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SUMMARY OF CLIMATIC INPUT FOR WASTE MANAGEMENT SITE SUITABILITY CRITERIA AND STATE OF PROGRESS

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ABSTRACT

Because groundwater movement can have important effects on buried nuclear wastes, hydrologists need to know if future climatic changes will influence the accuracy of groundwater flow calculations. Groundwater recharge (and therefore groundwater flow) depends on surface water balance. (Surface water balance equals precipitation less losses to evaporation, runoff, and storage.)

To develop input data for modeling future climatic effects, we have made the following simplifying assumptions:

- Climate (and therefore water balance) will behave in the future very much as it has in the past.
- Groundwater recharge responds linearly to precipitation.
- Future long-term climatic changes can be classified into groups or regimes that are similar to those of the past.

Our current research is aimed at providing input data to the Waste Management Program's site suitability task.

INTRODUCTION AND SUMMARY

As scientists explore options for deep geologic disposal of nuclear wastes, the importance of future climate becomes increasingly apparant. Climate, to a great extent, determines the availability of groundwater--the vehicle that could return buried nuclear wastes to the biosphere. This report summarizes the approaches adopted to assess and (eventually) predict future climate and its effects on ground water. This report is presented in three sections:

- The history of climate variation.
- Several causal theories of climatic variation and a predictive model.
- Regional climate reconstruction efforts at Lawrence Livermore Laboratory and at other institutions.

To study future climate, we first looked to the past million years for trends and indicators of things to come. As the study matured, we recognized that anthropogenic activities (specifically, coal burning) could exert a powerful influence on climate.

Ultimately, this research effort will provide two major inputs to the Waste Management Program (WMP):

- An overall assessment of those major features of past climate that must be incorporated in decisions affecting high-level waste management.
- Input to hydrological models used to test the effects of changes in hydrological head induced by climate.

PAST CLIMATIC VARIATION

THE RECORD

Climate obviously changes. The evidence is as blatant as the rock scars created by the advance and retreat of the great glaciers that once covered Europe and North America. We also know that as recently as 10,000 years ago, tropical forests bloomed in today's deserts and we possess other evidence of dramatic climatic change: ocean and lake sediments, tree rings, fossil pollen, and soils.

The science of paleoclimatology commonly provides descriptions of ancient climates. In addition, it can offer direct evidence about the processes behind long-term climate changes.

Figure 1 (NAS, 1974) illustrates general trends in global climate reconstructed by both instrumental and proxy data (tree rings, pollen, etc.). Figure 1a shows the changes in 5-y period average surface temperatures during the past 100 years. Each subfigure extends further into the past; the final subfigure (1e) shows the fluctuations in global ice volume during the past million years (recorded by the changes in isotopic composition of fossil plankton). The relationship between temperatures (or implied temperatures) and regional precipitation (ultimately regional water balance) is discussed in detail later. For the moment, it is sufficient to say that a strong correlation generally exists between temperature and precipitation although the correlation may be either positive or negative in different regions. Table 1 (NAS, 1974) lists the various proxy source of paleoclimatic data and the climatic inferences that can be made using variables derived from them.

FIG. 1. General trends in global climate.

TABLE 1. Characteristics of proxy paleoclimatic data sources.

Proxy data source	Variable measured	Continuity of evidence	Potential geographical coverage	Period open to study (Y. B. P.)	Minimum sampling interval (y)	Usual dating accuracy (y)	Climate inference
Layered ice cores	Oxygen isotope concentration, thickness (short cores)	Continuous	Antarctica, Greenland	10,000	1-10	$\pm$ 1-100	Temperature, accumulation
	Oxygen isotope concentration (long cores)	Continuous	Antarctica, Greenland	100,000 +	Variable	Variable	Temperature
Tree rings	Ring width, anomaly, density, isotopic composition	Continuous	Mid- and high-latitude continents	1,000 (common) 8,000 (rare)	1	$\pm$ 1	Temperature, runoff, precipitation, soil moisture
Fossil pollen	Pollen type concentration (varved core)	Continuous	Mid-latitude continents	12,000	1-10	$\pm$ 10	Temperature, precipitation, soil moisture
	Pollen type concentration (normal core)	Continuous	50 S to 70 N	12,000 (common) 200,000 (rare)	200	$\pm$ 5%	Temperature, precipitation, soil moisture
Mountain glaciers	Terminal positions	Episodic	45 S to 70 N	40,000	-	$\pm$ 5%	Extent of mountain glaciers
Ice sheets	Terminal positions	Episodic	Mid- to high-latitudes	25,000 (common) 1,000,000 (rare)	-	Variable	Area of ice sheets
Ancient soils	Soil type	Episodic	Lower and mid-latitudes	1,000,000	200	$\pm$ 5%	Temperature, precipitation, drainage
Cloned-basin lakes	Lake level	episodic	Mid-latitudes	50,000	1-100 (variable)	$\pm$ 5%	Evaporation, runoff, precipitation, temperature

TABLE 1 (continued) Characteristics of proxy paleoclimatic data sources.

Proxy data source	Variable measured	Continuity of evidence	Potential geographical coverage	Period open to study (Y. B. P.)	Minimum sampling interval (yr)	Usual dating accuracy (yr)	Climate inference
Lake sediments	Varve thickness	Continuous	Mid-latitudes	5,000	1	± 1	Temperature, precipitation
Ocean sediments (common deep-sea cores, 2-5 cm/1000 yr)	Ash and sand accumulation rates	Continuous	Global ocean (outside red clay areas)	200,000	500 +	± 50	Wind direction
	Fossil plankton composition	Continuous	Global ocean (outside red clay areas)	200,000	500 +	± 50	Sea-surface temperature, surface salinity, sea-ice extent
	Isotopic composition of planktonic fossils; benthic fossils; mineralogic composition	Continuous	Global ocean (above CaCO_3 compensation level)	200,000	500 -	± 50	Surface temperature, global ice volume; bottom temperature and bottom water flux; bottom water chemistry
(rare cores, >10 cm/1000 yr)	As above	Continuous	Along continental margins	10,000 +	20	± 50	As above
(cores, <2 cm/1000 yr)	As above	Continuous	Global ocean	1,000,000 +	1000 +	± 50	As above
Marine shorelines	Coastal features, reef growth	Episodic	Stable coasts, oceanic islands	400,000	-	± 50	Sea level, ice volume

National Academy of Science, Understanding Climate Change: A Program for Action, United States Committee for the Global Atmosphere Research Program, National Research Council, Washington, D.C. (1974).

THE VARIATIONS

The Last 100,000,000 Years

The climatic regime occurring approximately 1,000,000 to 100,000,000 years ago is not of primary importance to the WMP.

In general, the climate was considerably warmer than it is today and the polar regions were ice free. The configuration of the continents was different (e.g., the Atlantic Ocean was created during the last 250 000 000 years) which may, in part, have been responsible for the warmer temperatures.

About 10,000,000 years ago, a general cooling was evident (Shackleton and Kennett, 1974a,b) and for our purposes, the present glacial age began. The Antarctic ice sheets grew to their present ice mass between 10,000,000 and 4,000,000 years ago (Denton, et al., 1971). The present amount of water contained in the Antarctic ice mass, if melted, would raise the global sea level approximately 59 meters (NAS, 1974).

The Last 1,000,000 Years

For at least the past 1,000,000 years, the earth's climate has been characterized by a series of glacial and interglacial periods where the ice sheets have expanded and contracted--growing over continents and shrinking to cover only mountain and polar regions.

It is this basic glacial-interglacial transition that is most interesting for site suitability studies. These cycles have occurred with remarkable regularity during the past 50,000,000 years and provide most of the variation that might occur over a given site for at least the next 10 million years.

The Last 150,000 Years

The most striking feature of the past 150,000 years is the rapid, almost catastrophic deglaciation that occurred about 120,000 years ago and that may have lasted 10,000 years. Buildup of the glaciers after this deglaciation

occurred more gradually. The warm conditions prevailing over most of the planet were another important aspect of the interglacial period. Sea levels rose 6 or 7 m above today's levels. Although the source of the water is not apparent, the rise may have resulted from a complete melting of the Greenland ice cap, a melting of the East Antarctic ice sheet, or a combination of both.

The Last 25,000 Years

The present interglacial is generally considered the most significant period of the past 25,000 years. This interglacial (called the Holocene) began about 10,000 years ago with the rapid melting of continental glaciers. These continental ice sheets once covered parts of northern North America and northern Europe and reached their maximum size between 22,000 and 18,000 years ago. This relatively recent peak of continental glaciation represents a typical maximum glaciation of the past million years. The effects of these vast expanses of ice on regional climatic patterns have been extensively studied.

The Last 5000 Years

Between 7000 and 5000 years ago, a warm period occurred similar to the interglacial of 120,000 years ago. This warm period also has been referred to as an analogue to human intervention in future climate (increased atmospheric CO₂ from a coal-based energy system with atmospheric warming resulting from a CO₂ greenhouse effect). Since this peak warming, the global temperatures have been gradually dropping and mountain glaciers have become more extensive (Porter and Denton, 1967).

The Last 1000 Years

In the early part of the last 1000 years, global temperatures were probably about as high as temperatures were during the first half of the 20th century (discussed below). Later in the period (from 1430 to 1850), global temperatures dropped and mountain glaciers advanced farther than in any other time since the glacial maximum. Although no major ice sheets formed, this cold interval is often termed the Little Ice Age.

The Present

Generally, our present climate is considered to be interglacial and approximately 1°C cooler than the warm period of 6000 years ago. Over the past 100 years (since the Little Ice Age), temperatures peaked around 1940 and have been cooling since then.

Summary of Climatic Variations

Obviously, climate has changed dramatically in the past. Massive ice sheets that once covered much of North America and Europe were associated with generally drier climates in many regions. The last major ice advance was interrupted 120,000 years ago by an abrupt interglacial period that generated much more humid conditions in various deserts; approximately 10,000 years ago a less extreme interglacial warming occurred. We are now experiencing one of the warmer periods within the past few hundred thousand years, but there is reason to believe that this recent climate optimum may be ending. The bases for this belief are discussed in the next two sections.

THE CAUSES OF CLIMATIC CHANGE

There are probably as many theories about the causes of climate variation and ice ages as there are climatologists (Flint, 1971). Theories deal with such possible external factors as solar variation, cosmic dust, and volcanic dust as well as with internal mechanisms such as ocean circulation, the distribution of carbon dioxide between the ocean and atmosphere, and surging of Antarctic ice sheets. Recently, most of the claims that the variations in the earth's orbital elements lacked correspondence with the geologic data have generally been dismissed. New data have been published (Hays, Imbrie, and Shackleton, 1976) giving credibility to the idea that global climate change is forced by the earth's orbital elements (i.e., orbital elements and climatic changes show strong statistical correlations, although the chain of atmospheric processes has not yet been well defined).

GEOLOGIC DATA

Hays and his colleagues (Hays, et al., 1976) claim that the major barrier to establishing a responsible link between the ice ages and the earth's orbital elements lies in the uncertainty of geological chronology. Recent improvements in obtaining and dating ocean cores led to the selection of two cores with rapid accumulation rates (>3 cm/1000 years), depth (dated to 450,000 years ago) and resolution (resolving fluctuations of less than 20,000 years). The cores yielded:

- The ratio of ^{18}O to ^{16}O ($\sigma^{18}\text{O}$) in planktonic foraminiferas.
- An estimate of summer sea-surface temperature derived from the assemblage of radiolarians (bottom dwelling creatures).
- The relative abundance of another bottom dwelling creature, *Cycladophora davisiana*. The oxygen isotope analysis variation is thought to reflect changes in global (primarily Northern Hemisphere) ice sheets.

ORBITAL DATA

Variations in the earth's orbital elements (eccentricity, precession and obliquity, see Fig. 2), and the resulting changes in solar insolation (as opposed to changes in solar output) were first calculated by Milankovitch (1941) and have been revised and recalculated numerous times since (e.g., Vernekar, 1972). Orbital changes affect only the seasonal and geographical distribution of insolation while the annual totals remain unchanged (Kukla, 1975).

One major problem of relating these variations to the actual initiation of an ice age lies in determining the season during which the variation of solar insolation is the controlling factor. A Figure by Kukla (1975) shows the irradiation at the top of the atmosphere in the plane perpendicular to solar rays during the different seasons for the past 30,000 years. His autumnal equinox curve corresponds to the record of global ice volume with a maximum glacial 17,000 years ago, a warm period 6000 years ago, and a glacial period approximately

FIG. 2. Earth's orbital elements.

4000 years in the future. Although quite tentative, the solar radiation variations reaching the earth during autumn in the Northern Hemisphere may be partly responsible for some of the past global climate changes (Kukla, 1975).

RELATIONSHIP BETWEEN ORBITAL AND GEOLOGIC DATA

Testing the null hypothesis: geologic data are randomly distributed, Hays et al., (1976), rejected the hypothesis at $P = 0.02$ and $P = 0.05$ for the various plant and $\sigma^{18}O$ data from the sediment cores. The peaks in the spectrum of the geologic data (approximately 23,000, 42,000 and 100,000 years) were tested against the orbital parameters and found to correspond to the dominant periods of the earth's orbital elements (containing respectively 10, 25, and 50% of the climatic variance). Their conclusions indicate that

- The 42,000-y climatic record from deep sea cores has the same period and variation as the obliquity of the earth's axis and retains a constant phase relationship with it.
- The 23,000 year period is the same as the quasi-periodic precession index.
- The 100,000-year climate variations have the same period and phase as the orbital eccentricity. Using their data and ignoring anthropogenic influences, Hayes and his co-workers predict extensive Northern Hemisphere glaciation in the next few thousand years.

PREDICTION

Based on Hays, et al., (1976) it is possible to express the climatic controlled variable (e.g., $\sigma^{18}O$, the ratio of ^{18}O to ^{16}O --global ice volume) as a linear function of the orbital parameters (see Appendix). Our task is to express $\sigma^{18}O(t)$, viewed as a time series, as a linear function of $[x_1(t)]$ - obliquity, $[x_2(t)]$ - precession, and $[x_3(t)]$ - eccentricity. The linear model is then

$$\sigma^{18}O(t) = \sum_{k=1}^3 \sum_{j=1}^J \beta_{sj} [x_s(t-j) + \varepsilon(t)] \quad (1)$$

where the β_{sj} ($k = 1, 2, 3; j = 1, \dots, J$) are the unknown coefficients to be estimated and the $\epsilon(t)$ are the possibly randomly correlated variation terms. The analysis of this model involves regression techniques that take into account possible autocorrelation of $\epsilon(t)$.

This model is based on the assumption that future surface hydrologic behavior could be dramatically altered by future climate and that future climate will be similar to past climate. The model yields our best estimate of past climate sequence; for selected glacial and interglacial periods, it yields maximum and minimum temperatures.

REGIONAL CLIMATE RECONSTRUCTION

FIRST ESTIMATES

Data for first regional precipitation estimates (Appendix) were extrapolated from a paper by Lamb (1972). He presented 500 mb heights from his reconstructions that were based on a variety of data (geologic samples, pollen samples, ships logs). The climatic regimes (e.g., full glacial, boreal, etc.) that Lamb selected to represent regional variation were initially included in our first estimate as guidelines for constructing future climates.

REFINED ESTIMATES

The Full Glacial

As the Waste Management project refined its needs for future climate information, more complete sources of data were needed. After our first estimate, we found it unrealistic to attempt a reconstruction of a time history of all climatic oscillations during the past million years. Instead, we selected a subset of various climatic regimes that represent the major variations of the past million years (these could also be viewed as worst-case studies). These climate regimes have been studied extensively and in some cases, a measure of uncertainty can be assigned to them.

Figure 1-e shows maximal ice volumes occurring at nearly regular intervals. The peak, approximately 18,000 years ago, is rather typical of other major advances and represents the last great ice age for which widespread evidence is available. But, because most of the paleoclimatic evidence comes from deep sea cores and the geologic remains of ice sheets, very little can now be inferred about regional precipitation variations.

Using statistical techniques developed by Imbrie and Kipp (1971), estimates of the summer sea surface temperatures of the global ocean of 18,000 years ago have been produced by the Climate, Long-range, Investigation, Mapping, and

Prediction project (CLIMAP) (CLIMAP Project Members, 1976). Data for sea-surface temperatures, sea-levels, topography of ice, and surface albedo (reflectance) were used as boundary conditions in an atmospheric circulation model (also called the general circulation model or GCM); the atmospheric response was calculated (Gates, 1976, Manabe and Hahn, 1977). Other climate reconstructions (Williams, 1974 and Williams, et al., 1974) have been attempted using different boundary conditions.

Three other model experiments (Williams, 1974; Williams, et al., 1974; Gates, 1976, and Manabe and Hahn, 1977), using similar grid structures, yielded somewhat varied climatic effects (of the massive ice sheets) and modified sea-surface temperatures.

Figure 3 shows the difference between Ice Age and present precipitation rates (Ice Age minus present). Data are from Gates, 1976. Most of the rainfall calculated in this model occurs as small-scale precipitation (convective rainfall) and is generally a larger fraction of the total than large-scale precipitation (large storm systems). Generally, the continental United States shows less precipitation (precipitation decreased globally by 14%). This figure was taken from raw data; no smoothing techniques were applied. A drier southwestern U.S. has been corroborated by Brakenridge (1978), but this is in direct contradiction of earlier work by Flint, 1971. Also, geologic lake level data suggests more humid conditions in the deserts. A drier desert theory is a logical consequence of lowered evaporation rates in regions where the westerly winter storm tracks were less moist (Brakenridge, 1978). Total precipitation in the southwest may have been much like today's, or possibly less. The summers and winters were probably considerably colder, thus depressing local evaporation rates and giving the impression (from lake levels) that the climate was wetter.

Figure 4 (redrawn from Manabe and Hahn, 1977), shows the difference between Ice Age and present precipitation rates. The difference values have been smoothed to emphasize the large scale features (Manabe and Hahn, 1977). Although data were presented, the research discussed here does not emphasize results from higher latitudes because an input error neglected the effects of ice-sheet elevation. Instead, we have emphasized the tropics.

FIG. 3. Change in precipitation (Ice Age to present) July to August (cm/day).

FIG. 4. Change in precipitation (Ice Age to present) August (cm/day).

According to Manabe (personal communication), continental scale rainfall values should be viewed with caution. Figure 5 shows the geographical distribution of the difference (Ice Age minus control) in net water supply (rain plus snow, minus evaporation). This difference map shows that the water supply for most of the West and Southwest appear unchanged between the Ice Age and the present. Because the difference in evaporation rate almost balances the difference in precipitation rate, there is a relatively small difference in the amount of water available for runoff in the mid-latitudes (Manabe and Hahn, 1977). The eastern U.S. appeared to have more available water and higher precipitation rates.

The data from Williams (1974) and Williams, et al., (1974) do not assign numerical values to precipitation, but simply state relative wetness or dryness. The results are roughly similar to the other work discussed, however the study used different boundary conditions, thus making comparison difficult.

Outlook for Improvement

All of the model simulations mentioned above found the earth to be drier during the last glacial advance (18,000 years ago) than at present. They also showed similarities in precipitation difference patterns in the southwestern U.S. At least one of the three research groups (Gates, personal communication) plans to repeat the ice age experiment in the next few months using revised boundary conditions. They plan to study both January and July. The new boundary conditions include modifications of ice sheet location and elevation, surface albedo, and sea-surface temperatures. The model will also include data for a winter simulation. The new simulations are expected to have increased reliability (Gates, personal communication).

New evidence has recently been published regarding pollen in the southwestern U.S. during the last glacial (Brakenridge, 1978). This evidence tends to confirm the model simulations of glacial period summer conditions that showed that glacial summers were drier than today's summers.

FIG. 5. Change in net water supply (Ice Age to present) (cm/day).

The Hypsithermal

This section summarizes existing knowledge of the warm interglacial interval 6000 years ago (also known as the hypsithermal, altithermal, or post glacial optimum). Although data for reconstructing the climate of this period is very sparse, the hypsithermal is probably the most important climatic regime relative to waste disposal site suitability.

Future human activity becomes an integral part of the puzzle of climate reconstruction and poses special problems for prediction over the next few thousand years. Natural climatic variations may be disrupted by the continued release of CO_2 . Carbon dioxide is transparent to incoming solar radiation, but absorbs the earth's outgoing longwave radiation in selective bands. The absorption warms the lower atmosphere and the surface. Though atmospheric CO_2 may increase sharply in the next few hundred years, the warming effect could last a few thousand years. While we know little about the climatic consequences of a doubling of the CO_2 , some energy scenarios suggest an eightfold CO_2 increase (NAS, 1974). Recent reviews suggest that a 100% increase in CO_2 would raise average global surface temperatures by 1.5° to 3°C (Schneider, 1975). Until atmospheric model experiments can be completed and validated, we must rely on past reconstructions that are analogous to a potentially warmer earth.

The hypsithermal period (~6000 years ago) is the one period in the recent past that may be considered similar to the warmer earth scenario.

Figure 6 displays available information about precipitation differences between the present and the hypsithermal period. The numbers in the upper Midwest are from Bernabo (personal communication) and data on the generally wetter and drier regions in the West are from Kellogg (1977). The sparseness of data is disappointing, but there is a suggestion of a wetter southwestern U.S.

The major hope of improving the coverage of precipitation data is through use of pollen cores from the western U.S. (Heuser, personal communication). The upper Midwest differences (Bernabo and Webb, 1977) were based on pollen analyses of 62 cores with radiocarbon dates. Five pollen groups numerically

FIG. 6. Precipitation difference (cm/day) averaged for the year (6000 years before present minus present).

dominate the Holocene (last 10,000 years) record. The modern pollen distribution shows that these groups roughly define the extent of the boreal forest, the conifer-hardwood forest, the deciduous forest and the prairie. By mapping these pollen types as they occur in the dated cores, it is possible to monitor the changes in location of these four vegetational regions during the Holocene. Bernabo and Webb first calibrated modern pollen distribution to present day temperature and precipitation patterns. From their analysis, it was possible to relate past plant community make up and location to temperature and precipitation. Pollen analysis appears to be our only information link with the period between 4000 and 10,000 years ago.

The possibility of a wetter southwestern U.S. is extremely important to the Waste Management Program. We may also receive some estimate of the magnitude of the precipitation changes from Pisias (personal communication) at the University of Rhode Island.

Little Ice Age

The first-order estimate for Little Ice Age precipitation has some uncertainty because of proxy reconstructions. Generally, the continental U.S. was drier with the exception of the Pacific Northwest (or the entire Pacific Coast). The data are derived from a variety of sources:

- Instrumental data (some locations in the late 17th century were of primary interest, although precipitation was sampled to a lesser extent).
- Historical data (accounts from annals, chronicles, and ship's logs from Europe and the Orient).
- Proxy data (glacial advances, snowline, tree rings, pollen, bogs, river sediments, varves, ice cores, insect remains, and tree rings). (The primary problems with proxy data are dating, response time, and interpretation in light of meteorological data.)

H. C. Fritts of the University of Arizona Laboratory for Tree Ring Research has developed a method for relating tree ring width to climate variation (Fritts, 1976). A set of chronologies of several hundred years in various areas of the U.S. now exists and continued analysis reveals climatic patterns

in these regions. Presently, tree-ring related atmospheric surface pressure, temperature, and precipitation patterns have been established for each season from 1602 to 1900. This analysis proceeds in several phases:

- A growth function is calculated and the ring-width values are standardized for trees and groups of trees.
- Ten to thirty trees may then be merged for one chronology.
- The ring-width indices are related to available records of observational meteorological data.
- Once the relationship is established, the rings for past years are used to reconstruct past climate (which can then be verified by independent data).

Fritts has furnished the WMP with unpublished precipitation data estimates (1602 to 1900 minus present) for the winter periods (Fig. 7). Interestingly enough, this distribution shows a wetter Pacific Northwest in the past. It is consistent with Wigley (1977) who also suggested (in the Northwest) a wetter West Coast than we have at present (Fig. 8) but it differs from Wigley's picture of the Southwest. The maps provided by Fritts are still tentative and should be viewed with caution, however the trend is confirmed in a recent analysis (Fritts and Lofgren, 1978).

These precipitation estimates are improving as additional tree-ring data analyses become available. The next estimate will also include differences in summer precipitation.

FIG. 7. Change in precipitation (the period 1602-1900 minus 1901 to 1970; inches/season).

FIG. 8. Change in precipitation 1500 to 1600 minus present. W = wet, D = dry.

DATA GAPS

Implementation of the first-order precipitation estimates (and subsequent ground water recharge) will require the following data:

- Full glacial: January precipitation differences, runoff, and evaporation.
- Hypsithermal: West Coast and Southwest precipitation differences and temperature (we may have to settle for annual averages rather than seasonal). Evaporation will be calculated and runoff estimated.
- Little Ice Age: Summer precipitation and runoff may be available directly from stream flows and tree ring reconstruction (evaporation calculated from precipitation and temperature data).

ACKNOWLEDGMENTS

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APPENDIX A

FIRST ESTIMATES OF RAINFALL DIFFERENCES BETWEEN VARIOUS CLIMATIC REGIMES AND TODAY'S CLIMATE

Figure A-1) Present July precipitation averaged over the period from 1931 - 1960, crudely defining the wet, average and dry regions of the continental U.S.

Figure A-2) Full glacial January, 17,000 to 20,000 years ago. The basic geography of land ice and oceans differs from the present (revised sea levels can be seen in reconstructions for first order estimates). From Lamb's data, we can infer that the Southwestern U.S. was drier than it is today and that the East Coast was wetter. The values on the map are not based on any real precipitation or moisture data.

Figure A-3) Full glacial July, 17,000 to 20,000 years ago. The same pattern is prevalent as in Fig. A-2. Some evidence suggests the seasonal change may have been less at this time.

Figure A-4) Boreal January warm period, 8000 years ago. This period was characterized by ice age conditions over North America, but glaciers were absent in Europe. Very little information exists about this period and the prospects for reducing the uncertainties are almost nil. Any suggestion of slightly higher precipitation in the Southwest and Northwest cannot be verified.

Figure A-5) Boreal July. Same comments as for Fig. A-4 except possible drier Southwest and Western states.

FIG. A-1. July precipitation (1931 to 1960 averages).

FIG. A-2. Full glacial precipitation differences for January (17,000 to 20,000 years ago).

FIG. A-3. Full glacial precipitation differences for July (17,000 to 20,000 years ago).

FIG. A-4. Boreal precipitation differences for January, a warm interglacial period (8000 years ago).

FIG. A-5. Boreal precipitation differences for July, a warm interglacial period (8000 years ago).

Figure A-6) This Atlantic January warm period occurring about 6000 years ago marked the end of continental glaciation. It was slightly warmer than today. The map shows slightly more precipitation in the Southwest than today, but this is not entirely clear. Precipitation in the Midwest and through the Ohio Valley is probably incorrect in this representation; temperatures should be considerably higher.

Figure A-7) Atlantic July. The comments for Fig. A-6 apply.

Figure A-8) Little Ice Age, January. This is a reconstruction by Fritts using tree rings (personal communication). The map shows a drier Southwest and a wetter Northwest and is probably the most reliable representation of the precipitation differences that occurred during the Little Ice Age.

FIG. A-6. Atlantic precipitation differences for January, a moist interglacial period (6000 years ago).

FIG. A-7. Atlantic precipitation differences for July, a moist interglacial period (6000 years ago).

FIG. A-8. Little ice age precipitation differences for January.