LATE-EIGHTEENTH-CENTURY PRECIPITATION RECONSTRUCTIONS FROM JAMES MADISON'S MONTPELIER PLANTATION

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Tree-ring and meteorological diary reconstructions express a common climatic signal and suggest a shift in the seasonality of precipitation from Madison's era to the mid-twentieth century.

As early colonialists crossed the Atlantic Ocean from Europe to North America, they carried preconceived notions on the variation of climate with latitude. Perhaps not surprisingly, they expected to encounter the same climatic conditions at the same latitudes in the New World as they had experienced in the Old World (Kupperman 1982). While the Gulf Stream's moderating effect on the climate of Europe is now well known, the greater seasonal extremes of eastern North America frustrated early attempts to grow Mediterranean crops such as citrus trees within Virginia and were viewed as a shortcoming of an untamed continent that had not yet felt the salubrious and tempering influence of European cultivation (Kupperman 1982, 1984). Especially after the revolution of 1776, the capacity of North America to support a vigorous and prosperous society represented an important component of success for this political experiment (Chinard 1947). However, in the late eighteenth century, European scientists espoused a hypothesis claiming that the climate of North America was inherently inferior and deleterious, and would remain so despite any efforts to improve it through habitation (Chinard 1947). Both Thomas Jefferson and James Madison recognized that this hypothesis had to be refuted for this nation to be viewed as a peer to those in Europe. This study presents their scientific endeavors to demonstrate that the climate of North America was not inferior to that of Europe. Comparing meteorological diary data collected by Madison and dendroclimatic reconstructions from Montpelier, this study is also able to investigate new hypotheses regarding the seasonality of precipitation since the late eighteenth century. The focus is not centered as intently on the validity of these methods,

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as both diary and tree-ring data have demonstrated efficacy in the reconstruction of climate (Bradley and Jones 1995), but rather on the combined use of these independent sources to characterize the climate of Madison's era and contrast it with that of the mid-twentieth century.

Climatological interests of Jefferson and Madison. After returning home to his family's plantation, Montpelier in Virginia (35 km northeast of Charlottesville), James Madison wrote in a letter to Thomas Jefferson dated 12 June 1792:

> I found this Country labouring under a most severe drought. There had been no rain whatever since the 18 or 20 of April. The flax and oats generally destroyed; The corn dying in the hills, no tobacco planted, and the wheat in weak land suffering (Madison 1983, 316–319).

Although the communication of drought between two plantation farmers may not seem unexpected, the observation of climate held additional scientific interest for Madison and Jefferson (Davis 1964, p. 195; Ketcham 1990, p. 151). These two extraordinary individuals, both prolific participants in the founding of a new nation, also sought to disprove a degrading scientific theory advanced by no one less than the preeminent naturalist of the eighteenth century, the Comte de Buffon (Martin 1952, 151–153; Bedini 1990, p. 95; Ketcham 1990, 150–151). Buffon had achieved his status by writing an encyclopedic treatise, titled *Histoire Naturelle, Générale et Particulière* (Shuffelton 1999). This multivolume work, begun in 1749 (Mayr 1982, p. 330), delineated the characteristics and geographical distributions of the known fauna in the world. Interspersed within his descriptions (Chinard 1947), Buffon argued that the humid, cold New World climate degenerated the size and decreased the number of its native fauna as well as having an ill effect on its native inhabitants:

> In America, therefore, animated Nature is weaker, less active, and more circumscribed in the variety of her productions; for we perceive, from the enumeration of the American animals, that the number of species is not only fewer, but, in general, that all the animals are much smaller than those of the Old Continent . . . In this New World, therefore, there is some combination of elements and other physical causes, something that opposes the amplification of animated Nature: there are obstacles to the development . . . These effects must be referred to the quality of the earth and atmosphere, to the degree of heat and moisture, to the situation and height of mountains, to the quantity of running and stagnant waters, to the extent of forests, and, above all, to the inert condition of Nature in that country. In this part of the globe, the heat in general is much less, and the humidity much greater (Buffon 1812, p. 237, 250, 253–254).

Buffon's *Histoire Naturelle* was widely read throughout Europe and America (Martin 1952, 152–160; Mayr 1982, p. 330; Shuffelton 1999). Other contemporary scientists, most notably the Abbé Raynal, extended the logic of Buffon's theory of degeneracy to deduce that the New World climate would also adversely impact its colonists from Europe (Martin 1952, p. 161, 178; Jefferson 1999, p. 69).

While attending the College of New Jersey from 1769 to 1771,[1] James Madison had received a thorough education in Latin, Greek, mathematics, and philosophy, but not in science (Brant 1941, p. 278; Cohen 1995, 262–264). This knowledge was imparted later through his friendship with Jefferson (Cohen 1995, p. 267). Jefferson had studied Buffon extensively and was eager to disprove his theory (Chinard 1947; Martin 1952, p. 152, 162; Davis 1964, p. 190). To this end, Jefferson had assumed a "mysterious obligation" by writing a lengthy description on the state of Virginia intended initially as a private correspondence to the secretary of the French legation to the United States, François Marbois (Jefferson 1951, 167–168; Martin 1952, p. 162; Shuffelton 1999). In 1780, Marbois had inquired generally on the climate and people of Virginia by issuing letters to prominent delegates in Congress requesting information on each of the 13 states (Shuffelton 1999). Jefferson, upon receiving a copy of the letter, seized the opportunity to provide a more objective characterization of Virginia and by the following year produced detailed answers to all 22 of Marbois's inquiries (Shuffelton 1999). However, afraid of negative political connotations, especially with regard to his statements that slavery should eventually be abolished within Virginia, Jefferson had closely guarded the release of his notes (Malone 1951, p. 95; Shuffelton 1999).

Madison and Jefferson became close friends during the late 1770s when Madison served on the Council of State for Virginia while Jefferson was governor

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[1] This college is now Princeton University. Madison completed the traditional four years of study in half the time (Cohen 1995, p. 262).

(Ketcham 1990, 80–84; Cohen 1995, p. 267). By December 1783, Madison had acquired the first edition of Buffon's *Histoire Naturelle,* most likely as the result of the influence of Jefferson (Brant 1941, p. 278). Although severe winter weather prevented the shipment of these texts to Montpelier for "incidental reading," Madison remained actively engaged in his scientific conversations with Jefferson (Madison 1971, 418–420). For example, concerning Buffon's theory of the Earth's heat, Madison wrote to Jefferson of his own calculations on the difference in radius from the poles versus the equator due to the oblate dimensions of the Earth (Madison 1971, 401–406). Madison inferred that this difference would be far more insightful in determining the dissipation of heat from the center of the Earth than by comparing temperatures between adjacent mountains and valleys. Although Jefferson responded that he had misinformed Madison as to the details of this theory, Jefferson agreed that Madison's calculations were correct (Brant 1941, p. 279; Madison 1971, 411–414). The following month, Madison also wrote to Jefferson concerning the discovery of mammoth teeth in South America (Brant 1941, 280–281; Madison 1971, 418–420). While Jefferson was unaware of this particular discovery, he regarded the existence of mammoths in South America with some skepticism (Madison 1971, 422–435). Yet Jefferson must have been impressed with the improving scientific prowess demonstrated by Madison for, by that spring, Jefferson was encouraging Madison to join his effort in recording the variation in weather across Virginia:

> I wish you would keep a diary under the following heads or columns: 1. day of the month 2. thermometer at sunrise. 3. barometer at sunrise. 6. thermom. at 4. P. M. 7. barometer at 4. P. M. 4 direction of wind at sunrise. 8. direction of wind at 4. P. M. 5. the weather viz rain, snow, fair at sunrise &c. 9. weather at 4. P. M. 10. shooting or falling of the leaves of trees, of flours, & other remarkable plants. 11. appearance or disappearance of birds, their emigrations &c. 12. Miscellanea. It will be an amusement to you & may become useful . . . the above columns to be arranged according to the order of the numbers as corrected (Madison 1973, 15–17).

Madison embraced this task and began his observations on 1 April 1784, even without the benefit of a barometer, thermometer, or rain gauge (Madison 1973, 515–544). He was able to procure a thermometer by the end of October of that same year. A rain gauge, consisting of a tin cup mounted on the front gate to Montpelier (Ketcham 1990, p. 613), was not utilized until much later in the diaries, from December 1793 to January 1802. Apparently, a barometer was never obtained for use with the diaries (Madison 1973, 515–544, see editorial note). In accordance with Jefferson's request, the weather was observed twice a day to capture the maximum variations in temperature (Jefferson 1961, 351–352), but beginning on 1 January 1789 the weather at two o'clock in the afternoon was also recorded.

With the arrival of spring and his books, Madison also began his inquiry into the *Histoire Naturelle.* While reading the texts in French, Madison kept a separate notebook recording the species that Buffon considered peculiar to either the Old or New Continent or common to both (Madison 1975, 29–47, see editorial note). With regard to the animals in common, Madison noted that Buffon questioned whether some of these were truly separate species. Included among this list were the European marmotte and moles. Furthermore, Madison also was intrigued by Buffon's account that two species of weasel, the belette and l'Hermine, were very rare in North America. Madison's meteorological observations and scientific readings prompted Jefferson to nominate him for membership into the American Philosophical Society, the foremost American scientific institution of his time (Cohen 1995, pp. 63, 268). Madison was elected on 21 January 1785 (Madison 1973, p. 236).

Four years had now passed since Jefferson had written his reply to Marbois and his reluctance to its publication was diminishing. While serving as the American Minister to the French Government in 1785, Jefferson decided to publish a small number of his notes in order for close friends to advise him on whether a larger publication would be appropriate (Shuffelton 1999). On 11 May 1785, Jefferson wrote to Madison:

> They yesterday finished printing my notes. I had 200 copies printed, but do not put them out of my own hands, except two or three copies here, & two which I shall send to America, to yourself & Colo. Monroe . . . I beg of you to peruse it carefully because I ask your advice on it & ask nobody's else (Jefferson 1953, 147–148).

Upon receiving Jefferson's letter several months later, Madison replied that he considered the"facts and remarks which you have assembled too valuable not to be made known" (Madison 1973, 415–416).

Largely in response to Buffon's theory, Jefferson had included a lengthy discussion on the climate and fauna of the New World within his notes (Shuffelton 1999). Jefferson had observed that the climate of the New World in fact displayed a "greater proportion of sunshine" than that of the Old World and had supplemented his argument by constructing his own tables listing the diversity and size of quadrupeds in America in comparison to Europe, demonstrating that America had both a greater number of species and species of larger size (Jefferson 1999, 50–54, p. 80). Jefferson had also added summaries of temperature, pressure, and wind direction from Monticello and Williamsburg[2] (Jefferson 1999, 81–85).

In that same year, Jefferson sent a copy of his notes to Buffon (Henline 1947). On the final day of 1785, Jefferson received an invitation to dinner from Buffon (Malone 1951, p. 100). Jefferson found Buffon "singularly agreeable" but Buffon desired to see first-hand evidence of Jefferson's claims in addition to his notes (Malone 1951, p. 100; Martin 1952, p. 180). Over the next two years, Jefferson endeavored to collect specimens that would directly convince Buffon.

During this period, Madison displayed his most active interest in science as he assisted Jefferson in challenging Buffon. Madison scrutinized Jefferson's notes, focusing on his discussion of quadrupeds. After conferring with "several credible persons who have traversed the Western woods extensively" Madison correctly inferred that both Jefferson and Buffon had erred in ascribing the fallow and the roe deer as native species of North America (Madison 1975, 48–54). Madison also became directly engaged in the question of American quadrupeds by measuring the dimensions of a monax,[3] mole, and several weasels, animals that had intrigued him in Buffon's descriptions. His attention to detail is apparent in a table of 33 comparative morphological measurements between a weasel found at Montpelier and the belette and l'Hermine described by Buffon (Madison 1975, 76–81). Madison hoped to refute Buffon's corollary hypothesis that the only animals in common between the Old and New Worlds were those capable of withstanding the cold climate at which the continents connected (Madison 1975, 76–81). This hypothesis had been used by Buffon to suggest that the similarity in the northern species between the two hemispheres resulted from a migration of Old World animals. Madison concluded that these animals at Montpelier were the same species as from the Old World and that they could not "have traveled the road which leads from the old to the new World" because of their intolerance to the northern climate (Madison 1975, 48–54). In hindsight, it appears Madison was actually observing the native species; *Scalopus aquaticus* (eastern mole), *Marmota monox* (woodchuck), and *Mustela frenata* (long-tailed weasel; Walker 1968, p. 176, 706; Madison 1975, 48–54; Sheffield 1999), species that were not recognized by Jefferson or Buffon.

Madison also took advantage of Jefferson's appointment in France by requesting books that were "either old & curious or new & useful" (Madison 1973, 265–272) for financial debts that were owed by Jefferson to him. Included among the over 200 texts that composed Madison's "literary cargo" (Madison 1973, 500–504) were Buffon's supplements on birds and mineralogy, Clayton's *Flora Virginica,* and works by Linnaeus and Voltaire (Malone 1951, p. 87; Jefferson 1953, 460–464). This cargo was not limited to books, as Jefferson also sent Madison a pedometer, telescope, phosphoretic matches, and a chemical box to satisfy Madison's "itch to gain a smattering in Chymistry" (Madison 1973, 265–272; Madison 1975, 48–54).

At last in 1787, Jefferson was "happy to be able to present to you [Buffon] at this moment the bones & skin of a Moose, . . . the horns of the Caribou, the elk, the deer, the spiked horned buck, & the Roebuck of America" (Jefferson 1955, 194–195). These specimens finally convinced Buffon, who promised to make corrections in his next volume, but unfortunately he passed away the following spring (Malone 1951, p. 100; Cohen 1995, p. 87). However, Jefferson's *Notes on the State of Virginia* was soon widely available, as versions in French, English, and German were published by 1789 (Henline 1947).

In his *Notes,* Jefferson had written of his uncertainty in determining the most accurate means to average the climate of Virginia owing to the variation of temperature and winds between Monticello and Williamsburg:

> In an extensive country, it will of course be expected that the climate is not the same in all its parts. It is remarkable that proceeding on the same parallel of latitude westwardly, the climate becomes colder in like manner as when you proceed northwardly. This continues to be the case till you attain the summit of the Allegheny, which is the highest land between the ocean and the Missisipi. From thence, descend-

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[2] Rev. Madison, James Madison's cousin and president of the College of William and Mary, provided the climate observations from Williamsburg from 1772 to 1777.

[3] Monax, an earlier common name for the woodchuck, originated from the Native American word for "the digger" (Linzey 1998, p. 116).

> ing in the same latitude to the Missisipi, the change reverses (Jefferson 1999, p. 81)

Jefferson's interest in the variation of weather likely arose from his readings of Buffon, but he maintained interest in this subject after his discussions with Buffon as he began to question its cause and recognize its impact on the settlement of the country (Martin 1952, 141–142; Bedini 1990, p. 467).

Unlike Jefferson, Madison's scientific pursuits were greatly curtailed after their endeavors against Buffon. This transition reflected not so much a disinterest in science but rather a greater interest in reforming the Articles of Confederation (Rives 1859, p. 96). Accompanying the scientific texts from Jefferson were also works that Madison would use to guide his formulation of a new government for the United States (Brant 1948, p. 309; Malone 1951, p. 87). Madison's participation in the 1786 trade convention in Annapolis, which preceded the Constitutional Convention in 1787, led to increasing absences from Montpelier. As a result, the diaries gradually became the responsibility of his father. Colonel Madison recorded the majority of its entries until the end of the diaries in 6 February 1802. His role in maintaining the diaries is best evidenced in Jefferson's reference to them as "your father's meteorological diaries" in a letter to James Madison dated 22 June 1817 (Jefferson 1995, 1786–1787; see also Jefferson 1944, p. 625). However, Madison still actively exchanged meteorological diaries with his father during his many years in Washington (Madison 1981, 241–242; Ketcham 1990, p. 374). Throughout the diaries, the Madisons cooperated to consistently record not only climate observations but also phenological events describing garden plants, wildlife, and forests. Only one major hiatus occurs in the diaries from July 1796 to December 1797.[4] Transcription of the Madison weather diaries resulted in 16,227 weather observations from 1784 to 1802.

National natural landmark forest at Montpelier. A forest at Montpelier provides a second, although indirect, legacy from James Madison with regards to eighteenth-century climate. Though Montpelier was an active plantation with a slave-based system of agriculture (Chambers 1991), a forested slope adjacent to the house contains white oak trees (*Quercus alba*) dating to the Madison era (Fig. 1). Although the history of this forest through the Madison era and post-Madison owners of the property is currently under study, Madison did express strong views on the conservation of forests. In his 1818 address as the first president of the Albemarle County Agricultural Society, Madison lamented the mismanagement of forest resources:

> Of all the errors in our rural economy, none is perhaps, so much to be regretted, because none so difficult to be repaired, as the injudicious and excessive destruction of timber and fire wood. It seems never to have occurred that the fund was not inexhaustible, and that a crop of trees could not be raised as quickly as one of wheat or corn.
>
> Here again, we are presented with a proof of the continuance of the practice for which the reasons have ceased. When our ancestors arrived, they found the trees of the forest the great obstacle to their settlement, and cultivation. The great effort was of course to destroy the trees. It would seem that they contracted and transmitted an antipathy to them; for

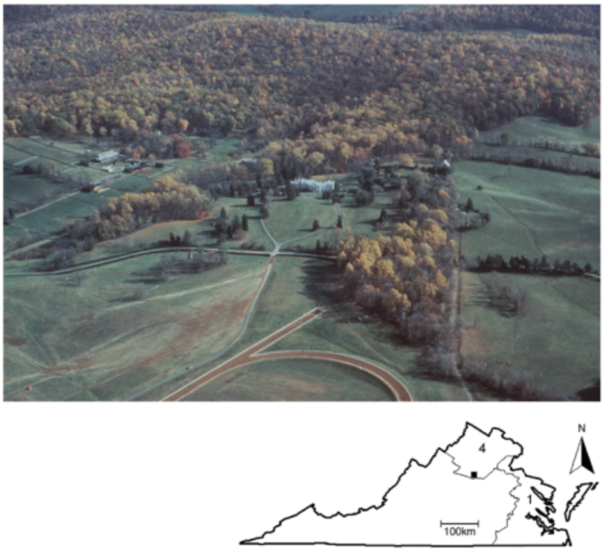

Fig. 1. Location of Montpelier, James Madison's Virginia plantation. Photograph shows the location of the National Natural Landmark Forest on the north-facing slopes just behind the mansion. Virginia Climate Divisions 1 and 4 are depicted on the map of Virginia. (Photograph courtesy of the Montpelier Foundation.)

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[4] The existence of this section of the diary is uncertain. However, it appears the Madisons did maintain their weather observations during this time, as James Madison summarizes thermometer and precipitation values through December in a letter to Jefferson dated 25 December 1797 (Madison 1991, 63–64). In a later summary, Jefferson also lists the minimum and maximum annual temperatures recorded by the Madisons for 1797 in his Weather Memorandum Book (Ludlum 1966, p. 216).

> the trees were not even spared around the dwellings, where their shade would have been a comfort and their beauty an ornament . . . Prudence will no longer delay to economize what remains of wood land; to foster the second growths where taking place in convenient spots; and to commence when necessary, plantations of the trees recommended by their utility and quickness of growth (Madison 1818).[5]

Economic difficulties after Madison's death forced Dolley Madison to sell Montpelier in 1844. After undergoing a series of additional ownership transfers, the National Trust for Historic Preservation acquired Montpelier in 1984 through a bequest from Marion duPont Scott (Miller 1988, 100-101). The Trust oversaw the designation of the forest south of the house as a National Natural Landmark Forest in 1987 (Tice 1988).

MOTIVATION FOR ANALYSIS OF THE MADISON METEOROLOGICAL DIARIES.

Instrumental meteorological diaries in eighteenth-century America were uncommon (Baron 1995), but other observers, outside the loose network established by Jefferson, also recorded the weather. Examples of other long and consistent instrumental observers include John Winthrop in Cambridge, Massachusetts, from 1742 to 1779 and Dr. John Lining and other observers in Charleston, South Carolina, from 1737 to 1759 (Ludlum 1966, 139–140; Landsberg et al. 1968; Baron 1995). Within Jefferson's network, Jefferson himself was likely the most consistent observer (Martin 1952, p. 131); however, his intense enthusiasm in the subject results in a shortcoming for climate reconstruction efforts. Jefferson frequently carried his meteorological instruments with him when traveling. As a result, his observations shift from his Monticello home to locations including Philadelphia, Annapolis, and Paris (Jefferson 1997, 433–435). In addition to their historical context, the Madison meteorological diaries feature a stationary location at Montpelier and a relatively consistent record from 1784 to 1802. Coupled with the existence of Madison-era trees for use in dendroclimatic reconstructions, Montpelier provides an excellent case for a comparative study using these two established methods of climate reconstruction.

Historical documents, such as meteorological diaries, have proven useful in reconstructing climate over a wide suite of regions and timescales (e.g., Ingram et al. 1978; Baron 1995; Bradley and Jones 1995; Catchpole 1995; Ogilvie 1995; Pfister 1995; Quinn and Neal 1995; Wang and Zhang 1995; Glaser et al. 1999; Mock 2000). Historical documents have also been combined with proxy records of climate to enhance reconstructions (e.g., Guiot 1992; Jones et al. 1998; Mann et al. 1998; Luterbacher et al. 1999; Crowley and Lowery 2000). Many studies have compared reconstructions generated by documentary and proxy data (e.g., Williams and Wigley 1983; Mock 1991; Bradley and Jones 1993; Ortlieb and Macharé 1993; Diaz and Pulwarty 1994; Dunbar et al. 1994; Hughes and Diaz 1994; Briffa et al. 1999; Pfister and Brázdil 1999; Rodrigo et al. 2001); however, we are not aware of any study in which this comparison is direct, quantitative, and at the same location. Stahle et al. (1998a) further supported their dendroclimatic reconstruction of growing-season drought with historical observations from the Chesapeake Bay region. Building upon that approach, this study compares precipitation reconstructions from tree-ring data and a historical instrumental record at the same site. Two independent reconstructions of monthly precipitation were gen-

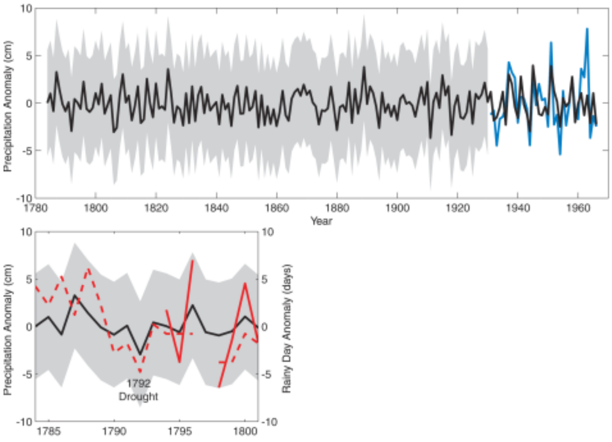

Fig. 2. Comparison of a dendroclimatic reconstruction of early summer precipitation (1784–1966) to modern and Madison diary precipitation data. (top) Reconstruction of early summer precipitation (black line) calibrated and verified with Jun precipitation data from Virginia Climate Divisions 1 and 4 (blue line). (bottom) Expanded view of Madison weather diary period with the early summer precipitation reconstruction (black line), Madison precipitation gauge values for May (red line), and the number of May rainy days observed by the Madisons (dashed red line). Light gray shading depicts two standard error uncertainty limits in the reconstruction (see the sidebar).

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[5] This address was later published in the *American Farmer* and read with great interest on both sides of the Atlantic (Brant 1961, p. 428; Rutland 1997, p. 243).

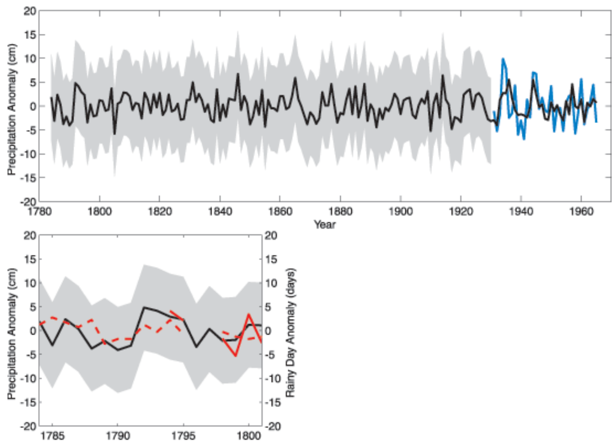

FIG. 3. Comparison of a dendroclimatic reconstruction of prior fall precipitation (1784–1965) to modern and Madison diary precipitation data. (top) Reconstruction of prior fall precipitation (black line) calibrated and verified with prior Sep precipitation data from Virginia Climate Divisions 1 and 4 (blue line). (bottom) Expanded view of Madison weather diary period with the prior fall precipitation reconstruction (black line), Madison precipitation gauge values averaged for prior Jun and Jul (red line), and the number of rainy days averaged for Jun and Jul observed by the Madisons (dashed red line). Light gray shading depicts two standard error uncertainty limits in the reconstruction (see the sidebar).

TABLE 1. Split period calibration–verification of early summer rainfall reconstruction with Virginia Climate Division 1 and 4 precipitation data. Pearson correlation coefficients are used to determine significance with n – 2 degrees of freedom. Probabilities are assessed using a one-tailed test assuming that the relationship between precipitation and tree-ring width will not be negatively correlated (*$P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

	Period I		**Period II**		**Total period**
Statistic	**Calibration 1949–66**	**Verification 1931–48**	**Calibration 1931–48**	**Verification 1949–66**	**Calibration 1931–66**
Pearson correlation (*r*)	0.661**	0.629**	0.629**	0.661**	0.626***
Variance (R^2)	0.437	0.395	0.395	0.437	0.392
Reduction of error (RE)	0.437	0.171	0.395	0.356	0.392

TABLE 2. Split period calibration–verification of prior fall rainfall reconstruction with Virginia Climate Division 1 and 4 precipitation data. Pearson correlation coefficients are used to determine significance with n – 3 degrees of freedom as two dependent variables are employed in the reconstruction. Probabilities are assessed using a one-tailed test assuming that the relationship between precipitation and tree-ring width will not be negatively correlated (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, $^\dagger P = 0.055$).

	Period I		**Period II**		**Total period**
Statistic	**Calibration 1948–65**	**Verification 1931–47**	**Calibration 1931–47**	**Verification 1948–65**	**Calibration 1931–65**
Pearson correlation (*r*)	0.603**	0.479*	0.602**	$0.402^\dagger$	0.570***
Variance (R^2)	0.364	0.229	0.363	0.162	0.325
Reduction of error (RE)	0.364	0.220	0.363	0.154	0.325

erated using tree-ring data from Montpelier (see the sidebar for methodology). Latewood width measurements from these tree rings produced a significant reconstruction of early summer precipitation (Fig. 2 and Table 1), and a bivariate reconstruction, which removed the latewood component from the annual ring width, produced a significant reconstruction of prior fall precipitation (Fig. 3 and Table 2). These reconstructions calibrated with June and prior September precipitation, respectively, in the modern period, and the monthly correlations were stronger than any correlations combining months. Both of these reconstructions were then compared with precipitation records from the Madison meteorological diaries.

MODERN AND MADISON-ERA PRECIPITATION COMPARISONS.

Comparison of the meteorological diary and dendroclimatic reconstructions. Both dendroclimatic reconstructions were compared with two monthly variables from the diaries; precipitation amount and number of rainy days. In each case, the dendroclimatic reconstruction shifted at least one month earlier in its correlation to monthly precipitation from the modern calibration period. Because of this shift, the reconstructions are referred to as early summer and prior fall instead of ascribing the precipitation signal of a particular month to each reconstruction. As the early summer precipitation reconstruction indicates greater levels of resolved variance, the following analysis focuses on this reconstruction. The seven years of May rain gauge measurements from the diaries yielded the strongest correlation of any month with the early summer precipitation reconstruction [$r = 0.945$, $p_{(1)} < 0.001$, $r^2 = 0.892$]. Since the rain gauge measurements suffer from a low sample size, an index of total May rainy days was also constructed as this proxy for precipitation was recorded by the Madisons for the entire 17 years of diary observations. The correlation between May rainy days and the reconstruction was also significant [$r = 0.429$, $p_{(1)} = 0.043$, $r^2 = 0.184$]. While precipitation frequency and total precipitation have been shown to differ in their statistical properties for the conterminous United States (Englehart and Douglas 1985), the monthly frequency of rainy days has proven to be a useful surrogate in precipitation reconstructions (e.g., Mock 1991; Pfister 1995; Murata 1995), and the May rainy day index and the Madison precipitation gauge values are highly positively correlated [$r = 0.633$, $p_{(1)} = 0.063$, $r^2 = 0.401$]. For comparison at this location, an analog of rainy days was constructed using data from a Cooperative National Weather Service station at the Northern Piedmont Agricultural Research and Extension Center in Orange, Virginia. A June rainy day index from this station for 1949–99, located less than 5 km from Montpelier, correlates with its June precipitation record to a similar extent [$r = 0.556$, $p_{(1)} < 0.001$, $r^2 = 0.309$]. Similar to the divisional data, the June precipitation data from this station also strongly correlates with the early summer dendroclimatic reconstruction from 1949 to 1966 [$r = 0.674$, $p_{(1)} < 0.01$, $r^2 = 0.455$]; however, the shorter temporal record of this station impaired its usefulness for calibrating and verifying the dendroclimatic reconstructions.

The prior fall reconstruction displayed the strongest correlations with the six years of Madison precipitation gauge values averaged for June and July [$r = 0.800$, $p_{(1)} = 0.028$, $r^2 = 0.640$] and for July and August [$r = 0.701$, $p_{(1)} = 0.060$, $r^2 = 0.491$]. Again, the frequency of rainy days averaged over 16 years for these two monthly periods did not correlate as well as the gauge [$r = 0.231$, $p_{(1)} = 0.194$, $r^2 = 0.054$ and $r = 0.182$, $p_{(1)} = 0.250$, $r^2 = 0.033$, respectively].

Comparison of the timing of precipitation seasonality. Hayden (1979, 138–140) observed a shift in the timing of the summer precipitation maxima for Virginia in the twentieth-century instrumental record. Station data prior to 1920 indicated mostly June or July as the months of peak precipitation, whereas station data from 1941 to 1970 indicated a predominance of July and August peak months. This change is also apparent in the statewide data for the time intervals of this study (Fig. 4). The distribution of monthly precipitation in the Madison diaries continued this advancing trend back in time (i.e., trend toward a *delayed* wet season as time progresses) observed in the twentieth-century statewide data. The standard deviation of the timing of peak summer rainfall among statistically independent 7-yr subintervals of the 1931–66 statewide precipitation data is 0.4 months, while the maximum deviation of any of the 7-yr subintervals from the 1931–66 mean is 0.5 months. Thus, although the Madison diaries only provide seven years of instrumental data from which to constrain the seasonal cycle, the approximately 1.3-month shift observed in the timing of peak summer rainfall relative to the 1931–66 statewide mean is highly unlikely to arise from sampling variations alone.

IMPLICATIONS FOR THE SEASONAL RELATIONSHIPS OF DENDROCLIMATIC RECONSTRUCTIONS.

Comparison of the Madison diaries with the early summer precipitation recon-

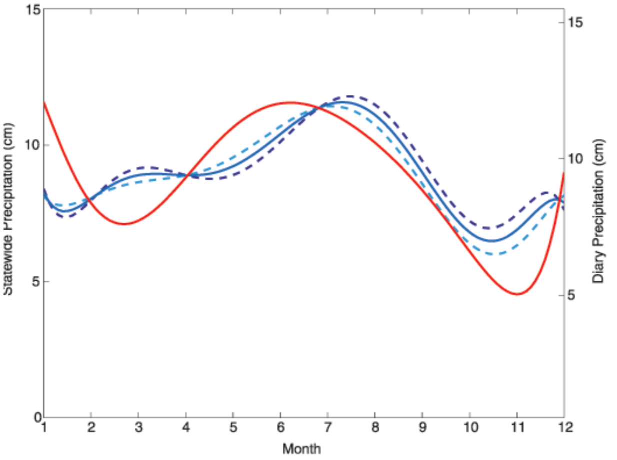

FIG. 4. Seasonality of precipitation for Virginia. Lines are seventh-order polynomial fits to the monthly data of precipitation during a seasonal cycle. This order was chosen as the best representation of the seasonal cycle without overfitting the monthly data. The blue line corresponds to the average distribution of statewide precipitation from 1895 to 1966. The dashed light blue line depicts the first half of this period (1895–1930) and the dashed dark blue line is the second half (1931–66). The red line displays the average distribution for the 7 yr of precipitation gauge measurements at Montpelier from 1793 to 1801. As the average monthly value of the Madison measurements was slightly higher than that of the statewide data from 1895 to 1966 (8.91 cm to 9.42 cm, respectively), the scale for the Madison precipitation gauge has been shifted down by the difference in means.

struction suggests a gradual delay in sensitivity from May precipitation in the Madison era to June in the modern instrumental record (Fig. 5 and Table 3). This observation does not appear to be influenced by the spatial scale of the divisional data, as the Piedmont Research Station also confirms a June precipitation signal in the modern instrumental record. Furthermore, a delay of at least one month is also implied by the prior fall precipitation reconstruction. The delays apparent in these comparisons are also consistent with the 1.3-month delay observed in the summer precipitation maximum from the Madison era. To explain these patterns, we consider three hypotheses; the influence of age on sensitivity of trees to climate, the influence of external climate forcings on precipitation seasonality, and the influence of land cover change on precipitation seasonality.

Studies considering the climatic response of trees with age or competitive status have produced conflicting results. For example, Szeicz and MacDonald (1994) found that the climate response of white spruce (*Picea glauca*) was notably different between trees less than 200 years of age and those greater than 200 years. Conversely, Colenutt and Luckman (1991) found very similar climatic sensitivities between alpine larch (*Larix lyallii*) averaging 81 and 303 years of age. While no study has directly investigated changes in the climatic response of white oak with age, estimates of tree ages (as the pith was not reached in all trees) used in these precipitation reconstructions averaged at least 50 years of age at the end of the Madison diary period (1801) and at least 180 years of age at the end of the modern divisional data series (1966). Supposing that chestnut oaks (*Quercus prinus*) initiate latewood growth first at buds and then progress basipetally down the stem, Phipps (1967) hypothesized that latewood widths at the base could become sensitive to climate progressively later in the year as a tree increased in height with age. This mechanism could explain the shift in sensitivity of the early summer reconstruction but not the prior fall reconstruction, as earlywood

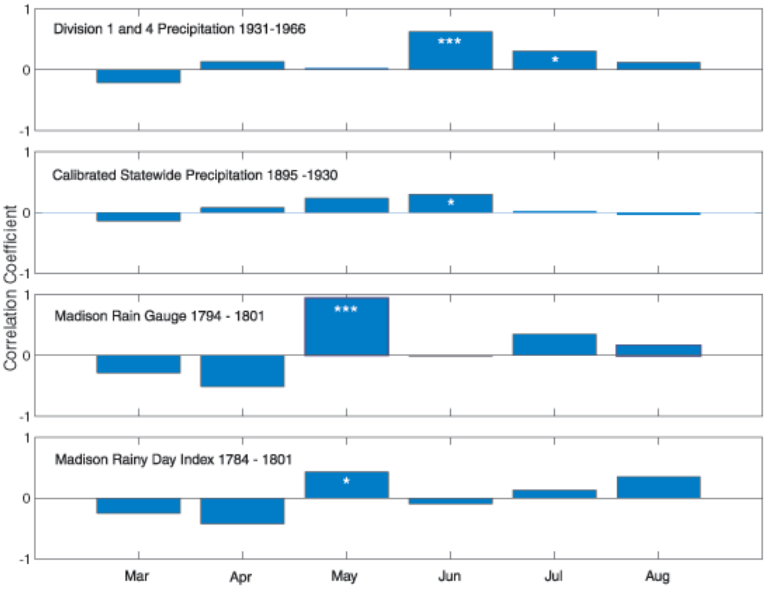

FIG. 5. Seasonality of correlation between precipitation indices and a dendroclimatic reconstruction of early summer rainfall. Sample size for the divisional and statewide data is 36 yr. Sample size for the precipitation gauge is 7 yr except for Jul and Aug, which are 6 yr. Sample size for the number of rainy days is 17 yr except for Mar, Jul, and Aug, which are 16 yr ($^{*}P < 0.05$, $^{***}P < 0.001$).

Table 3. Seasonality of correlation between precipitation indices and a dendroclimatic reconstruction of early summer rainfall, where N refers to sample size, and *P* values are reported using one tail. (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

Precipitation indices	May	*N*	Jun	*N*	Jul	*N*
Division 1 and 4 precipitation 1931–66	0.028	36	0.626***	36	0.309*	36
Calibrated statewide precipitation 1895–1930	0.234	36	0.299*	36	0.022	36
Madison rain gauge 1794–1801	0.945***	7	–0.01	7	0.349	6
Madison rainy day index 1784–1801	0.429*	17	–0.095	17	0.134	16

growth commences synchronously along a stem. While changes in tree physiology with age may be affecting these dendroclimatic reconstructions, the coincidence in the magnitude and direction of the delays with the 1.3-month delay in precipitation seasonality observed in the summer precipitation maximum from the Madison diaries points to a climatological effect. Although this finding is unexpected, a recent study by Biondi (2000) also supports the hypothesis that the seasonal relationships of dendroclimatic reconstructions may shift through time. The transition observed in this study suggests that the trees used in this reconstruction may be more sensitive to the timing of peak summer precipitation than to a particular month in the calendar year.

There is evidence that anthropogenic climate forcing may be leading to a trend toward slightly (i.e., on the order of a few days) advanced temperature seasonality (e.g., earlier spring) in the late twentieth century (Thomson 1995; Mann and Park 1996). Even larger advances (on the order of a month in some cases) have been observed in the seasonality of precipitation since 1950 for the western United States (Rajagopalan and Lall 1995). Similarly, Cayan et al. (2001) have also demonstrated the sensitivity of phenological networks to this advance in spring temperature seasonality in the western United States since the 1970s. These recent advances represent a departure from a longer-term trend over the past few centuries (Thompson 1995; Thomson 1995) toward a delay in seasonality (e.g., gradually later spring). It has been suggested that this long-term delay in seasonality is associated with the effects of orbital precession on the seasonal cycle (Thomson 1995), though the presence of considerable spatial variation in the magnitude and sign of observed shifts in the seasonality of temperature (Thomson 1995; Mann and Park 1996) suggests that other natural or external factors may be important. The reconstruction presented in this study does not span the most recent decades of the twentieth century due to the downward-trending mortality spiral present in the samples, and we thus cannot evaluate whether or not an advance in seasonality is evident in the most recent decades. However, the observed long-term trend toward a delayed seasonal precipitation cycle that is clearly present over several centuries is indeed qualitatively consistent with the trend toward a delayed temperature cycle on this longer time frame (Rajagopalan and Lall 1995; Thomson 1995).

Finally, it may also be possible that the clearing of land over the past 200 years has altered the timing of precipitation seasonality at Montpelier. The hypothesis that land cover affects regional climate was proposed well before the eighteenth century, and we now have evidence that vegetation, via evapotranspiration and surface roughness, impacts precipitation and wind patterns, respectively, on regional scales (Hayden 1998). Jefferson pondered this hypothesis in his notes when discussing the increase of eastern and southeastern breezes during his lifetime:

> They have advanced into the country very sensibly within the memory of people now living. They formerly did not penetrate far above Williamsburgh. They are now frequent at Richmond, and every now and then reach the mountains. They deposit most of their moisture however before they get that far. As the lands become more cleared, it is probable they will extend still further westward (Jefferson 1999, 83–84).

Using a coupled land–atmosphere model for the eastern and central United States, Bonan (1999) found that the conversion of land cover from presettlement forests to modern vegetation resulted in a 0.6°–1.0°C cooling in the mean annual surface air temperature with the greatest intra-annual effects occurring in summer and fall. Fitzjarrald et al. (2001) examined the variation in timing of spring phenology for dominant trees in the eastern United States by isolating the in-

DENDROCLIMATOLOGICAL METHODS

As a result of the National Natural Landmark designation, live trees in the Montpelier forest could not be sampled in this study. However, recently senesced white oak trees of canopy status were selected and cored according to standard dendrochronological techniques (Fritts 1976). Suitable cores were cross-dated and checked using the computer program COFECHA (Holmes 1983). Latewood and annual width measurements were used to generate two residual chronologies in the computer program ARSTAN (Cook and Peters 1981). Cores were first detrended using either a negative exponential or linear regression model to minimize the influence of biological age on rings widths. Secondly, a cubic smoothing spline removed 50% of the variance at a period of 20 yr to reduce the effect of suppression and release episodes on ring widths. The two chronologies consisted of 24 cores from 11 trees, with 12 cores from 5 trees extending to the start of the Madison weather diary (1784). Although the oldest core dated to 1712, the chronologies were truncated to the period 1784–1966 to maintain a sufficient sample size.

Precipitation data from Virginia Climate Divisions 1 and 4 (Karl et al. 1983) were utilized in a split calibration–verification technique to reconstuct the early summer (Fig. 2 and Table 1) and prior fall (Fig. 3 and Table 2) precipitation signals. Appropriately, this modern climate network realizes Jefferson's desire for a systematic observation of the New World climate (Martin 1952, 141–143). The early summer precipitation reconstruction was regressed with the latewood chronology (x_t), with year (t), yielding precipitation in centimeters:

$$y_{t,\text{early summer}} = 1.623 + 7.841x_t.$$

Because early season growth in particular is linked to antecedent soil moisture conditions, it is possible to reconstruct prior fall precipitation from a linear combination of the annual and latewood chronologies. The prior fall reconstruction thus employed a multivariate regression with both the latewood (x_{1t}) and annual chronologies (x_{2t}) with year (t), yielding:

$$y_{t,\text{prior fall}} = -12.854 - 14.796x_{1t} + 36.865x_{2t}.$$

Both reconstructions display similar levels of resolved variance in their respective calibration and verification intervals. Residuals for both reconstructions were homoscedastic. Reduction of error statistics (RE) were calculated according to Cook et al. (1999) and demonstrated skill in each of these reconstructions. For each reconstruction, t tests demonstrated that the regression coefficients were not significantly different for calibration periods 1 and 2. Two standard error uncertainty limits were calculated for each reconstruction using the greater of the two RE statistics from the verification periods. While the residuals from both reconstructions do not appear to be heteroscedastic, the two standard error uncertainties are only approximate as the residuals depart somewhat from a normal distribution.

Although the published division data for Virginia extends back to 1895, climate data prior to 1931 use calibrated state averages inducing substantial inhomogeneity in the climate time series (Guttman and Quayle 1996). For this reason, data prior to 1931 were not incorporated into the calibration and verification tests. Years more recent than 1966 were not included in the analysis as the correlation between June precipitation and latewood width greatly attenuated after 1966. This attenuation is likely an artifact of using senescent trees in the chronology. Prior to senescence, trees may exhibit a mortality spiral (Franklin et al. 1987; Manion 1991, 330–334) that reflects reduced and sometimes abnormal growth (Waring 1987). These spirals have been observed to persist for decades in oaks and cause reduced sensitivity to environmental fluctuations (Pederson 1998).

fluence of leaf presence on surface climate variables. Interestingly in the context of this study, Fitzjarrald et al. (2001) found that this measure of spring for the eastern United States is generally arriving 4 to 6 days earlier since the mid 1960s; however, central Virginia displayed an opposing trend, with dates of 3 to 10 days later. While considering the possible influence of land use change, they did not find a clear relationship between the fraction of forest cover and the timing or intensity of this spring transition. Similarly, it remains unclear whether the changes in precipitation seasonality observed in this study are the result of external climate forcing, land cover, or possibly a combination of both factors. Evaluation of these hypotheses concerning tree age, external climate forcing, and land cover requires additional research beyond the scope of this study; however, the questions raised by these results emphasize the dynamic nature not only of the climate system but also of the vegetation that serves as proxies for it.

CONCLUSIONS. Historical documents and tree rings present a wealth of data for reconstructing prior climate. This study has compared two approaches for reconstructing precipitation at Montpelier in the late eighteenth century. In addition to accounting for a significant portion of the variance in precipitation, these data also indirectly suggest the influence of larger-scale climatological processes. For example, the 1792 drought mentioned by Madison in the opening paragraph of this article corresponds with one of the strongest El Niño events on record, associated with prominent anomalies in reconstructed cold-season Niño-3 (Mann et al. 2000) and winter Southern Oscillation index (SOI) (Stahle et al. 1998b) indices and well-documented historical evidence (Quinn and Neal 1995; Grove 1998; Ortlieb 2000) that confirms the existence of an extreme El Niño during the period 1791/92. El Niño years have been shown to result in less than average precipitation for the eastern United States during the following March–May (Livezey et al. 1997).

More importantly in the context of this study, though the statistical significance of these comparisons are limited by the relatively short duration of the Madison rain gauge record, the data also suggest a delay of approximately one month in the arrival of maximum summer precipitation from Madison's era and a corresponding shift in the sensitivity of dendroclimatic reconstructions to this delay. Thus, these data not only provide a record of precipitation reaching back to Madison's era at Montpelier, but also indicate possible changes in the regional climate since the late eighteenth century. As Jefferson noted later in life, climatic trends are best characterized by long-term studies:

> Years are requisite for this, steady attention to the thermometer, to the plants growing there, the times of their leafing and flowering, its animal inhabitants, beasts, birds, reptiles, and insects; its prevalent winds, quantities of rain and snow, temperature of fountains, and other indexes of climate. We want this indeed for all the States, and the work should be repeated once or twice in a century, to show the effect of clearing and culture towards changes of climate (Jefferson 1905, 71–72).

Although Madison's scientific knowledge never rivaled that of Jefferson's, he too recognized the importance of experiment and comparison in understanding our Earth as a system:

> Experiment and comparison may be regarded as the two eyes of Philosophy, and it will require, I suspect, the best use of both, to reduce into a satisfactory system, the irregular and intermingled phenomena to be observed on the outside, and the penetrable inside of our little globe (Madison 1997, p. 96).

James Madison was recognized during his time for his scientific insight with membership into the American Philosophical Society. However, likely even beyond the expectations of Jefferson, Madison's scientific contributions are still "useful" toward furthering our understanding of the climate system 200 years later.

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