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A 5000-Year Record of Extreme Floods and Climate Change in the Southwestern United States

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A 5000-year regional paleoflood chronology, based on flood deposits from 19 rivers in Arizona and Utah, reveals that the largest floods in the region cluster into distinct time intervals that coincide with periods of cool, moist climate and frequent El Niño events. The floods were most numerous from 4800 to 3600 years before present (B.P.), around 1000 years B.P., and after 500 years B.P., but decreased markedly from 3600 to 2200 and 800 to 600 years B.P. Analogous modern floods are associated with a specific set of anomalous atmospheric circulation conditions that were probably more prevalent during past flood epochs.

Changes in the character of extreme events are likely to constitute a greater portion of the impact of climate change than slow alterations in mean conditions (*1–3*). Yet, even the longest available instrumental hydrological records inadequately represent rare, severe floods, which are commonly assumed to occur randomly in time for convenience in hazard assessment (*4*). Simulations with general circulation models have indicated that widespread increases in rainfall intensity and floods could be a consequence of climatic changes under increased atmospheric CO_2 (*2*), but an initial understanding of the full range and causes of natural variability in the existing hydrological system is essential to the forecasting and evaluation of the possible nature of these extreme events in the future. Geological evidence of ancient floods reveals that the magnitude and frequency of the largest floods vary with changing climatic conditions on time scales of centuries to millennia (*3, 5*). We combined analyses of a 5000-year paleoflood record and modern flood analogs to investigate the specific relation between extreme floods and broad-scale atmospheric circulation patterns, providing a basis for the incorporation of this hydrological response into climate simulations.

This study summarizes depositional evidence of 251 paleofloods on 19 rivers in Arizona and southern Utah (Fig. 1) (*5, 6*). During floods in stable bedrock river channels, fine-grained sediments settle out of suspension in eddies or backwater zones where the flow velocity is diminished (*7*). This setting selectively preserves a complete catalog of the largest floods, which tend to leave a sequence of high deposits in protected niches away from the main flow of the river (*8*). Lower inset deposits from smaller floods are more susceptible to subsequent erosion (*5*). Each site in this study contained deposits from several floods, the ages of which were determined from occasional cultural artifacts and over 150 radiocarbon (^{14}C) dates on incorporated organic materials (*5, 7, 9*). Correlative paleoflood chronologies from different sites along a river reach were consolidated into one.

Combination of the records from several rivers in the region highlights clustering in the frequency of large floods that is not detectable from a single river alone. The regional chronology (Fig. 2) shows distinct variations in the frequency of large floods over the last 5000 years. Periods of numerous large floods span 5 to 3.6 thousand ^{14}C years ago (ka) (3800 to 2200 B.C.), 2.2 to 0.8 ka (400 B.C. to 1200 A.D.), and 0.6 ka (1400 A.D.) to present (*10*). Large floods are completely absent between 3.6 and 2.2 ka (2200 to 400 B.C.), a period unlike any other in the 5000-year record. A sharp drop in the number of large floods also occurs from 0.8 to 0.6 ka (1200 to 1400 A.D.), immediately after a brief episode of particularly frequent high-magnitude floods from 1.0 to 0.8 ka (1000 to 1200 A.D.).

The number of flood deposits after 0.6 ka exceeds the scale of the graph (Fig. 2). To compare this peak with the earlier flood periods, we omitted sites with less than 400 years of record and recent inset deposits that are not likely to be preserved and divided the number of floods in each 200-year interval by the number of rivers represented in that interval. A substantial increase in floods in the last 600 years was still apparent, especially in the last 200 to 400 years, evidence that this pattern is not merely an artifact of differential preservation (*11*).

The extended periods of numerous large floods coincide with cool regional and global temperatures, reflected in neoglacial advances and vegetation changes (*12–14*). High lake levels before 3.6 ka and in the last 400 years also indicate wetter conditions in the Southwest during these periods (*15, 16*) (Fig. 2). The paleofloods provide the additional evidence of a concurrent increase in the frequency of extreme storms (*17*).

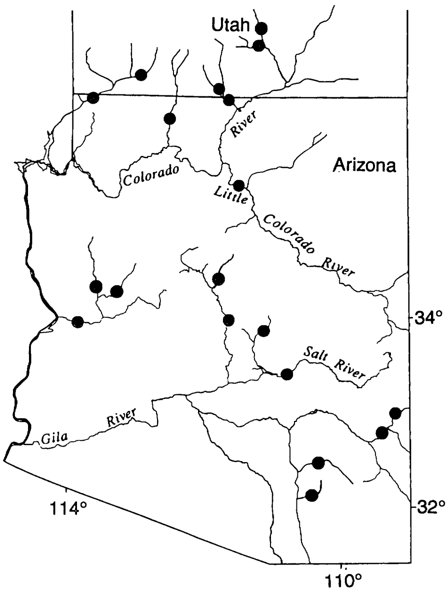

Fig. 1. Locations of flood deposit sites used in the regional paleoflood chronology (*5, 6*).

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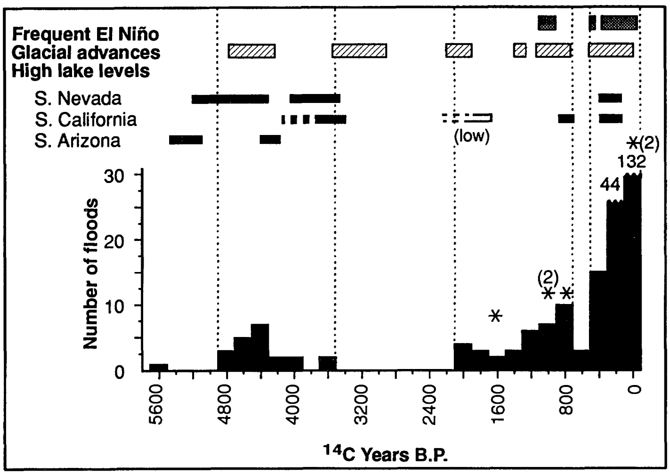

Fig. 2. Regional paleoflood chronology showing floods on rivers in Arizona and southern Utah in 200-year increments (each bar represents the increment that ended on the indicated year; that is, the bar centered on 800 covers the increment from 1000 to 800 years B.P.). An asterisk indicates that one of the largest floods in the record occurred in the increment (multiple events indicated by number in parentheses). The values for the last two increments are given as they exceed the scale of the graph (see text for details). Floods were placed in the interval that included the largest portion of the delimiting age range, and multiple floods in a time range were assumed to be evenly distributed through time unless evidence indicated otherwise. The few floods bounded only by a minimum or maximum age were assumed to fall within 200 years of that age. The chronology is based on uncalibrated ^{14}C dates for direct comparison with other paleoclimatic records, but the major features are the same when based on dendrocalibrated dates (*10*). Periods of numerous large floods correspond to high lake levels and ground-water recharge in the region (*15, 16*), global neoglacial advances (*12*), and frequent strong El Niño events (*23*). Solid horizontal bars are high lake stands or recharge.

The last 1000 years of high-resolution records demonstrate the strongest connection between regional climatic factors and the paleofloods. The changes in the frequency of floods over the last 1000 years (Fig. 2) coincide with hemispheric to global temperature changes: a brief cold period around 1 ka, followed by the much warmer Medieval Warm Period around 1100 to 1300 A.D., and finally the cold Little Ice Age around 1500 to the late 1800s A.D. (*5, 14*). The two periods of especially high magnitude floods around 1 ka and the late 1800s to early 1900s A.D. appear to occur during transitions from cool to warm climatic conditions. The relatively coarse degree of resolution in the ages of the paleofloods precludes a conclusive relation, but these results suggest that the transitional climatic periods may contain the highest hydrologic variance.

An analysis of modern flood analogs links the paleofloods with large-scale circulation patterns. Severe floods in the Southwest are currently associated with three broad categories of storms: (i) winter North Pacific frontal storms, (ii) late-summer and fall storms associated with Pacific tropical cyclones over northern Mexico in conjunction with a mid-latitude low-pressure trough, and (iii) local summer convective thunderstorms (*18, 19*). The conditions conducive to the first two storm types tend to be less favorable for floods from summer storms (*5*). Winter storms and tropical cyclones have produced the largest single floods on the rivers we studied and are the most likely causes of the paleofloods because the major features of the present global atmospheric circulation were in place by 5000 years ago (*20*).

During winter floods, the typical circulation pattern features a strong southerly displaced low-pressure anomaly off the California coast and, to the north, a high-pressure anomaly over the Aleutians or Gulf of Alaska (Fig. 3A). Tropical-cyclone floods exhibit a similar low-pressure anomaly and an expanded blocking high-pressure anomaly in the central North Pacific but also include the entrainment of an eastern Pacific tropical storm into the system (Fig. 3B). In both cases, this meridional pattern in the mid-latitude upper-air flow steers southerly shifted storms and moisture into the southwestern United States. In addition, the large floods from these two storm types are associated with multiple-year periods dominated by negative Southern Oscillation index (SOI) or El Niño conditions (*19, 21, 22*). The paleofloods also exhibit a positive relation with centennial-scale variations in the frequency of strong El Niño events, on the basis of a 1370-year record of El Niño constructed from annual Nile River fluctuations (*23*) (Fig. 2). Over at least the last 2000 years, the flood periods also coincide with fossil microfaunal evidence of El Niño–like warm sea surface temperatures off the coast of California (*24*).

The combined information from the modern and paleoflood records in the southwestern United States indicates that long-term flood variability is associated with distinct, persistent changes in regional climate, large-scale atmospheric circulation patterns, and the Southern Oscillation. It follows that integrated records of ancient floods at strategic points around the globe could delineate features of the general atmospheric circulation actually experienced under various climatic states in the past, thus not only identifying periods of in-

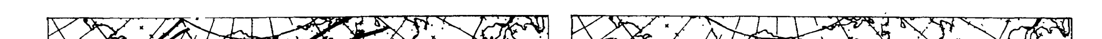

Fig. 3. Atmospheric circulation during severe winter and tropical-cyclone floods. (**A**) Composite anomaly map of 700-mbar heights (in meters) associated with winter floods (annual probability ≤0.1) on rivers in central Arizona; based on eight cases from 1947–88. Constructed with gridded daily 700-mbar heights. The values for each flood day were subtracted from the long-term mean (1947–72) for that month; the map represents the average departure from mean for all cases (*22*). (**B**) Same as (A) for tropical cyclones associated with floods on rivers in central and southern Arizona; based on seven cases.

creased extreme events, but providing a means to link their occurrence with climate models.

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Latest Pleistocene and Holocene Geomagnetic Paleointensity on Hawaii

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Geomagnetic paleointensity determinations from radiocarbon-dated lava flows on the island of Hawaii provide an estimate of broad trends in paleointensity for Holocene time and offer a glimpse of intensity variations near the end of the last glacial period. When the data from Hawaii are compared with others worldwide, the intensity of the geomagnetic field seems to have been reduced from the Holocene average by about 35 percent between 45,000 and 10,000 years ago. A long-term reduction of this magnitude is compatible with reported increases in the production rate of cosmogenic nuclides during the same interval.

Because radiocarbon (^{14}C) is one of several nuclides produced in the upper atmosphere by cosmic radiation, its abundance can be affected in a number of ways (*1*). To correct for these variations, researchers have well calibrated ^{14}C ages to about 9000 years before present (B.P.) and tentatively to about 13,000 years B.P., by comparison with tree-ring and glacial-varve chronologies (*2*). In an attempt to calibrate the ^{14}C time scale to older periods, a comparison was made of ages determined by the ^{14}C (*3*) and ^{234}U-^{230}Th (*4*) techniques on a sequence of cores from coral reefs off the island of Barbados. The ages were in general agreement for the last 9000 years, but the U-Th ages were consistently older than the ^{14}C ages in older material, with a maximum discrepancy of 3500 years at 20,000 years B.P. If the U-Th ages are correct, the concentration of ^{14}C in the atmosphere must have been about 40% larger than it is now. A study of sedimentary cores from the Pacific Ocean indicates that the global production of ^{10}Be was at least 25% greater during this same interval (*5*). The only factor that seems to function in producing such large increases in the amount of cosmogenic nuclides is a substantial decrease in the intensity of the geomagnetic field, which would allow an increased flux of cosmic rays to impinge on the Earth's upper atmosphere (*1, 4, 5*).

Little is known about variations in geomagnetic intensity over much of geologic time because of the difficulties in obtaining dated material that retains an accurate intensity record and because of the time-consuming nature of the experimental procedures. Absolute values of paleointensity can be obtained only from rocks and archaeological artifacts that have acquired a thermoremanent magnetization (TRM) upon cooling in the Earth's magnetic field. The paleointensity record from many globally distributed locations must be averaged to eliminate the effects of nondipole variations so that a true picture of the global (dipole) field can be obtained.

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