Southern California's Megaflood Event of ca. 1605 AD Linked to Large-scale Atmospheric Forcing

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Abstract: A distinct, 1- to 2-cm-thick flood deposit found in Santa Barbara Basin with a varve-date of 1605 AD ± 5 years testifies to an intensity of precipitation that remains unmatched for later periods when historical or instrumental records can be compared against the varve record. The 1605 AD ± 5 event correlates well with Enzel's (1992) finding of a Silver Lake playa perennial lake at the terminus of the Mojave River (^{14}C-dated 1560 AD ± 90 years), in relative proximity to the rainfall catchment area draining into Santa Barbara Basin. According to Enzel, such a persistent flooding of the Silver Lake playa occurred only once during the last 3,500 years and required a sequence of floods, each comparable in magnitude to the largest floods in the modern record. To gain confidence in dating of the 1605 AD ± 5 event, we compare Southern California's sedimentary evidence against historical reports and multi-proxy time-series that indicate unusual climatic events or are sensitive to changes in large-scale atmospheric circulation patterns. The emerging pattern supports previous suggestions that the first decade of the 17th century was marked by a rapid cooling of the Northern Hemisphere, with some indications for global coverage. A burst of volcanism and the occurrence of El Niño seem to have contributed to the severity of the events. The synopsis of the 1605 AD ± 5 years flood deposit in Santa Barbara Basin, the substantial freshwater body at Silver Lake playa, and much additional paleoclimatic, global evidence testifies for an equatorward shift of global wind patterns as the world experienced an interval of rapid, intense, and widespread cooling.

Introduction

The most obvious economic impact of climate on society results from extreme weather events rather than from gradually shifting climatic averages (Katz and Brown 1992). Modern extreme events act as a catalyst for public awareness about changing climate. California's 20th century floods made news mostly because the effects of peak runoff and mudslides interfered with the sprawling urbanization of coastal areas, but there is abundant evidence that floods of earlier centuries were occasionally much more severe. For example, historical sources described the 1861/62 "Noachian Deluge" when all rivers from Oregon to the Mexican border were above flood stage, rainfall was 300-400 percent above normal in many parts of California, and the Sacramento Valley became navigable. Steamboats and barges were the only means of connecting the flooded city of Sacramento with surrounding higher ground. Subsequently, a much reduced tax basis forced the State of California into bankruptcy (Farquhar 1966, p. 241ff; Roden 1989).

Pre-19th century floods in California have little or no historical documentation. An earlier report of extreme, prehistoric flood events in Southern California was based on laminated lake deposits in the Mojave Desert, at the terminus of the Mojave River at Silver Lake playa, with ^{14}C-dates of 1560

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AD ± 90 years and 3620 ± 70 years BP (Enzel *et al* 1989). Enzel (1992) concluded that each lake had persisted for at least a few decades and that a sequence of severe floods originating from intense precipitation in the San Bernardino Mountain area was necessary for their generation. By comparison, none of the 20th century major precipitation events of the area resulted in severe enough flooding to produce a perennial lake.

Here we document a flood deposit from the nearby Santa Barbara Basin that testifies to the worst regional flooding of this millennium and correlates well with the last Silver Lake playa episode and with other, multi-proxy regional evidence for unusual cool, moist conditions in the early part of the 17th century. Extreme climatic events in one region are frequently expressed by anomalous climates in neighboring areas, and may even be "teleconnected" to remote regions of the globe via changes in quasi-stationary atmospheric waves and storm track patterns (Trenberth 1993). Climatic teleconnections in the form of documented extreme and unusual climatic conditions around 1605 AD are indicated on a global scale, to support our hypothesis that a catastrophic Southern California flood was climatically linked to an equatorward shift of earth's major wind patterns during the most severe global cold spell of the last millennium.

Description of the Santa Barbara Basin Flood Deposit of About 1605 AD and Adjacent Layers

Extreme precipitation in the Mojave River catchment of Southern California around 1560 AD ± 90 years should also have resulted in flooding of other regional rivers and creeks, carrying increased loads of detritus into the Pacific Ocean. At a distance of about 250 km to the west of the San Bernardino Mountains lies the center of the Santa Barbara Basin, where below a water column of 590 meters, laminated, annually varved sediments have been accumulating for much of the Holocene (Kennett *et al* 1995). The preservation of laminae is due to the oxygen-deficiency of the bottom water that makes the center of Santa Barbara Basin inhospitable for large, sediment-dwelling and bioturbating benthos (Thunell *et al* 1995) combined with high export production of the surface waters. Kasten cores were recovered between 1987 and 1989 and the annual varves documented and counted down-core using thinsections and X-radiography of sediment slabs (Lange *et al* in press). The resulting varve-chronology of Santa Barbara Basin was independently verified by isotope-geochronological methods and by correlation with local tree-ring records (reviewed by Lange *et al* in press). Santa Clara River and Ventura River have been identified as the main sources of terrigenous detritus for the modern Santa Barbara Basin (Soutar and Crill 1977).

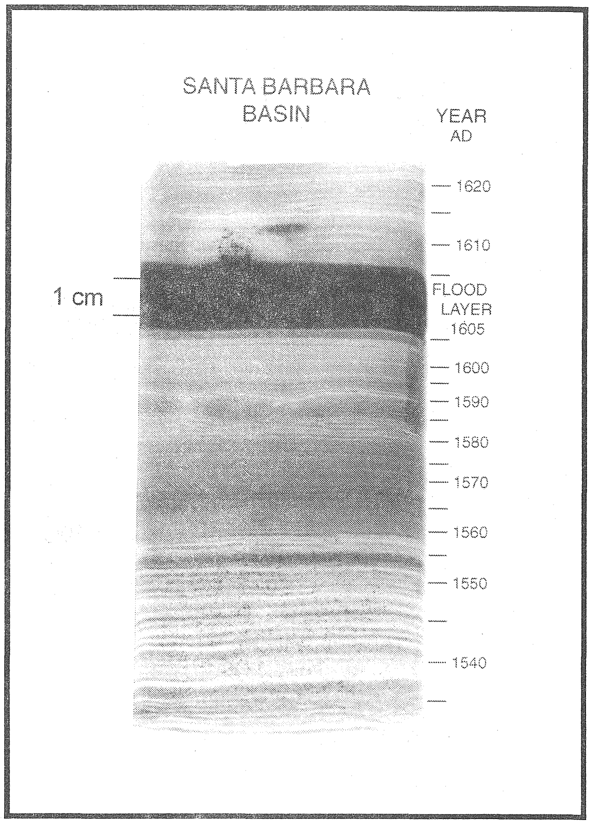

Figure 1. X-radiograph of a 1-cm-thick Santa Barbara Basin sediment slab (interval ca. 1530-1625 AD) from core KC4, cruise SABA 1993 (34°13.24'N, 120°03.66W; 590m water depth). Dark color indicates mineral-rich, less porous sediment.

At the 1605 AD ± 5 years level, at a sediment depth of about 1.18 meters, we observe a distinct, 1- to 2-cm-thick, clay-rich, gray layer (Munsell Soil Color 5Y 5/1) with sharp upper and lower boundaries against regular, varved sediment (color 5Y 4/2). An X-radiograph of this sediment interval indicates that the flood deposit may be the result of one or more closely spaced floods (Figure 1). All other identified flood deposits since 1420 AD have compacted to thicknesses below 1 mm (Lange *et al* in press), including the 1969 flood deposit in Santa Barbara Basin (Drake *et al* 1971), which resulted from intense precipitation in California in 1968/69 (Namias 1971). In contrast to normal olive-colored varves in Santa Barbara Basin, the gray flood deposit contains abundant terrigenous minerals that reduce the overall pore water content and the content of organic carbon (Figure 2). The depletion of ^{13}C in the organic carbon in the flood deposit is consistent with non-marine, continentally derived detritus in Santa Barbara Basin (Figure 2; Schimmelmann and Kastner 1993). A distinction between graded gray turbidites and gray flood deposits is important, because only flood deposits are caused by precipitation on land. By comparison to regular varves and to gray turbidite layers in the Santa Barbara Basin sedimentary record (Schimmelmann *et al* 1990) we found that flood deposits dated 1605 and 1418 AD have a significantly finer particle size and higher smectite content (Figure 3). These data are supported by studies of transported sediment in Santa Clara River during a severe flood in 1969 (Drake *et al* 1971).

Light-microscope analyses of smear-slides of acid-treated sediment permit the quantification of biogenic components (Figure 4). The interval 1603-1605, including the flood deposit, shows the highest non-carbonate proportion of terrigenous pollen and plant remains. The interval 1606-1611 above the flood deposit stands out with its large relative abundance of diatoms, which may indicate a burst in productivity following the flood event. A sudden increase in productivity could have been the result of strong upwelling after years with frequent or lasting El Niño conditions.

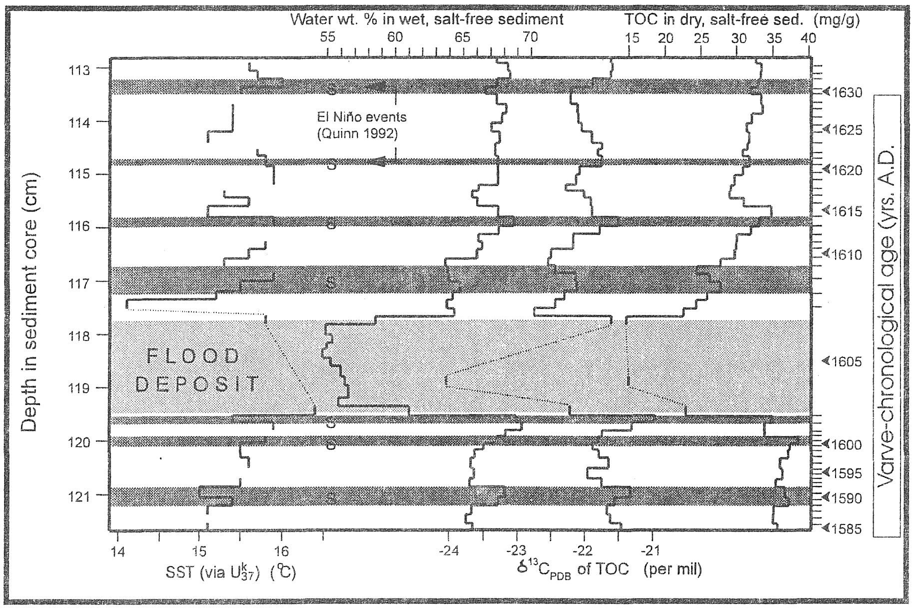

Figure 2. Geochemical time-series 1585-1635 AD from Santa Barbara Basin sediment, from left to right: alkenone-based sea surface temperature (SST); sediment water content; carbon stable isotope ratio $\delta^{13}C_{PDB}$ of total organic carbon (TOC); TOC content. Weighing of sediment samples before and after freeze-drying permitted the calculation of the water content in wet sediment. Samples were stored freeze-dried until aliquots were analyzed for TOC and their carbon stable isotope ratios (Schimmelmann and Tegner 1991). The determination of alkenone abundances followed Parry's (1993) description. SST was calculated from the $U^{k'}_{37}$ index using Prahl *et al's* (1988) equation: SST (°C) = $(U^k_{37}-0.039)/0.034$. The analytical precision of alkenone-based SST is about ± 0.5 °C. Quinn's (1992) historical strong El Niño events are indicated by shading.

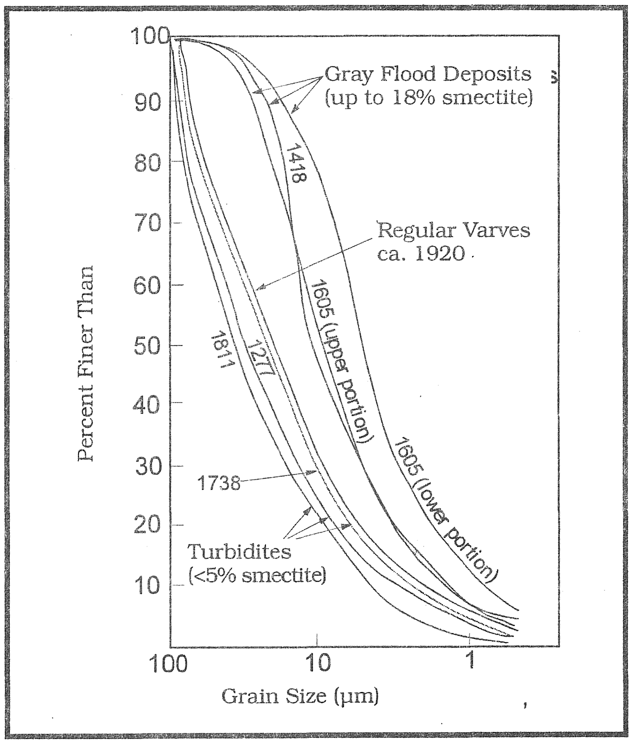

Figure 3. Particle size distribution in gray flood deposits (1605 and 1418 AD) in comparison with those of turbidites (1811, 1738, and 1277 AD) and of regular varves (ca. 1920). The smectite content was determined using the methylene blue method (American Petroleum Institute 1985).

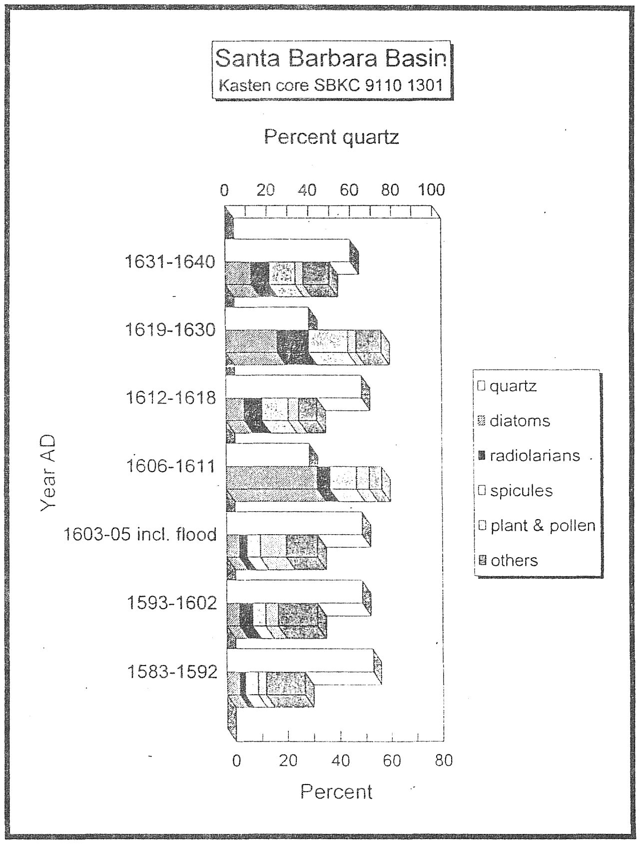

Figure 4. Light-microscope analyses of non-carbonate biogenic components (lower axis: diatoms, radiolarians, sponge spicules, pollen and plant debris) and quartz (upper axis) from smear slides of acid-treated sediment, as percent of total. "Others" include clay, silt, and non-identifiable particles that were not removed by the acid treatment. Sample resolution for varved intervals is about 5 to 10 years.

Matching Santa Barbara Basin Time-Series with Paleo-El Niño Events, 1585-1635 AD

Over much of the middle to lower latitudes, anomalies in the atmosphere and ocean circulation and temperature known as "El Niño-Southern Oscillation" (ENSO) events are an eminent source of year-to-year climate variability. During the Southern Oscillation phase, when the surface pressure is low in the southeastern tropical Pacific, warm water replaces the usually cool surface waters of the central and eastern Pacific — an event known as "El Niño" (Whetton and Rutherfurd 1994). Off the Americas, a strong El Niño event is typically characterized by anomalously warm sea surface temperatures, weakened circulation in the California Current system along the eastern margin of the Pacific, and reduced upwelling along the Californian and Peruvian coasts. The influence of ENSO extends to higher latitudes, mostly in winter, and changes the jet stream and storm track locations (Trenberth 1993) to more southerly locations over North America, such as documented for the 1982/83 ENSO event (Enfield 1992).

Quinn's (1992) latest compilation of historical ENSO events compares well with ENSO proxies from North China, Java, and India, because it bears more supraregional relevance in comparison to its earlier, South American-centered predecessors (Whetton *et al* 1996). For the 1585-1635 AD interval, Quinn's strong (S and S+) ENSO events include 1589-1591 (S), 1600/01 (S), 1604 (S), 1607/08 (S), 1614 (S), 1621 (S), and 1630/31 (S+) (see horizontally shaded intervals in Figure 2). Other, independent ENSO-sensitive time-series support specific ENSO occurrences for 1605 ± 5 years. The year 1600 is suggested by New Zealand tree-ring data (D'Arrigo *et al* 1995, with references therein).

Quinn's strong ENSO events around 1605 AD appear to be recorded in other high-resolution records, in part with a minor lag. The year 1607 AD was suggested as an ENSO-year by Lough's (1992) North American tree-ring record and by Dunbar's *et al* (1994) oxygen isotope record from Galápagos corals, making 1607 a most likely year for a widespread ENSO event. Further support for the relevancy of Quinn's (1992) ENSO data to Santa Barbara Basin around 1605 comes from detailed reports of the expedition of the Spanish explorer Sebastian Vizcaino, who sailed along the west coast of North America in the winter of 1602/03. Vizcaino's pilot (Wagner 1929) and an accompanying clergy (Wagner 1928) portray a rather benign California coastal climate without symptoms of an ENSO event. Santa Barbara Basin was calm, and abundant kelp beds were reported for off Point Loma, near San Diego, and adjacent to Isla Cedros, off Baja California, Mexico, at 28°N. Kelp beds are frequently reduced during strong ENSO events (Schimmelmann and Tegner 1991).

A comparison of Quinn's (1992) record with geochemical time-series from the 1585-1635 AD interval of Santa Barbara Basin sediment reveals that six of the seven S and S+ historical ENSO events are represented by ^{13}C-enrichment in total organic carbon (Figure 2). The comparable correspondence between modern, strong El Niño events and ^{13}C-spikes in an upper, 1845-1986 interval of Santa Barbara Basin varves was interpreted to be the result of El Niño-induced disturbances of ^{13}C-enriched, local kelp forests (Schimmelmann and Tegner 1991). It is highly unlikely that the 1585-1635 AD ENSO/^{13}C match is fortuitous. We obtained an independent proxy for paleo-sea surface temperature in Santa Barbara Basin by measuring the relative abundances of long-chain alkenone molecules, commonly expressed by the $U^{k'}_{37}$ index (Brassell *et al* 1986; Prahl *et al* 1988; Eglinton *et al* 1992), in selected samples, 1585 to 1635 AD (Figure 2). Kennedy and Brassell (1992) had successfully used alkenone abundances to correlate warming in Santa Barbara Basin with ENSO events of the 20th century. The highest sea surface temperature of the 50-year interval shown in Figure 2 was measured in the lowest part of the 1605 AD sample, containing the transition from olive, regularly varved sediment to the gray flood deposit. In contrast, the olive 1606 AD sample above the flood deposit features the coldest sea surface temperature. The high sea surface temperature suggests that the flood occurred in association with an ENSO event, followed by resumed upwelling, lowered sea surface temperature, and high productivity (as recorded by diatoms, Figure 4). The remarkable contrast between high and low sea surface temperature across the flood deposit seems to be resolved analytically because the flood deposit physically separates the opposing signals. In regularly varved sediment, where stratigraphic sample boundaries typically do not coincide with tightly spaced varve boundaries, the amplitude of geochemical signals may be dampened by uneven spacing of samples. For example, the warm season will be underrepresented in a sample encompassing 15 months of material from fall to winter, whereas the adjacent samples then tend to overrepresent warm seasons. These limitations, together with the analytical precision of ±0.5°C for reconstructed sea surface temperature, reduce the significance of smaller, warm sea surface temperature signals in varves assigned to Quinn's (1992) ENSO years 1589, 1600, 1608, 1614, and 1631 (Figure 2).

The fit between the historical paleo-ENSO pattern and the geochemical evidence suggests an accuracy of about ±2 years for our Santa Barbara Basin varve-chronology at the 1600 AD level. The base of the flood layer seems to be linked to a strong ENSO event, probably Quinn's 1604 AD event. We caution against overconfidence in year-to-year comparisons, because oceanographic changes in the strong upwelling areas of the eastern equatorial Pacific are sometimes not in synchrony with variations in other features of the Southern Oscillation (Diaz and Pulwarty 1992).

Additional Multi-Proxy and Historical Evidence for Unusual Climates around 1605 AD

The following paragraphs present major paleoclimatic evidence in light of general circulation theory. Tables 1-3 give a brief overview including other, additional paleoclimatic evidence.

Regional Evidence from Southwestern USA

Regional reconstructions of precipitation and temperature from the southwestern USA include sites near Santa Barbara, the larger Sacramento Basin catchment area, the Sierra Nevada, northeastern Nevada, and northwestern New Mexico (Table 1). The existence of a perennial lake in the Mojave Desert for at least a few decades requires not only initial, extreme rainfall, but subsequently also occasional replenishing floods in addition to cool summers to reduce evaporation. Abundant evidence for moist winters and cool summers in the southwestern USA during the early 17th century, in part extending into the 1640s (Table 1), fulfills

Table 1
REGIONAL EVIDENCE FOR UNUSUALLY WET, COLD CLIMATE AROUND 1605 AD

Time (AD)	Location and Evidence	Method	Source
1604; 1601-1611	Santa Barbara area, California; 1604 is the fourth wettest year, and 1601-1611 is the third wettest 11-year period in the entire 1366-1985 reconstruction of precipitation.	tree-ring width	Haston & Michaelsen 1994
1597-1613	Larger Sacramento Basin, Califormia; maximum reconstructed streamflow for 1660-1980, peaking around 1601 to 1606.	tree-ring width	Earle & Fritts1986
1602	Sierra Nevada; end of a 1566-1602 drought.	tree-ring width	Graumlich 1993
1580-1637	Sierra Nevada; no wide-spread drought recorded.	tree-ring width	Hughes & Brown 1992
1595-1644	Sierra Nevada; cold summer temperatures, especially 1604-1623 as the second largest 20-year temperature anomaly of the 800-1989 record.	tree-ring width	Graumlich 1993
1601, 1605	Sierra Nevada; two unusually narrow tree-rings suggest cold growing seasons; 1605 is even narrower than 1601.	tree-ring width	Scuderi 1990
about 1600-1650	Mono Lake fills rapidly to the record level of the past millennium.	sediment structural evidence	Stine 1990
1598; 1609-1623	Northwestern New Mexico; 1598 ended the worst decadal drought, followed in 1609-1623 by the fourth wettest decadal-scale interval in a 985-1970 reconstructed record of winter precipitation.	tree-ring width	D'Arrigo & Jacoby 1991
1601-1610	Northeastern Nevada; fifth wettest 10-year period in a 1601-1982 record, with a 1605/06 peak.	tree-ring width	Nichols 1989

these requirements. Especially noteworthy is a tree-ring-based reconstruction of overall annual streamflow in the larger Sacramento Basin since 1560 AD (Figure 5; Earle and Fritts 1986, p. 114) where an extremely wet spell occurred between 1599 and 1606. Each year's flow in 1599, 1603, 1604, and 1606 exceeded the annual flow data of the devastating flood years of 1861 and 1862. Increased wetness between 1601 and 1611, with a peak at 1604, is also indicated for the Santa Barbara area (Haston and Michaelsen 1994). A long-lasting drought in the Sierra Nevada ended in 1602 (Graumlich 1993), and 1601-1610 is among the five wettest 10-year periods in a 1601-1982 northeastern Nevada precipitation record (Nichols 1989). On the northwestern plateau of New Mexico, 1598 marked the end of the worst decadal drought of a millennial record (985-1971 AD), to be followed in 1609-1623 with the fourth wettest decadal-scale interval of winters (D'Arrigo and Jacoby 1991). Tree-ring data may severely underestimate the amount of precipitation when extreme events cause intensive runoff and/or detrimental waterlogging of the root system, whereas the water level record of the closed Mono Lake offers a more quantitative, cumulative measure of flood intensity. Mono Lake filled rapidly in the first half of the 17th century to briefly reach the highest level of the past millennium (Stine 1990). The ^{14}C-date of 1650 AD for the 17th century highstand of Mono Lake is corroborated by additional geological evidence (Stine 1987, pers comm).

A strong cooling trend in Sierra Nevada summer temperatures had started in 1595 and lowered the mean, smoothed summer temperature during the first half of the 17th century, to reach an absolute minimum for the entire 800-1989 AD time-series. The period 1604-1623 marks the second largest 20-year low temperature anomaly of the record (Graumlich 1993; see also Table 1). Scuderi (1990) finds tree-ring evidence for very cold growing seasons in the Sierra Nevada in 1601 and especially in 1605 (Figure 5).

The cited evidence agrees well with Enzel's (1992) hypothesis that winter atmospheric circulation patterns during the Silver Lake playa flood episodes were associated with an extreme southerly displacement of winter storm tracks and the Polar Jet over western North America and with a southerly shift of the central North Pacific winter low pressure zone (Figure 6). Major frontal cyclones would thus be steered into the southwestern USA, raising the potential for large floods. Much of the precipitation in the Mojave River basin falls in the high-elevation San Bernardino Mountains, which are ideally located to lift moist southwesterly airflow of winter cyclones (Ely *et al* 1994). Along with increasing regional winter precipitation, an equatorward shift of quasi-stationary planetary waves would have brought a decline in temperatures (Roden 1989; Hurrell 1995). For comparison, the "Noachian Deluge" of 1861/62 also was accompanied by an extreme cold spell in the Pacific Northwest that froze the mouths of the Fraser and Columbia rivers (Roden 1989).

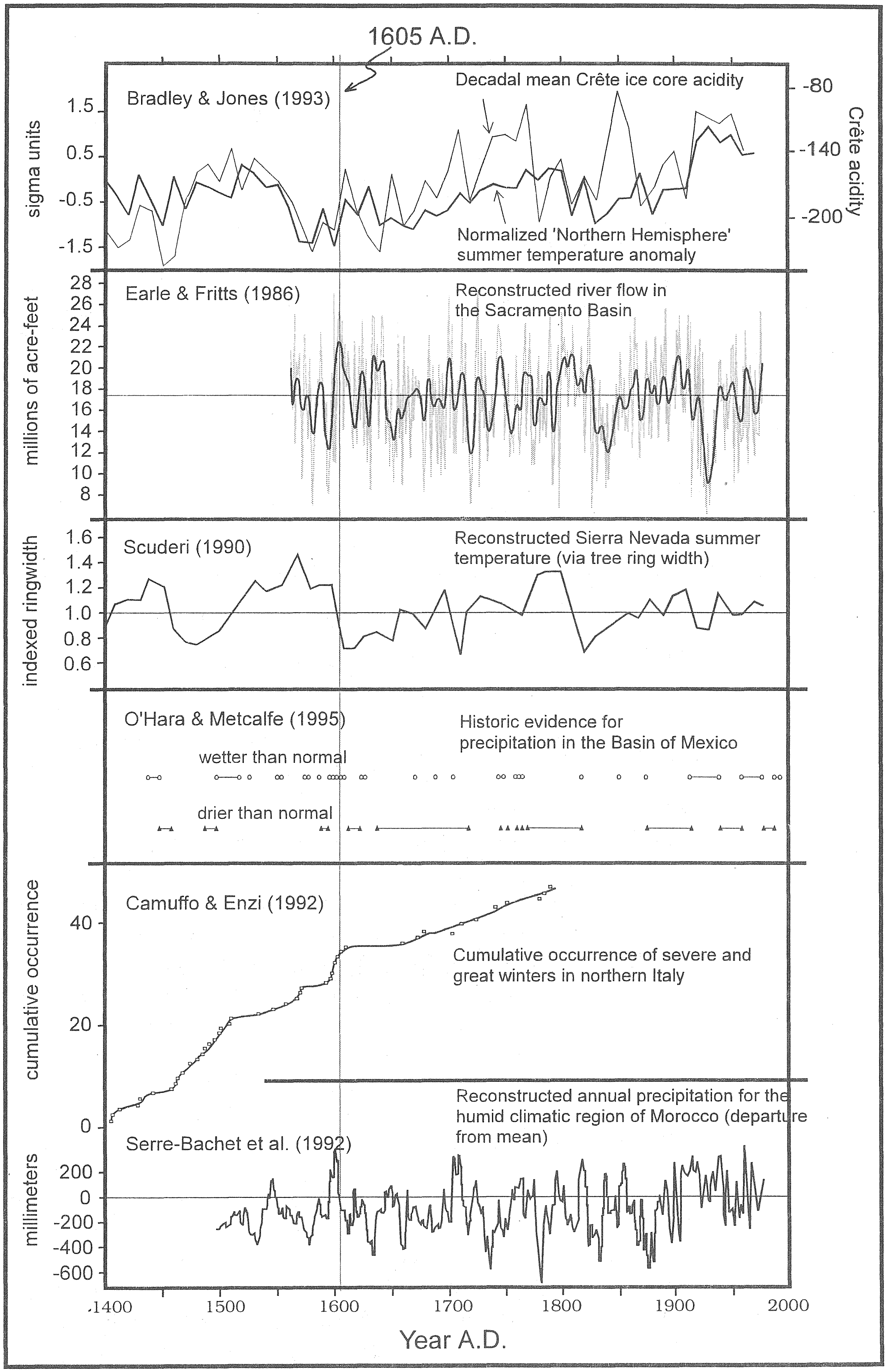

Figure 5. Selected paleoclimatic time-series with relevance to extreme events around 1605 AD.

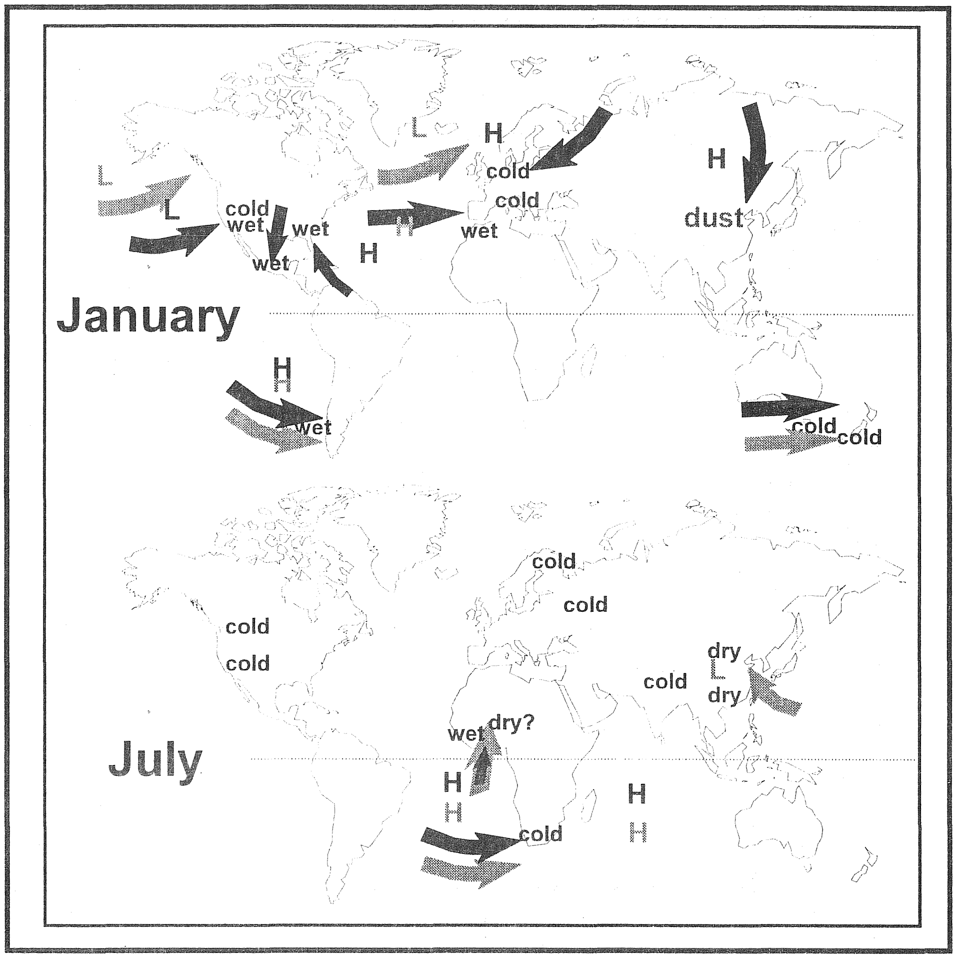

Figure 6. Suggested equatorward displaced atmospheric circulation for ca. 1605 AD (black arrows and black text). For comparison, modern mean conditions are displayed in gray tone.

Supraregional Evidence from the Northern Hemisphere

Supraregionally teleconnected climatic events frequently differ in their expression. For example, the southerly displacement of the westerlies and jet stream pattern over the Northern Hemisphere that brought intense precipitation to Southern California may have caused drought in parts of China. The unifying link in the following discussions is an equatorward shift in wind patterns. Observations are summarized in Table 2.

An accumulation of five unusually wet spring seasons in the southeastern USA, an occurrence rate more than five times higher than the long-term mean, was suggested to be linked to a westward shift of the North Atlantic subtropical high, or "Bermuda high" (Stahle and Cleaveland 1994). This implies that large-scale atmospheric circulation over eastern North America may have been amplified around 1596-1613 AD and was perhaps causally linked with climatic anomalies elsewhere in the Northern Hemisphere during the most consistent and extensive cold episode of the "Little Ice Age" (Stahle and Cleaveland 1994). A southerly displacement of atmospheric circulation patterns around 1605 AD is also

Table 2
SUPRAREGIONAL EVIDENCE FOR NORTHERN HEMISPHERE UNUSUAL CLIMATES AROUND 1605 AD

Time (AD)	Location and Evidence	Method	Source
1600-1609	Northern Hemisphere, comprehensive summer temperature evaluation; exceptionally cold decade.	multi-proxy	Bradley & Jones 1993
1580-1610	Canadian Rocky Mountains, cold summers. 1595 shows minimum for entire 1505-1970 record.	tree-ring width	Smith et al 1995
1607/08	Severe winter in Maine, Virginia (Jamestown), and Lake Superior	historical records	Lamb 1982, p. 230
ca. 1590-1610	Northern Mexico, unusually dry period in area between 23 and 30°N where summer precipitation predominates.	tree-ring width	O'Hara & Metcalfe 1995
1604, 1607	Basin of Central Mexico, Mexico City; following a 1590s drought, severe flooding occurred in 1604 and 1607; the severity of the 1607 flood prompted excavation of a drainage canal out through the northern part of the basin.	historical records	O'Hara & Metcalfe 1995
1596-1613	Southeastern USA; 5 of the 48 wettest spring rainfall years in a 1,053-year-long record fall between 1596 and 1613, namely 1596, 1600, 1602, 1605, and 1613.	tree-ring width	Stahle & Cleaveland 1994
1604-1614	Central Europe; increased precipitation, with a wet peak from winter 1608 through the very wet summer of 1609.	historical records	Rüdiger Glaser, pers comm
1600-1608	Central Europe; all seasons of the years 1600, 1601, 1606 and 1608 were significantly colder than the long-term mean.	historical records	Rüdiger Glaser, pers comm
1608	Europe; "great" winter.	historical records	Lamb 1985
1595-1608	Netherlands; densest cluster of unusual winters on record, since 1408; winters were cold [c], severe [s] or very severe [vs]: 1595vs, 1599c, 1600s, 1602c, 1603c, 1608vs.	historical records	Buisman 1984
1590s to 1610	Northern Fennoscandia; very cold July/August temperatures; 1600/1601 absolute minimum for entire record (1580-1975).	tree-ring width and maximum latewood density	Briffa & Schweingruber 1992
1601-1620	Fennoscandia; third-coldest 20-year interval in a 1,400-year record of summer temperatures, 500 to 1975.	tree-ring width and maximum latewood density	Briffa et al 1990
1595-1608	Northern Italy; densest cluster of severe and great winters in recorded history (since 1406): 1595, 1599, 1600, 1602, 1603, 1605, 1608.	historical records	Camuffo & Enzi 1992
1601-1603	Russia, "Great Famine", with "Godunov Hunger Riot"; reportedly "one third of the Moscow Tzardom" population died, 120,000 people perished from hunger in Moscow alone.	historical records	Borisenkov 1992
1590-1620	Mid-Russia; unusually low spring/summer temperatures.	historical records	Borisenkov 1992
ca. 1610 (?)	Africa, Lake Chad; most dramatic lake level decline of the last millennium? The radiocarbon dating is imprecise.	sediment records, pollen	Maley 1973

Table 2 (continued)
SUPRAREGIONAL EVIDENCE FOR NORTHERN HEMISPHERE UNUSUAL CLIMATES AROUND 1605 AD

Time (AD)	Location and Evidence	Method	Source
1602-03	Africa, Timbuktu (Mali), great flood from unusually heavy rains over the upper basin of River Niger.	historical records	Lamb 1982, p. 226
ca. 1610	North China; substantial increase in dust fall indicates increase in aridity and windiness; this record has decadal resoluton.	historical records	Liu Tungsheng et al 1989
shortly before 1600	Tibet Plateau and Qilianshan Mountains east of the Tibet Plateau begin strong cooling; southern China became drier and the Yangtze River level declined.	tree-ring width; historical evidence	Zhaodong Feng et al 1993
1602-1611; 1620-1629	Algeria experiences the worst episodes of famine since 1500 AD (reasons were not reported).	historical evidence	Nicholson 1980
1598-1604; 1602	Morocco; 1598-1604 unusually large amount of annual precipitation, with 1602 representing the absolute maximum of the 1499-1878 record.	tree-ring width	Serre-Bachet et al 1992
1601	Unknown location, but probably in the Northern Hemisphere: large volcanic eruption; recorded in Greenland ice sheet, tree-rings, and by historical accounts.	multi-disciplinary	Lamb 1970; Hammer et al 1980; Scuderi 1990; Briffa & Schweingruber 1992; Pavese et al 1992

in agreement with O'Hara and Metcalfe's (1995) historical climate record from central Mexico. Devastating drought conditions during the 1590s in the basin of central Mexico, which is climatically distinct from northern Mexico, ended about 1600 (Figure 5). In 1604 and 1607, flooding was so severe around Mexico City that a drainage canal was excavated through the northern part of the basin. At present, the regional precipitation pattern in central and part of northern Mexico is influenced primarily by seasonal shifts in the latitudes of the trade winds in summer and the subtropical high pressure belt in winter. During the Northern Hemisphere summer, a monsoon-type easterly flow brings the main rainfall to central Mexico. However, in late winter and early spring, with the Intertropical Conversion Zone[1] displaced equatorward, outbreaks of cold polar air, called "nortes", can bring rains as far south as the Yucatan Peninsula of southern Mexico (O'Hara and Metcalfe 1995). We suggest that after 1600 AD frequent nortes originated from a much colder North American continent, picked up moisture on their paths across the Gulf of Mexico, and brought intense precipitation to central Mexico (Figure 6).

With regard to summer temperatures, the decade 1600-1609 stands out as exceptionally cold in a comprehensive 1400-1970 Northern Hemisphere composite record based on historical, tree-ring, and ice core data

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[1] Zone of equatorial rainfall maximum where the two hemispheric wind systems adjoin.

(Figure 5; Bradley and Jones 1993). The largest effects are seen at higher latitudes such as in Svalbard, Northern Scandinavia, and South Greenland (Bradley and Jones 1993). The 1607/08 AD winter was severe in eastern North America. In Maine, "persistent northerly winds and such severe frosts ... [killed] many people ... both among the Europeans and the Indian population. At Jamestown it was reported that 'the extraordinary frost in most of Europe ... was as extreme in Virginia'. And Samuel Champlain, the founder of Quebec, found bearing ice on the edges of Lake Superior in June 1608." (Lamb 1982, p. 230). Lamb suspects that "there seems to have been a general reduction of the westerlies, which were shifted to a lower latitude over the Pacific." European archives document a unique concentration of severe winters near the turn of the 16th century (Table 2). The year 1608 is one of the few "great" winters listed in Lamb's (1985) classification of European historical winters. Between 1599 and 1608, Northern Italy experienced its densest cluster of severe and great winters since 1406 (Figure 5; Camuffo and Enzi 1992). Eyewitness accounts in 1603 describe "the Lagoon and all the canals in Venice froze over for 8 to 10 days" and in 1608 "the winter [in Venice] was so severe, as had never occurred from time immemorial. Due to an exceptional snowfall, it was impossible to walk in the streets or go out through the door" (Camuffo 1987, p. 60). A large central European database identifies 1600, 1601, 1606, and 1608 as extremely cold (Rüdiger Glaser, pers comm). Pfister *et al* (1994) interpret decadal cooling of western Europe as due to the shrinking of the Hadley cell, a zonal-mean tropospheric circulation linking the lower and middle latitudes. The influence of the westerlies with their warm, Atlantic air masses would be diminished, whereas polar air masses from the northeast would gain more access (Rogers 1985).

The proposed shift of wind patterns is consistent with a southerly displacement and/or weakening of the westerlies (Figure 6). Further evidence for this hypothesis is found in the humid climatic region of Morocco, where 1598-1604 AD brought unusually large annual precipitation, with 1602 reaching an absolute maximum in the 1499-1978 record (Figure 5; Serre-Bachet *et al* 1992). The Mediterranean winter/spring climate of Morocco apparently came under temporary influence of the equatorwardly displaced westerlies (Jinjun Ji *et al* 1993; Tyson and Lindesay 1992). Between 1602 and 1611 and again between 1620 and 1629, Algeria suffered through its worst 30-year period of famine in recorded history, since 1500 AD (Nicholson 1980). Climatic changes were likely responsible, although the actual reasons for the famine are not reported.

A change in northeast Asian wind patterns is indicated by substantially increased dustfall due to higher aridity around 1610 on the Loess Plateau of central China (record with decadal resolution shown in Liu Tungsheng *et al* 1989; also discussed in Zhaodong Feng *et al* 1993). Strong cooling trends starting shortly before 1600 are evident from tree-rings on the southern Tibet Plateau and the Qilianshan Mountains east of the Tibet Plateau. At the same time, southern China became drier and the water level of the Yangtze River declined (Zhaodong Feng *et al* 1993). During periods when the strong Mongolian winter high moves southward and reduces the strength of the Southern Pacific high, temperature and precipitation in China are relatively low (Zhaodong Feng *et al* 1993). The increased dustiness can be interpreted in the context of global cooling associated with an increase of the meridional temperature gradient, an increase in the intensity of the wind field over northern desert regions and the Chinese Loess Plateau, an expansion and strengthening of the Mongolian winter high, a decline of the humid summer monsoon influence, and a southward expansion of the north China desert (Liu Tungsheng *et al* 1989). This scenario of north Chinese drought is consistent with equatorward shifts of the polar jet stream (Zhang Linyuan *et al* 1995) and the Intertropical Conversion Zone (Jinjun Ji *et al* 1993).

A great flood in 1602-03 AD in the city of Tombouctoo (Timbuktu) in Mali resulted from unusually heavy rains in the previous summer over the upper basin of the River Niger in westernmost Africa in latitudes 10-12°N (Lamb 1982, p. 226). Summer rains in 1602 AD in west Africa fell much closer to the equator, rather than migrating seasonally to 15-20°N or beyond, as in this century before 1960. Geological and pollen evidence suggests an early 17th century low stand of Lake Chad in north Africa (Maley 1973) as the consequence of a severe drought caused by a displacement of the Intertropical Conversion Zone near west Africa closer to the equator (Jinjun Ji *et al* 1993). We caution, however, that Maley's (1973) underlying radiocarbon dates do not offer high precision, and that some sparse historical information indicates that droughts set in later, during the 1680s (Nicholson 1980).

Supraregional Evidence from the Southern Hemisphere

Southern Hemisphere climatic changes and extremes around 1605 are summarized in Table 3. Between 1590 and 1630, the seasonal oscillations of the oxygen isotope ratios of precipitation on the Quelccaya glacier in the Peruvian Andes are much lower than during adjacent centuries, marking 1590 and 1630 as times of rapid alternation of climate or environmental conditions (Thompson 1992).

Precipitation in central Chile is related to a northward shift of westerly storm tracks along the coast of Chile, in response to the latitudinal position and intensity of the Southeastern Pacific High (Figure 6). A northerly shifted position is characterized with a "weak" index, or "high index" (*ie,* weaker subtropical pressure) and is sometimes associated with El Niño conditions (Villalba 1994). Tree-ring studies suggest that summer precipitation on Chiloe Island, off south-central Chile at 42°S, increased dramatically between 1601 and 1604, synchronously with a minor shift of the anticyclone position toward the equator (Boninsegna 1992).

Tree-ring data from Tasmania indicate a rapid cooling of summer temperatures (November-April) between 1600 and 1610 (Cook *et al* 1992), parallel to similar observations in tree-rings from Patagonia, Argentina (Boninsegna 1992; Bradley and Jones 1993 show the two graphs in comparison). On the South Island of New Zealand, under the influence of the middle-latitude southern westerlies, extreme growth of silver pine in 1600 AD was followed by an abrupt, deep decline through 1604/05 (D'Arrigo *et al* 1995). Similarly, mean annual temperatures in southern Africa declined sharply around 1600 (Tyson and Lindesay 1992). The Southern Hemisphere mid-latitude climatic change around 1600 was suggested to be the result of an equatorward expansion of the Antarctic circumpolar vortex, together with a northward displacement of the westerlies in the Southern Hemisphere, and northward-shifted high pressure systems in the south Atlantic and south Indian oceans (Tyson and Lindesay 1992; Cohen and Tyson 1995; Figure 6).

Table 3

SUPRAREGIONAL EVIDENCE FOR SOUTHERN HEMISPHERE UNUSUAL CLIMATES AROUND 1605 AD

Time (AD)	Location and Evidence	Method	Source
1607 ± 5 year	Galápagos Islands.; second largest ^{18}O-depletion in 1607-1950 record of annual coral aragonite bands, suggesting strong El Niño conditions.	oxygen isotope ratios	Dunbar et al 1994
ca. 1600-1620	South Africa; decline of mean temperature in coastal water and in continental air. This study has relatively low time resolution.	oxygen isotope ratios	Tyson & Lindesay 1992
ca. 1590-1630	Peru, Quelccaya glacier; the oxygen isotope ratio in annual ice core layers shows distinctly reduced variability.	oxygen isotope ratio	Thompson 1992
1606; 1604-1628	Tasmania; summer temperature (Nov-Apr);1606 was cold, the only tree-ring year with especially notable "narrow and light" character in entire series 900-1988; 1604-1628 is the fifth-coldest 25-year interval of the summer temperature record.	tree-ring width	Cook et al 1992
ca. 1603-1610	South-central Chile, Chiloa island; unusually strong summer precipitation.	tree-ring width	Boninsegna 1992
1600	Southeastern Pacific Ocean; third highest winter anticyclone belt index for entire record (AD 1450-1972), suggesting El Niño conditions.	tree-ring width	Boninsegna 1992
1600; 1601-1605	New Zealand, South Island; 1600 AD absolute maximum growth in entire record (1350-1991); this is followed by a dramatic decline until about 1604/05, suggesting cooling.	tree-ring width	D'Arrigo et al 1995

Potential 1600-1610 AD Climatic Forcing Factors

Causes of decade- to century-scale climate variability, such as solar variability, volcanic aerosol loading, fluctuations in ocean circulation, and natural unforced variability interact at varying spatial and temporal scales to provide the climatic complexity of the last millennium (reviewed by Crowley and Kim 1993 and by Rind and Overpeck 1993). In addition to ENSO events (discussed above), we consider a few other likely causes that may have contributed to climatic anomalies around 1605 AD.

Solar Variability

The reconstructed solar irradiance was declining in the early 17th century (Lean *et al* 1995). The dramatic climatic changes around 1605 AD, including the observed cold temperatures during the first decades of the 17th century, clearly predate the 1650-1715 Maunder Minimum (Meko 1991; Stuiver and Braziunas 1993) when the absence of sunspots decreased the solar radiation influx to a long-term minimum (Eddy 1976). It appears that the Spörer Minimum low solar irradiance, which lasted into the 16th century, may have cooled the earth and thus contributed to the ca. 1605 AD extreme climatic events. However, 1604 AD marks the minimum of atmospheric $\Delta^{14}C$ between the Spörer and Maunder Minima, which indicates temporarily increased solar activity and shielding of the earth from ^{14}C-producing galactic cosmic rays (Stuiver and Braziunas 1993). This argues against a direct, major role of solar-induced cooling for the ca. 1605 AD events.

Explosive Volcanism

Explosive volcanism increases the stratospheric aerosol load and reduces solar radiation receipts in the lower troposphere. It is now recognized as a major factor for short-term atmospheric and continental cooling (Nesje and Johannessen 1992; Bradley and Jones 1993; Stuiver *et al* 1995), although the actual temperature effects differ geographically and over the few years following an eruption (Robock and Mao 1995; Portman and Gutzler 1996). Clusters of intense volcanism may cause a decadal-scale thermal excursion (Crowley and Kim 1996). The acid fallout from a large 1601 AD, albeit geographically unidentified, volcanic eruption is evident from the Crête ice core record in Greenland (Hammer *et al* 1980). Lamb (1970, p. 501) noted: "The sun greatly dimmed by a constant haze over southern Scandinavia in 1601... The Sun and Moon appeared 'reddish, faint and lacked brilliance' in central Europe all through the year 1601 and up to the end of July 1602". The spring of 1601 was anomalously cold in northern Italy (Pavese *et al* 1992). Cold temperatures are evident in western USA tree rings for 1601 AD (LaMarche and Hirschboeck 1984; Scuderi 1990) and in northern Fennoscandian tree-rings where

1600/1601 indicates the lowest reconstructed July/August temperature of the entire 1580-1975 record (Briffa and Schweingruber 1992).

Other known volcanic eruptions in 1600 to 1610 include Mount Etna in Italy, which was active from 1603 to 1610, with a climax around 1606/07 (Lamb 1970). In the Southern Hemisphere, eyewitness accounts noted the eruption of Huaynaputina in Peru, the most explosive event ever recorded in the central Andes of Peru. Its February/March 1600 eruption provided an absolute date for a prominent volcanic ash layer in the nearby Quelccaya glacier ice core (Thompson and Mosley-Thompson 1989). In the same year, the Ecuadorian volcano Quilotoa erupted (Bradley and Jones 1992). An unknown eruption around 1605/06 with influence on the Southern Hemisphere may have caused a 1606 AD "especially notable narrow and light" tree-ring in Huon pine in Tasmania, the only one of this character in a 900-1988 data series (Cook *et al* 1992).

The North Atlantic zone of main cyclonic acitivity tends to shift south in the summers after great eruptions, this accounting for many, perhaps most, of the coldest, wettest summers of the last 300 years in western Europe and eastern North America (Lamb 1982, p. 63). The severity of the 1600/01 eruptions seems to have caused a series of disastrous harvests in Russia, leading to the 1601-1603 "Great Famine" with a subsequent "Godunov Hunger Riot"; reportedly "one third of the Moscow Tzardom" population died — 120,000 people perished from hunger in Moscow alone (Borisenkov 1992).

Large-Scale Cooling, Meridional Shifts of Midlatitude Storm Tracks, and ENSO

The quasi-stationary planetary waves and the transient component of atmospheric heat transport (*eg*, frontal cyclones) are mainly forced by patterns of temperature gradients and by orography. Therefore, an alteration of global temperature gradients greatly influences the planetary waves, the storm track pattern of the transients, and ultimately is linked to changes in regional precipitation patterns (Trenberth 1993). More specifically, global cooling decreases the Hadley circulation and causes a southward shift of storm tracks in midlatitudes in the Northern Hemisphere, with severe socio-economic repercussions on human cultures (Bryson and Murray 1977).

With regard to the southwestern USA, several authors have noted a connection between precipitation, upper air pressure anomalies, elevated sea surface temperature in the eastern North Pacific, and ENSO events (Cayan and Webb 1992; Haston and Michaelsen 1994; Ely *et al* 1994; Graham *et al* 1994). ENSO is only one of many factors that affect the occurrence of winter floods in the southwest, but an increased frequency of large winter floods during multiple-year periods dominated by a negative Southern Oscillation Index and the near absence of large floods during the intervening periods led Ely *et al* (1994) to suggest that the warm phase of ENSO is influential in producing the most extreme winter floods. The ca. 1605 occurrences of ENSO-related, near-coastal, relatively warm sea surface temperature off California during a decade of very cold mean Northern Hemisphere continental summer temperatures are not contradictory. In fact, reconstructions of summer temperature using tree-ring data from the western USA correlate relatively poorly with the overall Northern Hemisphere summer temperature reconstruction (Bradley and Jones 1993). Presumably this is because western North American summer temperatures are strongly buffered by winds from the Pacific Ocean.

Synthesis of Paleoenvironmental Evidence: What Led to the ca. 1605 AD Flood Event?

Starting around 1550 AD, large-scale cooling had set in, covering much of the Northern Hemisphere (Bradley and Jones 1993). One may speculate that the cooling was in response to reduced solar irradiance, based on a strong correlation between reconstructed solar irradiance and Northern Hemisphere surface temperature that was shown for the subsequent, pre-industrial period 1610-1800 (Lean *et al* 1995; Crowley and Kim 1996). Although the concept of a global "Little Ice Age" is no longer supported by the available evidence (Hughes and Diaz 1994), the first decade of the 17th century stands out as having exceptionally cold conditions that were sufficiently widespread to represent a large-scale climatic signal (Bradley and Jones 1993). Our suggested paleoclimatic scenario for 1600-1610 is illustrated in Figure 7. Starting in 1600/01, pre-existing cool conditions were exacerbated in many regions by a cluster of large volcanic activities that caused further, excessive short-term cooling. Strong El Niño conditions in the eastern Pacific, probably around 1604, increased the sea surface temperature and the moisture loading of vigorous cyclones that were forced to travel eastward along southerly displaced storm tracks into Southern California. The major flooding likely occurred in 1605 AD ± 1 year. The region was just recovering from a severe, late-16th-century drought (Graumlich 1993; D'Arrigo and Jacoby 1991; Biondi *et al* this volume), which had left the soil vulnerable to erosion and may thus have contributed to the remarkable thickness of the flood deposit in Santa Barbara Basin.

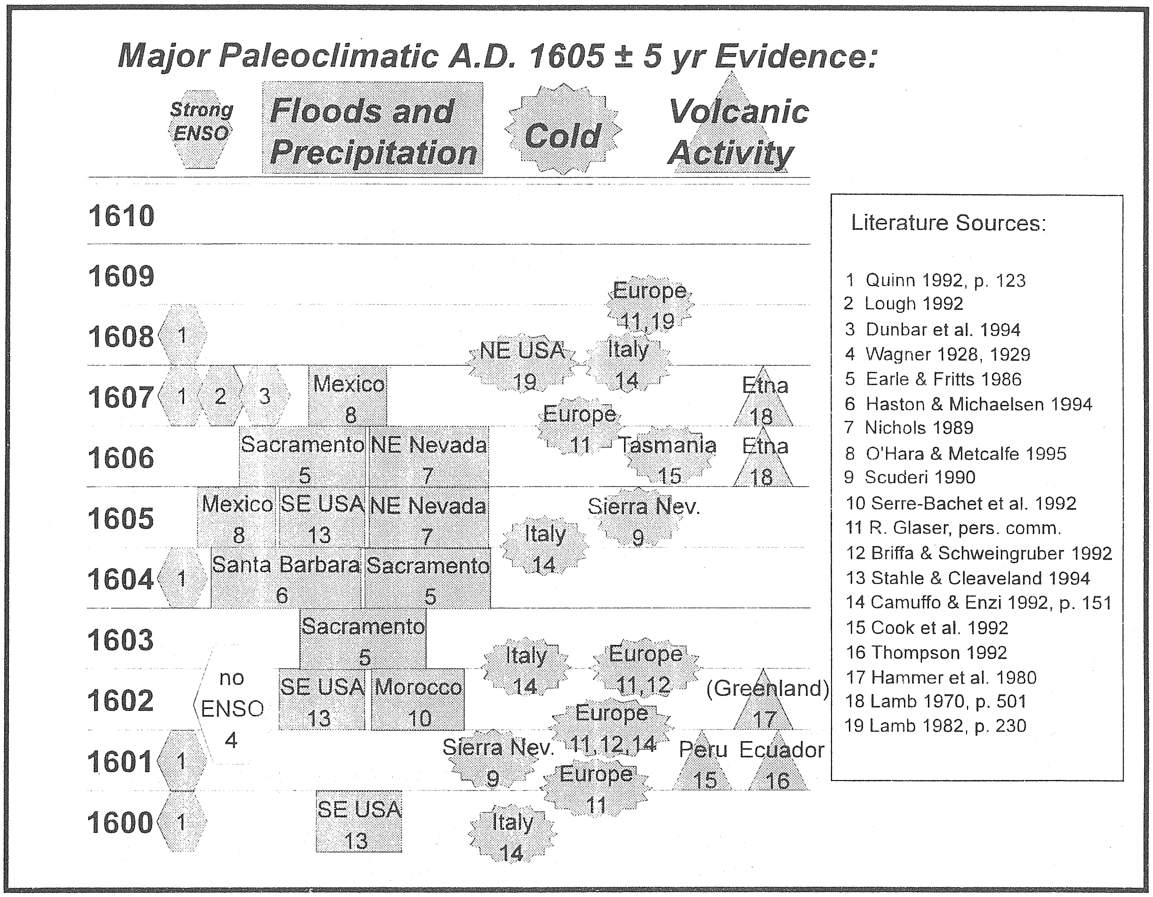

Figure 7. Chronology of major climatic evidence and relevant historical observations, 1600-1610 AD.

Conclusion

The paleoclimatic contrasts around 1605 AD from many regions in both hemispheres seem to be consistent with an equatorward displacement of major wind patterns and associated storm tracks. A relatively cool mean global temperature around the turn of the 16th century was exacerbated after 1600 AD by a sharp volcanic-induced cold spell. With the additional influence of a strong ENSO event around 1604 AD, precipitation in Southern California from vigorous, southerly displaced cyclones climaxed and resulted in highly unusual and distinctive flood and lake deposits in Santa Barbara Basin and at the terminus of the Mojave River.

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