Variations in High-Intensity Precipitation under Climate Changes in the LMRB and Implications for Drinking Water Supply Security

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ABSTRACT

A systematic temporal and spatial analysis is being conducted at the U.S. EPA on historical precipitation and stream flow in the Lower Mississippi River basin (LMRB) and their relationships with Atlantic hurricanes and flooding events. The objectives are to decipher the periodicity and long-term trends exhibited in the hydroclimatic regime, and to determine their implications on the security of community water supplies in the region and the Gulf Coast, the parts of the continental U.S. prone to the negative impacts of extreme weather events under the current and future climate conditions.

Statistical modeling using wavelet functions shows periodicity of continental precipitation and hurricanes with characteristic changes of trends around 1890-1900, 1940-1960, and the 1990s. These long-term decadal and multi-decadal changes were identified in a spatial modeling and wavelet frequency analysis of the 24-hour daily precipitation data obtained from the National Climatic Data Center. Long-term variations are also detected in hurricane and flooding events. Based on these findings, one can incorporate the hydroclimatic periodicity and long-term variations into the emergency water supply management and system designs. Measures such as water intake protection, using decentralized water supply, and planning emergency management are potential options in natural disaster preparedness. The results of the first phase investigation are discussed.

Key Words:

Disaster preparedness, global climate change, extreme weather, drinking water supply, wavelet analysis, precipitation periodicity

Introduction

Changes in precipitation and stream flow, their intensity and duration due to climate forcings have been observed in general (Coulibaly, 2006; Labat, 2008) and in many parts of the contiguous U.S. (Novotny and Stefan, 2007; Lecce, 2000; Rajagopalan and Lall, 1998; Hereford et al., 2006). Yang et al. (2008) observed regional differences in hydrologic response to climate change, which require customized adaptation measures to increase resilience of water resources services for enhanced surface water ecological carrying capacity, uninterrupted water supply, and proper water treatment justifications. In this paper we examine the historical and future precipitation changes and extreme hydroclimatic events in the Lower Mississippi River basin, and discuss the implications on emergency water supply preparedness in flood-related natural disasters.

The Lower Mississippi River basin (LMRB) covers an 181600-km^2 region of Louisiana, Mississippi, Arkansas, and Tennessee (Figure 1), and is prone to the natural disasters from extreme climatic events. In the river basin, occurrence of cyclic flooding events is well known since the early work of Thomas (1928). The infamous 1927 floods, for example, have been investigated since then (e.g., Barry, 2002; Muller, 1976). These extreme events and substantial economic loss have prompted extensive studies in hydrologic causes and event timing (Pinter et al., 2006; Remo and Pinter, 2007; Lecce, 2000; Muller, 1976), and led to programmatic hydrological mapping and flood management by the U.S. Army Corp of Engineers (e.g., USACOE, 2007). In addition, tropic cyclones have occurred frequently in the basin impacting the many social functions including water supplies; the devastating Katrina hurricane in 2005 is an example. Blake et al. (2007) analyzed the frequency of tropic cyclones, and listed 30 deadest and 30 costliest tropical cyclones during the 1851-2006 and the 1900-2006 periods in the continental U.S. Among them, 8 deadest and 7 costliest events occurred in LMRB.

Associated with extreme weather events is the disruption to water supply and adverse impacts on water quality, a factor that deserves consideration in drinking water treatment and disaster preparedness planning. It is known that flood water has high levels of turbidity, organic matters, microbial contaminants as in the case of 2005 Katrina hurricane (e.g., Muirhead et al., 2004; Dortch et al., 2007; Furey et al., 2007). Long-term impacts from extreme events are less understood. Muirhead et al. (2004) hypothesized the long-term storage and post-flood release of *E.Coli* from sediment storage in streams, while Michot et al. (2002) reported minimal long-term impact on water quality, sediments and ecology following hurricane Mitch in Guatemala. Despite the need for further characterization, the water quality impacts ***during*** extreme events are clear. Timing and prediction of these events are helpful in preparing emergency water supplies.

Recent studies (Jansen and Overpeck, 2007; and references therein) have demonstrated strong influences of climate changes on the timing and occurrence of extreme weather events. Correlations with synoptic process such as the El Nino – Southern Oscillation (ENSO) have been explored statistically (El-Askary et al., 2004; Coulibaly, 2006) or in climatological models since the early time (e.g., Bradley et al., 1987). For a given watershed basin, flooding events are directly related to precipitation intensity and duration, which in turn depend on not only synoptic changes but also land use alterations, land feedback and other microclimatic conditions (Fowler et al., 2007; Pinter et al., 2006; Rome and Pinter, 2007). This complexity can make it difficult to assess the timing, location and nature of the extreme events. One viable approach is the statistical analysis of historical climatic data is often combined with the forward computer modeling. Predictions from such a hybrid approach can afford the accuracy in a time and space resolution required in the management of water resources and associated infrastructures, a central topic in the holistic nationwide investigation under way at the U.S.EPA National Risk Management Research laboratory

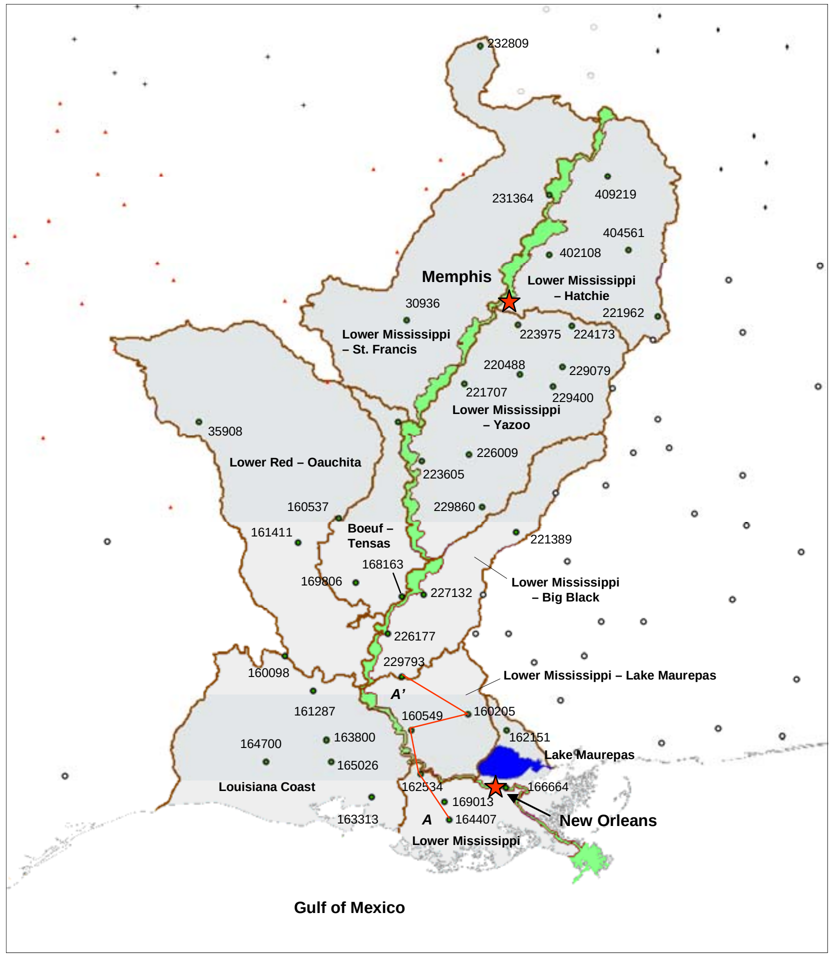

Figure 1 The Lower Mississippi River basin (LMRB), its sub-basins, and the distribution of 39 USHCN climatic stations used for precipitation periodicity and trending analysis. Other symbols are USHCN climatic stations in other major river basins. Mississippi river and associated immediate flood plains are marked in Green. A-A' marks the transit section of stations described in Figure 3.

This paper describes the investigation results on extreme weather conditions in LMRB through statistical analysis of precipitation, flood, and tropical cyclone events. The discussion centers on the forecasting of extreme climatic events (i.e., high-intensity precipitation) and their spatial distributions. Implications on emergency water supply and disaster preparedness will be also discussed.

METHODOLOGY

In this study, the wavelet frequency analysis technique (Labat, 2005) was used in trending and periodicity analysis of extreme precipitation events in historical daily (24-hour) precipitation data. The identified extreme precipitation was further correlated with flooding and hurricane events described in literature (Blake et al., 2007; Muller, 1976; Thomas, 1928; and Patterson, 1964).

Precipitation and Hurricane Records

The low-elevation LMRB traces a nearly 1600-km lower reach of Mississippi River entering the Gulf of Mexico 150-km downstream of New Orleans (Figure 1). It consists eight sub-basins: the Louisiana Coast and Lower Mississippi along the Gulf of Mexico, and other sub-basins associated with Mississippi tributaries. Lower Mississippi-Hatchie sub-basin upstream of Memphis (TN) and the Lower Mississippi-St.Fancis across the river are the sub-basins in the north. In LMRB, 39 climatic stations distribute throughout the basin as a part of the U.S. Historical Climatology Network (USHCN) administrated by NOAA and DOE (Table 1). Their elevations range from 0.37 to 14.73 meters reflecting the gentle topographic variations. The 24-hour daily precipitation records are available for the 30 stations.

In time-series wavelet analysis, monthly precipitation averages for all stations are computed to identify long-term variation trends. Daily precipitation (24-hour duration) for all but 9 climatic stations (Table 1) has a data length of 71 years in average; the longest record (1893-2005) is available for station LA162151. The high-resolution daily precipitation data were analyzed to identify extreme precipitation events and their periodicity. As noted in Williams et al. (2007) and Easterling et al. (1996), the USHCN precipitation database is compiled from a network of collaborative climatic stations where there exists a systematic

Table 1. Climate stations, their geographic and hydrological locations in the Lower Mississippi river basin.

Station ID	Latitude	Longitude	Geographic location	Sub-basin	Elevation (m)	Daily precipitation data from	to
30936	34.88	-91.18	Brinkley, AR	Upper Mississippi - St. Francis	6.10	1948	2005
35908	33.8	-93.38	Prescott, AR	Lower Red - Ouachita	9.39	1930	2005
36253	33.8	-91.27	Rohwer 2NNE, AR	Boeuf - Tensas	4.57	NA	
160098	31.32	-92.47	Alexandria, LA	Louisanna Coast	2.65	1930	2005
160205	30.7	-90.53	Amite, AR	Lower Mississppi - Lake Maurepas	5.18	1948	2005
160537	32.78	-91.9	Bastrop, LA	Lower Red - Ouachita	4.57	1948	2005
160549	30.53	-91.13	Baton Rouge WSO AP, LA	Lower Mississppi - Lake Maurepas	1.95	1930	2005
161287	30.95	-92.17	Bunkie, LA	Louisanna Coast	2.44	NA	
161411	32.52	-92.33	Calhoun Research Station, LA	Lower Red - Ouachita	5.49	1948	2005
162151	30.53	-90.12	Covington 4NNW, LA	Lower Mississppi - Lake Maurepas	1.22	1893	2005
162534	30.07	-91.03	Donaldsonville 4SW, LA	Lower Mississppi	0.91	1930	2005
163313	29.82	-91.55	Franklin 3NW, LA	Louisanna Coast	0.37	1948	2005
163800	30.43	-92.03	Grand Coteau, LA	Louisanna Coast	1.68	NA	
164407	29.58	-90.73	Houma, LA	Lower Mississppi	0.46	1930	2005
164700	30.2	-92.67	Jennings, LA	Louisanna Coast	0.76	1948	2005
165026	30.2	-91.98	Lafayette FCWOS, LA	Louisanna Coast	1.16	1948	2005
166664	29.92	-90.13	New Orleans Audubon, LA	Lower Mississppi	0.18	NA	
168163	31.95	-91.23	Saint Joseph 3N, LA	Boeuf - Tensas	2.38	1930	2005
169013	29.77	-90.78	Thibodaux 3ESE, LA	Lower Mississppi	0.46	NA	
169806	32.1	-91.72	Winnsboro 5SSE, LA	Boeuf - Tensas	2.44	NA	
220488	34.3	-89.98	Batesville 2SW, MS	Lower Mississippi - Yazoo	6.71	1948	2005
221389	32.63	-90.02	Canton, MS	Lower Mississippi - Big Black	6.86	1948	2005
221707	34.2	-90.57	Clarksdale, MS	Lower Mississippi - Yazoo	5.27	1930	2005
221962	34.92	-88.52	Corinth City, MS	Lower Mississippi - Hatchie	11.74	1930	2005
223605	33.38	-91.02	Greenville, MS	Lower Mississippi - Yazoo	4.02	1920	2005
223975	34.83	-90	Hernando, MS	Lower Mississippi - Yazoo	11.07	1930	2005
224173	34.82	-89.43	Holly Springs 4N, MS	Lower Mississippi - Yazoo	14.73	NA	
226009	33.45	-90.52	Moorhead, MS	Lower Mississippi - Yazoo	3.57	1940	2005
226177	31.55	-91.38	Natchez, MS	Lower Mississippi - Big Black	5.95	1930	2005
227132	31.97	-91	Port Gibson 1NW, MS	Lower Mississippi - Big Black	3.66	1930	2005
229079	34.38	-89.53	MS University	Lower Mississippi - Yazoo	11.59	1930	2005
229400	34.17	-89.63	Water Valley 1NNE, MS	Lower Mississippi - Yazoo	11.46	1948	2005
229793	31.1	-91.23	Woodville 4ESE, MS	Lower Mississippi - Big Black	12.20	1948	2005
229860	32.9	-90.38	Yazoo City 5NNE, MS	Lower Mississippi - Yazoo	3.26	NA	
231364	36.2	-89.67	Caruthersville, MO	Upper Mississippi - St. Francis	8.54	1918	2005
232809	37.78	-90.4	Farmington, MO	Upper Mississippi - St. Francis	27.44	NA	
402108	35.57	-89.67	Covington 1W, TN	Lower Mississippi - Hatchie	9.45	1928	2005
404561	35.62	-88.83	Jackson Experiment Station, TN	Lower Mississippi - Hatchie	12.20	1900	2005
409219	36.4	-89.05	Union City, TN	Lower Mississippi - Hatchie	10.67	1930	2005

Note: NA - Daily 24-hour precipitation data are not available from UCHCN.

difference, for example, in the starting time of a 24-hr measurement period. The resulted impacts are noticeable in temperature measurements (Williams et al., 2007), while the effect on average daily precipitation is not assessed.

The contiguous U.S. had received 279 tropical cyclones of grade 1-5 (U.S. Saffir-Simpson hurricane scale) during the 154-year period (1851-2005), of which 68 have landed in Louisiana and Mississippi (Blake et al., 2007). Only these 68 cyclone events were examined for correlation with the identified extreme precipitations. In the analysis, the higher Saffir-Simpson hurricane scale is selected for an event that occurred in both Mississippi and Louisiana.

Wavelet frequency analysis

Precipitation and other hydroclimatic data contain synoptic process information shadowed in background noises of local and short-term variations. In defining precipitation periodicity and long-term trends, this study employed the wavelet denoise technique and frequency spectrum analysis. Labat (2005) and Schaefli et al. (2007) provided a thorough review of the wavelet techniques and developments in hydrological applications. To analyze the precipitation data, a 2-dimensional continuous Morlet wavelet transformation (CWT) was computed in wavelet denoise and reconstruction:

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \sqrt{\frac{\Delta t}{s}} \Psi_0\left[\frac{(n'-n)\Delta t}{s}\right] \qquad (1)$$

$$\Psi_0(\eta) = \pi^{-0.25} e^{im\eta} e^{-0.5\eta^2} \qquad (2)$$

$\Psi_0(\eta)$ is the mother Morlet wavelet, a Gaussian-windowed complex sinusoid as a function of dimensionless time parameter η and wave number *m*. Parameter *N* is the data length, Δt is the sample interval, *s* is the wavelet scale, and *n* is the localized time index. Using the equations, a data sequence is convoluted in form of a scaled and translated mother wavelet by which successive segment of a data stream is compared. Compared to continuous fast-Fourier transformation (FFT), the wavelet transformation is uniquely effective for detection of discontinuities in variation such as climatic changes and transition from one dominant state to another. In this investigation, the Morlet wave number m=6 for time-frequency spectrums construction. The data noise was filtered at a frequency (dB) to detect short-term precipitation disturbances.

In this investigation, the wavelet analysis was performed on a set of precipitation data subsets: the 30-day moving average of 24-hour daily precipitations, the 75% quartile and maximum 24-hour precipitation in backward moving time window (approximately 160 days), and calendar monthly averages. The 30-day moving average likely retains the information, though reduced, of short-term extreme precipitation events and the high-frequency small precipitations. Using the moving average, the high-frequency small precipitations were excluded in calculation of 75% quartile values and the maximum precipitations in consecutive 30 observations. This data treatment assumes that the 75% quartile and the maximum precipitations are reflective of major high-intensity precipitations in the basin, the focus of this investigation.

RESULTS AND DISCUSSIONS

Data Separation and Precipitation Periodicity

To identify variations and trends in extreme rainfall events, precipitation data were separated for those greater than 30-day moving averages and analyzed in wavelet frequencies. Figure 2 shows an example for climate station AR35908 in the Lower Red – Oauchita sub-basin for which the wavelet filter were applied at a frequency threshold dB=6 Hz and dB=7 Hz. At the higher threshold (dB=7), more extreme precipitation events were identified (R^2=0.39). The identification were verified at lower frequency threshold dB=6 (R^2=0.26). Similar wavelet treatment was applied to the 75% quartile and maximum MA data sets (Figures 2b, 2c).

As shown in Figure 2a, 1960-1966 and 1995-1997 are two major precipitation periods with high density precipitation events. The time interval between the periods is 33 years. Other precipitation events of smaller amplitudes show inter-annual variations in a periodicity of 5.6±1.1 years (m±σ, N=10). The two major precipitation periods coincide with the extreme precipitations in the maximum MA plots (Figure 2c), indicating the extreme precipitations as the principal contributor to the event identifications in the 30-day MA (Figure 2a). In a higher frequency events, the 1978 – 2003 period has a similar periodicity at 5.7±1.2 years (m±σ, N=6). Comparatively, the 75% quartile of the filtered precipitation shows a weak wavelet signal change at the two periods and a large decrease in 75% quartile precipitations since the early 1990s (Figure 2b). All together, it is suggested that the high-intensity precipitation at the station is largely caused by extreme precipitation events, which

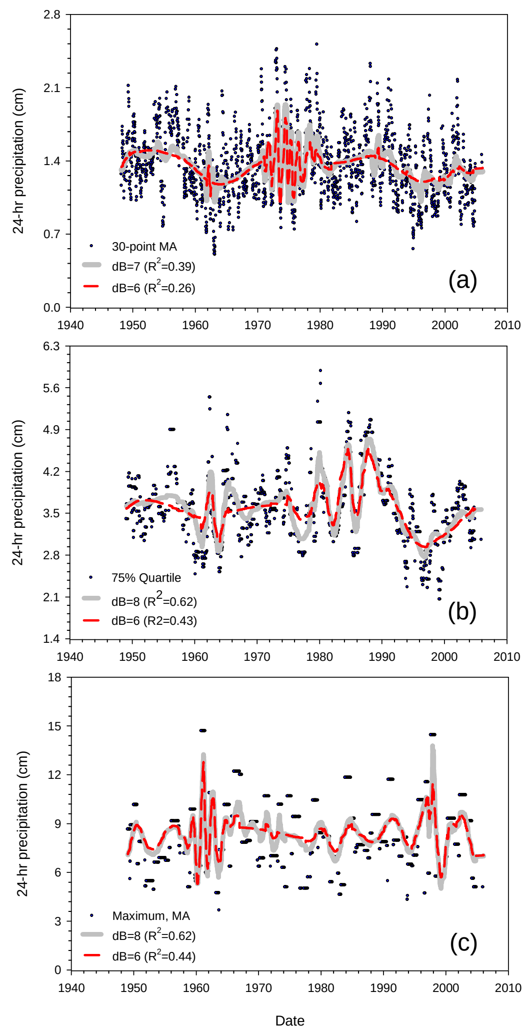

Figure 2 Wavelet denoising and reconstructed 24-hour precipitations for the 30-day moving average of, the 75% quartile, and the maximum precipitation. The 75% quartile and maximum precipitations reflect high-intensity precipitation changes at station AR35908 as an example for illustration.

often are associated with flooding events. At AR35908 station, a 33-year multi-decadal periodicity and ~5-year precipitation cycles are identified.

In a similar approach, the precipitation periodicities and variations were investigated on all other climate stations within LMRB. Spatial correlations of substantial changes were delineated to reveal the pattern of high-intensity precipitation events. Due to the space limitation, the subsequent sections are focused on two principal observations: a consistent precipitation increase along the Lower Mississippi River, and a landward gradation of precipitation periodicity changes in the coastal sub-basins. Their potential hydroclimatic causes is not discussed here. Instead, the implications of the likely future precipitation changes on water supply and emergency preparedness are discussed.

Periodicity Changes in Coastal Sub-basins

The precipitation records at climate stations of the Louisiana Coast and the Lower Mississippi sub-basins displayed strong periodicity in precipitation variations. The periodicity changes in frequency and amplitudes from the Gulf of Mexico coast toward inland. In the Lower Mississippi sub-basin, where New Orleans and Lake Maurepass are located, the 75% quartile precipitation time-series plots are shown in Figure 3 for stations arranged along a NNW-SSE transit. The transit location is shown in Figure 1. Also plotted is the timing of tropic cyclones that have landed in Mississippi and Louisiana since 1950.

In coastal climate stations LA164407 and LA162151 near the coast line, the high-intensity precipitation occurred in years marked in Figure 3. The timing is generally consistent with the historical floods in the Lower Mississippi River, but not with the occurrence of historical tropic cyclones. Notable flood events occurred in 1936, 1945, 1950, 1957-1958, 1973-1975, 1979, 1983-1984, 1993, and 1997 (Trotter et al., 1998). This general agreement is considered a result of the climate teleconnection in synoptic scales, rather than of the short-lived hydroclimatic events such as hurricanes. Time interval of the high-intensity precipitation cycles is 9.7±1.2 (m±σ, N=6) years and 10.2±1.9 (m±σ, N=5) for stations LA16447 and LA162151, respectively. Based on wavelet power spectrums in time-frequency space, the decadal periodicities are further grouped into three periods. The period in the middle of 1990s is marked by strong inter-annual variations of high cyclic frequency and large precipitation intensity.

The decadal regulation is approximately 10 years in the coastal climate stations LA16447 and LA162151, and it is changed to 2-5 year cycle in inland direction (Figure 3). Not only different in periodicity duration, the inland stations also show more irregular cyclic variations and the high-intensity precipitations in timing associated with the LMRB 1993-1997, 2002-2004 flood events.

The Increase of High-Intensity Precipitation along the Mississippi River

In Figure 3, we have shown the periodicity change in high-intensity precipitations in LMRB from the coast toward inland. A close examination of the precipitation variations further shows a large increase of high-precipitation intensity with time in the central and lower LMRB; the precipitation in other parts of the basin shows cyclic variations but no apparent increase over the record periods. The LMRB with high-precipitation increase covers a narrow strip along nearly 1000-km segment of the Mississippi River downstream from Memphis, Tennessee (Figure 4).

All 19 except for four stations in the central and southern LMRB show an increase >0.4% cm/24-hour/year in the 75% quartile 24-hour precipitation over the record period. Figure 5 gives an example for stations in the Louisiana Coast and the Lower Mississippi – Big Black sub-basins. The 75% quartile precipitation increased constantly through time at stations LA160098 and MS229793. A linear regression of all data in the records, discounting the effect of periodicity, shows a yearly increase of 0.8% cm/24-hours/year and 2.8% cm/24-hours/year, respectively. For other stations that contain decadal and multi-decadal variations, the increase of high-intensity precipitation becomes clear after the wavelet denoise and reconstruction (Figure 5). Collectively, the LMRB region with increased 75% quartile precipitation is outlined in Figure 4. The average rate increase is 0.008±0.007 cm/24-hour/year for all stations (m±σ, N=19), and 0.011±0.007 cm/24-hour/year (m±σ, N=15) when four stations with steady precipitations are

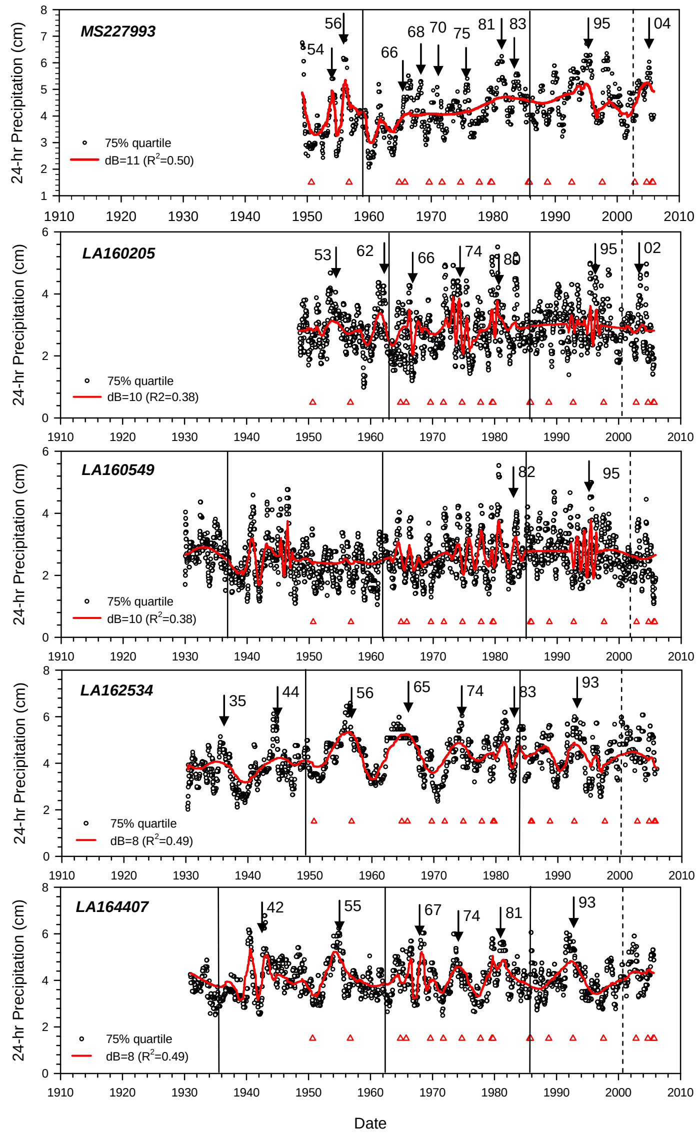

Figure 3 Time-series plot of the 75% quartile 24-hour precipitation and wavelet-denoised variations for climate stations along transit A-A' in the Lower Mississippi sub-basin near New Orleans. The A-A' section is shown in Figure 1. Vertical lines indicate the period boundaries identified by using wavelet power spectrums in time-frequency domain. Note the multi-decadal 30-50 year major periodicity and the 2-5 year and 10 year precipitation cycles. Two major historical floods (1981-1983 and around 1993) are indicated consistently at all stations. Small triangles mark the timing of historical tropical cyclones that landed in Mississippi, or Louisiana or both.

excluded.

It is noted that the linear regressions assumes a uniform population of 24-hour precipitation within a hydroclimatic system. This assumption discounts the effect of precipitation periodicity and short-lived events such as tropic cyclones in the region. For the stations in Figure 5, the major periods of variations are marked showing the 30-50 year multi-decadal periods within which the increase in high-intensity precipitations is relatively uniform. Assuming similar rate of increase in the current cyclic period, then it is possible to forecast the likely high-intensity precipitation for a full cycle. At an average rate 0.008 cm/24-hour/year in the LMRB region, the high-intensity 75% quartile 24-hour precipitation could increase by 0.24 cm/24-hour or 5-10% for most stations in the next 30 years.

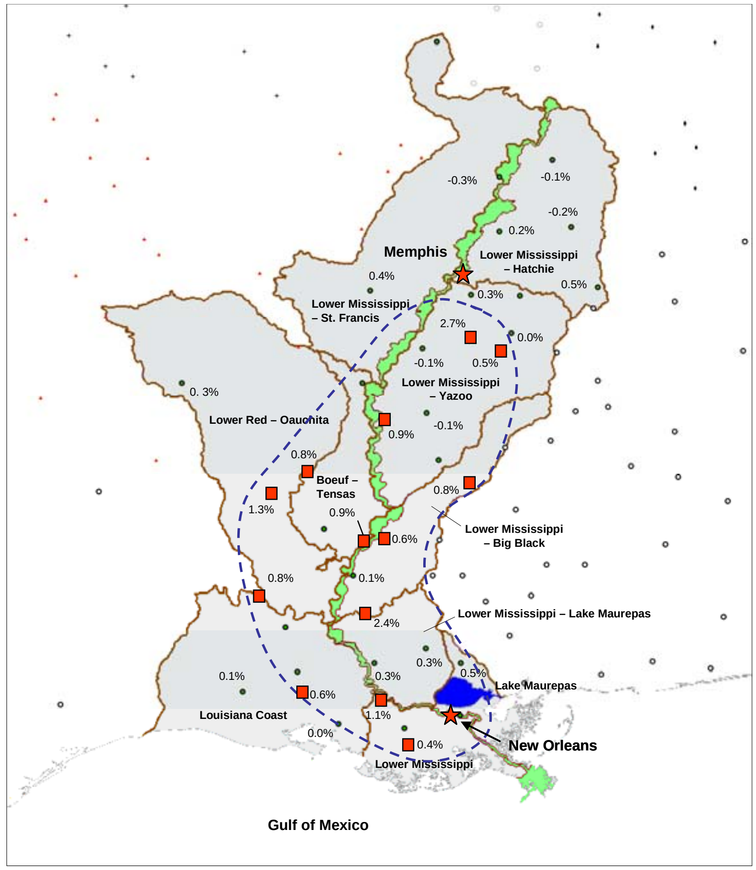

Figure 4 The approximate region in the middle and southern LMRB below Memphis (TN) have experienced an increase in high-intensity 75% quartile precipitations as indicated by the climatic stations (square). The rate of increase (cm/24-hour/year) is given for each station.

The other factor affecting the high-intensity precipitations in the LMRB is the tropical cyclones that are not fully accounted in the 75% quartile precipitation analysis. Their signals in extreme precipitation are overlooked when the 75% quartile values are calculated in a ~160-day moving time window. Consequently the hurricane events are not well registered, which nonetheless have negatively impacts on the region with financial and property lossses (Trotter et al., 1998). These short-lived extreme climatic events are better reflected in maximum precipitations and in short-term water quality variations, for which investigations are being conducted.

Implications for Water Supply and Emergency Preparedness Planning

The increased high-intensity precipitation along the Lower Mississippi River and the strong periodicity in other parts of the LMRB, have implications on water treatment, supply and disaster emergency planning. On the one hand, physical damages to the water intake, water treatment plant and distribution system in flood events cause interruptions to water supplies.

Emergency actions for drinking water facility protection can be made using the near-real-time storm weather forecasting and flash flooding warning services available from NOAA National Weather Services (http://www.spc.noaa.gov/products/wwa/). Long-term preparedness often involves flood insurance protections and proactive engineering measures such as water intake and treatment plant protection during flood events (AWWA/ASCE, 1998), multiple locations of water treatment and supply systems to reduce vulnerability. Planning and design of such measures can be helped from understanding of the periodicity and forecasting of timing and magnitudes of future high-intensity precipitation events.

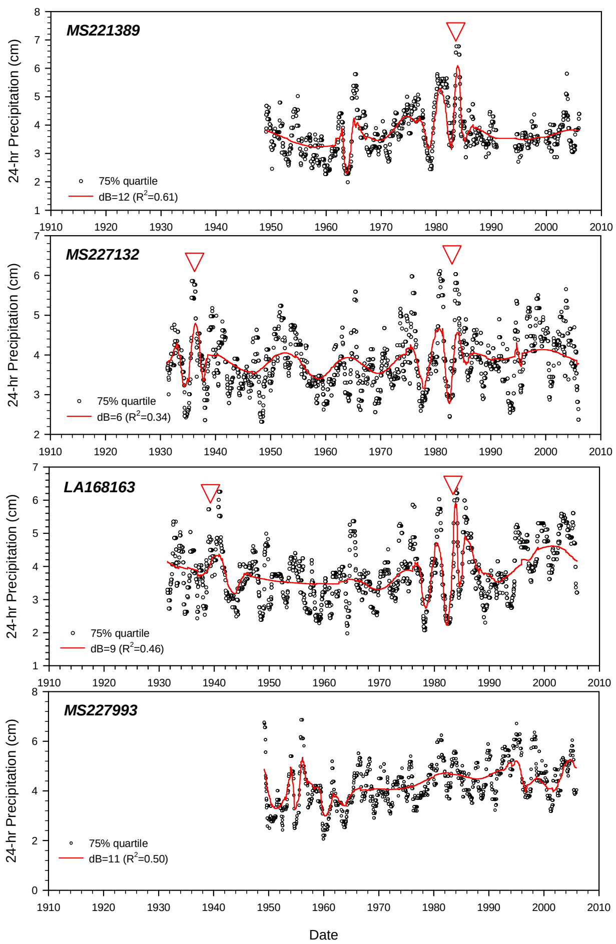

Figure 5 Time-series variations of the 75% quartile 24-hour high-intensity precipitation and the wavelet denoised variations at a given frequency threshold (dB) for climate stations in the Lower-Mississippi – Big Black sub-basin. Triangles mark the large intense precipitation periods in 1938-1940 and 1982-1984 periods; the latter period coincides with the historical flood event in the LMRB.

Furthermore, the increased high-intensity precipitation is often associated with flash floods (Lecce, 2000; Patterson, 1964), propagation of water-born biological contaminants during and after the floods (Ferey et al., 2007; Muirhead et al., 2004; Few et al., 2004; Barry, 2002; Dortch et al., 2007), and deterioration of source water quality (Donner and Scavia, 2007). These impacts require an adaptation strategy in consideration of timing and the nature of the high-intensity precipitation/flood events and associated water quality changes. In light of the climate change that leads to increased high-intensity precipitations and variance in stream flows (Novotny et al., 2007; Few et al., 2004), such disaster adaptation planning becomes more important.

CONCLUSIONS

The high-intensity 75% quartile 24-hour precipitation in LMRB is analyzed to show decadal and multi-decadal variations, and long-term variation trends. Their occurrences are correlated with major flood events but not short-lived tropic cyclones. The wavelet frequency analysis indicates that the high-intensity precipitations occurred in a 30-50 year periodicity and in 2-5 year inter-annual cycles, which are considered a result of larger scale hydroclimatic synoptic process. Above the periodicity, a large increase in high-intensity precipitation is delineated in the lower LMRB along the Mississippi River downstream of Memphis, Tennessee. With four exceptions, all other 15 climatic stations show an average rate of the increase 0.011±0.007% cm/24-hour/year (m±σ, N=15) equal to an increase of 0.24 cm/24-hour in the 75% quartile precipitation in the next 30 years.

The high-intensity precipitation events in LMRB identified in the wavelet analysis coincide in time with most, but not all of the known historical flood events. Notable agreement can be observed for the 1997, 1993, 1983-1984 floods. Less correlation was observed with the short-lived tropical cyclones. The findings on the periodicity and hydroclimatic changes and further studies on water quality variations during and after the high-intensity precipitation events could provide a basis to enhance disaster preparedness planning of emergency water supplies.

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