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Understanding the low-frequency variability in hydroclimatic attributes over the southeastern US

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SUMMARY

Most studies on evaluating the potential in developing seasonal to interannual hydroclimatic forecasts have focused on associating low-frequency climatic conditions with basin-level precipitation/streamflow. The motivation of this study is to provide an understanding on how land surface characteristics modulate the low-frequency (interannual to decadal) variability in precipitation to develop low-frequency signal in streamflow. For this purpose, we consider basins with minimum anthropogenic impacts over southeastern United States and apply Singular Spectrum Analysis (SSA), a data-driven spectrum analysis tool, on annual precipitation and streamflow time series for detecting the dominant frequencies and for estimating the associated variability with them. Hypothesis test against an AR(1) process is carried out via Monte Carlo SSA for detecting significant (at 90% confidence level) low-frequency oscillations. Thus, the study investigates how the observed low-frequency oscillations in precipitation/streamflow vary over the southeastern United States and also their associations with climatic conditions. For most study basins, precipitation exhibits higher low-frequency oscillations than that of streamflow primarily due to reduction in variability by basin storage. Investigating this further, we found that the percentage variance accounted by low-frequency oscillations in streamflow being higher for larger basins which primarily indicates the increased role of climate and basin storage. To develop a fundamental understanding on how basin storage controls the low-frequency oscillations in streamflow, a simple annual hydrological model is employed to explore how the given low-frequency signal in precipitation being modified under different baseflow index conditions and groundwater residence time. Implications of these analyses relating to streamflow predictions and model calibration are also discussed.

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1. Introduction

Detection and attribution of low-frequency oscillations in hydroclimatic data are of importance to understanding climate variability and their implications on water management. Understanding the association between low-frequency sea surface temperature (SST) conditions and local/regional hydroclimatology could also provide useful information for improving decadal hydroclimatic prediction. Contrary to the centenary-long span of typical climate projections, decadal climate predictions over the next 10–30 years have been gaining attention due to the interest in their relevance to supporting infrastructure planning and decision making. Meehl et al. (2009) discussed the challenges in decadal climate projections and suggested that reliable projections of climatic conditions such as El-Nino Southern Oscillations (ENSO) over the near-term (10–30 years) could significantly improve decadal climate projections. But, hydroclimatic variability at interannual to decadal time scales could be influenced by changing climatic signals as well as by land-surface characteristics. In this study, we investigate the role of basin storage in modulating the low-frequency variability in streamflow over the Southeast US (SEUS).

It is well documented in the hydroclimatic literature that climatic teleconnections such as ENSO influence regional precipitation and streamflow. Peel et al. (2002) investigated the variability of annual precipitation and its relation to El Niño-Southern Oscillation (ENSO) on global scale and concluded that the annual precipitation variability in ENSO-influenced continent is higher compared to continents that are not influenced by ENSO. Zeng (1999) studied the hydrological cycle in the Amazon basin and found that on interannual timescales the hydrologic variability in the atmosphere and at the land surface is closely related to ENSO. Westra and Sharma (2006) examined the relationship between

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ENSO and annual precipitation for 216 stations over Australia and found significant correlation between the two attributes over eastern Australia. Tootle et al. (2005) investigated the coupled oceanic–atmospheric variability and US streamflow. Their results show that in addition to the well-established ENSO signal the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) and North Atlantic Oscillation (NAO) influence streamflow variability in the United States. Almanaseer and Sankarsubramanian (2012) also show that ENSO influences precipitation, temperature, streamflow and groundwater during the winter season over the Southeast US. Milly and Wetherald (2002) carried a theoretical study to investigate the effect of the land process on the runoff variability and found that groundwater and surface water storage could cause a strong reduction in low-frequency variability in many basins. Shun and Duffy (1999) detected and analyzed low-frequency oscillations in precipitation, temperature and runoff for a mountain watershed in Utah and concluded that low-frequency oscillation in streamflow could be introduced by groundwater storage alone even if precipitation does not exhibit any oscillatory behavior.

Most of the above studies could be grouped into two categories: (a) dependency analyses between ENSO index and the hydroclimatic attributes using correlation or similar measures (Peel et al., 2002; Tootle et al., 2005; Almanaseer and Sankarsubramanian, 2012), and (b) spectral analyses on streamflow for identifying low-frequency components (Shun and Duffy, 1999; Milly and Wetherald, 2002). This study, on the other hand, performs detailed spectral analyses using Singular Spectrum Analyses (SSA) both for identifying the periodic components on the hydroclimatic attributes – precipitation and streamflow – and for quantifying and comparing the percentage variance explained by the interannual and interdecadal components in the hydroclimatic attributes. By comparing the percentage variance explained by low frequency components in streamflow and precipitation, we quantify the role of land surface storage in modulating/enhancing the low-frequency components in precipitation. Further, the study also explores how land-surface storage itself alone could modulate/enhance low-frequency variability in streamflow in the absence/presence of low-frequency components in the forcings – precipitation and potential evapotranspiration – using a conceptual water balance model.

The main intent of this paper was to: (1) systematically decompose the observed hydroclimatic variability based on long time series of precipitation and streamflow into low-frequency components at interannual and interdecadal time scales; and (2) to understand how those components are modulated due to storage and basin characteristics over the SEUS. Given the significant correlation between El Niño-Southern Oscillation (ENSO) and precipitation variability over the SEUS (Ropelewski and Halpert, 1987; Almanaseer and Sankarsubramanian, 2012), it is natural to expect similar low-frequency oscillatory components in streamflow over many watersheds in the region. However, streamflow variability does not depend only on the local precipitation variability and exogenous climatic variability (e.g., ENSO), but also on the basin storage and watershed characteristics. For this purpose, we have assembled long time series of precipitation and streamflow over these 56 basins in the SEUS (Table 1). There are different approaches for frequency analysis, e.g., Multi-taper spectral analysis (Lall and Mann, 1995; Mann et al., 1995; Rajagopalan et al., 1998), wavelet analysis (Sang, 2013) and Singular Spectrum Analysis (SSA). We employ a data driven approach, Singular Spectrum Analysis (SSA) to detect the low-frequency oscillations in precipitation and streamflow. There are three advantages of SSA: (1) it is data driven in the sense that one does not have to assume its data structure; (2) its simplicity for use; and (3) its robustness in separating noise from low-frequency signals by employing Monte Carlo SSA, which is discussed in the methodology section. We further compare the variability explained by the respective components in each variable to explain the role of land-surface storage in modulating/introducing low-frequency components in streamflow for the selected watersheds over the SEUS.

The paper is organized as follows: Section 2 provides a brief description of data set and the SSA methodology. Results from the SSA and the diagnostic analyses using a conceptual water

Table 1
Basin drainage area and data length of precipitation and streamflow time series of the 56 selected basins over SEUS in this study.

Station ID	USGS gage (starting year)	Area (Km^2)	Station ID	USGS gage (starting year)	Area (Km^2)
1	02045500(1931)	579	29	02296750(1932)	1367
2	02051500(1930)	552	30	02298830(1937)	229
3	02061500(1938)	320	31	02301500(1933)	335
4	02070000(1937)	108	32	02313000(1932)	1825
5	02074500(1930)	112	33	02314500(1938)	1260
6	02083000(1927)	526	34	02317500(1933)	1400
7	02083500(1932)	2183	35	02320500(1932)	7880
8	02085500(1926)	149	36	02321500(1932)	575
9	02102000(1931)	1434	37	02322500(1933)	1017
10	02126000(1930)	1372	38	02329000(1927)	1140
11	02132000(1930)	1030	39	02347500(1938)	1850
12	02134500(1930)	1228	40	02349500(1931)	2900
13	02136000(1930)	1252	41	02358000(1929)	17200
14	02138500(1923)	66.7	42	02361000(1936)	686
15	02154500(1931)	116	43	02369000(1939)	474
16	02156500(1939)	2790	44	02371500(1938)	500
17	02198000(1938)	646	45	02374500(1938)	176
18	02202500(1938)	2650	46	02375500(1935)	3817
19	02203000(1938)	555	47	02387500(1894)	1602
20	02225500(1938)	1110	48	02392000(1937)	613
21	02226000(1932)	13600	49	02398000(1938)	192
22	02226500(1938)	1200	50	02448000(1939)	768
23	02228000(1931)	2790	51	02450000(1929)	365
24	02231000(1927)	700	52	02467000(1929)	15385
25	02232500(1934)	1539	53	02472500(1939)	304
26	02236000(1934)	3066	54	02475500(1939)	369
27	02246000(1932)	177	55	02479000(1931)	6590
28	02256500(1932)	311	56	02488500(1939)	4993

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