1 A multi-century tree-ring record of spring flooding on the Mississippi River

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Abstract

Widespread destructive flooding is a common phenomenon along the Lower Mississippi River, and river managers have long sought to understand the temporal variability and relevant climatic factors of the system. One of the important drawbacks to better understanding the flood regime of this and similar large river systems is the relatively short instrumental record of flooding. In this study, we present a novel, annually-resolved tree-ring record of spring flooding based on anatomically anomalous “flood rings” preserved in trees growing about 60 km downstream of the Mississippi and Ohio River confluence. Our chronology records 39 flood-ring years between 1770-2009 including nearly all of the observed significant floods of the 20th century as well as severe floods documented in prior centuries. Comparison of the flood ring record with stream gage observations suggests that large-magnitude floods lasting for more than 10 days, during the spring flood season, are most likely to cause a flood ring in sampled trees. Instrumental and paleo-proxy records of atmospheric circulation features relevant to spring flooding on the Lower Mississippi were also examined. Results of this research suggest that similar flood-ring records could provide important insight into flood history elsewhere in the Mississippi River system and perhaps climate variability over North America.

Keywords: Dendrochronology, Tree ring, Flood ring, Paleoflood, Mississippi River, Flooding

1. Introduction

Many regions of the U.S. are prone to destructive flooding (Downton et al., 2005). Communities along the Mississippi River and its major tributaries in particular have been affected by the great environmental and social impacts of flooding (e.g., Barry, 1997; Welky, 2011). Recent research has emphasized understanding the underlying mechanisms that force these types of events including the effects of climate variability (e.g., Changnon and Kunkel, 1995; Knox, 2000; Villarini et al., 2011), and human modification of the hydrology of the river (e.g., Pinter et al., 2008). Although estimating the natural variability of flooding on major rivers throughout the world is hindered by the relatively short (~120 years) instrumental record of streamflow (e.g., Klemes, 1989), paleoflood hydrology offers the potential to improve the spatial and temporal record of flooding and reduce uncertainty in hydrologic analyses of river flooding (e.g., Jarrett, 1991; Baker et al., 2002; Benito and Thorndicraft, 2005; Baker, 2008).

A variety of primarily geomorphological methods have been used to reconstruct the frequency and magnitude of past floods. Common approaches include studying: slackwater sediment deposits (e.g., Kochel and Baker, 1982; 1988; Jarret, 1990; Wohl, 1992; Ely et al., 1993), deposits from more dynamic events (e.g., Costa, 1983; Wang and Leigh, 2012), fluvial geomorphology (e.g., Baker, 1977; 1987), speleothems (e.g., Springer, 2008; Gazquez et al., 2014), and archaeological materials (Patton and Dibble, 1982).

Dendrochronology has long been used to date a variety of geomorphological processes and hazards (Stoffel and Bollschweiler, 2008), and precisely dated tree rings can indicate past flooding through examination of mechanical or systemic damage to trees caused by flooding. Sigafos (1964) was among the first to demonstrate the potential of precisely dated botanical

evidence to indicate past flooding through an examination of mechanical damage to trees caused by flooding along the Potomac River. Other relevant studies focused on reconstructing flood history through examination of mechanical injury to riparian trees include those conducted by Harrison and Reid (1967) in North Dakota, Helley and LaMarche (1968), in California, Yanosky (1982; 1983) on the Potomac, McCord (1990; 1996) in the southwestern U.S., Gottesfeld (1990) in British Columbia, Fanok and Wohl (1997) on the Shenandoah in West Virginia, Tardiff and Bergeron (1997) in Quebec, Yanosky and Jarret (2002) in Colorado as well as Ballesteros et al. (2011) in Spain. Also see Hupp (1987; 1988). In 1983 Yanosky found that Ash (*Fraxinus sp.*) growing in the floodplain of the Potomac River formed “flood rings” as the result of massive defoliation of young trees inundated by floodwaters. Yanosky (1983) also discussed the development of anatomical anomalies resulting from inundation of only the roots of trees, rather than defoliation but did not find significant evidence of this type of response. However, Astrade and Begin (1997) found that flood rings formed in *Quercus rober* as a result of root flooding along the Saone River in France. In North America, St. George (2010) and St. George and Nielsen (2000; 2003) and Wertz et al., (2013) have utilized similar flood ring evidence from *Quercus macrocarpa* trees to study paleoflood hydrology in the Red River basin in North Dakota and Manitoba, Canada.

In this study, we present the first long, annually resolved tree-ring record of destructive spring flooding on the Lower Mississippi River (LMR), which is based on anatomical tree-ring signatures of flooding from samples collected in the upper portion of the LMR. We also compare the tree-ring record of flooding to modern instrumental and historical records of flooding.

2. MATERIALS AND METHODS

2.1 Tree Ring Data

In 2009 as part of a dendroecological investigation, we collected tree-ring samples from 33 living and two dead oak (*Quercus lyrata* and *Q. macrocarpa*) trees, from Big Oak Tree State Park (BOT), which is located in Mississippi County in southeast Missouri (Figure 1). This site represents one of the few remaining stands of virgin wet-mesic bottomland hardwood forests within the lower Mississippi alluvial valley (NPS, 1999). One or two increment core samples were extracted from each tree at breast height (~1.4 m) using 5-mm diameter Swedish increment borers. Cross-sections from dead trees were collected as close to the base of the tree as possible. All samples were absolutely crossdated using the skeleton-plot method of dendrochronology (Stokes and Smiley, 1996). Tree-ring widths were measured on a stage micrometer to a nominal resolution of 0.001 mm. We crosschecked the accuracy of our visual dating using the computer program COFECHA (e.g., Holmes, 1983).

Our tree-ring record extends from 1694-2009 and includes six trees over 200 years old. We determined flood-ring years by examining each tree-ring series for any evidence of flood injury consistent with the anomalous anatomical features caused by flooding as described by previous flood-ring studies (Astrade and Begin, 1997; St. George and Nielsen, 2000; 2002; Wertz et al., 2013). Like several of the previous studies, we found that the most pronounced characteristic of flood rings in the oaks sampled is a reduction in the cross-sectional area of earlywood (EW) vessels during the year of inundation. Additional characteristics we used for identification included “jumbled” or “additional ranks” of EW vessels or zones of “extended earlywood” (Yanosky, 1983), and disorganized flame parenchyma (St. George and Nielsen, 2002) as well as

“offset” EW ranks (Figure 2). Although Yanosky’s (1983) findings were primarily focused on the effects of defoliation of Ash trees (*Fraxinous* sp.) caused by flooding, we also observed similar anatomical anomalies in oaks sampled at the BOT site. For example, we also noted “jumbled” EW as well as “additional ranks” of EW vessels and zones of “extended earlywood” in our samples, which we know in many cases could not have been defoliated to any great extent by flooding given the height of the sampled trees.

Also, although “frost rings” are known to occur in other species of oaks (*Q. alba*, *Q. stellata*) in this general region (e.g., Stahle, 1990), the predominant anatomical features of frost rings are quite different from flood rings. For example, while we did observe some similar traumatic injury features such as EW cells that were offset from the terminal parenchyma of the previous year, we did not observe any instances of the most distinguishing feature of frost rings, which is the presence of crescent shaped or “lunate” EW vessels (Stahle, 1990). Furthermore, comparison of our flood ring record with frost ring records in the region (Stahle, 1990) indicates few years in common and we did not observe evidence of known widespread, severe frost ring events that we would expect to observe in our samples.

We listed the dates of potential flood rings for each tree and calculated an event response index similar to those developed for debris flows (e.g., Shroder, 1978), where “*I*” for each year (*t*) is the percentage of trees injured by flooding (*R*), divided by the total sample depth of trees (*A*) for each year *t*:

1.

$$I_t = (\sum_{i=1}^n R_i) / (\sum_{i=1}^n A_i) * 100\%$$

Although the entire tree-ring chronology extends from 1694-2009, we only calculate the event response index from 1770-2009 when at least two trees are available for analysis and we do not include years in which less than 10% of trees sampled register injury (e.g., Reardon et al., 2008). This restriction resulted in the exclusion of 1907, 1993, and 1995 from the analysis. Although there was significant flooding in the region in these years these exclusions do not materially affect the analysis.

2.2 Streamflow Data

We compared our flood-ring record with daily Mississippi River stage-height measurements obtained from gage MS115 located at New Madrid, Missouri for the period 1879-2010 (USACE, 2010). The New Madrid gage is located 22 km (13.6 miles) south of the BOT site near the outlet of the Birds Point-New Madrid Floodway, within which the study site is situated (Figure 1). Other gages are geographically closer to the BOT site (e.g., Hickman, KY), but the New Madrid gage record is much longer. Although the BOT site is currently less than 2 km (1.24 miles) from the Mississippi River, its direct connectivity to the river has been obstructed to various degrees by levees since the early 20th century. However, the site has never been completely cut off from the river and routinely floods during periods of high water when backwater flooding occurs through a 460 m (1,500 ft) gap in the levee near New Madrid (USACE, 2000).

The New Madrid stage hydrograph is typical of much of the Middle Mississippi River system, with a peak in March through May (MAM) and low stages occurring in autumn (Brooks et al., 2003). With notable exceptions (e.g., 1937, 1950), most of the high magnitude flooding that occurs along this portion of the river also takes place in the months of March-May.

The elevation of the study site ranges from 88.09 m (289 ft) to 89.92 m (295 ft) and local observers confirm that the site begins to flood when the New Madrid stage height reaches “flood” stage, which is 10.36 m (34 ft), and should be completely inundated at “moderate” (12.19 m; 40 ft) and “major” (>13.41 m; 44ft) flood stage heights. In addition to the depth of flooding (represented by stage height), the season of occurrence and the duration of flooding strongly affect flood-ring formation (St. George and Nielsen, 2002). To determine duration of flooding, we calculated “days in flood” (DIF), or number of days that daily stage values exceeded flood stage (i.e., >10.36 m; 34ft) and moderate flood stage (>12.19 m; 40ft) during the spring flood period (March-May; MAM), and compared these data to our event response index.

We also conducted a limited survey of the historical record of flooding in the region prior to the modern instrumental period for evidence of flooding that might be expected to show up in the tree-ring record. Although very little quantitative information regarding flooding in the region exists prior to the instrumental period, destructive flooding was of great concern to communities and landowners in the floodplain and therefore frequently documented in local and even national newspapers and reported in government surveys and historical texts.

2.3 Climate Data

We also examined the flood-ring record in the context of relevant climate and atmospheric circulation features. Research on the influence of large-scale climate forcing mechanisms on Mississippi Basin streamflow indicates that there are several potential factors operating at different scales within the basin including the Atlantic Multidecadal Oscillation, the El Niño-Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (e.g., Olsen et al., 1999; Twine et al., 2005, Tootle and Piechota, 2006; Sanchez-Rubio et al., 2011). In particular, the Pacific North American (PNA) teleconnection pattern appears to exert a strong influence on

rainfall and streamflow in late winter and early spring in the middle Mississippi and Ohio River valleys (e.g., Brooks and Thiessen, 1937; Leathers et al., 1991; Coleman and Rogers, 2003; Rogers and Coleman, 2003; Yin, 1994). This is believed to result from variability in the position of the polar front jet, with enhanced cyclonic activity and precipitation over the upper Mississippi and Ohio River regions resulting from a northward displacement of the jet occurring during the so-called “reverse” PNA (RPNA) phase (Leathers et al., 1991; Archambault et al., 2008). Although the observed records of the PNA are too short (1950-2012) to adequately compare to the record of major flood events in the tree-ring record, we compared the flood-ring record to both an instrument-based reconstruction of the PNA (1895-1988; Yin, 1994), as well as two long tree-ring records of PNA variability (Wiles et al., 2009; Trouet and Taylor, 2010) and we computed composite means of observed daily 500 mb geopotential height over the U.S. for up to seven days prior to peak flooding, during spring flood years (Compo, 2011).

3. Results

3.1 The flood-ring record and correspondence with instrumental streamflow data

The tree-ring data from BOT provide a record of flooding from 1770-2009 (Figure 3; Table 1). Over that period, the tree-ring record indicates that 39 floods were of a magnitude sufficient to form flood rings in more than 10% of sampled trees. Twenty-two of the 39 flood rings identified in the tree-ring record occur during the instrumental streamflow record at New Madrid (1879-2009; 1892 stage data missing). Examination of daily stage-height values during these flood-ring years clearly indicates a relationship between the flood-ring record and the magnitude (stage height), duration (DIF), and timing of major flood events (Figure 4). The most obvious

relationship is that between moderate or greater (>12.19 m stage height) MAM flooding and the production of a flood ring. For example, 14 of the 22 flood-ring years that occurred in the instrumental period were coincident with moderate or greater flooding that lasted more than 10 days. All but one of these floods (1916) achieved maximum stage between March 10 and May 20 (Figure 4a). This relationship is relevant given that this is very likely when EW formation is occurring in the sampled bottomland oak species. However, not all observed floods produced a flood ring. For example, flooding in 1884 as well as the very destructive Ohio River floods of 1937 and 1950 occurred in January and February while the trees were apparently dormant and there is no visual evidence of a flood ring in those years (Figure 4b). Three instances of spring (MAM) flooding are also evident in the stage data but apparently did not cause flood rings to form (e.g., 1933, 1936; 2002; Figure 4b). Eight flood-ring years are coincident with flooding, between March 10 and May 20 that lasted more than 10 days, but did not exceed moderate levels (Figure 4c). One potential reason for this is that all but one of these years (1994) occurred before the era of levee building in the region, when headwater flooding would likely have frequently flooded the BOT site at lower stages.

3.2 The flood-rings record in the pre-instrumental context

Prior to the instrumental period, the flood-ring record indicates that 17 (including 1892) floods occurred in the 18th and 19th centuries (Figure 3). The historical record provides evidence that flooding may have occurred at BOT during all but two (1779, 1789) of the recorded flood-ring years. Many floods indicated in the flood-ring record are documented up and/or downriver from BOT (e.g. 1785, 1811, 1813, 1815, 1823, 1844). Among the worst of these were the so-called *L'année des grandes eaux* (the year of the great waters) in 1785, which destroyed

Kaskaskia, Illinois as well as the original settlement of Ste. Genevieve, Missouri (Belting, 1976; Norris, 1991), and the “Great Flood” of 1844, when flooding occurred on the LMR, the Missouri and other Great Plains rivers such as the Arkansas and Red (Humphreys and Abbot, 1867; Fuller, 1914). Other early floods suggested by the tree-ring record (e.g., 1792, 1813), are not reported in records from the upper Mississippi (e.g., at St Louis) but are documented at locations upstream on the Ohio or downstream such as in Natchez (Lloyd, 1856; Humphreys and Abbot, 1867). This suggests that these floods originated in the Ohio basin. Historical records of flooding are fairly common after 1844, although quantification of flows is very limited. It should be noted however that historical records of significant flooding in the region exist for years when no flood ring is recorded. For example in 1764 and 1772 in the vicinity of St. Louis (Fausz, 2011) and 1782 in Louisiana (Gould, 1889).

3.3 Climate influences on flooding in the LMR region

Comparisons of the flood-ring record to paleo proxies of PNA variability do not appear to show any clear relationship. Flood-rings appear in approximately equal proportions in years of both negative and positive reconstructed PNA in the Trouet and Taylor (2010) reconstruction and do not appear to be particularly associated with strong events in either direction. The same is true of the comparison to the Wiles et al. (2009) record. It should be noted however that these records represent large-scale seasonal variations in the PNA while our flood ring record is relatively more temporally and spatially limited. Comparison of the flood-ring record to the PNA variability record (1895-1988) of Yin, (1994) indicates that while there is no statistically significant relationship between spring flooding and periods (winters) of strong RPNA (6 of 17

years), it is quite improbable that flooding will occur in seasons with strong PNA patterns (one of 16 years). In addition, composite analysis of daily 500 mb geopotential heights, five-days prior to exceeding moderate flood stage, during the 13 spring flood-ring events that exceeded 10 days of moderate flooding in the 20th century (Figure 4a) clearly indicates that a strong “RPNA-like” pattern is associated with these spring flood events (Figure 5).

4. Discussion

4.1. Reliability of the tree-ring record of flooding

Our new paleoflood record is the first multi-century, tree-ring record of flooding developed for the Mississippi River. As such, it provides compelling new insights into the dynamic nature of flooding in one of the most important riverine systems in the world. Nearly all the significant spring floods that occurred in this region during the instrumental period are evident in the flood-ring chronology and no flood rings occurred in years without significant associated flooding. The fact that all flood rings occurred in association with some level of flooding, clearly suggests that while the flood-ring record does not preserve evidence of all major flooding (e.g., floods occurring outside the growing season), it is very likely that spring flooding did occur in years when flood rings are formed by at least some trees, and serious flooding likely occurred in years when a substantial percentage of trees are injured by flooding. Comparison with historical records also suggests that the flood-ring record is very robust for most of the 19th century and despite the low sample size prior to the early 19th century (e.g., ~1820), the flood-ring record is

probably reasonably reliable, though certainly limited sample size in this period must be considered.

4.2. Links between climate and flooding

Although we are not able to demonstrate any association between the flood-ring record and other paleo-proxy records of PNA variability such as tree-ring records in relevant PNA teleconnection regions (Wiles et al., 2009; Trouet and Taylor, 2010), given the known influence of the PNA on LMR flooding (Coleman and Rogers, 1993; Yin, 1994), as well as the clear association of many 20th century-floods indicated in the flood-ring record with an “RPNA-like” pattern, it seems reasonable to suggest that although our flood-ring record does not provide continuous annual values, it could potentially provide information about pre-instrumental atmospheric circulation variability from an important PNA influence region where no such paleo proxies currently exist.

4.3. Future tree-ring studies of flooding in the LMR

Potential improvements to the flood-ring record would include collecting samples from a broader geographical range of sites within the basin. This might help expand the seasonal window of response to flood injury and help determine whether flood rings in the pre-instrumental period are specific to a given location. As an example, cursory examination of a tree-ring collection from a site adjacent to the LMR but 466 km (290 miles) downriver in Arkansas (Stahle, 1980) reveals that trees at this site frequently formed flood rings coincident

with those recorded at BOT, both during (e.g., 1927, 1945, 1973, 1975), and prior to the instrumental period (e.g., 1792, 1851, 1858, 1874). And although old growth bottomland forests are rare in the LMR, we are aware of additional sites where tree ring records of flooding could potentially be developed. Another potential method of improvement might include the quantitative measurement of vessel size. St. George et al., (2002) found that EW vessel size in Bur Oak (*Q. macrocarpa*) along the Red River in Canada was responsive to large-scale flooding. Given the characteristic reduction in EW diameter noted here and by other studies, a chronology of vessel size (e.g., diameter) might provide a useful continuous quantitative record of flooding. Also because this site (BOT) was initially sampled for a dendroecology study core samples were collected at breast height. St. George et al., (2002) suggest that flood ring signatures may be more fully expressed near the base of tree stems and therefore future sampling should focus on taking cores as low on the stem as possible.

5. Conclusions

While traditional tree-ring width data have been widely used to reconstruct streamflow (e.g., Cleaveland, 2000; Meko et al., 2001; Cook et al., 2013), these data cannot be used to reliably reconstruct the magnitude or duration of flooding. An additional limitation to conventionally derived tree-ring reconstructions of streamflow is the fact that trees typically respond more strongly to drought than to wet conditions, especially those of short duration (e.g., Fritts, 1976; Stahle et al., 2001). Our tree-ring data provide a new, high-resolution record of past flood variability and demonstrate the potential utility of flood-ring records to contribute to understanding both the history of flooding and the role of climate variability in the LMR. These findings also corroborate other studies (e.g., St. George and Nielsen, 2003), which suggests that

343 this technique is potentially widely applicable on other large rivers in the temperate regions. The
344 highly managed nature of the LMR and many similar river systems makes paleoflood hydrology
345 an especially relevant issue, particularly considering the common history of floodplain alteration
346 that further complicates water and other environmental resource management. Proper
347 management of these resources will require longer-term knowledge of the timing and impact of
348 both natural and anthropogenic flood disturbance than that provided by the instrumental record
349 alone.

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551 Table 1. Flood ring years identified based on anatomical ring anomalies are shown as well as
 552 number and percentage of sampled trees injured. All of the flood rings during the instrumental
 553 period (1879-2010) are associated with spring flooding (date flooding began listed for
 554 instrumental period). All but two of flood ring years (1779; 1789) prior to the beginning of the
 555 instrumental record, (as well as the year 1892 when streamflow data are missing), occur in years
 556 when flooding, in the region, is noted in the historical record (comments regarding flood are
 557 provided from one representative source though evidence often appears in multiple sources).

558

Year	Trees Sampled	Trees Injured	Percent Trees Injured	Historical comment/ Flood Date	Year	Trees Sampled	Trees Injured	Percent Trees Injured	Flood Date
1779	2	1	50		1904	27	6	22	Apr 6
1785	3	2	67	“Great waters” ¹	1907*	28	2	7	Mar 5
1789	3	2	67		1908	28	23	82	Feb 5
1792	3	1	33	”Ohio rose 63 feet above low water” ³	1912	29	17	59	Mar 28
1811	6	2	33	“Early May” ¹	1913	31	6	19	Apr 1
1813	6	5	83	“higher than 1811” ²	1916	32	8	25	Feb 1
1815	6	5	83	“A very great flood.” ²	1920	32	25	78	Mar 4
1823	8	6	75	“freshet on Arkansas and White” ⁴	1922	32	30	94	Mar 21
1844	13	7	54	“greatest flood	1927	33	33	100	Mar 25

				known” ¹					
1850	16	2	13	“highest rise in May” ²	1929	33	14	42	Mar 19
1851	16	3	19	Late May ¹	1945	34	31	91	Mar 8
1858	18	11	61	“four great rises” ¹	1973	35	34	97	Mar 20
1859	18	7	39	“long duration” ²	1975	35	9	26	Mar 22
1862	20	13	65	“great flood” ⁴	1979	35	29	83	Mar 7
1865	20	17	85	“great flood” ⁴	1983	35	28	80	May 5
1874	22	8	36	“high from Cairo down” ⁴	1984	35	11	31	May 11
1886	23	14	61	Apr 16	1993*	35	2	6	Apr 18
1892	23	21	91	“culminated 28, Apr” ⁴	1994	35	7	20	Apr 22
1893	23	14	61	Apr 9	1995*	35	2	6	May 29
1897	23	3	13	Mar 25	1997	35	10	29	Mar 13
1903	25	18	72	Feb. 1	2008	35	5	14	Mar 24

559

560 Note: * Years in which a flood ring occurred on less than 10% of sampled trees (not analyzed).

561 Sources for historical comments ¹Gould, (1889); ²Humphries and Abbot, (1867); ³Lloyd, (1856);

562 ⁴Starling, (1897).

Figure Captions

Fig. 1. The BOT site (black star) is located at the southern end of the Bird's Point-New Madrid Floodway (dark gray area within dashed black line) about 60 kms downstream of the confluence of the Mississippi and Ohio River (heavy gray lines). The dashed black lines indicate the frontline and setback levees designed to provide a floodway for major flood events.

Fig. 2 Microphotographs of Quercus annual rings (highlighted) showing various anatomical anomalies during six pronounced flood ring years. Each example shows the diminished earlywood (EW) vessels relative to normal rings during flood years. Jumbled and extended EW can be seen in (a), (b), (d), and (e) while offset EW growth and misshapen vessels can be seen in (a) and (d). Disorganized parenchyma are evident in (c) and (f).

Fig. 3. Histogram showing the percentage of trees injured by flooding (vertical black bars) and sample depth of trees (thin black line) from 1770-2009 (see Table 1). Some notable floods (e.g., 1927) are indicated, but virtually every year registered in this record was coincident with flooding indicated in the instrumental or historical record. Some known flood events (e.g., Figure 4b) took place prior to or after the growing season and are not recorded.

Fig. 4. Daily stage height during (a) the 13 years of moderate to major spring (MAM) flooding (SH >12.19 m for >10 days) evident in the flood ring record (b), the six years of moderate to

major flooding not evident in the flood-ring record, and (c) all other (eight) flood-ring years. Note in (a) that only the 1916 flood ring falls outside the MAM seasonal window and in (b) that only two floods (1933, 1936) occurred when tree-ring formation appears to be most sensitive to flooding, yet did not cause a flood ring. Heavy runoff in the upper Ohio that caused the 1936 flooding was anomalous compared to most of the U.S., including the study site, which experienced severe drought at this time.

Fig. 5. Composite analysis (top) of observed daily 500 mb heights five days prior to the onset of moderate to major flooding, during the 13 spring (MAM) floods recorded in our BOT record, in the 20th century and selected individual daily patterns (lower). These figures suggest that large-scale floods in the Mississippi River basin are associated with an RPNA-like pattern. Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at <http://www.esrl.noaa.gov/psd/>.

20th Century Reanalysis V2
500mb geopotential Height (m) Composite Anomaly (1981-2010 Climatology)

1912, 1913, 1922, 1927, 1929, 1945, 1973, 1975, 1979, 1983, 1984, 1997, 2008

Fig. 1

Fig. 4

Fig. 5