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#### **Key Points:**

- On the basin scale, only a significant wetting trend in dry season (November–May) precipitation was detected during the period 1952–2015
- Dominant patterns of annual and seasonal precipitation were found across the Lancang-Mekong River Basin (LMRB)
- South Asian Summer Monsoon Index, Southern Oscillation Index, and Indian Summer Monsoon Index strongly influenced precipitation variability

#### **Supporting Information:**

- Supporting Information S1
- Supporting Information S2

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# Influential Climate Teleconnections for Spatiotemporal Precipitation Variability in the Lancang-Mekong River Basin From 1952 to 2015

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Abstract The Lancang-Mekong River Basin (LMRB) in Mainland Southeast Asia is home to ~70 million people, mostly living in poverty and typically working in primary freshwater-related sectors, particularly agriculture and fishery. Understanding the mechanisms of the historical variability in precipitation (as the crucial water source) plays a key role in regional sustainable development throughout the LMRB. Herein, the spatiotemporal variability in interannual and intra-annual precipitation over the LMRB was analyzed using the Global Precipitation Climatology Centre (GPCC) data for the period 1952-2015. The empirical orthogonal function (EOF) and wavelet transform coherence methods were utilized to investigate the relationships of such historical variations in annual (water year: November-October), dry season (November-May), and wet season (June-October) precipitation with 13 different climate teleconnections (eight large-scale oceanic-atmospheric circulation patterns and five summer monsoons). On the basin scale, only a significant (p < 0.05) wetting trend in the dry season precipitation (DSP) was uncovered. Spatially, significant wetting (drying) trends in annual precipitation detected over the northeastern (most western) parts of the Mekong River Basin during the water years 1952-2015, largely contributed by the substantial increases (decreases) in historical wet season precipitation. The most important precipitation pattern (EOF1) was identified as a strong (relatively weak) positive center in the eastern (southwestern) Mekong River Basin accompanying by a significantly high (relatively low) positive value for the first EOF mode of the dry season precipitation (wet season precipitation). Precipitation variability in the LMRB was significantly associated with the South Asian Summer Monsoon Index, Southern Oscillation Index, and Indian Summer Monsoon Index.

# 1. Introduction

The global average surface air temperature exhibited a significant warming trend during the 20th century, with acceleration after 1975 (IPCC, 2013), primarily in response to the substantial increases in the anthropogenic concentrations of greenhouse gas emissions to the Earth's atmosphere (Scheffer et al., 2006; Zahn, 2009). In recent decades, sea surface temperature (SST) has also increased, mainly due to the intensive and extensive rise of atmospheric  $CO_2$  concentration around the world (Iz, 2018). These warmer air and sea temperatures have fundamentally caused considerable increases in the atmospheric moisture content (e.g., Mishra et al., 2012), leading to significant changes in the global climate system (e.g., Flato et al., 2013; Zahn, 2009). Such an indisputable, ongoing climate change has already influenced water resources by prominently altering hydrological cycle components, particularly precipitation and evapotranspiration (e.g., Berghuijs et al., 2017; Immerzeel et al., 2012; IPCC, 2013). Analysis of the spatiotemporal variability and trends of these components, as factors controlling water resource availability, has been one of the important research topics for studies focusing on climatic and environmental changes on both regional and global scales (e.g., Barros et al., 2014; IPCC, 2014).

Precipitation is the most basic link between atmospheric (e.g., evaporation and cloud) and land-surface (e.g., soil moisture and infiltration) hydrological processes in the water cycle mechanism (e.g., Andersson et al., 2005). It is also considered to be one of the key hydrometeorological variables for detecting regional climatic changes around the world (e.g., Barros et al., 2014; Cannarozzo et al., 2006; Du et al., 2019; McVicar et al., 2007). Although precipitation has significantly decreased and increased over the low and high latitudes in recent decades, respectively (Barros et al., 2014), changes in the global precipitation pattern have



still been inconsistent and inconclusive (IPCC, 2014; Wang et al., 2018). Actually, global warming has considerably increased both saturated vapor pressure and warm air moisture content, thereby already altering regional precipitation variability (e.g., Bengtsson, 2010) and consequently water resource availability (e.g., Barros et al., 2014; IPCC, 2014). This has positively and/or negatively influenced the economy (e.g., industrial and agricultural production), environment (e.g., soil erosion and chemical leaching intensification), and society (e.g., health hazards and human fatalities) in different parts of the world (Guhathakurta et al., 2011; Pall et al., 2011; Rajeevan et al., 2008), specifically in developing countries due to their vulnerable infrastructures, high human population density, and poor land-use and development practices (Liu et al., 2017; Mirza, 2003; Yin et al., 2011). Since precipitation predominantly contributes to the freshwater requirements for human activities, it plays a critical role in the sustainable development of both life and livelihoods worldwide (Bates et al., 2008; Todd et al., 2011).

Located in Mainland Southeast Asia, the Lancang-Mekong River Basin (LMRB) is home to approximately 70 million people from the six countries of China, Laos, Myanmar, Cambodia, Thailand, and Vietnam (MRC, 2010). The residents are generally (~40%) poor (Dugan et al., 2010; Hortle, 2007; MRC, 2010) and dependent upon the ecosystem services provided by the LM River, (Pech & Sunada, 2008; Ziv et al., 2012). As the predominant freshwater source for this river, precipitation is vital for the sustainable development of such inhabitants in the LMRB (Chi et al., 2016; Choi et al., 2018; Gu et al., 2017; Ziv et al., 2012). Owing to the changes in hydrological processes induced by the climate warming impacts on regional precipitation patterns (Hasson et al., 2016; Hoang et al., 2016; IPCC, 2013), water-related hazards (particularly floods and droughts) have also increased throughout the LMRB during the last few decades (MRC, 2010; Pokhrel et al., 2018; Räsänen et al., 2012). Indeed, both water abundance and shortage can greatly threaten individuals living on the margins of economic development in the LMRB (Delgado et al., 2010; MRC, 2015; Phi Hoang et al., 2016), particularly a large proportion of the population working in the primary freshwater-related sectors of agriculture, forestry, and fishery. Thus, the spatiotemporal analysis of precipitation variability and trends throughout the LMRB can guide its riparian countries toward achieving the sustainable development goals (SDGs) adopted by the United Nations in 2015 (UN, 2015).

In addition to detecting changes in regional precipitation patterns, it is important to investigate their possible underlying complex causal and physical mechanisms. In general, natural and human activities influence regional climate variability and change (Angélil et al., 2017; Mukherjee et al., 2018; Ren & Zhou, 2014). Although the LMRB is a large area with the relatively high population density of 88 people per km<sup>2</sup> (FAO, 2011; Pech & Sunada, 2008), both interannual and intra-annual precipitation variations throughout this basin exhibit significant relationships with large-scale oceanic-atmospheric circulation patterns (e.g., A. Chen et al., 2019; Delgado et al., 2012; Juneng & Tangang, 2005; O'Gorman & Schneider, 2009; Räsänen et al., 2016) and summer monsoons (e.g., Delgado et al., 2012; MRC, 2010). The strength and influence of these patterns and monsoons over a particular region during a particular period of the year are generally expressed by climate teleconnection indices (hereafter, teleconnections); for example, the Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO). Previous studies, however, have only focused on the relationships of precipitation variability in the LMRB with a few of these teleconnections, particularly the SOI and Indian Summer Monsoon Index (ISMI).

This study attempted to identify influential teleconnections for the spatiotemporal variability and trends in interannual and intra-annual precipitation throughout the LMRB in recent decades. The specific objectives were to (1) determine spatiotemporal changes in annual (water year: from November to the following October) as well as in dry season (November–May) and wet season (June–October) precipitation in the LMRB from 1952–2015; (2) identify the dominant patterns of regional precipitation variability over time, applying the empirical orthogonal function (EOF) method; and (3) explore and analyze the relationships of historical precipitation variability across the LMRB with teleconnections, employing wavelet transform coherence and Spearman's rank correlation.

# 2. Materials and Methods

# 2.1. Study Area Overview

The Lancang-Mekong River (LMR) is geographically located in Mainland Southeast Asia (Figure 1a), with an elevation ranging from 0 to 5,730 m above the mean sea level (Figure 1b). It is the world's (i) 8th largest river





**Figure 1.** Lancang-Mekong River Basin (LMRB): (a) location, (b) digital elevation model (DEM) or elevation, (c) upper section (Lancang River Basin, LRB), and (d) lower section (Mekong River Basin, MRB); (e) temporal variations in the number of precipitation measurement stations used to calculate the GPCC monthly gridded data set throughout the LMRB during January 1951 to December 2015.

in terms of discharge, with an average outflow of 15,000  $m^3/s$ ; (ii) 12th longest, ranging from 4,200 to 4,909 km due to differences in measurement methods and time periods; and (iii) 21st largest in basin area (795,000 km<sup>2</sup>) (Gupta et al., 2002; Jacobs, 2002; MRC, 2010). The LMR originates from the Tibetan Plateau in China and flows through Myanmar, Laos, Thailand, and Cambodia before entering the Mekong Delta in Vietnam, ultimately releasing into the South China Sea (Figure 1a). Shared by all of the six aforementioned countries, the LMRB is one of the most complex transboundary water drainage systems worldwide.

At Chiang Saen in Thailand, which is the nearest measurement station of river discharge to the Chinese border (Figure 1a), the LMRB is divided into the upper (Lancang River Basin or LRB) (Figure 1c) and lower (Mekong River Basin or MRB) sections (Figure 1d). Over the ~2,000-km length of the LRB (from the headwaters to the Chiang Saen station), the elevation falls sharply (2 m/km) from 4,500 to ~500 m (MRC, 2005). In the MRB, however, the elevation experiences a moderately steep slope of 0.25 m/km over a distance of 2,000 km from the Chiang Saen to Kratie discharge measurement stations, that is, from about 500 m to only a few tens of meters (MRC, 2005). With a slight slope of 0.03 m/km, the river bed is almost flat downstream from Kratie on the Mekong Delta to the South China Sea, a length of ~600 km (MRC, 2005). Accordingly, the LMRB area is shared between (i) the LRB (24%), including contributions from both China (21%) and Myanmar (3%), and (ii) the MRB (76%), consisting of contributions from Laos (25%), Thailand (23%), Cambodia (20%), and Vietnam (8%) (MRC, 2005).

In the LMRB, precipitation is basically influenced by the El Niño-Southern Oscillation (ENSO), the East Asian Monsoon (EAM), the Indian Summer Monsoon (ISM), and tropical cyclones (TCs) (A. Chen, Ho, et al., 2019; Delgado et al., 2012; MRC, 2010). Interannual precipitation variability across the LMRB is principally associated with the ENSO, which also regulates the variability in the Asian monsoon, including the



ISM and the Western North Pacific Monsoon (WNPM) (Räsänen & Kummu, 2013; Ward et al., 2010). Hence, the ISM conveys a substantial water vapor content from the Indian Ocean to the southwestern and partially the southeastern LMRB during the wet season (June–October), contributing approximately 70% of the annual precipitation. Influencing extreme precipitation events during the wet season, particularly the last 3 months (August–October), TCs also contribute to annual precipitation over the LMRB (A. Chen, Ho, et al., 2019). The EAM, however, covers the LMRB with a high-pressure system during the dry season (November–May). Accordingly, the long-term (1981–2010) average values for annual precipitation typically increase from the northwestern LRB (464 mm) to the eastern and southeastern MRB (4,300 mm). However, temperatures are persistently warm across the MRB, with some moderation throughout the LRB associated with higher elevations (Lutz et al., 2014). Thus, the lowest and highest annual mean temperature were –4.8°C in the most upper part of northern LRB and 29.0°C in the southwest of MRB, respectively, during the period 1981–2010 (Lutz et al., 2014).

#### 2.2. Data Description

Sparsely and unevenly distributed measurement stations restrict monitoring the spatiotemporal precipitation variability across the LMRB (Wang et al., 2016). Such precipitation records are also discontinuous, short term, uncertain, and not even readily available mainly as a result of the various transboundary conflicts among all of the riparian countries concerning the exploitation of available freshwater resources in the LMRB (Lutz et al., 2014; Villafuerte & Matsumoto, 2015). Previous studies have already confirmed the functionality of gauge-based gridded precipitation data sets in assessing precipitation variability and changes in Southeast Asia (Sun et al., 2018; Villafuerte & Matsumoto, 2015; Yatagai et al., 2009, 2012), particularly in the LMRB (Chen et al., 2018; Lutz et al., 2014; Ono et al., 2013). Hence, this study extracted high-resolution ( $0.25^{\circ} \times 0.25^{\circ}$ ), gauge-based, gridded monthly precipitation time series over the LMRB for the period 1951–2015 from the Global Precipitation Climatology Centre (GPCC) product (Becker et al., 2013; Rudolf et al., 2009; Schneider et al., 2014). The GPCC covers a period of over 200 years and includes data from more than 85,000 stations around the world. In total, precisely 65,335 stations passed the minimum limit of 10 uninterrupted years for each of the 12 months of the year. The best- and worst-covered months in the GPCC data set are June and December, respectively, including precisely 67,298 and 67,149 stations worldwide. Hence, the GPCC product has commonly been used as "reference data" for assessing the reliability of other gauge-based, reanalysis, and satellite-related precipitation data sets on both regional and global scales (e.g., Sun et al., 2018). Figure 1e represents temporal variations in the number of precipitation measurement stations used to calculate the GPCC monthly gridded data set throughout the LMRB for the period January 1951 to December 2015. The minimum and maximum number of precipitation measurement stations in the LMRB are 38 (in January and February 1951) and 163 (all months in 1999, except June and December), respectively (Figure 1e). However, only a few studies have previously applied the GPCC data set to study climate change trends throughout the LMRB in recent decades (e.g., Fan & Luo, 2019; Ruiz-Barradas & Nigam, 2018).

It is worth mentioning that this study preferred the GPCC data set to the Asian Precipitation-Highly Resolved Observational Data Integration Toward Evaluation of water resources (APHRODITE), which has been generated by the Research Institute for Humanity and Nature and the Meteorological Research Institute of the Japan Meteorological Agency (Yatagai et al., 2009, 2012). APHRODITE is the only available long-term regional gauge-based daily gridded precipitation data set produced by utilizing a dense network of daily in situ records in Asia (Tanarhte et al., 2012), and has previously been selected as "reference data" for evaluating the reliability of satellite-based and reanalysis precipitation data sets in different parts of Asia (Sidike et al., 2016; Sohn et al., 2012; Tan et al., 2017), including the LMRB (Chen et al., 2018). The developer of APHRODITE (Yatagai et al., 2009), however, actually confirmed its accuracy and reliability based on the monthly GPCC data sets (Yatagai et al., 2012).

Given the existing research results and controversies (Caesar et al., 2011; A. Chen, Ho, et al., 2019; Ding et al., 2019; Fan & Luo, 2019; Villafuerte & Matsumoto, 2015), this study selected 13 teleconnections, including eight oceanic-atmospheric circulation patterns (Nos. 1–8 in Table 1) and five dominant summer (June–September) monsoons (Nos. 9–13 in Table 1). The main characteristics, coverage areas, and monthly time series (1951–2015) for all of these teleconnections can be found in the references and data sources listed in Table 1. For water years 1952–2015, this study calculated annual (water year: from November to the



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Summary of the Teleconnections Considered in This Study

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No.	ID	Climate teleconnection	Data source	Reference
1	AMO	Atlantic Multidecadal Oscillation	<sup>a</sup> NOAA Physical Sciences Division (PSD)	Enfield et al. (2001)
2	AO	Arctic Oscillation	NOAA Climate Prediction Center (CPC)	Thompson and Wallace (1998)
3	EP/NP	Eat Pacific/North Pacific	NOAA Climate Prediction Center (CPC)	Barnston and Livezey (1987)
4	NAO	North Atlantic Oscillation	NOAA Climate Prediction Center (CPC)	Barnston and Livezey (1987)
5	PDO	Pacific Decadal Oscillation	National Center for Atmospheric Research (NCAR)	Zhang and Levitus (1997)
6	SOI	Southern Oscillation Index	National Center for Atmospheric Research (NCAR)	Trenberth (1984)
7	TPI	Tibetan Plateau Index	National Climate Center (NCC) of CMA <sup>b</sup>	Yao and Chen (2015)
8	WP	West Pacific	NOAA Climate Prediction Center (CPC)	Barnston and Livezey (1987)
9	ISMI	Indian Summer Monsoon Index	Asia-Pacific Research Data Center (APRDC) of IPRC <sup>c</sup>	Wang and Fan (1999)
10	WNPMI	Western North Pacific Monsoon Index	Asia-Pacific Research Data Center (APRDC) of IPRC	Wang et al. (2001)
11	EASMI	East Asian Summer Monsoon Index	(http://ljp.gcess.cn/dct/page/65544) <sup>d</sup>	Wang et al. (2008)
12	SASMI	South Asian Summer Monsoon Index	(http://ljp.gcess.cn/dct/page/65544)	Li and Zeng (2002, 2003)
13	SCSMI	South China Sea Summer Monsoon index	(http://ljp.gcess.cn/dct/page/65544)	Li and Zeng (2002, 2003)

<sup>a</sup>NOAA (National Oceanic and Atmospheric Administration of the United States). <sup>b</sup>CMA (China Meteorological Administration). <sup>c</sup>IPRC (international Pacific Research Center). <sup>d</sup>Last accessed 7 April 2020.

following October), dry season (November–May), and wet season (June–October) data sets of the large-scale oceanic-atmospheric circulation patterns (Nos. 1–8 in Table 1) as the average of their corresponding monthly values. Hence, the period from November 1951 to October 1952 was considered to be the water year 1952, consisting of both the dry (November 1951 to May 1952) and wet (June 1952 to October 1952) seasons of 1952.

#### 2.3. Analytical and Statistical Methods

The EOF (Lorenz, 1956) is commonly applied for identifying and extracting the spatiotemporal patterns of hydrometeorological variables (Hannachi et al., 2007). EOF analysis includes three components: eigenvectors (EOFs representing Spatial Patterns), principal components (PCs, i.e., corresponding time coefficients), and eigenvalues (Hannachi et al., 2007). Numerous previous studies have comprehensively described and reviewed the EOF and its application for climate variability and change assessment (e.g., Fujinami et al., 2016; Gong et al., 2018; Jiang et al., 2014; Yao et al., 2015). Therefore, this study used the EOF to simplify the interpretation of interannual and intra-annual precipitation variability across the LMRB in the space-time domain. The North criterion significance test (North et al., 1982) was also employed to distinguish the physical signal from the noise through the estimation of EOFs. The leading PCs that contained most of the original variance were also selected as the substitutions to investigate the relationships of annual and seasonal precipitation across the LMRB with teleconnections.

The wavelet transform coherence (WTC) method was employed in this study to explore significant relationships of the predominant annual and seasonal precipitation EOFs in the LMRB with different teleconnections. The WTC is a new signal-analysis approach that combines wavelet transform with cross-spectrum analysis. It has recently been used to measure the covarying relationships of hydrometeorological variables with their potential drivers in the time-frequency domain at multiple time scales (Asong et al., 2018; Jevrejeva et al., 2003; Su et al., 2019). Hence, the WTC is a correlation coefficient localized in time and frequency space for quantifying the degree of possible linear relationships between two nonstationary series through the time and frequency domains (Jiang et al., 2019; Su et al., 2019). Its significance level (5% in this study) for each scale is computed by the Monte Carlo method using only values outside of the cone-of-influence (Grinsted et al., 2004; Torrence & Compo, 1998). In the WTC method, the relative phase relationship is shown as small arrows, with in-phase (positive) pointing right (0°) and antiphase (negative) pointing left (180°). In this study, the PC leads (lags) the teleconnection by 90°, pointing downward (upward).

To measure correlations of annual and seasonal precipitation time series on the basin scale of the LMRB with teleconnections, this study preferred Spearman's rank correlation ( $\rho$ ) to Pearson's correlation coefficient (r). This was primarily because  $\rho$ , unlike r, fundamentally assumes no particular distribution functions for variables (Helsel & Hirsch, 1992). In order to detect statistically significant (p < 0.05) trends in interannual and intra-annual precipitation, as well as their corresponding dominant PCs, the present study employed the rank-based nonparametric Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945). Accordingly, the slope of



Table 2

Variability and Changes in Annual (November–October), Dry Season (November–May), and Wet Season (June–October) Precipitation, As Well As Their Correlations With Teleconnections on the Basin Scale of the LMRB, LRB, and MRB During the Water Years (November–October) 1952–2015

	LMRB				LRB		MRB		
	Annual	Dry	Wet	Annual	Dry	Wet	Annual	Dry	Wet
Long-term Average (mm)	1,489.7	380.2	1,109.5	903.7	219.8	683.9	1,772.1	466.6	1,305.5
Minimum (mm)	1,301.9	238.1	983.8	793.5	104.3	579.8	1,505.7	286.6	1,134.5
Year of Minimum	1977	1963	2012	1992	1969	1992	1998	1992	2012
Maximum (mm)	1,809.8	581.7	1,244.3	1,046.8	309.7	828.8	2,182.7	766.6	1,481.6
Year of Maximum	2000	2000	1952	2000	2000	1966	2000	2000	1978
Absolute Trend	0.05	0.34*	-0.30	-0.27	0.38*	-0.65	0.12	0.35	-0.23
(mm/year)									
Relative Trend (%/year)	0.003	0.091*	-0.027	-0.029	0.172*	-0.095	0.007	0.076	-0.018
AMO	0.28*	0.23	0.13	0.11	-0.03	0.12	0.29*	0.25*	0.09
AO	0.08	0.11	0.33*	-0.04	0.21	0.01	0.10	0.09	0.38*
EP/NP	-0.22	-0.33*	-0.07	$-0.27^{*}$	$-0.26^{*}$	0.13	$-0.22^{*}$	$-0.31^{*}$	-0.08
NAO	-0.02	-0.03	0.17	-0.07	0.18	-0.03	-0.04	-0.03	0.18
PDO	-0.38*	$-0.31^{*}$	$-0.29^{*}$	$-0.28^{a}$	0.03	-0.12	-0.41	-0.32	-0.28
SOI	0.30*	$0.40^{a}$	0.11	0.21	0.22	0.05	0.33*	$0.51^{a}$	0.10
TPI	0.14	0.15	0.27*	0.03	0.07	0.09	0.15	0.14	0.22
WP	-0.13	-0.10	0.06	-0.02	-0.12	0.22	-0.14	-0.11	0.03
ISMI	0.22	0.01	0.34 <sup>a</sup>	-0.03	$0.32^{a}$	$-0.25^{a}$	0.21	-0.05	$0.37^{\mathrm{a}}$
WNPMI	0.16	0.15	0.14	-0.18	-0.14	-0.08	0.22	0.18	0.19
EASMI	0.15	0.24	0.05	-0.06	-0.07	-0.04	0.20	0.25*	0.08
SASMI	0.39 <sup>a</sup>	0.19	0.32*	0.21	0.23	0.05	$0.40^{a}$	0.17	0.36*
SCSMI	0.07	0.13	0.01	-0.09	-0.15	-0.02	0.11	0.15	0.03
	Long-term Average (mm) Minimum (mm) Year of Minimum Maximum (mm) Year of Maximum Absolute Trend (mm/year) Relative Trend (%/year) AMO AO EP/NP NAO PDO SOI TPI WP ISMI WNPMI EASMI SASMI SCSMI	AnnualLong-term Average (mm)1,489.7Minimum (mm)1,301.9Year of Minimum1,977Maximum (mm)1,809.8Year of Maximum2000Absolute Trend0.05(mm/year)0.05Relative Trend (%/year)0.003AMO0.28*AO0.08EP/NP-0.22NAO-0.02PDO-0.38*SOI0.30*TPI0.14WP-0.13ISMI0.22WNPMI0.16EASMI0.15SASMI0.07	LMRBAnnualDryAnnualDryAnnual38.0.2Minimum (mm)1,30.9238.1Year of Minimum19771963Maximum (mm)1,809.8581.7Year of Maximum20002000Absolute Trend0.050.34*(mm/year)0.030.091*AMO0.0280.23AO0.080.11EP/NP-0.22-0.33*NAO-0.02-0.03PDO-0.34*0.31*SOI0.30*0.40*TPI0.140.15WP-0.13-0.10ISMI0.220.01WNPMI0.160.55EASMI0.150.24SOSMI0.03*0.019	Long-term Average (nm)AnnualDryWetLong-term Average (nm)1,489.7380.21,109.5Minimum (nm)1,301.9238.1983.8Year of Minimum197719632012Maximum (nm)1,809.8581.71,244.3Year of Maximum200020001952Absolute 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*Note*. LMRB = Lancang-Mekong River Basin; LRB = Lancang River Basin; MRB = Mekong River Basin.

<sup>a</sup>Strongest (most) significant correlation: the highest absolute Spearman's rank correlation. <sup>b</sup>Teleconnections: Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), East Pacific/North Pacific (EP/NP), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Southern Oscillation Index (SOI), Tibetan Plateau Index (TPI), West Pacific (WP), Indian Summer Monsoon Index (ISMI), Western North Pacific Monsoon Index (WNPMI), East Asian Summer Monsoon Index (EASMI), South Asian Summer Monsoon Index (SASMI), and South China Sea Summer Monsoon Index (SCSMI). \*Statistically significant (p < 0.05).

such significant trends was estimated using Sen's method (Sen, 1968). The relative trend (%) was also calculated as (trend/mean precipitation)  $\times$  100. In general, however, using the nonparametric MK trend test requires serially independent hydrometeorological time series. The positive autocorrelation in such time series typically increase the possibility of rejecting the null hypothesis of no trend in the nonparametric MK test, while the null hypothesis is actually true. It means that the nonparametric MK test detects statistically significant trends in hydrometeorological time series with positive serial correlation, while none may really exist (Yue et al., 2002). Similarly, the positive correlations in the time series for one and/or both hydrometeorological variables might influence measuring their statistically significant correlations (Park & Lee, 2001). Given the existence of positive autocorrelation in precipitation and/or teleconnections time series, hence, the trend-free prewhitening (TFPW) approach (Yue et al., 2002) was used to identify significant trends, and the residual bootstrap (RB) technique (Park & Lee, 2001) with 5,000 independent replications was employed to assess the standard deviation of the  $\rho$  values.

# 3. Results

# 3.1. Historical Precipitation Analysis

On the basin scale, a significant (p < 0.05) wetting trend (0.34 mm/year) was only found in the dry season precipitation (hereafter, DSP) across the LMRB during the water years 1952–2015 (Table 2). This trend was basically driven by a significant increase (0.38 mm/year) in historical DSP across the LRB over the same period (Table 2). Similarly, the relative trends indicated that such a significant increase in DSP was much more pronounced across the LRB (0.172%) than across the LMRB (0.091%) (Table 2). In the MRB, DSP also exhibited a wetting trend in recent decades, although it was insignificant (p > 0.05; Table 2). Despite the wetter dry seasons, annual precipitation (hereafter, AP) displayed no clear changes in the LMRB, LRB, or MRB with time (Table 2). This may be attributed to the (i) statistically insignificant drying trends in wet season precipitation (hereafter, WSP) and (ii) typically smaller contribution of DSP (24.3–26.3%) than WSP (73.7–75.7%) to AP across all of the three basins (Table 2).





Figure 2. Anomaly time series with trend line and most influential teleconnection for (a) annual, (b) dry season, and (c) wet season precipitation on the basin scale of the Lancang-Mekong river Basin (LMRB) during the water years (November–October) 1952–2015. Dry and wet seasons referred to the periods November–May and June–October during the water year, respectively. The time series for the most influential teleconnections are referred to their corresponding annual and seasonal averaged values.

The long-term (1952–2015) AP averages were approximately 1,489.7, 903.7, and 1,772.1 mm over the basin scale of the LMRB, LRB, and MRB, respectively (Table 2). Across all of these basins, the maximum AP amounts were observed in the water year 2000, when the maximum DSP amounts also occurred (Table 2). The minimum DSP amounts generally exerted no effect on the minimum AP in the LMRB, LRB, and MRB, however. Historical variations in AP ( $\rho = 0.39$ ) and WSP ( $\rho = 0.34$ ) over the LMRB were most significantly correlated with the SASMI and ISMI, respectively, which were also the strongest teleconnections influencing AP ( $\rho = 0.40$ ) and WSP ( $\rho = 0.37$ ) over the MRB (Table 2). In these two basins (the LMRB and MRB), the DSP variability displayed the most significant correlations ( $\rho = 0.40$  and 0.51, respectively) with the SOI (Table 2). Across the LRB, however, AP was most strongly correlated with the PDO ( $\rho = -0.28$ ), while DSP ( $\rho = 0.32$ ) and WSP ( $\rho = -0.25$ ) were most correlated with the ISMI. Figure 2 presents the anomalies, significant trends, and most significant teleconnections for annual (AP) and seasonal (DSP and WSP) precipitations over the LMRB during the water years 1952–2015.

Spatially, the significant increases in AP over the northern LRB during the water years 1952–2015 (Figures 3a and 3d) were primarily driven by the historical wetting trends of DSP (Figures 3b and 3e). Throughout the MRB, however, significantly increasing (decreasing) trends in AP were mainly seen in the northeastern (most western) sections (Figures 3a and 3d), in association with historical wetter (drier) wet seasons (Figures 3c and 3f). The increasing trends detected in AP and DSP across the northern LRB ranged from 0.5–1.5 to 0.3–1.9 mm/year, respectively (Figures 3a and 3b). For AP and WSP, significant drying (wetting) trend rates (in mm/year) were, in turn, 3.1–5.6 (3.4–6.8) and 2.5–5.9 (2.5–6.1) over most of the western (northeastern) MRB (Figures 3a and 3c). In the LMRB, annual and seasonal precipitation (AP, DSP, and WSP) typically increased from the northern LRB to the southern MRB, while there was a decreasing gradient from east to west (Figures 3g–3i).

The most influential teleconnections for variations in both AP and WSP were generally the same over the portions of the LMRB (Figures 4a and 4c) in which the contributions of WSP to AP were relatively high (85–90%) (Figures 3g–3i and S1). Accordingly, the strongest correlations of AP and WSP with the WNPMI (SASMI) were positive across the eastern (northeastern) MRB, as well as negative (positive) with the





**Figure 3.** Spatial distribution maps of absolute and relative trends as well as long-term average values of (a, d, g) annual, (b, e, h) dry season, and (c, f, i) wet season precipitation throughout the Lancang-Mekong River Basin (LMRB) during the water years (November–October) 1952–2015. The stippling in (a–f) indicates areas in which the trends are statistically significant (p < 0.05). DSP and WSP denote precipitation during the dry (November–May) and wet (June–October) seasons through the water year, respectively.

AMO (TPI) over the northern (most of the upper northern) LRB (Figures 4a, 4c, 4d, and 4f). However, the 25–35% and 65–75% contributions of DSP and WSP to AP, respectively, over the southern and southwestern MRB (Figures 3g–3i and S1) led to similar spatial distributions of the most significant teleconnections influencing AP and DSP throughout the LMRB (Figures 4a and 4b). Thus, over these regions, AP and DSP exhibited the most significant positive correlations with the SOI (Figures 4a and 4b), with  $\rho = 0.35-0.55$  (Figures 4d and 4e). DSP in the uppermost section of the LRB, however, had the most significant positive relationships with the AO ( $\rho = 0.35-0.45$ ) (Figures 4b and 4e). The spatial patterns for the correlations ( $\rho$ ) of AP, DSP, and WSP with all of the 13 teleconnections considered in this study throughout the LMRB during the water years (November–October) 1952–2015 are shown in Figures S2–S4, respectively.

#### 3.2. Dominant Patterns of Annual and Seasonal Precipitation

The first five EOFs of long-term annual and seasonal precipitation patterns throughout the LMRB are listed in Table 3. Approximately 35.2%, 56.2%, and 30.1% of the total variance in AP, DSP, and WSP, respectively, across the LMRB were reflected in the first two EOFs (Table 3), which were then used for subsequent analysis and discussion. The first EOF (EOF1) component accounted for 26.6% of AP, 48.1% of DSP, and 18.7% of





**Figure 4.** Spatial distribution maps of the most influential climate teleconnection and Spearman's rank correlation ( $\rho$ ) for variations in (a, d) annual, (b, e) dry season, and (c, f) wet season precipitation throughout the Lancang-Mekong River Basin (LMRB) during the water years (November–October) 1952–2015. The stippling indicates areas in which the correlations are statistically insignificant (p > 0.05). DSP and WSP denote precipitation during the dry (November–May) and wet (June–October) seasons through the water year, respectively. Table 1 expresses the abbreviations of different teleconnections.

WSP variability over the LMRB (Table 3). Meanwhile, the percentages of EOF1 for AP and WSP (DSP) across the MRB were lower (higher) than those across the LRB (Table 3). Hence, variations in AP and WSP over the MRB are more complex than those over the LRB. The EOF1 of AP across the LMRB identified two positive centers: (i) a strong high-value center in the eastern LMRB and (ii) a relatively weak center in the southwestern MRB (Figure 5a). Such a comparatively strong (weak) AP center was mainly associated with the robust positive high-value center of DSP (WSP) over the eastern (southwestern) MRB (Figures 5b and 5c). The EOF2 components of AP, DSP, and WSP, however, were, respectively, approximately 8.6%, 8.1%, and 11.4% over the LMRB, but 19.4%, 23.0%, and 16.9% over the LMRB and 8.6%, 8.1%, and 11.0% over the MRB (Table 3). Accordingly, AP (DSP) was widely spread over the LMRB, with a negative (positive) center at lower latitudes in the northeastern (southeastern) MRB (Figures 5d and 5e). This spatial pattern was also found in WSP, with the exception of positive values in the southeastern and southwestern MRB (Figure 5f).

Figure 6 shows the corresponding time coefficients (PC1 and PC2) of the first two EOF modes (EOF1 and EOF2) identified for interannual and intra-annual precipitation over the LMRB during the water years 1952–2015. Trend analysis determined no clear changes in the PC1 and PC2 of annual and seasonal precipitation across the LMRB over time (Figure 6). The PC1 of AP, DSP, and WSP was most significantly associated



#### Table 3

Percentage of Variance Explained by the First Five Varimax Loadings (EOFs) of Annual and Seasonal Precipitation Throughout the LMRB, LRB, and MRB During the Water Years (November–October) 1952–2015

		LMRB			LRB		MRB			
EOF	Annual (November– October)	nual Dry season Wet season mber– (November– (June– ober) May) October)		Annual (November– October)	Annual Dry season Iovember- (November- October) May)		Annual (November– October)	Dry season (November– May)	Wet season (June– October)	
EOF1 (%)	26.6	48.1	18.7	35.1	49.2	31.3	28.7	53.2	19.6	
EOF2 (%)	8.6	8.1	11.4	19.4	23.0	16.9	8.6	8.1	11.0	
EOF3 (%)	7.5	6.3	8.7	8.1	7.5	10.8	8.0	5.4	8.7	
EOF4 (%)	6.6	4.1	6.8	6.3	4.2	7.7	6.7	3.5	7.6	
EOF5 (%)	4.9	3.3	5.8	5.3	2.7	6.2	5.4	3.4	5.3	
Total Value (%)	53.9	69.9	50.3	74.1	86.7	72.9	57.4	73.6	52.2	

*Note.* EOF = Empirical Orthogonal Function; LMRB = Lancang-Mekong River Basin; LRB = Lancang River Basin; MRB = Mekong River Basin.

with the SASMI ( $\rho = -0.39$ ), SOI ( $\rho = 0.52$ ), and ISMI ( $\rho = 0.37$ ), respectively (Figures 6a, 6c, and 6e). For PC2, however, only WSP was in statistically significant relationships with different teleconnections, most strongly with the SOI ( $\rho = -0.43$ ) (Figures 6b, 6d, and 6f). The PDO was the second-most influential teleconnection for variations in the PC1s of AP and DSP over the LMRB, with  $\rho = -0.38$  (Table 4).

#### 3.3. Phase Difference Between Teleconnections and Precipitation Variability

Figures 7 and S5–S11 illustrate the WTCs for the first two PCs (PC1 and PC2) of AP, DSP, and WSP over the LMRB and all of the 13 teleconnections considered in this study. The main results obtained by these WTCs are listed in Tables S1–S6. In particular, Figures 7 and S5 represent the WTCs of the first three most influential teleconnections with the PC1 and PC2, respectively, of annual and seasonal precipitation across the LMRB, although only the WTCs between these three influential teleconnections and the PC1 (as the most important mode) of AP, DSP, and WSP (Figure 7) are discussed below to simplify and limit the length of this manuscript.

On the interannual scale, the PC1 of AP throughout the LMRB generally exhibited significant coherences with the SASMI, AO, and ISMI during the 1950s-1980s, and with the SOI, PDO, WP, SCSMI, and EP/NP after the mid-1980s (Figures 7a-7c and S6). The significant coherence between the PC1 of AP and the SASMI was mainly found in the 1- to 3-year time scale (1954-1962, 1972-1980, and 1988-1991), with phase differences from 0-10° (Figure 7a), indicating that the SASMI positively led the PC1 of AP in the LMRB by 0 (simultaneous) to 1 month, respectively. On the same interannual time scale (1-3 years), the coherences between the PC1 of AP and the SOI were positively significant in the periods 1985-1988, 1996-1999, and 2008-2011 (Figure 7b), but with phase differences of 0° (simultaneous), 90° (lag of 3-9 months), and 0-20° (lag of 0-2 months), respectively (Table S1). The SOI also influenced the PC1 of AP on the 4- to 6-year time scale from 1997–2003 (Figure 7b), with the phase difference ranging from 0° (simultaneous) to 45° (lead of 6-9 months) (Table S1). For the period 1988-2008, the PC1 of AP exhibited significant negative coherences with the PDO on the 5- to 8-year time scale, with a  $-180^{\circ}$  phase difference (Figure 7c), indicating simultaneous wet (dry) conditions associated with the mature negative (positive) PDO mode. Likewise, this teleconnection (PDO) was negatively influential for decadal (9- to 12-year) variability in the PC1 of AP, with a lead between 0 and 18-24 months. On the decadal time scale, the AO, NAO, EP/NP, and WNPMI also displayed significant coherences with the PC1 of AP over the LMRB (Table S1).

On the interannual (decadal) time scale, the PC1 of DSP was significantly associated with the SOI, EP/NP, PDO, and WNPMI after the early 1970s (1990s), and with the ISMI and SASMI before then (Figures 7d–7f and S8). It mainly displayed significantly positive (negative) coherences with the SOI (PDO) on the 1- to 5-year time scale from 1982 to 2008 (1969–1989) (Figures 7d and 7e), with phase differences from  $0^{\circ}$  ( $-80^{\circ}$ ) to  $-20^{\circ}$  ( $-90^{\circ}$ ), indicating lags between 0 (3–8) and 1–3 (6–15) months (Table S3). The SOI was also a significant teleconnection simultaneously affecting variations in the PC1 of DSP on the 6- to 8-year time scale from 1994 to 2004 (Figure 7d). At the same time scale (6–8 years), the lags of EP/NP with the PC1 of DSP ranged from 0 to 3–5 months from 1991 to 2005 (Figure 7f). Before the 1970s, however, the PC1 of DSP exhibited significant relationships with the ISMI (SASMI) on the interannual time scale of 1–2 years





**Figure 5.** Spatial patterns of (a–c) EOF1 and (d–f) EOF2 throughout the Lancang-Mekong River Basin (LMRB) during the water years (November–October) 1952–2015 for (a, d) annual, (b, e) dry season, and (c, f) wet season precipitation. EOF1 refers to the first mode of Empirical Orthogonal Function (EOF), while EOF2 to the second mode. DSP and WSP denote precipitation during the dry (November–May) and wet (June–October) seasons through the water year, respectively.

from 1954–1964 and 1970–1976 (1956–1964 and 1970–1976), with a phase difference ranging from 0–45° (Table S3). On the decadal scale of 8–13 years, the PC1 of DSP showed significant coherences with the EP/ NP, PDO, and SOI from 1994–2004, 1994–2003, and 1983–2008, respectively (Figures 7d–7f), with corresponding phase differences of  $-180^{\circ}$  (negative simultaneous), 160° (lag of 5–9 months), and 0° to  $-10^{\circ}$  (lead time between 0 and 3–4 months) (Table S3). Similarly, the WNPMI (NAO) had a significant negative coherence with the PC1 of DSP on the 10- to 14- (12 to 16) year decadal time scale from 1984–2004 (1980–2000) (Figure S8), with a phase difference of  $-135^{\circ}$ , indicating lags of 15–21 (18–24) months (Table S3). Before the mid-1990s, however, both the ISMI and SASMI were significant teleconnections simultaneously exerting negative influences on the PC1 of DSP on the decadal scale of 10–14 years from 1964–1994 and 1966–1994, respectively (Figure S8 and Table S3).

In general, the PC1 of WSP was simultaneously associated with the AO before the 1970s, the SASMI and ISMI during the 1980s, and the AMO in the 1990s on the interannual time scale of 1–3 years (Figures 7g–7i and S10). The AO and ISMI also influenced interannual variability in the PC1 of WSP throughout the LMRB from the late 2000s to the early 2010s, but with phase differences of 75–85° (lead time between 3–5 and 3–6 months) and 45–60° (lead time between 2–5 and 2–6 months), respectively (Table S5). On the interannual scale of 6–8 years, the AO, WP, AMO, and PDO exhibited significant coherences with the PC1 of DSP from the late 1980s to the mid-2000s (Figures 7i and S10). Accordingly, the phase difference was 0° for the AO, 45–90° for the WP and AMO, and –170 to –180 for the PDO (Table S5). On the decadal time





**Figure 6.** Corresponding time coefficients (PCs) of the first two Empirical Orthogonal Function (EOF) modes with their most influential teleconnections for (a, b) annual, (c, d) dry season, and (e, f) wet season precipitation throughout the LMRB during the water years (November–October) 1952–2015. Dry and wet seasons referred to the periods November–May and June–October during the water year, respectively. Teleconnections here are SASMI (South Asian Summer Monsoon Index), SOI (Southern Oscillation Index), and ISMI (Indian Summer Monsoon Index).

scale of 9–12 years, the ISMI, SASMI, and AO were all influential teleconnections (Figures 7g–7i and S10), with phase differences of  $45^{\circ}$ ,  $0-45^{\circ}$ , and  $-90^{\circ}$ , respectively (Table S5). The ISMI (AO) was also associated with the PC1 of WSP on the decadal time scale of 16–22 years from 1974–1984 (Figures 7 and S10), with a phase difference of  $45^{\circ}$  (180°) indicating a lead time of 24–33 (0) months (Table S5).

# 4. Discussion

This study found a significant increase in dry season (November–May) precipitation across the LMRB during 1952–2015, but no clear changes in wet season (June–October) and annual (November–October) precipitation. This can be due to the relatively low contribution of DSP (~30%) to the annual precipitation over the LMRB. Indeed, significant increasing trend found in DSP was not sufficient to cause substantial changes in the annual precipitation in the LMRB. Similarly, some previous investigations also reported no clear trends of AP and WSP over the LMRB, LRB, and MRB in recent decades (e.g., Grumbine et al., 2012; Kiem et al., 2008; Lyon et al., 2017; Xue et al., 2011), but significant increases in DSP over the LRB (Fan & He, 2015). Conversely, a number of other studies previously reported significant increasing trends in historical AP and WSP across the LMRB (A. Chen, Ho, et al., 2019; Delgado et al., 2010, 2012; Räsänen et al., 2012), LRB (Fan & He, 2015), and MRB (Lutz et al., 2014). Such differences between previous research and this study could be attributed to the selected stations, applied data sets, defined annual and seasonal time scales, and study periods.

On both interannual and intra-annual scales, drying and wetting tendencies in precipitation were fundamentally accompanied by substantial increases in precipitation variability throughout the LMRB, as reported in previous studies (e.g., Delgado et al., 2012; Lutz et al., 2014; Räsänen et al., 2012). Such



Table 4

Spearman's Rank Correlations (ρ) Between the First Five Corresponding Time Coefficients (PCs) of Precipitation (Annual and Seasonal Scales) and Teleconnections Throughout the LMRB During the Water Years (November–October) 1952–2015

	Annual						Seasonal									
	Water year (November–October)						Dry (November–May)					Wet (June–October)				
Teleconnections <sup>b</sup>	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5	
АМО	0.29*	-0.18	0.21	0.17	$-0.33^{a}$	0.23	0.07	0.14	-0.18	$0.28^{\mathrm{a}}$	0.08	-0.16	0.28*	-0.10	-0.14	
AO	0.05	0.06	0.00	-0.02	0.20	0.04	-0.06	-0.12	0.15	-0.19	0.33*	-0.17	-0.07	-0.05	-0.05	
EP/NP	-0.20	0.07	$-0.31^{*}$	-0.18	0.00	-0.33*	0.19	0.03	-0.21	$-0.25^{*}$	-0.11	0.11	-0.13	0.02	$0.30^{a}$	
NAO	-0.08	0.18	-0.25	-0.11	0.24	-0.07	0.00	-0.10	0.22	-0.17	0.16	-0.03	-0.26	-0.05	0.04	
PDO	$-0.38^{*}$	0.15	-0.19	0.02	0.02	$-0.38^{*}$	-0.03	-0.14	-0.08	-0.07	-0.20	0.30*	-0.01	-0.02	0.11	
SOI	0.32*	-0.17	0.20	0.00	-0.03	$0.52^{\mathrm{a}}$	-0.09	$0.24^{\mathrm{a}}$	0.18	0.00	0.03	$-0.43^{a}$	0.11	$-0.33^{a}$	-0.08	
TPI	0.18	-0.08	0.08	0.00	-0.13	0.11	0.03	0.01	0.01	0.13	0.24*	-0.24	0.10	0.10	0.06	
WP	-0.13	0.03	0.07	0.07	0.10	-0.12	0.06	0.11	0.09	0.04	-0.02	-0.19	-0.21	0.00	-0.04	
ISMI	0.21	-0.01	0.03	$0.28^{\mathrm{a}}$	-0.04	-0.06	-0.23	-0.20	0.11	0.11	$0.37^{a}$	-0.05	0.25	-0.19	-0.09	
WNPMI	0.23	0.09	$-0.50^{a}$	-0.19	-0.09	0.18	0.06	0.23	-0.10	-0.21	0.28*	0.23	$-0.44^{a}$	0.12	-0.08	
EASMI	0.24	0.08	$-0.39^{*}$	-0.23	0.06	0.28*	0.05	0.10	-0.09	-0.18	0.17	0.21	$-0.40^{*}$	0.20	-0.16	
SASMI	0.39 <sup>a</sup>	-0.17	-0.02	0.12	0.06	0.18	-0.21	-0.16	-0.11	-0.03	0.35*	-0.13	0.01	0.06	-0.01	
SCSMI	0.14	0.19	$-0.38^{*}$	-0.09	0.08	0.17	-0.01	0.17	-0.10	-0.17	0.11	0.31*	-0.33*	0.22	-0.10	

<sup>a</sup>Strongest (most) significant correlation: the highest absolute Spearman's rank correlation. <sup>b</sup>Teleconnections: Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), East Pacific/North Pacific (EP/NP), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Southern Oscillation Index (SOI), Tibetan Plateau Index (TPI), West Pacific (WP), Indian Summer Monsoon Index (ISMI), Western North Pacific Monsoon Index (WNPMI), East Asian Summer Monsoon Index (EASMI), South Asian Summer Monsoon Index (SASMI), and South China Sea Summer Monsoon Index (SCSMI) \*Statistically significant (p < 0.05).

increases in precipitation variability can primarily be due to global warming, which strengthens both ocean evaporation and terrestrial evapotranspiration rates, intensifying the regional water cycle (e.g., IPCC, 2013) and consequently recycling the local moisture, leading to more precipitation (Zhang et al., 2017). Hence, throughout the LMRB, significant increases in DSP were principally related to the weaker westerlies and robust southerly winds, which are conducive to the northward transport of increased water vapor from the western Pacific Ocean and the Indian Ocean (B. Chen, Zhang, et al., 2019 Xu et al., 2020; Zhang et al., 2017). In general, the sources and transport pathways of atmospheric water vapor are driven by climate teleconnections (Liu et al., 2020; Trenberth et al., 2003). In order to interpret such a complex role of teleconnections, this study first used the EOF method to reduce the dimensionality of annual and seasonal precipitation time series over the LMRB.

The spatial patterns in both the EOF1 and EOF2 of AP, DSP, and WSP highly resembled those in the long-term averages of annual and seasonal precipitation shown in Figures 3g–3i, particularly for either wetter or drier conditions. In summary, it is suggested that the first two EOFs can represent the dominant patterns of interannual and intra-annual precipitation throughout the LMRB. However, since the EOF1s of AP, DSP, and WSP were approximately 3, 5.9, and 1.6 times higher than those of the EOF2, respectively, the EOF1 principally reflects the most important patterns of both annual and seasonal precipitation over the LMRB. Similarly, Yang et al. (2019) reported that the EOF1 can individually expose the major pattern of WSP variability over the LMRB using daily ERA-Interim reanalysis data from the European Centre for Medium-range Weather Forecasts (ECMWF) (Dee et al., 2011; Simmons et al., 2004) from 1979 to 2016. Yang et al. (2019) also showed, in agreement with this study, that such a leading mode (EOF1) of WSP throughout the LMRB is nearly positive across the MRB, while it alternates between positive and negative values over the LRB.

The most significant teleconnections influencing the EOF1s of AP, DSP, and WSP were highly consistent with those displaying the strongest correlations with the annual and seasonal precipitation across the basin-scale of the LMRB. Accordingly, the SASMI, SOI, and ISMI showed the strongest relationships (all positive) with historical variations in AP, DSP, and WSP as well as their EOF1s over this basin, respectively. The SASMI consists of two main independent components (SASMI1 and SASMI2), with quite different connections to the monsoon precipitation throughout South Asia (Li & Zeng, 2002). The SASMI2 has previously shown significant positive correlations with summer (June–August) precipitation over the LMRB, particularly the lower section (i.e., the MRB) (Li & Zeng, 2002). The present study also reflected such





**Figure 7.** Wavelet transform coherence and phase differences for the first three most significant teleconnections and the first EOF (PC1) mode of (a–c) AP, (d–f) DSP, and (g, h) WSP over the Lancang-Mekong river Basin (LMRB). The PC1 of AP was most significantly associated with (a) SASMI, (b) SOI, and (c) PDO; the PC1 of DSP with (d) SOI, (e) PDO, and (f) EP/NP; and the PC1of WSP with (g) ISMI, (h) SASMI, and (i) AO. The color bar indicates squared wavelet coherence. Thick contours denote the 5% significance level against red noise. The cone of influence (COI), in which edge effects might distort the results, is marked in a lighter shade. The relative phase relationship is shown as small arrows, with in-phase (positive) pointing right (0°) and antiphase (negative) pointing left (180°). The first time series leads (lags) the second by 90°, pointing downward (upward). Table 1 expresses the abbreviations of different teleconnections. AP, DSP, and WSP refer to precipitation during the water year (November–October), the dry (November–May), and wet (June–October) seasons, respectively.

relationships by detecting significant positive correlations of the SASMI with WSP and its EOF1 over the LMRB (mainly the MRB). Despite such association with WSP, the SASMI was specifically identified as the most influential teleconnection for variations in AP and its EOF1 across the LMRB and MRB. This is consistent with the previous study by Li and Zeng (2002), which reported that the SASMI is highly effective for clarifying interannual variability in the ISM, which principally has significantly positive relationships with WSP variability throughout the LMRB, particularly the western MRB (Delgado et al., 2012; Xue et al., 2011; Yang et al., 2019). Similarly, the present study identified the ISMI as the strongest teleconnection positively influencing WSP and its EOF1 over both the LMRB and MRB. In agreement with previous investigations (Juneng & Tangang, 2005; Räsänen et al., 2016; Räsänen & Kummu, 2013; Wang et al., 2000), this study also found that the strong positive/negative SOI events (La Niña/El Niño) generally increased/decreased DSP and its EOF1 over the LMRB, especially the MRB.

Generally speaking, positive/negative anomalies of AP over the LMRB were simultaneously associated with the positive/negative SASMI during the period before the mid-1980s. The influence of the SASMI on the atmospheric water vapor transport pathway is generally related to the considerable thermal gradients between the warm Asian continent to the north (low pressure) and the cooler water bodies (most importantly the Arabian Sea, Indian Ocean, and Bay of Bengal) to the south (high pressure). Accordingly, the strong southwesterly winds bring a significant supply of water vapor into the LMRB, particularly the southwestern and southern MRB, resulting in heavier summer precipitation over these areas (Li & Zeng, 2002). Consistent with the present study, Li and Zeng (2005) also reported a significant weakening trend in the intensity of the SASMI since the mid-1980s. This can be related to the Arabian Sea warming, which



decreases the power of westerlies over the southern Bay of Bengal and the Arabian Sea; increases the convergence of moisture across the Arabian Sea; indirectly prohibits the moisture-laden winds coming from the Arabian Sea toward the land regions, thereby decreasing precipitation; and produces an anticyclonic circulation over the land, amplifying monsoon precipitation reduction over the southwestern and southern LMRB (Mishra et al., 2020).

After the mid-1980s, the positive/negative SOI (La Niña/El Niño) events preceded abnormally wetter/drier AP over the LMRB by approximately 0–9 months. The significant coherences between AP and the SOI over the LMRB since the mid-1980s may essentially be related to the substantial positive coherences of the SOI with DSP after the early 1980s, indicating that the positive/negative SOI (La Niña/El Niño) events simultaneously increase/decrease DSP across this basin. During La Niña/El Niño events, the southeast to southwest Pacific Ocean temperature difference increases/decreases, which generally strengthens/weakens the Walker circulation and the trade winds. With the higher/lower ocean temperatures, Southeast Asia (partially including the LMRB) experiences more/less evaporation and clouds, and consequently more/less precipitation (e.g., Cherchi & Navarra, 2013; Hrudya et al., 2020; Juneng & Tangang, 2005; Räsänen et al., 2016; Räsänen & Kummu, 2013). During La Niña/El Niño events, the temperatures over the Arabian Sea, Indian Ocean, and the Bay of Bengal also remain cooler/warmer than normal. Hence, the pressure difference between these large water bodies to the south and the Asian landmass to the north is high (low) and substantially intensifies (moderates) the flow of atmospheric water vapor toward the LMRB, resulting in increased/decreased precipitation across this basin, particularly in the southwestern and southern sections (e.g., Cherchi & Navarra, 2013; Hrudya et al., 2020).

Consistent with previous investigations (Delgado et al., 2012; Tsai et al., 2015; Xue et al., 2011; Yang et al., 2019), this study also found that the ISMI is the most significant teleconnection positively affecting variations in WSP throughout the LMRB, particularly the MRB. During the strong positive ISMI phase, the South China Sea and Bay of Bengal are dominated by positive anomalies of diabatic heating. Accordingly, the anomalous easterlies in the South China Sea and the significantly anomalous westerlies in the Bay of Bengal, which transport more warm-wet atmospheric water vapor, induce significantly strong convergence and ascending motion over the LMRB. This essentially increases WSP over the LMRB, particularly across the MRB (Yang et al., 2019).

Many different factors are involved in the complex driving mechanism of regional precipitation variability, including solar radiation changes, climate system structures (e.g., the periodicity in climate oscillations), geographical features (e.g., longitude, latitude, and elevation), oceanic-atmospheric circulation patterns (e.g., the SOI and AO), and human activities (anthropogenic aerosols) (Lu et al., 2014; Ma et al., 2018; Qian et al., 2009). There are also disputes concerning studies focusing specifically on the role of these factors in precipitation variability over different parts of the world. For the LMRB, identifying the strongest influential teleconnections for annual and seasonal precipitation, particularly WSP, has recently received considerable attention as an important debate in international research communities. Some scientists believe it is the SOI (e.g., Räsänen et al., 2016; Räsänen & Kummu, 2013), while others mention the PDO (e.g., Chen et al., 2018; Verdon & Franks, 2006) and ISMI (e.g., Tsai et al., 2015; Yang et al., 2019). The present study, however, found that the roles of climate teleconnections in precipitation variability over the LMRB are different, but interdependent. This is in agreement with the results of Liu et al. (2016), who concluded that regional precipitation variability is primarily attributable to the integrated effect of all of these climate teleconnections. Accordingly, large-scale teleconnections significantly influence DSP variability over the LMRB, while playing small or no clear role in WSP fluctuations, which are strongly associated with summer monsoons. Although such knowledge is beneficial for understanding oceanic-atmospheric circulation patterns controlling regional/local precipitation variability on different time scales, the interrelationships among teleconnections and their combined effects on annual and seasonal precipitation (particularly across the LMRB) require further and deeper investigation in the future.

# 5. Conclusions

This study investigated climate teleconnections influencing spatiotemporal patterns in interannual and intra-annual precipitation throughout the LMRB during the water years 1952–2015. The following major conclusions were drawn:

- 1. On the basin scale, the only significant trend was an increase in historical DSP across the LMRB, which was simultaneously contributed by a significant wetting trend in DSP over the LRB. According to the relative trends, such a significant increase in DSP over the LRB was also more noticeable than the increase over the LMRB. Typically, DSP contributed approximately 24.3–26.3% to AP across the LMRB, MRB, and LRB. Despite such a low contribution, both the maximum DSP and AP amounts over all of the three basins occurred in the water year 2000.
- 2. Spatially, significant wetting trends in AP throughout the northern LRB were accompanied by relatively wet dry seasons during the water years 1952–2015. However, the significant increases (decreases) in historical AP found across the northeastern (most western) MRB were primarily driven by wetting (drying) trends of WSP in recent decades. Analysis of the spatiotemporal precipitation variability throughout the LMRB indicated that all of the AP, DSP, and WSP typically increased from the northern LRB to the southern MRB, while there was a decreasing gradient from east to west. Accordingly, the contribution of WSP (DSP) to AP was relatively high (low), approximately 85–90% (25–35%), across the eastern and northeastern MRB, as well as the northern and southeastern LRB (the southern and southwestern MRB).
- 3. Accounting for more than 30% of the total variance, two dominant patterns (EOF1 and EOF2) of annual and seasonal precipitation were highly consistent with the spatial distributions of typical AP, DSP, and WSP over the LMRB. The most important precipitation structure (EOF1) of AP identified (i) a strong positive center in the eastern MRB accompanied by a robust positive EOF1 value of DSP, and (ii) a relatively weak positive center over the southwestern MRB that was supplemented by the substantial positive EOF1 value of WSP. The EOF1 values, however, revealed that variations in AP and WSP (DSP) over the MRB were more complex (identifiable) than those over the LRB.
- 4. The most predominant pattern (PC1) of AP across the LMRB was significantly associated with the SASMI during the 1950s–1980s and the SOI (PDO) after the mid-1980s on the 1- to 3- (approximately 5 to 8) year interannual scale, and with the PDO from 1964 to 2004 on the decadal (9- to 12-year) time scale. The PC1 of DSP on the interannual (decadal) time scale was significantly associated with (i) the ISMI and SASMI before the early 1970s (1990s) based on the lags between 0 and 2–3 months (simultaneous), and (ii) the EP/NP, PDO, and SOI after the 1970s (1990s), with lags ranging from 0 to 3–5 months (simultaneous), lead times between 3–8 and 6–15 months (simultaneous), and lags between 1–3 and 3–6 (0 and 3–4) months, respectively. For WSP, the PC1 was simultaneously associated with the AO before the 1970s, the SASMI and ISMI through the 1980s, and the AMO during the 1990s on the interannual scale of 1–3 years. Both the AO and SASMI also displayed significant coherences on the decadal-scale of 16–22 years from 1974 to 1984, with lead times of 0 and 24–33 months, respectively.
- 5. Spatially, most significant teleconnections correlating with AP and DSP (WSP) were the same over the sections of the LMRB in which the contribution of DSP (WSP) to AP was approximately 25–35% (85–90%). Accordingly, both DSP and AP were most significantly connected to the SOI over the southern and southwestern LMRB. The WSP and AP, however, exhibited the strongest correlations with the WNPMI (SASMI) over the eastern (northeastern) MRB, and the AMO (TPI) across the northern (uppermost northern) LRB.

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