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Mississippi River low-flows: context, causes, and future projections

Samuel E Muñoz[1,2,*], Sylvia G Dee[3], Xinyue Luo[3], M Rezaul Haider[3], Michelle O'Donnell[2], B Parazin[1] and Jonathan W F Remo[4]

1 Department of Marine & Environmental Sciences, Northeastern University, Marine Science Center, Nahant, MA, United States of America
2 Department of Civil & Environmental Engineering, Northeastern University, Boston, MA, United States of America
3 Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX, United States of America
4 School of Earth Systems and Sustainability, Southern Illinois University, Carbondale, IL, United States of America
* Author to whom any correspondence should be addressed.

E-mail: s.munoz@northeastern.edu

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Abstract

The Mississippi River represents a major commercial waterway, and periods of anomalously low river levels disrupt riverine transport. These low-flow events occur periodically, with a recent event in the fall of 2022 slowing barge traffic and generating sharp increases in riverine transportation costs. Here we combine instrumental river gage observations from the lower Mississippi River with output from the Community Earth System Model v2 Large Ensemble (LENS2) to evaluate historical trends and future projections of Mississippi River low streamflow extremes, place the 2022 low-flow event in a broader temporal context, and assess the hydroclimatic mechanisms that mediate the occurrence of low-flows. We show that the severity and duration of low-flow events gradually decreased between 1950 and 1980 coincident with the establishment of artificial reservoirs. In the context of the last ∼70 years, the 2022 low-flow event was less severe in terms of stage or discharge minima than other low-flow events of the mid- and late-20th century. Model simulations from the LENS2 dataset show that, under a moderate-high emissions scenario (SSP3-7.0), the severity and duration of low-flow events is projected to decrease through to the end of the 21st century. Finally, we use the large sample size afforded by the LENS2 dataset to show that low-flow events on the Mississippi River are associated with cold tropical Pacific forcing (i.e. La Niña conditions), providing support for the hypothesis that the El Niño-Southern Oscillation plays a critical role in mediating Mississippi River discharge extremes. We anticipate that our findings describing the trends in and hydroclimatic mechanisms of Mississippi River low-flow occurrence will aid water resource managers to reduce the negative impacts of low water levels on riverine transport.

1. Introduction

On the world's major river systems, periods of anomalously low river discharge or stage are economically costly, and reflect the combined effects of hydrological drought, geomorphic processes, and river management practices (Smakhtim 2001). In the fall of 2022, the Mississippi River experienced one such low-flow event (figure 1(a)), where low river levels slowed barge traffic and resulted in sharp increases in downbound grain barge rates (USDA 2022, USDOT 2022). The Mississippi River and its major tributaries represent an economically critical waterway that is federally managed to facilitate navigation and mitigate flooding using a system of levees, river training structures, spillways, and dams known as the Mississippi River and Tributaries (MR&T) project (Camillo and Pearcy 2004). Despite the implementation of these management efforts in the mid-20th century, low-flow events remain disruptive and occur periodically

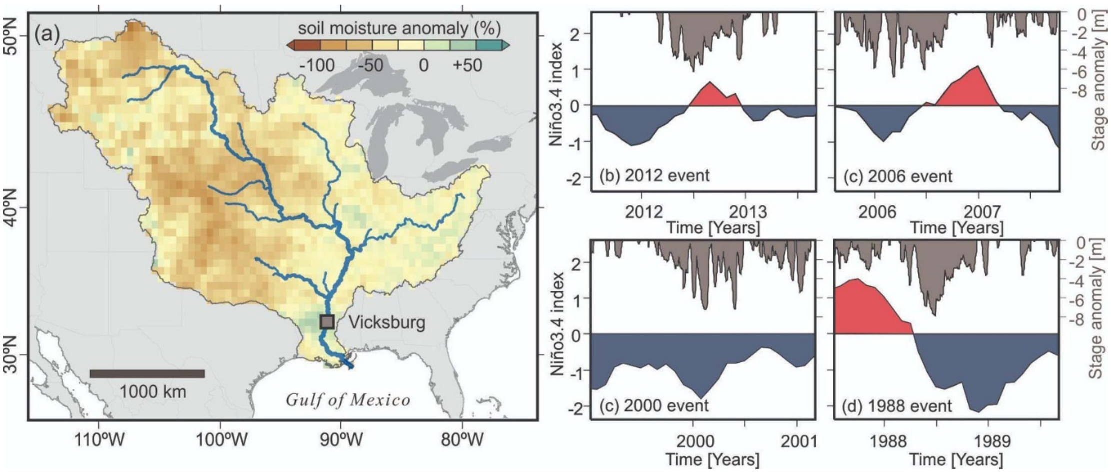

Figure 1. Recent Mississippi River low-flows in relation to soil moisture and El Niño-Southern Oscillation (ENSO): (a) Mississippi River basin soil moisture anomalies in September 2022 (Climate Prediction Center [CPC] Soil Moisture V2; Fan and van den Dool 2004) and location of Vicksburg, Mississippi stream gage; river stage anomalies in relation to Niño3.4 index during historic low-flow events in (b) 2012, (c) 2006, (d) 2000, and (e) 1988.

(Remo *et al* 2018, Turner 2022), with other notable low-flow events in 2012, 2006, 2000, and 1988 (figures 1(b)–(d)). As part of this study, we investigate how the 2022 low-flow event compares to other historical events, and assess historical trends in the severity and duration of low-flows.

In addition to management, climate variability and change also mediate the discharge of the Mississippi River and its tributaries via their influence on precipitation, soil moisture, and evapotranspiration (Mallakpour and Villarini 2016, Munoz and Dee 2017, Munoz *et al* 2018, van der Wiel *et al* 2018, Wiman *et al* 2021, Luo *et al* 2023). Interannual variations in discharge and flood hazard of the lower Mississippi River are strongly influenced by the El Niño-Southern Oscillation (ENSO), where El Niño events are associated with positive soil moisture and discharge anomalies that result in enhanced flood hazard (Chen and Kumar 2002, Munoz and Dee 2017, Muñoz *et al* 2023)—particularly during eastern Pacific El Niño events (Luo *et al* 2023). Historical low-flow events correspond to periods of anomalously low soil moisture within the Mississippi River basin and are often preceded by La Niña events (figure 1), although the small sample size associated with the observational period precludes a robust statistical assessment of how ENSO mediates the occurrence of low-discharge events (figure S1). Attribution of greenhouse forcing on Mississippi River discharge also remains difficult to evaluate due to the competing roles of climate change, land use change, and MR&T project infrastructure on regional hydrology (Pinter *et al* 2008, Remo *et al* 2009, St. George 2018, Dunne *et al* 2022), as historical and projected trends in river discharge extremes are sensitive to river engineering and emissions scenarios (Tao *et al* 2014, Munoz *et al* 2018, van der Wiel *et al* 2018, Dunne *et al* 2022). This study uses ensemble earth system model simulations to evaluate the roles of both internal climate variability and external forcing on the severity, duration, and timing of low-flows on the lower Mississippi River.

Here we combine observations from instrumental river gage records with output from an earth system model to evaluate historical trends and future projections of Mississippi River low streamflow extremes, and assess the hydroclimatic mechanisms that mediate the occurrence of low-flows. We focus our analyses on the lower Mississippi River at Vicksburg (USGS ID 07289000) after 1950 to encompass the period when contemporary river management practices and infrastructure of the MR&T project were expanded (1950–1980) and established (1980–present) (Smith and Winkley 1996, Remo *et al* 2018). We first examine trends in observed annual stage and discharge minima from 1950–2022, and then use output from the recently published Community Earth System Model version 2 (CESM2) Large Ensemble (LENS2) to examine historical and projected trends (1950–2100) in river runoff, soil moisture, and sea surface temperatures under the SSP3-7.0 future emissions scenario (Danabasoglu *et al* 2020, Rodgers *et al* 2021). The CESM2 LENS2 simulations do not simulate the influence of reservoirs or other river management infrastructure, allowing us to test hypotheses concerning the drivers of historical and projected changes in low-flows. Finally, the ensemble model simulations of sea surface temperature and soil moisture anomalies are used to evaluate the role of internal climate variability on low-flow occurrence.

2. Methods

2.1. Instrumental stream gage data

To evaluate observed trends in lower Mississippi River stages and discharge, daily stage and discharge data were compiled for water years 1950 through 2022 for the stream gage at Vicksburg, Mississippi (USGS ID 07289000). For the period 1950 through 2014, these data were obtained directly from the United States Army Corps of Engineers (USACE). Daily discharge and stage data for the period 2015 through 2022 were obtained from the United States Geological Survey (USGS) National Water Dashboard (USGS 2022) and the USACE Hydrologic Database (USACE 2022), respectively. From these daily stage and discharge data, we computed the annual mean, minima, and maxima for each water year, as well as the number of days in a water year where stages were $<$1.5 m (i.e. low-stage duration). We use the threshold of $<$1.5 m because it is consist with the low water reference (5 feet) used by the National Oceanic and Atmospheric Administration at the Vicksburg gage; the low water reference is defined as a stage low enough to cause impacts to commerce and shipping.

2.2. Reanalysis datasets

To examine historical patterns of soil moisture and sea surface temperature anomalies associated with low-flow events, we use the Extended Reconstructed Sea Surface Temperature v5 (ERSST v5; Huang *et al* 2017a) and Climate Prediction Center (CPC) Soil Moisture (Fan and van den Dool 2004) reanalysis products. We computed the Niño3.4 index in the 18 months before and after historic low-flow events in 2012, 2006, 2000, and 1988 from the ERSST dataset following Munoz and Dee (2017). We also examined the full sea surface temperature anomaly field for the month of these events as well as events in 1977, 1964, and 1954, where anomalies are computed based on the long-term climatological mean for the period 1950–2021. We also computed a composite mean sea surface temperature anomaly for all events and tested the significance of the anomalies using bootstrapping of the full ERSST dataset for the period 1950–2021 with $n = 10\,000$ iterations. We also examined soil moisture anomalies within the Mississippi River basin for the same low-flow events using a similar procedure as above, and express these anomalies as percent differences from the long-term climatological mean.

2.3. Ensemble model simulations

We employ open source, fully-coupled large ensemble numerical climate simulations from the CESM2, a state-of-the-art general circulation model developed at the National Center for Atmospheric Research (Danabasoglu *et al* 2020, Rodgers *et al* 2021). The Large Ensemble dataset of CESM2, LENS2, contains a 100-member Large Ensemble at $\sim$1° horizontal resolution for the period 1850–2014 based on historical radiative forcing, and the same number of members for the future climate (2015–2100) using the SSP3-7.0 radiative forcing scenario (Rodgers *et al* 2021). In this study, we employed the 50-member sub-ensembles based on the original CMIP6 biomass burning emissions protocol. A runoff routing model known as the Model for Scale Adaptive River Transport (MOSART), is integrated into CESM2 via the Community Land Model version 5 (Lawrence *et al* 2019), and simulates river discharge through the downslope routing of water from surface runoff, subsurface runoff, and tributaries using a horizontal spatial resolution of $\sim$0.5° although hydrography and related inputs are at higher resolution (Li *et al* 2015). Importantly, MOSART does not directly simulate the effects of reservoir operation, surface water withdrawal, groundwater pumping, and irrigation on river discharge, so we use simulated discharge to evaluate the role of climate variability and change on low-flows. River discharge simulated by MOSART reproduces the seasonality and magnitude of the Mississippi River (figure S2) as well as other large rivers reasonably well (Li *et al* 2015), and represents an improvement from the River Transport Model integrated into CESM1 used in prior work investigating the role of climate variability and change on Mississippi River streamflow (Branstetter 2001, Munoz and Dee 2017, Wiman *et al* 2021, Dunne *et al* 2022).

From the LENS2 simulations, we extracted daily river discharge (QCHANR, $m^3\ s^{-1}$), sea surface temperature (SST, K), and soil moisture (SOILLIQ, kg m^{-2}) for subsequent analysis. For QCHANR, we extracted data from the model grid cell closest to Vicksburg (32.315°N, 90.906°W). We then computed the annual minimum and mean for each simulated water year of each ensemble member, extracted the day that annual minima occurred, and calculated the ensemble mean. We also computed the 1%, 5%, and 10% lowest discharge events for each ensemble member based on a quantile analysis, and used these quantiles to calculate low-flow event duration and the relationships between low discharge events, soil moisture, and sea surface temperatures. The timing of low-flows was used to extract sea surface temperature and soil moisture patterns during and in the months prior to low-flow events; composite averages maps and time series were produced to examine these patterns.

Finally, we employed an unsupervised machine learning method known as Self Organizing Maps (SOMs) to detect shifts in the frequency of sea surface temperature patterns in the LENS2 simulations before and after low-flow events on the lower Mississippi River. The SOM method allows us to examine tropical Pacific sea surface temperature anomalies associated with low-flow events in both time and space. The SOM method preserves the underlying data structure of high-dimensional data while projecting it into two-dimensional space. Each annual sea surface temperature anomaly pattern is classified to a best-fit SOM node which minimizes the Euclidean distance between the actual year's sea surface temperature pattern and a predefined set of SOM nodes. (Kohonen 1990, Liu *et al* 2006, Johnson *et al* 2008, Yonggang and Weisberg 2011). Here we use six nodes because, based on our prior work where we conducted sensitivity analyses using different numbers of nodes (Dee and Steiger 2022, Luo *et al* 2023), we found that six nodes maximized the number of meaningful SOMs produced, while assigning fewer nodes did not fully capture observed variability in tropical Pacific sea surface temperature patterns. Sea surface temperature fields were pre-processed prior to applying the SOM algorithm by detrending (i.e. removal of the 100 year smoothed time series; Horton *et al* 2015), and area-weighting by the cosine of latitude. Finally, we perform a simple frequency analysis for each sea surface temperature pattern during low-flow years (lowest 1% and 10% discharge quantiles) and 'normal' years (25%–75% discharge quantiles). To test the significance of frequency shifts in the SOM patterns, we compute the change in the frequency of each SOM node in low-flow years relative to the frequency of this SOM node in normal years. We then draw the same number of low-flow years from normal years with a 1000-iteration bootstrap resampling and compute the frequency change of each SOM node in sampled years relative to the 'normal' years as a background reference. The departure of low-flow SOM frequency changes from the resampled distribution of normal frequency changes is then used to test whether the frequency shifts of SOM patterns in low-flow years are unusual compared to the background state. The SOM methodology avoids information loss common in composite averaging techniques (Kohonen 1990, Sheridan and Lee 2011)) and provides critical information surrounding the temporal shifts in tropical Pacific oceanic forcing during low-flow years in the LENS2 dataset.

3. Results and discussion

3.1. Historical trends of Mississippi River low-flows

The severity and duration of low-flows on the Mississippi River at Vicksburg has decreased from the mid-20th century to present (figure 2). Both annual minimum discharge (Q_{min}) and stage (H_{min}) gradually increased over water years 1950–2022, with the largest increases observed between 1950 and 1980 (figure 2(a)) during the rapid expansion of reservoirs within the Mississippi River basin (Smith and Winkley 1996, Remo *et al* 2018). Parallel trends in discharge and stage minima, as well as the ratio of annual minimum to mean discharge ($Q_{\mathrm{min}}/Q_{\mathrm{mean}}$), imply that these increases primarily reflect an increase in low-water discharge, while aggradation of the river bed around Vicksburg likely plays a secondary influence (Harmar *et al* 2005, Wang and Xu 2018). The duration of low stage events (i.e. number of days <1.5 m stage) has also declined over the period of analysis (figure 2(b)), where the duration of low-flow events in water years 1954 and 1964 exceeded 150 d, while the longest duration low-flow events of the 21st century (2006 and 2012) were less than 100 d. These observed trends in river discharge and stage are consistent across multiple gages of the lower Mississippi River and its tributaries (Turner and Song 2022) and have previously been attributed through statistical analyses of stream gage records to the establishment of reservoirs throughout the basin during the mid-20th century and geomorphic adjustment of the channel to river engineering infrastructure (Jacobson and Galat 2008, Remo *et al* 2018). The tendency for reservoirs to reduce the severity and duration of low-flows is widely observed on other regulated rivers (Smakhtin 2001, Verbunt *et al* 2005, Döll *et al* 2009, Tijdeman *et al* 2018, Brunner *et al* 2019, Brunner and Naveau 2022), and reflects the ability of dams to gradually release water stored in reservoirs downstream during hydrologic drought.

In the context of increasing annual discharge and stage minima since the mid-20th century, the low-flow event of 2022 is of moderate severity relative to other historical low-flow events (figure 2). The discharge observed at Vicksburg during the nadir of the 2022 event on 23 October (~5200 $\mathrm{m^3\ s^{-1}}$) is lower than annual minima during other recent low-flow events in 2012 and 2006 (5650 and 5858 $\mathrm{m^3\ s^{-1}}$, respectively), but not as severe as annual minima in 1988, 1964, and 1954 (3900, 3570, and 3850 $\mathrm{m^3\ s^{-1}}$, respectively) during and shortly after the rapid expansion of reservoirs (figure 2(a)). River stage minima follow a similar trajectory, where October 2022 stages are higher than annual minimum stages during other low-flow events, particularly those prior to 1980. The severity of the 2022 low-flow event relative to other historic low-flow events within our period of analysis may differ at other reaches of the Mississippi River, but the trend towards increasing magnitudes of annual discharge minima observed at multiple gages across the basin (Remo *et al* 2018, Turner and Song 2022) implies that the 2022 event is of moderate severity within this historical frame

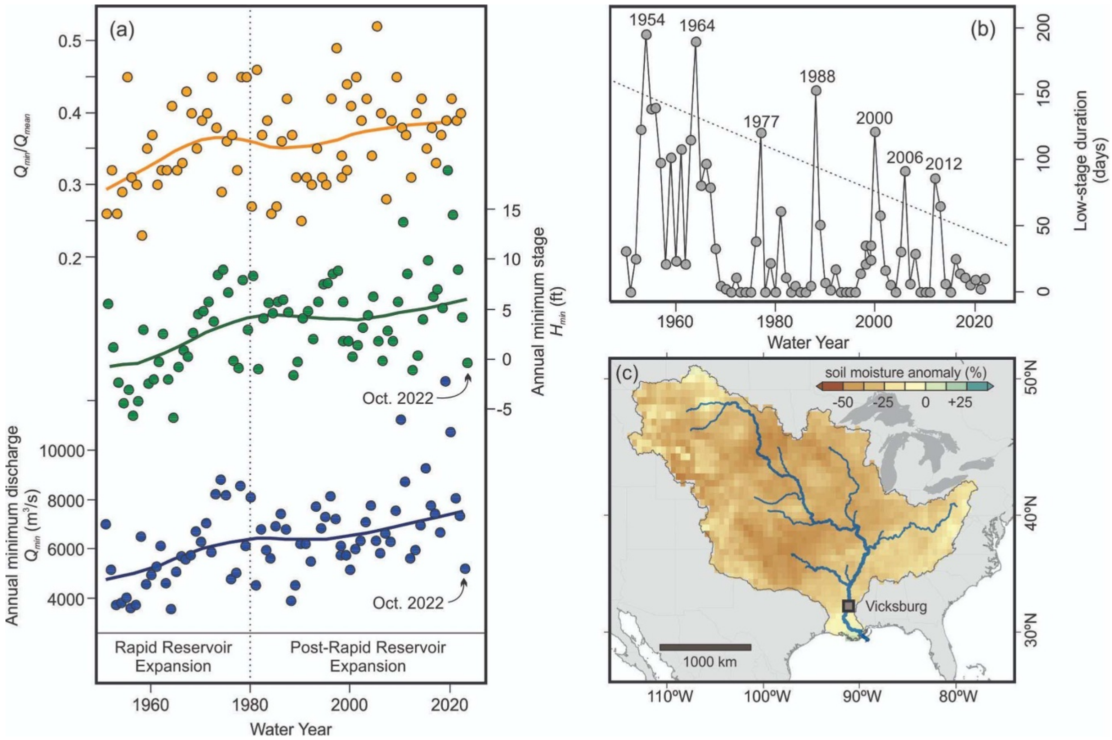

Figure 2. Historic trends in lower Mississippi River low-flows: (a) annual minimum discharge (Q_{min}; blue), annual minimum stage (H_{min}; green), and ratio of annual minimum discharge to annual mean discharge ($Q_{\mathrm{min}}/Q_{\mathrm{mean}}$) for water years 1950–2022 showing corresponding loess curve (lines) and reservoir expansion periods after Remo *et al* (2018), with daily stage and discharge values for 24 October 2022 also shown; (b) number of low-stage (<1.5 m) days in a water year for water years 1950–2022, with years of anomalously high duration noted that exceed $+1\sigma$ of a linear regression (dashed line); (c) mean soil moisture anomalies (CPC v2) for the month of minimum stage in 1954, 1964, 1977, 1988, 2000, 2006, and 2012.

of reference. The pattern of soil moisture anomalies associated with historical low-flow events (figure 2(c)) is consistent with those of the 2022 event (figure 1(a)), supporting our assertion that the historical trend towards decreasing severity of low-flow events primarily reflects management of the Mississippi River and its watershed.

3.2. Simulations of historic and projected low-flows

To isolate the influence of hydroclimatic change on lower Mississippi River discharge minima from river management practices, we examine simulations of lower Mississippi River discharge in the LENS2 dataset which uses historic and projected (SSP3-7.0 scenario) radiative forcing but does not account for the influence of reservoirs and other river engineering infrastructure on streamflow (figure 3). In the LENS2 dataset, the ensemble mean is composed of 40 individual ensemble members, and should primarily reflect the response of the discharge to external forcing because this external forcing is common across all ensemble members. Internal variability is simulated in individual ensemble members, and the ensemble mean minimizes (but does not remove) the influence of internal variability. The ensemble mean of simulated annual minima (Q_{min}) diverges from observations, declining between 1950 and 2020 before increasing abruptly through to the end of the 21st century, while the ratio of $Q_{\mathrm{min}}/Q_{\mathrm{mean}}$ is stable through the simulation until declining after 2050 (figure 3(a)). The duration of simulated low-discharge events (number of days $\leqslant$0.05 percentile) follows a similar trajectory, increasing from a mean of 16–22 d between 1950 and 2020 before declining such that low-discharge events last <10 d by the end of the 21st century (figure 3(b)). The moderate influence of historic anthropogenic forcing on Mississippi River streamflow in the LENS2 dataset is consistent with other model simulations (Tao *et al* 2014, Dunne *et al* 2022), implying that external forcing of the late 20th and early 21st century has exerted a minor influence on streamflow during this time. Thus, we assert that the divergence of simulated and observed trends during the historic period—where stream gage data document increases in annual minima between 1950 and 2020 (figure 2(a)) while simulations predict decreases in Q_{min} during this same period (figure 3(a))—primarily reflect the influence of reservoirs and other river infrastructure that are not included in the CESM2 simulations. The observed increase in Q_{min} between 1950 and 2020 (slope of linear regression = 39.77%) is well outside the range of slopes simulated in LENS2 over

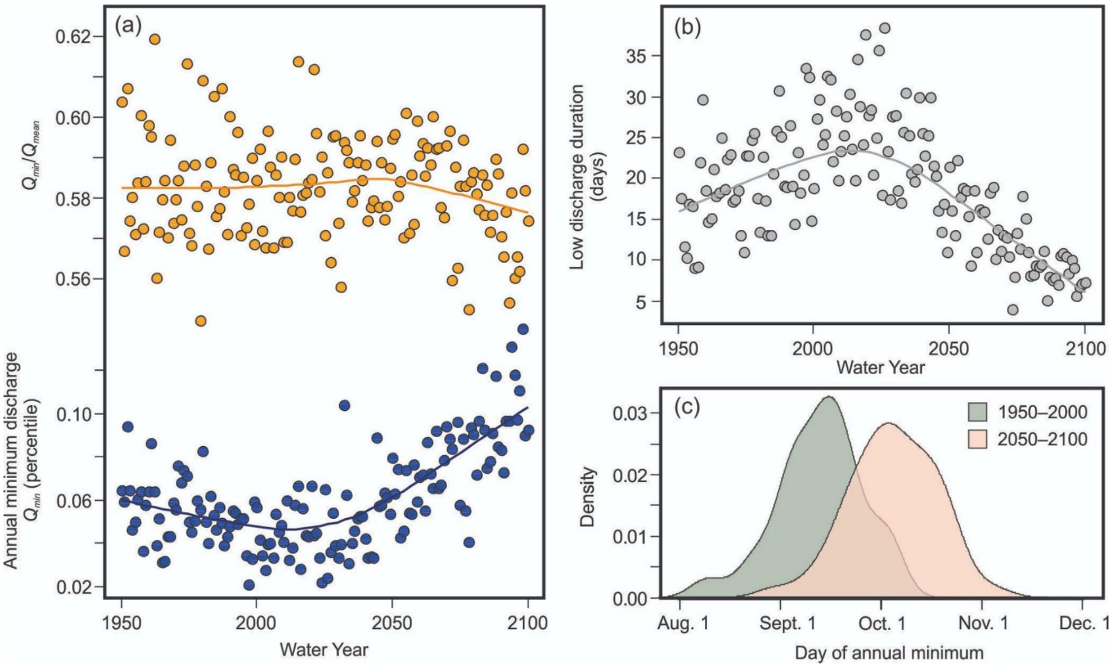

Figure 3. Simulations of historic and projected (SSP3-7.0) trends in lower Mississippi River low-flows using CESM2 large ensemble (LENS2) ensemble mean: (a) annual minimum discharge (Q_{min}; blue) as a percentile of all values in the ensemble member, and ratio of annual minimum discharge to annual mean discharge (Q_{min}/Q_{mean}) for the period 1950–2100 showing corresponding loess curves (lines); (b) number of low discharge days (lowermost 5% of daily discharge values) for the period 1950–2100; (c) timing of annual minimum for the late 20th (1950–2000) and late 21st centuries (2050–2100).

the same time period ($\bar{x} = -4.89\%$, $\sigma = 11.77\%$), implying that observed trends are also not primarily driven by internal variability (figure S3). Our approach, comparing trends in the ensemble mean of simulations without reservoirs to trends observed in stream gage data, provides support to the hypothesis that reservoirs play a critical role in regulating Mississippi River streamflow to reduce the severity of low-flow events.

Projections of Mississippi River discharge under a high emissions scenario show that the severity, duration, and seasonality of low-flows shifts during the mid- and late-21st century (figure 3). Between 2050 and 2100, the ensemble mean of annual minima increases by ∼60% while the ratio of annual minimum to mean discharge (Q_{min}/Q_{mean}) decreases as a result of larger increases in mean and peak annual flows (Dunne *et al* 2022; figure 3(a)). The duration of low-flow events mirrors these trends, with a ∼70% decline in the number of low-flow days between 2050 and 2100 (figure 3(b)). The timing of low-flows also shifts ∼20 d later in the year between the late-20th and late-21st centuries, such that simulated annual minima from 1950–2000 occur between 28 August–1 October (0.1 and 0.9 percentiles; median = 14 September) but shift to 19 September–20 October (median = 4 October) between by 2050–2100 (figure 3(c)). A projected shift towards higher, shorter, and later low-flows under a high emissions scenario harbors important implications for the economic consequences of low-flow events, reducing their impact on shipping by alleviating their severity and shifting them further from fall harvest of row crops currently planted in the midwestern United States. We caution that although the trends in discharge we observe in the CESM2 LENS2 simulations are broadly consistent with other model projections (Tao *et al* 2014, Lewis *et al* 2019, Dunne *et al* 2022), simulations of Mississippi River discharge are sensitive to the model and emissions scenario used, and do not include the influence of river management practices or the geomorphic adjustments that arise from those management practices.

3.3. Hydroclimatic mechanisms of low-flows

The relatively small number of observed low-flow events since the mid-20th century, together with the confounding influence of reservoir operations, limit the statistical power of the observational record to assess the influence of ENSO on low-flow events (figure 1). However, the LENS2 simulations produced by CESM2—which reproduces hydroclimatic teleconnections associated with ENSO reasonably well (Capotondi *et al* 2020, Danabasoglu *et al* 2020)—bolsters the sample size, and allows us to extend prior work analyzing the role of ENSO-related variability on Mississippi River discharge (Twine *et al* 2005, Liang *et al*

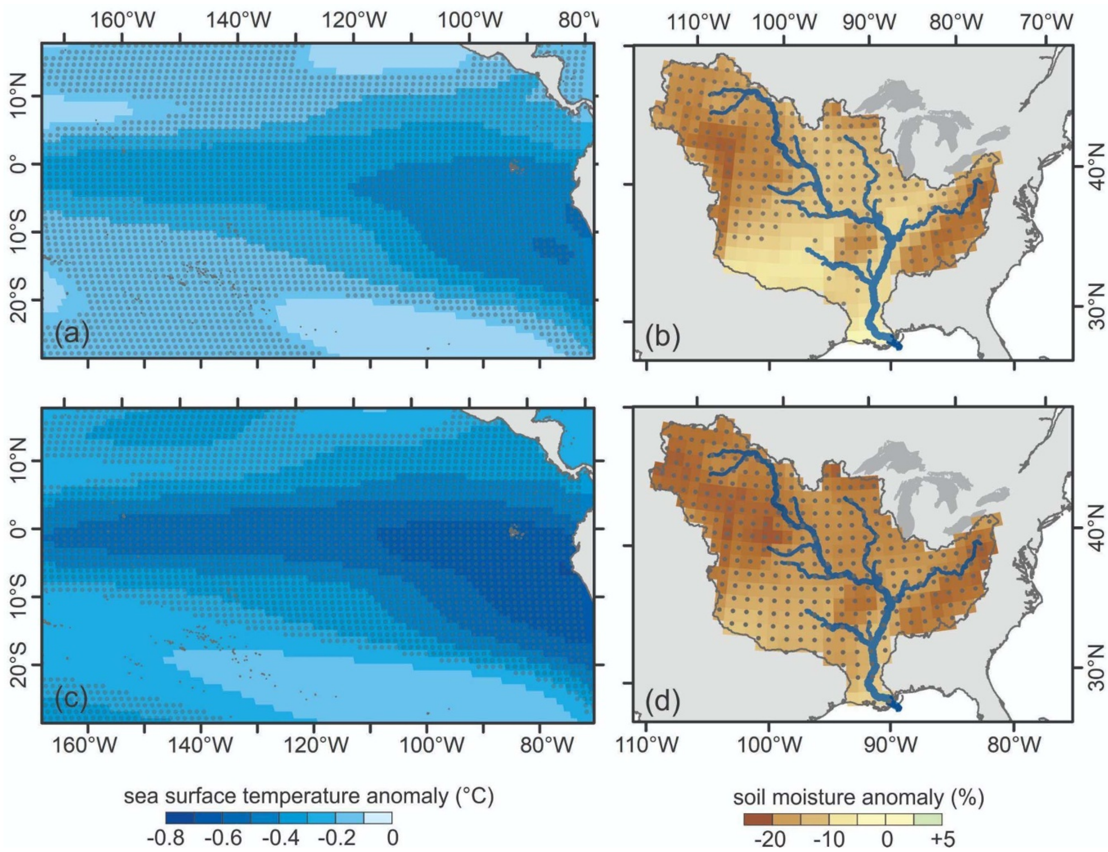

Figure 4. Simulations from CESM2 large ensemble (LENS2) for the period 1930–2100 of (a) sea surface temperature anomalies and (b) soil moisture anomalies, expressed as a percent difference of the interquartile range, of the water year associated with the lowest 1% of discharge events ($n = 90$), and (c) sea surface temperature anomalies and (d) soil moisture anomalies of the water year associated with the lowest 10% of discharge events ($n = 900$) on the lower Mississippi River at Vicksburg. Stippling shows significance of the anomalies via bootstrapping at the 95% level.

2014, Munoz and Dee 2017, Munoz *et al* 2023, Luo *et al* 2023) to evaluate the correspondence of La Niña events to low-flow events.

We use the LENS2 simulations to examine the role of tropical Pacific sea surface temperature and soil moisture anomalies in low-flow events over the period 1930–2100, and find support for the hypothesis that the ENSO modulates soil moisture and lower Mississippi River discharge (figure 4). In the year of the lowest simulated discharge events ($\leqslant$1%; $n = 90$ years), the composite mean of sea surface temperature anomalies in the eastern equatorial Pacific are -0.6 °C to -0.4 °C (figure 4(a)), and strongly resembles the cold tongue characteristic of La Niña events (Philander 1985). Simulated low-flow extremes also coincide with negative soil moisture anomalies across the Mississippi River basin (figure 4(b)). Similar and more pronounced patterns emerge for sea surface temperature (figure 4(c)) and soil moisture anomalies (figure 4(d)) for the lower 10% of simulated discharge events ($\leqslant$10%; $n = 900$ years). The influence of ENSO on soil moisture and streamflow within the Mississippi River basin is documented in observations, reanalysis, and model simulations including CESM (Munoz and Dee 2017, Munoz *et al* 2018, Luo *et al* 2023), where La Niña conditions result in the poleward displacement of the polar jet and reduce precipitation and soil moisture across the lower Mississippi River valley and its western tributaries including the Arkansas and Missouri Rivers (Ropelewski and Halpert 1986, Hoerling and Kumar 1997, Twine *et al* 2005, Luo *et al* 2023). We include both the historical and projected simulations in this analysis to increase sample size, but this is sensitive to both internal climate variability and longer-term climate change.

To further examine the influence of tropical Pacific sea surface temperature patterns on Mississippi River low-flow events, we applied SOMs to the CESM2 LENS2 dataset (figure 5). Our analysis, based on labeling each year's sea surface temperature field to one of six SOM map nodes of closest resemblance, shows that the lowest 10% of simulated discharges are associated with SOM 1 (figure 5(a)) and SOM 2 (figure 5(b)) which feature negative sea surface temperature anomalies across the eastern equatorial Pacific that closely resemble La Niña conditions (Philander 1985). In contrast, warmer sea surface temperatures across this region are

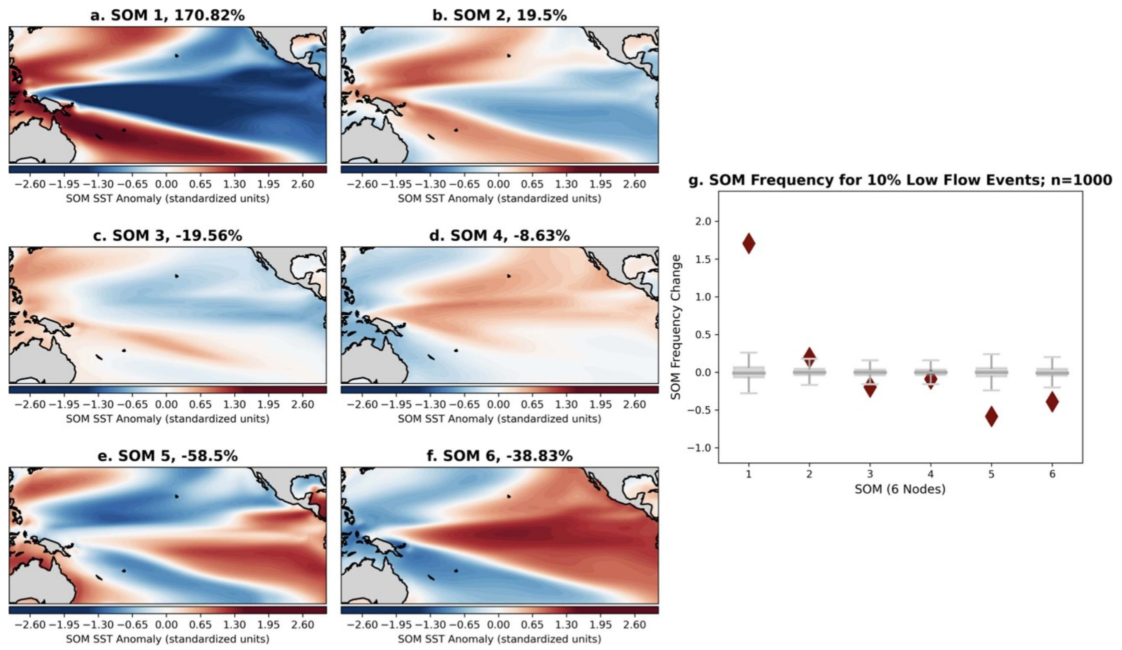

Figure 5. Self organizing map (SOM) and frequency analysis for the lowest 10% flow years on the lower Mississippi River in the CESM2 LENS2 dataset with: (a) through (f) showing SOM node spatial patterns 1 through 6 of SST anomalies in standardized units, with panel label indicating the percent change in the frequency of that node during low-flow years relative to its frequency in normal years (25%–75%); (g) the change in SOM node frequencies during the 10% lowest flow years ($n = 900$ years), where frequency changes of SOM nodes in low-flow events are shown as red diamonds and gray box-plot show background event frequency changes established via resampling with $n = 1000$ iterations in normal years.

shown in SOM 5 (figure 5(e)) and SOM 6 (figure 5(f)), and the frequencies of these El Niño-like conditions decrease during Mississippi River low-flows (figure 5(g)). An additional test examining only the lowest 1% flow years confirms these results, where the frequency of SOM1 increases by 381%, indicating a strong increase in the frequency of tropical Pacific cooling during the lowest-flow years (figure S4). We also examine how the frequency of the SOMs for the lowest 10% of events differ against a resampling of the background in all years, and show that the frequency of strong equatorial Pacific cooling associated with SOM 1 is significantly greater, while El Niño conditions associated with SOMs 5 and 6 are significantly less frequent, during low-flow extremes (figure 5(g)). Taken together, the coupled composite SST and soil moisture anomaly maps for low-flow events (figure 4) are consistent with shifts in the frequency of SOMs associated with these same events (figure 5). These analyses provide strong support for tropical Pacific modulation of low-flow events on the lower Mississippi River.

The projected decrease in low-flow severity and duration in the LENS2 simulations (figure 3) is consistent with projections of sea surface temperature warming in the central and eastern tropical Pacific simulated by coupled climate models in the 21st century (e.g. Collins *et al* 2010, Xie *et al* 2010, Stevenson 2012, Cai *et al* 2015, Zheng *et al* 2016, Arias *et al* 2021). The CESM2 LENS2 simulations are no exception, and show pronounced sea surface temperature warming across the tropical Pacific during the 21st century (figure S5). These projected changes in mean sea surface temperatures (i.e. warmer tropical Pacific background state), or changes to the variability of ENSO, likely plays a role in modulating the severity and duration of low-flow events on the lower Mississippi River, and provides an example of how changes in mean ocean state may alter streamflow of a major river system.

We acknowledge important caveats in our use of the CESM2 LENS2 dataset to evaluate the role of tropical Pacific sea surface temperatures on lower Mississippi River discharge. First, we rely on a single model (CESM2) albeit with a large ensemble of 50 ensemble members. Biases in the model's representation of tropical Pacific sea surface temperature and air-sea fluxes are well documented, and indicate that ENSO variance in CESM2 is exaggerated relative to observations (Capotondi *et al* 2020, Chen *et al* 2021). Teleconnections linking tropical Pacific sea surface temperature forcing to North American precipitation may be too strong in CESM2, partially biasing our results with respect to spatial patterns in soil moisture anomalies. Our use of SOMs, however, which rely solely on the frequency of sea surface temperature patterns in relation to low-flow events, provide evidence consistent with observations (figure 1) and simulated anomalies (figure 4) that supports a broader hypothesis placing importance of ENSO variability on Mississippi River discharge.

4. Conclusions

Given recent disruptions to riverine transportation on the Mississippi River as a result of low river levels, here we combined observational and simulated datasets to investigate: (i) historical trends in low-flows, (ii) projected trends in low-flows under a moderate-high emissions scenario (SSP3-7.0), and (iii) the role of climate variability, namely ENSO, on low-flow occurrence. Stream gage records from the Mississippi River at Vicksburg show that low-flows, measured in terms of minimum annual stage, minimum annual discharge, and duration of low-stages, have gradually become less severe since 1950, with the largest change between 1950 and 1980 coinciding with the establishment of upstream reservoirs (figure 2). In this context, the 2022 low-flow event was less severe than several annual discharge and stage minima of the mid- and late-20th century. We then use earth system model simulations from the CESM2-LENS2 dataset to evaluate the response of Mississippi River low-flows to historic and projected changes in climate, and show that low-flows are projected to become less severe in terms of discharge and duration through to the end of the 21st century (figure 3). Finally, we extend prior work examining the role of the ENSO on Mississippi River streamflow to show that La Niña conditions are strongly associated with low-flow events (figure 4).

Our findings provide broader context for the 2022 Mississippi River low-flow event, and support the hypothesis that water resources management—particularly the expansion of artificial reservoirs and the MR&T system during the mid-20th century—exert a strong influence on the severity of low-flows on a major commercial waterway. Further, we clarify how climate change (i.e. anthropogenic forcing) and a dominant mode of climate variability (ENSO) influence the properties and probability of Mississippi River low-flows. Our work implies that La Niña conditions increase the likelihood of low-flows on the lower Mississippi River. Given advances in the seasonal predictability of ENSO (Wu *et al* 2021), we anticipate these findings will aid reservoir operations to reduce the negative impacts of low river levels on river transport.

Data availability statement

No new data were created or analyzed in this study.

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ORCID iDs

Samuel E Muñoz https://orcid.org/0000-0002-0994-0483
Sylvia G Dee https://orcid.org/0000-0002-2140-785X

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