Impacts of Sea Surface Temperature Factors at Different Time Scales on Summer Precipitation in Eastern Northwest China and Prediction Postprint

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Abstract

Using monthly mean summer precipitation data for eastern Northwest China from 1961-2020, NCEP/NCAR atmospheric reanalysis, and monthly sea surface temperature (SST) data from the UK Hadley Centre, this study employs power spectrum analysis, composite analysis, and multiple linear regression to analyze the dominant SST modes of the interdecadal and interannual precipitation components in eastern Northwest China during summer, and establishes precipitation prediction models using SST factors obtained before and after time-scale separation. The results show: (1) Summer precipitation in eastern Northwest China exhibits not only an interdecadal oscillation period of approximately 30 years, but also a quasi-3-year interannual cycle. The interdecadal component of precipitation is dominated by the Interdecadal Pacific Oscillation (IPO); when the IPO is in its positive phase during spring and summer, it favors a background of above-normal summer precipitation in eastern Northwest China, and vice versa for below-normal precipitation. (2) The dominant signals for the interannual precipitation component originate from the tropical Indian Ocean, tropical western Pacific, and North Atlantic. When the tropical Indian Ocean exhibits a negative (positive) phase of the Indian Ocean Basin-wide warming (IOBW) mode, the North Atlantic displays a positive (negative) phase of the North Atlantic Tripole (NAT) pattern, and the tropical western Pacific shows cold (warm) SST anomalies during spring, it favors the development of high (low) pressure anomalies over the Baikal region in the mid-high latitudes during summer, with the western Pacific subtropical high being weaker (stronger) and positioned more southward (northward), leading to below-normal (above-normal) precipitation in eastern Northwest China. (3) During the independent verification period, the comprehensive score of annual mean trend anomalies (Ps) and the sign consistency rate score (Pc) for summer precipitation in eastern Northwest China based on the time-scale separation model improved by 6% and 7%, respectively, compared with the original model, demonstrating certain predictive capability.

Full Text

The Influence and Prediction of Sea Temperature Factors at Different Timescales on Summer Precipitation in the Eastern Part of Northwest China

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Abstract: Using monthly sea surface temperature (SST) data, NCEP/NCAR reanalysis circulation data, and SST data from the UK Hadley Centre from 1961 to 2020, this study employs power spectrum analysis, composite analysis, and multiple linear regression to investigate the dominant SST modes influencing decadal and interannual variations in summer precipitation over the eastern part of Northwest China. Prediction models for summer precipitation were established using SST predictors both before and after timescale decomposition. The results indicate that summer precipitation in this region exhibits not only a decadal oscillation period of approximately 30 years but also a quasi-3-year interannual cycle. The decadal component of precipitation is dominated by the Interdecadal Pacific Oscillation (IPO). When the IPO maintains a positive phase during spring and summer, it favors a background of above-normal precipitation; conversely, a negative phase corresponds to below-normal conditions. The dominant signals for the interannual precipitation component originate from the tropical Indian Ocean, tropical western Pacific, and North Atlantic. When the tropical Indian Ocean exhibits a basin-wide uniform SST mode with negative (positive) phase, the Atlantic tripole shows a positive (negative) phase, and the tropical western Pacific displays cold (warm) SST anomalies during spring, these conditions favor high (low) pressure anomalies over the Lake Balkhash region in mid-to-high latitudes during summer, with the western Pacific subtropical high being weaker (stronger) and positioned more southward (northward). Consequently, precipitation over the eastern part of Northwest China tends to be below (above) normal. During the independent verification period, the annual average trend anomaly comprehensive score (Ps) and sign consistency rate score (Pc) for the summer precipitation prediction model based on timescale decomposition improved by 6% and 7%, respectively, compared with the original model, demonstrating enhanced predictive capability.

Keywords: time-scale decomposition; sea surface temperature mode; the eastern part of Northwest China; precipitation prediction

1. Data and Methods

1.1 Data

The datasets used in this study include: (1) Monthly precipitation data from 155 national meteorological observation stations in the eastern part of Northwest China (encompassing Shaanxi, Ningxia, Gansu, and western Inner Mongolia), which belong to the same climatic zone; (2) Monthly mean circulation reanalysis data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) with a horizontal resolution of 2.5°$×2.5°, *includinggeopotentialheightandwindfields*; (3)*Seasurfacetemperature*(*SST*)*datafromtheUKM* and (4) Monthly Pacific Decadal Oscillation (IPO) index data from the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory, obtained by applying low-pass filtering to annual mean values.

1.2 Methods

Given that this study focuses on different timescales, we first employ power spectrum analysis to identify the decadal and interannual oscillation periods in the original summer precipitation time series over the eastern part of Northwest China, thereby establishing the precipitation variation patterns at different timescales. Based on the identified decadal period, we extract the corresponding decadal precipitation component using low-pass filtering and determine the SST modes affecting decadal precipitation variations through composite analysis. Similarly, we extract the interannual variation component using high-pass filtering, screen for anomalous precipitation years, apply high-pass filtering to SST and atmospheric circulation anomaly fields to remove decadal signals, and then perform composite analysis on these anomalous years to identify the key SST regions and dominant SST modes at different timescales.

To compare the prediction effects with and without timescale separation, we establish two sets of multiple regression prediction models for summer precipitation at 155 meteorological stations in the study region using original SST precursor factors and timescale-separated SST factors, respectively. The models are evaluated using the trend anomaly comprehensive score (Ps) and sign consistency rate score (Pc) currently employed in China' s short-term climate prediction operations.

2. Decadal Variations in Summer Precipitation over the Eastern Part of Northwest China

Power spectrum analysis of the summer precipitation time series averaged over the eastern part of Northwest China from 1961 to 2020 reveals a significant period of approximately 30 years (figure omitted), representing the decadal oscillation cycle of precipitation and one of the most prominent periods for precipitation in Northwest China. A 3-year quasi-period represents the interannual oscillation cycle.

Filtering can emphasize signals at different timescales. To extract the decadal component of summer precipitation, we apply low-pass filtering (cutoff period of 15 years) to the summer precipitation anomalies. As shown in Figure 1, precipitation generally exhibits a "drought-flood" pattern, with below-normal precipitation dominating before 1977 and above-normal precipitation prevailing after 1977. Notably, summer precipitation in the eastern part of Northwest China shifted from "drought" to "flood" around 1977, coinciding with the interdecadal transition time of the IPO.

To characterize the decadal variations, we standardize the decadal precipitation component and define periods with absolute values exceeding 0.5 standard deviations as "drought periods" (below-normal precipitation) and "flood periods" (above-normal precipitation). The "drought period" is further specified as 1961–1976, while the "flood period" spans 1977–2020. The average precipitation during the "drought" and "flood" periods is 185.7 mm and 228.0 mm, respectively, with a difference of 42.3 mm. For a region like the eastern part of Northwest China where precipitation is generally scarce, this indicates substantial differences in precipitation across different decadal backgrounds. Additionally, the standard deviations for the "drought" and "flood" periods are 32.5 mm and 47.0 mm, respectively, indicating greater interannual variability and more pronounced anomaly amplitudes during the "flood period."

Composite analysis of global SST anomaly fields during spring and summer for the "drought" and "flood" periods reveals the dominant SST modes affecting the decadal component of summer precipitation. During the "drought period" spring (Figure 2a), Pacific SST anomalies exhibit a "warm-cold-warm" tripole pattern from north to south, with warm anomalies in the mid-to-western North Pacific (120°E–160°W, 25°N–50°N), cold anomalies in the tropical central-eastern Pacific (10°S–10°N, 180°W–90°W), and warm anomalies off the east coast of the North American continent. The southern hemisphere shows significant cold SST anomalies east of the dateline (15°S–50°S). This pattern represents a negative IPO phase. During the "drought period" summer (Figure 2b), the Pacific tripole SST anomaly pattern remains largely unchanged, with the negative IPO phase persisting.

During the "flood period" spring (Figure 2c), Pacific SST anomalies are opposite to those in the "drought period," with significant cold SST anomalies in the mid-to-western North Pacific, warm anomalies along the east coast of North America and in the tropical central-eastern Pacific, and cold anomalies east of the dateline in the southern hemisphere. This "cold-warm-cold" pattern represents a positive IPO phase that persists from spring through summer. The correlation coefficient between the filtered spring (March–May) IPO index and the decadal component of summer precipitation over the eastern part of Northwest China is 0.42, significant at the 99% confidence level, indicating a close relationship.

The analysis demonstrates that the background field of summer precipitation over the eastern part of Northwest China is dominated by the decadal-scale IPO SST mode. When the IPO maintains a positive phase during spring and summer, it favors a background of above-normal precipitation; conversely, a negative phase favors below-normal conditions. The IPO' s influence appears more significant during the "flood period," suggesting an asymmetric effect across different precipitation backgrounds, though the decadal SST signal remains consistent overall.

3. Interannual Variations in Summer Precipitation over the Eastern Part of Northwest China

The original precipitation time series contains both decadal and interannual variations, with these two scales typically mixed together. Therefore, when discussing interannual variations, we remove the decadal component to isolate the interannual signal. Using high-pass filtering (cutoff period of 15 years), we extract the interannual component with a period of approximately 3 years. Years with interannual component anomalies exceeding 0.75 standard deviations are defined as anomalously high or low precipitation years, yielding 11 high-precipitation years (1964, 1967, 1978, 1979, 1981, 1983, 1988, 1990, 1996, 2003, 2018) and 11 low-precipitation years (1965, 1966, 1969, 1972, 1974, 1980, 1982, 1986, 1991, 1995, 1997). We apply high-pass filtering to SST and circulation anomaly fields and perform composites for these anomalous years to examine the characteristics of SST and atmospheric interannual components that independently influence precipitation after removing decadal signals.

Composite analysis of spring SST anomalies for low-precipitation years (Figure 3a) and high-precipitation years (Figure 3c) reveals opposite patterns. During low-precipitation years, the Pacific shows weak overall anomalies with significant cold SST anomalies in the South Pacific. The IPO-like feature is weak, while prominent SST signals concentrate in the Indian Ocean to western Pacific region, all showing warm anomalies. The Indian Ocean exhibits a basin-wide uniform SST mode (IOBM) positive phase, while the North Atlantic shows a "warm-cold-warm" pattern resembling a weak negative phase of the Atlantic tripole. During high-precipitation years spring, the patterns are reversed, with significant cold SST anomalies in the tropical eastern Pacific and warm anomalies in the western Pacific warm pool, representing a typical La Niña pattern. The Indian and Atlantic Oceans show minimal interannual SST signals.

During summer (Figure 3b, d), key SST regions adjust significantly compared to spring. For low-precipitation years, the Oyashio region in the North Pacific (20°N-40°N, 140°E-170°E) shows warm SST anomalies, while the equatorial Pacific exhibits a "west-cold, east-warm" El Niño pattern. For high-precipitation years, the equatorial eastern Pacific shows significant cold anomalies, the western

Pacific warm pool shows warm anomalies, and the Atlantic displays a "cold-warm-cold" tripole pattern similar to the North Atlantic Tripole (NAT) but with the low-latitude "warm-cold" anomalies shifted westward.

These analyses indicate that precursor signals dominating the interannual component of summer precipitation likely originate from the tropical Indian Ocean, tropical western Pacific, North Atlantic, and South Pacific. Specifically, negative (positive) IOBM phase, positive (negative) NAT phase, cold (warm) SST anomalies in the tropical western Pacific, and warm (cold) SST anomalies in the South Pacific favor below-normal (above-normal) interannual precipitation components. The South Pacific SST anomalies may partially reflect the influence of the IPO' s decadal scale.

Atmospheric circulation anomalies directly cause precipitation anomalies. To investigate circulation changes at interannual scales, Figure 4 presents composite fields of summer 500 hPa geopotential height anomalies for anomalous precipitation years. During low-precipitation years (Figure 4a), geopotential height anomalies over the Eurasian mid-to-high latitudes (near Novaya Zemlya, Lake Balkhash to Northeast China, and the subtropical western Pacific) show a "negative-positive-negative" pattern, with most areas passing the 95% significance test. This represents an eastward-propagating zonal teleconnection wave train across mid-to-high latitudes, likely forced by Atlantic SST anomalies. The Ural high-pressure ridge is weak, while high-pressure anomalies dominate the Lake Balkhash to Lake Baikal region, resulting in relatively weak cold air moving southward to mid-latitudes. Influenced by cold SST anomalies in the Indian Ocean during spring and summer (Figure 3a, b), the western Pacific subtropical high is weak, creating poor water vapor transport conditions and thus unfavorable for above-normal summer precipitation.

During high-precipitation years (Figure 4b), the 500 hPa geopotential height anomalies are opposite to those in low-precipitation years, showing a "positive-negative-positive" pattern. The Ural high-pressure ridge is strong and extends eastward, while an anomalous low-pressure system exists over Lake Balkhash to Lake Baikal. Influenced by warm Indian Ocean SST anomalies (Figure 3c, d), the western Pacific subtropical high is strong and positioned westward and northward. The mid-to-high latitudes of China exhibit a "west-low, east-high" pattern, with cold air moving southward through the Ural ridge and being transported southward and eastward by the low-pressure system over Lake Baikal. The eastern part of Northwest China is located on the western edge of this anomalous anticyclone, where the airflow originates from the relatively moist Pacific, favoring above-normal summer precipitation.

Figure 5 shows 700 hPa wind anomalies for anomalous precipitation years. During low-precipitation years (Figure 5a), an anticyclonic circulation anomaly east of Lake Baikal influences the study region with northeasterly winds that originate from the continental anticyclone rather than the western Pacific, resulting in insufficient moisture and unfavorable precipitation conditions. During high-precipitation years (Figure 5b), an anticyclonic circulation anomaly extends from eastern China to southern Japan, with its center near 130°E. Tropical easterly anomalies transport moisture northward and then eastward into this anticyclonic circulation, placing the eastern part of Northwest China on its western side where the airflow from the Pacific is relatively moist, favoring above-normal precipitation.

4. Application of Summer Precipitation Prediction over the Eastern Part of Northwest China Based on Timescale Decomposition

The above analyses demonstrate that precipitation components at different timescales over the eastern part of Northwest China are influenced by distinct SST modes. To further illustrate the role of timescale separation in predicting regional interannual precipitation anomalies, we screen precursor SST signals using the original precipitation time series and establish two summer precipitation prediction models for the 155 meteorological stations based on original and timescale-separated SST anomalies.

We rank the original summer precipitation series and define typical anomalous years using the top and bottom 11 years (based on precipitation anomalies). Low-precipitation years are 1965, 1966, 1969, 1972, 1974, 1980, 1982, 1986, 1991, 1995, and 1997; high-precipitation years are 1964, 1967, 1978, 1979, 1981, 1983, 1988, 1990, 1996, 2003, and 2018. Composite analysis of SST anomalies for these years identifies the key precursor SST factors. As shown in Figure 6, the equatorial eastern Pacific (5°S-5°N, 120°W-80°W) and tropical northwestern Pacific (15°S-20°N, 105°E-135°E) are key precursor regions, referred to as the equatorial eastern Pacific SST index (SSTI_1) and tropical northwestern Pacific SST index (SSTI_2). Notably, while the spatial distribution of original SST anomalies (Figure 6) shows some similarity to the interannual component fields (Figure 3), particularly regarding the importance of the tropical western Pacific, the interannual component fields reveal additional significant modes such as the IOBM-like pattern and South Pacific SST anomalies that are not apparent in the original SST composites.

Based on the five interannual SST component indices (SSTI_3, SSTI_4, SSTI_5) and the decadal IPO signal, we establish a multiple regression prediction model for summer precipitation at each station, termed the scale-separated model. For comparison, we also develop an original model using SSTI_1 and SSTI_2. The modeling period is 1961-2010, with independent verification for 2011-2020.

During the modeling period, the scale-separated model shows improved fitting performance compared to the original model. The average explained variance is 35% for the original model versus 42% for the scale-separated model. Using China' s operational short-term climate prediction scoring method, the scale-separated model demonstrates higher Ps and Pc scores in the independent verification period (Figure 7). Specifically, the annual average Ps score is 6% higher (relative error reduction of 15% compared to the original model' s 9%), and the Pc score is 7% higher (relative error reduction of 16% compared to the original model' s 9%). These results indicate that the SST prediction model based on timescale decomposition outperforms the original model overall, confirming that timescale separation is an effective method for identifying external forcing factors and that objective prediction methods based on this approach hold promise for short-term climate prediction.

5. Conclusions

Using monthly precipitation data from 155 national stations, NCEP/NCAR reanalysis data, and Hadley SST data from 1961 to 2020, this study employs a timescale decomposition approach to investigate the dominant SST modes influencing decadal and interannual components of summer precipitation over the eastern part of Northwest China. Precursor factors extracted from these SST modes are used to construct a timescale-decomposition-based prediction model, which is compared with a model using original SST data. The main conclusions are:

1) Summer precipitation over the eastern part of Northwest China exhibits a significant decadal oscillation period of about 30 years and a quasi-3-year interannual cycle. The precipitation shows "drought-flood" variations from 1961 to 2020, with more pronounced anomaly amplitudes during the "flood period." The decadal component is dominated by the IPO, whose positive phase during spring and summer favors above-normal precipitation backgrounds, while its negative phase favors below-normal conditions.
2) The interannual component of summer precipitation is influenced by precursor signals from the tropical Indian Ocean, tropical western Pacific, and North Atlantic. During spring, when the IOBM is in negative (positive) phase, the Atlantic tripole is in positive (negative) phase, and the tropical western Pacific shows cold (warm) SST anomalies, the summer circulation features high (low) pressure anomalies over Lake Balkhash in mid-to-high latitudes, with the western Pacific subtropical high being weaker (stronger) and positioned more southward (northward). This results in a "west-high, east-low" ("west-low, east-high") geopotential height pattern over China' s mid-to-high latitudes, favoring below-normal (above-normal) precipitation.
3) During the 2011–2020 independent verification period, the scale-separated model shows significantly improved prediction skill, with annual average Ps and Pc scores increasing by 6% and 7%, respectively, compared to the original model. Overall, SST factors obtained through timescale decomposition demonstrate predictive utility, and the resulting precipitation model achieves higher accuracy.

Timescale decomposition proves valuable for screening external forcing factors and establishing objective prediction methods for short-term climate forecasting.

However, the climate system is extremely complex, involving interactions across timescales and nonlinear relationships among numerous factors. Future work should incorporate additional physically meaningful forcing signals and consider nonlinear relationships to further improve prediction models.

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