



HOKKAIDO UNIVERSITY

Title	The mechanism of summer heatwaves over eastern Siberia and its linkage to atmospheric and oceanic variability in the western North Pacific
Author(s)	周, 習靈
Degree Grantor	北海道大学
Degree Name	博士(環境科学)
Dissertation Number	甲第16208号
Issue Date	2025-03-25
DOI	https://doi.org/10.14943/doctoral.k16208
Doc URL	https://hdl.handle.net/2115/97684
Type	doctoral thesis
File Information	ZHOU_Xiling.pdf



Ph.D. dissertation

The mechanism of summer heatwaves over eastern
Siberia and its linkage to atmospheric and oceanic
variability in the western North Pacific

(東シベリアにおける熱波のメカニズムおよび
北西太平洋の大気海洋変動との関係)

Xiling Zhou

Division of Environmental Science Development,

Hokkaido University

A dissertation submitted for the degree of

Doctor of Philosophy

February 2025

Abstract

Summer heatwaves have become increasingly frequent and intense worldwide with the progression of global warming. These rapid increases have also been observed in high-latitude regions, including eastern Siberia, a region underlain by carbon-rich permafrost. Summer heatwaves over eastern Siberia exert significant adverse impacts on the local ecosystems and have a potential role in amplifying global warming. Compared to densely populated regions such as Europe and East Asia, summer heatwaves over eastern Siberia have received limited attention from climate scientists. Moreover, earlier research suggests that these heatwaves are linked to weather variability in East Asia, with potential implications for sea surface temperature variability in the western North Pacific (WNP). However, the processes underlying this linkage remain unclear. Addressing these research gaps, this dissertation aims to elucidate the mechanism of summer heatwaves over eastern Siberia and examine its linkage to atmospheric and oceanic variability in the WNP.

This study compares the atmospheric circulation patterns and mechanisms associated with heatwaves over northeastern Siberia (NES) in July and August. While the frequency of NES heatwaves significantly increases during these two months, their interannual variations are out of phase. Regression analysis reveals clear wave train features along northern Eurasia associated with NES heatwaves in July. Empirical Orthogonal Function analysis further confirms that the British–Okhotsk Corridor pattern primarily regulates NES heatwaves in this month. However, this teleconnection is less clear in August because the Rossby waveguide effect is weaker in August than in July. In contrast, NES heatwaves in August are associated with a meridional atmospheric circulation pattern extending from the Arctic to the WNP. An Arctic low-pressure anomaly facilitates the formation of NES heatwaves through the propagation of Rossby wave, as supported by the linear baroclinic model experiment. Additionally, the heatwave-related high-pressure anomaly over the NES in August may influence weather and sea surface temperature variability in the WNP.

The impacts of NES heatwave-related atmospheric circulation patterns on weather and sea surface temperature variability in the WNP are further examined. The results show a strong linkage between August heatwaves over the NES and subsequent sea surface temperature cooling in the WNP,

which primarily arises from an anomalous dipole pressure pattern over the NES and WNP. Anomalous high pressure over the NES leads to clear sky and enhanced insolation, promoting heatwave formation. Conversely, anomalous low pressure over the WNP leads to cloudy sky and reduced insolation. Furthermore, anomalous northeasterly winds from the Bering Sea enhance the release of latent heat flux from the ocean surface. These processes lead to surface heat loss in the WNP and subsequent sea surface temperature cooling. The shallow mixed layer depth in the WNP during the warm season makes sea surface temperature more sensitive to the heat loss, contributing to the uniqueness of this linkage.

The impacts of global warming on summer heatwaves over the NES are further explored by comparing large ensemble historical simulation and non-warming simulation datasets. The results indicate that, while external forcings have contributed to the observed recent increase in heatwaves, internal atmospheric variability remains a key factor on a yearly basis. Event attribution analysis of major observed heatwave periods reveals that global warming has increased the occurrence probability of such extreme periods. An additional analysis of the dominant modes of summer heatwaves over northern Eurasia identifies three primary patterns: a pattern with a single positive anomaly centered over western Siberia, which seems driven by the external forcings and sea surface temperature warming, and the other two patterns exhibiting tripolar distribution across northern Eurasia, which are predominantly regulated by internal atmospheric variability.

The findings of this study offer valuable insights into the characteristics and mechanisms of summer heatwaves over eastern Siberia. These enhanced understandings can help inform strategies to address associated challenges, such as the monitoring of wildfires and permafrost thawing, thereby contributing to the protection of the ecosystems in eastern Siberia. Furthermore, the study underscores the role of atmospheric forcing from eastern Siberia as a potential precursor for predicting weather and sea surface temperature variability in the WNP. These results deepen our understanding of the regional climate system and provide important implications for the conservation of regional marine ecosystems.

Content

Abstract.....	1
Chapter 1 General introduction of summer heatwaves over eastern Siberia	5
1.1 Global warming and recent frequent summer heatwaves	5
1.2 Significance of studying summer heatwaves over eastern Siberia	7
1.3 Drivers of summer heatwaves over eastern Siberia	10
1.4 Objective of this study	14
Chapter 2 Different atmospheric circulation patterns associated with heatwaves over northeastern Siberia in July and August.....	15
2.1 Introduction.....	15
2.2 Data and methods.....	17
2.3 Results.....	21
2.3.1 Spatiotemporal characteristics of summer heatwaves over northeastern Siberia	21
2.3.2 Thermodynamic and surface energy budget analyses on northeastern Siberian heatwave events	25
2.3.3 Atmospheric circulation patterns associated with summer heatwaves over northeastern Siberia	28
2.3.4 Possible drivers of summer heatwaves over northeastern Siberia	32
2.4 Discussions	36
2.5 Conclusions.....	39
Chapter 3 Linkage between late-summer heatwaves over northeastern Siberia and subsequent sea surface temperature cooling in the western North Pacific	41
3.1 Introduction.....	41
3.2 Data and methods.....	44
3.3 Results.....	47
3.3.1 Linkage between late-summer heatwaves over northeastern Siberia and subsequent sea surface temperature cooling in the western North Pacific.....	47
3.3.2 Atmospheric and oceanic processes contributing to the linkage	52
3.4 Discussions	56

3.5 Conclusions.....	60
Chapter 4 The impacts of global warming on summer heatwaves over eastern Siberia.....	62
4.1 Introduction.....	62
4.2 Data and methods.....	65
4.3 Results.....	67
4.3.1 The impacts of global warming on summer heatwaves over northeastern Siberia.....	67
4.3.2 Dominant modes of summer heatwaves over northern Eurasia and their drivers	74
4.4 Discussions	77
4.5 Conclusions.....	79
Chapter 5 Discussions and outlook.....	80
5.1 Siberian heatwaves influenced by land–atmosphere interactions.....	80
5.2 The impacts of heatwaves over eastern Siberia on ecosystems	81
Chapter 6 Conclusions.....	82
Reference.....	85
Acknowledgement	94

Chapter 1 General introduction of summer heatwaves over eastern Siberia

1.1 Global warming and recent frequent summer heatwaves

The global surface temperature increased by approximately 1.1°C in 2011–2020 compared to the pre-industrial period (1850–1900), with land surface warming (1.59°C) exceeding ocean surface warming (0.88°C) (IPCC, 2023). This phenomenon is known as global warming, which is unequivocally driven by human activity, primarily through greenhouse gas emissions (e.g., CO₂, CH₄, N₂O) (IPCC, 2023). Alongside global warming, extreme weather events, especially extreme hot events, have occurred more frequently and intensively.

Land heatwaves (distinguished from marine heatwaves and hereafter referred to as heatwaves) are events characterized by temperature that remain significantly above normal for consecutive days (Domeisen et al., 2023). The frequency and intensity of summer heatwaves have increased globally since the 1950s (Perkins-Kirkpatrick & Lewis, 2020), and projections suggest that these trends will persist across nearly all inhabited regions (Domeisen et al., 2023).

Since 2000, severe and prolonged heatwaves have occurred across the Eurasian continent during recent summers, as summarized in [Figure 1.1](#). Synonymous with the record-breaking global temperature of 2023, Japan experienced unprecedented summer temperature at numerous weather stations, resulting in an unusually high number of heat stroke cases (Takemura et al., 2024). This extreme heat was attributed to an intensified North Pacific Subtropical High and exceptionally high sea surface temperature around Japan this year (Sato et al., 2024; Takemura et al., 2024). In July and August 2022, central-eastern China endured consecutive and record-breaking heatwave events, which led to severe drought and energy shortages (Wang et al., 2023). These events were triggered by a Rossby wave train originating from convective heating over Pakistan and an intensified Silk Road pattern (Hong et al., 2023; Wang et al., 2023). In July and August 2010, persistent heatwaves over western Russia resulted in significant mortality, crop

Chapter 1: General introduction

failures, and economic losses (Barriopedro et al., 2011). These heatwaves were attributed to abnormally high sea surface temperature in the Indian Ocean and early-summer soil moisture deficit in western Russia (Trenberth & Fasullo, 2012; Capua et al., 2021). The 2003 European summer heatwaves were estimated to have caused over 70,000 deaths (Robine et al., 2008), with human activities very likely doubling the risk of such extreme events (Stott et al., 2004).

Eastern Siberia is known as one of the coldest regions in the world. However, in June 2020, it experienced unprecedented warmth, with surface air temperature reaching 38 °C over Verkhoyansk, setting a new temperature record within the Arctic Circle (WMO, 2021). Atmospheric methane concentrations increased considerably during and after the 2020 Siberian heatwaves (Froitzheim et al., 2021). Fire emissions during the 2020 fire season were extraordinarily high, reaching approximately 350 TgC/year, over four times what is emitted during a typical season (Ponomarev et al., 2021). The extremely positive Arctic Oscillation phase in the preceding winter (Overland & Wang, 2021), early snowmelt in spring (Collow et al., 2022), and the development of local atmospheric blocking in early summer (Nakamura & Sato, 2022) all contributed to the unprecedented warmth in eastern Siberia in 2020.

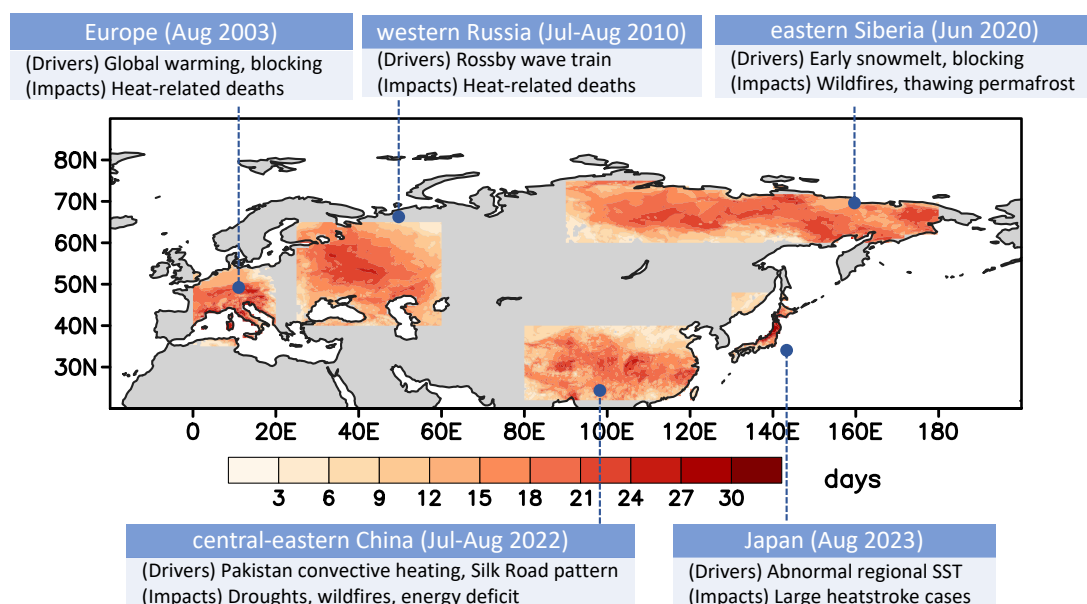


Figure 1.1 | Major summer heatwave periods across the Eurasian continent since 2000. Heatwave frequency over Europe in August 2003, western Russia in July–August 2010, eastern Siberia in June 2020, central-eastern China in July–August 2022, and Japan in August 2023, along with the associated drivers and impacts. Refer to [Section 2.2](#) for details on the data and methods used in calculating heatwave frequency.

1.2 Significance of studying summer heatwaves over eastern Siberia

Despite the 2020 heatwaves over eastern Siberia receiving considerable attention from climate scientists, summer heatwaves over this region are less studied compared to those over more densely populated areas like East Asia and Europe. Understanding summer heatwaves over eastern Siberia is crucial for local ecosystem conservation and has implications for global carbon storage and East Asia weather prediction, as summarized below.

Eastern Siberia is underlain by carbon-rich permafrost, with soil organic carbon storage under 0–3cm being about 50 kg/m² (Schuur et al., 2015; Figure 1.2). As ground temperature rises, thawing permafrost releases carbon dioxide and methane. For instance, methane release from carbonate rock formations in the Siberian permafrost during and after the 2020 Siberian heatwaves considerably increased atmospheric methane concentrations (Froitzheim et al., 2021). The released greenhouse gases are expected to amplify global warming through positive permafrost carbon feedback (Schaefer et al., 2014). Additionally, increased active layer thickness caused by permafrost warming has also led to reduced summer discharge (Suzuki et al., 2021). One-third of pan-Arctic infrastructure and 45% of hydrocarbon fields in the Russian Arctic are at high risk due to thaw-induced ground instability (Hjort et al., 2018).

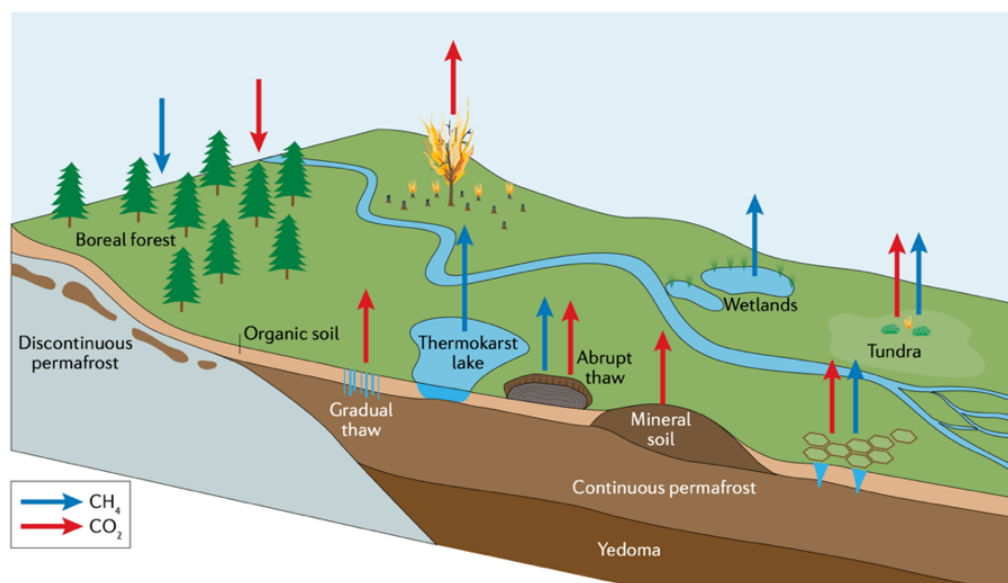


Figure 1.2 | Carbon flux dynamics in permafrost landscapes. Carbon transformation in an idealized Arctic environment experiencing wildfire and thermokarst disturbances. Figure adapted from ACIA (2004).

Chapter 1: General introduction

Hegedűs et al. (2024) pointed out that the wildfires are strongly positively correlated with summer heatwave activity in eastern Siberia. Alongside rising temperature and heatwaves, northeastern Siberia experienced unprecedented fire activity during the summers of 2019, 2020, and 2021 (Scholten et al., 2020). Wildfires contribute to air pollution (Yasunari et al., 2021; Tomshin & Solovyev, 2022) and lead to extensive forest destruction (Ponomarev et al., 2022). Moreover, wildfires have significant implications for carbon storage, as they release carbon into the atmosphere (Ponomarev et al., 2021) and act as a strong accelerator of permafrost thaw (Gibson et al., 2018).

Summer heatwaves over eastern Siberia are also linked to East Asian weather variability. These heatwaves typically form under the condition of atmospheric blocking, a persistent anticyclonic circulation, which also impacts East Asian weather (Chen et al., 2021; Nakamura & Sato, 2022; Song & Ahn, 2024). For instance, the early summer 2020 eastern Siberian heatwaves were caused by the development of local atmospheric blocking, which also intensified East Asian precipitation by enhancing the East Asian subtropical jet (Nakamura & Sato, 2022; [Figure 1.3](#)). East Siberian blocking is also associated with the surface Okhotsk High (Tachibana et al., 2004), which in turn affects East Asian weather (Ninomiya & Mizuno, 1985). Therefore, a clear understanding of the mechanisms behind summer heatwaves over eastern Siberia can improve weather prediction for East Asia.

Summer heatwaves over eastern Siberia may contribute to Arctic sea ice decline through increased riverine heat. The Arctic Ocean is the most river-influenced ocean, as it receives a significant amount of freshwater discharge from large Russian Pan-Arctic rivers such as the Yenisei and Lena (Hu et al., 2023). Increased solar insolation during these heatwaves leads to a greater heat discharge from these rivers, contributing to oceanic warming and Arctic sea ice decline (Park et al., 2020; Dong et al., 2022).

[Figure 1.4](#) summarizes the significance of studying summer heatwaves over eastern Siberia. Accompanied by heatwaves, wildfires cause extensive forest destruction, contribute to air pollution, and significantly affect carbon storage by releasing carbon into the atmosphere and

Chapter 1: General introduction

accelerating permafrost thaw. Thawing permafrost can damage infrastructure, influence river discharge, and contribute to global warming. East Siberian blocking also impacts East Asian weather. Additionally, summer heatwaves over eastern Siberia may contribute to Arctic sea ice decline through increased riverine heat. Given these significant impacts, it is crucial to understand the characteristics and mechanisms of summer heatwaves over eastern Siberia.

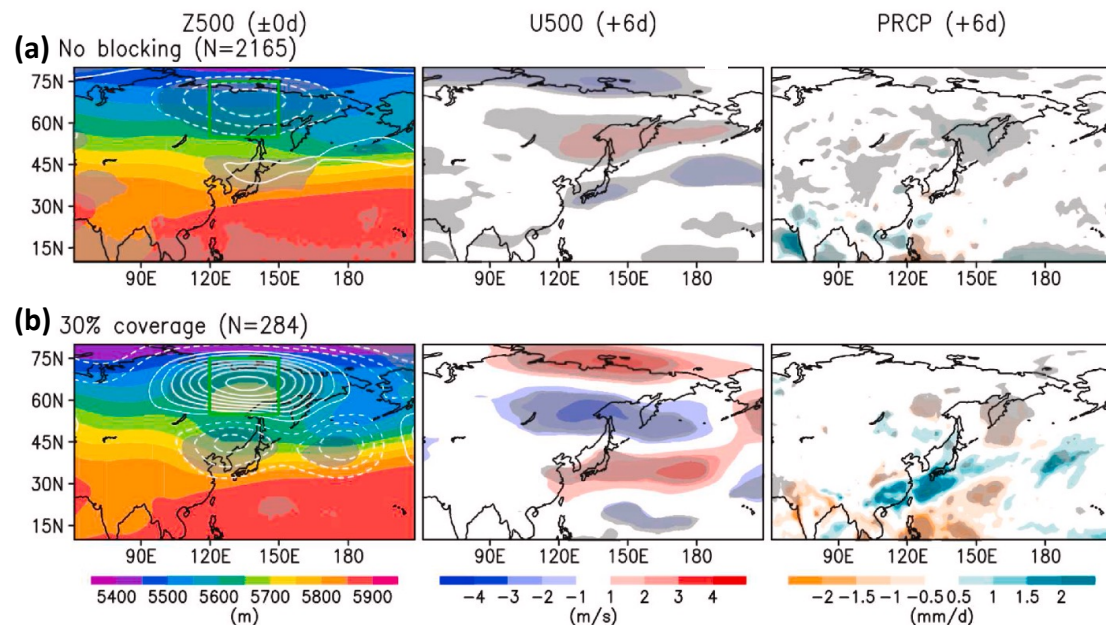


Figure 1.3 | Statistical evidence of East Siberian blocking and East Asian rainfall anomalies. Composite 500-hPa geopotential height (shading) and its anomaly (contour; interval of 10 m, with negative value shown as dashed), 500-hPa zonal wind anomaly, and precipitation anomaly for days of (a) no blocking and (b) 30% coverage of the blocking index over eastern Siberia (green rectangle in left panels). The study period is June and July during 1958–2021. N is the sampling number. Grey shading indicates statistical significance at the 90% confidence level. Figure adapted from Nakamura & Sato (2022).

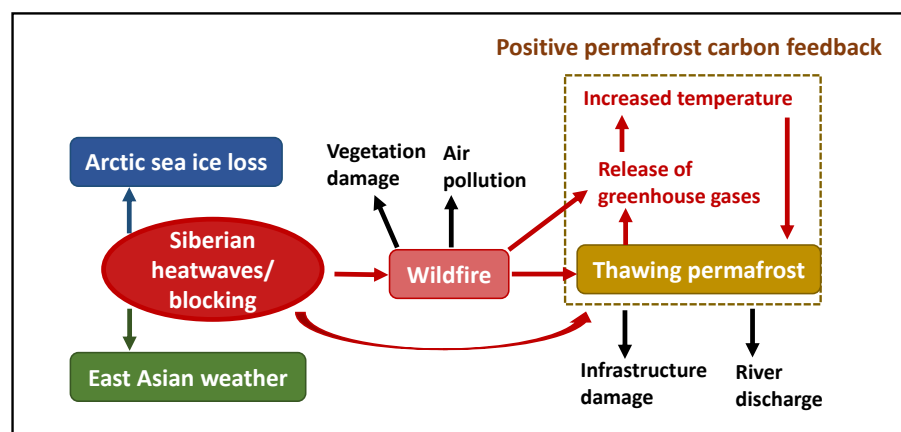


Figure 1.4 | Schematic diagram summarizing the significance of studying summer heatwaves over eastern Siberia.

1.3 Drivers of summer heatwaves over eastern Siberia

In this section, the drivers of summer heatwaves over eastern Siberia are reviewed based on existing literature. Although heatwaves manifest as local intraseasonal phenomena, they arise from complex interactions of large- and small-scale processes across various temporal scales (Barriopedro et al., 2023). Atmospheric processes, land surface conditions, and global warming can all act as drivers of summer heatwaves over eastern Siberia, as summarized below.

(i) Atmospheric blocking and polar jet

Atmospheric blocking refers to large, stationary (typically lasting 4 or 5 days) anticyclonic weather system in the middle to high latitudes (Woollings et al., 2018). Blocking often brings about anomalous, sometimes extreme, weather. It is considered a key driver of summer heatwaves in these latitudes, primarily by reducing cloud cover and increasing solar radiation (Woollings et al., 2018; Domeisen et al., 2023). Eastern Siberia is one of the Northern Hemisphere regions where atmospheric blocking events frequently occur (Tibaldi et al., 1994). Atmospheric blocking in this area plays a crucial role in the formation of summer heatwave. For instance, the unprecedented heatwaves in early summer 2020 over eastern Siberia were largely driven by the development of atmospheric blocking (Nakamura & Sato, 2022; [Figure 1.3](#)).

Atmospheric blocking acts like a traffic jam in the jet stream (Nakamura & Huang, 2018). Recent studies have shown that summer heatwaves and extreme fire weeks in northeastern Siberia are accompanied by a strengthened polar jet (Rousi et al., 2022; Scholten et al., 2022). Scholten et al. (2022) reported that during the unusually warm and dry extreme fire weeks in northeastern Siberia, there was a local higher geopotential height, along with a strengthened polar jet ([Figure 1.5](#)). Rousi et al. (2022) highlighted that summer heatwave intensity over Europe and northeastern Siberia exceeds climatology under a double jet structure, characterized by two zonally oriented bands of stronger 250-hPa zonal wind around 40°N and 70°N. However, the connection between summer heatwaves over northeastern Siberia and the double jet structure remains unclear and requires further investigation.

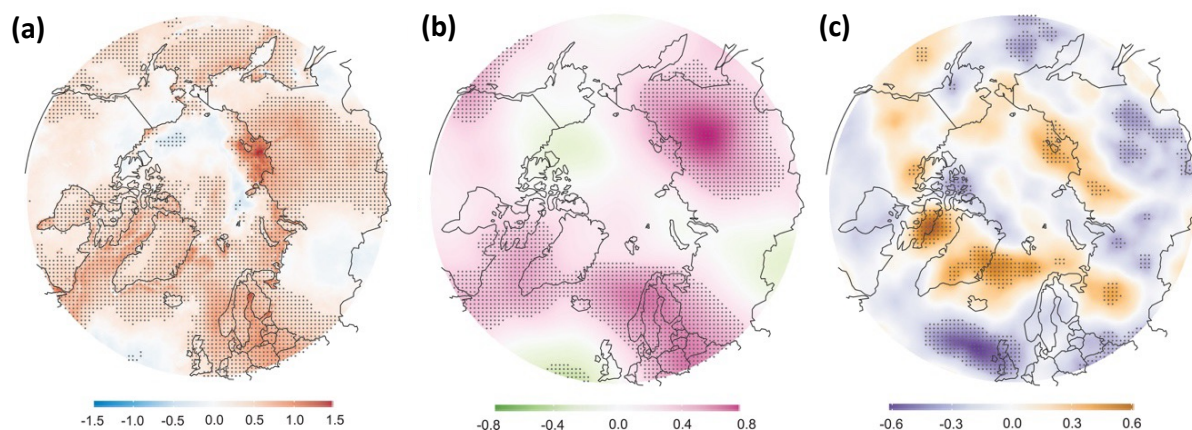


Figure 1.5 | Composite anomalies in synoptic and surface weather during weeks of high fire activity in northeastern Siberia in summer for the period 2001–2021. (a) 2-m temperature anomaly, (b) 500-hPa geopotential anomaly, (c) 250-hPa wind anomaly. All anomalies are temporal normalized. Stippled areas indicate where differences between the composite and climatology are significant at the 95% confidence level. Figure adapted from Scholten et al. (2022).

(ii) Teleconnection patterns

Both polar jet and subtropical jet act as an efficient waveguide formed by both stretching vorticity gradient and absolute vorticity gradient (Iwao & Takahashi, 2008). These waveguides, with a limited meridional dimension, confine wave activity to a zonal band and transport it downstream over a long distance before it is dispersed (Ding & Wang, 2005). Zonally oriented teleconnection patterns along the subtropical jet (e.g., the Silk Road pattern) have been extensively studied and are known to influence summer heatwaves over East Asia (Wang et al., 2023; Fu et al., 2024). Teleconnection patterns along the polar jet have received less attention compared to those along the subtropical jet, but they have recently begun to attract the interest of climate scientists. Xu et al. (2021) suggested that waveguide teleconnections along the polar jet promote extreme summer temperature over northern Eurasia. Xu et al. (2019, 2022) were the first to systematically investigate the two main teleconnection patterns along the polar jet, which they termed the British–Baikal Corridor pattern and the British–Okhotsk Corridor pattern. These two patterns can significantly influence the climate along their route. For instance, the concurrent heatwave over western Russia and eastern Siberia in July 2010 occurred under a typical British–Okhotsk Corridor pattern.

Chapter 1: General introduction

In addition to the zonally oriented teleconnection patterns, meridionally oriented teleconnection patterns, such as the western Pacific pattern and the Arctic Oscillation/North Atlantic Oscillation, can influence summer heatwaves over eastern Siberia. The western Pacific pattern is characterized by opposite geopotential height anomalies centered over the Kamchatka Peninsula and the western North Pacific and is linked to fluctuations in the strength and position of the East Asian subtropical jet (Wallace & Gutzler, 1981). Early summer heatwaves over eastern Siberia are connected to the negative phase of the western Pacific pattern, when anomalous positive geopotential height occurs over eastern Siberia (Collow et al., 2022). The Arctic Oscillation is a large-scale mode of climate variability, characterized by a dipole pressure pattern in the Arctic and mid-latitudes, typically strongest in winter (Thompson & Wallace, 1998). The influence of the positive phase of Arctic Oscillation in the preceding winter can be memorized in the snow cover, resulting in early snowmelt over eastern Siberia, leading to a higher temperature and fire activity over eastern Siberia in early summer (Ogi et al., 2003; Kim et al., 2020).

(iii) Land–atmosphere interactions

Land–atmosphere interactions also have important implications for the predictability of summer temperature and heatwaves over eastern Siberia (e.g., Matsumura & Yamazaki, 2012; Gloege et al., 2022; Scholten et al., 2022). In early snowmelt years in central Siberia, surface heating through the snow-hydrological effect can trigger the formation of stationary Rossby waves that move eastward toward eastern Siberia, leading to the development of a strong anticyclonic circulation there (Matsumura & Yamazaki, 2012). Gloege et al. (2022) reported that early spring snowmelt in 2020 led to substantial vegetation greening in eastern Siberia, followed by decreased soil moisture and vegetation browning in summer, facilitating the formation of heatwaves through land–atmosphere feedback. Scholten et al. (2022) noted that the recent extreme fire activity years of 2019–2021 in eastern Siberia were all characterized by an earlier-than-usual snowmelt. Kim & Lee (2022a) suggested that enhanced latent heating over Yakutia can excite the anticyclonic circulation over northeastern Siberia, causing the abnormally high temperature over northeastern Siberia.

(iv) Global warming and Arctic amplification

It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial times, particularly temperature extremes (Seneviratne et al., 2021). Without human influence, the unprecedented warm period in the first half of 2020 in Siberia would have been practically impossible (Ciavarella et al., 2021). As a hotspot of global warming, the Arctic has warmed nearly four times faster than the globe average in recent decades (Rantanen et al., 2022), a phenomenon known as Arctic amplification. Summer sea ice concentration along the Siberian coast is also showing a rapid decline. The Arctic warming may have profound impacts on mid-latitude summer atmospheric circulation through shifted jet streams and amplified quasi-stationary waves (Coumou et al., 2018). For instance, Chen et al. (2021) noted that the low Arctic sea ice cover in the late spring to early summer of 2020 along the Siberian coast caused local warming, resulting in excessive atmospheric blocking over eastern Siberia. Nakamura & Sato (2022) revealed that the atmospheric circulation response to Arctic warming shows a robust high-pressure anomaly over eastern Siberia, with an increased upper tropospheric zonal wind that extends over the Siberian coast. Luo et al. (2024) underscored that the recent rapid loss of summer Arctic sea ice increases wildfires over eastern Siberia.

(v) Summary of drivers

As outlined above, drivers with various temporal and spatial scales contribute to the formation of summer heatwaves over eastern Siberia. Atmospheric processes (e.g, local atmospheric blocking and zonally and meridionally oriented teleconnection patterns) act as fast-varying drivers. Land–atmosphere interactions, associated with early spring snowmelt, act as slow-varying drivers. Global warming acts as a background driver of long-term trends in the frequency and intensity of heatwaves. Arctic amplification and sea ice loss can alter high-latitude atmospheric circulation, influencing the temperature and heatwave variability over eastern Siberia. These drivers can interact with each other and often combine to induce summer heatwaves over eastern Siberia.

1.4 Objective of this study

Compared to densely populated regions, summer heatwaves over eastern Siberia have received relatively limited attention from climate scientists. The limited existing research, combined with the significance of this topic, underscores the need for a comprehensive investigation into the heatwaves over this region. The overall objective of this study is to investigate the mechanism of summer heatwaves over eastern Siberia and examine its linkage to atmospheric and oceanic variability in the western North Pacific through three chapters, as outlined below.

Summer heatwaves have rapidly increased over northeastern Siberia. However, the characteristics and mechanisms of these heatwaves remain unclear. [Chapter 2](#) compares the typical atmospheric circulation patterns associated with heatwaves over northeastern Siberia in July and August and examines the potential mechanisms of these heatwaves.

The impacts of summer East Siberian blocking on East Asian weather have been examined in several studies. How sea surface temperature in the western North Pacific is modulated by summer high-latitude atmospheric forcing, and its linkage to northeastern Siberian heatwaves, remains unclear. [Chapter 3](#) explores the linkage between late-summer heatwaves over northeastern Siberia and sea surface temperature variability in the western North Pacific, further examining the underlying atmospheric and oceanic processes.

Global warming serves as a background driver of long-term trends in heatwave frequency and intensity. However, its contribution to past long-term summer heatwave variability and the observed major summer heatwave periods over northeastern Siberia remains unclear. [Chapter 4](#) investigates the impacts of global warming on heatwaves over northeastern Siberia from a broader northern Eurasian perspective by analyzing two large ensemble simulation datasets with and without global warming.

[Chapter 5](#) provides an outlook on future research directions, including land–atmosphere interactions in the summer heatwaves over Siberia and interdisciplinary research on heatwaves and ecosystems. [Chapter 6](#) summarizes the overall conclusions of this study.

Chapter 2 Different atmospheric circulation patterns associated with heatwaves over northeastern Siberia in July and August

2.1 Introduction

Alongside global warming, summer heatwaves have become more frequent and intense worldwide, including over eastern Siberia. Summer heatwaves over eastern Siberia exert significant adverse impacts on local ecosystems, potentially amplify global warming, and may affect East Asian weather variability. However, the current understanding of summer heatwaves over eastern Siberia remains limited, including their associated atmospheric circulation patterns and underlying drivers.

Most of the literature investigates summer heatwaves on the seasonal mean. However, the factors controlling heatwaves can vary among months. For instance, western Russia experienced severe heatwaves in July and August 2010, yet with different temperature and atmospheric circulation patterns in the two months. In July, anomalous tripolar temperature and geopotential height patterns were observed over northern Eurasia, contributing to concurrent heatwaves over western Russia and northeastern Siberia (Schubert et al., 2011; [Figure 2.1a](#)). Instead, this tripolar pattern was absent in August ([Figure 2.1b](#)). Similarly, differences exist in the mechanisms behind the exceptional heatwaves over central-eastern China in July and August 2022 (Jiang et al., 2023; Wang et al., 2023). Wang et al. (2023) suggested that the July heatwaves were triggered by a Rossby wave train originating from convective heating over Pakistan ([Figure 2.1c](#)). The study further pointed out that this Rossby wave train combined with an intensified Silk Road pattern, leading to more severe heatwaves over central-eastern China in August ([Figure 2.1d](#)).

Teleconnection patterns along the subtropical and polar jets influence weather across Eurasia. Ding & Wang (2005) studied the subseasonal variation of the circumglobal teleconnection pattern along the subtropical jet for each summer month and pointed out that this pattern is most

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

prominent in August, when the strongest linkage between the Atlantic and central Asia occurs. Subseasonal variations also exist in the teleconnection patterns along the polar jet. Wakabayashi & Kawamura (2004) examined two teleconnection patterns prevalent over northern Eurasia, termed Europe–Japan 1 and Europe–Japan 2, and noted that these patterns are particularly prevalent in early summer but not in August. However, the detailed mechanism behind this monthly difference remains unclear.

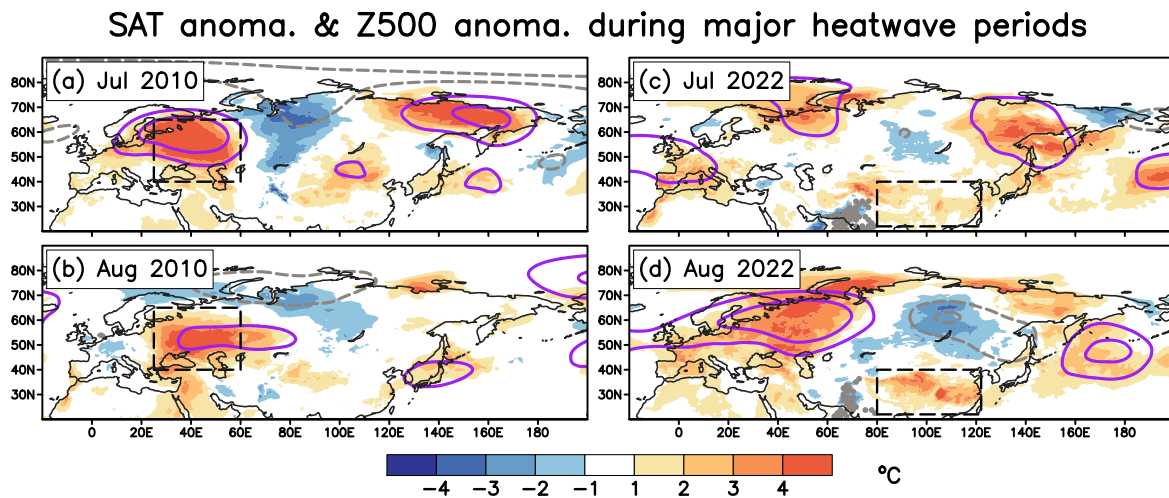


Figure 2.1 | Temperature and atmospheric circulation anomalies during major summer heatwave periods over western Russia in 2010 and central-eastern China in 2022. Surface air temperature anomalies (shading; °C) and 500-hPa geopotential height anomalies (contour; m) in (a) July 2010, (b) August 2010, (c) July 2022, and (d) August 2022. Grey dots in (c) and (d) denote precipitation anomalies greater than 3 mm/day in Pakistan (20°N–40°N, 60°E–80°E). The contour interval is 50 m, with negative contours dashed and zero contours omitted. Anomalies are calculated relative to the monthly climatology during 1979–2023. The black dash boxes in (a) and (b) outline western Russia (40°N–65°N, 25°E–60°E), and those in (c) and (d) outline central-eastern China (22°N–40°N, 80°E–122°E). See [Section 2.2](#) for data details.

Building on the aforementioned research gap, an analysis focused solely on the seasonal mean state may overlook crucial environmental characteristics behind the heatwaves. This chapter compares the typical atmospheric circulation patterns associated with heatwaves over northeastern Siberia (NES; 60°N–70°N, 130°–180°E) in July and August. The structure of this chapter is as follows: [Section 2.2](#) describes the data and methods used. [Section 2.3](#) examines the spatiotemporal characteristics, thermodynamic energy budget, typical atmospheric circulation patterns, and potential drivers of NES heatwaves in July and August. [Section 2.4](#) presents the discussions, and [Section 2.5](#) summarizes the conclusions.

2.2 Data and methods

(i) Reanalysis dataset

The study period for this study spans 1979–2023. Hourly and monthly data used in this study are derived from the European Center for Medium-Range Weather Forecasting 5th Generation Reanalysis dataset (ERA5; Hersbach et al., 2020). The ERA reanalysis dataset has a horizontal resolution of $0.25^{\circ} \times 0.25^{\circ}$ in latitude and longitude, with 37 vertical pressure levels extending up to 1-hPa level. The variables analyzed include temperature, precipitation, and atmospheric circulation parameters (e.g., geopotential height, horizontal wind, potential vorticity) at multiple vertical levels, as well as surface heat flux. ERA5 precipitation data has demonstrated high skill in extratropical regions, making it suitable for precipitation analysis in these areas (Lavers et al., 2022). For heat flux values, positive values indicate a downward direction (toward the surface), while negative values indicate an upward direction (from the surface).

(ii) Definitions of heatwave frequency and intensity at each grid point

Following Perkins-Kirkpatrick & Lewis (2020), heatwave days are defined as days when the daily maximum surface air temperature (SAT) exceeds the daily heatwave threshold for at least three consecutive days (Figure 2.2a). Here, the daily heatwave threshold is defined as the 90th percentile value of the daily maximum SAT during 1979–2023. The daily 90th percentile value is computed based on a 15-day moving window of daily maximum SAT to ensure a sufficient sample size for a realistic threshold estimation (Perkins & Alexander, 2013). Heatwave frequency is calculated as the total number of heatwave days within a given month. Heatwave cumulative intensity (hereafter referred to as heatwave intensity) is calculated as the sum of the excess maximum SAT above the heatwave threshold across all heatwave days within a given month.

(iii) Selection of heatwave events over northeastern Siberia

To select heatwave events over the NES, the regionally averaged daily maximum SAT over the NES is first calculated. The definition of heatwave days for the entire region aligns with that

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

for individual grid points (Figure 2.2b). The “lag 0 day” for each event is defined as the day with the highest maximum SAT within the event. A “lag 0 day” in July or August corresponds to a heatwave event occurring in the respective month. Consequently, 43 NES heatwave events in July and 36 NES heatwave events in August are selected for the period 1979–2023.

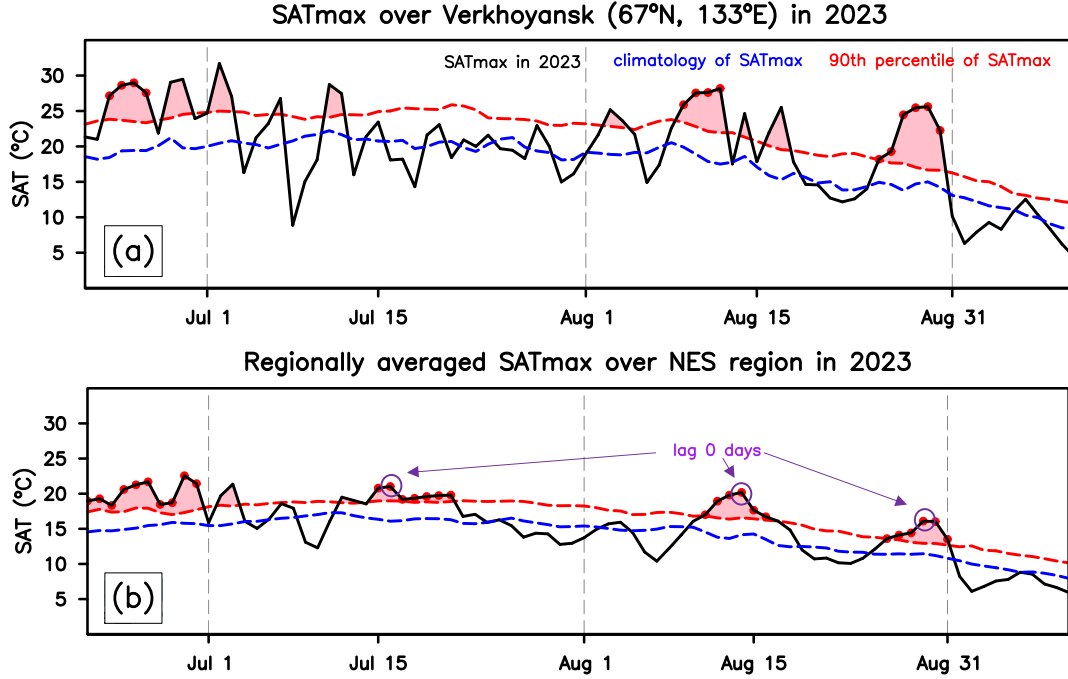


Figure 2.2 | Definition of heatwaves. (a) Daily maximum SAT over Verkhoyansk (67°N, 133°E) in summer 2023, shown as a solid black line. The blue and red dashed lines represent the climatological mean and the 90th percentile of maximum SAT for this grid point, respectively. Red dots indicate heatwave days, and pink shadings with red dots denote excess maximum SAT above the heatwave threshold across the heatwave days. (b) Similar to (a), but for regionally averaged maximum SAT over the NES. Purple circles indicate the lag 0 days for heatwave events in July and August.

(iv) Diagnosis of local physical processes through thermodynamic equation

The thermodynamic equation is applied to evaluate the contribution of various physical processes to the initiation and maintenance of NES heatwave events. Calculations are performed using parameters at the 975-hPa level, as this level represents the lowest layer where the vertical temperature gradient (i.e., between 1000-hPa and 950-hPa levels) can be assessed in the ERA5 reanalysis dataset. The equation, adapted from Yanai et al. (1973), is expressed as follows:

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \omega \left(\frac{RT}{C_p P} - \frac{\partial T}{\partial P} \right) + \frac{Q_1}{C_p}$$

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

where T , t , ∇ , V , ω , P , R , C_p , and Q_1 represent temperature, time, horizontal gradient operator, horizontal velocity vector, vertical pressure velocity, pressure, gas constant for dry air (287 J/kg/K), specific heat at constant pressure for dry air (1005 J/kg/K), and apparent heat source, respectively. The left-hand side of the equation represents the local temperature tendency. On the right-hand side, the first term denotes horizontal temperature advection, the second term represents the combined effect of adiabatic compression and vertical temperature advection, and the third term corresponds to total diabatic heating. Total diabatic heating, which includes radiation, turbulent heat flux, and other subgrid-scale processes, is estimated as the residual of the thermodynamic equation.

(v) Regression and correlation analyses

Regression analyses are applied to various meteorological variables (e.g., temperature, geopotential height) on standardized NES heatwave frequency to investigate the typical atmospheric circulation patterns associated with NES heatwaves. To remove the influence of global warming, both meteorological variables and heatwave frequency are linearly detrended before performing regression and correlation analyses. The statistical significance of these analyses is assessed using a two-tailed Student's t-test.

(vi) Definition of teleconnection patterns

Empirical Orthogonal Function (EOF) analysis of meridional wind has been widely employed to extract Rossby wave activity along jet streams (Yasui & Watanabe, 2010; Xu et al., 2019). The waveguide along the polar jet is most distinct around the 250-hPa level, where it clearly separates from the subtropical waveguide (Iwao & Takahashi, 2008). Accordingly, EOF analysis is applied to the latitude-weighted 250-hPa meridional wind within the domain 50°N–80°N, 20°W–180°E to identify the main teleconnection patterns along the polar jet. This domain extends farther east than those used in previous studies (Xu et al., 2019; Kim & Seo, 2023) to encompass the NES region. The North test is applied to assess the separability of different EOF modes (North et al., 1982).

(vii) Detection of causal linkage

The wave activity flux is suitable for examining Rossby wave propagation, as it is independent of wave phase and parallel to the local group velocity of stationary Rossby waves embedded in the climatological mean flow (Takaya & Nakamura, 2001). This study computes the TN01 wave activity flux to detect the origin and propagation of stationary Rossby waves.

Additionally, a dry version of the linear baroclinic model (Watanabe & Kimoto, 2000) is used to examine the atmospheric response to vorticity forcing imposed on the Arctic and NES. The model incorporates primitive equations linearized with a background basic state, with a T42 spatial resolution ($2.8^\circ \times 2.8^\circ$ in latitude and longitude) and 20 vertical sigma levels.

2.3 Results

2.3.1 Spatiotemporal characteristics of summer heatwaves over northeastern Siberia

Firstly, long-term spatiotemporal characteristics of summer heatwaves during 1979–2023 are investigated. Figure 2.3 illustrates the spatial distribution of climatological heatwave frequency and intensity over the Eurasian continent in July and August. The distribution of climatological heatwave frequency is largely similar in both months, with some differences noted in western Siberia (Figure 2.3a, b). Heatwaves are frequent over eastern Siberia, central Eurasia, and eastern China, lasting longer than 5 days per month. Even though the background mean air temperature is low over Siberia, this region experienced the highest heatwave intensity over the Eurasian continent, exceeding 18°C per month (Figure 2.3c, d). This feature is attributable to the large difference between the actual maximum SAT and heatwave threshold during heatwave periods. Given that the underlying carbon-rich permafrost is susceptible to excess abnormal heat and wildfires (Gibson et al., 2018), a more detailed investigation of the summer heatwaves over eastern Siberia is urgently warranted.

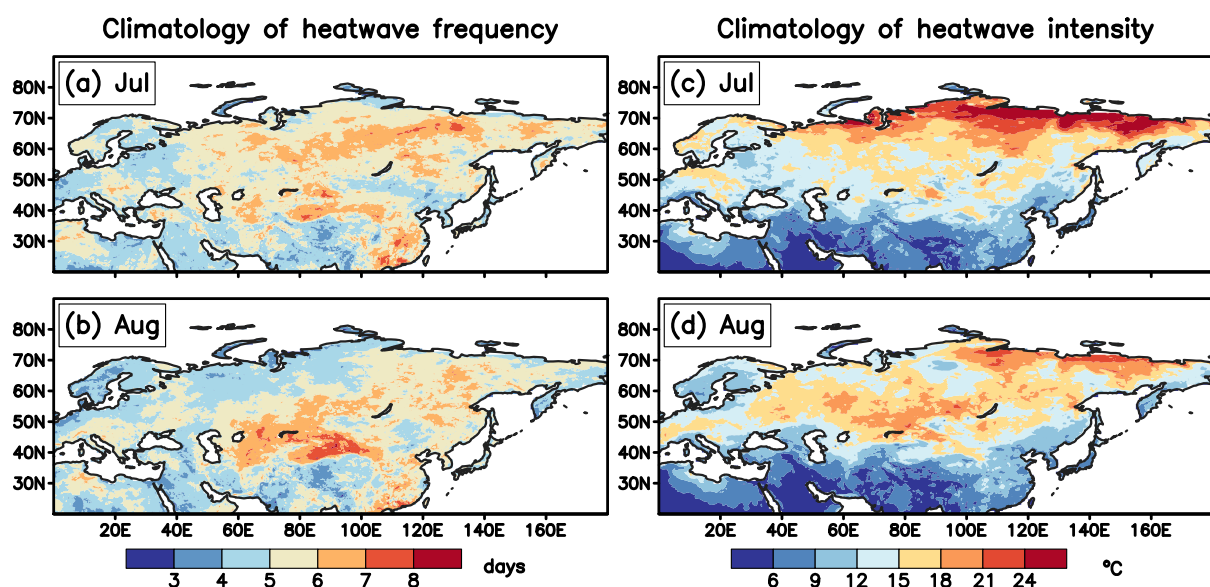


Figure 2.3 | Climatological heatwave frequency and intensity over the Eurasian continent in July and August during 1979–2023. (a–b) Spatial distribution of climatological heatwave frequency in (a) July and (b) August. (c–d) Spatial distribution of climatological heatwave intensity in (c) July and (d) August.

Figure 2.4 depicts the spatial distribution of heatwave frequency and intensity trends over the Eurasian continent in July and August. The spatial distribution of these trends (both frequency and intensity) are similar for the two months. Most regions of Eurasia show increasing heatwave trends, except for western Siberia. Consequently, the heatwave trends exhibit a tripolar pattern across northern Eurasia, characterized by a rapid increase over western Russia and the NES, while no significant changes are observed over western Siberia. Notably, the magnitude of this tripolar pattern is stronger in August than in July, with a particularly larger trend evident over western Russia.

The spatial distribution of these heatwave trends closely aligns with the SAT trends (not shown). Sato & Nakamura (2019) reported a similar tripolar SAT trend pattern over northern Eurasia and suggested that this pattern is amplified by steady warming induced by external forcings as well as inhomogeneous warming induced by internal land–atmosphere interactions. The potential mechanisms underlying the tripolar heatwave trends pattern over northern Eurasia are discussed in Section 4.4, with consideration of the impacts of global warming on summer heatwaves over northern Eurasia.

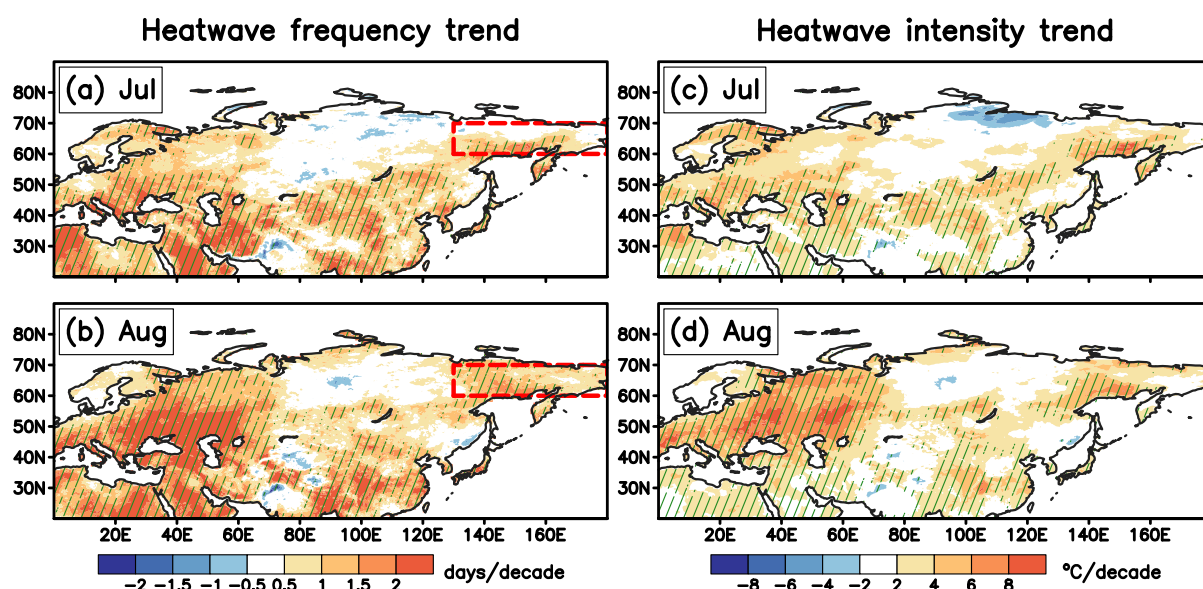


Figure 2.4 | Heatwave frequency and intensity trend over the Eurasian continent in July and August during 1979–2023. (a–b) Spatial distribution of heatwave frequency trend in (a) July and (b) August. (c–d) Spatial distribution of heatwave intensity trend in (c) July and (d) August. The red dashed boxes in (a) and (b) outline the NES region. Hatched areas indicate the trends significant at the 95% confidence level.

Figure 2.5 illustrates the interannual variations in regionally averaged heatwave frequency and intensity over the NES in July and August. Both frequency and intensity exhibit significant increases over the NES in these two months, with a stronger trend observed in August compared to July. The interannual variability in NES heatwaves is also substantial. The interannual variations in NES heatwave frequency between July and August are not significantly correlated ($r = 0.11$, $p = 0.47$), suggesting low persistence of NES heatwaves from July to August. This result underscores the importance of conducting investigations on a monthly basis.

Severe heatwave conditions have larger adverse impacts on local ecosystems. To further examine the temperature and atmospheric patterns when NES experienced severe heatwaves, four months with high NES heatwave frequency are selected for July (1991, 2001, 2003, and 2010) and August (1991, 2008, 2014, and 2017) as major NES heatwave periods (squares in Figure 2.5). The selection criterion requires that monthly NES heatwave frequency exceeds the climatological mean by more than 1.5 standard deviations for the respective month.

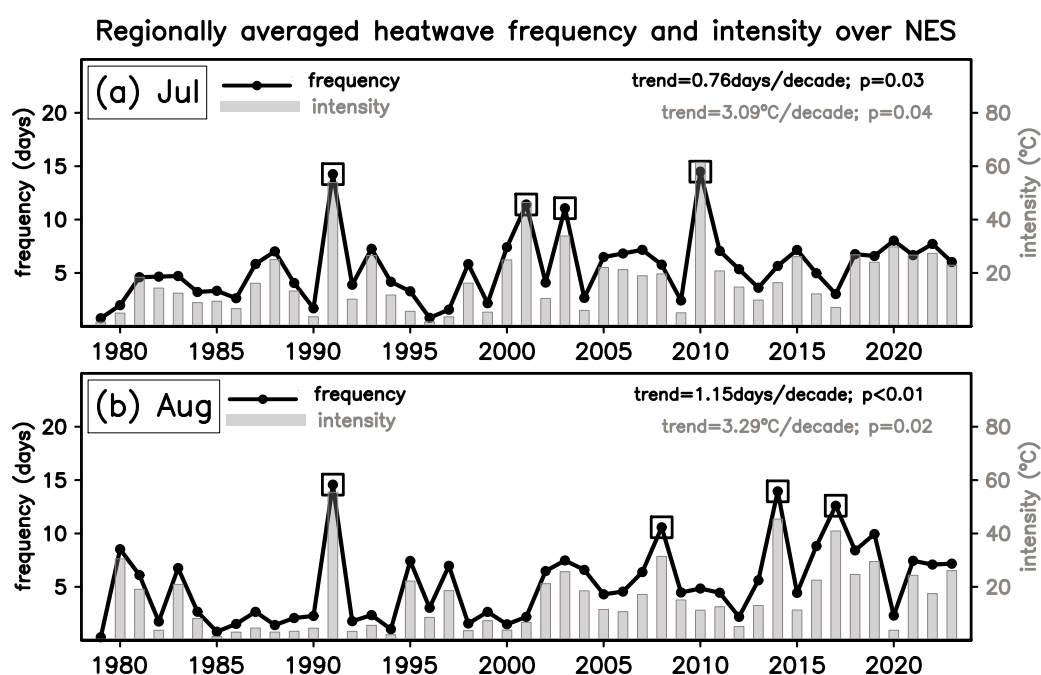


Figure 2.5 | Interannual variations in regionally averaged heatwave frequency and intensity over northeastern Siberia in July and August during 1979–2023. Black line and grey bar denote NES heatwave frequency and intensity, respectively. Black and grey numbers denote the trends and p-values for NES heatwave frequency and intensity, respectively. Black squares mark the selected major NES heatwave periods when NES heatwave frequency exceeds the climatological mean by more than 1.5 standard deviations for the respective month.

Figure 2.6 illustrates the spatial distribution of SAT anomalies and 500-hPa geopotential height anomalies (Z500) for the observed major NES heatwave periods in July and August. In July, these anomalies exhibit a tripolar pattern over northern Eurasia, characterized by positive anomalies over western Russia and the NES and negative anomalies over western Siberia, as observed in July 2001, 2003, and 2010, except for July 1991 (Figure 2.6a–d). These results indicate that the tripolar pattern of temperature and height anomalies over northern Eurasia is a primary feature when NES experienced high heatwave frequency in July. However, unlike the typical tripolar patterns found in July, the SAT anomalies and Z500 anomalies in August display different characteristics across the four months (Figure 2.6e–h). This suggests that NES heatwaves in August are not associated with the tripolar pattern across northern Eurasia, as found in July, but are more likely triggered by other factors.

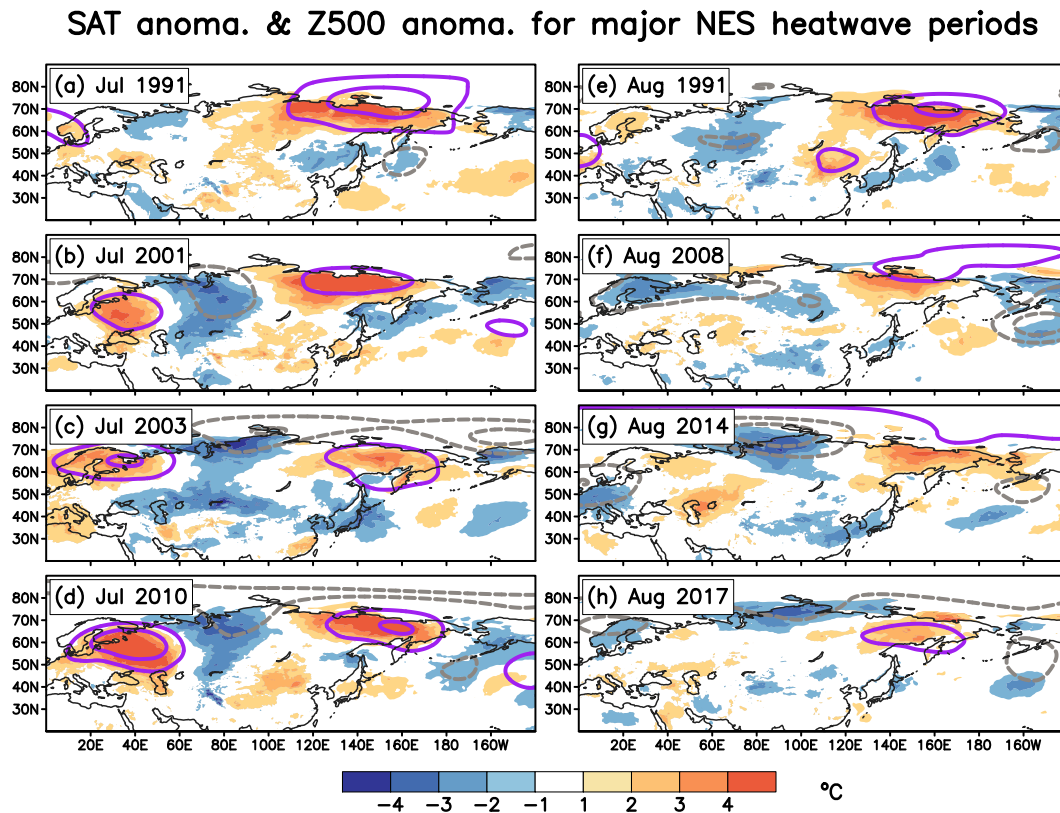


Figure 2.6 | Temperature and atmospheric circulation anomalies for observed major northeastern Siberian heatwave periods in July and August. (a–d) Surface air temperature anomalies (shading; °C) and 500-hPa geopotential height anomalies (contour; m) for (a) July 1991, (b) July 2001, (c) July 2003, and (d) July 2010. **(e–h)** Similar to (a–d), but for (e) August 1991, (f) August 2008, (g) August 2014, and (h) August 2017. The contour interval is 50 m, with negative contours dashed and zero contours omitted. Anomalies are calculated from detrended values and are relative to the monthly climatology.

2.3.2 Thermodynamic and surface energy budget analyses on northeastern Siberian heatwave events

To assess the contributions of various physical processes to the initiation and maintenance of NES heatwave events, thermodynamic and surface energy budget analyses are applied to selected NES heatwave events. [Figure 2.7](#) illustrates the lead-lag composite anomalies in thermodynamic energy and surface energy for NES heatwave events. [Figures 2.8](#) and [2.9](#) represent the spatial distribution of composite anomalies in 975-hPa horizontal temperature advection and surface net shortwave radiation during the initiation and decaying stages of NES heatwave events, respectively.

In July, horizontal temperature advection is the primary driver of temperature increases during NES heatwave events, followed by the combined effects of adiabatic compression and vertical temperature advection ([Figure 2.7a](#)). This positive horizontal temperature advection is mainly concentrated on the northeastern side of the NES ([Figure 2.8a](#)), likely resulting from an anomalous southwesterly flow associated with local high pressure. In the NES, the presence of high pressure allows for increased shortwave radiation to heat the land surface, reaching its maximum value at lag 0 day ([Figures 2.7c](#) and [2.9a, b](#)). The warmed land surface subsequently releases more longwave radiation into the atmosphere ([Figure 2.7c](#)). Additionally, increased latent heat flux is released from the land surface, likely due to the drier air conditions. In western Siberia, less shortwave radiation reaches the land surface before the peak of NES heatwaves ([Figures 2.7e](#) and [2.9a](#)). This is consistent with the anomalous tripolar SAT and Z500 pattern over northern Eurasia, as depicted in the major NES heatwave periods in July ([Figure 2.6b–d](#)).

In August, positive horizontal temperature advection is also the primary driver of temperature increase during NES heatwave events, followed by the combined effect of adiabatic compression and vertical temperature advection ([Figure 2.7b](#)). However, this horizontal temperature advection is weaker than in July, resulting in a weaker temperature tendency during the initiation stage of NES heatwave events in August. In the NES, the enhancement of shortwave radiation during NES heatwave events is weaker in August than in July ([Figure 2.7d](#) and [2.9c, d](#)).

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

Additionally, western Siberia does not display changes in surface heat flux preceding the onset of NES heatwaves in August (Figures 2.7f and 2.9c).

Overall, the local physical processes contributing to the initiation of NES heatwaves in July and August are similar, with horizontal temperature advection playing a major role. However, horizontal temperature advection is stronger in July than in August, and the behaviors of the surface energy budget in western Russia differ between these months. These differences are likely linked to variations in typical atmospheric circulation patterns associated with NES heatwaves in July and August.

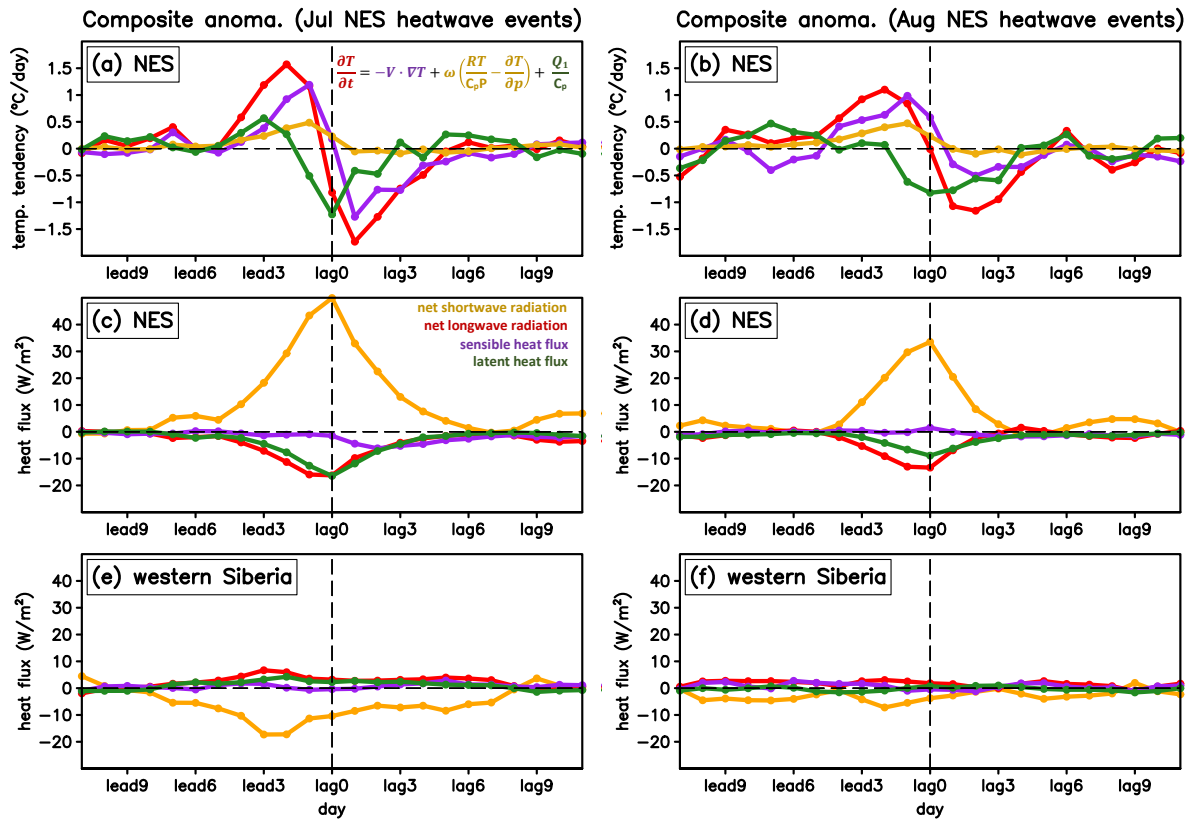


Figure 2.7 | Lead-lag composite anomalies in thermodynamic energy and surface energy for northeastern Siberian heatwave events. (a–b) Lead-lag composite anomalies for each term in the thermodynamic energy equation at 975-hPa level, averaged over the NES, for (a) July and (b) August. Red, purple, orange, and green lines denote local temperature tendency, horizontal temperature advection, the sum of adiabatic heating and vertical temperature advection, and diabatic heating, respectively. **(c–d)** Lead-lag composite anomalies for each term in the surface energy balance equation, averaged over the NES, for (c) July and (d) August. Orange, red, purple, and green lines denote surface net shortwave radiation, surface net longwave radiation, latent heat flux, and sensible heat flux, respectively. **(e–f)** Similar to (c–d), but for surface heat flux anomalies averaged over western Siberia (60°N–70°N, 70°E–100°E).

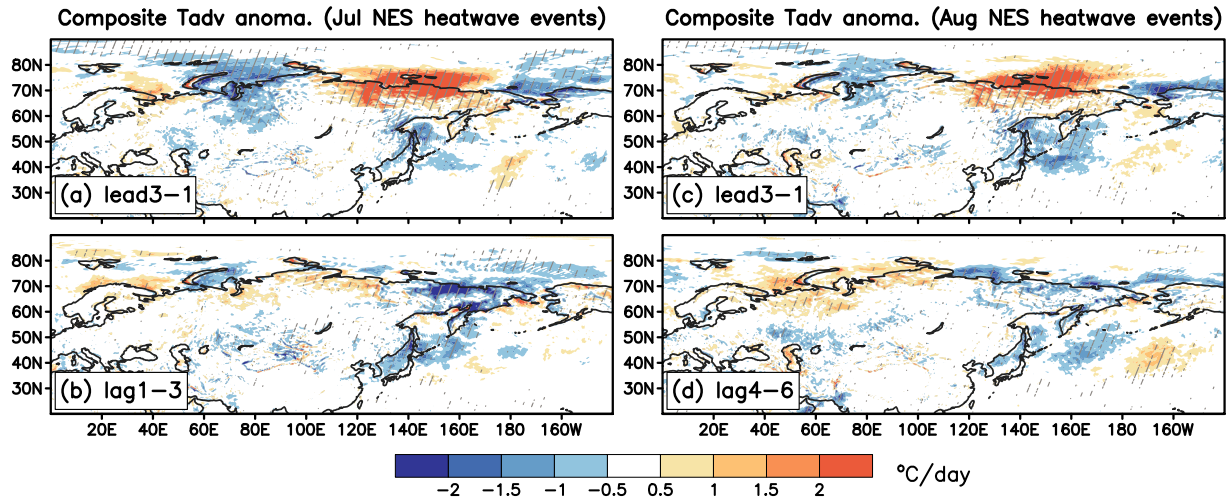


Figure 2.8 | Spatial distribution of composite 975-hPa horizontal temperature advection anomalies for northeastern Siberian heatwave events. (a–b) Composite 975-hPa horizontal temperature advection anomalies averaged (a) from lead 3 to 1 days and (b) from lag 1 to 3 days for July NES heatwave events. **(c–d)** Similar to (a–b), but for August NES heatwave events. Hatched areas denote the anomalies significant at the 95% confidence level.

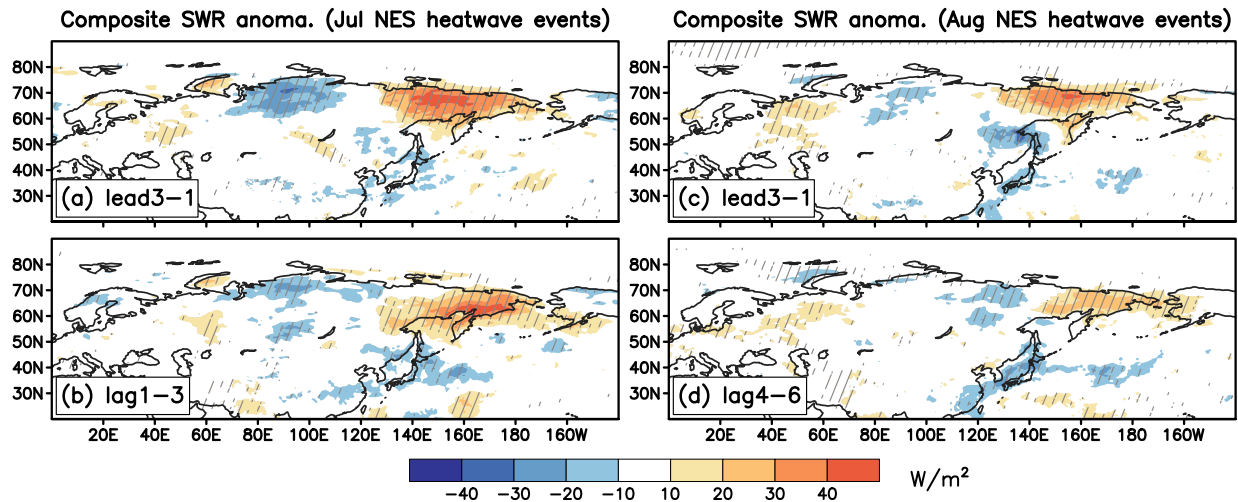


Figure 2.9 | Spatial distribution of composite surface net shortwave radiation anomalies for northeastern Siberian heatwave events. (a–b) Composite surface net shortwave radiation anomalies averaged (a) from lead 3 to 1 days and (b) from lag 1 to 3 days for July NES heatwave events. **(c–d)** Similar to (a–b), but for August NES heatwave events. Hatched areas denote the anomalies significant at the 95% confidence level.

2.3.3 Atmospheric circulation patterns associated with summer heatwaves over northeastern Siberia

This section examines the differences in typical atmospheric circulation patterns associated with NES heatwaves in July and August. To investigate these differences, regression analyses are applied to various meteorological variables on standardized NES heatwave frequency for each month. [Figure 2.10](#) illustrates the spatial distribution of regressed SAT and sea level pressure anomalies, comparing July and August. The results reveal distinct typical surface temperature and circulation patterns associated with NES heatwaves in each month.

When heatwaves frequently occur over the NES in July, regressed SAT anomalies exhibit a tripolar pattern over northern Eurasia, featuring positive anomalies over western Russia and the NES and negative anomalies over western Siberia ([Figure 2.10a](#)). Consequently, the interannual variations in heatwave frequencies over western Russia (40°N–60°N, 20°E–60°E) and the NES are significantly correlated ($r = 0.36$, $p < 0.05$), suggesting that heatwaves over these two remote regions often occur concurrently in July. This finding is also supported by the case study on major NES heatwave periods in July 2001, 2003, and 2010 ([Figure 2.6b–d](#)). Additionally, positive sea level pressure anomalies are observed over the Sea of Okhotsk, suggesting that the strengthened Okhotsk High tends to coincide with the warmer NES ([Figure 2.10c](#)). This was also noted by Tachibana et al. (2004), which reported that warming in the NES can increase the thermal contrast between the NES and the Sea of Okhotsk, contributing to the development of the Okhotsk High.

In contrast, when heatwaves frequently occur over the NES in August, negative SAT anomalies are observed over northern Japan, with evident negative sea level pressure anomalies over the western North Pacific ([Figure 2.10b, d](#)). These results suggest a connection between heatwaves over the NES and weather in the western North Pacific in August. Additionally, positive sea level pressure anomalies centered over the Chukchi Peninsula rather than the Sea of Okhotsk ([Figure 2.10d](#)). Furthermore, negative sea level pressure anomalies predominate over the Arctic ([Figure 2.10d](#)), indicating a possible link between Arctic atmospheric circulation and NES heatwaves.

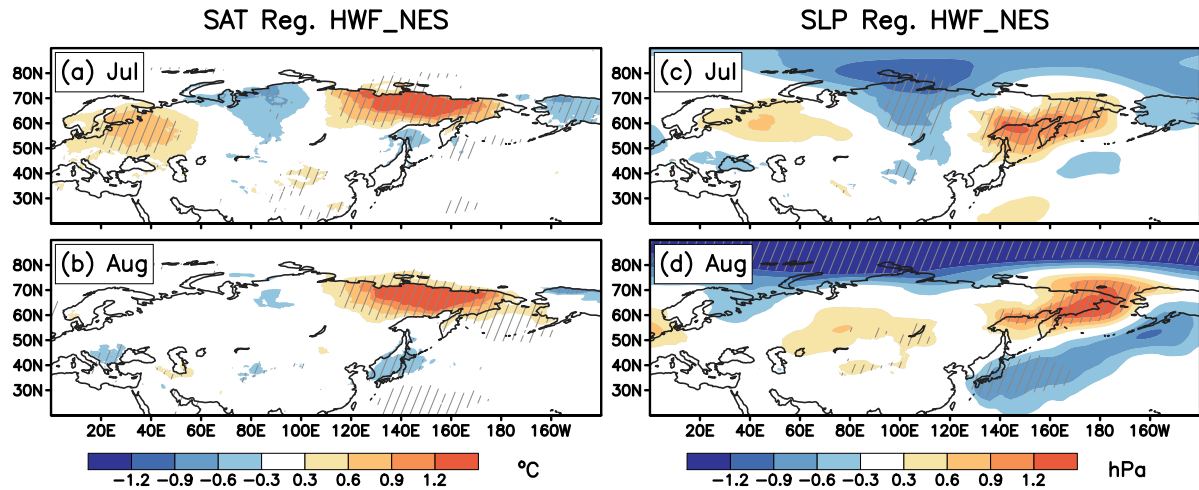


Figure 2.10 | Surface air temperature and sea level pressure associated with northeastern Siberian heatwave frequency. (a–b) Regressed surface air temperature anomalies on standardized NES heatwave frequency in (a) July and (b) August. **(c–d)** Regressed surface level pressure anomalies on standardized NES heatwave frequency in (c) July and (d) August. Hatched areas denote the anomalies significant at the 95% confidence level.

Figure 2.11a and b depict the spatial distribution of regressed Z500 anomalies, comparing July and August. When heatwaves frequently occur over the NES in these two months, strong positive height anomalies are observed in this region. These positive height anomalies extend the entire troposphere, with a maximum value located around the 300-hPa level, as illustrated in the latitude-vertical cross-section of geopotential height anomalies averaged over the domain 130°E–180°E (shading in Figure 2.11c and d). Such a deep high-pressure structure can result in a strong subsidence, leading to clear sky conditions, allowing for increased absorption of shortwave radiation at the land surface and facilitating the formation of NES heatwaves (not shown).

In July, corresponding to the SAT anomalies, the Z500 anomalies also exhibit a tripolar pattern over northern Eurasia, with wave activity flux propagating from western Russia to the NES (Figure 2.11a). These results indicate that the Rossby wave train along northern Eurasia likely contributes to initiating NES heatwaves in July. Tachibana et al. (2004) also pointed out that the warmth of NES in July is probably due to the eastward propagating Rossby wave along northern Eurasia. Since the magnitude of the positive height anomalies over the NES is stronger than that of the other two anomaly centers, local factors, such as latent heating near the NES, as suggested by Kim & Lee (2022a), may also contribute to the formation of NES heatwaves. In

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

addition, the latitude-vertical cross-section of geopotential height anomalies averaged over the domain 140°E – 160°E shows a baroclinic structure, with positive height anomalies tilting southward with decreasing altitude, partially overlapped with the area of Okhotsk High at the surface level (contour in Figure 2.11c).

In contrast to the zonal structure of the geopotential height anomalies over northern Eurasia in July, those exhibit a meridional structure from the Arctic to the western North Pacific in August. When heatwave frequency is high in August, significantly negative Z500 anomalies are present over the north of the Kara Sea, with wave activity flux propagating from this region to the NES (Figure 2.11b). These negative height anomalies exist throughout the troposphere (not shown). These results suggest that abnormal Arctic low pressure may contribute to the formation of NES heatwaves in August. Additionally, negative height anomalies are noted over northern Japan, with wave activity flux propagating from the NES, indicating the influence of anticyclonic circulation over the NES on weather in northern Japan (Figure 2.11b, d).

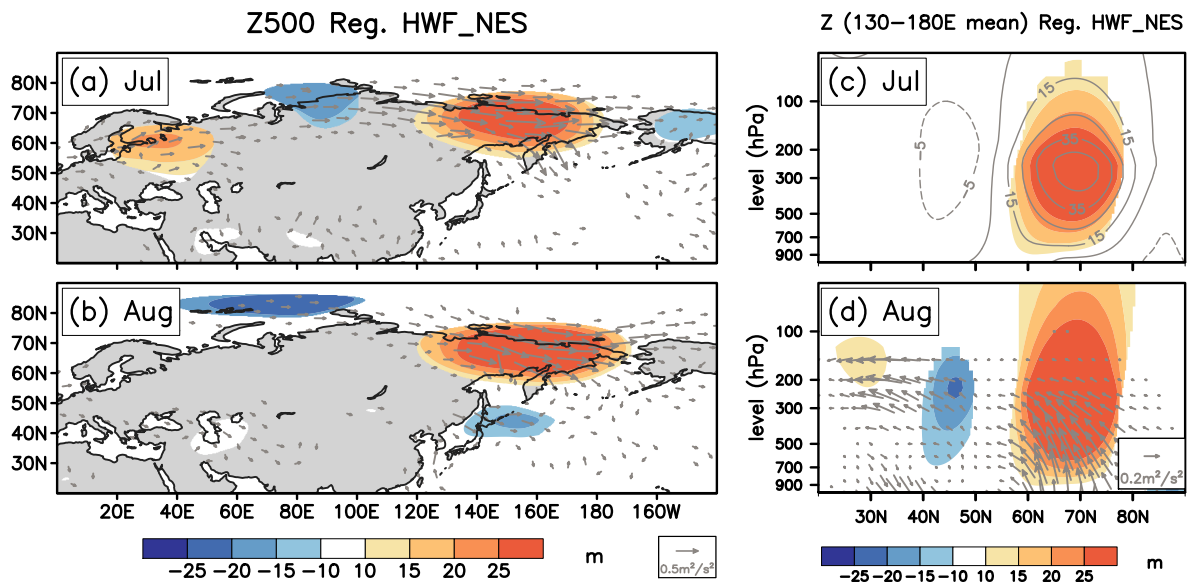


Figure 2.11 | Geopotential height associated with northeastern Siberian heatwave frequency. (a–b) Regressed 500-hPa geopotential height anomalies on standardized NES heatwave frequency in (a) July and (b) August. The vectors denote horizontal wave activity flux at this level, with vectors greater than $0.1 \text{ m}^2/\text{s}^2$ displayed. (c–d) Latitude-vertical cross-sections of the regressed geopotential height anomalies (130°E – 180°E mean) on standardized NES heatwave frequency in (c) July and (d) August. The contours in (c) denote the geopotential height anomalies averaged over 140°E – 160°E , starting from 5 m with an interval of 10 m. The vectors in (d) denote vertical wave activity flux, with vectors greater than $0.02 \text{ m}^2/\text{s}^2$ displayed. Shadings are displayed only for regions where anomalies are significant at the 95% confidence level.

Chapter 2: Different atmospheric circulation patterns associated with NES heatwaves

Under the condition of a strengthened polar jet along the Eurasian Arctic coast, the NES experiences higher temperature (Rousi et al., 2022) and increased fire activity (Scholten et al., 2022). To further elucidate jet stream conditions, regressed zonal wind anomalies in July and August are compared in Figure 2.12. For both months, when heatwave frequency is high, zonal wind strengthens along the Siberian coast, with maximum values around the 250-hPa level. These results suggest that a warmer NES is accompanied by a strengthened polar jet, which is consistent with the previous studies.

Specifically, the polar jet strengthens along the coastal area of western Russia in July (Figure 2.12a), corresponding to positive height anomalies over western Russia (Figure 2.11a). While precipitation increases along the Meiyu-Baiu front in July, a strengthened East Asian subtropical jet is not found (Figure 2.12a), despite being suggested by previous studies (Nakamura & Sato, 2022; Figure 1.3). Instead, a strengthened East Asian subtropical jet is evident in August, accompanied by intensified upward motion and increased precipitation in the western North Pacific (Figure 2.12b, d). These results suggest that weather in the western North Pacific may be strongly linked to NES heatwaves and associated atmospheric circulation in August.

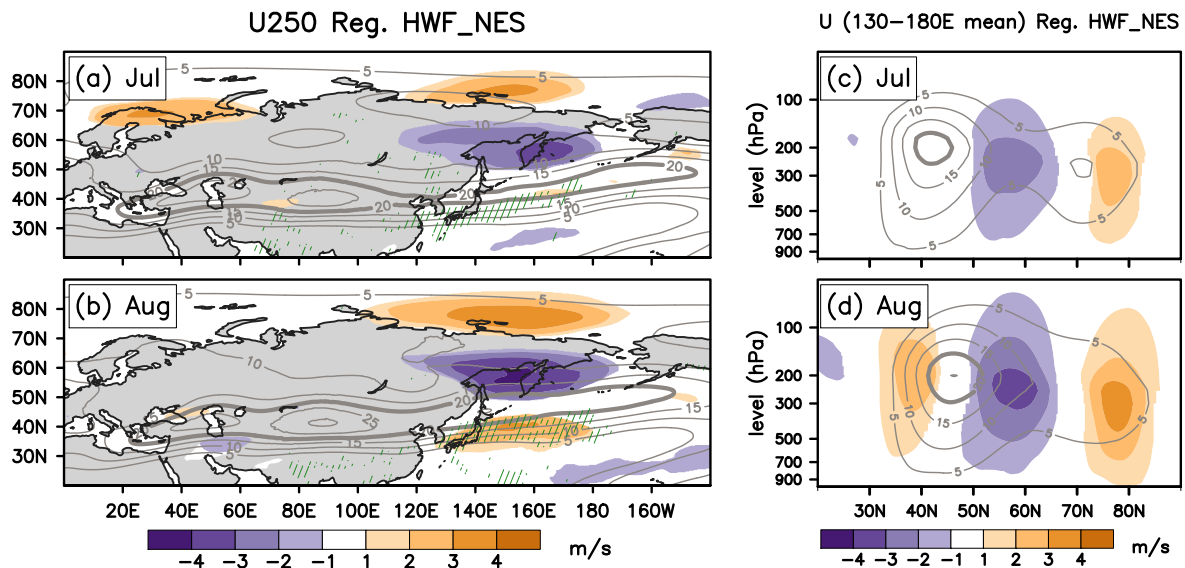


Figure 2.12 | Jet streams associated with northeastern Siberian heatwave frequency. (a–b) Regressed 250-hPa zonal wind anomalies on standardized NES heatwave frequency in (a) July and (b) August. Hatched regions denote regressed precipitation anomalies where values exceed 0.5 mm/day. **(c–d)** Latitude-vertical cross-sections of the regressed zonal wind anomalies (130°E–180°E mean) on the standardized NES heatwave frequency in (c) July and (d) August. Shadings are displayed only for regions where anomalies are significant at the 95% confidence level. Contours denote the climatology with an interval of 5 m/s.

2.3.4 Possible drivers of summer heatwaves over northeastern Siberia

As indicated by the regression analyses above, the typical atmospheric circulation patterns associated with NES heatwaves differ between July and August. In July, a Rossby wave train along northern Eurasia may play a crucial role in the formation of NES heatwaves (Figure 2.11a). In August, an Arctic low-pressure anomaly may contribute to their development (Figure 2.11b). This section further explores the potential drivers of NES heatwaves in both months.

The main teleconnection patterns along the polar jet in July are examined by applying EOF analysis to the latitude-weighted 250-hPa meridional wind over the domain 50°N–80°N, 20°W–180°E. The first mode, which explains 24% of the total variance, represents anomalous southerly winds over Scandinavia and central Siberia and northerly winds over the Ural Mountains and Kamchatka Peninsula (shading in Figure 2.13a). The second mode, which explains 19% of the total variance, is shifted westward relative to the first mode (shading in Figure 2.13b). The first and second modes correspond to the British–Okhotsk Corridor pattern and the British–Baikal Corridor pattern, respectively, which are excited by nonlinear interactions between the mean flow and low- and high-frequency variabilities at the exit of the Atlantic jet (Xu et al., 2019, 2022).

The spatial distribution of regressed 250-hPa meridional wind anomalies on NES heatwave frequency in July aligns well with the first mode, with a spatial correlation coefficient of 0.87 over the EOF domain (Figure 2.13a). Furthermore, the interannual variations in NES heatwave frequency and the first principal component exhibit a strong correlation ($r = 0.50$, $p < 0.01$) in July (Figure 2.13c). For instance, the British–Okhotsk Corridor pattern was in a strong positive phase in July 2001, 2003, and 2010, during which NES also experienced frequent heatwaves (Figure 2.6b–d). Therefore, it is likely that the British–Okhotsk Corridor pattern plays an important role in forming NES heatwaves in July. The dissimilarity between the spatial distribution of regressed 250-hPa meridional wind anomalies and the second mode (Figure 2.13b), along with the out-of-phase variations in heatwave frequency and the second principal component (Figure 2.13d), suggests that NES heatwaves in July are not regulated by the British–Baikal Corridor pattern.

Main teleconnection patterns along the polar jet in Jul

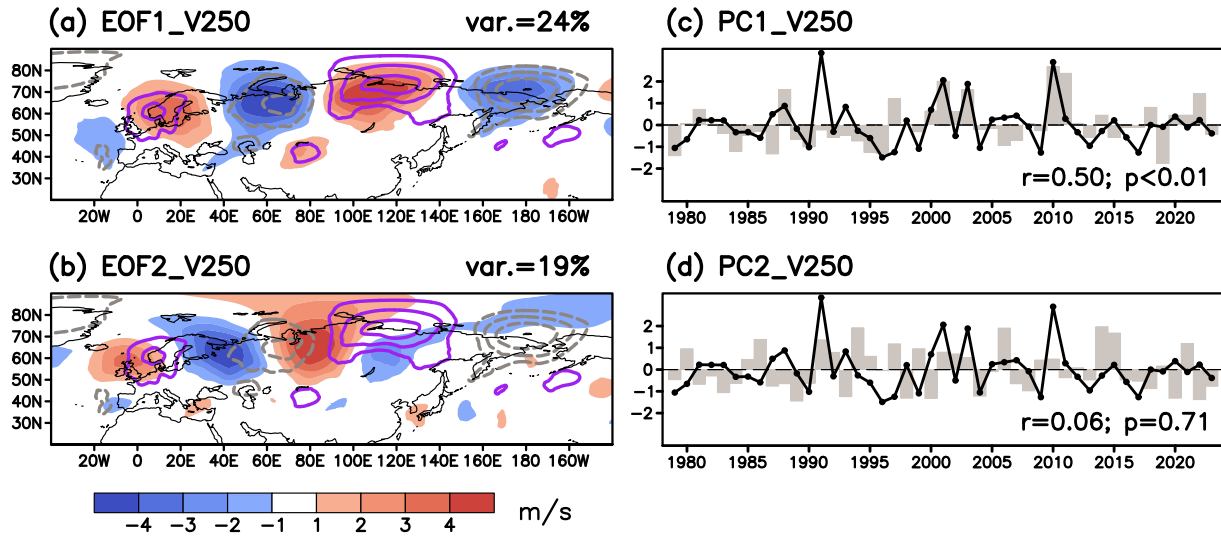


Figure 2.13 | Main teleconnection patterns along the polar jet in July. (a–b) Regressed 250-hPa meridional wind anomalies (shading) on the (a) first and (b) second principal components in July. The percentage denotes the explained variance. The contours in (a) and (b) denote regressed 250-hPa meridional wind on standardized NES heatwave frequency in July. The contour interval is 1 m/s, with negative contours dashed and zero contours omitted. (c–d) Interannual variations in the (c) first and (d) second principal components (PC1: bar) in July. The lines in (c) and (d) denote the standardized detrended NES heatwave frequency in July. The numbers represent the correlation coefficients and p-values between heatwave frequency and principal component for July during 1979–2023.

Similarly, the main teleconnection patterns along the polar jet for August are extracted. Unlike the confined action centers over northern Eurasia in July, the teleconnection patterns along the polar jet in August tend to be linked to meridional wind variability along the subtropical jet (shading in Figure 2.14a, b). Xu et al. (2022) also reported that the British–Okhotsk Corridor pattern can occasionally couple with the Silk Road pattern in summer and suggested that the basic flow may indirectly influence this linkage. The results of this study further indicate that this linkage is prominent in August but not in July.

The spatial distribution of regressed 250-hPa meridional wind anomalies on NES heatwave frequency in August does not align well with these two teleconnection patterns (Figure 2.14a, b). Furthermore, on an interannual time scale, the strength of these main teleconnection patterns along the polar jet shows no correlation with NES heatwave frequency in August (Figure 2.14c, d). Thus, teleconnection patterns along the polar jet exert a weaker influence on NES heatwaves in August.

Main teleconnection patterns along the polar jet in Aug

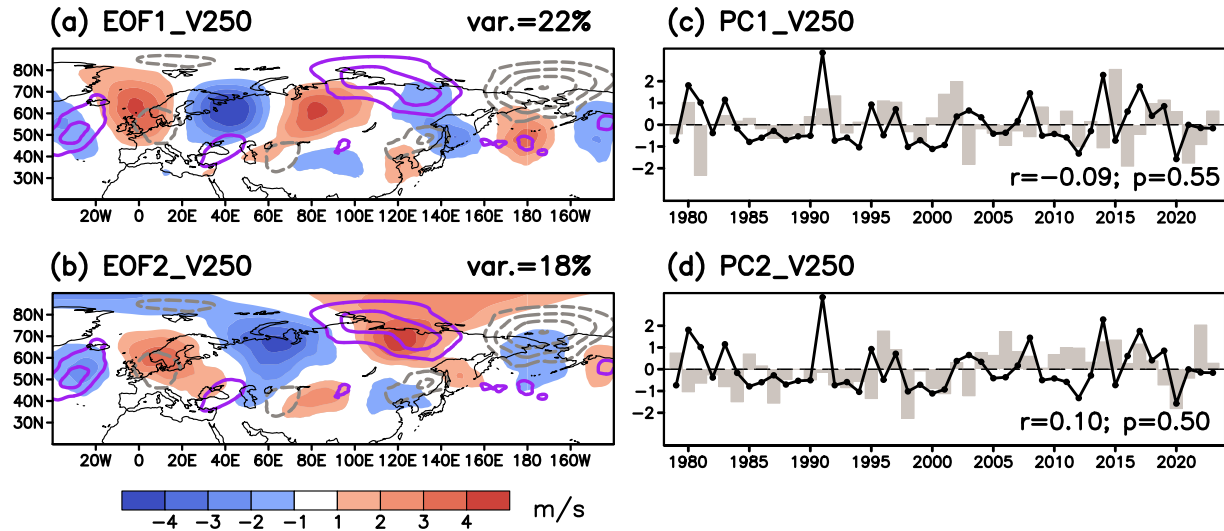


Figure 2.14 | Main teleconnection patterns along the polar jet in August. (a–b) Regressed 250-hPa meridional wind anomalies (shading) on the (a) first and (b) second principal components in August. The percentage denotes the explained variance. The contours in (a) and (b) denote regressed 250-hPa meridional wind on standardized NES heatwave frequency in August. The contour interval is 1 m/s, with negative contours dashed and zero contours omitted. (c–d) Interannual variations in the (c) first and (d) second principal components (PC1: bar) in August. The lines in (c) and (d) denote the standardized detrended NES heatwave frequency in August. The numbers represent the correlation coefficients and p-values between heatwave frequency and principal component for July during 1979–2023.

Instead of the main teleconnection patterns along the polar jet (Figure 2.14), there is a possibility that the Arctic low-pressure anomaly facilitates the formation of NES heatwaves in August through the propagation of the Rossby wave, as suggested by the regression analysis (Figure 2.11b). The formation process of this Arctic low-pressure anomaly may result from Arctic warming, including sea ice decline (Deng et al., 2020; Nakamura & Sato, 2022). The response of such Arctic forcing under the basic state in August is examined by a linear baroclinic model experiment. Positive vorticity is prescribed over the north of the Kara Sea, with a maximum value in the upper troposphere (Figure 2.15a, b). In response to this Arctic forcing, positive Z500 anomalies are generated over the NES (Figure 2.15c). Thus, there is a possibility that the formation of NES heatwaves in August is related to Arctic atmospheric circulation change.

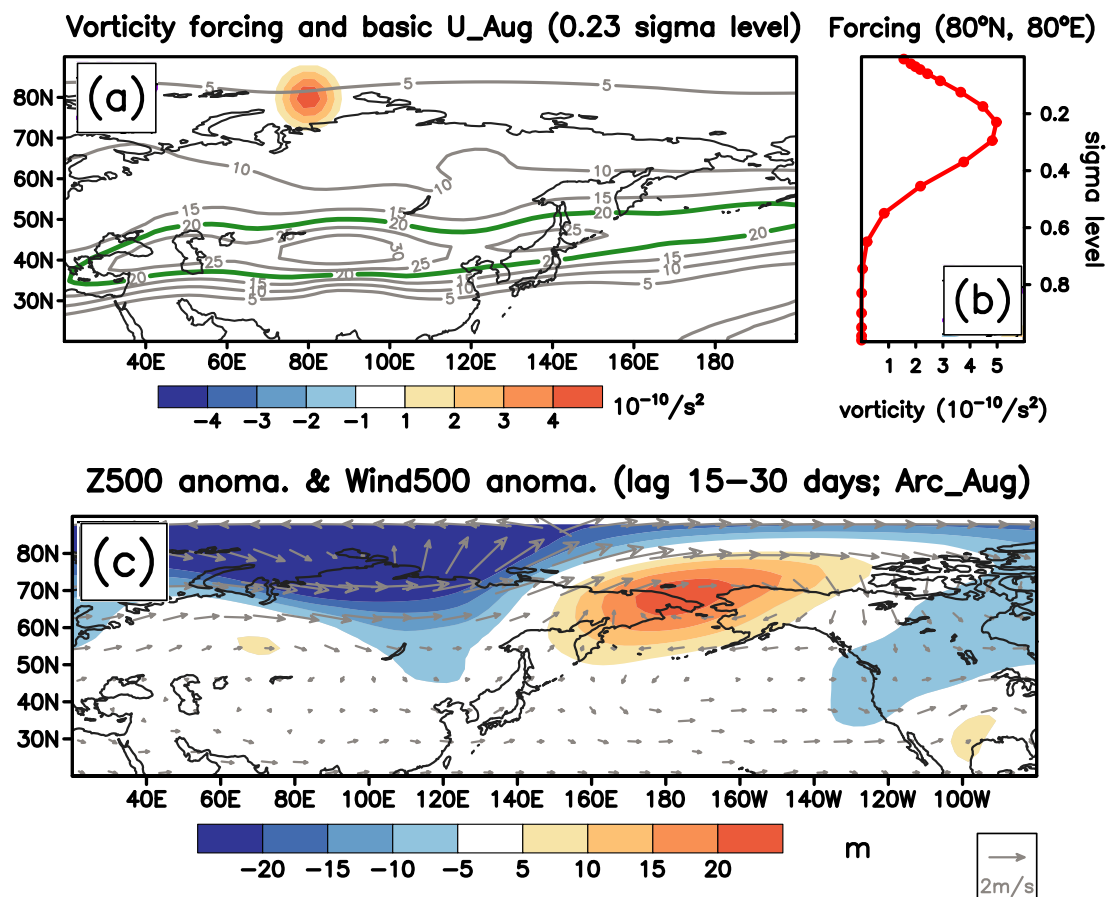


Figure 2.15 | Response of vorticity forcing over the Arctic under August basic state by using linear baroclinic model. (a) Arctic vorticity forcing at 0.23 sigma level. (b) Vertical profile of vorticity forcing at 80°N, 80°E. (c) Response of the 500-hPa geopotential height (shading) and 500-hPa horizontal wind (vector) averaged from 15 to 30 days.

2.4 Discussions

(i) Different atmospheric background states in July and August

Section 2.3.3 underscores that the typical atmospheric circulation patterns associated with NES heatwaves differ between July and August. These differences are likely due to variations in the atmospheric background states. In July, northern Eurasia is already warm, while the Arctic coastal region remains cold with sea ice. In August, northern Eurasia cools compared to July, whereas the Arctic coastal region becomes warmer as sea ice melts. This background state leads to a stronger thermal contrast and a more intense polar jet in July than in August. The meridional gradient of climatological 250-hPa potential vorticity, which indicates waveguide ability, is stronger over northern Eurasia in July compared to August (Figure 2.16a, b). Consequently, the interannual variability in 250-hPa meridional wind, which reflects Rossby wave activity, is also stronger in July (Figure 2.16c, d). This may explain why the British–Okhotsk Corridor pattern is identified as the main trigger of NES heatwaves in July but is unlikely to play a similar role in August.

These differences in atmospheric background states between July and August may also result in varying interactions between teleconnection patterns along the polar and subtropical jets. The interactions between teleconnection patterns along the two jets are stronger in August than in July (Figures 2.13 and 2.14), suggesting a higher probability of concurrent heatwaves between Europe and East Asia in August.

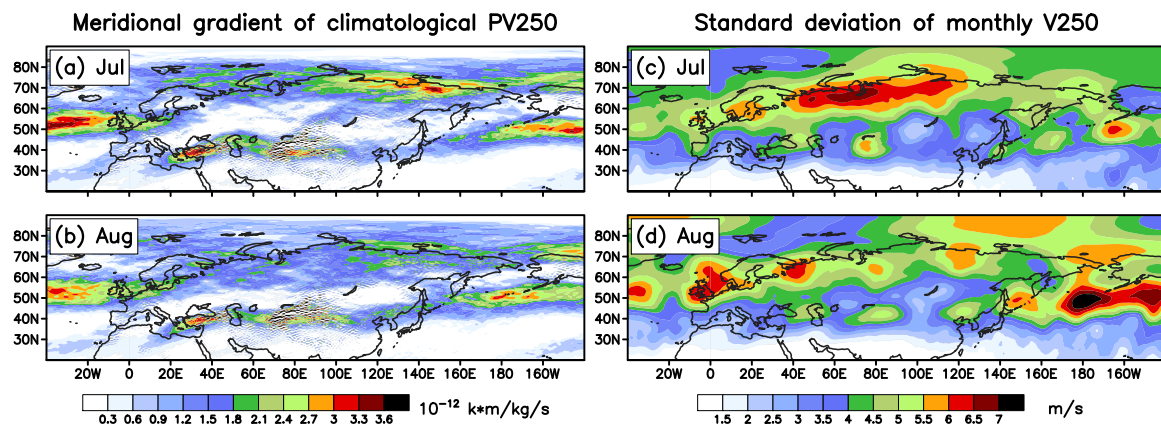


Figure 2.16 | Waveguide ability and Rossby wave activity. The meridional gradient of the climatological 250-hPa potential vorticity in (a) July and (b) August. The temporal standard deviation of the monthly 250-hPa meridional wind in (c) July and (d) August.

(ii) The responses of vorticity forcing over northeastern Siberia

The difference in atmospheric circulation over the western North Pacific related to NES heatwaves in July and August may be attributed to the varying climatological positions of the subtropical jet in these two months. In August, the climatological East Asian subtropical jet is located farther north, around 45°N, and is closer to the NES compared to its position in July, which is around 40°N (contour in Figure 2.12). To examine this speculation, the responses of vorticity forcing over the NES under the July and August basic states are examined using the baroclinic model, as shown in Figure 2.17. The results suggest that the atmospheric circulation over the western North Pacific is more susceptible to the influence of the anticyclonic circulation over the NES in August than in July, supporting this speculation.

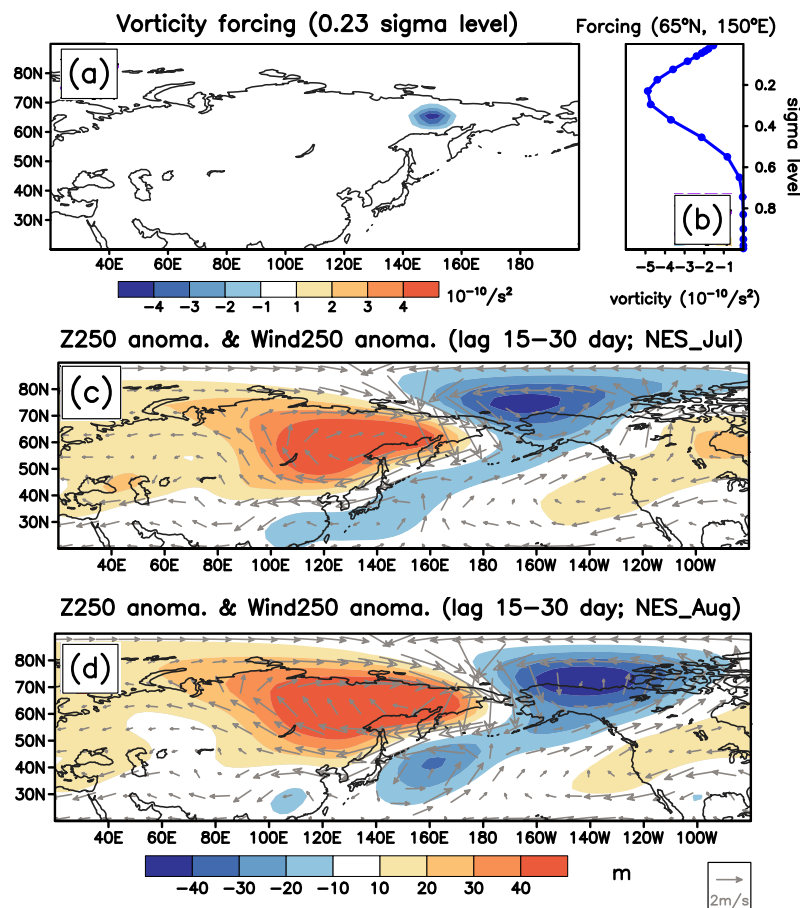


Figure 2.17 | Responses of vorticity forcing over northeastern Siberia under the July and August basic states by using linear baroclinic model. (a) NES vorticity forcing at 0.23 sigma level. (b) Vertical profile of vorticity forcing at 65°N, 150°E. (c) Response of the 250-hPa geopotential height (shading) and 250-hPa horizontal wind (vector) averaged from 15 to 30 days under the July basic state. (d) Similar to (c), but for the response under the August basic state.

(iii) Extreme weather links to Arctic warming

Arctic warming may have profound impacts on atmospheric circulation in middle and high latitudes. Recent studies suggest that Arctic warming may contribute to summer high-pressure anomaly and heatwaves over eastern Siberia (e.g., Chen et al., 2021; Nakamura & Sato, 2022), as described in [Section 1.3](#). In this chapter, regression analysis and linear baroclinic model experiment also indicate that an Arctic low-pressure anomaly plays a role in the formation of NES heatwaves in August ([Figures 2.11b](#) and [2.15](#)). The development of this Arctic low-pressure anomaly may be linked to Arctic sea ice decline (Deng et al., 2020; Nakamura & Sato, 2022).

Along with rapid Arctic warming, winter cold spells also occurred frequently in central Eurasia, forming the Warm Arctic–Cold Eurasia pattern, which is characterized by two distinct winter temperature anomalies centered over the Barents–Kara Seas and central Eurasia. The influence of Arctic warming on cold Eurasia remains a subject of ongoing debate. Some studies proposed that sea ice decline over the Barents–Kara Seas has contributed to recent cold Eurasia by modulating cyclone tracks (Inoue et al., 2012) and through the troposphere–stratosphere pathway (Zhang et al., 2018). Some other studies suggested that internal atmospheric variability is a crucial factor in the occurrence of cold Eurasia (e.g., He et al., 2020; Zhou et al., 2023). For instance, by analyzing a large ensemble historical simulation, Zhou et al. (2023) examined the winter Warm Arctic–Cold Eurasia pattern and concluded that internal atmospheric variability plays a critical role in regulating the magnitude of this pattern.

Although recent studies have increasingly focused on the influence of Arctic warming on extreme weather in middle and high latitudes, the extent to which Arctic amplification affects these events remains not fully understood. For the future investigation into the impacts of Arctic warming, a multi-model intercomparison with and without the Arctic warming signal, such as that conducted under the Polar Amplification Model Intercomparison Project (Smith et al., 2019), would be highly beneficial.

2.5 Conclusions

Globally, heatwaves have become more frequent over recent decades. However, summer heatwaves over eastern Siberia have received less attention. This chapter investigates NES heatwaves in July and August, focusing on their spatiotemporal characteristics, thermodynamic and surface energy budget, typical atmospheric circulation patterns, and possible drivers.

The results show that NES heatwaves have significantly increased in frequency and intensity in July and August. The thermodynamic energy budget analysis of the NES heatwave events suggests that local physical processes contributing to the initiation of NES heatwaves are similar in both months, with horizontal temperature advection playing a major role. However, horizontal temperature advection is stronger in July than in August.

Case studies and regression analyses reveal an anomalous tripolar pattern in SAT and Z500 across northern Eurasia, associated with NES heatwaves in July. EOF analysis further confirms that the British–Okhotsk Corridor pattern primarily regulates NES heatwave frequency on the interannual timescale, suggesting that this pattern plays a crucial role in the formation of NES heatwaves in July.

In contrast to the prevailing zonal structure across northern Eurasia in July, the atmospheric circulation pattern associated with NES heatwaves in August features a meridional structure from the Arctic to the western North Pacific. Arctic low-pressure anomaly may contribute to the formation of NES heatwaves in August, as examined by the linear baroclinic model. Additionally, heatwave-related high pressure over the NES in August may influence weather in the western North Pacific through a strengthened East Asian subtropical jet.

This chapter highlights that the typical atmospheric circulation patterns and drivers of NES heatwaves differ between July and August due to the different atmospheric background states. These findings enhance the current understanding of summer heatwaves over eastern Siberia, suggesting their connection to Arctic atmospheric circulation and their importance for subseasonal weather predictions in the western North Pacific.

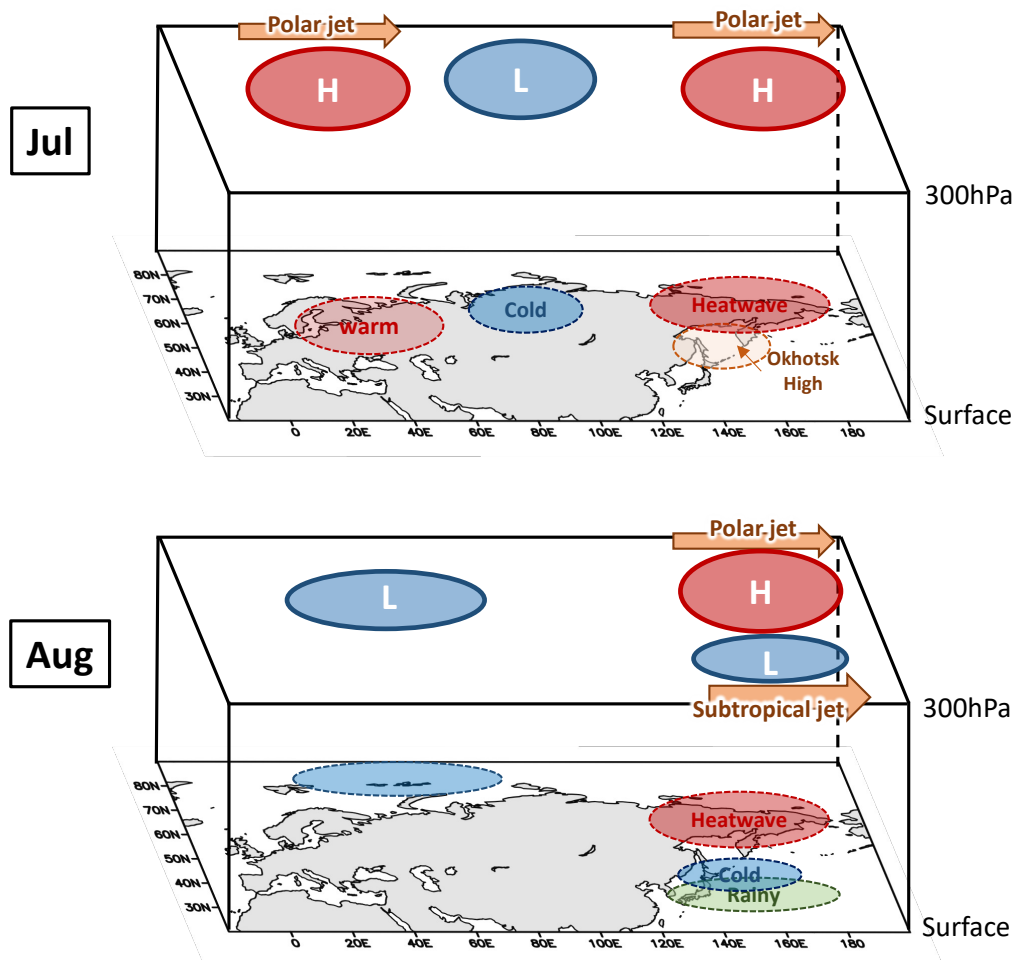


Figure 2.18 | Schematic diagram illustrating the main findings of Chapter 2. The atmospheric circulation associated with northeastern Siberian heatwaves in July features a zonal structure across northern Eurasia. In contrast, northeastern Siberian heatwaves in August are linked to an atmospheric circulation characterized by a meridional structure extending from the Arctic to the western North Pacific.

Chapter 3 Linkage between late-summer heatwaves over northeastern Siberia and subsequent sea surface temperature cooling in the western North Pacific

3.1 Introduction

(i) Summer East Siberian blocking and its impacts

Atmospheric blocking refers to a large anticyclonic weather system in the middle to high latitudes that is persistent, often stationary (typically lasting four or five days), and disrupts the usual westerly flow (Woollings et al., 2018). It is recognized as a key driver of summer heatwaves in these latitudes, primarily by reducing cloud cover and enhancing solar radiation (Woollings et al., 2018; Domeisen et al., 2023). Eastern Siberia is one of the regions in the Northern Hemisphere where frequent blocking events occur (Tibaldi et al., 1994). Summer East Siberian blocking (also referred to as Okhotsk or Kamchatka blocking) can lead to local heatwaves (Nakamura & Sato, 2022) and wildfires (Luo et al., 2024). For instance, the unprecedented heatwaves in early summer 2020 over eastern Siberia were largely driven by the development of atmospheric blocking (Nakamura & Sato, 2022).

In addition to impacting local extreme weather events, summer East Siberian blocking can remotely influence East Asian weather (Chen et al., 2021; Nakamura & Sato, 2022; Song & Ahn, 2024). For instance, in early summer 2020, excessive atmospheric blockings over eastern Siberia triggered cold air outbreaks into the Meiyu-Baiu region, halting the seasonal northward movement of the Meiyu-Baiu front and leading to record-breaking rainfall over eastern China and Japan (Chen et al., 2021). A composite analysis of East Siberian blocking days in early summer over the past six decades shows that summer East Siberian blocking enhances East Asian precipitation by strengthening the subtropical jet (Nakamura & Sato, 2022). Additionally, East Siberian blocking evident in the upper troposphere is accompanied by the Okhotsk High, a surface

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

high-pressure system over the cold waters of the Sea of Okhotsk (Nakamura & Fukamachi, 2004; Tachibana et al., 2004). The frequent occurrence of the Okhotsk High contributes to cooler summer temperature in northern Japan (Ninomiya & Mizuno, 1985). Zhou et al. (2025) pointed out that the local high-pressure anomaly associated with NES heatwaves in August may influence weather in the western North Pacific (WNP), with the subsequent sea surface temperature (SST) in this region tending to be colder.

(ii) Significance of studying sea surface temperature in the western North Pacific

Studying SST in the WNP is crucial due to its significant impact on the regional climate system and marine ecosystem. Due to the vast heat-holding capacity and strong ocean–atmosphere interactions in the WNP, the SST in this region influences the atmospheric circulation, affecting weather and climate in East Asia (e.g., Geng et al., 2022; Tao et al., 2024). For instance, Geng et al. (2022) suggested that positive SST anomalies in the WNP induce anomalous atmospheric circulation, leading to higher temperature in northeastern East Asia. Tao et al. (2024) found that spring SST anomalies in the WNP can persist into summer, generating nearly reversed atmospheric circulation anomalies to their north side and modulating precipitation in the Pan-Pacific regions. Additionally, SST in the WNP affects storm track activity (Taguchi et al., 2009). As one of the most productive and biologically diverse regions in terms of marine life, abnormal SST in the WNP impacts the regional marine ecosystem and fisheries (Yatsu et al., 2013; Ichii et al., 2018).

(iii) Factors contributing to sea surface temperature changes in the western North Pacific

Both atmospheric and oceanic forcings can contribute to summer SST changes in the WNP. Wu & Kinter (2010) claimed that shortwave radiation change associated with positive cloud–SST feedback is a dominant factor in the development of summer SST anomalies in the WNP, and the contribution of latent heat flux is secondary, mainly due to the sea–air humidity difference. The atmospheric circulation over the WNP is also influenced by atmospheric forcing from low and high latitudes. Noh et al. (2023) reported that the positive phase of the Pacific–Japan pattern

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

induces anomalous cyclonic circulation over the WNP, leading to decreased insolation and increased ocean-to-atmosphere latent heat flux, resulting in SST cooling in the WNP during summer. Zhou et al. (2025) suggested that SST cooling in the WNP may be linked to atmospheric circulation over the NES. However, the detailed physical processes underlying this lagged impact remain unclear.

Atmospheric forcing can alter SST through its influence on ocean currents. Seager et al. (2001) pointed out that intensified westerlies increased the equatorward Ekman drift of the underlying ocean, promoting SST cooling in the WNP. Due to a significant poleward meander of the Kuroshio Extension, the cool Oyashio water was replaced with much warmer water, causing exceptional marine heatwaves around northern Japan in the summer of 2023 (Sato et al., 2024). The oceanic background state, such as the surface mixed layer, also controls the sensitivity of SST to surface heat exchange between the ocean and atmosphere (Tozuka et al., 2023).

(iv) Objective and structure of this chapter

Existing studies have primarily focused on the impacts of summer East Siberian blocking on East Asian weather, with little attention given to its connection to SST changes in the WNP. Addressing this research gap, [Chapter 3](#) reveals the linkage between late-summer heatwaves over the NES and subsequent SST cooling in the WNP. The structure of this chapter is as follows: [Section 3.2](#) describes the data and methods used. [Section 3.3](#) investigates the linkage and the atmospheric and oceanic processes contributing to it. The discussions are presented in [Section 3.4](#), followed by the conclusions summarized in [Section 3.5](#).

3.2 Data and methods

(i) Reanalysis dataset

The study period for this study spans 1979–2023. Hourly and monthly fields for temperature (including air temperature and SST), atmospheric circulation parameters (e.g., geopotential height, horizontal wind) at multiple levels, and surface heat flux are obtained from the ERA5 reanalysis dataset, as described in [Section 2.2](#).

This chapter also uses the ocean reanalysis dataset, including mixed layer depth, ocean potential temperature, and sea surface height, from the Ocean Reanalysis System 5 (Zuo et al., 2019). The spatial horizontal resolution is approximately $0.25^\circ \times 0.25^\circ$ in latitude and longitude. This dataset consists of 75 ocean model levels, with the deepest level being around 5900 m. The Ocean Reanalysis System 5 is consistent with ERA5 as they use the same SST records to contain their surface boundary conditions. The mixed layer depth refers to the upper layer of the ocean where temperature, salinity, and density are relatively uniform due to the mixing of water. Here, the mixed layer depth is defined as the depth at which the averaged seawater density exceeds the near-surface density by 0.03 kg/m^3 . The ocean potential temperature is the temperature that seawater would have if it were moved adiabatically to the sea surface.

(ii) Partial correlation analysis

Partial correlation analysis is used to detect the direct relation between two variables by removing the influence of confounding factors. The partial correlation coefficient between variables x and y , removing the influence of variable z , is given by:

$$r_{xy \cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{1 - r_{xz}^2} \sqrt{1 - r_{yz}^2}}$$

Where r_{xy} is the correlation between x and y , r_{xz} is the correlation between x and z , and r_{yz} is the correlation between y and z .

(iii) Maximum covariance analysis

Maximum covariance analysis is a statistical technique used to identify dominant spatial patterns of covariability between two fields and provide their temporal variations. This method has been widely used, including the heatwave studies (e.g., Rodrigues et al., 2019; Fu et al., 2024). To assess the covariability between August atmospheric circulation over the North Pacific and September SST variability in the WNP, maximum covariance analysis is performed using August Z500 within the domain 30°N–80°N, 120°E–170°W and September SST within the domain 30°N–60°N, 120°E–170°W for the period 1979–2023. Regression analysis is then applied to the atmospheric circulation fields on their respective temporal scores to examine the relationships between the two fields.

(iv) Detection of two-dimensional atmospheric blocking

Following the approach of Woollings et al. (2018) and Michel et al. (2023), a two-dimensional index based on the Z500 field is used to detect atmospheric blocking. This index identifies whether the meridional geopotential height gradient is reversed at a given point, indicating the intrusion of a large-scale high-pressure anomaly in the middle latitudes. For each longitude λ , the following meridional Z500 gradients are computed for both the north and south of a given latitude ϕ :

$$\text{GHGN}(\lambda, \phi) = \frac{Z(\lambda, \phi + \Delta) - Z(\lambda, \phi)}{\Delta} < -10 \text{ gpm/}^\circ$$

$$\text{GHGS}(\lambda, \phi) = \frac{Z(\lambda, \phi) - Z(\lambda, \phi - \Delta)}{\Delta} > 0$$

$$\text{GHGS}_2(\lambda, \phi) = \frac{Z(\lambda, \phi - \Delta) - Z(\lambda, \phi - 2\Delta)}{\Delta} < -5 \text{ gpm/}^\circ$$

where λ ranges from 30°N to 75°N, and $\Delta = 15^\circ$ in latitude. GHGN and GHGS₂ are used to avoid detecting cut-off lows and low-latitude blocks, respectively. Similar to the persistence criterion for heatwaves, these Z500 conditions should persist for at least three days in this study to prevent the spurious detection of short-term blocking situations that would not significantly impact weather conditions at sub-seasonal timescale.

(v) Sea surface temperature tendency induced by surface heat flux change

Variations in the SST are determined by the heat balance of the surface mixed layer. SST tendency induced by surface heat flux change is assessed by $\frac{Q_{net}-Q_{-h}}{\rho C_p h}$ (Qiu & Kelly, 1993), where ρ represents mean density of seawater 1025 kg/m³, C_p represents specific heat capacity of seawater 3940 J/kg/K, h represents mixed layer depth. Q_{net} represents net surface heat flux and is calculated as the sum of surface net shortwave radiation, surface net longwave radiation, surface latent heat flux, and surface sensible heat flux. Q_{-h} represents downward shortwave radiation at the base of the mixed layer depth and is calculated based on an assumption of exponential decay with depth, as expressed below (Qiu & Kelly, 1993; Noh et al., 2023):

$$Q_{-h} = Q_0 [R e^{-\frac{h}{\gamma_1}} + (1 - R) e^{-\frac{h}{\gamma_2}}]$$

Here, Q_0 represents the downward shortwave radiation at the sea surface, and R , γ_1 , and γ_2 are constants depending by water quality. Typically, Jerlov water type 1 is assumed for calculating the attenuation quantity, with the constants of $R = 0.77$, $\gamma_1 = 0.35$, $\gamma_2 = 23.0$.

3.3 Results

3.3.1 Linkage between late-summer heatwaves over northeastern Siberia and subsequent sea surface temperature cooling in the western North Pacific

Firstly, the linkage between late-summer heatwaves over the NES and subsequent SST in the WNP is examined through the case study. Figure 3.1a–c illustrates anomalies in heatwave frequency and Z500 for August in 1991, 2004, and 2017 as representative months when NES experienced exceptionally high heatwave frequency. During these major NES heatwave periods, the NES is accompanied by strong local positive Z500 anomalies. Figure 3.1d–f represents anomalies in SST and Z500 for the subsequent month of September, revealing negative SST anomalies in the WNP, along with negative Z500 anomalies. These findings of the case study indicate a lagged linkage between August heatwaves over the NES and September SST cooling in the WNP.

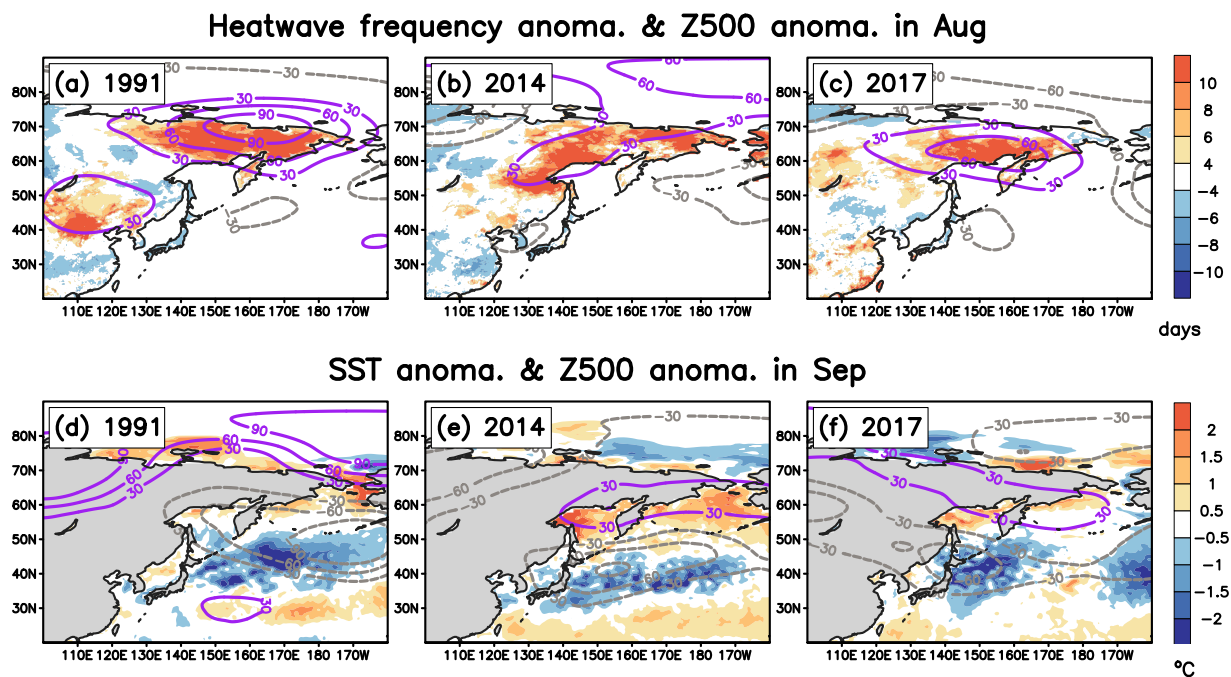


Figure 3.1 | Anomalies in heatwave frequency and sea surface temperature for major northeastern Siberian heatwave periods. (a–c) Heatwave frequency anomalies (shading) and 500-hPa geopotential height anomalies (contour) for August in (a) 1991, (b) 2014, and (c) 2017. **(d–f)** Sea surface temperature anomalies (shading) and 500-hPa geopotential height anomalies (contour) for September in (d) 1991, (e) 2014, and (f) 2017. The contour interval is 30 m, with negative contours dashed and zero contours omitted. Anomalies are calculated from detrended values and are relative to the monthly climatology.

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

NES heatwaves may not directly influence SST variability in the WNP, as they occur over land, while the WNP is a distant oceanic region. Instead, this connection is more likely mediated by atmospheric circulation linking high and middle latitudes. To further investigate the long-term relationship between August atmospheric circulation over the NES and subsequent SST in the WNP, correlation analyses are conducted for the period 1979–2023.

Figure 3.2a shows the correlation coefficient between regionally averaged August Z500 over the NES and both August heatwave frequency and SST at each grid point. The results reveal a significantly positive correlation with heatwave frequency over the NES, suggesting that NES heatwaves often develop due to strong solar radiation under unusually local high pressure. Moreover, a weakly negative correlation with SST is observed in the WNP. Figure 3.2b shows the correlation coefficient between the regionally averaged August Z500 over the NES and September SST in each grid point. The negative correlation in the WNP strengthens in September compared to August, suggesting a more pronounced linkage between Z500 over the NES and subsequent SST in the WNP. This may be due to the time required for SST to respond to changes in surface heat exchange (Sun & Wu, 2021). Additionally, there is a significant positive correlation with SST in the Bering Sea in August, which strengthens further in September (Figure 3.2a, b). These results suggest that atmospheric blocking not only triggers local land heatwaves but also contributes to marine heatwaves in adjacent oceanic regions, as also reported by Holbrook et al. (2020).

Figure 3.2c illustrates the interannual variations in regionally averaged anomalies of August Z500 and heatwave frequency over the NES, as well as the anomalies of September SST in the WNP. On an interannual timescale, August heatwave frequency and Z500 over the NES are out of phase with September SST in the WNP. The August heatwave frequency over the NES exhibits a strong negative correlation with September SST in the WNP ($r = -0.41$, $p < 0.01$). However, after removing the influence of August Z500, the partial correlation between the two approaches zero. Therefore, the following section further examines the connection between August atmospheric circulation over the NES and subsequent SST cooling in the WNP.

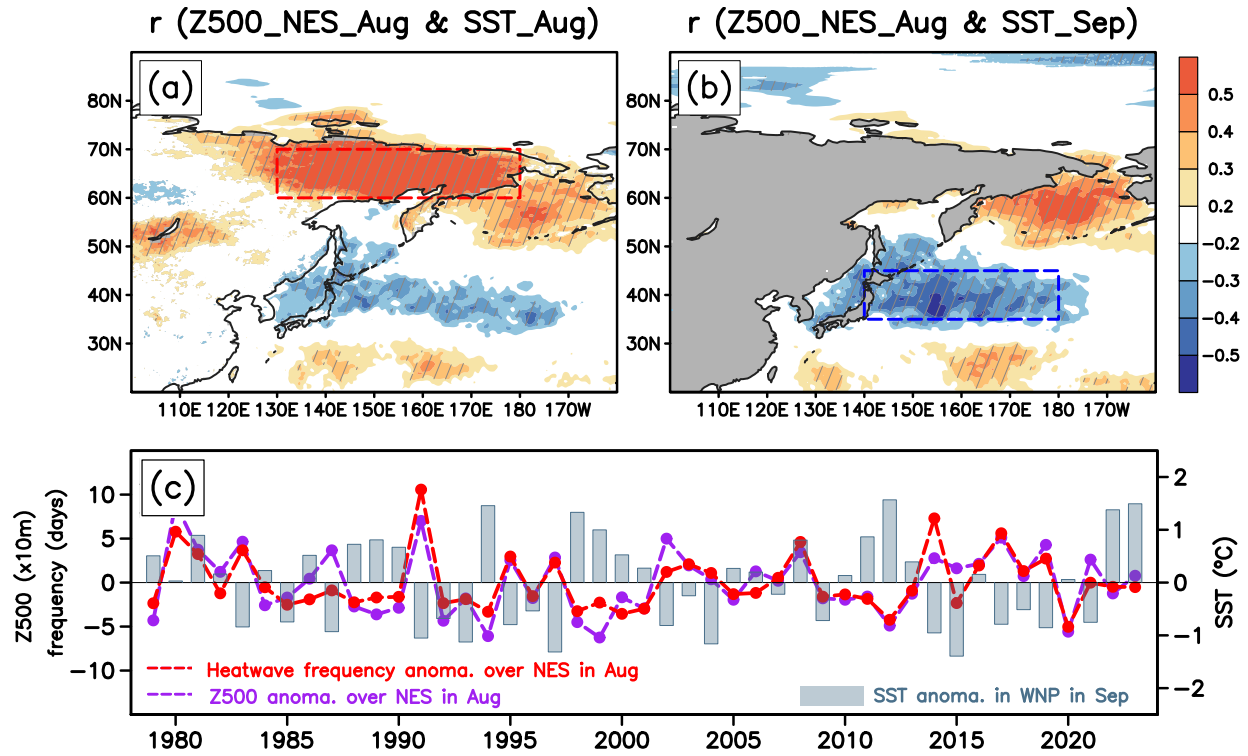


Figure 3.2 | Linkage between August heatwaves over northeastern Siberia and September sea surface temperature cooling in the western North Pacific through correlation analysis. (a) Correlation coefficient between regionally averaged August Z500 over the NES and both August heatwave frequency and SST at each grid point. The red dashed box denotes the NES region. (b) Correlation coefficient between the regionally averaged August Z500 over the NES and September SST at each grid point. The blue dashed box denotes the WNP region (35°N–45°N, 140°E–180°E). Hatched regions in (a) and (b) indicate correlations significant at the 95% confidence level. (c) Interannual variations in regionally averaged August NES Z500 anomalies (purple line), August NES heatwave frequency anomalies (red line), and September WNP SST anomalies (bar). Anomalies are calculated from detrended values and are relative to the monthly climatology.

To confirm the covariability between August atmospheric circulation over the North Pacific and September SST in the WNP, maximum covariance analysis is performed on August Z500 over the domain 30°N–80°N, 120°E–170°W and September SST in the domain 30°N–60°N, 120°E–170°W. The first mode explains 74% of the total covariance. The Z500 field exhibits a dipole height pattern, with positive anomalies over the NES and negative anomalies over the WNP (Figure 3.3a). This August dipole height pattern covaries with September negative SST anomalies in the WNP (Figure 3.3b), with a very strong positive interannual correlation coefficient between the two time series ($r = 0.74$; $p < 0.01$) (Figure 3.3c). Therefore, the maximum covariance analysis effectively captures the covariability between the August dipole height pattern over the North Pacific and September SST cooling in the WNP.

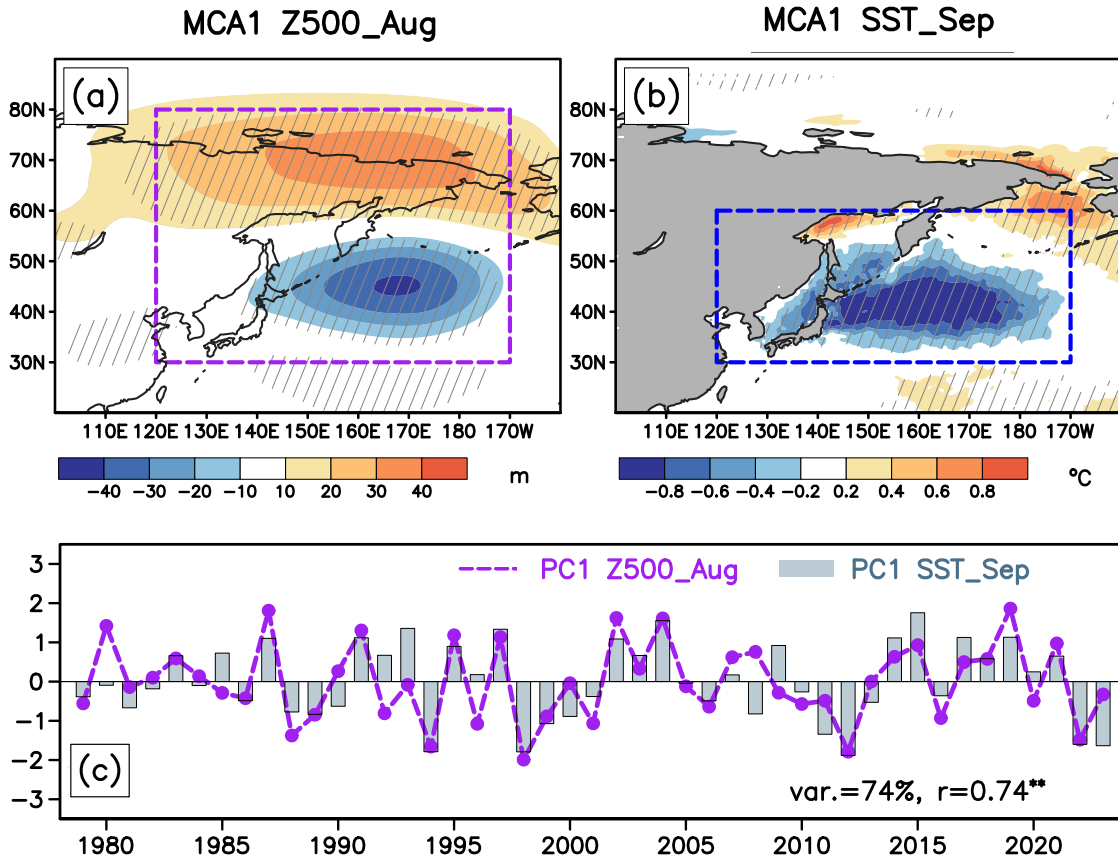


Figure 3.3 | The first coupled mode between August 500-hPa geopotential height over the North Pacific and September sea surface temperature in the western North Pacific through maximum covariance analysis. (a) Regressed Z500 anomalies on the first principal component for Z500. The purple dashed box is the analysis region for Z500 (30°N–80°N, 120°E–170°W). **(b)** Regressed SST anomalies on the first principal component for SST. The blue dashed box denotes the analysis region for SST (30°N–60°N, 120°E–170°W). Hatched regions in (a) and (b) indicate anomalies significant at the 95% confidence level. **(c)** Time series of the first principal components for Z500 (purple line) and SST (blue bar). The variance of this mode and the temporal correlation between these principal components are denoted at the bottom. Ending with two asterisks indicate that the correlation is significant at the 99% confidence level.

To examine whether this linkage exists in other months, the interannual correlation coefficient between Z500 over the NES and subsequent SST in the WNP for different months is calculated and summarized in the heatmap, as shown in [Figure 3.4a](#). The results show that August Z500 over the NES is significantly correlated with SST in the WNP not only from August to September but also persisting into October and November. This persistent linkage is particularly intriguing and may be related to ocean heat capacity and the seasonal evolution of the mixed layer depth. Notably, no similar persistent negative correlation is found in other months, highlighting the uniqueness of this linkage.

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

Since SST variability in the WNP is largely regulated by local atmospheric circulation, the interannual correlation coefficient between Z500 over the NES and WNP for different months is analyzed in Figure 3.4b. The results show simultaneous negative correlations in almost every month except for July. This absence is also noted in Figure 2.11a, which shows a lack of regressed negative geopotential height anomalies over the WNP associated with NES heatwave frequency in July.

The simultaneous negative correlation between Z500 over the NES and WNP reflects the western Pacific pattern. This pattern is a primary mode of low-frequency atmospheric variability over the North Pacific, characterized by opposite geopotential height anomalies centered over the Kamchatka Peninsula and the WNP (Wallace & Gutzler, 1981). While this dipole height pattern occurs almost every month, the unique linkage is observed only in late summer, suggesting that both atmospheric processes and oceanic background states may contribute to the distinct connection between August Z500 over the NES and subsequent SST in the WNP.

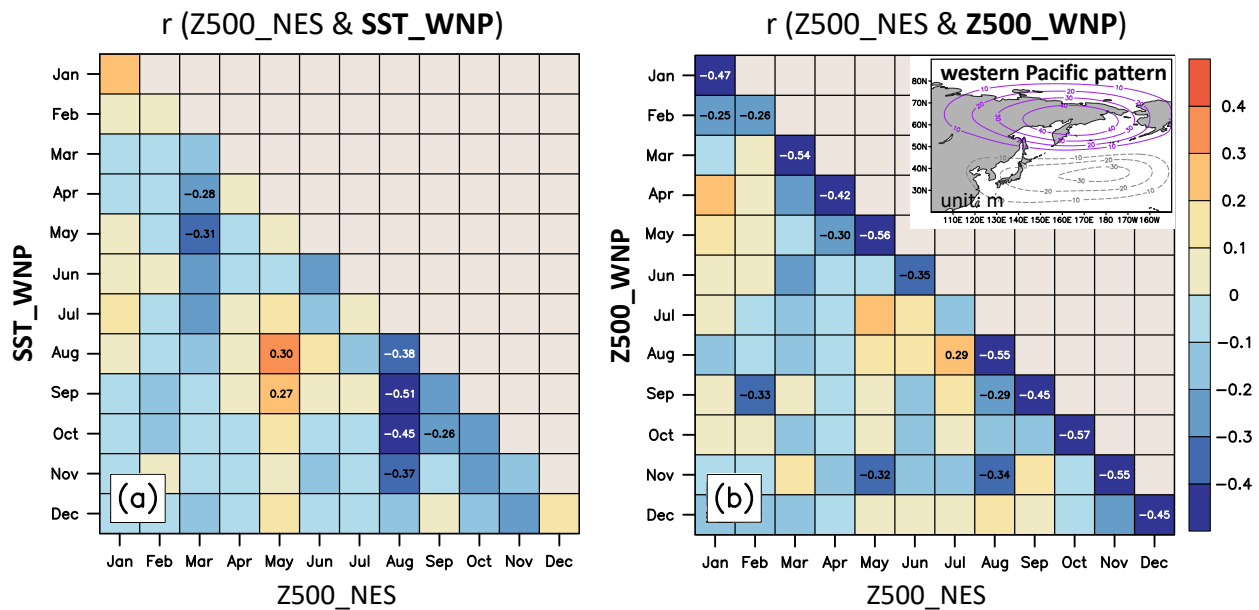


Figure 3.4 | Heatmap of correlation coefficient. (a) Correlation coefficient in the interannual variability between Z500 over the NES and subsequent SST in the WNP. (b) Correlation coefficient in the interannual variability between Z500 over the NES and subsequent Z500 over the WNP. Black values in (a) and (b) indicate that the correlation coefficient is significant between the 99% and 90% confidence level, while white values indicate that the correlation coefficient is significant at the 99% confidence level. The figure in (b) illustrates the spatial distribution of the western Pacific pattern. The western Pacific pattern is defined as the first EOF mode of monthly mean latitude-weighted Z500 over the domain 20°N–70°N, 120°E–180°E (Nishii et al., 2010). The contour interval is 10 m, with negative contours dashed and zero contours omitted.

3.3.2 Atmospheric and oceanic processes contributing to the linkage

The persist and unique linkage between August Z500 over the NES and the subsequent SST in the WNP is confirmed in [Section 3.3.1](#). Both atmospheric and oceanic processes may contribute to this linkage, and these processes are examined in this section. To elucidate changes in atmospheric circulation, surface heat flux, and SST associated with August NES over the NES, regression analyses are applied to various variables on the regionally averaged August Z500 over the NES, as depicted in [Figure 3.5](#).

The positive height anomalies over the NES contribute to increased surface temperature anomalies through increased insolation, facilitating the formation of surface land heatwaves ([Figure 3.5a, c](#)). In association with these positive height anomalies over the NES in August, negative height anomalies develop over the WNP ([Figure 3.5a](#)), exhibiting a barotropic structure that peaks around the 250-hPa level (not shown). These negative height anomalies may reflect the western Pacific pattern and could also be induced by NES blocking. At the surface level, anomalous northeasterly winds extend from the Bering Sea to the WNP ([Figure 3.5b](#)).

For surface heat flux, the WNP receives less shortwave radiation due to increased cloud cover ([Figure 3.5c](#)). Additionally, latent heat flux from the WNP increases, driven by drier surface air ([Figure 3.5d](#)). Surface net longwave radiation anomalies partially offset the net shortwave radiation anomalies but with a much smaller magnitude (not shown). Similarly, sensible heat flux anomalies are in phase with latent heat flux anomalies but also exhibit a much smaller magnitude (not shown). This is consistent with Wu & Kinter (2010), which noted that summer SST variability in the WNP is primarily regulated by shortwave radiation, with surface latent heat flux playing a secondary role.

The significant reduction in shortwave radiation reaching the ocean surface, along with a secondary contribution from increased latent heat flux released from the ocean surface to the atmosphere, contributing to a large surface heat loss in the WNP. This surface heat loss induces a negative SST tendency here in August ([Figure 3.5e](#)). In the subsequent September, negative SST anomalies emerge in the WNP ([Figure 3.5f](#)).

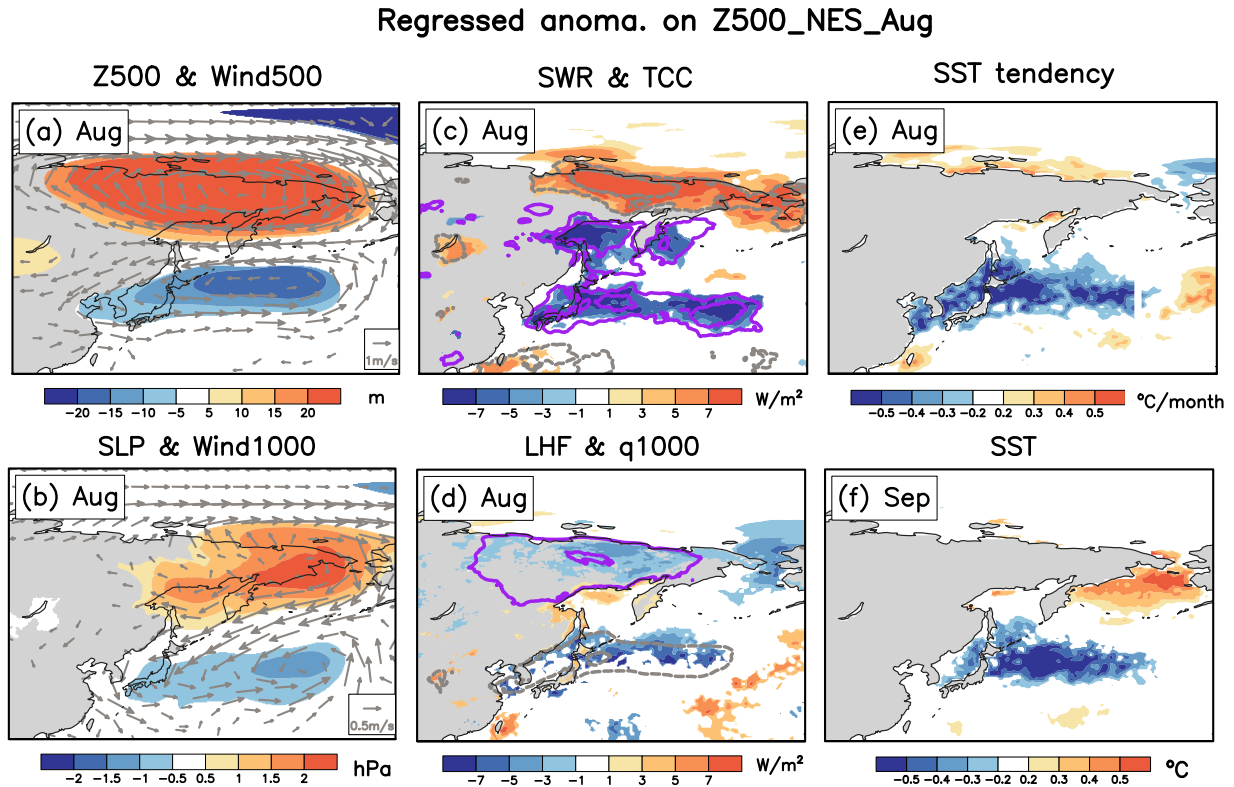


Figure 3.5 | Atmospheric circulation, surface heat flux, and sea surface temperature associated with August NES 500-hPa geopotential height through regression analysis. (a) Regressed August Z500 anomalies (shading) and 500-hPa horizontal wind anomalies (vector; > 0.05 m/s). **(b)** Regressed August sea level pressure anomalies (shading) and 1000-hPa horizontal wind anomalies (vector; > 0.2 m/s). **(c)** Regressed August net shortwave radiation anomalies (shading) and total cloud cover anomalies (contour). The contour interval is 0.2°C , with negative contours dashed and zero contours omitted. **(d)** Regressed surface latent heat flux anomalies (shading) and 1000-hPa specific humidity anomalies (contour). The contour interval is 0.3 g/kg, with negative contours dashed and zero contours omitted. **(e)** Regressed anomalies in August SST tendency induced by surface heat flux change. **(f)** Regressed September SST anomalies. Only shadings where anomalies are significant at the 95% confidence level are shown.

Figure 3.6 illustrates the monthly evolution of regressed air and ocean temperature anomalies at different levels over the WNP region. Associated with lower geopotential height and increased cloud cover, significant cooling is observed in the troposphere in August and September. Ocean cooling is not confined to the sea surface but extends into the mixed layer, reaching a depth of approximately 10 m in September. This cooling can penetrate to greater depths and persist into November. In November, a significant cooling signal re-emerges in the troposphere, suggesting that colder ocean temperature may, in turn, influence lower atmospheric temperature and circulation.

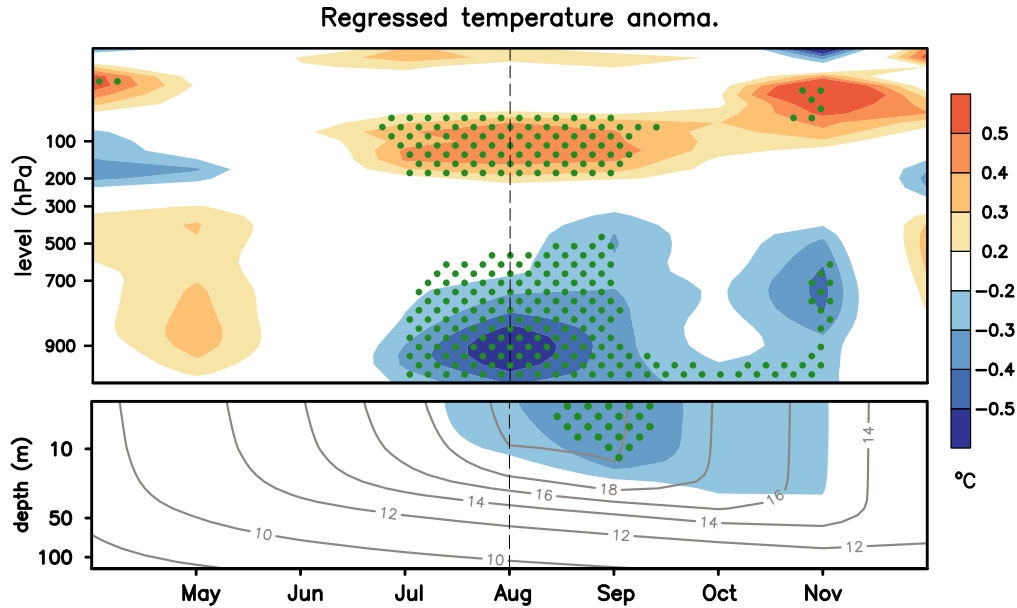


Figure 3.6 | Monthly evolution of air and ocean temperatures averaged over the western North Pacific, associated with August NES 500-hPa geopotential height through regression analysis. (a) Monthly vertical cross-section of air temperature anomalies regressed onto August NES 500-hPa geopotential height. **(b)** Similar to (a), but for ocean potential temperature anomalies. Contours indicate climatological ocean potential temperature. Dotted regions denote anomalies significant at the 95% confidence level.

In addition to the influence of surface heat flux changes driven by atmospheric circulation, background ocean states and oceanic processes also contribute to this linkage, as suggested in [Figure 3.4](#). Seasonal changes in upper-ocean salinity and surface wind lead to seasonal variations in mixed layer depth. Mixed layer depth plays an important role in determining the magnitude of SST variance (Tomita & Nonaka, 2006). With a shallow mixed layer depth, even small surface heat flux anomalies can induce a large SST change (Wu & Kinter, 2010).

To confirm this, the spatial distribution of climatological mixed layer depth and the temporal standard deviation of SST in both winter and summer are investigated in [Figure 3.7a–d](#). It shows that, in the WNP, surface wind is much weaker, and the mixed layer is significantly shallower in summer than in winter. Corresponding to that, interannual SST variability in the WNP is greater in summer than in winter.

To further examine the ocean background states in the WNP across each month, the monthly evolution of regionally averaged climatological mixed layer depth and temporal standard deviation of SST in the WNP is examined in [Figure 3.7e](#). It reveals that as winter transitions to

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

summer, the mixed layer depth decreases, and SST variability increases in the WNP region. Therefore, this shallow mixed layer depth makes SST in summer more sensitive to surface heat loss, resulting in larger SST cooling and contributing to the negative correlation between August Z500 over the NES and subsequent SST in the WNP.

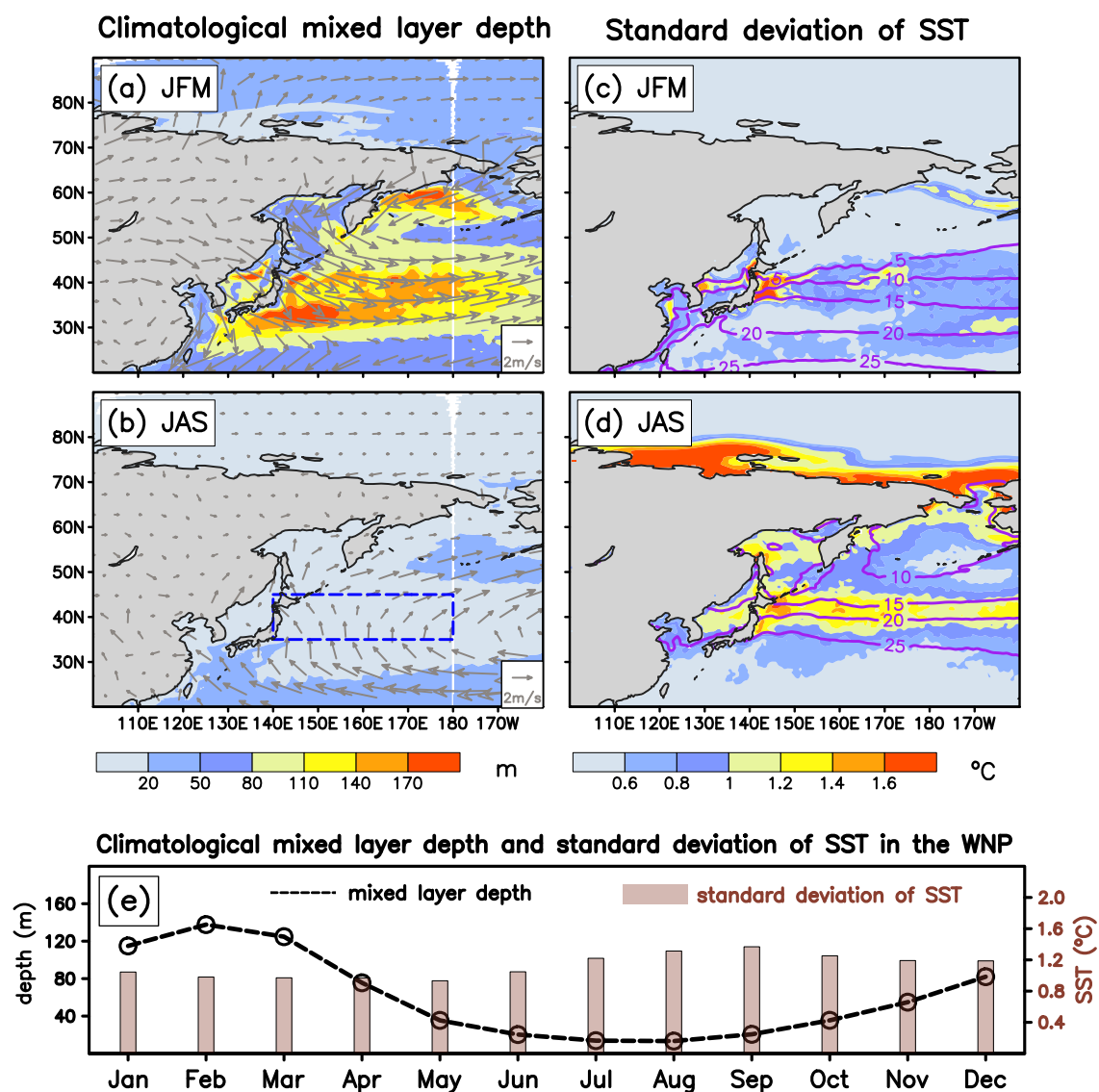


Figure 3.7 | Climatological mixed layer depth and temporal standard deviation of sea surface temperature in winter and summer. (a–b) Spatial distribution of climatological mixed layer depth (shading) and 10 m horizontal wind (vector, > 0.2 m/s) in (a) winter (January–March mean) and (b) summer (July–September mean). (c–d) Spatial distribution of temporal standard deviation (shading) and climatological mean (contour) of sea surface temperature in (c) winter and (d) summer. The blue dashed box in (b) denotes the domain of the WNP. (e) Monthly evolution of climatological mixed layer depth (line) and temporal standard deviation of sea surface temperature (bar) averaged in the WNP.

3.4 Discussions

(i) Other factors contributing to summer SST change in the western North Pacific

Over the NES, heatwave frequency is closely correlated with blocking activity (Figure 3.8a). Blocking is considered a key driver of summer heatwaves over the NES, primarily by reducing cloud cover and increasing solar radiation (Figure 3.5c). August Z500 over the NES and WNP exhibits a strong negative correlation (Figure 3.8b), which may result from the western Pacific pattern (Figure 3.4b). Reduced shortwave radiation due to increased cloud cover and enhanced release of surface latent heat flux, driven by drier surface air, contribute to surface heat loss in the WNP (Figure 3.8c). The surface heat loss leads to a negative SST tendency in this region in August, contributing to colder SST in the WNP in September (Figure 3.8d). However, some cases, such as 2008, 2022, and 2023, do not exhibit these processes. Next, additional factors contributing to summer SST change in the WNP in September are discussed.

Noh et al. (2023) reported that the positive phase of the Pacific–Japan pattern induces anomalous cyclonic circulation over the WNP, leading to reduced insolation and enhanced ocean-to-atmosphere latent heat flux, resulting in SST cooling in the WNP during summer. To examine the potential influence of atmospheric circulation on September SST variability in the WNP, the spatial distribution of the correlation coefficient between regionally averaged September SST in the WNP and the preceding Z500 at each grid point is investigated in Figure 3.9. The results indicate that local atmospheric circulation predominantly regulates September SST variability in the WNP, extending to the preceding months of July and August, which may be due to oceanic heat persistence. Furthermore, negative correlations are found over the NES in August, suggesting potential predictability of SST based on preceding atmospheric circulation over the NES, as discussed in Section 3.3. Negative correlations are also observed in the western Tropical Pacific, indicating an influence from low-latitude atmospheric circulation, similar to the findings of Noh et al. (2023). The linkage between SST variability in the WNP in September and atmospheric circulation over the NES and appears to be stronger than that over the western Tropical Pacific.

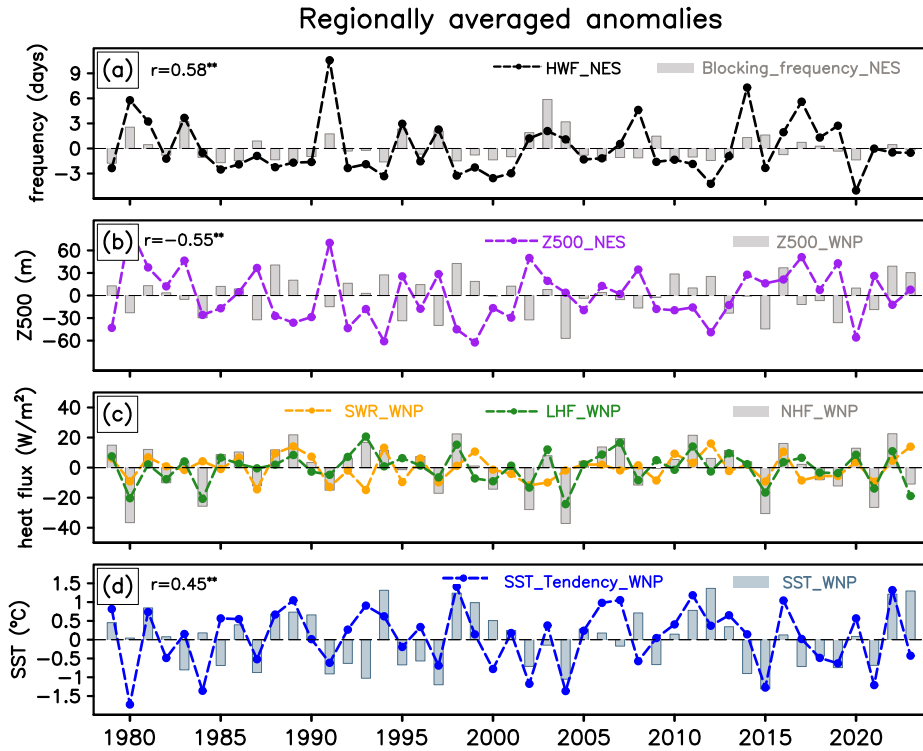


Figure 3.8 | Interannual variations in regionally averaged monthly anomalies over northeastern Siberia and the western North Pacific. (a) Anomalies in blocking frequency and heatwave frequency averaged over the NES in August. (b) Anomalies in Z500 averaged over the NES and WNP in August. (c) Anomalies in surface net shortwave radiation, surface latent heat flux, and surface net heat flux averaged over the WNP in August. (d) SST tendency induced by surface heat flux change averaged over the WNP in August and SST anomalies averaged over the WNP in September. Anomalies are calculated from detrended values and are relative to the monthly climatology. The temporal correlation is denoted at the top left. Ending with two asterisks indicates that the correlation is significant at the 99% confidence level.

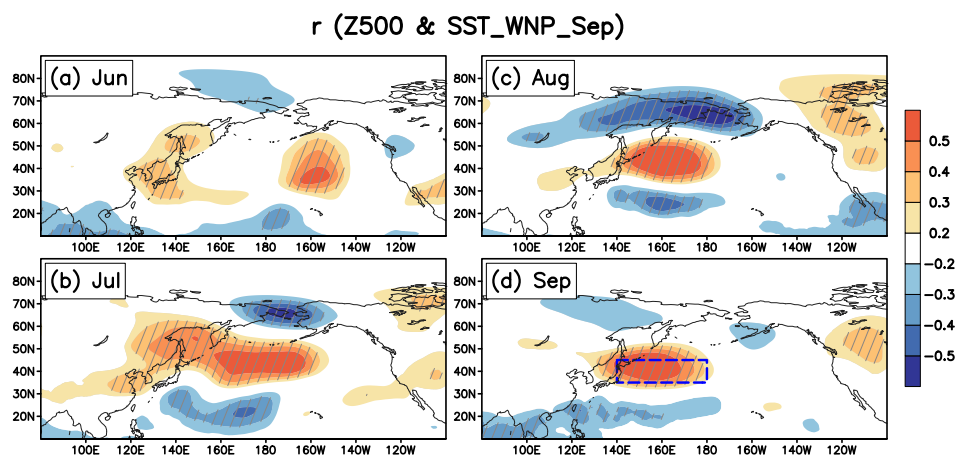


Figure 3.9 | Covariability between September sea surface temperature in the western North Pacific and preceding atmospheric circulation. Spatial distribution of correlation coefficient between regionally averaged September SST in the WNP and Z500 at each grid point in (a) June, (b) July, (c) August, (d) September. Hatched regions indicate correlations significant at the 95% confidence level. The blue dashed box in (d) denotes the WNP region.

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

The meandering of the Kuroshio Extension also influences SST variability in the WNP region (Sato et al., 2024). In September 2022 and 2023, SST in the WNP region was exceptionally high, despite normal pressure over the NES in the preceding August (Figure 3.8b). Figure 3.10 shows that sea surface height was abnormally elevated in the WNP region during these months, indicating that the poleward meander of the Kuroshio Extension contributed to warmer SST in the WNP region in September 2022 and 2023.

In contrast, NES experienced abnormally high pressure in August 2008 (Figure 3.8b). The sea surface height was lower than usual in the following month of September (Figure 3.10c), suggesting a southward meander of the Kuroshio Extension. Despite these, SST in the WNP was still higher than usual in September (Figure 3.8d). These results suggest that factors other than preceding NES atmospheric circulation and the Kuroshio Extension's location played a role in this case. The relative role of each factor in SST variability in the WNP for each year can be investigated in future studies.

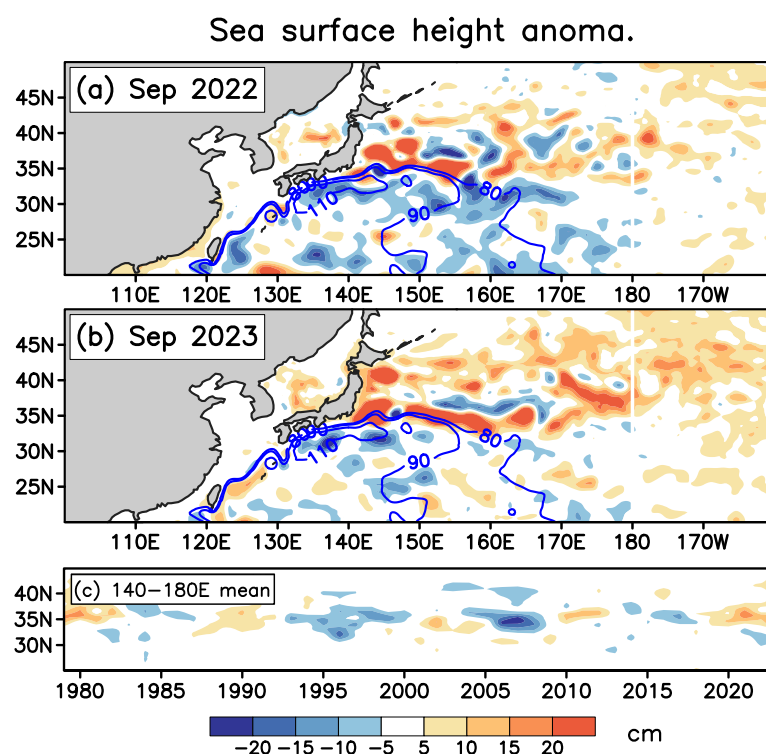


Figure 3.10 | Sea surface height anomalies in the western North Pacific. Sea surface height anomalies in the western North Pacific for (a) September 2022 and (b) September 2023. The purple contour denotes the climatological sea surface height. (c) Sea surface height anomalies averaged in 140°E–180°E from 1979 to 2023. Anomalies are calculated from detrended values and are relative to the monthly climatology.

(ii) Robustness of linkage between late-summer heatwaves over northeastern Siberia and subsequent sea surface temperature cooling in the western North Pacific

The linkage between late-summer heatwaves over the NES and subsequent SST cooling in the WNP is examined based on 45 reanalysis cases without the consideration of global warming. To assess the robustness of this relationship, large simulation datasets from the Coupled Model Intercomparison Project Phase 6 (Eyring et al., 2016) could be utilized in future research. Moreover, there is a possibility that the abnormally low pressure over the WNP is a result of the abnormally high pressure over the NES. A sensitivity experiment imposing high pressure over the NES could be conducted to examine and compare the subsequent impacts on SST in the WNP.

(iii) Predictability of East Siberian blocking on sea surface temperature in the western North Pacific

The sub-seasonal to seasonal forecast datasets can be used for the prediction of extreme weather events (Vitart & Robertson, 2018). For instance, Xiao et al. (2024) assessed the predictability of the record-breaking heatwaves over northern China in summer 2023 using sub-seasonal to seasonal models and suggested that these models can effectively predict the occurrence of heatwaves 2–5 days in advance. This chapter highlights that atmospheric forcing from the NES in August could serve as a key factor for predicting subsequent SST variability in the WNP. The extent to which NES blocking affects the predictability of summer SST in the WNP could be evaluated using sub-seasonal to seasonal ensemble forecast datasets in future research.

(iv) Concurrent land heatwaves over northeastern Siberia and marine heatwaves in the Bering Sea

Atmospheric blocking not only triggers local land heatwaves but also contributes to marine heatwaves in adjacent ocean regions (Holbrook et al., 2020). This chapter also suggests that SST in the Bering Sea tends to be warmer in September following the abnormally high pressure over the NES in August. The land heatwaves over the NES may also provide insight into marine heatwaves in the Bering Sea, which is an urgent topic for further investigation.

3.5 Conclusions

Existing studies have primarily investigated the impacts of summer East Siberian blocking on East Asian weather without attention to its connection to SST in the WNP. This chapter examines the linkage between late-summer NES heatwave-related atmospheric circulation patterns and SST variability in the WNP using reanalysis dataset.

The case study on the three major NES heatwave periods in August indicates a lagged connection between August heatwaves over the NES and September SST cooling in the WNP. Further correlation analyses for the entire study period further confirm this linkage and suggest that it is primarily driven by the influence of August Z500 over the NES. The maximum covariance analysis effectively captures the linkage. Interestingly, no similarly persistent negative correlation is found in other months, highlighting the uniqueness of the linkage between August Z500 over the NES and subsequent SST in the WNP.

To explore the processes contributing to the linkage, linear regression analyses are performed. The results suggest that this connection primarily arises from the dipole pressure pattern over the NES and WNP. Anomalous high pressure over the NES leads to clear sky and enhanced insolation, promoting heatwave formation. Conversely, anomalous low pressure over the WNP leads to cloudy sky and reduced insolation. Furthermore, the drier surface air enhances the release of latent heat flux from the ocean surface in the WNP. These processes lead to surface heat loss and subsequent SST cooling in the WNP. Shallow mixed layer depth in the WNP during the warm season makes SST more sensitive to heat flux loss, resulting in larger SST cooling and contributing to the uniqueness of this linkage.

This study deepens the current understanding of summer linkages between atmospheric circulation in high and middle latitudes and air–sea interactions in the WNP. It also suggests that atmospheric forcing from eastern Siberia can serve as a precursor for predicting summer SST in the WNP.

Chapter 3: Linkage between heatwaves over NES and SST cooling in western North Pacific

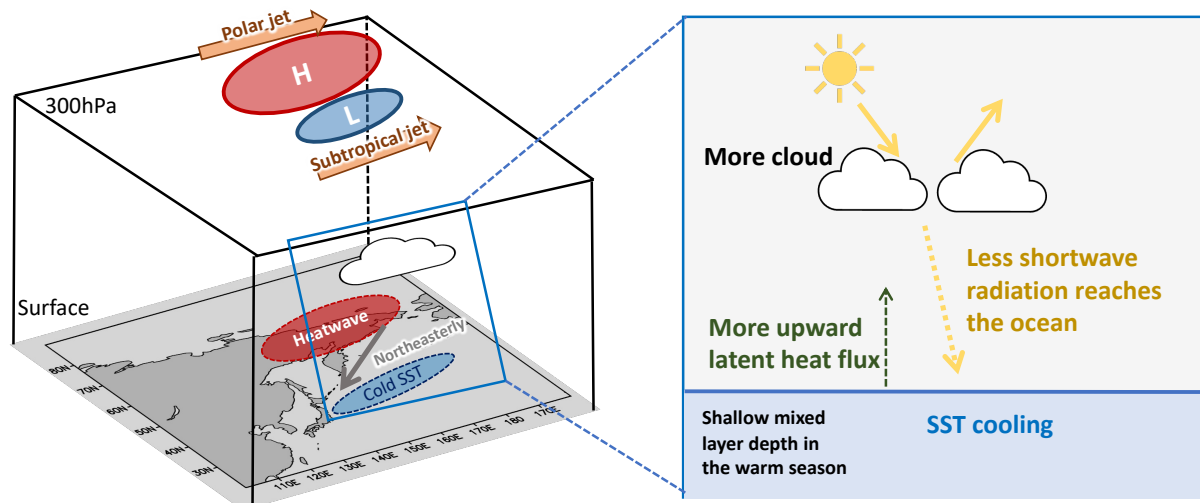


Figure 3.11 | Schematic diagram illustrating the main findings of Chapter 3. A strong linkage between August heatwaves over the NES and subsequent SST cooling in the WNP, which primarily arises from an anomalous dipole pressure pattern over the NES and WNP. The shallow mixed layer depth in the WNP during the warm season makes SST more sensitive to the heat loss, contributing to the uniqueness of this linkage.

Chapter 4 The impacts of global warming on summer heatwaves over eastern Siberia

4.1 Introduction

(i) The roles of external forcings and internal variability in summer heatwaves

With rising temperature and the increasing frequency of heatwaves, the roles of external forcings (stemming from natural or anthropogenic forcing) and internal variability (arising from natural processes within the climate system) in heatwaves have attracted scientific attention. Statistical classifications of long-term observed regional summer heatwaves are widely conducted to distinguish their primary spatial patterns of heatwaves and reveal the distinct physical processes contributing to each spatial pattern (e.g., Deng et al., 2019; Kim et al., 2022). For instance, Deng et al. (2019) investigated the dominant modes of summer heatwaves over China through EOF analysis, concluding that these heatwaves are driven by a combination of SST anomalies in the tropical Atlantic and Pacific, as well as North Atlantic Oscillation. Kim et al. (2022) examined the factors contributing to summer heatwaves over East Asia through singular value decomposition, finding that these heatwaves are mainly affected by long-term externally forced variability attributed to global warming and interannual variability associated with the circumglobal teleconnection and Arctic–Siberian Plain teleconnection patterns.

Large ensemble simulations performed by climate models provide an effective approach to disentangling the roles of external forcings and internal variability (e.g., Dole et al., 2011; Watanabe et al., 2013; Sato & Nakamura, 2019; Cai et al., 2024). Using the large ensemble simulations performed by an atmospheric general circulation model (AGCM), Sato & Nakamura (2019) reported a tripolar SAT trend pattern over northern Eurasia and suggested that this pattern is amplified by steady warming induced by external forcings as well as inhomogeneous warming induced by internal land–atmosphere interactions. Using the large ensemble simulations

Chapter 4: The impacts of global warming on summer heatwaves over eastern Siberia

performed by coupled general circulation models (CGCM), Cai et al. (2024) argued that external forcings alone cannot explain the observed abrupt and exceptionally strong warming over the Mongolian Plateau, attributing this extreme warming instead to the combined effects of the Interdecadal Pacific Oscillation and the Atlantic Multidecadal Oscillation.

The large ensemble simulations could also be used to assess the role of external forcings and internal variability for the major heatwave events. For instance, using large ensemble simulations of an AGCM experiment, Dole et al. (2011) and Watanabe et al. (2013) assessed the contributions of human-induced warming and internal atmospheric variability on western Russia heatwaves in July and August 2010, respectively. Both studies concluded that the intense 2010 western Russia heatwaves were primarily driven by internal atmospheric variability.

(ii) Event attribution analysis for summer heatwaves

It is well-established that human-induced greenhouse gas emissions have contributed to an increased frequency and/or intensity of certain weather and climate extremes since pre-industrial time, particularly for temperature extremes (Seneviratne et al., 2021). Risk-based event attribution was employed to examine how anthropogenic climate change has altered the probability of occurrence of individual extreme events, such as the heatwaves and heavy rainfall (e.g., Watanabe et al., 2013; Imada et al., 2020; Ma et al., 2024).

Historical and counterfactual non-warming simulations by state-of-the-art climate models provide the basis for conducting risk-based event attribution (Shepherd, 2016). By comparing AGCM experiments with and without past observed SST changes and anthropogenic external forcings, Watanabe et al. (2013) found that anthropogenic forcings increased the probability of the August 2010 western Russia heatwaves from 0.6% to 3.3%. Using a similar approach, Imada et al. (2019) indicated that the high temperature event in July 2019 in Japan would not have occurred without anthropogenic global warming. Ma et al. (2024) suggested that the anthropogenic forcings were responsible for approximately 50% of the concurrent heatwaves in August 2022 over eastern Europe and southern China.

(iii) Objective and structure of this chapter

The role of external forcings and internal variability in long-term trends of heatwaves over the NES remains unknown. Additionally, despite the occurrence of several severe summer heatwaves over this region, no risk-based event attribution studies have yet been conducted for these heatwaves. Furthermore, the dominant modes of summer heatwaves over northern Eurasia and their associated physical processes are not documented. Addressing these research gaps, this chapter examines the impacts of global warming on summer heatwaves over eastern Siberia. The structure of this chapter is as follows: [Section 4.2](#) describes the simulation data and method. [Section 4.3](#) represents the results, including the impacts of global warming on summer heatwaves over the NES, as well as an investigation into the dominant modes of summer heatwaves over northern Eurasia and their drivers. The discussions are presented in [Section 4.4](#), and the conclusions are summarized in [Section 4.5](#).

4.2 Data and methods

(i) Large ensemble simulation datasets

This chapter utilizes large ensemble simulation data from the “Database for Policy Decision-Making for Future Climate Change,” produced by the Meteorological Research Institute AGCM version 3.2 with a high-resolution grid interval of 60 km (Mizuta et al., 2017). Simulation datasets from the historical experiment (hereafter referred to as HIST) and the non-warming experiment (hereafter referred to as NAT), spanning the period from 1979 to 2023 are analyzed.

The HIST experiment assumes past historical climate conditions, with historical SST and sea ice thickness/concentration from COBE-SST2 prescribed as lower boundary conditions, along with historical greenhouse gases and solar irradiance as external forcings. The RCP4.5 emission scenario was used for the period after 2014. In contrast, the NAT experiment assumes that global warming has not taken place since the preindustrial time, with long-term trends in boundary conditions removed and external forcings set to pre-industrial levels. Comparing the results of HIST and NAT experiments enables an assessment of the impacts of global warming on summer heatwaves.

Both the HIST and NAT experiments consist of 100 ensemble members with perturbed initial and boundary conditions. The large ensemble size of this dataset provides an opportunity to analyze internal atmospheric variability. Variations among the ensemble members reflect the internal atmospheric variability of the climate system, while the ensemble mean represents the response to external forcings.

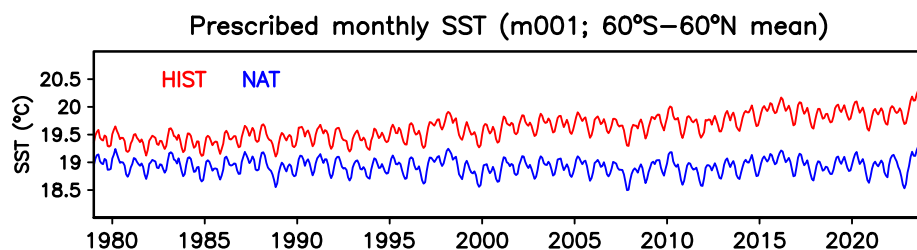


Figure 4.1 | Monthly latitude-weighted sea surface temperature prescribed for historical and non-warming simulations, averaged over the 60°S–60°N for the period 1979–2023.

(ii) Definitions of heatwave frequency and intensity in simulations for each grid point

The definition of heatwave frequency and intensity in simulations is similar to that in observation as described in [Section 2.2](#). For each member in the historical simulation, heatwave days are defined as days when the daily maximum SAT exceeds the daily heatwave threshold for at least three consecutive days. The daily heatwave threshold is defined as the 90th percentile value of the daily maximum SAT during 1979–2023, which is computed based on a 15-day moving window of daily maximum SAT. Heatwave frequency is calculated as the total number of heatwave days within a given month. Heatwave intensity is calculated as the sum of the excess maximum SAT above the heatwave threshold across all heatwave days within a given month. For each member in the non-warming simulation, the heatwave threshold is consistent with that used in the historical simulation.

(iii) Extracting dominant modes of summer heatwaves over northern Eurasia

To extract the dominant modes of summer heatwaves over northern Eurasia in historical simulations, EOF analysis is applied to the concatenated 100-member historical simulations of summer (July–August mean) latitude-weighted heatwave frequency anomalies over northern Eurasia (land area within 50°N–80°N, 0°E–180°E) for the period 1979–2023. These anomalies are calculated as deviations from the mean of 4,500 snapshots (45 years $\times$ 100 ensemble members). The corresponding principal components are then rearranged along the time axis to represent the principal component for each ensemble member.

4.3 Results

4.3.1 The impacts of global warming on summer heatwaves over northeastern Siberia

(i) Validation of model reproducibility

Firstly, the model's reproducibility in simulating past summer heatwave frequency and intensity is validated. Figure 4.2 illustrates the spatial distribution of climatological heatwave frequency and intensity over the Eurasian continent in July and August based on the 100-member ensemble mean of historical simulations. The historically simulated climatological heatwaves exhibit a high heatwave frequency over central Eurasia and a high heatwave intensity over Siberia, consistent with observed distribution (Figures 4.2 and 2.3). Over northern Eurasia, the spatial distribution of the historically simulated climatological heatwaves closely aligns with the observed distribution, with a spatial correlation coefficient exceeding 0.8. These results suggest that the model can effectively reproduce the spatial distribution of observed climatological heatwave frequency and intensity over northern Eurasia.

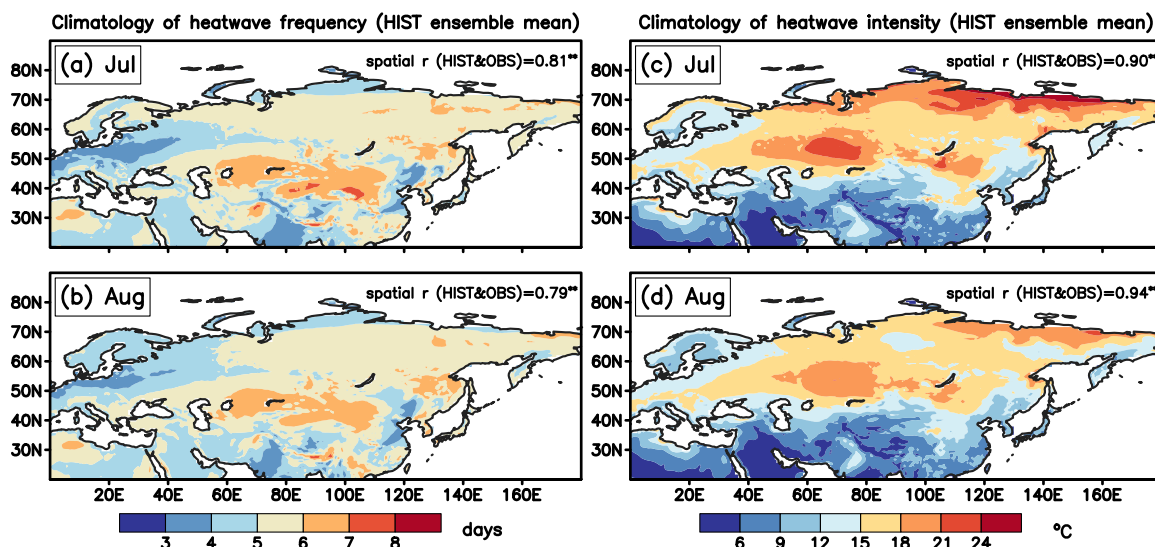


Figure 4.2 | Climatological heatwave frequency and intensity over Eurasia in July and August based on the 100-member ensemble mean of the historical simulation. (a–b) Climatological heatwave frequency in (a) July and (b) August. (c–d) Climatological heatwave intensity in (c) July and (d) August. The spatial correlation coefficient between the simulations and observation over northern Eurasia (50°N–80°N, 0°E–180°E) is shown, with two asterisks indicating significance at the 99% confidence level.

(ii) The role of external forcings on observed heatwave trends and major heatwave periods

The role of external forcings on observed long-term heatwave trends is also examined. Figure 4.3 illustrates the spatial distribution of heatwave frequency and intensity trends over the Eurasian continent in July and August based on the 100-member ensemble mean of historical simulations. The ensemble mean reflects trends driven by external forcings. The spatial distribution of the ensemble mean SAT trend closely resembles that of the ensemble mean heatwave intensity trend (not shown). Across the Eurasian continent, the ensemble mean trends are positive, indicating that external forcing has generally increased heatwave frequency and intensity over the Eurasian continent.

However, the ensemble mean trends in historical simulations differ from the observed trends (Figures 4.3 and 2.4). The magnitude of the ensemble mean trends is much weaker over Europe but comparable over Mongolia when compared to the observed trends, suggesting that the recent increase in heatwaves over Europe is largely attributable to internal atmospheric variability, while over Mongolia, it is primarily driven by external forcing. Over northern Eurasia, the observed tripolar patterns of heatwave trends are absent in the ensemble mean trends, indicating that internal atmospheric variability plays a crucial role in shaping these patterns.

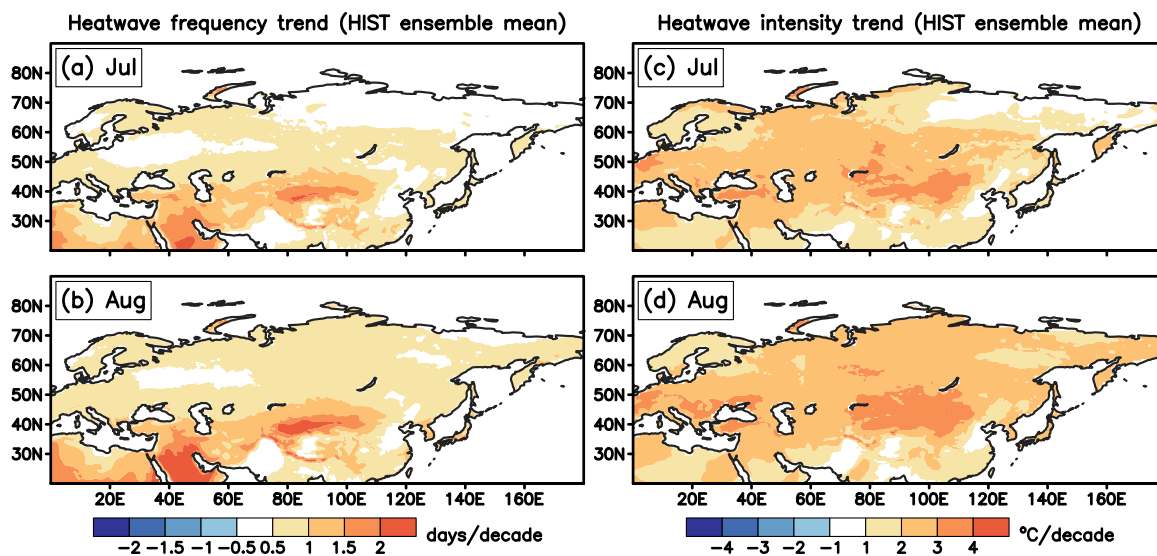


Figure 4.3 | Heatwave frequency and intensity trends over the Eurasian continent in July and August based on the 100-member ensemble mean of the historical simulation. (a–b) Heatwave frequency trend in (a) July and (b) August. (c–d) Heatwave intensity trend in (c) July and (d) August.

Chapter 4: The impacts of global warming on summer heatwaves over eastern Siberia

The inter-member spreads of NES heatwave trends in historical simulations in July and August are shown in [Figures 4.4a–b](#) and [4.5a–b](#), respectively. For both heatwave frequency and intensity, the ensemble mean exhibits an increase over the past several decades, with a larger trend in August than in July. In both months, substantial inter-member spreads of NES heatwave trends are found. These results suggest that the observed increases in NES heatwave trends are induced by both external forcings and internal atmospheric variability.

Next, the interannual variations in NES heatwaves in July and August in historical simulations are examined in [Figures 4.4c–d](#) and [4.5c–d](#), respectively. In terms of year-to-year variability, the observed heatwave frequency and intensity generally fall within the range of historical simulations, indicating the simulations' ability to reproduce the magnitude of heatwaves. However, the exceptionally strong and persistent NES heatwaves observed in July and August 1991 are not captured in the historical simulations. For the major observed summer heatwave periods over the NES in July (1991, 2001, 2003, 2010) and August (1991, 2008, 2014, 2017), the ensemble mean heatwave frequency and intensity are notably lower than the observed values. This finding underscores the critical role of internal atmospheric variability in driving these major heatwave periods in both July and August.

To further evaluate the model's ability to reproduce observed heatwaves with the correct physical processes, members with good reproducibility of NES heatwaves for each observed major NES heatwave period are selected. [Figures 4.6](#) and [4.7](#) illustrate the spatial distribution of Z500 anomalies in these selected members for the observed major NES heatwave periods in July and August, respectively. In July 1991, the atmospheric circulation in members 100 and 52 closely resembles observation, exhibiting zonally extended positive Z500 anomalies along the Siberian coast ([Figures 4.6a, c](#)). In July 2010, members 38 and 47 capture a similar pattern to observation, displaying a tripolar pattern over northern Eurasia ([Figures 4.6j, l](#)). In August 2014, member 54 reproduces the observed negative Z500 anomalies over the Arctic ([Figure 4.7i](#)). Overall, the model can better reproduce the observed heatwaves with the correct physical processes in July than in August.

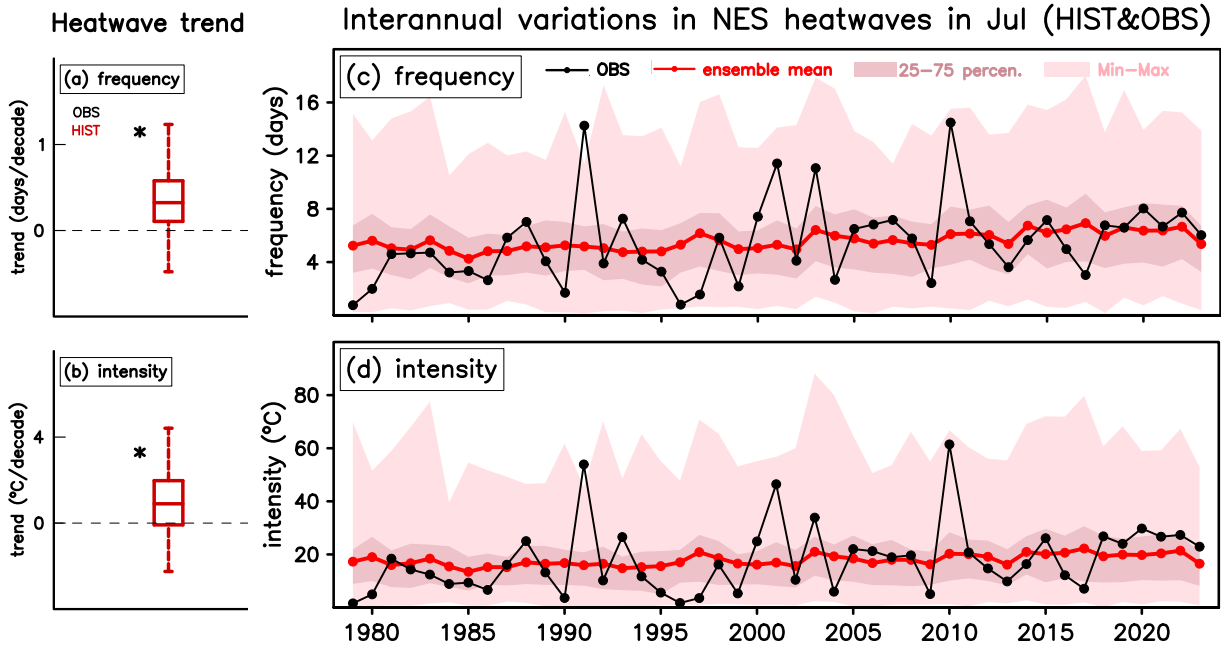


Figure 4.4 | Regionally averaged heatwaves over northeastern Siberia in July in historical simulations and observation. (a–b) Inter-member spread of NES (a) heatwave frequency and (b) intensity trends. The red boxes denote results from historical simulations. The horizontal solid lines within the boxes denote the 100-member ensemble mean. The whiskers represent the minimum and maximum values, while the lower and upper edges of the box indicate the 25th and 75th percentiles, respectively. The black stars indicate observed heatwave trends. **(c–d)** Interannual variations in NES (c) heatwave frequency and (d) intensity in July. Black and red lines denote heatwaves in observation and the historical-simulated 100-member ensemble mean, respectively. The deep and shallow pink shading represent the 25th–75th percentile range and the minimum–maximum spread of the historical simulation, respectively.

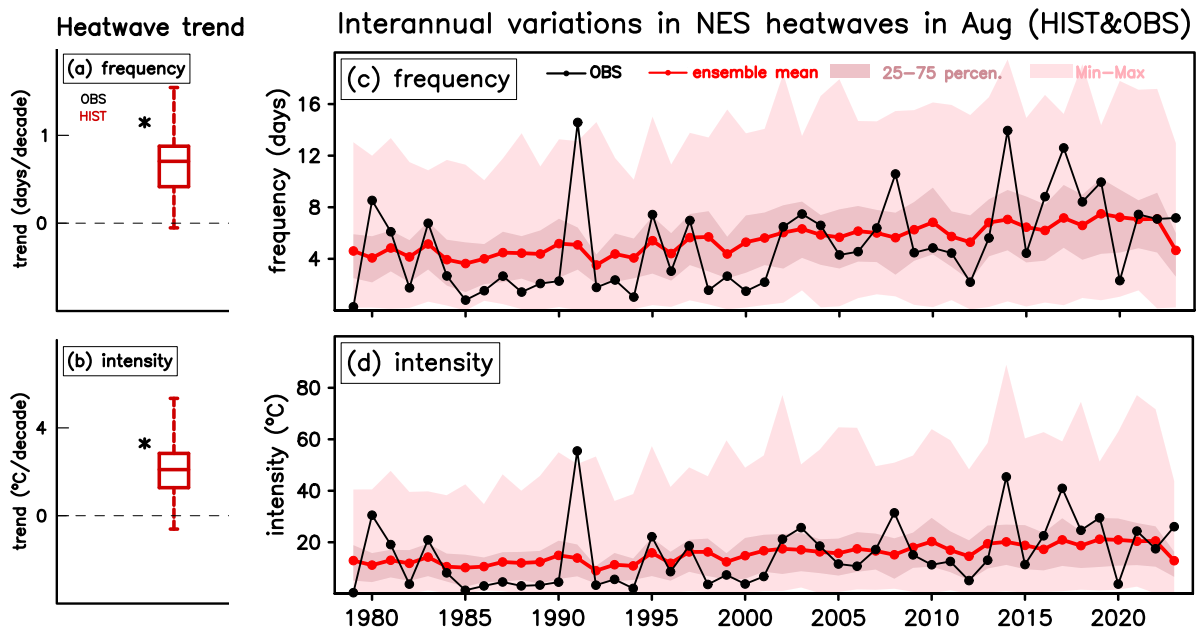


Figure 4.5 | Regionally averaged heatwaves over northeastern Siberia in August in historical simulations and observation. Similar to Figure 4.4, but for NES heatwaves in August.

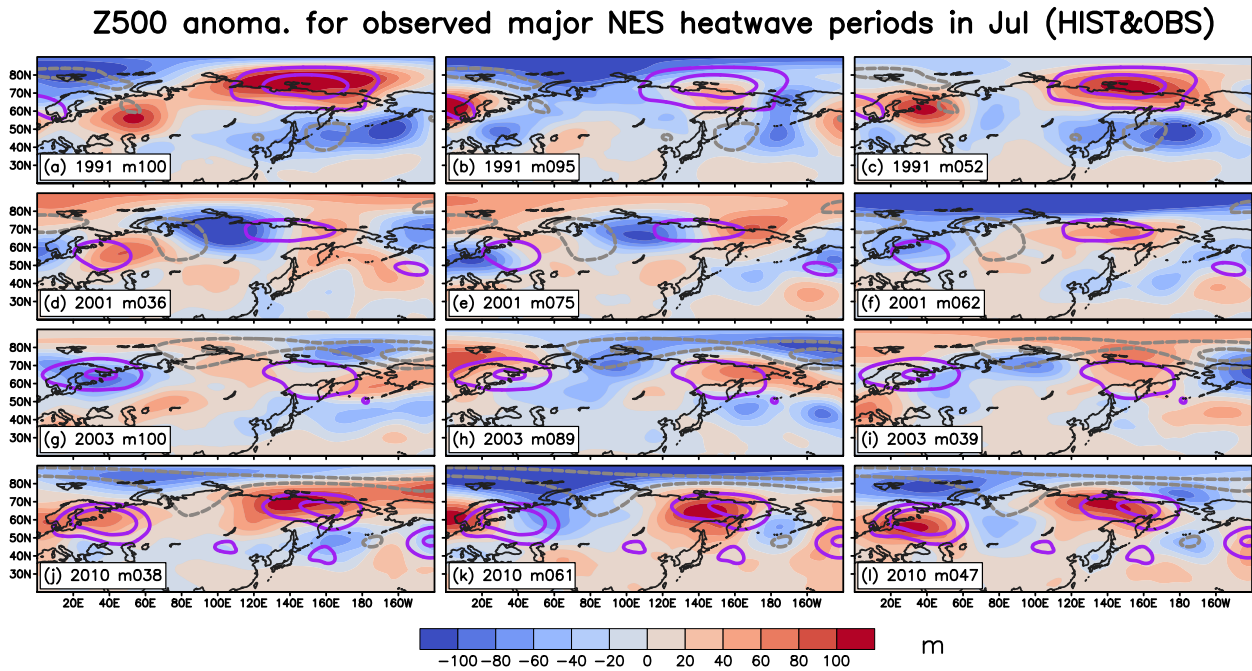


Figure 4.6 | 500-hPa geopotential height anomalies in historical simulations and observation for the four observed major NES heatwave periods in July. Z500 anomalies for (a–c) July 1991, (d–f) July 2001, (g–i) July 2003, and (j–l) July 2010. The shading represents historically simulated Z500 anomalies in selected ensemble members, chosen based on the smallest difference from the observed heatwave frequency for each major NES heatwave period. The contours indicate observed Z500 anomalies, with a contour interval of 50 m; negative contours are dashed, and the zero contour is omitted. Anomalies are relative to the monthly climatology.

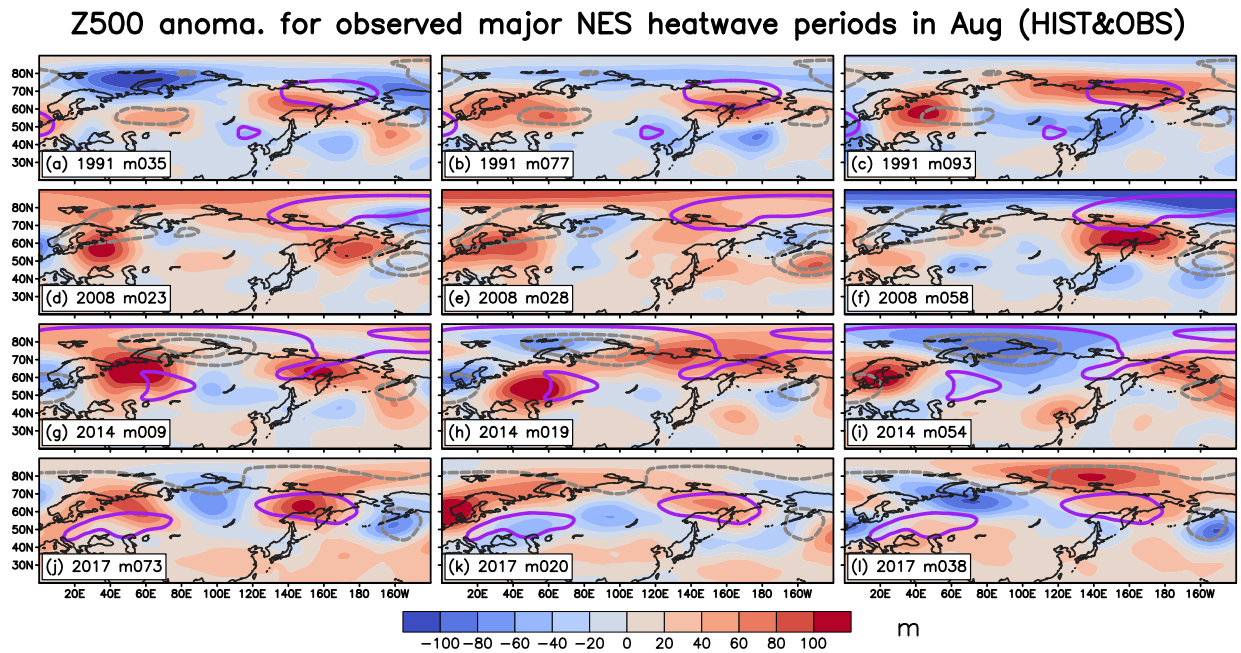


Figure 4.7 | 500-hPa geopotential height anomalies in historical simulations and observation for the four observed major NES heatwave periods in August. Similar to Figure 4.6, but for Z500 anomalies for (a–c) August 1991, (d–f) August 2008, (g–i) August 2014, and (j–l) August 2017.

(iii) Event attribution for the observed major heatwave periods

To assess the impacts of global warming on the observed major NES heatwave periods, event attribution is performed by comparing historical and non-warming simulations. Figures 4.8 and 4.9 show the probability distributions of monthly SAT, heatwave frequency, and heatwave intensity for the observed major NES heatwave periods in the two simulations for July and August, respectively. When comparing observations with the historical simulation, the observed monthly SAT and heatwave metrics are positioned at the upper edge of the historical simulations and even exceed the highest historical simulation values in August 1991 (Figures 4.8 and 4.9). These results underscore the substantial influence of internal atmospheric variability in shaping the observed major NES heatwave periods, as also noted in Figures 4.4c–d and 4.5c–d.

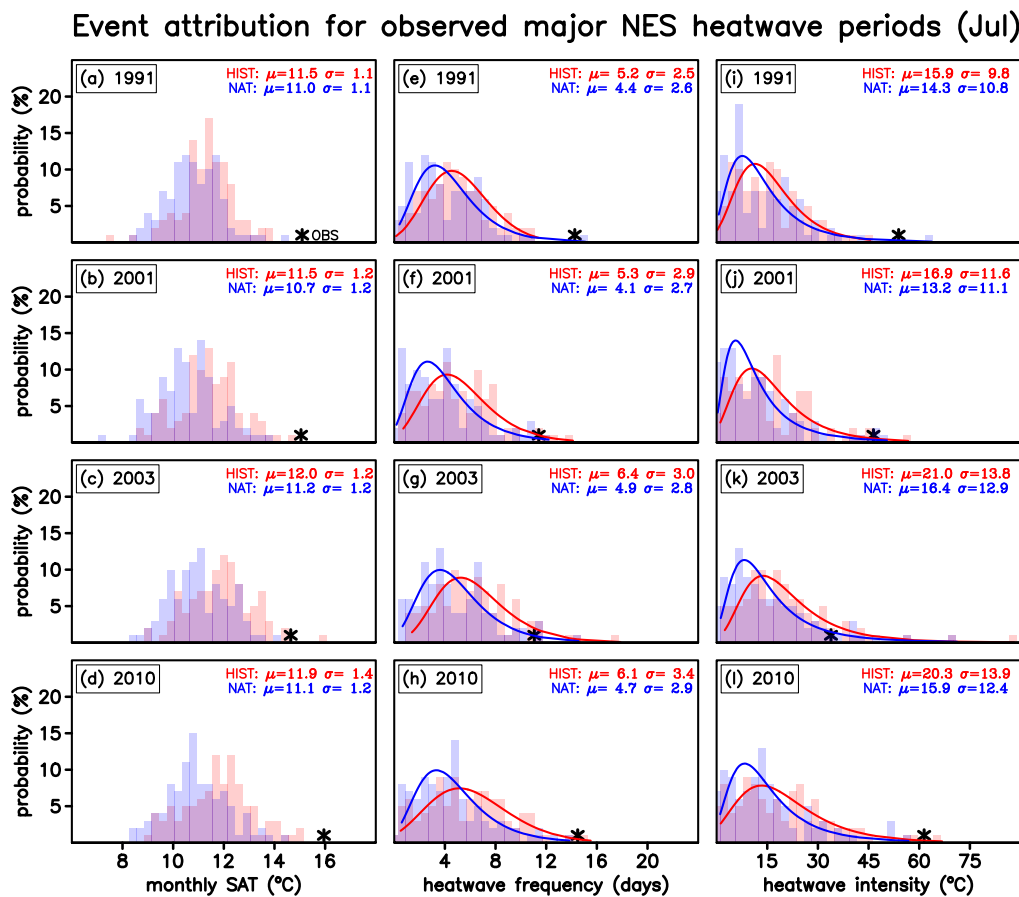


Figure 4.8 | Event attribution for the four observed major NES heatwave periods in July. Probability of NES (a–d) monthly SAT, (e–h) heatwave frequency, and (i–l) heatwave intensity in historical simulations (red histogram) and non-warming simulations (blue histogram) for July 1991, 2001, 2003, and 2010. The lines in (e–l) represent the generalized extreme value distribution for the histogram. The texts denote the mean value and standard deviation of 100 members. The black stars denote the observation results.

When comparing historical and non-warming simulations, monthly SAT and heatwave metrics in the historical simulations shift toward warmer conditions relative to the non-warming simulations. During the observed major NES heatwave periods in July, the mean value of heatwave frequency and intensity increases by approximately 20% in historical simulations when compared with non-warming simulations (Figure 4.8). In August, heatwave frequency increases by about 30%, while heatwave intensity rises by approximately 50% (Figure 4.9). This finding suggests that global warming has contributed to an increase in both the frequency and intensity of the observed major NES heatwave periods in July and August, with a stronger impact in August. The greater influence in August may be linked to rapid Arctic warming, as examined in Section 2.3.4.

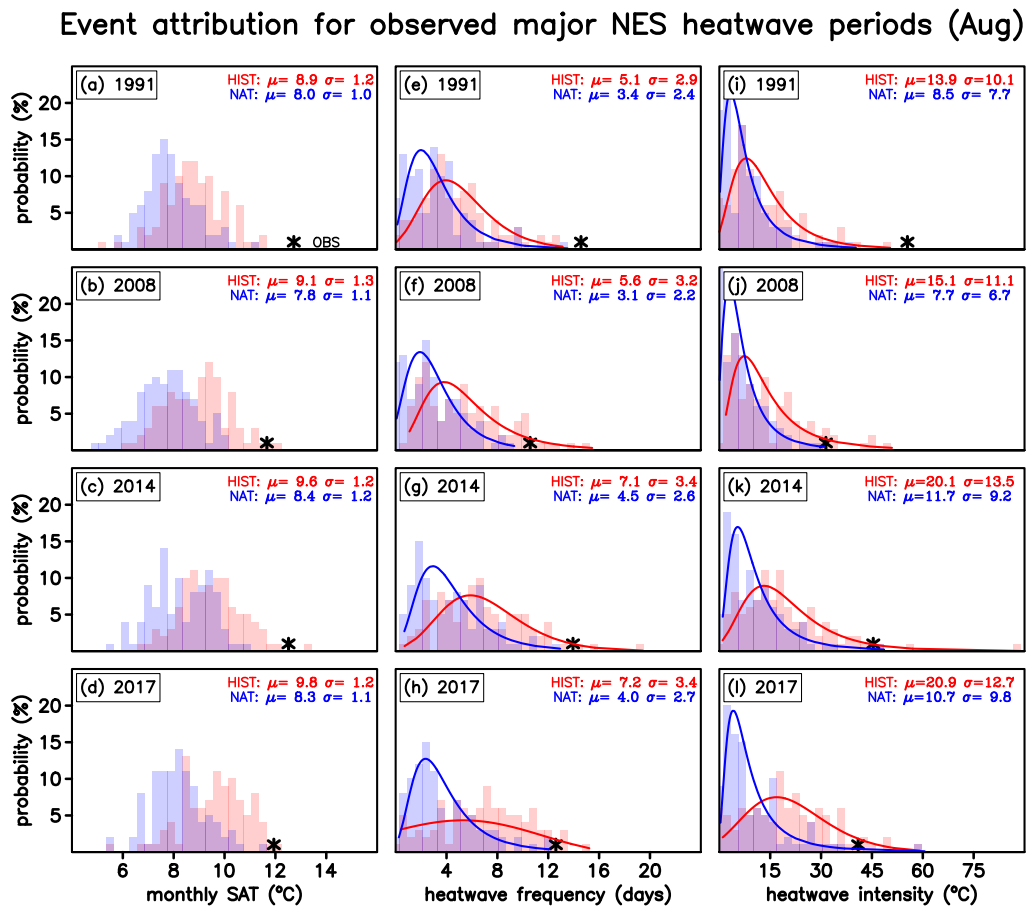


Figure 4.9 | Event attribution for the four observed major NES heatwave periods in August. Probability of NES (a–d) monthly SAT, (e–h) heatwave frequency, and (i–l) heatwave intensity in historical simulations (red histogram) and non-warming simulations (blue histogram) for August 1991, 2008, 2014, and 2017. The lines in (e–l) represent the generalized extreme value distribution for the histogram. The texts denote the mean value and standard deviation of 100 members. The black stars denote the observation results.

4.3.2 Dominant modes of summer heatwaves over northern Eurasia and their drivers

For the long-term regional heatwave variability, statistical classifications of regional summer heatwaves are widely conducted to distinguish their primary spatial patterns of heatwaves and reveal the distinct physical processes contributing to each spatial pattern. Large ensemble simulations also provide an effective approach to disentangling the roles of external forcing and internal variability. In this section, dominant modes of summer heatwaves over northern Eurasia and their potential drivers are examined by using the large ensemble of historical simulations. EOF analysis is applied to concatenated 100-member historical/non-warming simulations of July–August mean heatwave frequency anomalies over northern Eurasia during 1979–2023.

Figure 4.10a–c illustrates the spatial patterns of dominant modes of summer heatwaves over northern Eurasia in the historical simulation. The first mode, accounting for 13% of the total variance, exhibits a tripolar pattern over northern Eurasia, with positive anomalies over western Russia and the NES and negative anomalies over western Siberia (Figure 4.10a). The second mode, which explains 12% of the total variances, exhibits positive anomalies centered over western Siberia (Figure 4.10b). The third mode, explaining 10% of the total variance, also exhibits a tripolar pattern and is shifted westward compared to the first mode, with positive anomalies over eastern Europe and central Siberia and negative anomalies over the Ural region (Figure 4.10c).

Figure 4.10d–f represents the temporal change of the dominant modes in historical simulation. Figure 4.11 shows the inter-member spreads of trends in the trends of the strength of these dominant modes. The strength of the two tripolar patterns exhibits no clear trend in the last four decades. The strength of the pattern with a single center over western Siberia shows an increasing trend in the last four decades. These findings suggest the two tripolar heatwave patterns are unaffected by external forcings but by internal atmospheric variability, while the external forcings have contributed to strengthening heatwave frequency over western Siberia in recent decades.

Dominant modes of heatwave frequency over northern Eurasia in Jul–Aug (HIST)

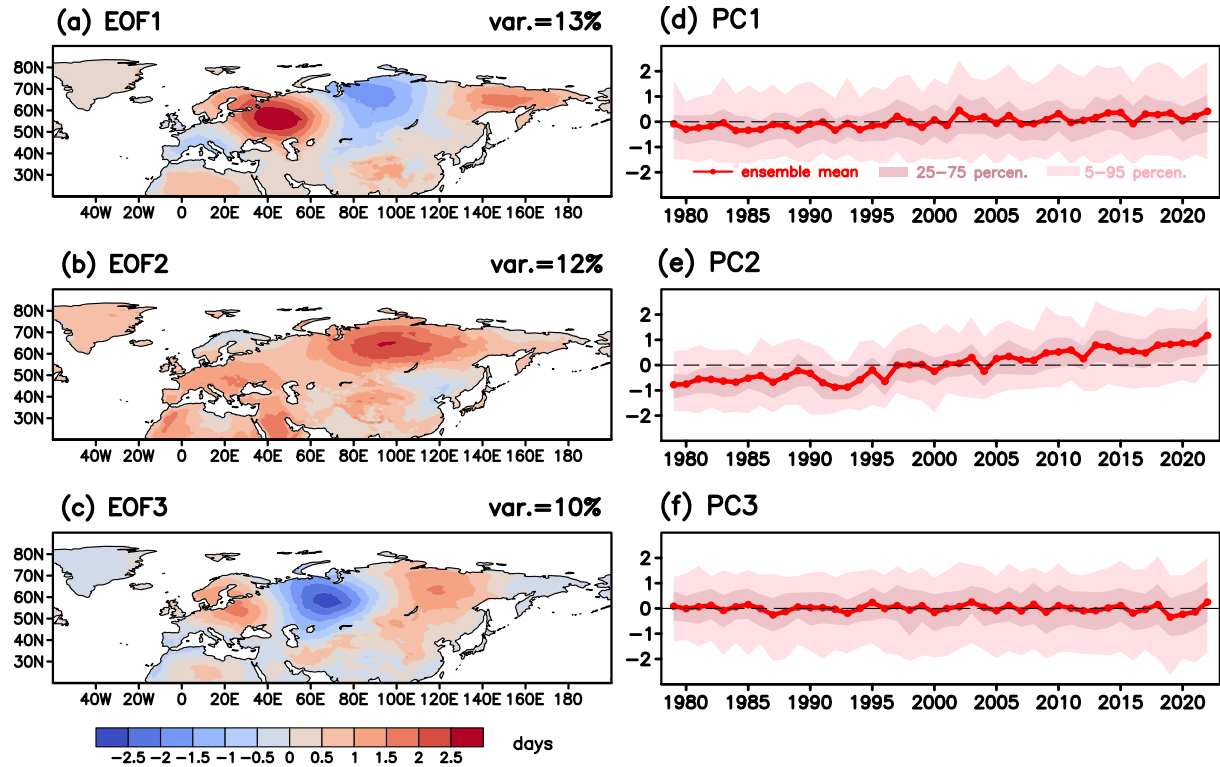


Figure 4.10 | Dominate modes of summer heatwave over northern Eurasia for the historical simulations. (a–c) Regressed July-August mean heatwave frequency anomalies on the 100-member-concatenated (a) PC1, (b) PC2, and (c) PC3 for the historical simulation. (d–f) Interannual variation of the simulated (d) PC1, (e) PC2, (f) PC3. The deep and shallow pink shadings represent the 25–75 percentile and 5–95 percentile spreads of PCs, respectively. The red lines denote the 100-member ensemble mean of PCs.

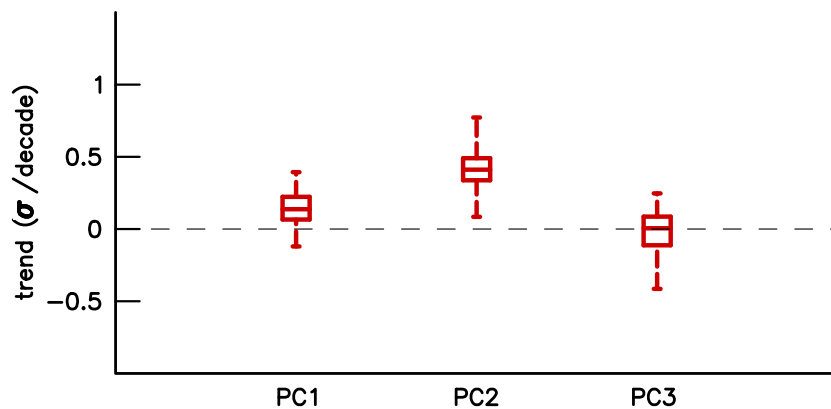


Figure 4.11 | Inter-member spreads of trends in principal component scores for historical simulations. The horizontal solid lines within the boxes denote the 100-member ensemble mean. The whiskers represent the minimum and maximum values, while the lower and upper edges of the box indicate the 25th and 75th percentiles, respectively.

To further explore the physical processes contributing to each mode, atmospheric circulation anomalies and SST anomalies associated with the dominant modes of summer heatwaves over northern Eurasia are investigated. Figure 4.12 represents regressed Z500 and SST anomalies on concatenated 100-member principal component for the historical simulation. For all three modes, the centers of Z500 anomalies overlap with the centers of heatwave frequency anomalies along northern Eurasia (Figure 4.12a–c). For the regressed SST anomalies, no clear changes are found associated with first and third modes (Figure 4.12d, f). In contrast, the SST associated with the second mode exhibit positive anomalies in the Northern Hemisphere, particularly in the Arctic and North Pacific (Figure 4.12e), resembling the spatial distribution of recent SST warming trend (not shown).

Overall, the two modes with tripolar patterns along northern Eurasia, which exhibit no clear trends over the past four decades, are more likely driven by internal atmospheric variability independent of SST warming. In contrast, the mode with a single center over western Siberia, which shows significant increasing trends in recent decades, is attributed to SST warming.

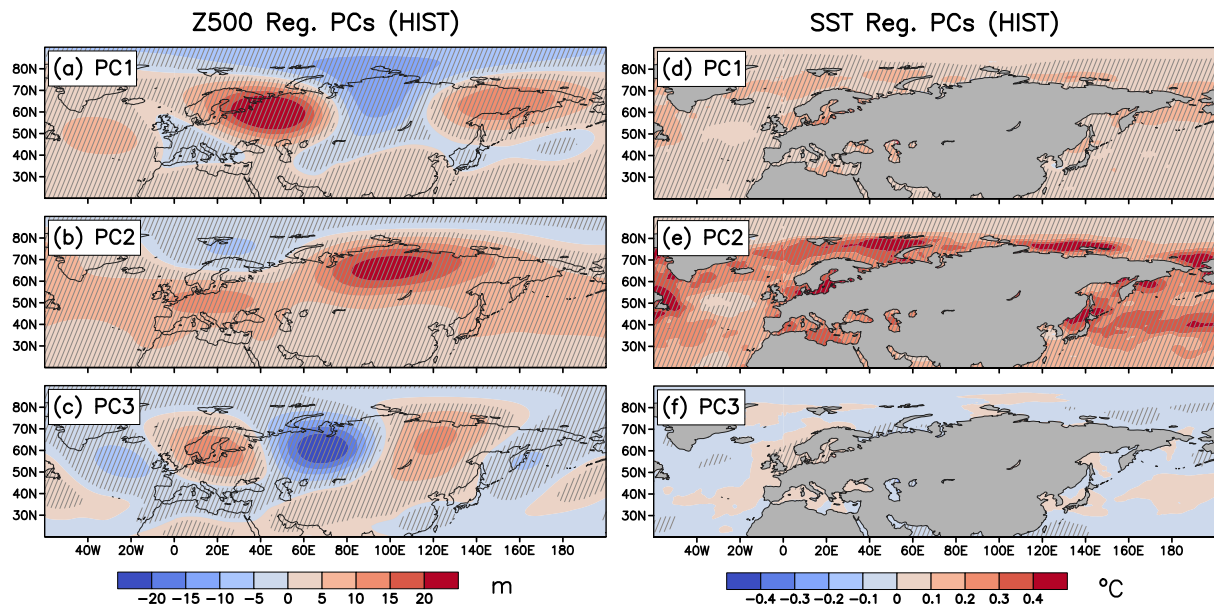


Figure 4.12 | Atmospheric circulation and sea surface temperature associated with the dominant modes of summer heatwaves over northern Eurasia. (a–c) Regressed July–August mean Z500 anomalies on the concatenated 100-member (a) PC1, (b) PC2, and (c) PC3 for the historical simulations. (d–f) Similar to (a–c), but for regressed SST anomalies. Hatched areas indicate the anomalies significant at the 99% confidence level.

4.4 Discussions

(i) The mechanisms of observed tripolar heatwave trend over northern Eurasia

In observation, heatwave trends (both in frequency and intensity) over northern Eurasia in July and August exhibit a tripolar pattern, characterized by a rapid increase over western Russia and the NES, while no clear changes are observed over western Siberia (Figure 2.4). However, in the ensemble mean of historical simulations, heatwave frequency and intensity trends over northern Eurasia are not like that observed (Figure 4.3), suggesting that internal atmospheric variability plays a crucial role in the observed tripolar patterns. This tripolar pattern also manifests the first mode of summer heatwaves over northern Eurasia, with no evident trend in its strength in recent decades (Figure 4.10a, d). The atmospheric circulation pattern associated with the first mode of heatwaves resembles the British–Okhotsk Corridor pattern and seems independent of the SST warming (Figure 4.12a, d).

Several mechanisms operating across different time scales contribute to the formation of the tripolar pattern of summer temperature and heatwaves over northern Eurasia. On a subseasonal scale, enhanced latent heating centered over the North Sea and suppressed latent heating centered over the Caspian Sea can excite this tripolar pattern (Kim & Lee, 2022b). On a seasonal scale, land–atmosphere interactions may amplify quasi-stationary waves, leading to inhomogeneous summer warming over northern Eurasia (Sato & Nakamura, 2019). On a decadal scale, SST fluctuations associated with the Atlantic multidecadal variability and the interdecadal Pacific Oscillation play a role in shaping the tripolar pattern, with the former shifting to a positive phase and the latter to a negative phase in the 1990s (Teng et al., 2022).

(ii) Limitation of the model simulations

Based on reanalysis dataset, Section 2.3.3 suggests that the typical atmospheric circulation patterns associated with NES heatwaves differ between July and August, with a prevailing zonal structure across northern Eurasia in July and a meridional structure extending from the Arctic to the western North Pacific in August. However, these differences are not evident in the historical

Chapter 4: The impacts of global warming on summer heatwaves over eastern Siberia

simulations, as indicated by the composite Z500 anomalies when NES experienced a high frequency of heatwaves in the historical simulations (Figure 4.13).

The large ensemble simulation datasets used in this section are generated using a single AGCM, which does not incorporate air-sea coupling. Additionally, the dataset has a limited representation of land surface processes, which may also play a crucial role in elevated temperatures over the NES. Such model deficiencies can contribute to discrepancies between observation and model simulations.

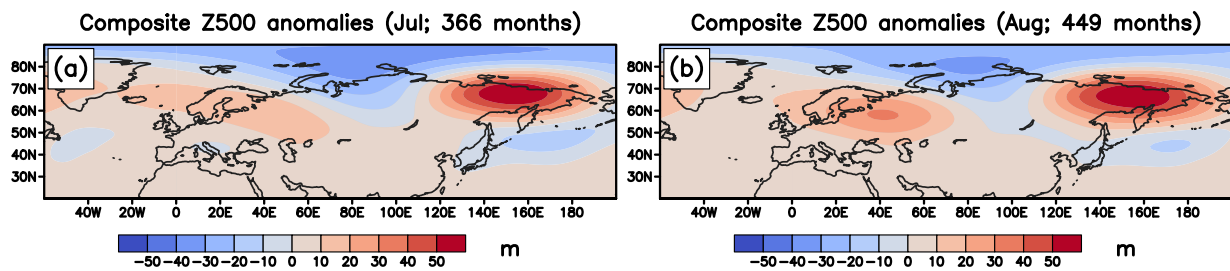


Figure 4.13 | Composite 500-hPa geopotential height anomalies when NES experiences a high frequency of heatwaves in historical simulations. (a) Composite Z500 anomalies in July for 366 months. (b) Composite Z500 anomalies in August for 449 months. The selection criterion is that the heatwave frequency is greater than 10 days per month. Anomalies are relative to the monthly climatology.

For future research, large ensemble experiments conducted with multiple CGCMs are desirable. A multi-model intercomparison can help compensate for deficiencies in individual models (e.g., the limited representation of land surface processes). According to event attribution results, global warming has contributed to an increase in both the frequency and intensity of major NES heatwave periods in July and August. With 2023 and 2024 consecutively breaking the global temperature record, future projections of summer heatwaves over Siberia under warmer conditions are of critical importance. These projections could be assessed using future scenario runs, such as those from the Coupled Model Intercomparison Project Phase 6.

4.5 Conclusions

In the context of rising temperature, the impacts of global warming on summer heatwaves over eastern Siberia remain poorly understood. By analyzing a large ensemble of historical and non-warming simulation datasets, this chapter examines the impacts of global warming on summer heatwaves over the NES from a broader northern Eurasian perspective.

For the NES, inter-member spreads of heatwave trends in July and August in historical simulations suggest that the observed increases in the NES heatwaves are induced by both external forcings and internal atmospheric variability. For the observed major NES heatwave periods in July and August, the role of internal atmospheric variability is crucial. As suggested by event attribution, global warming has contributed to an increase in both the frequency and intensity of these heatwave periods, with a stronger impact in August than in July.

The dominant modes of summer heatwaves over northern Eurasia and their potential drivers are further investigated. In the historical simulations, the first mode exhibits a tripolar pattern over northern Eurasia, resembling the observed tripolar heatwave trend pattern. The third mode also presents a tripolar pattern and is shifted westward compared to the first mode. These two tripolar heatwave patterns, which show no significant trends over the past four decades, are likely driven by internal atmospheric variability, independent of SST warming. In contrast, the second mode, characterized by positive heatwave frequency anomalies centered over western Siberia, has shown significant increasing trends in recent decades and is attributed to SST warming.

This chapter deepens the current understanding of summer heatwaves not only over eastern Siberia but also across northern Eurasia. While global warming positively contributes to warmer temperature and more frequent heatwaves over northern Eurasia, the role of internal atmospheric variability remains critical. This variability may be related to multiscale processes, including land–atmosphere interactions, which warrant further investigation in future studies.

Chapter 5 Discussions and outlook

5.1 Siberian heatwaves influenced by land–atmosphere interactions

This dissertation focuses on heatwaves over eastern Siberia in July and August. Heatwave frequency and intensity have shown exceptionally strong positive trends across the entire Siberian region in June (Figure 5.1), coinciding with rapid spring snow cover retreat. Land–atmosphere interactions play a crucial role in the predictability of temperature and heatwave variability in Siberia (e.g., Matsumura & Yamazaki, 2012; Gloege et al., 2022; Scholten et al., 2022). Atmospheric conditions from the preceding winter are also stored in the snow cover, subsequently influencing temperature and heatwave variability in early summer (Ogi et al., 2003; Overland & Wang, 2021). Early summer heatwaves over Siberia linking land–atmosphere interactions require urgent investigation in future research.

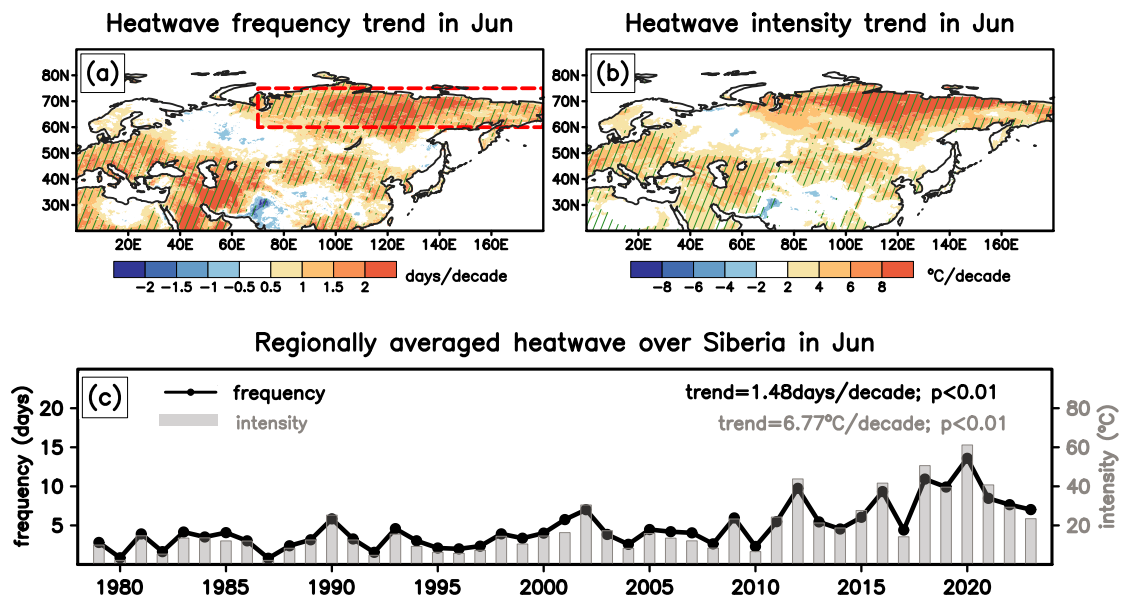


Figure 5.1 | Heatwave frequency and intensity trend over Siberia in June during 1979–2023. (a) Spatial distribution of heatwave frequency trend in June. **(b)** Spatial distribution of heatwave intensity trend in June. Red dashed boxes in (a) denote Siberia region (land area in 60°N–70°N, 70°E–180°E). Hatched areas in (a) and (b) indicate the trends significant at the 95% confidence level. **(c)** Interannual variation in regionally averaged heatwave frequency and intensity over Siberia in June. Black line and grey bar denote Siberia heatwave frequency and intensity, respectively. Black and grey numbers denote the trends and p-values for Siberia heatwave frequency and intensity, respectively.

5.2 The impacts of heatwaves over eastern Siberia on ecosystems

This study shows that both heatwave frequency and intensity over eastern Siberia have exhibited rapid increasing trends in recent decades (Figures 2.4 and 5.1). As summarized in Section 1.2, eastern Siberia is underlain by carbon-rich permafrost. Heatwaves can lead to increased land temperature, a greater active layer thickness of the permafrost, and enhanced greenhouse gases release from the permafrost. Additionally, heatwaves are often accompanied by more frequent wildfires, which contribute to air pollution and act as a strong accelerator of permafrost thaw.

Several studies assess the impacts of heatwaves on permafrost. For instance, Zhu et al. (2024) highlighted that the impacts of heatwaves in 2022 led to rapid permafrost warming in the central Qinghai-Tibet Plateau, with the contribution of heatwaves to the seasonal thaw depth of the active layer ranging from 6.6% to 13.6%. Froitzheim et al. (2021) assessed methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heatwaves over Siberia, suggesting that atmospheric methane concentrations increased considerably during and after the event.

For the observed major summer heatwave periods over eastern Siberia in recent decades, atmospheric conditions have been examined in this study. However, research quantitatively analyzing the impacts of eastern Siberian heatwaves on permafrost thawing—such as changes in active layer thickness and greenhouse gas emissions—as well as the occurrence of wildfires, remains limited. This research gap may be attributed to the limited attention given to eastern Siberian climate change and the scarcity of station data due to the region's harsh climate and remoteness. Nevertheless, further interdisciplinary studies are needed to address this issue. The outcomes of such research would contribute to preserving the local ecosystem and have significant implications for the global carbon and climate systems.

Chapter 6 Conclusions

Summer heatwaves have become increasingly frequent and intense worldwide, including in eastern Siberia, which is underlain by carbon-rich permafrost. These heatwaves exert significant adverse impacts on local ecosystems, may amplify global warming, and affect East Asian weather. Compared to densely populated regions, summer heatwaves over eastern Siberia have received limited attention from climate scientists. This study elucidates the mechanism of summer heatwaves over the NES and examines its linkage to atmospheric and oceanic variability in the WNP.

Heatwave frequency and intensity have increased rapidly over the NES in both July and August. [Chapter 2](#) investigates and compares the characteristics and mechanisms of NES heatwaves during these two months. Case studies and regression analyses reveal an anomalous tripolar height and temperature pattern across northern Eurasia associated with NES heatwaves in July. EOF analysis further confirms that the British–Okhotsk Corridor pattern primarily regulates NES heatwave frequency in July on the interannual timescale. In contrast, the atmospheric circulation pattern linked to NES heatwaves in August exhibits a meridional structure extending from the Arctic to the WNP. An Arctic low-pressure anomaly may contribute to the formation of NES heatwaves in August, as examined by the linear baroclinic model. Additionally, the heatwave-related high pressure over the NES in August may influence weather patterns in the WNP by strengthening the East Asian subtropical jet. This chapter highlights that the typical atmospheric circulation patterns and mechanism of NES heatwaves differ between July and August due to variations in the atmospheric background state.

Existing studies have primarily investigated the impacts of summer East Siberian blocking on East Asian weather, with limited attention to its connection with SST variability in the WNP. [Chapter 3](#) explores the linkage between late-summer NES heatwave-related atmospheric circulation patterns and SST variability in the WNP using reanalysis dataset. Both the case study of major NES heatwave periods in August and the correlation analysis for the entire period

Chapter 6: Conclusions

indicate a unique connection between August heatwaves over the NES and subsequent SST cooling in the WNP. This linkage is primarily driven by the influence of August Z500 over the NES. Further regression analyses suggest that this linkage mainly arises from a dipole pressure pattern over the NES and WNP. Anomalous high pressure over the NES leads to clear sky and enhanced insolation, promoting heatwave formation. Conversely, anomalous low pressure over the WNP results in increased cloud cover and reduced insolation. Additionally, drier surface air enhances latent heat flux release from the ocean surface in the WNP. These processes contribute to surface heat loss and subsequent SST cooling in this region. The shallow mixed layer depth in the WNP during the warm season makes SST more sensitive to heat flux loss, amplifying SST cooling and contributing to the uniqueness of this linkage.

In the context of rising temperature, the impacts of global warming on summer heatwaves over eastern Siberia remain poorly understood. [Chapter 4](#) investigates these impacts from a broader northern Eurasian perspective by analyzing a large ensemble of historical and non-warming simulation datasets. The results suggest that observed increases in the NES heatwaves are induced by both external forcings and internal atmospheric variability. Event attribution on the observed major NES heatwave periods suggests that global warming has contributed to an increase in both the frequency and intensity of these heatwave periods.

Regarding the dominant modes of summer heatwaves over northern Eurasia, two modes characterized by tripolar heatwave patterns across the region have shown no significant trends over the past four decades, suggesting they are primarily driven by internal atmospheric variability. In contrast, a mode characterized by positive heatwave frequency anomalies centered over western Siberia has exhibited significant increasing trends in recent decades, attributed to SST warming.

The findings of this study offer valuable insights into the characteristics and mechanisms of summer heatwaves over eastern Siberia. These enhanced insights can help inform strategies to address associated challenges, such as monitoring wildfires and permafrost thawing, thereby contributing to the protection of eastern Siberian ecosystems. Interdisciplinary research linking

Chapter 6: Conclusions

heatwaves, permafrost thawing, and wildfire occurrences in eastern Siberia requires urgent investigation. Furthermore, this study highlights the role of atmospheric forcing from eastern Siberia as a potential precursor for predicting weather and SST variability in the WNP, deepening our understanding of weather linkages between high and mid-latitudes and offering important implications for the conservation of regional marine ecosystems in the WNP.

Reference

- ACIA. (2004). *Impacts of a warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press
- Barriopedro, D., García-Herrera, R., Ordóñez, C., Miralles, D. G., & Salcedo-Sanz, S. (2023). Heat Waves: physical understanding and scientific challenges. *Reviews of Geophysics*, 61(2). <https://doi.org/10.1029/2022RG000780>
- Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., & García-Herrera, R. (2011). The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, 332(6026), 220–224. <https://doi.org/10.1126/science.1201224>
- Cai, Q., Chen, W., Chen, S., Xie, S. P., Piao, J., Ma, T., & Lan, X. (2024). Recent pronounced warming on the Mongolian Plateau boosted by internal climate variability. *Nature Geoscience*, 17(3), 181–188. <https://doi.org/10.1038/s41561-024-01377-6>
- Ciavarella, A., Cotterill, D., Stott, P., Kew, S., Philip, S., et al. (2021). Prolonged Siberian heat of 2020 almost impossible without human influence. *Climatic Change*, 166(1–2). <https://doi.org/10.1007/s10584-021-03052-w>
- Capua, D. G., Sparrow, S., Kornhuber, K., Rousi, E., Osprey, S., Wallom, D., et al. (2021). Drivers behind the summer 2010 wave train leading to Russian heatwave and Pakistan flooding. *Npj Climate and Atmospheric Science*, 4(1). <https://doi.org/10.1038/s41612-021-00211-9>
- Chen, X., Dai, A., Wen, Z., & Song, Y. (2021). Contributions of Arctic Sea-Ice Loss and East Siberian Atmospheric Blocking to 2020 Record-Breaking Meiyu-Baiu Rainfall. *Geophysical Research Letters*, 48(10). <https://doi.org/10.1029/2021GL092748>
- Coumou, D., Capua, D. G., Vavrus, S., Wang, L., & Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, 9(2959). <https://doi.org/10.1038/s41467-018-05256-8>
- Collow, A. B. M., Thomas, N. P., Bosilovich, M. G., Lim, Y. K., Schubert, S. D., & Koster, R. D. (2022). Seasonal variability in the mechanisms behind the 2020 Siberian heatwaves. *Journal of Climate*, 35(10), 3075–3090. <https://doi.org/10.1175/JCLI-D-21-0432.1>
- Deng, K., Yang, S., Ting, M., Zhao, P., & Wang, Z. (2019). Dominant modes of China summer heat waves driven by global sea surface temperature and atmospheric internal variability. *Journal of Climate*, 32(12), 3761–3775. <https://doi.org/10.1175/JCLI-D-18-0256.1>
- Deng, K., Jiang, X., Hu, C., & Chen, D. (2020). More frequent summer heat waves in southwestern China linked to the recent declining of Arctic sea ice. *Environmental Research Letters*, 15(7). <https://doi.org/10.1088/1748-9326/ab8335>
- Ding, Q., & Wang, B. (2005). Circumglobal teleconnection in the Northern Hemisphere summer. *Journal of Climate*, 18, 3483–3505. <https://doi.org/10.1175/JCLI3473.1>
- Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., et al. (2011). Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, 38(6). <https://doi.org/10.1029/2010GL046582>

- Domeisen, D. I. V., Eltahir, E. A. B., Fischer, E. M., Knutti, R., Perkins-Kirkpatrick, S. E., Schär, C., et al. (2023). Prediction and projection of heatwaves. *Nature Reviews Earth and Environment*, 4(36–50). <https://doi.org/10.1038/s43017-022-00371-z>
- Dong, J., Shi, X., Gong, X., Astakhov, A. S., Hu, L., Liu, X., et al. (2022). Enhanced Arctic sea ice melting controlled by larger heat discharge of mid-Holocene rivers. *Nature Communications*, 13(1). <https://doi.org/10.1038/s41467-022-33106-1>
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Froitzheim, N., Majka, J., & Zastrozhnov, D. (2021). Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave. *Proceedings of the National Academy of Sciences of the United States of America*, 118(32). <https://doi.org/10.1073/pnas.2107632118>
- Fu, Z. H., Zhou, W., Xie, S. P., Zhang, R., & Wang, X. (2024). Dynamic pathway linking Pakistan flooding to East Asian heatwaves. *Science Advances*, 10(17). <https://doi.org/10.1126/sciadv.adk9250>
- Geng, Y., Ren, H. L., Ma, X., Zhao, S., & Nie, Y. (2022). Responses of East Asian Climate to SST Anomalies in the Kuroshio Extension Region during Boreal Autumn. *Journal of Climate*, 35(21), 3407–3423. <https://doi.org/10.1175/JCLI-D-21-0711.1>
- Gibson, C. M., Chasmer, L. E., Thompson, D. K., Quinton, W. L., Flannigan, M. D., & Olefeldt, D. (2018). Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications*, 9(1). <https://doi.org/10.1038/s41467-018-05457-1>
- Gloege, L., Kornhuber, K., Skulovich, O., Pal, I., Zhou, S., Ciais, P., & Gentine, P. (2022). Land-Atmosphere Cascade Fueled the 2020 Siberian Heatwave. *AGU Advances*, 3(6). <https://doi.org/10.1029/2021AV000619>
- He, S., Xu, X., Furevik, T., & Gao, Y. (2020). Eurasian Cooling Linked to the Vertical Distribution of Arctic Warming. *Geophysical Research Letters*, 47(10). <https://doi.org/10.1029/2020GL087212>
- Hegedűs, D., Ballinger, A. P., & Hegerl, G. C. (2024). Observed links between heatwaves and wildfires across Northern high latitudes. *Environmental Research Letters*, 19(3). <https://doi.org/10.1088/1748-9326/ad2b29>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V. E., Nelson, F. E., et al. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. *Nature Communications*, 9(1). <https://doi.org/10.1038/s41467-018-07557-4>
- Holbrook, N. J., Sen Gupta, A., Oliver, E. C. J., Hobday, A. J., Benthuisen, J. A., Scannell, H. A., et al. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth and Environment*, 1, 482–493. <https://doi.org/10.1038/s43017-020-0068-4>

- Hong, C. C., Huang, A. Y., Hsu, H. H., Tseng, W. L., Lu, M. M., & Chang, C. C. (2023). Causes of 2022 Pakistan flooding and its linkage with China and Europe heatwaves. *Npj Climate and Atmospheric Science*, 6(1). <https://doi.org/10.1038/s41612-023-00492-2>
- Hu, D., Xu, M., Kang, S., Chen, J., Yang, C., & Yang, Q. (2023). The Effects of Discharge Changes in Siberian Rivers on Arctic Sea-Ice Melting. *Remote Sensing*, 15(14). <https://doi.org/10.3390/rs15143477>
- Ichii, T., Nishikawa, H., Mahapatra, K., Okamura, H., Igarashi, H., Sakai, M., et al. (2018). Oceanographic factors affecting interannual recruitment variability of Pacific saury (*Cololabis saira*) in the central and western North Pacific. *Fisheries Oceanography*, 27(5), 445–457. <https://doi.org/10.1111/fog.12265>
- Inoue, J., Hori, M., & Takaya, K. (2012). The role of Barents sea ice in the wintertime cyclone track and emergence of a warm-Arctic cold Siberian anomaly. *Journal of Climatology*, 25:2561–2568. <https://doi.org/10.1175/JCLI-D-11-00449.1>
- Imada, Y., Kawase, H., Watanabe, M., Arai, M., Shiogama, H., & Takayabu, I. (2020). Advanced risk-based event attribution for heavy regional rainfall events. *Npj Climate and Atmospheric Science*, 3(1). <https://doi.org/10.1038/s41612-020-00141-y>
- Imada, Y., Watanabe, M., Kawase, H., Shiogama, H., & Arai, M. (2019). The July 2018 high temperature event in Japan could not have happened without human-induced global warming. *Scientific Online Letters on the Atmosphere*, 15(A), 8–12. <https://doi.org/10.2151/sola.15A-002>
- Intergovernmental Panel on Climate Change. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, 35–115. <https://dor.org/10.59327/IPCC/AR6-9789291691647>
- Iwao, K., & Takahashi, M. (2008). A precipitation seesaw mode between northeast Asia and Siberia in summer caused by Rossby wave over the Eurasian continent. *Journal of Climate*, 21(11), 2401–2419. <https://doi.org/10.1175/2007JCLI1949.1>
- Jiang, J., Liu, Y., Mao, J., & Wu, G. (2023). Extreme heatwave over Eastern China in summer 2022: the role of three oceans and local soil moisture feedback. *Environmental Research Letters*, 18(4). <https://doi.org/10.1088/1748-9326/acc5fb>
- Kim, D. W., & Lee, S. (2022a). Dynamical mechanism of the summer circulation trend pattern and surface high temperature anomalies over the Russian Far East. *Journal of Climate*, 35(19), 2781–2793. <https://doi.org/10.1175/JCLI-D-22-0244.1>
- Kim, D. W., & Lee, S. (2022b). The role of latent heating anomalies in exciting the summertime eurasian circulation trend pattern and high surface temperature. *Journal of Climate*, 35(2), 801–814. <https://doi.org/10.1175/JCLI-D-21-0392.1>
- Kim, J. H., Kim, S. J., Kim, J. H., Hayashi, M., & Kim, M. K. (2022). East Asian heatwaves driven by Arctic-Siberian warming. *Scientific Reports*, 12(1). <https://doi.org/10.1038/s41598-022-22628-9>
- Kim, J. Y., & Seo, K. H. (2023). Physical mechanisms for the dominant summertime high-latitude atmospheric teleconnection pattern and the related Northern Eurasian climates. *Environmental Research Letters*, 18(10). <https://doi.org/10.1088/1748-9326/acfa13>

- Kim, J.-S., Kug, J.-S., Jeong, S.-J., Park, H., & Schaepman-Strub, G. (2020). Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation. *Science Advances*, 6:eaax3308. <https://doi.org/sciadv.aax3308>
- Lavers, D. A., Simmons, A., Vamborg, F., & Rodwell, M. J. (2022). An evaluation of ERA5 precipitation for climate monitoring. *Quarterly Journal of the Royal Meteorological Society*, 148(748), 3152–3165. <https://doi.org/10.1002/qj.4351>
- Luo, B., Luo, D., Dai, A., Xiao, C., Simmonds, I., Hanna, E., et al. (2024). Rapid summer Russian Arctic sea-ice loss enhances the risk of recent Eastern Siberian wildfires. *Nature Communications*, 15(1). <https://doi.org/10.1038/s41467-024-49677-0>
- Ma, K., Gong, H., Wang, L., Liu, B., Li, Y., Ran, H., & Chen, W. (2024). Anthropogenic forcing intensified internally driven concurrent heatwaves in August 2022 across the Northern Hemisphere. *Npj Climate and Atmospheric Science*, 7(1). <https://doi.org/10.1038/s41612-024-00828-6>
- Matsumura, S., & Yamazaki, K. (2012). Eurasian subarctic summer climate in response to anomalous snow cover. *Journal of Climate*, 25(4), 1305–1317. <https://doi.org/10.1175/2011JCLI4116.1>
- Michel, S. L. L., von der Heydt, A. S., van Westen, R. M., Baatsen, M. L. J., & Dijkstra, H. A. (2023). Increased wintertime European atmospheric blocking frequencies in General Circulation Models with an eddy-permitting ocean. *Npj Climate and Atmospheric Science*, 6(1). <https://doi.org/10.1038/s41612-023-00372-9>
- Mizuta, R., Murata, A., Ishii, M., Shiogama, H., Hibino, K., Mori, N., et al. (2017). Over 5,000 years of ensemble future climate simulations by 60-km global and 20-km regional atmospheric models. *Bulletin of the American Meteorological Society*, 98(7), 1383–1398. <https://doi.org/10.1175/BAMS-D-16-0099.1>
- Nakamura, H., & Fukamachi, T. (2004). Evolution and dynamics of summertime blocking over the Far East and the associated surface Okhotsk high. *Quarterly Journal of the Royal Meteorological Society*, 130, 1213–1233. <https://doi.org/10.1256/qj.03.101>
- Nakamura, N., & Huang, C. S. Y. (2018). Atmospheric blocking as a traffic jam in the jet stream. *Science*, 361(42–47). <https://doi.org/10.1126/science.aat0721>
- Nakamura, T., & Sato, T. (2022). A possible linkage of Eurasian heat wave and East Asian heavy rainfall in Relation to the Rapid Arctic warming. *Environmental Research*, 209. <https://doi.org/10.1016/j.envres.2022.112881>
- Ninomiya, K., & Mizuno, H. (1985). Anomalous cold spell in summer over northeastern Japan caused by northeasterly wind from polar maritime airmass, Part1. EOF analysis of temperature variation in relation to the large-scale situation causing the cold summer. *Journal of the Meteorological Society of Japan*, 63(5), 845–857. https://doi.org/10.2151/jmsj1965.63.5_845
- Nishii, K., Nakamura, H., & Orsolini, Y. J. (2010). Cooling of the wintertime Arctic stratosphere induced by the western Pacific teleconnection pattern. *Geophysical Research Letters*, 37(13). <https://doi.org/10.1029/2010GL043551>
- Noh, E., Kim, J., Jun, S. Y., Pak, G., Kim, J. H., & Kim, H. G. (2023). Atmospheric pathway of marine

- heatwaves over the Northwestern Pacific. *Scientific Reports*, 13(1). <https://doi.org/10.1038/s41598-023-49833-4>
- North, G.R., Bell, T.L., Cahalan, R.F., and Moeng, F.J. (1982). Sampling errors in the estimation of Empirical Orthogonal Functions. *Monthly Weather Review*, 110(7), 699–706. [https://doi.org/10.1175/1520-0493\(1982\)110<0699:SEITEO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2)
- Ogi, M., Tachibana, Y., & Yamazaki, K. (2003). Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation. *Geophysical Research Letters*, 30(13). <https://doi.org/10.1029/2003GL017280>
- Overland, J. E., & Wang, M. (2021). The 2020 Siberian heat wave. *International Journal of Climatology*, 41(S1), E2341–E2346. <https://doi.org/10.1002/joc.6850>
- Park, H., Watanabe, E., Kim, Y., Polyakov, I., Oshima, K., Zhang, X., et al. (2020). Increasing riverine heat influx triggers Arctic sea ice decline and oceanic and atmospheric warming. *Science Advances*, 6:eabc4699. <https://doi.org/10.1126/sciadv.abc4699>
- Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. *Journal of Climate*, 26(13), 4500–4517. <https://doi.org/10.1175/JCLI-D-12-00383.1>
- Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020). Increasing trends in regional heatwaves. *Nature Communications*, 11(1). <https://doi.org/10.1038/s41467-020-16970-7>
- Ponomarev, E., Yakimov, N., Ponomareva, T., Yakubailik, O., & Conard, S. G. (2021). Current trend of carbon emissions from wildfires in Siberia. *Atmosphere*, 12(5). <https://doi.org/10.3390/atmos12050559>
- Ponomarev, E., Zabrodin, A., & Ponomareva, T. (2022). Classification of Fire Damage to Boreal Forests of Siberia in 2021 Based on the dNBR Index. *Fire*, 5(1). <https://doi.org/10.3390/fire5010019>
- Qiu, Bo., & Kelly, K. A. (1993). Upper-ocean heat balance in the Kuroshio Extension region. *Journal of Physical Oceanography*, 23(9), 2027–2041. [https://doi.org/10.1175/1520-0485\(1993\)023<2027:UOHBIT>2.0.CO;2](https://doi.org/10.1175/1520-0485(1993)023<2027:UOHBIT>2.0.CO;2)
- Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, 3(1), 168. <https://doi.org/10.1038/s43247-022-00498-3>
- Robine, J. M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P., & Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus - Biologies*, 331(2), 171–178. <https://doi.org/10.1016/j.crv.2007.12.001>
- Rodrigues, R. R., Taschetto, A. S., Sen Gupta, A., & Foltz, G. R. (2019). Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. *Nature Geoscience*, 12(8), 620–626. <https://doi.org/10.1038/s41561-019-0393-8>
- Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications*, 13(1). <https://doi.org/10.1038/s41467-022-31432-y>
- Sato, H., Takemura, K., Ito, A., Umeda, T., Maeda, S., Tanimoto, Y., et al. (2024). Impact of an unprecedented marine heatwave on extremely hot summer over Northern Japan in 2023. *Scientific Reports*, 14(1).

- <https://doi.org/10.1038/s41598-024-65291-y>
- Sato, T., & Nakamura, T. (2019). Intensification of hot Eurasian summers by climate change and land–atmosphere interactions. *Scientific Reports*, 9(1). <https://doi.org/10.1038/s41598-019-47291-5>
- Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G., & Witt, R. (2014). The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters*, 9(8). <https://doi.org/10.1088/1748-9326/9/8/085003>
- Scholten, R. C., Luo, F., & Veraverbeke, S. (2022). Early snowmelt and polar jet dynamics co-influence recent extreme Siberian fire seasons. *Science*, 378(6623), 1005–1009. <https://doi.org/10.1126/science.abn4419>
- Schubert, S., Wang, H., & Suarez, M. (2011). Warm season subseasonal variability and climate extremes in the northern hemisphere: The role of stationary Rossby waves. *Journal of Climate*, 24(18), 4773–4792. <https://doi.org/10.1175/JCLI-D-10-05035.1>
- Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., et al. (2015). Climate change and the permafrost carbon feedback. *Nature*, 520, 171–179. <https://doi.org/10.1038/nature14338>
- Seager, R., Kushnir, Y., Naik, N. H., Cane, M. A., & Miller, J. (2001). Wind-Driven Shifts in the Latitude of the Kuroshio-Oyashio Extension and Generation of SST Anomalies on Decadal Timescales. *Journal of Climate*, 14(22), 4249–4265. [https://doi.org/10.1175/1520-0442\(2001\)014<4249:WDSITL>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<4249:WDSITL>2.0.CO;2)
- Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. et al. (2021). Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 1513–1766. <https://doi.org/10.1017/9781009157896.013>
- Shepherd, T. G. (2016). A Common Framework for Approaches to Extreme Event Attribution. *Current Climate Change Reports*, 2:28–38. <https://doi.org/10.1007/s40641-016-0033-y>
- Smith, D. M., Screen, J. A., Deser, C., Cohen, J., Fyfe, J. C., García-Serrano, J., et al. (2019). The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: Investigating the causes and consequences of polar amplification. *Geoscientific Model Development*, 12(3), 1139–1164. <https://doi.org/10.5194/gmd-12-1139-2019>
- Song, C. Y., & Ahn, J. B. (2024). Characteristics of precipitation in East Asia associated with Okhotsk Sea blocking in June and July. *International Journal of Climatology*, 44(5), 1654–1675. <https://doi.org/10.1002/joc.8403>
- Stott, P. A., Stone, D. A., & Allen M.R. (2004). Human contribution to the European heatwave of 2003. *Nature*, 432, 610–614. <https://doi.org/10.1038/nature03130>
- Sun, X., & Wu, R. (2021). Seasonality and time scale dependence of the relationship between turbulent surface heat flux and SST. *Climate Dynamics*, 56(9–10), 3173–3186. <https://doi.org/10.1007/s00382-021-05631-0>
- Suzuki, K., Park, H., Makarieva, O., Kanamori, H., Hori, M., Matsuo, K., et al. (2021). Effect of permafrost thawing on discharge of the kolyma river, northeastern Siberia. *Remote Sensing*, 13(21). <https://doi.org/10.3390/rs13214389>

- Tachibana, Y., Iwamoto, T., Ogi, M., & Watanabe, Y. (2004). Abnormal meridional temperature gradient and its relation to the Okhotsk high. *Journal of the Meteorological Society of Japan*, 82(5), 1399–1415. <https://doi.org/10.2151/jmsj.2004.1399>
- Taguchi, B., Nakamura, H., Nonaka, M., & Xie, S. P. (2009). Influences of the Kuroshio/Oyashio extensions on air-sea heat exchanges and storm-track activity as revealed in regional atmospheric model simulations for the 2003/04 cold season. *Journal of Climate*, 22(24), 6536–6560. <https://doi.org/10.1175/2009JCLI2910.1>
- Takaya, K., & Nakamura, H. (2001). A formulation of a phase-independent wave- activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. *Journal of the Atmospheric Sciences*, 58(6), 608–627. [https://doi.org/10.1175/1520-0469\(2001\)058<0608:AFOAPI>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2)
- Takemura, K., Sato, H., Ito, A., Umeda, T., Maeda, S., Hirai, M., et al. (2024). Preliminary Diagnosis of Primary Factors for an Unprecedented Heatwave over Japan in 2023 Summer. *Scientific Online Letters on the Atmosphere*, 20, 69–78. <https://doi.org/10.2151/SOLA.2024-010>
- Tao, L., Sun, X., Yang, X. Q., Fang, J., Cai, D., Zhou, B., & Chen, H. (2024). Cross-Season Effect of Spring Kuroshio-Oyashio Extension SST Anomalies on Following Summer Atmospheric Circulation. *Geophysical Research Letters*, 51(12). <https://doi.org/10.1029/2024GL108750>
- Teng, H., Leung, R., Branstator, G., Lu, J., & Ding, Q. (2022). Warming Pattern over the Northern Hemisphere Midlatitudes in Boreal Summer 1979–2020. *Journal of Climate*, 35(11), 3479–3494. <https://doi.org/10.1175/JCLI-D-21-0437.1>
- Thompson, D., & Wallace, J. (1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*, 25(9), 1297–1300. <https://doi.org/10.1029/98GL00950>
- Tibaldi, S., Tosi, E., Navarra, A., & Pedulli, L. (1994). Northern and southern hemisphere seasonal variability of blocking frequency and predictability. *Monthly Weather Review*, 122, 1971–2003. [https://doi.org/10.1175/1520-0493\(1994\)122<1971:NASHSV>2.0.CO;2](https://doi.org/10.1175/1520-0493(1994)122<1971:NASHSV>2.0.CO;2)
- Tomita, T., & Nonaka, M. (2006). Upper-Ocean Mixed Layer and Wintertime Sea Surface Temperature Anomalies in the North Pacific. *Journal of Climate*, 19(300–307). <https://doi.org/10.1175/JCLI3616.1>
- Tomshin, O., & Solovyev, V. (2022). Features of the Extreme Fire Season of 2021 in Yakutia (Eastern Siberia) and Heavy Air Pollution Caused by Biomass Burning. *Remote Sensing*, 14(19). <https://doi.org/10.3390/rs14194980>
- Tozuka, T., Toyoda, T., & Cronin, M. F. (2023). Role of mixed layer depth in Kuroshio Extension decadal variability. *Geophysical Research Letters*, 50(12). <https://doi.org/10.1029/2022GL101846>
- Trenberth, K. E., & Fasullo, J. T. (2012). Climate extremes and climate change: The Russian heat wave and other climate extremes of 2010. *Journal of Geophysical Research Atmospheres*, 117(17). <https://doi.org/10.1029/2012JD018020>
- Vitart, F., & Robertson, A. W. (2018). The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *Npj Climate and Atmospheric Science*, 1(1). <https://doi.org/10.1038/s41612-018-0013-0>

- Wakayabashi, S., & Kawamura, R. (2004) Extraction of major teleconnection patterns possibly associated with the anomalous summer climate in Japan. *Journal of the Meteorological Society of Japan*, 82(6), 1577–1588. <https://doi.org/10.2151/jmsj.82.1577>
- Wallace, J., & Gutzler, S. (1981) Teleconnections in the geopotential height field during the northern hemisphere winter. *Monthly Weather Review*, 109(784-812). [https://doi.org/10.1175/1520-0493\(1981\)109<0784:TITGHF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2)
- Wang, Z., Luo, H., & Yang, S. (2023). Different mechanisms for the extremely hot central-eastern China in July-August 2022 from a Eurasian large-scale circulation perspective. *Environmental Research Letters*, 18(2). <https://doi.org/10.1088/1748-9326/acb3e5>
- Watanabe, M., & Kimoto, M. (2000). Atmosphere-ocean thermal coupling in the North Atlantic: A positive feedback. *Quarterly Journal of the Royal Meteorological Society*, 126(570), 3343–3369. <https://doi.org/10.1002/qj.49712657017>
- Watanabe, Masahiro, Shiogama, H., Imada, Y., Mori, M., Ishii, M., & Kimoto, M. (2013). Event attribution of the August 2010 Russian heat wave. *Scientific Online Letters on the Atmosphere*, 9(1), 65–68. <https://doi.org/10.2151/sola.2013-015>
- World Meteorological Organization. (2021). State of the Global Climate 2020. <https://library.wmo.int/records/item/56247-state-of-the-global-climate-2020>
- Woollings, T., Barriopedro, D., Methven, J., Son, S. W., Martius, O., Harvey, B., et al. (2018). Blocking and its response to climate change. *Current Climate Change Reports*. 4:287–300. <https://doi.org/10.1007/s40641-018-0108-z>
- Wu, R., & Kinter, J. L. (2010). Atmosphere-ocean relationship in the midlatitude North Pacific: Seasonal dependence and east-west contrast. *Journal of Geophysical Research Atmospheres*, 115(6). <https://doi.org/10.1029/2009JD012579>
- Xiao, H., Xu, P., & Wang, L. (2024). The Unprecedented 2023 North China Heatwaves and Their S2S Predictability. *Geophysical Research Letters*, 51(6). <https://doi.org/10.1029/2023GL107642>
- Xu, P., Wang, L., & Chen, W. (2019). The British-Baikal Corridor: A teleconnection pattern along the summertime polar front jet over Eurasia. *Journal of Climate*, 32(3), 877–896. <https://doi.org/10.1175/JCLI-D-18-0343.1>
- Xu, P., Wang, L., Vallis, G. K., Geen, R., Screen, J. A., Wu, P., et al. (2021). Amplified waveguide teleconnections along the polar front jet favor summer temperature extremes over northern Eurasia. *Geophysical Research Letters*, 48(13). <https://doi.org/10.1029/2021GL093735>
- Xu, P., Wang, L., Dong, Z., Li, Y., Shen, X., & Chen, W. (2022). The British–Okhotsk Corridor pattern and its linkage to the Silk Road pattern. *Journal of Climate*, 35(17), 5787–5804. <https://doi.org/10.1175/JCLI-D-21-0705.1>
- Yanai, M., Esbensen, S., & Chu, J.-H. (1973). Determination of Bulk properties of tropical cloud clusters from large-scale heat and moisture Budgets. *Journal of the Atmospheric Sciences*, 30(4), 611–627. [https://doi.org/10.1175/1520-0469\(1973\)030<0611:DOBPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1973)030<0611:DOBPOT>2.0.CO;2)
- Yasui, S., & Watanabe, M. (2010). Forcing processes of the summertime circumglobal teleconnection pattern

- in a dry AGCM. *Journal of Climate*, 23(8), 2093–2114. <https://doi.org/10.1175/2009JCLI3323.1>
- Yasunari, T. J., Nakamura, H., Kim, K. M., Choi, N., Lee, M. I., Tachibana, Y., & Da Silva, A. M. (2021). Relationship between circum-Arctic atmospheric wave patterns and large-scale wildfires in boreal summer. *Environmental Research Letters*, 16(6). <https://doi.org/10.1088/1748-9326/abf7ef>
- Yatsu, A., Chiba, S., Yamanaka, Y., Ito, S. I., Shimizu, Y., Kaeriyama, M., & Watanabe, Y. (2013). Climate forcing and the Kuroshio/Oyashio ecosystem. *ICES Journal of Marine Science*, 70(5), 922–933. <https://doi.org/10.1093/icesjms/fst084>
- Zhang, P., Wu, Y., Simpson, I. R., Smith, K. L., Zhang, X., De, B., & Callaghan, P. (2018). A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss. *Science Advances*, 4:eaat6025. <https://doi.org/10.1126/sciadv.aat6025>
- Zhou, X., Sato, T., & Li, S. (2023). Interannual variation of the Warm Arctic–Cold Eurasia pattern modulated by Ural blocking and the North Atlantic Oscillation under changing sea ice conditions. *Progress in Earth and Planetary Science*, 10(1). <https://doi.org/10.1186/s40645-023-00591-x>
- Zhou, X., Sato, T., & Li, S. (2025). Different atmospheric circulation patterns associated with heatwaves over northeastern Siberia in July and August. *International Journal of Climatology*, in press. <https://doi.org/10.1002/joc.8731>
- Zhu, X., Wu, T., Chen, J., Wu, X., Wang, P., Zou, D., et al. (2024). Summer heat wave in 2022 led to rapid warming of permafrost in the central Qinghai-Tibet Plateau. *Npj Climate and Atmospheric Science*, 7(1). <https://doi.org/10.1038/s41612-024-00765-4>
- Zuo, H., Balmaseda, M. A., Tietsche, S., Mogensen, K., & Mayer, M. (2019). The ECMWF operational ensemble reanalysis-analysis system for ocean and sea ice: A description of the system and assessment. *Ocean Science*, 15(3), 779–808. <https://doi.org/10.5194/os-15-779-2019>

Acknowledgement

I would like to express my deep gratitude to Hokkaido University for providing me with the opportunity to study in such a beautiful environment and the EXEX fellowship to cover my living expenses during my doctoral course. The EXEX fellowship and ArCS II project funded my attendance at the 2024 and 2023 AGU conferences, respectively. Coming from a small town in southwestern China to studying in northern Japan and representing my research in the United States has been a remarkable experience for me.

I appreciate the previous researchers whose work laid the foundation for my study. I am also grateful to my research lab members. My sincere thanks go to Prof. Tomonori Sato for his valuable research guidance and for providing a flexible research style in the lab. I would like to thank Ms. Keiko Ono for her administrative support. I am also grateful for the research feedback and other support from all my lab members, especially Dr. Shixue Li and Dr. Kenta Tamura. Thanks to my Ph.D. defense committee for attending my defense and providing me with valuable comments.

The stunning landscapes and comfortable climate of Hokkaido have brought me inner peace and energy throughout my studies, while Japanese manga has been a delightful source of joy. A heartfelt thanks to the reliable Rikuto, the adorable Bob, and the brave Wanko for providing a cozy home in Hokkaido, bringing moments of joy, and supporting one another through challenges. I am immensely grateful to my friends, especially Ms. Qiao Li for her warmth and Ms. Jinya Cheng for her companionship. Most of all, I am deeply thankful to my family. My mother's delicious dishes, my younger brother's youthful energy, and my older sister's unwavering strength have been my greatest sources of comfort and encouragement.

Having grown and learned in both China and Japan, I have received support from many people along the way. Though my efforts remain humble, I will work diligently in my career, hoping that my contributions can positively impact both Chinese and Japanese societies as well as the Earth's climate and ecosystem in the future.