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Key Points:

- Monopole mode of precipitation variability over China during 1470–1849 is evident in a reconstruction using data assimilation
- Monopole mode is associated with a distinct baroclinic structure over the central part of eastern China
- Monopole mode is linked to sea surface temperature anomalies in the South China Sea via a Gill-type response

Supporting Information:

- Supporting Information S1

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Monopole Mode of Precipitation in East Asia Modulated by the South China Sea Over the Last Four Centuries

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Abstract Precipitation in East Asia affects one quarter of the global population. However, the mechanisms governing precipitation changes at the century scale remain unclear. Reconstructions of warm season precipitation over the last 531 years show that the dominant mode of variability is a monopole covering most of China. However, this mode is mostly absent from Coupled Model Intercomparison Project Phase 5 results. In contrast, experiments using data assimilation reproduce this monopole mode well. Results show that sea surface temperature in the South China Sea is a major driver of the monopole mode of precipitation via a Gill-type response. Warm sea surface temperatures induce a distinct baroclinic structure over the central part of eastern China comprising a low-pressure cyclone in the lower troposphere and a high-pressure anticyclone in the upper troposphere with rising airflow, resulting in water vapor convergence and increased precipitation in East Asia.

Plain Language Summary Precipitation in East Asia affects more than one billion people. Although recent changes in precipitation depend on latitude, reconstructions based on paleoclimate archives show that over the last four centuries, East Asia has been characterized by a spatially homogeneous change in precipitation. However, this feature is not present in current climate model simulations. Here, we reproduce this monopole pattern using a combination of model results and observational data using a data assimilation approach and identify the physical processes that lead to this pattern. The observed increase in precipitation over China is due to increased water transport and rising air in this region. These atmospheric circulation changes are linked to a heat source at the surface of the South China Sea caused by higher water temperatures. This work demonstrates that the dominant mode of precipitation variability in East Asia over the past four centuries may differ from the current mode.

Introduction

Investigations of the characteristics and mechanisms governing precipitation changes are important for predicting large-scale trends in droughts and floods in East Asia (Ding et al., 2009; B. Wang et al., 2001). Precipitation variability in this region has been explored over both the recent past, using abundant instrumental meteorological data sets (e.g., Webster & Yang, 1992), and the last several millennia (e.g., Cheng et al., 2016; Guo et al., 2002). However, relatively little is known about precipitation variability over the last few centuries (F. Shi et al., 2017).

Two hypotheses have been proposed in previous studies to describe monsoon precipitation variability in East Asia over the past 500 years. The first suggests that precipitation variability over East China is dominated by multipole meridional patterns that depend on the latitudinal band (e.g., a dipolar or tripolar mode; Feng et al., 2013; Ge et al., 2013; Shen et al., 2009; Wang & Zhao, 1979), whereas the second suggests a homogeneous, monopole mode (F. Shi et al., 2017; H. Shi et al., 2018; Wang & Zhao, 1979).

The first hypothesis was mainly derived from reconstructions based on historical documents. The “north drought and south flood” pattern in eastern China was first observed in the Yearly Charts of

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Dryness/Wetness in China for the Last 500-Year Period data set (Chinese Academy of Meteorological Science, 1981; Shen et al., 2009; Wang & Zhao, 1979). Subsequent analyses of 63 long drought/flood proxy-based indices show drought (flood) in the northern (southern) part of eastern China during four warm periods (650–750, 1000–1100, 1190–1290, and 1900–2000 CE; Hao et al., 2016; Zheng et al., 2014). This pattern was redefined in Ge et al. (2016) as a “drought-flood-drought” tripolar mode for a small drought region in southwestern part of eastern China. This inverse phase of the “northern wet and southern dry” pattern during the Medieval Warm Period (1000–1300 CE) was also found by J. Chen et al. (2015) using a multiproxy record comparison. This meridional precipitation pattern over eastern China persisted over the last 530 years according to a multiproxy gridded warm season precipitation reconstruction for Asia (Feng et al., 2013).

Several studies have provided evidence for the existence of the monopole mode (F. Shi et al., 2017; H. Shi et al., 2018). The monopole was identified as the leading mode using an empirical orthogonal function (EOF) analysis applied to a May–September (MJJAS) precipitation variability reconstruction covering China over the past 500 years, based on tree ring data and historical documents (F. Shi et al., 2017). The EOF main loading is located in the middle and lower reaches of the Yangtze and Yellow Rivers, as shown in Figure 1a1. This was subsequently confirmed and extended to East Asia by H. Shi et al. (2018), based on EOF analyses applied to a summer precipitation reconstruction using mostly the same tree ring data and historical documents (H. Shi et al., 2018).

In contrast, models participating in the fifth phase of the Coupled Model Intercomparison Project Phase 5 do not simulate a monopole mode as the dominant mode of precipitation variability in China over the last five centuries (F. Shi et al., 2017). Here, we use a data assimilation method based on a particle filter (Dubinkina et al., 2011) to drive model output toward signals reconstructed by proxy records. This allows an investigation of the physical mechanisms behind the reconstructed precipitation monopole pattern that are consistent with climate model simulations.

2. Data and Methods

Experiments applying data assimilation based on a particle filter method (Dubinkina et al., 2011) are performed using a reconstruction of MJJAS precipitation over China for the period 1470–2000 CE (F. Shi et al., 2017) as a constraint. The model ensemble is derived from the Community Earth System Model–Last Millennium Ensemble (CESM–LME; Otto-Bliesner et al., 2016).

2.1. Instrumental and Reconstructed Precipitation Data

The high-resolution (0.5° latitude $\times$ 0.5° longitude) MJJAS precipitation reconstruction over China used here is based on 479 proxy records, which include 371 tree ring total ring width chronologies, one tree ring $\delta^{18}\text{O}$ chronology, and 107 drought/flood indices from historical documents using the optimal information extraction method (F. Shi et al., 2017). This data set can successfully reproduce the leading mode of precipitation variability during the instrumental period 1961–2000 CE (compare Figures 1b1–1b3 with Figures 1c1–1c3). This data set is similar to the summer precipitation reconstruction developed by H. Shi et al. (2018), because both data sets are based on many common proxy records (e.g., Chinese Academy of Meteorological Science, 1981; Zhang et al., 2003).

The other seven instrumental precipitation data sets are used to assess the presence of the monopole mode during various periods. The three sea surface temperature (SST) data sets are employed to evaluate the relationship between precipitation and SST (see supporting information Text S1).

2.2. Simulation Results

Data assimilation experiments use model ensembles based on the results of three climate models (CESM, CCSM4, and MPI-ESM-P). The forcings used to drive the simulations throughout the last millennium are those recommended by the third phase of the Palaeoclimate Modelling Intercomparison Project Phase 3 (Schmidt et al., 2012). A brief description of the three models are given in Text S2. Model results are only used for the period 850–1849 CE.

2.3. Data Assimilation Method

The data assimilation method is based on a particle filter and has been applied to several previous paleoclimate assimilation studies (e.g., Hugues Goosse et al., 2012; Mairesse et al., 2013; Klein & Goosse, 2018). In

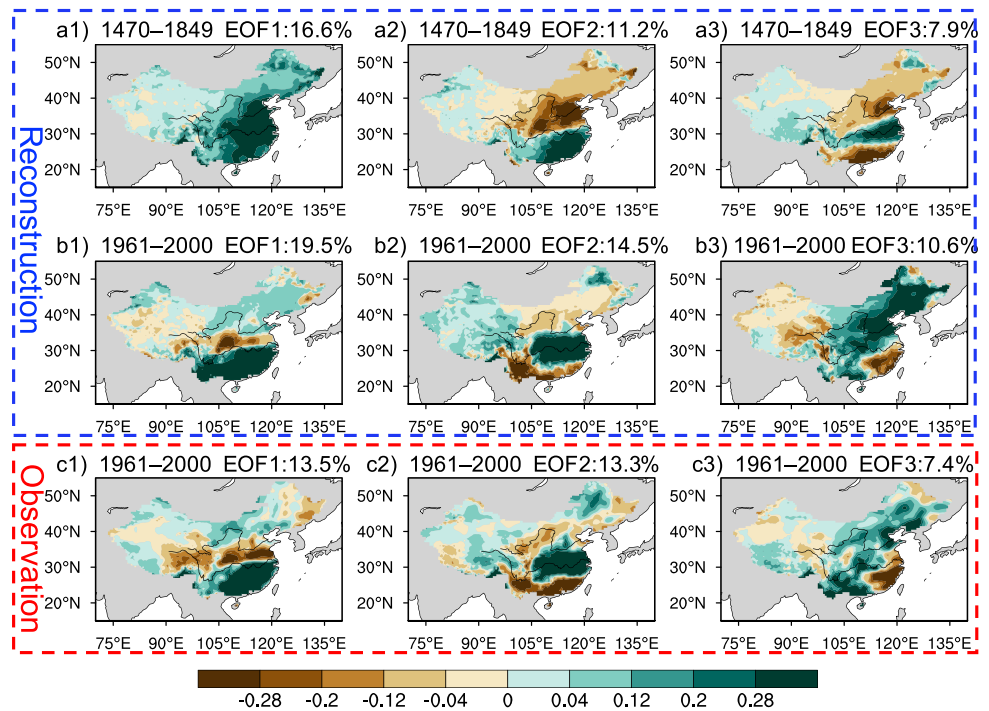


Figure 1. Comparison of the proxy-based reconstructed (a1–b3) and instrumental (c1–c3) May–September precipitation fields in China based on empirical orthogonal function (EOF) analyses.

the particle-filtering method, weights are computed for each model member based on their likelihood (i.e., their agreement with observations) to obtain an estimation of the probability distribution of the system state combining model results and observational data (van Leeuwen, 2009). The reconstruction is then obtained by averaging the model members considering those weights, for all the variables simulated by the model.

Two approaches have been applied in data assimilation in paleoclimatology: offline and online methods. The difference between these methods lies in how the model ensemble is generated. In the offline approach, the ensemble is built once for the entire simulation period, and may come from a preexisting ensemble of simulations, as is the case here. In the online approach, the ensemble is sequentially generated, based on the simulation analysis of previous subperiods, (e.g., Matsikaris et al., 2015). The performance of the online method is expected to be better than the offline method in which the assimilation leads to changes in the states of slowly varying components of the climate system (e.g., assimilating a slow variation of ocean temperature) because the climate model would be able to propagate this information forward in time (Matsikaris et al., 2015).

In this study, an offline approach is used to assimilate the precipitation data in China with 480 members, using the methodology of Klein and Goosse (2018). This approach is used because precipitation variations have no long-term memory. Moreover, a large ensemble of simulations covering the past millennium using a general circulation model would be prohibitively expensive. As only 12 simulations are available from CESM-LME, climate states from different time steps of the simulations are used to produce more members. This approach is only valid if the forcings play a negligible role compared with natural variability (Klein & Goosse, 2018). Based on the frequency over which the various simulations are sampled to produce more members (in addition to the actual year of the data assimilated), experiments using 120, 240, 480, 960, and 2,400 particles are performed.

3. Results and Discussion

3.1. Sensitivity of Data Assimilation-Based Reconstructions to Input Parameters

The impact of data error, the number of data points assimilated, and the number of particles contained in the model ensembles on data assimilation-based reconstructions is assessed (Text S3 and Figure S1). Results are based on data errors calculated as $2 \times \text{RMSError}$, where RMSError is the root-mean-square error of the

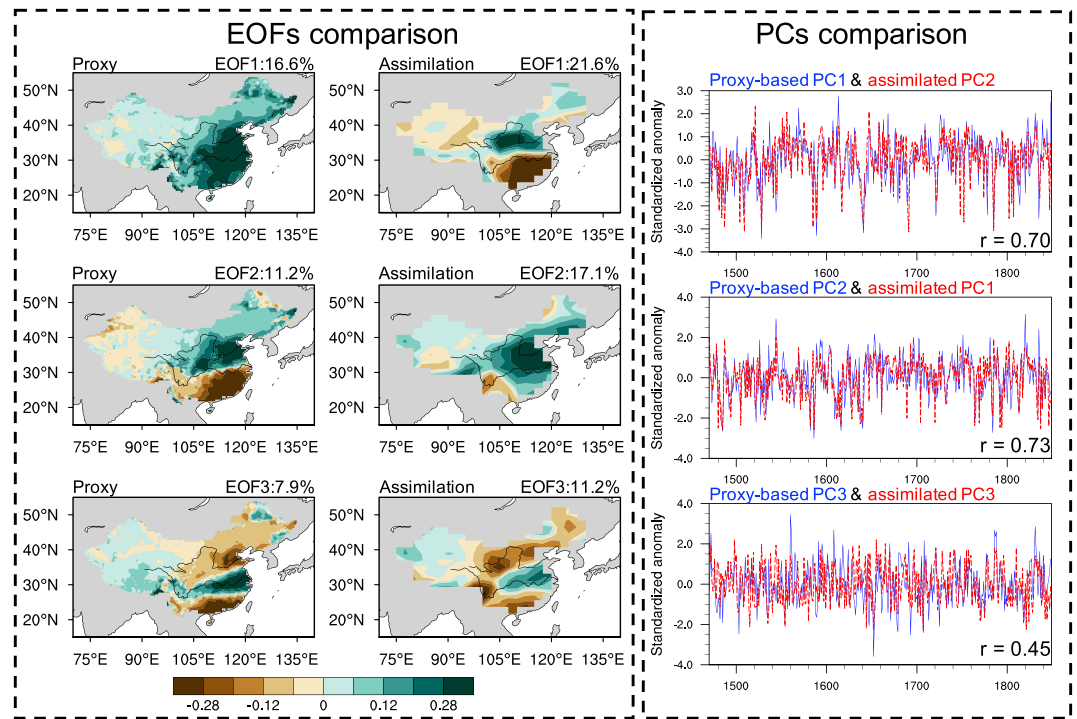


Figure 2. Comparison of the proxy-based reconstructed and data assimilation-based May–September precipitation in China based on empirical orthogonal function (EOF) analyses.

proxy-based reconstructions. This is a good compromise between deviations from the instrumental data and adequate constraints to drive the model ensemble. Based on several tests, 480 particles and 43 grid points are used in the data assimilation experiments analyzed here. The choice of the model used to produce the ensemble is also assessed, with ensembles built from simulations of the past 1,000 years performed with MPI-ESM-P and CCSM4, instead of CESM. The three reconstructions with data assimilation using these three model ensembles show similar monopole modes of precipitation variation in China (Figure S2). In addition, their three time coefficients (principal components [PCs]) are significantly correlated at the 99% confidence level based on a Student's *t* test, but the correlation coefficient between the data assimilation-based reconstructed PC and the proxy-based reconstructed PC for CESM ($r = 0.7$) is larger than those of CCSM4 ($r = 0.5$) and MPI-ESM-P ($r = 0.4$). This indicates that the monopole mode can be roughly reproduced by the three climate models after data assimilation, and the monopole reproduced by the data assimilation reconstruction using multimember simulations of CESM is more accurate than those from reconstructions based on single simulation ensembles of CCSM4 and MPI-ESM-P. This may be due to specific model characteristics or to the number of simulations (see the discussion of model biases in Text S4 and Figures S3–S6).

3.2. EOF Analysis of the Reconstruction With Data Assimilation

To further assess the validity of the data assimilation, a comparison of EOF analyses of the reconstruction based on proxies and the reconstruction with data assimilation is shown in Figure 2. The leading modes are ordered differently in the proxy-based and data assimilation-based reconstructions. The monopole pattern is the first leading mode in the proxy-based reconstruction, whereas it is the second leading mode in the data assimilation-based reconstruction. In the reconstruction with data assimilation, the first EOF has a dipole pattern, as it does in the free model run without data assimilation. After adjusting the order, the spatial pattern of the three leading modes of MJAS precipitation are similar in the data assimilation-based and proxy-based reconstructions. The correlation coefficients between the PCs of the reconstruction based on proxies and the reconstruction with data assimilation are also significant: 0.70, 0.73, and 0.45, respectively. The monopole pattern is also reproduced in the reconstruction with data assimilation (Figure 2), and this can be used to determine its origin.

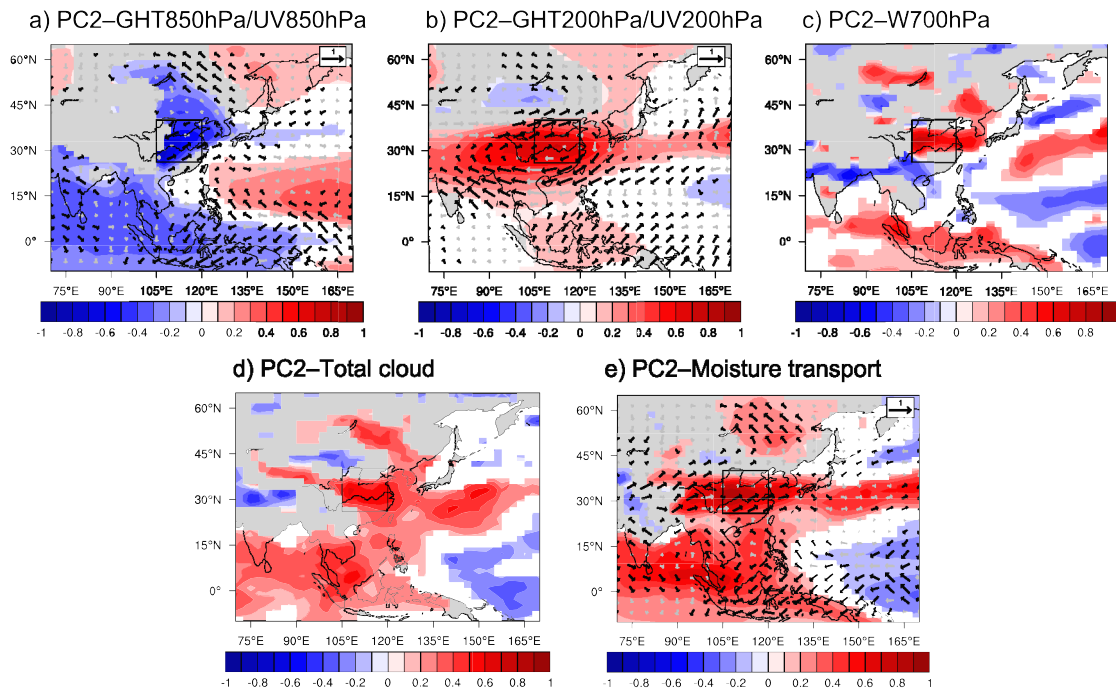


Figure 3. Correlation of the PC of the monopole mode (PC2) with May–September (MJJAS) anomaly patterns for (a) 850-hPa wind (vector) and 850-hPa geopotential height (shading), (b) 200-hPa wind (vector) and 200-hPa geopotential height (shading), (c) 700-hPa vertical velocity ($-\Omega$, shading), (d) total cloud fraction (shading), and (e) vertical integral moisture transport (vector) and precipitable water (shading). The white areas indicate that the correlation does not exceed the 90% confidence level based on a Student's t test. The black arrows correspond to a correlation significant at the 90% confidence level. Gray arrows indicate a Student's t test failure. The black box indicates the central part of eastern China (core region of the EOF2).

3.3. Atmospheric Circulation Corresponding to the Monopole Mode

To understand the physical mechanisms driving the monopole mode of precipitation variability over East Asia in the data assimilation-based reconstruction, Figure 3 shows the circulation (Figures 3a–3c), cloud (Figure 3d), and moisture transport (Figure 3e) anomalies associated with the second PC of precipitation variability over East Asia. The vertical velocity at 700 or 500 hPa is typically used to describe vertical motion in the midlayer atmosphere. Here, results for 700 hPa are similar to those for 500 hPa (Figure S7). Thus, the 700-hPa vertical velocity was chosen for Figure 3c.

Correlation patterns between circulation and the PC of the monopole mode of precipitation variability over East Asia reveal a distinct baroclinic structure over central eastern China, with a cyclonic low in the lower troposphere (Figure 3a), an anticyclonic high in the upper troposphere (Figure 3b), and strong ascending anomalies in the middle troposphere (Figure 3c). In addition to the upward-motion anomalies, significant convergence anomalies of vertically integrated moisture flux accompanied by cyclonic circulating moisture flux anomalies cover most of the middle and lower reaches of the Yangtze and Yellow Rivers (Figure 3e), which enhance the climatological northeastward moisture transport from the Bay of Bengal and the South China Sea (SCS). Accordingly, significant increases in total cloud fraction and precipitable water are seen in the central part of eastern China (Figure 3d and 3e), indicating that anomalous circulation dynamically enhances convection and contributes to increased rainfall over the central part of eastern China.

3.4. Origin of the Monopole Mode

What causes the change in circulation responsible for the monopole mode? There is a significant relationship between warm SST anomalies over the SCS and the monopole mode (PC2; Figure 4a) in the reconstruction with data assimilation. The PC2 exhibits strong interannual and decadal variations in phase with an index computed from SST anomalies averaged over the SCS (100.5–123.5°E, 0.5–23.5°N), with correlation coefficients of 0.63 (Figure 4b1) and 0.74 for a decadal smoothed version (Figure 4b2). This suggests that SSTs in the SCS may affect PC2 variability. The correlations between the vertical velocity (meridional velocity) along 70°–140°E and the PC of the monopole mode are shown in Figure 4c1 (Figure 4c2), and the

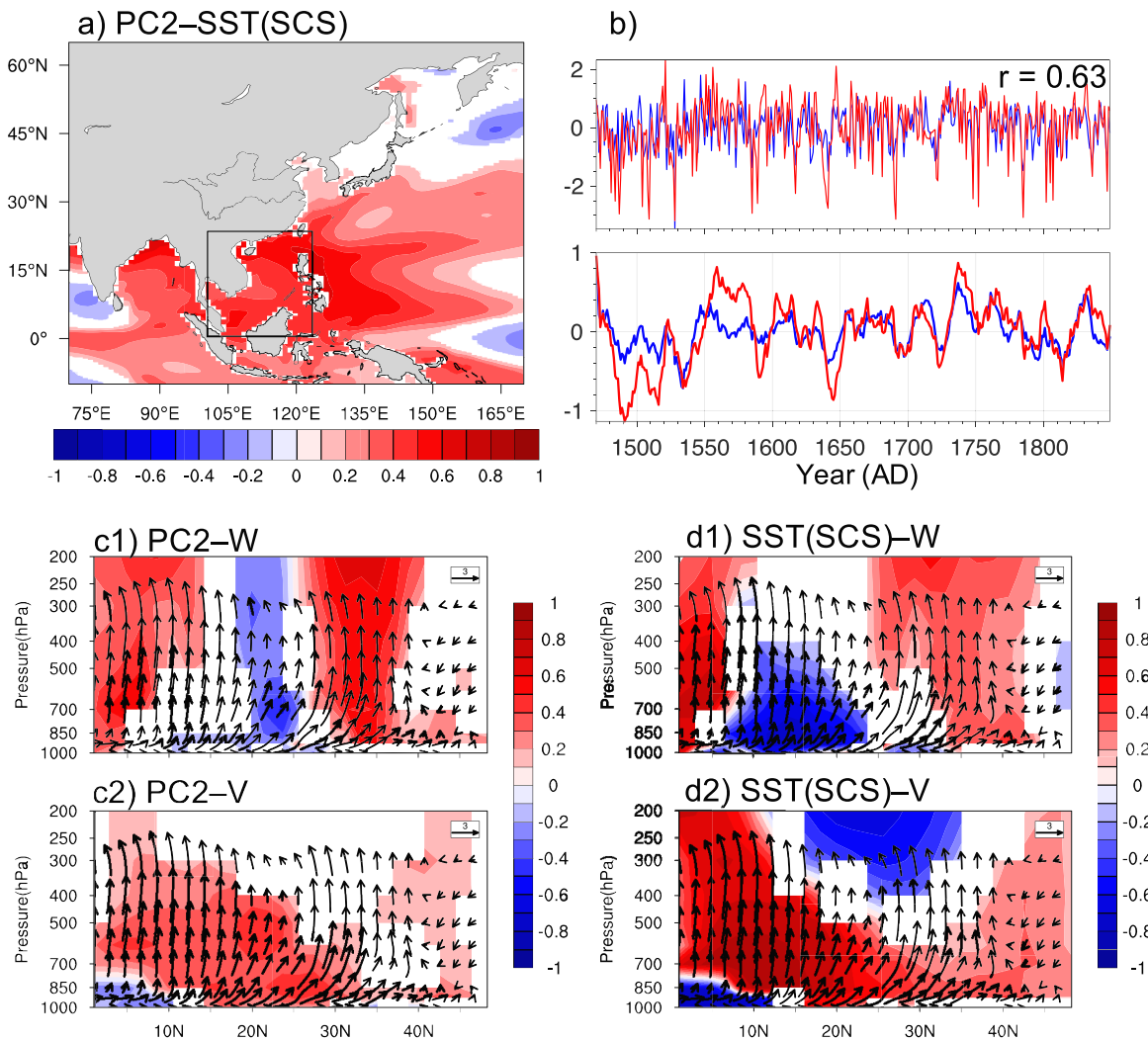


Figure 4. (a) Correlation of the PC of the monopole mode (PC2) with May–September (MJAS) sea surface temperature; (b) comparison of PC2 (red line) of the data assimilation-based reconstructed MJAS precipitation anomalies in China with sea surface temperature anomalies (blue line) in the South China Sea within the black box (100.5–123.5°E, 0.5–23.5°N) for the unfiltered data and the data smoothed using a 13-year running mean; (c and d) correlation of PC2/(the regional mean sea surface temperature anomalies in the South China Sea) with MJAS vertical velocity ($-\Omega$) (c1/d1) and meridional velocity (c2/d2) over East Asia (along 70–140°E). Shading indicates the correlation, and the climatology is indicated by vectors.

correlation of the regional mean SST anomalies in the SCS with vertical velocity (meridional velocity) along 70–140°E is shown in Figure 4d1 (Figure 4d2). These results show that for the positive phase of PC variability, the abnormal updraft in the central part of eastern China (core area of the EOF2; 105–120°E, 26–40°N; box in Figure 4c1) and the abnormal southerly wind in the lower troposphere of the central part of eastern China (Figure 4d1) strengthen the climatological mean state of the updraft and southerly winds. This causes more precipitation anomalies and is consistent with the EOF2 pattern shown in Figure 2. Figures 4c2 and 4d2 also show an abnormal updraft in the central part of eastern China and southerly wind anomalies in the lower troposphere when positive SST anomalies are present in the SCS.

From the above results, we hypothesize that warm SST anomalies in the SCS act as a heat source and excite anomalous cyclonic circulation to their northwest (East Asia). The circulation anomalies shown in Figures 3, 4c, and 4d resemble a Gill solution for the atmospheric response to tropical heating with a center away from the equator (Gill, 1980; Xing et al., 2014). When the heating is symmetric about the equator, anomalous westerlies (easterlies) are induced to the east (west) of the heat source via a Rossby (Kelvin) wave response, with a low-level cyclonic circulation pair to the west and poleward sides. When the heating is located north of the equator, the anomalous cyclonic circulation to the northwest (southwest) of the heat

source is strengthened (weakened). Importantly, the pressure field is in approximate geostrophic balance with the winds, suggesting that the low-pressure center over the central part of eastern China (Figure 3a) is dynamically consistent with warm SST anomalies in the SCS (Figure 4a).

A significant relationship between SSTs in the SCS and the PC of the monopole mode of proxy-based reconstructed MJJAS precipitation in China can also be found in the three observational data sets for the twentieth century (Figure S8). Furthermore, the SCS is the dominant moisture source for precipitation in the Yangtze River Basin region in boreal summer during the instrumental period 2004–2009 CE (Chen et al., 2013). The direct source of subtropical water vapor converges with midlatitude water vapor above the main rainbelt between the lower reaches of the Yangtze and Yellow River valleys during the instrumental period 1951–1999 CE (Zhou & Yu, 2005). The Indian Ocean is also an important moisture source for the other leading mode of East Asian summer monsoon rainfall (e.g., Baker et al., 2015; Zhou & Yu, 2005). However, the monopole mode is not dominant during the twentieth century. Several hypotheses may explain this behavior. The first is that this monopole is only evident at long time scales. The evidence for this is that the monopole is not only dominant over 380 years in the recent past (1470–1849 CE) but is dominant for each century over the last half millennium, although the primary loading zone varies slightly from century to century (Figure S9; e.g., the main loading zone moves to southeastern China during the twentieth century). Further evidence for this hypothesis is that the monopole mode becomes more and more visible in instrumental data sets of MJJAS precipitation as the period covered by these data sets increases (Figures S10 and S11). Moreover, the moisture transport pattern of the monopole mode of MJJAS precipitation during 1470–1849 CE is different than the first leading mode of precipitation during 1961–2000 CE (Text S5 and Figure S12). Alternatively, additional processes may be specific to the late twentieth century (e.g., those related to aerosol forcing) that may dampen the variability associated with the monopole pattern or enhance a dipole pattern (Menon et al., 2002; T. Wang et al., 2013). However, this is difficult to verify given that the effect of aerosols included in these simulations has large uncertainties (Li et al., 2016; Wu et al., 2016).

An additional question is the origin of warm SST anomalies in the SCS. The El Niño–Southern Oscillation (ENSO) is a potential source as it is the largest mode of interannual climate variability in the region (Timmermann et al., 2018). Our results show that the ENSO index calculated from the data assimilation-based reconstructed SSTs is significantly and negatively correlated to the data assimilation-based reconstructed precipitation PC2 ($r = -0.57$) and the proxy-based reconstructed precipitation PC1 ($r = -0.50$) shown in Figure S13. However, the hypothesis that the monopole mode may be affected directly by ENSO through modulating SSTs in the SCS is not valid, as discussed below.

First, the link between the monopole mode and ENSO is less robust between models than the link between the monopole mode and SSTs in the SCS. The data assimilation-based reconstruction using the CCSM4 model ensemble shows a K-shape SST pattern in the Pacific (Figure S14a), which may be related to mega-ENSO variability (B. Wang et al., 2013). The reconstruction using the MPI-ESM-P model shows that the monopole mode is related to a large-scale positive SST anomaly over the whole tropical Pacific Ocean (Figure S14b). In addition, the data assimilation-based reconstruction using the CESM model ensemble displays a “La Niña-like” SST pattern (Figure S14c). The reason for this may be related to model bias (see the discussion of model biases in Text S4 and Figures S3–S6). Second, these patterns relating the monopole mode and SSTs shown in Figure S14 are distinctly different than the Niño 3.4 index and the SSTs shown in Figure S15. Third, there is no significant relationship between the ENSO index reconstructed from data assimilation and the proxy-based reconstructed ENSO index. There is also no significant relationship between the ENSO index reconstructed from data assimilation and the instrumental index shown in Figure S16. This suggests that the precipitation data reconstructed from data assimilation for China is not strongly linked to ENSO and thus the data assimilation does not improve ENSO evolution compared with the instrumental ENSO index. Alternatively, this may indicate a problem with the assimilation or in the teleconnection patterns in CESM (see Text S4 and Figure S6). Finally, the correlation between the proxy-based reconstructed ENSO index and the proxy-based reconstructed precipitation in Figure S17a and in Figure 9 of F. Shi et al. (2017) follows a north-south dipole pattern rather than a monopole pattern in East China. The ENSO index is defined and calibrated by the annual mean (July–June) Niño 3.4 region SST anomalies (McGregor et al., 2010). The reconstructed precipitation based on data assimilation also shows this north-south dipole of correlation with ENSO, except in northeast China (Figure S17b). In addition, the correlation pattern between

the annual mean (July–June) Niño 3.4 region SST anomalies and the data assimilation-based and proxy-based reconstructed MJJAS precipitation indicates a weak north-south dipole (Figure S18).

4. Conclusions

The dominant monopole mode of precipitation variability over the period 1470–1849 found in proxy-based reconstructions in East Asia is reproduced by combining precipitation data and model results from CESM-LME applying a data assimilation technique based on a particle filter method. The EOF main loading of the monopole mode is located in the middle and lower reaches of the Yangtze and Yellow Rivers. This suggests that the monopole mode of the precipitation conforms to physical climate laws used by climate models. Based on an atmospheric circulation analysis, the monopole mode of MJJAS precipitation variability over East Asia is linked with warm SST anomalies in the SCS, which leads to a distinct baroclinic structure over the central part of eastern China via a Gill-type response. Correspondingly, local rising airflow, more water vapor convergence, a greater cloud fraction, and more precipitable water would result in increased rainfall over most of East Asia. However, the origin of the warm SST anomalies in the SCS is still unclear.

This monopole mode provides a large-scale representation of the precipitation-based proxy record and also explains why speleothem records in northern China are significantly correlated with those of southern China (Tan, 2016). Moreover, precipitation in most of China is projected to increase under future representative concentration pathway scenarios (Sun & Ding, 2010), and a homogeneous wetting pattern is projected across China (Tian et al., 2015). This suggests that the monopole mode may be enhanced in the future, and its mechanism will be increasingly important for projecting precipitation in China.

Acknowledgments

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