Research Paper

Fluvial activity in major river basins of the eastern United States during the Holocene

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Abstract

In the eastern United States, existing paleo-reconstructions in fluvial environments consist primarily of site-specific investigations of climate and human impacts on riverine processes. This paper presents the first meta-analysis of fluvial reconstructions focused on regional watersheds of the eastern United States, including the Lower Mississippi, Tennessee, South Atlantic–Gulf Coast, Ohio, Mid-Atlantic, and New England regional watersheds. Chronologies of fluvial activity (i.e. alluvial deposition) and stability (i.e. landscape stability) were developed by synthesizing data from existing, published, and site-specific fluvial reconstruction studies conducted across the eastern United States. Overall, regional watersheds show variable patterns of synchronicity across watersheds and did not demonstrate cyclic behavior through the Holocene. During the last millennium, only the Lower Mississippi and Ohio regional watersheds exhibit high rates of fluvial activity active during the 'Medieval Climate Anomaly' (650–1050 yr BP), while nearly all other regional watersheds in the eastern United States were active during the 'Little Ice Age' (100–500 yr BP). These findings imply that fluvial activity may be more spatially restricted during warmer/drier climatic conditions than during cooler/wetter periods. We find an increase in fluvial activity during the era of Euro-American colonization (400 yr BP to present) in the southeastern United States but not the northeastern United States, implying a heterogeneous response of fluvial systems to human activities in the eastern United States related to climatic, cultural, and/or physiographic variability. These new insights gained from fluvial chronologies in the eastern United States demonstrate the utility of regionally synthesized paleo-records to understand large-scale climate variation effect on rivers.

Keywords

climate change, eastern United States, flooding, fluvial sediments, Holocene, meta-analysis, radiocarbon, rivers

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Introduction

Understanding the coupling between rivers and the climate system offers a means to improve the predictability of fluvial systems to climate variability and change. Modern and paleo-hydrologic records connect large-scale synoptic changes in the atmosphere to regional fluvial processes (Munoz and Dee, 2017; Tootle et al., 2005), glaciation (Licciardi et al., 1999), and sea level rise (Leigh and Feeney, 1995). Fluvial responses to Quaternary environmental change have been reconstructed for some rivers of the eastern United States, mainly within the mid- and southern Atlantic Coastal Plain (Dury, 1965, 1976; Goman and Leigh, 2004; LaMoreaux et al., 2009; Leigh, 2006; Leigh and Feeney, 1995; Suther et al., 2018; Walter and Merritts, 2008) and within the Mississippi River drainage (Knox, 1985; Munoz et al., 2015, 2018). While these site-specific studies provide insights into the responses of individual river reaches to environmental variability, regional patterns of fluvial activity in response to environmental changes over the Holocene have not been evaluated for the eastern United States.

The eastern United States is one of the most densely populated regions of North America, and it regularly experiences loss of life and property from high-magnitude riverine floods associated with frontal systems, landfalling hurricanes, and other atmospheric phenomena (Hirschboeck, 1988; O'Connor and Costa, 2003; Schlef et al., 2019). Climate changes are projected to intensify the hydrologic cycle and, consequently, result in an overall increase in flood and drought risk (Hoegh-Guldberg et al., 2018; Tebaldi et al., 2002). Assessing long-term flood and drought hazard for specific river basins and/or climate regions is hampered by systematic records of river flow

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generally being too short to include hydrologic variability associated with centennial- and millennial-scale climate change processes. These records overlap with the period of human occupation, further limiting their utility in isolating fluvial response to climate change. To address these shortcomings, this paper presents a meta-analysis of fluvial paleorecords from across the eastern United States to elucidate large-scale, spatio-temporal variation of alluvial deposition events, referred to herein as 'fluvial activity', during the Holocene (last 12,000 years), including the Pleistocene/Holocene transition, for six major regional watersheds of the eastern United States (Figure 1).

Regional syntheses of site-specific, paleo-reconstructions are increasingly used in a variety of disciplinary contexts to provide a more comprehensive understanding of regional processes and patterns, including in paleohydrology (Benito et al., 2015; Ely et al., 1993; Johnstone et al., 2006; Knox, 1985; Macklin and Lewin, 1993; Marriner et al., 2017), paleoecology (Mayle and Power, 2008; Smith and Mayle, 2018), paleotempestology (Oliva F et al., 2018), and archeology (Munoz and Gajewski, 2010; Rick, 1987). Regional syntheses provide a spatial context to temporal changes observed in site-specific paleo-reconstructions and can be used to identify the scale and pattern of changes in a system. In the eastern United States, a regional perspective describing environmental changes during the Holocene is critically needed because rivers in these regions respond to multiple drivers, including climate change (Knox, 1985; Leigh, 2008), extreme tropical and extratropical events (Magilligan et al., 2015), and land-use/cover change (Knox, 2001).

Regional meta-analyses of fluvial behavior spanning the Holocene exist for several other world regions and are typically developed from radiocarbon-dated alluvial units collated from hundreds of site-specific studies (Benito et al., 2008; Harden et al., 2010; Kale, 2007; Macklin et al., 2006; Thorndycraft and Benito, 2006; Zielhofer and Faust, 2008). These regional meta-analyses of fluvial activity have provided new insights into mechanisms of change in river systems, including the influence of climate variability (Benito et al., 2008; Ely et al., 1993; Harden et al., 2010; Knox, 1993; Leigh, 2008) and land-use change (Benito et al., 2008; Hoffmann et al., 2008; Macklin et al., 2006).

This paper uses a meta-analysis approach to examine spatio-temporal changes in fluvial activity in regional watersheds of the eastern United States (Figure 1), including the Ohio, Lower Mississippi, Tennessee, South Atlantic–Gulf Coast (SAGC), Mid-Atlantic, and New England watersheds. Chronologies of fluvial activity during the Holocene for the regional watersheds are examined to answer the following questions: (1) How synchronous was fluvial activity between watersheds and through the Holocene? and (2) How does regional fluvial activity vary in response to centennial- and millennial-scale climate change?

General geomorphologic context

The regional watersheds span a range of physiographic settings. Here, we use physiography to describe landscape characteristics broadly related to the geologic and climatic setting (Figure 1; Fenneman, 1928). One of the most important physiographic distinctions in the study region is between northeastern regional watersheds (New England, Mid-Atlantic, and Ohio) and southeastern regional watersheds (SAGC, Tennessee, and Lower Mississippi) because of the direct influence of continental ice sheets during glaciations, including the Last Glacial Maximum approximately 18,000 years ago. The extent of the Laurentide Ice Sheet during the Last Glacial Maximum covered the entire New

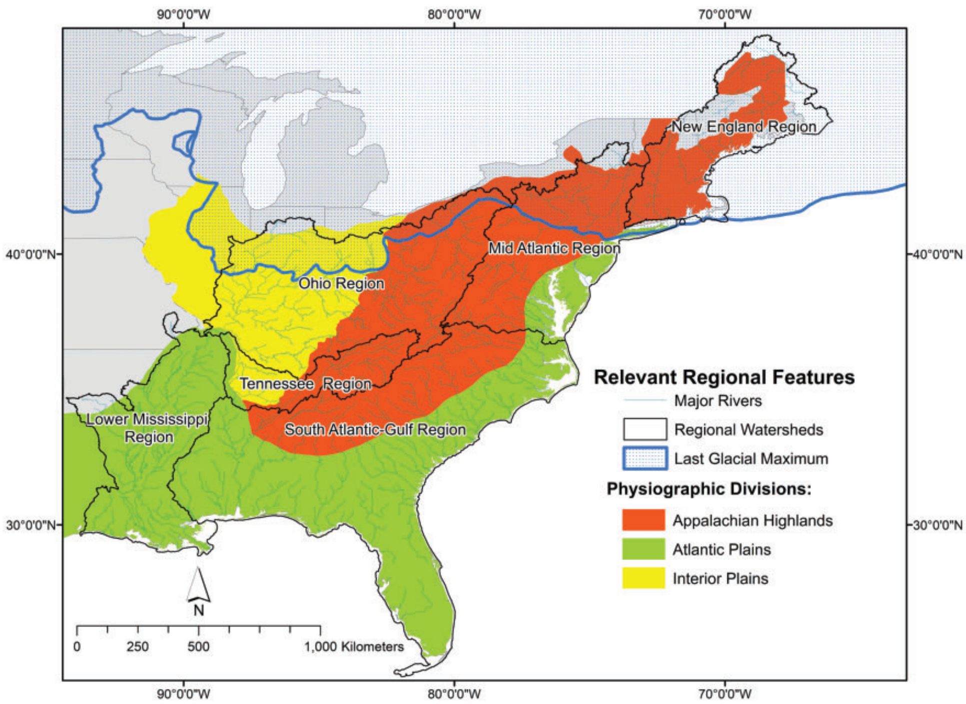

Figure 1. This study focuses on the six major regional watersheds in the eastern United States. Here, we highlight relevant geomorphic features of river basins in the eastern United States including the last glacial maximum extent of the Laurentide Ice Sheet 18,000 years ago (Ehlers et al., 2011) and physiographic divisions (Fenneman and Johnson, 1946).

England watershed and parts of the Ohio and Mid-Atlantic watersheds (Ehlers et al., 2011; Figure 1). Discontinuous permafrost also likely extended throughout the remaining unglaciated Mid-Atlantic watershed and through the Appalachian Highlands (Lindgren et al., 2016). Previously glaciated river valleys are typically sediment starved because of erosion and post-glacial streambed incision (Clague, 1986), which could influence hydrologic response.

In addition to glaciation, varying geology across the eastern United States has helped create geomorphologically diverse river landscapes within the region. The Interior Plains division extends through parts of the Ohio and Tennessee regional watershed and is characterized by small local relief, plains or plateaus, glacial till, and other glacial features in the northern portion of the division. To the east, the Appalachian Highlands extend through nearly every watershed except the Lower Mississippi. This physiographic division consists of highly dissected plateaus in the west, highly dissected mountains, folded valley and ridge structures in the southern portion, and piedmont plateaus and plains in the eastern portion of the division. Finally, the Atlantic Plain stretches along the Gulf and most of the Atlantic coasts. This region contains young to mature floodplains, terraces, and meander belts and swampy lowlands near the coast (Figure 1).

Methods

Fluvial radiocarbon databases

Regional chronologies of fluvial behavior are generated by assembling key information about radiocarbon-dated alluvial units, representing either active deposition or landscape stability from a large number of sites. Histograms of floods or other fluvial depositional events, with ages expressed as uncalibrated radiocarbon dates, comprised the earliest iterations of regional fluvial chronologies (Ely et al., 1993; Knox, 1975). Regional chronologies, however, are most often presented in summed probability curves (Benito et al., 2008; Harden et al., 2010; Johnstone et al., 2006). Summed probability curves are created by summing ^{14}C age probability density functions (PDF) generated during the process of calibrating uncalibrated radiocarbon ages (Johnstone et al., 2006; Reimer et al., 2013). If one or more ^{14}C age PDF overlap in time, we interpret a higher likelihood that the event corresponding to the summed probability curve occurred over a larger spatial extent.

While regional chronologies of fluvial activity made from radiocarbon-dated alluvial units are widely used, there are limitations to the approach associated with the radiocarbon ages themselves described by Chiverrell et al. (2011), including the following: (1) deposited organic samples can be re-worked and re-deposited, resulting in older radiocarbon ages; (2) lack or misinterpretation of geomorphic context, resulting in fluvial activity events being over- or under-represented; and (3) large uncertainties associated with calibrated radiocarbon dates. The presence of reworked organic material in alluvium is an issue affecting all paleo-reconstructions conducted in riverine settings, meaning care must be taken in the selection of radiocarbon material used for dating. For our analyses, we assume the authors of studies from which we used radiocarbon dates sufficiently interpreted and sampled their radiocarbon samples. We include only radiocarbon dates from studies that provide sufficient sedimentological data to avoid misinterpretation of geomorphic context (see *Compiling Fluvial Activity Database of Eastern United States (FADEU)* for details). We minimize errors associated with radiocarbon

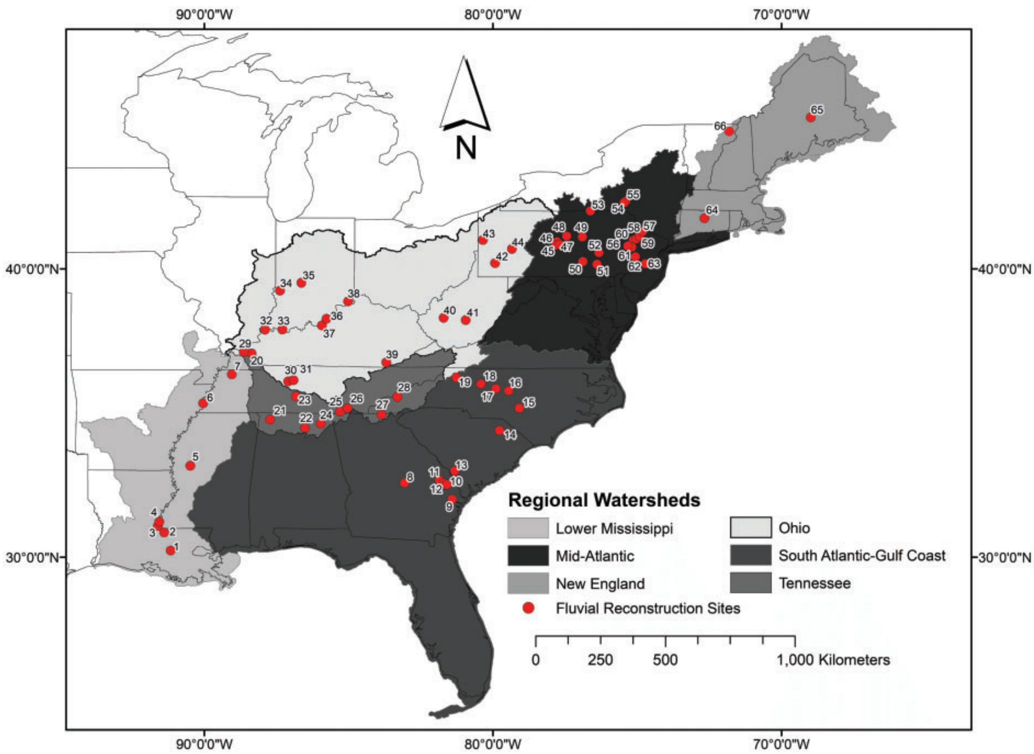

Figure 2. Map of radiocarbon-dated alluvial sites in the Fluvial Activity Database of the Eastern United States (FADEU). Site numbers correspond to sources in Table 1.

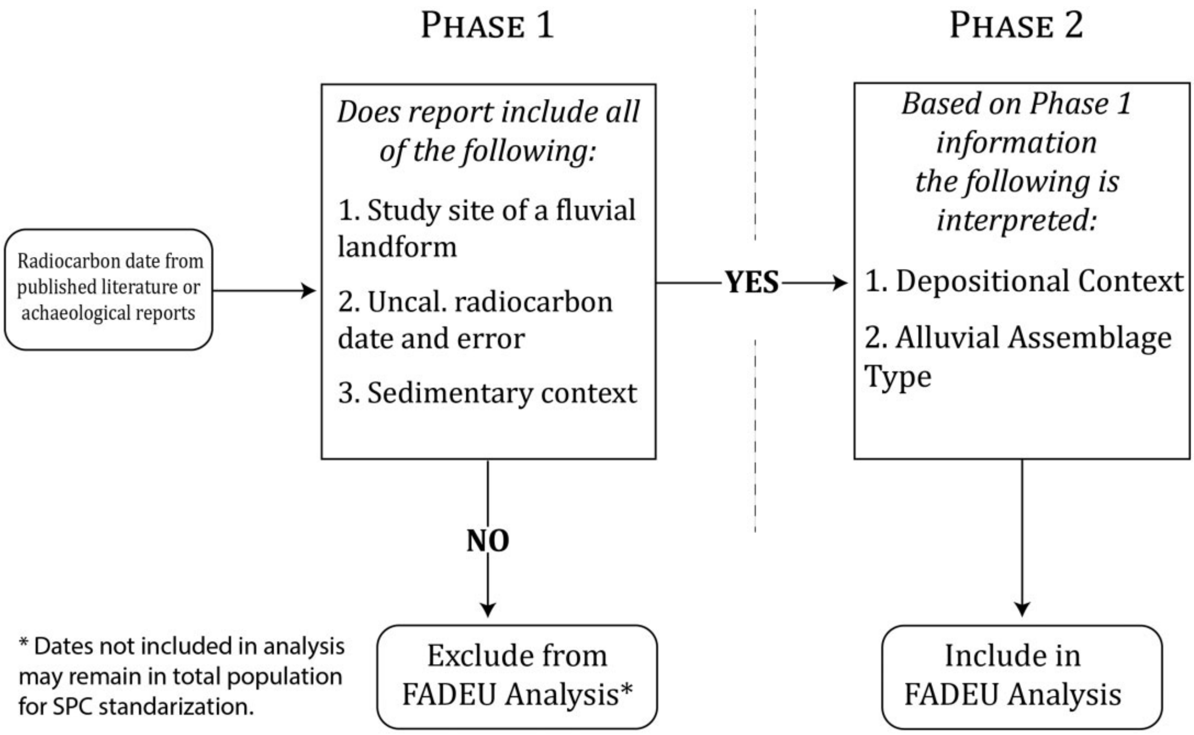

Figure 3. Decision-making flowchart for carbon sample inclusion in meta-analyses.

ages themselves in two ways. First, we excluded all uncalibrated radiocarbon dates with 2σ errors >400 years from our analyses (cf. Harden et al., 2010). Second, we normalized the summed probability curves (Eqs. 1 and 2) to minimize error contained within the summed probability curves associated with the radiocarbon age calibration process.

Compiling FADEU

We compiled the FADEU from a systematic search of peer-reviewed literature and archeological reports. We designed and implemented a decision tree for determining whether a radiocarbon sample was suitable for the meta-analysis (Figure 3). The decision tree employed for database entries included two separate phases, consisting of Phase 1 (data acquisition) and Phase 2 (data interpretation). The two-phase approach ensured consistent and unbiased data interpretation for the regional chronologies and future chronology iterations. To include a radiocarbon date in Phase 1, we evaluated whether the study provided sufficient sedimentological data to interpret its depositional context. The minimum information required included the following: grain size, particle shape, sorting, and color and descriptions of sedimentary and pedogenic features, following guidelines provided in Johnstone et al. (2006), Hoffmann et al. (2008), and Harden et al. (2010). Radiocarbon ages in studies that satisfied all Phase 1 requirements moved to the second phase. Phase 2 required interpretation of depositional context based on sedimentary information and the assignment of an alluvial assemblage based on the planform characteristics of the fluvial system. Alluvial assemblages used were chosen to conform with assemblages previously used by Johnstone et al. (2006) and included meandering system, braided system, and upland/gully. Depositional context designations were chosen based on criteria previously used by Hoffmann et al. (2008) and included floodplain fine-grained deposits, sandy/gravelly alluvium, soil, peat/wetland, organic-rich sediment, or back swamp. For the purpose of identifying depositional activity associated with flooding and/or channel migration, we assigned the following depositional contexts as being 'active' alluviation: fine-grained deposits that occurred in floodplain settings or sandy or gravelly alluvium found within floodplain settings. By design, 'active' sedimentation includes both flood and lateral migration deposits. Wetter flow regimes, which are also likely to experience more frequent flooding, increase lateral migration processes. For this reason, we chose to include lateral migration deposits in the active sedimentation group as an indirect metric of flood activity and as representing more hydrologically active times resulting from wetter flow regimes. We assigned a condition of 'stability' to depositional contexts that included the following: soils, peat, and wetland/back swamps locations with evidence of stability.

In total, FADEU contains 398 radiocarbon dates from fluvial settings across the eastern United States (Figure 2; Table 1). The number of radiocarbon dates per area varied across the region of analysis, with the largest number of activity dates in the Ohio region ($n = 61$) and the New England region the least well represented ($n = 14$). The FADEU data are available for download at the following hyperlink: https://ldavis.people.ua.edu/fadeu.html.

Fluvial activity chronologies

Data from FADEU were divided into six regional watersheds (Figure 2) based on National Oceanic and Atmospheric Administration (NOAA) hydroclimatological classifications (NOAA, 2018), and two summed probability curves – one for 'active' and one for 'stable' dates – were produced for each regional watershed. Uncalibrated radiocarbon dates corresponding to each regional watershed

Table 1. The number of $_{14}C$ samples per region, site, and activity state with associated sources (site numbers correspond to those shown in Figure 2).

	No. of activity samples	No. of stability samples	Sources
Lower Mississippi	30	6	
By site			
1	11	2	Kesel (2008)
2	1	–	Alford et al. (1983)
3	12	–	Kesel (2008)
4	1	–	Munoz et al. (2018)
5	–	3	Saunders and Allen (2003)
6	4	1	Barnhardt (1988), Dotterweich et al. (2014)
7	1	–	Rodbell (1996)
South Atlantic–Gulf Coast	27	12	
By site			
8	2	1	LaMoreaux et al. (2009)
9	6	–	Leigh (2006)
10	1	–	Leigh and Feeney (1995)
11	1	–	Leigh and Feeney (1995)
12	1	–	Leigh and Feeney (1995)
13	2	–	Waters et al. (2009)
14	–	1	Leigh et al. (2004)
15	–	4	Goman and Leigh (2004)
16	–	1	Bamann and Bradley (2009)
17	11	2	Willard et al. (2010)
18	1	2	Webb and Leigh (1995)
19	2	1	Bamann et al. (2007)
Tennessee	35	14	
By site			
20	1	–	Nance (1986)
21	17	–	Sherwood et al. (2004)
22	1	–	Kocis (2011)
23	4	10	Brackenridge (1984)
24	2	2	Kocis (2011)
25	3	1	Kocis (2011)
26	3	–	Driese et al. (2008)
27	1	1	Leigh (1996)
28	4	–	Leigh and Webb (2006)
Ohio	61	59	
By site			
29	4	–	Alexander and Prior (1971)
30	1	–	Bradbury and McKelway (1996)
31	1	2	Miller et al. (2012)
32	3	–	Counts et al. (2005)
33	5	–	Counts et al. (2015)
34	–	2	Gooding (1971)
35	–	1	Gooding (1971)
36	10	20	Gray (1984), Simpson and Scholl (2014)
37	7	–	De Rago (2012)
38	1	22	Gooding (1971), Stafford and Creasman (2002)
39	28	–	Creasman et al. (1996)
40	–	2	Cremeens et al. (2003)
41	–	2	Driese et al. (2005)
42	–	4	Hart (1993)
43	–	4	Siegel and Heaton (2002)
44	1	–	Ciolkosz (2000)
Mid-Atlantic	35	78	
By site			
45	2	–	Ciolkosz (2000)
46	1	–	Ciolkosz (2000)
47	1	–	Ciolkosz (2000)

(continued)

Table 1. Continued.

	No. of activity samples	No. of stability samples	Sources
48	3	22	Custer et al. (1996); Cremeens et al. (1998)
49	–	8	Wall (2000)
50	–	5	Schuldenrein and Thieme (1999)
51	1	–	Ciolkosz (2000)
52	1	–	Ciolkosz (2000)
53	1	–	Coates et al. (1971)
54	4	6	Scully and Arnold (1981)
55	4	7	Scully and Arnold (1981)
56	1	–	Stinchcomb et al. (2012)
57	7	8	Stinchcomb et al. (2011, 2012)
58	–	5	Stinchcomb et al. (2012)
59	–	3	Stinchcomb et al. (2012)
60	–	5	McNett et al. (1977)
61	9	–	Schuldenrein (2003)
62	–	7	Schuldenrein et al. (1991)
63	2	2	Southgate (2010)
New England	14	27	
By site			
64	–	16	Thorson et al. (2014)
65	–	11	Petersen (1991)
66	14	–	Brackenridge et al. (1988)

were sorted from oldest to youngest in radiocarbon years and input into OxCal 4.3 radiocarbon calibration software (Bronk Ramsey, 2009; Macklin et al., 2012). The procedure we used to calibrate and create summed probability curves in OxCal is explained in detail by Macklin et al. (2012). Summed probabilities were calculated in 5-year bins across 12,000 years and converted from radiocarbon years to calendar years before present (cal. yr BP) by subtracting radiocarbon years by 1950. The calibration process was executed for each radiocarbon age included in the regional watersheds' activity and stability chronologies.

The radiocarbon calibration curves for all individual ages were summed within each regional watershed and divided by the summed probability curve of the total dataset (Eq. 1). Standardization helped minimize errors in the timing of depositional events potentially introduced by the radiocarbon calibration process (Hoffmann et al., 2008). The summed probability curves were normalized (Eq. 2) using methods described in Harden et al. (2010), resulting in relative probability curves for the depositional activity or stability for each regional watershed (RW):

$$\frac{\text{RW SPC}}{\text{Total SPC}} = \text{Standard RW SPC} \tag{1}$$

$$\frac{\text{Standard RW SPC}}{\text{Max. standard RW SPC probability}} = \text{Relative probability} \tag{2}$$

where regional watershed SPC is the summed probability curve of radiocarbon dates from each study system. Total SPC is the summed probability curve of all FADEU radiocarbon dates, including only the SPC values, which correspond with the temporal extent of the regional watershed SPC.

The frequency of active depositional events was evaluated by examining the probability curves to identify dates when there was an above-average probability that a depositional event had occurred. Average probabilities were calculated for the activity and stability summed probability curves and plotted with respect to time for each study watershed (see Supplemental Material, available online). Relative probability peaks with above-average probability were interpreted as having a strong likelihood of being a depositional event or an episode of stability, depending on the curve being examined, similar to methods used by Harden et al. (2010). Finally, we quantified the duration of active episodes within each study system chronology by counting the number of consecutive years with a higher relative probability of activity than the regional average of relative probability (Biondi et al., 2005). A 100-year running average was applied to the regional activity chronologies to smooth data noise and improve delineation of activity episodes.

Results and discussion

Holocene fluvial activity variation of the eastern United States

Activity summed probability curves were created for major regional watersheds of the eastern United States (Figures 4 and 5). Stability summed probability curves were also generated for each regional watershed to support interpretation of region-wide activity identified in chronologies (Supplemental Material, available online). In each of the 12,000-year chronologies, above-average activity and stability occurred simultaneously in fewer than three instances in the Lower Mississippi, Tennessee, SAGC, and New England regional watershed chronologies and frequently occurred in the Ohio regional chronologies. The increased

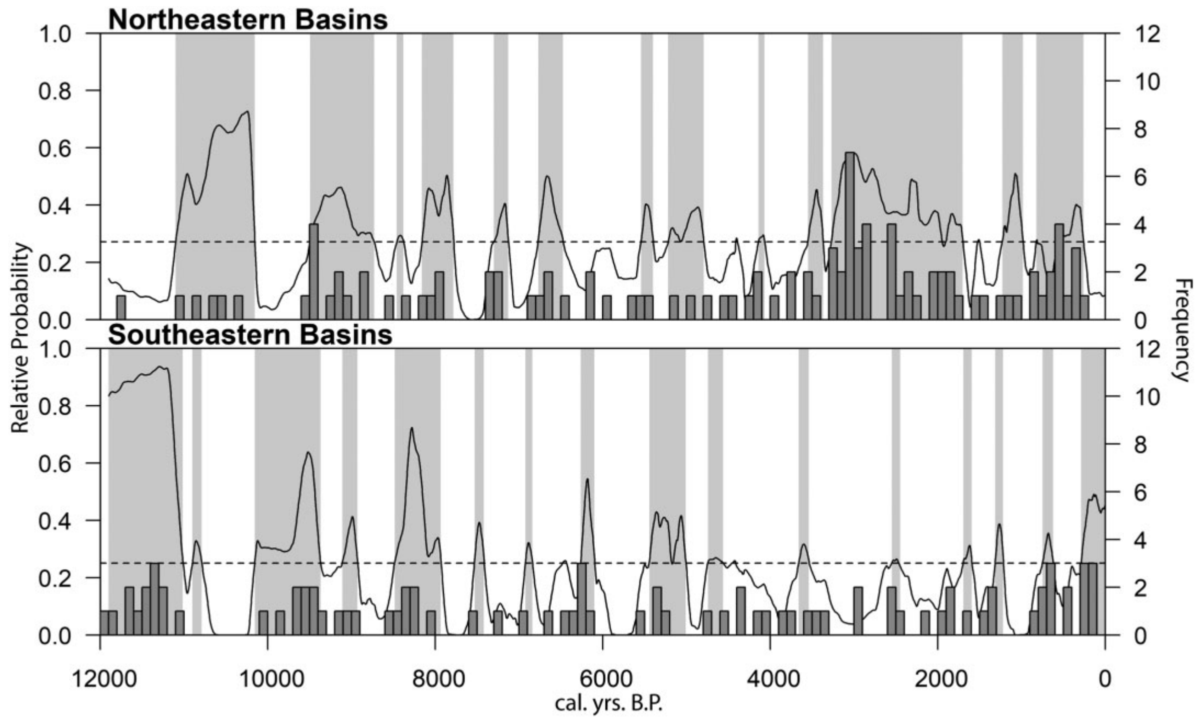

Figure 4. Activity date frequency (vertical bar, right axis) and activity curves (line, left axis) for northeastern watersheds (New England, Ohio, and Mid-Atlantic) and southeastern watersheds (Tennessee, South Atlantic–Gulf Coast, and Lower Mississippi). An average probability of relative probability for each region is represented by dotted lines. The duration of active episodes is highlighted with large vertical gray bars.

regional probability in activity and stability dates simultaneously occurred as a result of differing active states between the rivers within a regional watershed suggesting spatial variation.

The chronologies show variation in the timing and frequency of active depositional episodes (Figures 4 and 5; Table 2). During the early Holocene, the watersheds with the greatest number of activity episodes included the Lower Mississippi, the Tennessee, and the SAGC, with activity episodes clustered within two timespans, ~11,000–10,000 yr BP and ~8000–9000 yr BP for these watersheds. The Ohio River watershed demonstrated significantly greater fluvial activity than all other watersheds and its most active period of fluvial activity occurred during the middle Holocene (7920–4030 yr BP). The middle Holocene was also the Tennessee watershed's most active time, with episodes during 7895–5235 yr BP, though it had fewer episodes than the Ohio. The Lower Mississippi and the SAGC followed the Tennessee in number of active episodes, with episodes occurring during ~7000–5000 yr BP for both watersheds. The late Holocene showed the greatest amount of fluvial activity overall. The SAGC experienced its greatest fluvial activity during this time (episodes occurring ~3000 to ~55 yr BP). The Ohio, Lower Mississippi, Mid-Atlantic, and New England watersheds all experienced considerable fluvial activity from ~3700 to ~300 yr BP. Notably, the Tennessee watershed was the least active of all watersheds during the late Holocene, with limited activity during ~235 yr BP to modern day.

The regional watersheds in the northeast and regional watersheds in the southeast tended toward similar activity state patterns, respectively. Activity curves generated from combined radiocarbon dates in the northeastern and southeastern regional watersheds emphasized the out-of-phase and in-phase behavior (Figure 4). The northeastern and southeastern regions were out of phase for most of the Holocene. Only six fluvial activity duration periods overlapped between the northeastern and southeastern regions. In-phase fluvial activity occurred from ~11,100–10,800 yr BP, ~9100–8900 yr BP, ~8300–7900 yr BP, ~5200–5000 yr B.P, 2550–2450 yr BP, and 750–625 yr BP.

In summary, the early Holocene was active for a number of watersheds, including the Lower Mississippi, the Tennessee, and the SAGC but not the Ohio, Mid-Atlantic, and New England watersheds. The later onset of active periods during the early Holocene in the northeastern regions may have resulted from the lingering effects of the Laurentide Ice Sheet as it retreated out of the study region. The middle Holocene stood out as being a highly, fluvially active time for the Ohio and Tennessee watersheds. The middle Holocene was characterized by generally warmer and drier conditions during the Holocene Climatic Optimum (Renssen et al., 2012; Wanner et al., 2011). The overall level of fluvial activity during the middle Holocene suggests periodic regional fluvial activity. The late Holocene was an active time for fluvial activity for most watersheds but was also marked by a lack of fluvial activity in the Tennessee watershed, which prior to this time consistently demonstrated fluvial activity. In addition, the late Holocene was the most fluvially active time for the Mid-Atlantic and New England watersheds, which prior to this time demonstrated far less fluvial activity than the other study watersheds. The addition of fluvial activity generated by the Mid-Atlantic and New England watersheds resulted in the late Holocene having the most active episodes overall in the eastern United States, implying that fluvial activity had generally increased since the Pleistocene/Holocene transition approximately 12,000 years ago.

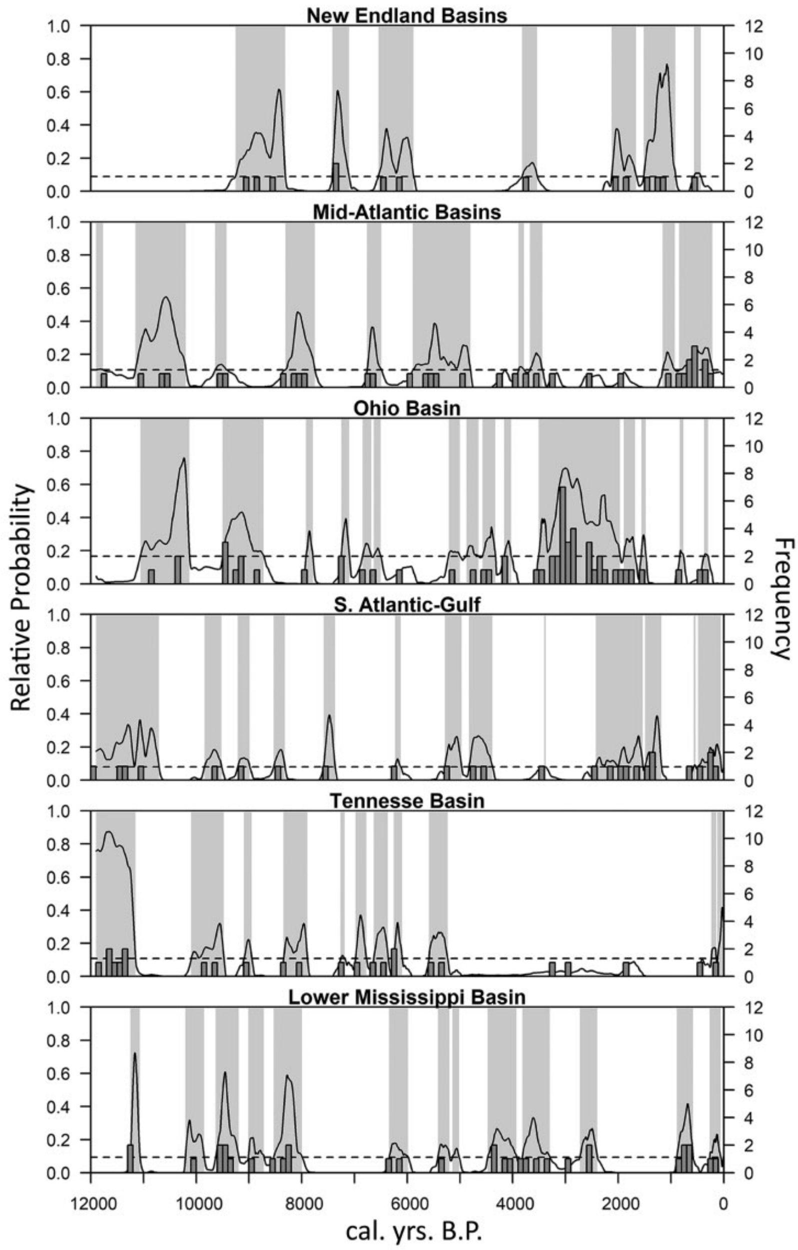

Figure 5. Activity date frequency (vertical bar, right axis) and activity curves (line, left axis) in the eastern United States where peaks represent the relative probability of fluvial activity in the respective regional watershed. An average probability for each regional watershed is represented by dotted lines. The duration of active episodes is highlighted with vertical gray bars. Most regional watersheds do not have clear patterns of activity during the Holocene; however, the Lower Mississippi activity chronology suggests more regular episodes than other regional watersheds.

Fluvial activity related to global climate change

Global-scale variation in temperature and moisture has occurred episodically throughout the Holocene. A large-scale cooling event noted in several paleorecords occurred approximately 8200 yr BP, referred to herein as the 8.2 ka cooling event (Alley et al., 1997; Clark et al., 2001). The 8.2-ka cooling event is widely attributed to the draining of Lake Agassiz into the North Atlantic Ocean through Hudson Bay in Canada (Clark et al., 2001). The New England fluvial activity chronology shows increased depositional activity prior to the 8.2-ka cooling event (Figure 6) that occurred within the age ranges estimated for the Lake Agassiz meltwater pulse – 8400 to 8000 yr BP (Alley et al., 1997). The Lower Mississippi Basin fluvial activity chronology also indicates increased fluvial activity during the 8.2-ka cooling event (Figure 6). Increased activity on the Lower Mississippi during this period was potentially related to hydroclimate variation associated with the 8.2-ka event (Morrill et al., 2013). This regional approach improves insight into fluvial response to large-scale hydroclimate variation in the early Holocene.

In the middle Holocene, the Lower Mississippi exhibits increased activity relative to the other regional watersheds, with active periods varying at the millennial time scale. In the Upper Mississippi Basin, shifts in channel morphology

Table 2. The onset and termination of active depositional episodes in northeast, southeast and individual regional watersheds.

Northeast	Southeast	Lower Mississippi	Tennessee	S. Atlantic-Gulf Coast
11100 – 10155	11900 – 11015	11250 – 11070	11900 – 11150	11900 – 10710
9495 – 8730	10900 – 10790	10205 – 9850	10095 – 9480	9840 – 9525
8460 – 8380	10155 – 9370	9630 – 9195	9095 – 8950	9215 – 8990
8160 – 7785	9110 – 8930	9015 – 8720	8345 – 7895	8530 – 8320
7300 – 7130	8485 – 7935	8530 – 7995	7265 – 7185	7585 – 7370
6770 – 6475	7530 – 7420	6345 – 5985	6980 – 6775	6230 – 6125
5545 – 5400	6925 – 6840	5415 – 5200	6635 – 6370	5285 – 4970
5220 – 4795	6265 – 6100	5140 – 5020	6255 – 6100	4825 – 4385
4140 – 4069	5445 – 5010	4475 – 3930	5590 – 5235	3405 – 3375
3550 – 3370	4745 – 4565	3815 – 3295	235 – 140	2425 – 1535
3270 – 1704	3660 – 3540	2725 – 2400	115 – 0	1490 – 1180
1230 – 985	2550 – 2450	885 – 585		570 – 535
825 – 260	1695 – 1595	265 – 60		485 – 55
	1315 1220			
	750 – 625			
	290 – 0			
Ohio	Mid-Atlantic	New England		
11060 – 10130	11900 – 11770	9255 – 8315		
9500 – 8725	11150 – 10200	7420 – 7105		
7920 – 7790	9640 – 9425	6545 – 5880		
7250 – 7100	8310 – 7750	3820 – 3535		
6845 – 6680	6760 – 6490	2125 – 1660		
6635 – 6505	5890 – 4805	1515 – 915		
5210 – 5005	3890 – 3785	565 – 435		
4875 – 4650	3675 – 3440			
4570 – 4330	1155 – 925			
4160 – 4030	835 – 215			
3505 – 1965				
1895 – 1680				
1560 – 1480				
835 – 765				
370 – 300				

The number and length of duration dates were compared between the early Holocene (12,000–8000 cal. yr BP), middle Holocene (8000–4000 cal. yr BP), and late Holocene (4000 cal. yr BP to present).

during the middle to late Holocene have demonstrated that these rivers are highly sensitive to millennial- and centennial-scale climate variability (Daniels and Knox, 2005; Knox, 1985, 1993, 2000). Knox (1985) found several periods of larger and smaller bankfull discharges relative to modern channels in the Upper Mississippi Basin. During episodes of larger bankfull discharges in the Upper Mississippi, increased fluvial activity was found in the Lower Mississippi watershed (Figure 7). Conversely, smaller bankfull discharges did not consistently coincide with increased fluvial activity in the Lower Mississippi watershed. These patterns suggest stronger hydroclimate connectivity between the Upper and Lower Mississippi watershed during wetter climate episodes – particularly during the late Holocene. For example, large-scale hydroclimate drivers such as El Niño resulting in wetter conditions in the Mississippi Basin may be more likely to result in regional increases in fluvial activity. Drier periods in the Mississippi Basin may have more localized hydroclimate drivers of fluvial activity in the Upper and Lower Mississippi basins. Notably, regional activity episodes were not as sustained in the Lower Mississippi during the Upper Mississippi large flood period from 6000 to 4500 yr BP as they were in large flood periods after 3000 yr BP. Also, increased Lower Mississippi fluvial activity was out of phase with the Upper Mississippi smaller flood period from 4500 to 3000 yr BP but was not out of phase during similar small-magnitude flood periods from 8000 to 6500 yr BP and 2000 to 1200 yr BP (Figure 7). The increased synchronicity between basins after 3000 yr BP suggests increased connectivity during the late Holocene.

The ‘Medieval Climate Anomaly’ (MCA) and the ‘Little Ice Age’ (LIA) were periods of climate variation in the late Holocene that provide important insights into river response to warmer/drier and cooler/wetter climates, respectively (Christiansen and Ljungqvist, 2012). In the eastern United States, only the Ohio and Lower Mississippi Basins show increased fluvial activities during the MCA. Overall, eastern regional watersheds were less active during the MCA than during the LIA (Figure 8). In contrast to the distinct lack of synchronicity between all regional watersheds throughout the MCA, nearly every watershed was active during the LIA period (Figure 7).

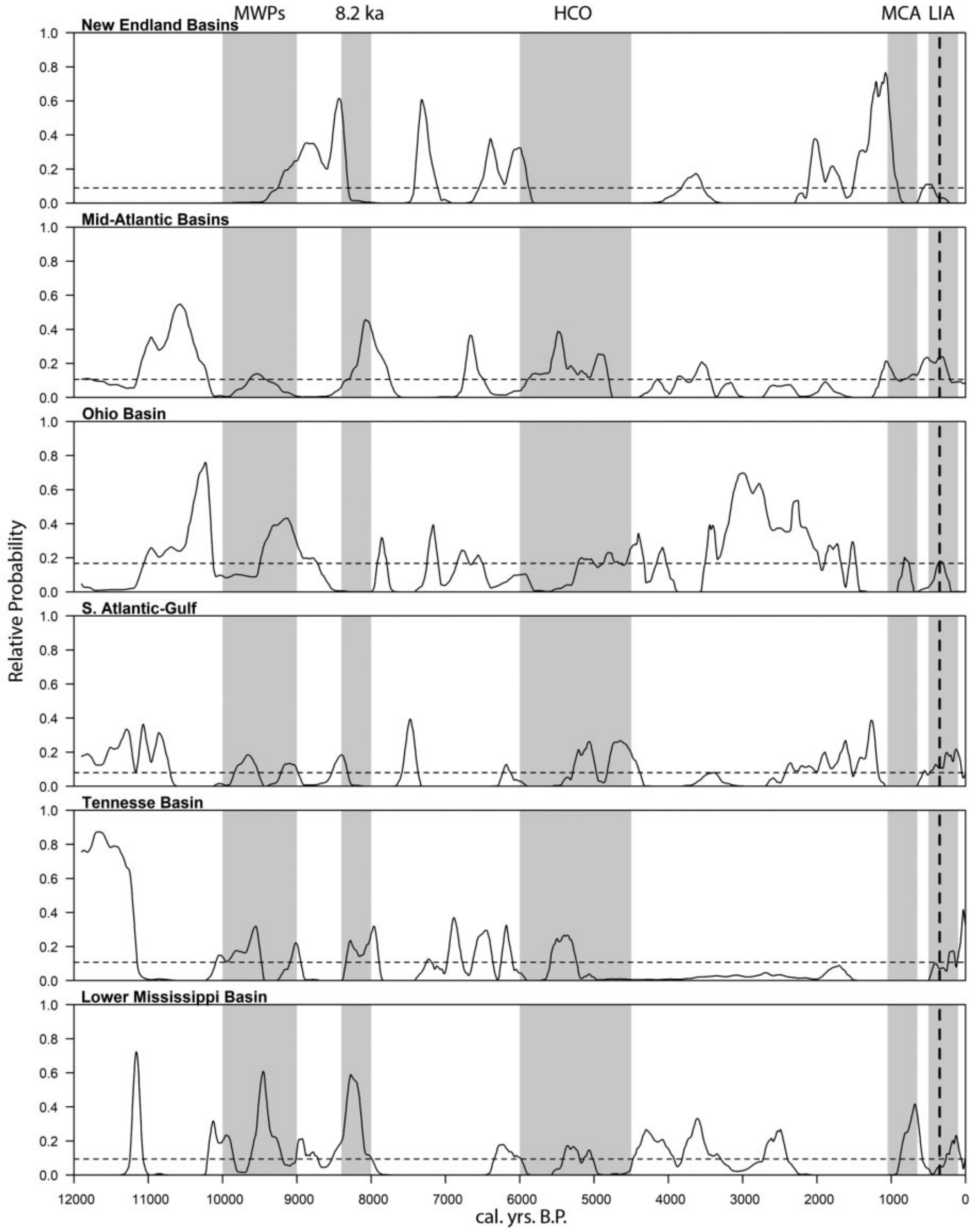

Figure 6. Relative activity curves for major regional watersheds in the eastern United States overlain with significant climate periods including the meltwater pulses (MWPs) in the early Holocene, the 8.2-ka (8200 cal. yr BP) cooling event, the 'Holocene Climatic Optimum' (HCO), the 'Medieval Climate Anomaly' (MCA), and 'Little Ice Age' (LIA). The vertical dotted black line represents the approximate timing of European contact 350 cal. yr BP.

Several hypotheses have been proposed to explain the temperature and precipitation changes of the MCA and LIA, including changes in volcanism, solar activity, and ocean circulation (Koch et al., 2019; Mann et al., 2009; Trouet et al., 2012; Wanner et al., 2011), though it is clear that these periods were dissimilar and asynchronous regionally and globally (PAGES 2k, 2013). In southern European rivers, the increased precipitation associated with North Atlantic Oscillation (NAO) negative phases generated more frequent flooding during the LIA (Oliva M et al., 2018; Trouet et al., 2012). This pattern likely also increases precipitation in eastern North America, but recent observations have found the NAO to have little influence on streamflow of regional watersheds in the southern United States (Engstrom and Waylen, 2018). The Atlantic Multidecadal Oscillation (AMO), however, does influence streamflow of the lower Mississippi River (Enfield et al., 2001; Munoz et al., 2018), and a persistent cool phase of the AMO during the LIA (Mann et al., 2009) may account for the increased fluvial activity in the southeastern United States (Engstrom and Waylen, 2018). The warmer MCA was characterized by frequent extreme floods in paleoflood chronologies (Daniels and Knox, 2005; Harden et al., 2015), but a decline in extreme flood frequency in others (Munoz et al., 2015; Wang and Leigh, 2015). The lack of a cohesive regional fluvial response in the regional watershed

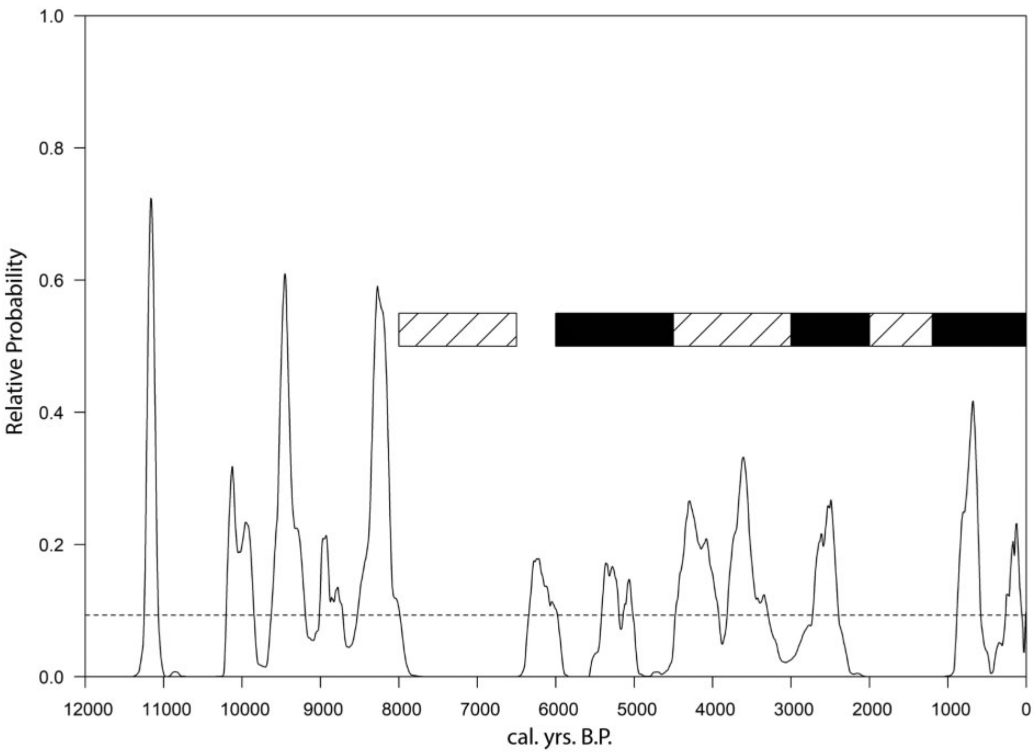

Figure 7. A comparison of reconstructed bankfull floods in the Upper Mississippi basin (Knox, 1985) with the Lower Mississippi activity chronology (significant peaks occur above the dotted black line). Periods of large-magnitude floods in the Upper Mississippi are indicated with black boxes. Periods of small-magnitude flooding in the Upper Mississippi basin are indicated with boxes with diagonal lines.

chronologies during the MCA implies that fluvial activity was more localized at this time.

Fluvial activity related to human influence

In studies of modern fluvial systems, it is widely acknowledged that humans are significant geomorphic agents and affect sedimentation rates (Knox, 1977, 2001; Trimble, 1974). Disentangling anthropogenic and natural climate influences on river variability during the late Holocene is challenging. Fluvial activity chronologies developed for regional watersheds in Europe show that intensive human landscape modifications beginning in the Bronze Age related to agriculture increased fluvial activity (Benito et al., 2008; Hoffmann et al., 2008; Macklin et al., 2006). Human influences on fluvial behavior in the eastern United States are not as clearly delineated from the fluvial activity chronologies constructed for the regional watersheds. Regional watersheds located in the southeastern United States show increased fluvial activity in recent centuries. Despite episodes of fluvial activity earlier during the late Holocene, watersheds located in the northeastern United States did not show increased fluvial activity in the last 400 years. It is important to note that northeastern regional watersheds contained a total of four activity units with calibrated median ages occurring after 400 yr BP and none occurring from 200 yr BP to 1950. In geomorphic studies, there are several other geochronologic options, including dendrochronology and ^{210}Pb, which may account for lack of radiocarbon-dated units in the last 200 years. Still, increased activity in the last 400 years occurred in the southeastern United States was observed with six activity units, and the same types of dated materials contributing to activity chronologies suggesting radiocarbon sample bias cannot exclusively explain differences and warrants future research.

Increased fluvial activity began in the Tennessee River and South Atlantic–Gulf Coast regional watersheds 500 years ago (1450 CE) and 900 years ago in the Lower Mississippi Basin (1050 CE). These activity chronologies include, to differing extents, the *Late Prehistoric Period* from 1000 to 1600 CE (Stinchcomb et al., 2011). While the timing of increases in late Holocene fluvial activity temporally corresponds to Euro-American occupation of the landscape in southern regions of the eastern United States, the concurrent climate variation related to MCA, LIA, and modern warming make it difficult to determine whether climate or human influence was the primary cause of increased fluvial activity.

FADEU: Limitations and Opportunities

The compilation of the first iteration of FADEU revealed several key limitations of this meta-analytical approach. First, chronologies were limited to where geomorphologists conducted funded research, which resulted in sampling bias within the regions. For example, the western portion of the SAGC regional watershed was not represented in the database. Spatially limited data within regions may have resulted in underestimated fluvial activity chronologies. Therefore, results were interpreted conservatively given the currently synthesized data available in the database. This was not because this area lacks a suitable floodplain environment. Rather, there is a lack of investigations of radiocarbon-dated alluvial units in this region to date. Thus, there is a need for future site-specific reconstructions

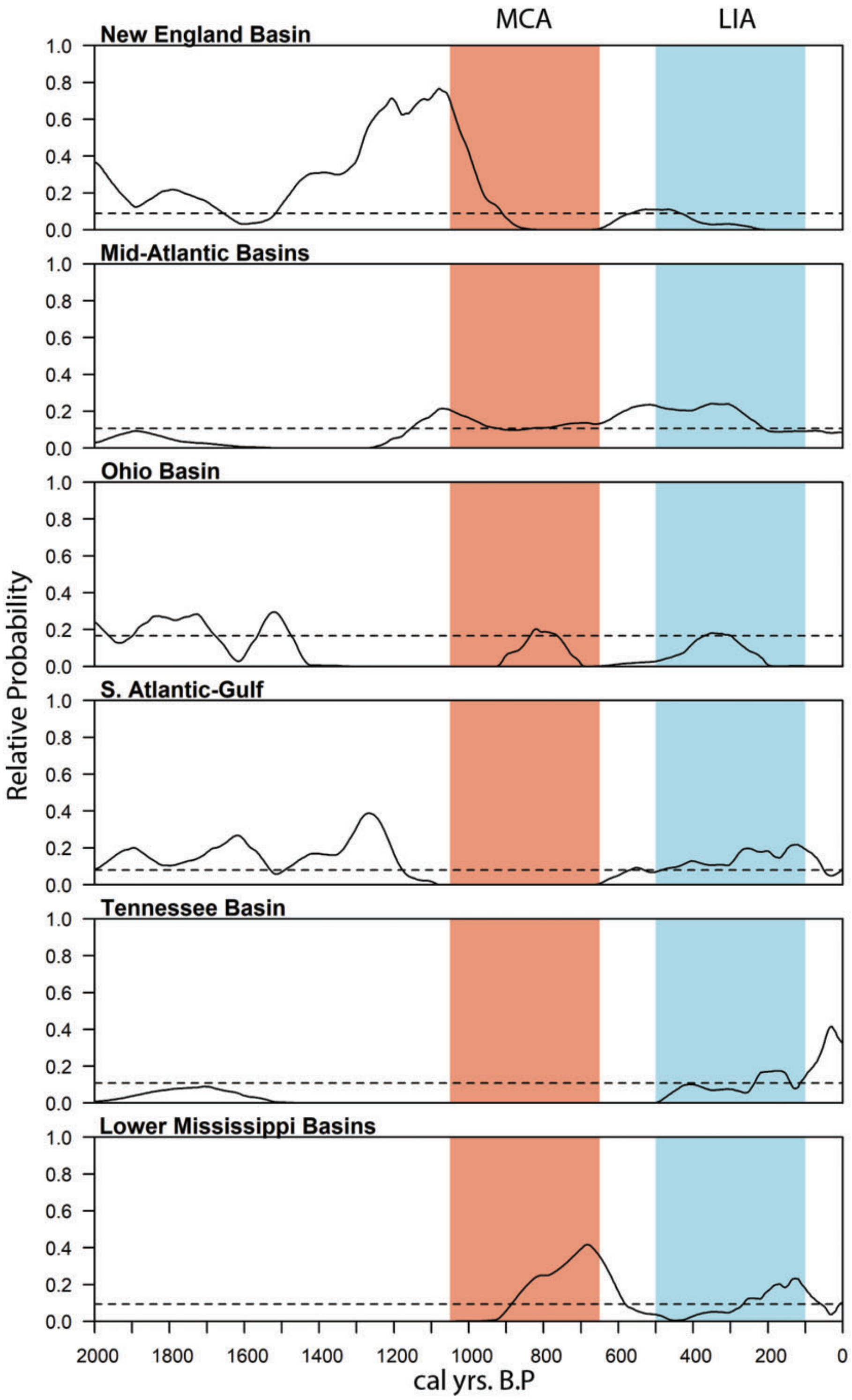

Figure 8. Relative probability for fluvial during the late Holocene. Black boxes highlight the 'Medieval Climate Anomaly' (MCA) from 1050 to 650 cal. yr BP and the 'Little Ice Age' (LIA) from 500 to 100 cal. yr BP. The vertical dotted black line represents approximate timing of European contact 350 cal. yr BP.

with robust geochronology in underrepresented regions in FADEU. Second, as the first synthesis in the region, the overall quantity of radiocarbon-dated alluvial units used in the meta-analysis was small relative to the size of the regions. Notably, no fluvial meta-analysis study to date has contained a sufficient number of dates to be considered statistically large enough to become insensitive to additional data (Jones et al., 2015; Williams, 2012). Nonetheless, fluvial activity chronologies provide valuable regional perspectives on hydrologic responses to environmental change. Meta-analysis results from FADEU radiocarbon-dated alluvial units presented here are consistent with well-researched climate change events during the Holocene, implying that this first comprehensive meta-analysis for these regional watersheds provides valuable insight into regional hydroclimate signals in eastern US rivers.

Conclusion

Fluvial chronologies for six regional watersheds located in the eastern United States exhibit variable patterns of synchronicity of river depositional events between regional watersheds and throughout the Holocene. Based on the frequency and duration of active episodes, river activity during the early Holocene was likely driven by large inputs of water from the retreating Laurentide Ice Sheet. In contrast, mid-Holocene river activity may have been driven by asynchronous, localized fluvial activity within regional watersheds. During the MCA, the depositional activity and stability were spatially variable, with a notable lack of synchronicity of stability or activity occurring between the regional watersheds. In contrast, during the LIA, increased fluvial activity was found in nearly the entire eastern United States. These chronologies may indicate more localized drivers of fluvial activity during the MCA and more widespread, regional explanations of fluvial activity during the LIA. Finally, the role of human land-use/cover change post-European contact is not well represented in the fluvial chronologies. The cause for the differences in depositional activity after 1600 CE between northeastern and southeastern regional watersheds were not clear but may be compounded by the approach's reliance on radiocarbon ages as the date of the fluvial activity. Future research should include multiple geochronology techniques in order to better characterize differences in hydrologic response between the northeastern and southeastern United States in the last 400 years.

As the first synthesis of river activity in the eastern United States, this study found compelling differences in the timing and location of increased fluvial activity related to climate. Despite the limitations of this approach, these results indicate there is a need to better understand the complex response of rivers to variation in climate. The late Holocene (prior to European contact) remains a poorly understood period in the fluvial history of the eastern United States. Based on river chronologies present in this study, the most recent climate periods – MCA and LIA – offer great potential for enhancing understanding of flood mechanisms under future climate patterns.

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Supplemental material

Supplemental material for this article is available online.

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