certainly show far more variability than that implied by the plot presented here. Specifically, Figure VII-6 may fail to record abnormal precipitation lows during the Holocene, and it may also underestimate the number of high-precipitation peaks during the same period. It is also possible that precipitation variability during the Pleistocene was comparable to that of the Holocene, with fluctuations occurring above and below the higher average level indicated in Figure VII-6.

With these observations in mind, three significant conclusions can be drawn from the climatic record of the American Southwest. First, maximum precipitation in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice present levels. Minimum levels may have been 90 percent of present levels. Third, short-term fluctuations in precipitation have occurred during the present, relatively dry, interglacial period, but they have not exceeded the upper limits of the glacial maximum.

It would be unrealistic to attempt a direct extrapolation of the precipitation curve of Figure VII-6 into the future. Too little is known about the relatively short-term behavior of global circulation patterns, and it is at present difficult to accurately predict the probability of a recurrence of a wetter climate such as that of approximately 1000 years ago. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full-glacial conditions is highly unlikely within the next 10,000 years.

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