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Synergistic Effects of Sea Ice and Sea Surface Temperature on June Precipitation Anomalies in Central Northwest China: A Postprint

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Abstract

Using NCEP monthly mean reanalysis wind and height fields since 1961, NOAA reconstructed sea surface temperature, daily precipitation data in June from 54 meteorological stations in central Northwest China, and Arctic sea ice area in 10 regions since 1979, this study analyzes the causes of the June 2019 precipitation anomaly in central Northwest China to reveal the key sea ice areas and time periods that significantly influence June precipitation in this region, as well as the key influence periods of the North Atlantic Tripole (NAT). Combined with El Niño–Southern Oscillation (ENSO) events, their synergistic effects and influence mechanisms are analyzed. The results show that: since 1990, sea ice area anomalies in the Chukchi Sea during spring (March–April) tend to excite the EU2 (Eurasian type 2) teleconnection pattern in the mid-high latitudes of Eurasia (i.e., the summer EU (Eurasian) teleconnection pattern), which is favorable for precipitation anomalies in central Northwest China; since 1992, spring NAT has a significant influence on the EU2 teleconnection pattern, but its influence is smaller than that of the Chukchi Sea sea ice area; when the Chukchi Sea sea ice area is low and NAT is in its positive phase (or when sea ice area is high and NAT is in its negative phase), their synergistic effect significantly increases the probability of increased (decreased) precipitation in central Northwest China; ENSO events have no significant direct impact on June precipitation in central Northwest China, but in the year following an El Niño event, the subtropical high becomes abnormally strong and westward. In 2019, the Chukchi Sea sea ice area was abnormally low, and spring NAT was abnormally strong; under their synergistic effect, the EU2 teleconnection pattern exhibited positive anomalies (“+ - + -”), particularly causing the blocking high near Lake Baikal to be abnormally strong and the low pressure near the Sea of Okhotsk and Ural Mountains to be abnormally deep; the El Niño event caused the subtropical high to be abnormally strong and westward, transporting moisture from the western Pacific to the North Pacific, where it connected with the deep low pressure near the Sea of Okhotsk; sufficient cold air and moisture led to anomalous precipitation in central Northwest China. The research results can provide a basis for short-term climate prediction, while atmosphere-ice-ocean interactions require further study.

Full Text

Synergistic Effects of Sea Ice and Sea Surface Temperature on June Precipitation Anomalies in Central Northwest China

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Abstract

Using monthly mean reanalysis wind field and geopotential height data from the National Centers for Environmental Prediction (NCEP), NOAA reconstructed sea surface temperature data, daily precipitation data for June in central Northwest China, and Arctic sea ice area data from ten regions since 1979, this study analyzes the causes of June precipitation anomalies in central Northwest China. The key sea ice areas and time periods that significantly influence June precipitation in this region are identified, along with North Atlantic Triple (NAT) events. The synergistic effects and influence mechanisms of these factors are examined. The results show that: (1) The relationship between precipitation and the 500 hPa height field in central Northwest China changed significantly in June. Since the 1990s, when the height anomaly field distribution in mid-high latitudes follows the Eurasian 2 (EU2) teleconnection pattern (i.e., the summer EU teleconnection pattern), precipitation anomalies are favored. When EU2 is in its positive phase, precipitation tends to be above normal, and vice versa. (2) The influence of March-April Chukchi Sea ice area and spring NAT on the 500 hPa height field changed markedly around 1990 and 1992, respectively. Both factors significantly affect the EU2 teleconnection pattern, but NAT' s influence is smaller than that of Chukchi Sea ice area. When sea ice area is reduced and NAT is in its positive phase (or when sea ice area is increased and NAT is in its negative phase), the probability of above-normal (below-normal) precipitation in central Northwest China increases substantially. (3) ENSO events have no direct impact on June precipitation, but El Niño events in the following year cause the subtropical high to be abnormally strong and westward. In 2019, the Chukchi Sea ice area was abnormally low while spring NAT was strongly positive, resulting in a positive EU2 teleconnection anomaly. The El Niño event transported water vapor from the western Pacific to the North Pacific, which combined with the EU2 teleconnection pattern to bring sufficient cold air and moisture, leading to abnormal precipitation in central Northwest China. These findings can provide a basis for short-term climate prediction, though further research is needed on the interactions between the atmosphere, ice, and ocean.

Keywords: central Northwest China; abnormal precipitation; atmospheric circulation; sea ice area; sea surface temperature; synergistic impact

1. Introduction

Central Northwest China, comprising Gansu and Ningxia provinces between 103°E and 108°E, experiences a dry and semi-arid temperate continental climate at the boundary between monsoon and non-monsoon regions. Precipitation is scarce with large interannual variability, and the ecosystem is vulnerable. Even precipitation below storm magnitude can cause significant disasters. In June 2019, both precipitation amount and rainy days were markedly above normal across most of central Northwest China, with frequent heavy rainfall events and rare continuous low-temperature rainy weather. Particularly in Ningxia and the Hexi Corridor of Gansu, precipitation exceeded normal by more than double. This anomalous precipitation caused substantial adverse impacts on agriculture during critical growth periods, especially for wolfberry at maturity and wheat at the filling stage. Given that June precipitation accounts for only 30-40% of total summer rainfall, studies focusing on entire summer seasons may not fully explain monthly anomalies. Moreover, previous research on Northwest China often used regional average precipitation, but responses to external forcing factors vary across this topographically complex region.

Most studies on summer precipitation anomalies in Northwest China have focused on tropical sea surface temperature (SST) forcing, particularly ENSO. However, ENSO events during their development phase tend to produce below-normal rainfall in eastern Northwest China, especially in June. Other research has linked summer precipitation to the position and intensity of the Northwest Pacific subtropical high, though some studies find little influence from the subtropical high on June precipitation. Spring warming of the Indian Ocean equatorial SST and winter warming of the central-eastern Pacific have also been associated with extreme summer precipitation events.

Arctic sea ice, as a driver of global climate change, has decreased significantly under climate warming and affects mid-latitude regions through various feedback mechanisms, causing extreme weather events. However, research specifically on June precipitation in central Northwest China remains limited. While some studies have examined relationships between eastern Northwest China precipitation and ENSO, the role of Arctic sea ice amplification effects on this mid-latitude region' s June precipitation anomalies remains unclear. Furthermore, the Atlantic Ocean, as the second largest water body, can directly influence western China' s weather and climate through mid-latitude westerlies. The synergistic effects of multiple anomalous factors may have greater impacts than individual factors alone. Therefore, this study investigates the causes of June precipitation anomalies in central Northwest China, identifies key sea ice areas and periods, and analyzes the synergistic effects and mechanisms of Chukchi Sea ice, North Atlantic Triple (NAT), and ENSO events to provide a basis for short-term climate prediction.

1.1 Data

The study region includes 54 meteorological stations in Gansu and Ningxia provinces. Daily precipitation data from China' s National Meteorological Information Center are used for June. Atmospheric circulation data from NCEP/NCAR reanalysis include geopotential height, wind field, and water vapor flux at 2.5°$×$2.5° resolution. Sea surface temperature data are from NOAA Extended Reconstruction SST (ERSST). Arctic sea ice area data for ten regions are obtained from ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/seaice_{analysis}/. NAT events are from China' s National Climate Center operational network. The climatological baseline period is 1981-2010.

1.2 Methods

Primary statistical methods include correlation and composite analysis. Partial correlation analysis is used when multiple variables interact, allowing examination of relationships while controlling for other factors. For example, when analyzing relationships between dependent variable y and independent variables x_1 and x_2, partial correlation coefficients r_{y1·2} and r_{y2·1} represent the correlation between y and each x while eliminating the influence of the other variable.

2. Characteristics of June 2019 Precipitation Anomaly in Central Northwest China

In June 2019, precipitation amount and rainy days were exceptionally high across central Northwest China. Regional average precipitation reached 84.5 mm, 84.5 mm above normal and ranking first since records began. Precipitation exceeded normal by more than double in most areas, with 11 stations setting new records. Average rainy days were 13.7 days, also a record high, with most areas experiencing 2-7 days of continuous rain—a rare event for June. Some locations recorded their longest continuous rainy periods of the year, with Zhongwei experiencing heavy rain on dates that ranked earliest in local records.

[Figure 1: see original paper]

3. Atmospheric Circulation Anomalies in June 2019

At 500 hPa, the Eurasian region exhibited a "+ - + -" wave train pattern: a high-pressure ridge over Europe (Region A), a blocking high from North China across Lake Baikal to East Siberia and Lake Balkhash (Region C), and long-wave troughs in the Novaya Zemlya-Okhotsk Sea area (Region B) and east of Japan (Region D). The anomaly field showed this "+ - + -" distribution, with negative anomalies in Regions B and D exceeding 80 gpm below normal and positive anomalies in Regions A and C exceeding 80 gpm above normal. Central Northwest China was located at the base of the blocking high in Region C, representing a typical "west low-east high" pattern. High geopotential heights over the polar region facilitated cold air outbreaks, while high heights in low latitudes helped maintain cold air over eastern Northwest China.

[Figure 2: see original paper]

At 700 hPa, the wind anomaly field showed anticyclonic circulation in Region A and cyclonic circulation in Region B. The western Pacific subtropical high was abnormally strong and westward, with its western ridge point reaching 104.68°E—second only to 1998. This configuration transported moisture from the western Pacific east of the Bay of Bengal along the subtropical high' s edge from South China to the North Pacific, connecting with the cyclone in Region B. The strong anticyclone in Region A guided cold air from East Siberia southward, while the deep cyclone in Region B guided warm moist air from the North Pacific northward. These air masses converged near the Okhotsk Sea, with one branch moving directly westward and another continuing northward before turning west to converge with polar cold air near Lake Baikal, eventually reaching central Northwest China.

[Figure 3: see original paper]

[Figure 4: see original paper]

4. Causes of June Precipitation Anomalies in Central Northwest China

Since precipitation amount and rainy days show significant positive correlation ($r = 0.97$), precipitation amount is used for analysis.

4.1 500 hPa Height Field

The "+ - + -" wave train in the mid-high latitude 500 hPa height field significantly impacts precipitation anomalies in central Northwest China. Correlation analysis between June precipitation and concurrent height field reveals that the relationship stabilized after the 1990s. The correlation pattern (Fig. 5) shows the EU2 teleconnection pattern, with significant positive correlations over central Europe and North China, and negative correlations over the Ural Mountains and east of Japan. The polar region shows negative correlation, while low latitudes show broad positive correlation. Although the anomaly centers in June 2019 differ slightly in position, their distribution matches the correlation pattern well.

[Figure 5: see original paper]

To diagnose external forcing factors affecting precipitation through the EU2 pattern, four key regions at high and low correlation centers are selected: central Europe (A), Ural region (B), North China (C), and east of Japan (D). The EU2 intensity index is defined as:

$$EU2I = 0.25Z\_A - 0.25Z\_B + 0.25Z\_C - 0.25Z\_D$$

where Z represents standardized 500 hPa height anomalies. Positive EU2I corresponds to above-normal precipitation, negative to below-normal.

4.2 Chukchi Sea Ice Area

4.2.1 Sea Ice and 500 hPa Height Field Arctic sea ice influences China' s climate through atmospheric circulation responses. Moving correlation analysis between Arctic regional sea ice areas and EU2I reveals that the relationship between March-April Chukchi Sea ice area and EU2I shifted from positive to negative correlation around 1990 (Fig. 6). Since 1990, they have maintained significant negative correlation ($r = -0.55$, exceeding 0.01 significance level). When sea ice area is reduced, EU2I tends to be positive, and vice versa. The opposite rate reaches 73.3%.

[Figure 6: see original paper]

The correlation pattern between Chukchi Sea ice area and 500 hPa height field (Fig. 8) shows a distribution opposite to the precipitation-height correlation pattern, with high correlation areas overlapping the anomaly centers in June 2019 (Fig. 2). This indicates that reduced Chukchi Sea ice area in March-April can excite the EU2 teleconnection pattern, strengthening blocking highs over Europe and Lake Baikal-East Siberia while deepening troughs over the Ural Mountains and Okhotsk Sea. This enhances both polar cold air and North Pacific warm moisture transport, while positive height anomalies in tropical regions help maintain the convergence of these air masses over central Northwest China, leading to precipitation anomalies.

[Figure 7: see original paper]

[Figure 8: see original paper]

The relationship between actual precipitation in central Northwest China and Chukchi Sea ice area shows correlation coefficient $r = -0.48$ (significant at 0.05 level) with 63.2% opposite rate. In years with reduced sea ice, precipitation was above normal in 72.7% of cases. Among years with precipitation exceeding one standard deviation since 1990, most corresponded to reduced sea ice, including 2019 when ice area ranked second lowest.

[Figure 9: see original paper]

4.2.2 Sea Ice, Wind Field, and Water Vapor Transport Compositing years with anomalously low and high Chukchi Sea ice area (exceeding 0.5 standard deviation) reveals significant differences in 700 hPa wind anomalies and vertically integrated water vapor transport (Fig. 10-11). In low ice years, the anticyclone north of Region A and the cyclone north of Region B are stronger than in high ice years, enhancing convergence near the Ural Mountains. South of 40°N, differences are significant over the Pacific and Indian Oceans. In low ice years, moisture primarily originates from the western Pacific, transported by easterly winds north of an anomalous cyclone. Vertically integrated water vapor flux shows convergence over central Northwest China in low ice years, creating anomalous moisture convergence.

[Figure 10: see original paper]

[Figure 11: see original paper]

Thus, reduced Chukchi Sea ice enhances the EU2 teleconnection pattern, strengthening cold air from the polar region and guiding warm moisture from the western Pacific northward.

4.3 Synergistic Effects of Multiple Factors

4.3.1 North Atlantic SST Influence Moving correlation analysis between monthly NAT and EU2I shows weak negative correlation before the early 1990s, shifting to positive correlation after 1992, reaching significance at 0.10 level (Fig. 8). The 500 hPa height pattern associated with NAT positive phase resembles that of reduced Chukchi Sea ice, though with some differences in center positions. The partial correlation coefficient between NAT and EU2I is 0.40 (significant at 0.05 level), while that between sea ice area and EU2I is -0.55. After eliminating NAT' s influence, the sea ice-EU2I correlation remains -0.48; after eliminating sea ice' s influence, the NAT-EU2I correlation reduces to 0.28, indicating sea ice has greater influence on EU2 than NAT.

The difference in 500 hPa height fields between combined phases shows that when reduced sea ice coincides with NAT positive phase, positive anomalies in Region A and negative anomalies in Region B are enhanced (Fig. 12). Conversely, when increased sea ice coincides with NAT negative phase, the opposite pattern is strengthened (Fig. 13). This demonstrates that NAT positive phase enhances (while negative phase weakens) the EU2 teleconnection pattern excited by reduced Chukchi Sea ice.

[Figure 12: see original paper]

[Figure 13: see original paper]

Table 1 shows precipitation outcomes for four sea ice-NAT configurations. When sea ice is reduced and NAT is positive, precipitation is above normal in 80% of cases. When sea ice is increased and NAT is negative, precipitation is below normal in 75% of cases. Antagonistic combinations (reduced ice/negative NAT or increased ice/positive NAT) show weaker signals, with 50-57% of cases following the sea ice phase. In 2019, with record-low sea ice and strongly positive NAT, the probability of above-normal precipitation was maximized.

4.3.2 El Niño Event Influence While El Niño events in the following year make the subtropical high abnormally strong and westward, analysis shows that March-April Chukchi Sea ice area and spring NAT have no direct effect on this. Among 11 years since 1990 when the subtropical high' s western ridge point was west of 110°E, 8 were El Niño event years. In reduced sea ice years, precipitation was above normal in 80% of cases when the western ridge point exceeded 110°E, compared to 66.7% when it was east of 110°E. This suggests the subtropical high' s position modulates but doesn' t directly cause precipitation anomalies.

The 500 hPa and 700 hPa wind anomaly patterns in El Niño event years differ from 2019, showing "west high-east low" patterns unfavorable for precipitation. However, in low latitudes, El Niño years resemble 2019 with anomalous anticyclones over the South China Sea to Pacific region. Thus, while El Niño doesn' t directly impact June precipitation, it enhances the subtropical high, transporting western Pacific moisture to the North Pacific where it connects with the deep Okhotsk Sea low pressure associated with the EU2 pattern. This synergy between reduced Chukchi Sea ice (exciting EU2) and El Niño (enhancing moisture transport) provides sufficient cold air and moisture for abnormal precipitation in central Northwest China.

5. Conclusions

Analysis of the 2019 precipitation anomaly in central Northwest China reveals that the relationship between June precipitation and the 500 hPa height field changed significantly after the 1990s. When the mid-high latitude height anomaly field follows the EU2 teleconnection pattern, precipitation anomalies are favored. The EU2 intensity index, defined by height anomalies in four key regions, shows that positive phase corresponds to above-normal precipitation.

Both March-April Chukchi Sea ice area and spring NAT significantly influence the EU2 teleconnection pattern, with sea ice having greater impact. When reduced sea ice coincides with NAT positive phase (or increased sea ice with NAT negative phase), the probability of above-normal (below-normal) precipitation increases substantially. ENSO events have no direct effect on June precipitation, though El Niño events strengthen and westward-extend the subtropical high.

In 2019, record-low Chukchi Sea ice area and strongly positive NAT enhanced the EU2 teleconnection pattern, while an El Niño event transported moisture from the western Pacific to the North Pacific. This synergy between sea ice, Atlantic SST, and tropical Pacific conditions provided sufficient cold air and moisture, resulting in abnormal precipitation in central Northwest China.

6. Discussion

External forcing factors affecting regional climate include snow cover, plateau sensible heat, sea ice, and SST. This study examined impacts from Arctic sea ice, Atlantic SST, and ENSO on June precipitation in central Northwest China. Impacts from other ocean temperature anomalies and snow cover require further investigation. The relationships among June precipitation, March-April Chukchi Sea ice, spring NAT, and the height field all changed around the 1990s, suggesting that atmosphere-ice-ocean interactions need more comprehensive study.

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