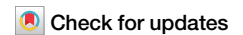


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Arctic wildfire carbon emissions strongly influenced by midsummer Tibetan Plateau precipitation



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Wildfires in the Arctic are accelerating ecosystem damage and increasing global carbon emissions. Siberia, a major Arctic wildfire hotspot, is shaped by both local weather and distant climate influences. Here we use climate reanalysis data and numerical model experiments to show that summer wildfires in Siberia are strongly influenced by rainfall patterns over the Tibetan Plateau, one of the Northern Hemisphere's largest summer heat sources. A dipole in Tibetan Plateau rainfall—wetter in the west, drier in the east—coincides with more fires in central Siberia and fewer in the east. This pattern alters high-altitude winds, shifting the jet stream northward and generating air flow changes that create favorable fire conditions across Siberia. Model experiments support a causal link. The resulting carbon dioxide emissions can match annual emissions from all Nordic countries. These findings highlight an overlooked driver of Arctic wildfires and improve our understanding of their role in the global carbon cycle.

The geographic range of wildfires has continuously expanded towards higher latitudes in recent years, burning permafrost and tundra environments in the Arctic^{1,2}. Arctic wildfires have devastating impacts on natural ecosystems, destroying habitats that many endangered species depend on for survival³. Wildfires rapidly deplete carbon stored in vegetation and soil, causing vegetation degradation, and release large amounts of greenhouse gases and aerosols into the atmosphere, fueling a vicious cycle that exacerbates climate change^{4–10}. Arctic wildfires are primarily concentrated in Sakha region of Siberia, Russia^{7,9,11}. Previous studies have indicated that, compared with the period 2000–2010, the frequency of wildfires in the Sakha tripled between 2010 and 2020 with the total area burned more than doubling, especially in western and central Siberia (CSB)^{12,13}.

Climate change has intensified compound extreme weather events such as heatwaves and droughts, resulting in hotter, drier, and longer wildfire seasons^{11,14,15}. Arctic warming has also led to an increase in lightning frequency, further raising the likelihood of natural fires^{16,17}. In addition, Arctic warming weakens the meridional temperature gradient and enhances

atmospheric blocking, which fosters warm and dry weather conditions conducive to wildfires¹⁸. In the coming years, rising temperatures, increasing lightning frequency, and intensifying heatwaves are likely to continue and escalate, potentially leading to more Arctic wildfires¹⁹. It is estimated that the number of Arctic and global wildfires could increase by a third by 2050^{10,20}. In addition to local factors, the crucial role of large-scale teleconnection wave trains in regulating Arctic-boreal fires on an interannual scale has been highlighted in recent studies^{21,22}. As a critical conduit for the propagation of teleconnection waves, the dynamic processes associated with jet streams have been identified as key drivers of Siberian wildfires²³. However, existing research has given limited attention to the potential impact of signals from regions beyond high latitudes on Siberian wildfires.

As one of the largest summer heat sources in the Northern Hemisphere during the wildfire season, the intense latent heat released by abundant precipitation over the Tibetan Plateau (TP) can disturb the atmosphere and influence remote regions^{24–26}. Specifically, the dynamic linkage between TP precipitation and the East Asian subtropical jet stream is widely

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recognized^{27–30}. Compared to the substantial internal atmospheric variability and uncertainty of the jet stream, TP precipitation offers far greater predictability^{31–33}. Confirming a causal link between plateau precipitation and Arctic wildfires could significantly enhance our ability to anticipate changes in wildfire activity and assess their impacts.

Taking advantage of the robust connection between TP precipitation and the East Asian subtropical jet stream, we examine the relationship between TP precipitation and Siberian wildfire patterns using both observational analysis and numerical simulations and identify the associated underlying mechanisms. Furthermore, we show that carbon emissions from Arctic wildfires driven by TP precipitation will increase by ~89.9 million tons per year during the top 5 years with the pronounced TP precipitation dipole pattern; this equates to 2.7 times the total annual emissions of Sweden in 2020. This study provides new insights into understanding the causes of Arctic wildfires and improving the ability to forecast them.

Results

The summer heat source over the TP markedly influences global climate³⁴. Specifically, the latent heat released by precipitation in July and August contributes to this heat source; this differs from the climatic effect observed in June³⁵. Here, we used the empirical orthogonal function (EOF) analysis to obtain the dominant spatiotemporal variations in mid-summer (July–August) precipitation over the TP, following the method in previous study³⁵. Figure 1a and Supplementary Fig. 1 display the spatial distributions of the first leading mode (EOF1) of two different precipitation datasets and their associated time series. This mode explained approximately one-third of the total variance of each of the two datasets (34% in

GPCP and 30% in CRU), and overall, the two datasets showed similar spatial patterns and temporal variations. Spatially, precipitation varied inversely between southeastern Tibet and Nepal, which lies to the southwest of Tibet. Temporally, both datasets showed similar variations with a correlation coefficient of 0.83 (the black line in Fig. 1f and Supplementary Fig. 1b). Combining the spatial distributions and associated time series, precipitation increased in southwestern Tibet and decreased in Nepal in years where the time series exhibited positive values. Over the past two decades, almost all extreme floods in Pakistan have occurred in years when the associated time series was positive (e.g., 2006, 2010, 2013, 2016, 2019, and 2022, as shown in Fig. 1f). As an interacting system, this portion of precipitation suppresses moisture transport into the southeastern part of the TP, jointly contributing to the formation of a dipole pattern^{36–38}. The immense latent heat released by these extreme precipitation patterns can bring abnormal weather to downstream regions through the propagation of the circum-global wave train^{33,37}; meanwhile, the released heat interaction with the jet stream also suggests that it may markedly influence extreme weather in high-latitude regions³⁹. As shown in Fig. 1d, there is a statistically significant correlation between the seemingly unrelated TP precipitation and Arctic wildfires.

Arctic wildfires mainly occur during mid-summer in the Siberian region, particularly in eastern Siberia (ESB). Here, each $1^\circ \times 1^\circ$ grid recorded an average of over 80 ignition points annually (Fig. 1b), with a maximum of up to 900 incidents, accounting for >80% of total annual wildfire occurrences across nearly all analyzed regions at latitudes of $55^\circ\text{--}70^\circ\text{N}$. The highest wildfire frequency was observed at $\sim 65^\circ\text{N}$, 130°E . Statistically, wildfire frequency in the Siberian region showed a strong correlation with PC1 of TP precipitation (Fig. 1f). In years with higher PC1 values, wildfires were more

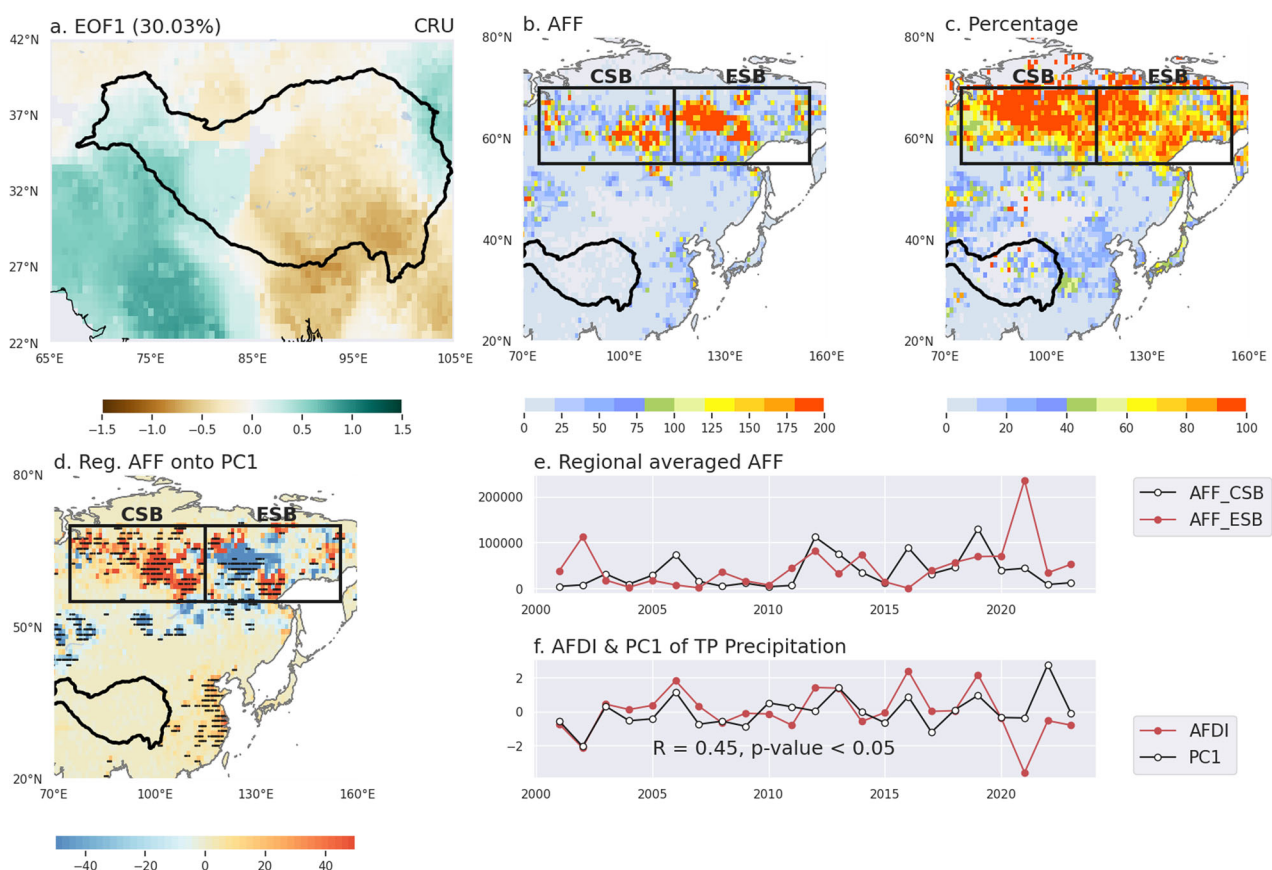


Fig. 1 | Mid-summer Tibetan Plateau (TP) precipitation and its relationship with Siberian wildfires. a Leading empirical orthogonal function mode (EOF1) of TP precipitation in mid-summer from 2001 to 2023 for the CRU dataset. **b** Annually averaged Active wildfire frequency (AFF, in unit of ignition point numbers) over East Asia in mid-summer from 2001 to 2023. **c** Percentage of AFF in mid-summer compared with the annual AFF. **d** Linear regression of mid-summer AFF onto the

first principal component (PC1) of TP precipitation. The dotted areas are significant at the 95% confidence level. **e** Regional averaged AFF in central Siberia (CSB, black line) and eastern Siberia (ESB, red line). **f** Difference in AFF between CSB and ESB (AFDI, shown as red line) and PC1 of TP precipitation (black line). Black boxes denote the CSB and ESB domains respectively.

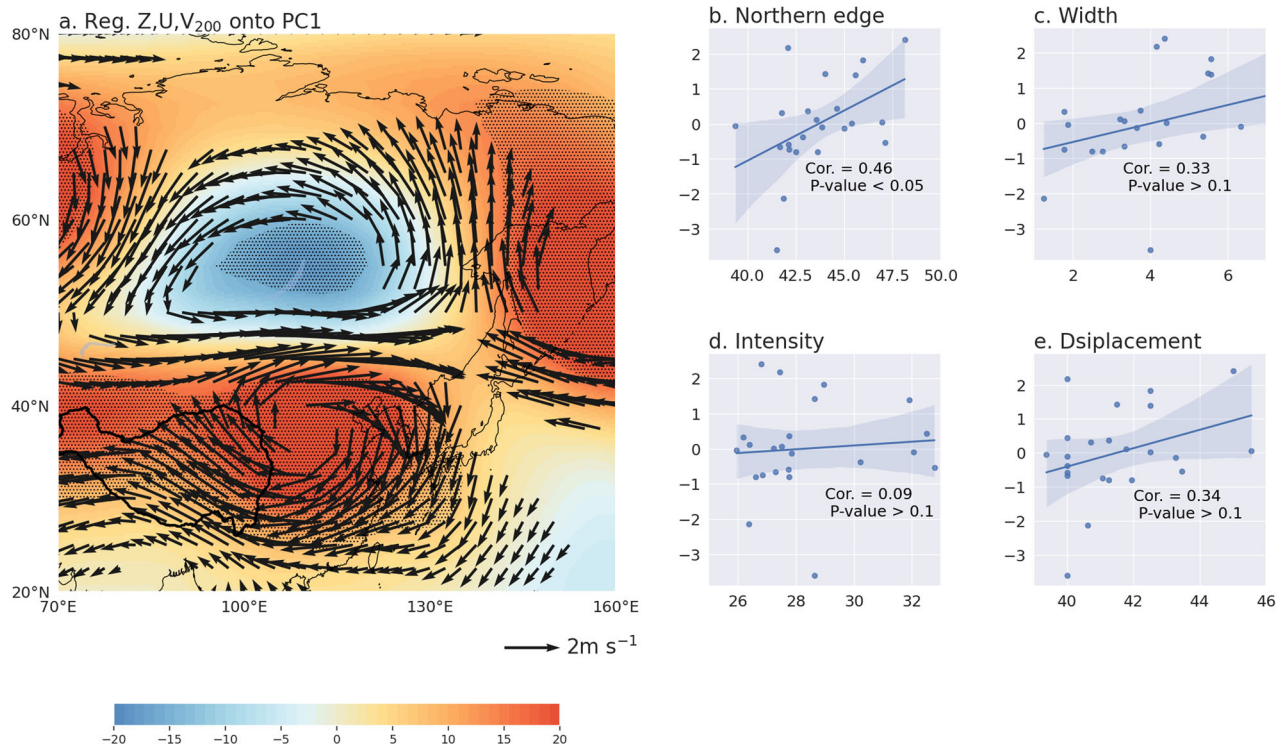


Fig. 2 | Circulation anomalies related to Tibetan Plateau (TP) precipitation and relationships between the East Asia jet stream and Arctic wildfires. a Linear regression of mid-summer horizontal winds (vectors, unit: m s^{-1}) and geopotential height (shading, unit: gpm) at 200 hPa onto the first principal component (PC1) of TP precipitation. The dotted areas are significant at the 95% confidence level.

Relationship between the “normalized difference of active fire frequency between central Siberia (CSB) and eastern Siberia (ESB)” and jet stream (b) northern edge (unit: degree), c width (unit: degree), d intensity (unit: m s^{-1}), and e displacement (unit: degree). The shaded area in (b–e) represents the uncertainty range, corresponding to one standard deviation.

active in CSB (55–70°N, 75–115°E), while the frequency of wildfires in ESB (55–70°N, 115–155°E) decreased. We defined the difference in wildfire frequency between CSB and ESB as the active fire frequency difference index (AFDI) to characterize the spatial patterns of Siberian wildfires. This index has a correlation coefficient of 0.45 with PC1 of TP precipitation, which is statistically significant at the 0.05 level. The circulation anomalies in response to PC1 can effectively explain this statistical correlation. The zonal dipole pattern in TP precipitation, characterized by positive anomalies in the west, induces a substantial anticyclonic anomaly in the upper troposphere to the northeast of the TP (Fig. 2a). This response can be explained by the steady barotropic vorticity equation for large scales and the circum-global wave train propagation mechanism^{24,29}. The large-scale latent heat anomaly associated with the dipole precipitation pattern extends into the upper troposphere, exciting a stationary Rossby wave response^{40,41}. Further supporting this, simulations of TP heat source forcing using the Linear Baroclinic Model³³, along with dynamical diagnostics of Rossby wave sources and wave activity flux propagation (Supplementary Fig. 2), confirm the response of anticyclonic anomalies and the jet stream to TP precipitation forcing. This anticyclonic anomaly results in stronger westerlies to its north, causing the East Asian subtropical westerly jet stream to shift further north compared to its usual climatological position (Fig. 2 and Supplementary Fig. 3), with a correlation coefficient of 0.46 between PC1 and the northern edge of the jet stream (JSNE). Here, we analyzed several key characteristics of the East Asian subtropical jet stream, including its intensity, width, displacement, and northern edge, and examined their relationships with PC1 of TP precipitation (Fig. 2b–e). The leading mode of TP precipitation exhibited an insignificant relationship with the intensity of the jet stream but showed a close association with the position of the jet stream, particularly the latitude of JSNE. Therefore, the subtropical East Asian jet stream may be a crucial link between mid-summer TP precipitation and Siberian wildfires.

The northward expansion of the subtropical jet stream induces cyclonic curvature and positive vorticity anomalies to its north, creating an

anomalous cyclone centered over Lake Baikal. This cyclonic anomaly leads to a decrease in surface air temperature (Supplementary Fig. 4a) by increasing cloud cover and reducing solar radiation in the affected region (Supplementary Fig. 4b, c), resulting in a lower fire weather index (FWI) in ESB (Fig. 3). Meanwhile, the southerly wind anomalies to the east of the cyclonic anomaly enhance precipitation in ESB, suppressing fire activity from the perspectives of both initial spread and buildup conditions (van Wagner, 1987). Together, these factors contribute to the suppression of wildfires in ESB. Conversely, the reduced cloud cover and increased solar radiation in CSB lead to decreased precipitation, creating more favorable conditions for wildfire occurrences. The meridional circulation formed between the northeastern TP and CSB further promotes the occurrence of wildfires in CSB through an enhanced adiabatic sinking motion, while the anomalous updraft in ESB increases the potential for precipitation (Supplementary Fig. 5). Our quantitative results showed that the FWI in CSB during years with high PC1 values increased by ~27.1%, while in ESB, it decreased by approximately 14.0% compared with years having normal PC1 values (see Supplementary Table 1); this was driven changes in surface temperature, cloud cover, and precipitation. Such FWI anomalies led to a 59.9% increase in annual average wildfire frequency in the CSB compared with years having normal PC1 values, while the wildfire frequency in ESB has experienced a 64.9% decrease. Sensitivity experiments based on CAM5.3 further validated the crucial role of the subtropical jet stream in linking TP precipitation patterns with Arctic wildfires (Fig. 4 and Supplementary Fig. 6). The position of the JSNE exhibited a strong northward movement response to the latent heat released by observed TP precipitation when comparing the sensitivity experiments (~45.2°N) with the control experiments (~42.7°N). Consequently, there was a substantial difference in precipitation and cloud cover between CSB and ESB (Fig. 4b, d). The sensitivity simulations revealed a slightly higher difference in T_{as} between CSB and ESB compared with the control experiments (Fig. 4c), but this difference was <0.5

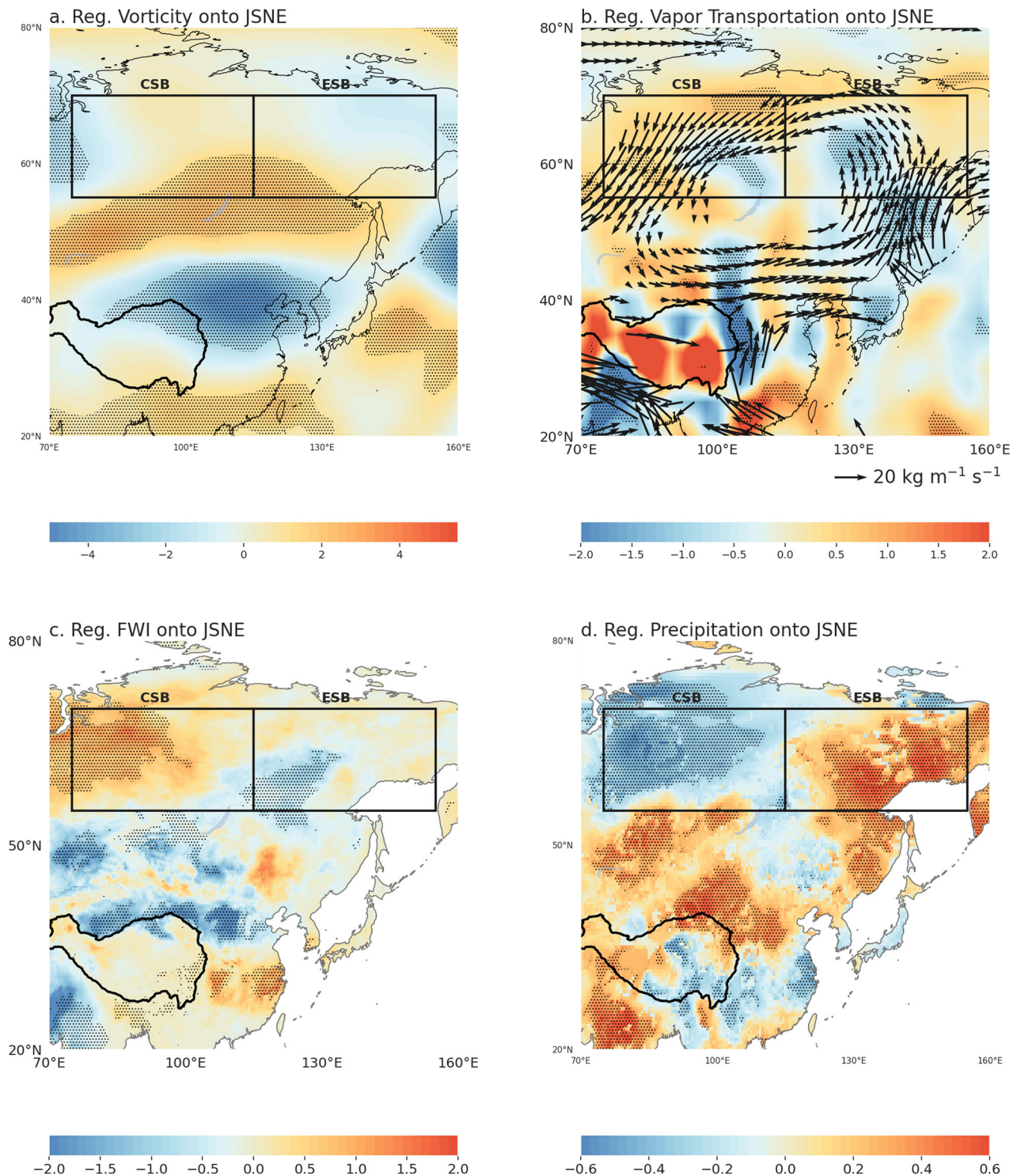


Fig. 3 | Fire weather conditions related to the East Asia jet stream. a–d Linear regression of mid-summer jet stream northern edge (JSNE) index onto **a** vorticity (unit: 10^{-5} s^{-1}), **b** total layer water vapor flux (vectors, unit: $\text{kg m}^{-1} \text{ s}^{-1}$) and its

divergence (shading, unit: $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$), **c** fire weather index (FWI), and **d** precipitation (unit: mm). The dotted areas are significant at the 95% confidence level.

standard deviations. The FWI derived from the simulation data also exhibits a significant response to TP precipitation anomalies (Fig. 4e). Compared to the control experiment, the sensitivity experiment shows a notable increase in the difference in FWI between the CSB and ESB regions, supporting the mechanism proposed in the observational analysis. These simulation results were highly consistent with observational data in terms of both key metrics (Fig. 5) and spatial distribution (Supplementary Figs. 6 and 7). These numerical simulation results verify

the physical mechanism of the response of Siberian wildfire weather conditions to TP precipitation proposed based on observational analysis.

The robust causal relationship between TP precipitation and Siberian wildfire patterns enhances our confidence in estimating related carbon emissions (Fig. 5). Owing to the limited temporal coverage of the emission dataset, we used 0.5 times the standard deviation of the normalized PC1 of TP precipitation as a threshold to categorize the 19 years from 2002 to 2022 into three groups: five high PC1 years ($\text{PC1} > 0.5$: 2006, 2010, 2013, 2016,

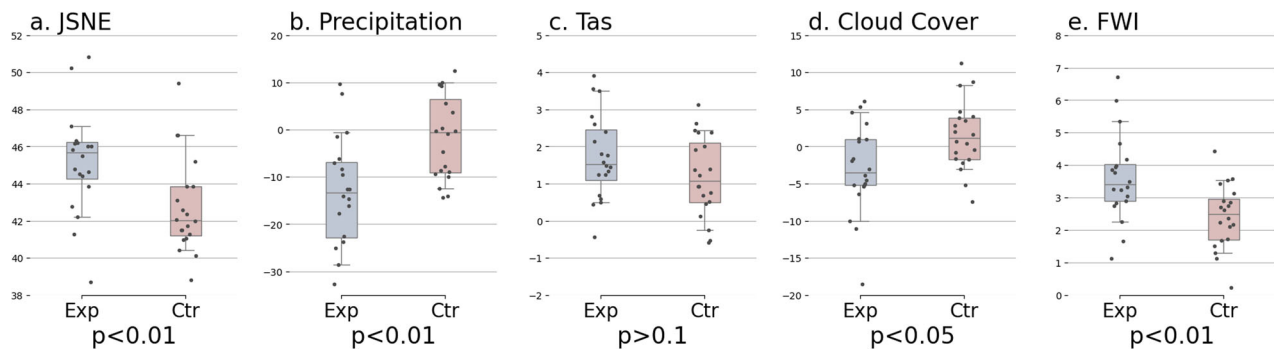


Fig. 4 | Response of East Asia jet stream and fire weather conditions to the Tibetan Plateau precipitation. **a–d** Comparisons between control simulations (Ctr) and sensitivity simulations (Exp) in **a** jet stream northern edge (JSNE, unit: degree), **b** difference in precipitation (unit: mm) in central Siberia (CSB) and eastern Siberia (ESB), **c** difference in surface air temperature (Tas, unit: °C) in CSB and ESB, and **d** difference in cloud cover (unit: %) in CSB and ESB, **e** difference in FWI in CSB and

ESB. The height of each box represents the interquartile range of contributions for all grid points, with the black horizontal line in each box indicating the mean value. Whiskers depict the minimum and maximum contribution values, excluding outliers exceeding 1.5 times the interquartile range. Black dots are 20 samples for each box. The significance level of the p -value from the t -test is specified below the subfigures.

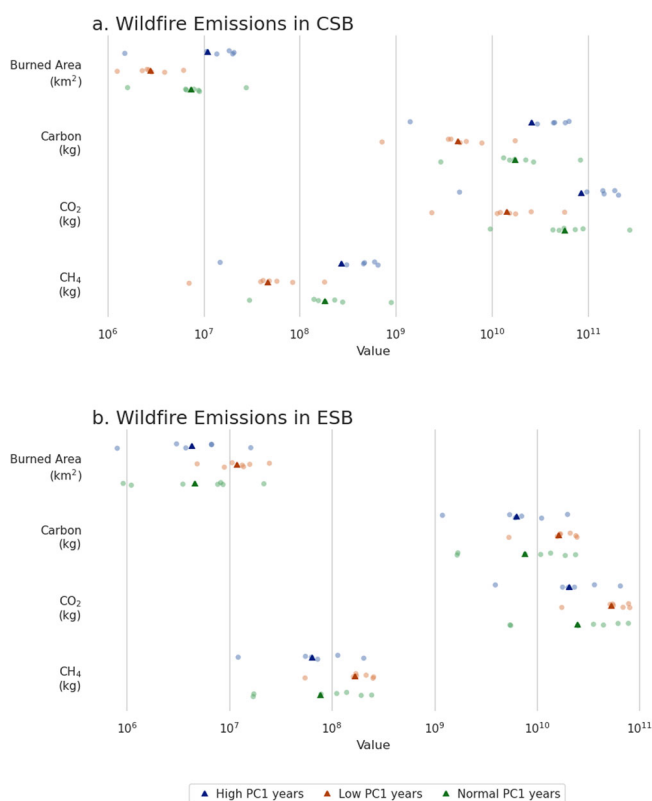


Fig. 5 | Wildfire emissions related to Tibetan Plateau (TP) precipitation anomalies. **a, b** The burned area (unit: km²) and released carbon (unit: kg), CO₂ (unit: kg), and CH₄ (unit: kg) in years with high (normalized first principal component (PC1) > 0.5), low (normalized PC1 < −0.5), and normal PC1 (0.5 > normalized PC1 > −0.5) PC1 of TP precipitation in **a** central Siberia (CSB) and **b** eastern Siberia (ESB). The triangle (circular) marks indicate the multi-year average (annual average) of the variable within each year group.

and 2019), seven low PC1 years (PC1 < −0.5: 2002, 2004, 2007, 2008, 2009, 2015, and 2017), and seven normal PC1 years (0.5 > PC1 > −0.5: 2003, 2005, 2011, 2012, 2014, 2018, and 2020). In high PC1 years, the burned area (14.9 million km²) and emissions (C: 42.5 million tons; CO₂: 139.1 million tons; CH₄: 441.8 thousand tons) in the CSB region were substantially higher than those in other years (Fig. 5a). The burned area and carbon-related emissions were 3.8 and 5.8 times higher, respectively, compared with those in low PC1 years. This quantity of CO₂ emissions was equivalent to the total

anthropogenic and natural CO₂ emissions of the five Nordic countries combined in 2020 (Crippa et al.⁴²). In normal PC1 years, the burned area and carbon-related emissions generally fell between the values recorded in high PC1 and low PC1 years. Similarly, the burned area and carbon-related emissions in ESB across the three groups of years were also analyzed (Fig. 5b). In high PC1 years, the burned area and carbon-related emissions in ESB decreased compared to other years, although the differences were much smaller than those observed in CSB across the three groups of years. Overall, in high PC1 years, the total burned area from wildfires across Siberia was 5.3 million km² greater than that in low PC1 years, and CO₂ emissions were 89.9 million tons higher, the latter being equivalent to 2.7 times the total CO₂ emissions of Sweden in 2020⁴³. From the spatial distribution results, we found that the impact of TP precipitation on wildfires in CSB was much greater than its impact on wildfires in ESB (Supplementary Fig. 8). In summary, our results highlight the substantial contribution of interannual climate variability to global carbon emissions and emphasize the need to carefully account for the impact of non-local climate signals when assessing Arctic wildfire risk.

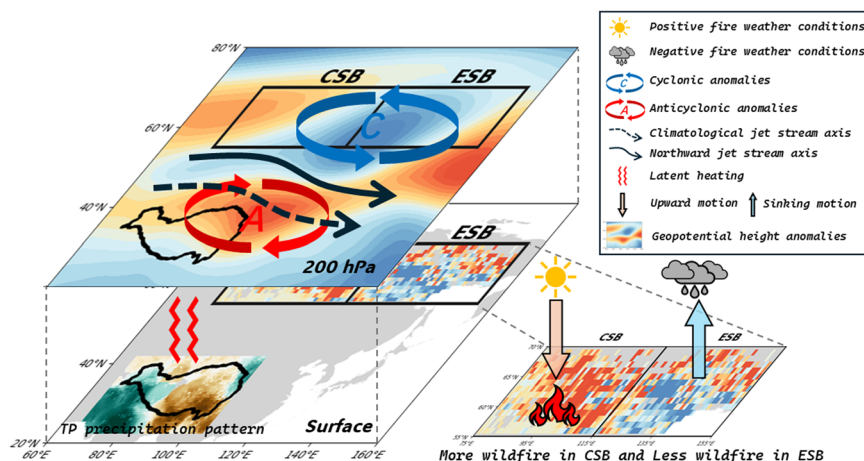
Discussion

The Arctic was warming at a rate far exceeding the global average, leading to a marked increase in extreme weather events, particularly wildfires. These fires not only release large amounts of greenhouse gases directly through forest combustion but also increase the risk of carbon release from permafrost and tundra^{2,4,9}.

Our analysis reveals that, beyond local meteorological conditions, climate signals from mid-low latitudes could also be strongly linked to Arctic wildfires. A mid-summer precipitation dipole anomaly over the TP was strongly associated with increased wildfire activity in CSB and decreased activity in ESB (Fig. 6). Evidence for this relationship comes from both observational analyses and numerical simulations. Our study also highlighted the important contribution of this connection to the annual variability in carbon emissions from Arctic wildfires. Given the predictability of summer precipitation over the TP³¹, it may serve as a potentially effective indicator of Siberian wildfires.

Previous studies have shown that wildfires were influenced by both current climate conditions and pre-fire-season factors such as soil moisture, snowmelt, and vegetation cover^{23,44,45}. Therefore, the combined effects of these pre-existing conditions and TP precipitation require further investigation. Additionally, although TP precipitation was closely related to the East Asian subtropical jet stream, the interaction between TP precipitation and the jet stream was complex and cannot be simply characterized as one-way^{31,35}). As a key component of internal atmospheric variability, changes in the jet stream itself may simultaneously impact precipitation over the TP and boreal wildfires. Therefore, a large number of ensemble simulations will

Fig. 6 | Physical mechanisms of the mid-summer dipole TP precipitation pattern affecting the wildfires in Siberia. The large-scale latent heating released by the mid-summer dipole pattern in TP precipitation triggers anticyclonic anomalies in the upper-level troposphere to the northeast of the TP, leading to a northward shift of the subtropical jet stream. The vorticity forcing on the northern flank of the jet induces cyclonic anomalies, creating atmospheric conditions favorable for wildfires in Central Siberia (CSB), while suppressing wildfire occurrence in Eastern Siberia (ESB). The results were derived from composing the differences between cases with high and low PC1 of TP precipitation.



need to be performed in the future to quantify the relative contribution of TP precipitation further.

Data and methods

Data

The observed active fire data were derived from the Fire Information for Resource Management System; this distributes near real-time active fire data from the Moderate Resolution Imaging Spectroradiometer aboard the Aqua and Terra satellites, and the Visible Infrared Imaging Radiometer Suite aboard S-NPP, NOAA 20, and NOAA 21. The original data records the location (in latitude and longitude coordinates) and date of each active fire. To facilitate spatiotemporal analysis from a climatic perspective, we counted the frequency of daily active fires with a horizontal resolution of $1^\circ \times 1^\circ$. Therefore, the daily AFF is measured as the frequency of fires (number of ignition points) occurring within each grid cell per day. This method can, to some extent, reflect the fire area and intensity within the grid cell.

The GPCC and CRU precipitation data were available from the National Oceanic and Atmospheric Administration Physical Sciences Laboratory and the Centre for Environmental Data Analysis Archive, respectively.

The ERA5 reanalysis products were available from the Climate Data Store. The dataset contains geopotential heights (Z), zonal and meridional winds (U and V), relative humidity at different levels, and surface air temperature (T_s). The FWI used in this study is based on the Canadian FWI system⁴⁶, which has been widely recognized and applied in global fire weather research. The FWI can be calculated using ERA-5 reanalysis (including daily total precipitation, surface air temperature, wind speed, and relative humidity), incorporating both the initial spread index and the build-up index; this provides a numerical rating of potential frontal fire intensity⁴⁶. The calculation of observed and simulated FWI can be implemented through the following code storage (<https://github.com/steidani/FireDanger>).

The fifth version of the Global Fire Emissions Database (GFED5) was also used to determine wildfire emissions caused by Tibetan Plateau (TP) precipitation anomalies. The monthly gridded estimates of burned area and emissions including C, CO₂, and CH₄, from 2002 to 2022 with a horizontal resolution of 0.25° .

Due to data limitations, the results related to wildfire emissions are based on 2002–2022, while all other results are based on 2001–2023.

Leading mode of TP precipitation and East Asian jet stream index

In this study, “TP precipitation” refers to precipitation within the broader extent of the TP, consistent with the commonly used definition in previous studies. The leading mode of mid-summer (July–August) TP precipitation was obtained via EOF analysis. The results of the EOF analysis were not sensitive to the choice of domain³⁵.

A jet stream was traditionally defined as a high-speed wind belt in the upper troposphere with wind speeds $>30 \text{ m s}^{-1}$. However, owing to the relatively lower intensity of jet streams in summer, a threshold of 25 m s^{-1} was commonly used for detection^{47,48}.

Previous studies have typically used the regional average wind speed in a fixed region to describe the intensity or other features of jet streams, while some have employed EOF to capture the intensity and displacement variations of jet streams^{49,50}. However, both approaches have limitations: the former fails to adequately describe jet stream characteristics in years with substantial shifts in jet stream position, while the latter was overly dependent on the available dataset. To address these limitations, we here used self-adaptive jet stream indices to describe the key characteristics of the East Asia jet stream⁵¹. These indices include key features such as intensity, displacement, and width, where the width was calculated as the difference between the northern and southern edges of the jet stream.

To identify the northern (JSNE) and southern edges of the jet stream at each longitude in $70^\circ\text{--}130^\circ\text{E}$, the average latitude at point i was defined as the south (north) edge if the wind speed $w_{si} \geq 25 \text{ m s}^{-1}$ ($<25 \text{ m s}^{-1}$) and $w_{s(i-1)} < 25 \text{ m s}^{-1}$ ($\geq 25 \text{ m s}^{-1}$). The meridional displacement of the jet stream was defined as the average latitude of the points corresponding to the maximum wind speed along each longitude line from 70°E to 130°E . The jet stream intensity was calculated from the average wind speed between its northern and southern edges. The horizontal jet stream core was identified as a grid point where the wind speed was $>25 \text{ m s}^{-1}$ and greater than the surrounding eight grid points.

Numerical simulations

Control and sensitivity experiments based on the Community Atmosphere Model version 5.3 (CAM5.3) were conducted to verify the physical mechanism by which mid-summer TP precipitation affects Siberian wildfire patterns. CAM5.3 is the atmospheric component of the Community Earth System Model version 1.2.2 and was widely used to verify the response of the atmosphere to heat source variations on the TP^{18,52,53}. We use the finite-volume dynamic core configured with a horizontal resolution of 1.9° latitude $\times$ 2.5° longitude (f19_g16 scheme) and 30 vertical hybrid levels. For more details of this model, see the official tutorial⁵⁴.

Following the experimental scheme designed by previous studies^{53,55}, we first performed a series of control experiments (global sea ice and sea surface temperature are maintained at the climatological levels of 1979–2023 interpolated from Hadley Centre HadISST dataset to match the model resolution; emissions and radiation levels are fixed at the levels of the year 2000) under the default settings to derive different initial fields. The model was spun up for 5 years and then integrated forward for 20 years. Simulations of the 1st January of the last 20 years were used as the initial field for sensitivity ensemble simulation, and the sensitivity experiments with 20 members were integrated from the beginning of January to the end of

August. A 20-member sensitivity ensemble experiment was sufficiently robust and reliable to eliminate uncertainties brought about by differences in the initial conditions⁵⁶. In mid-summer, latent heat released from precipitation was the dominant contributor to the total diabatic heating over the TP (Duan and Wu, 2005), which can be calculated as follows:

$$Q_1 = \frac{1}{g} C_p \left(\frac{\partial T}{\partial t} - \omega \sigma + \mathbf{V} \cdot \nabla T \right) \quad (1)$$

where C_p is the specific heat capacity at a constant pressure of dry air, T denotes the air temperature, ω represents vertical velocity, σ is the static stability, and $\mathbf{V}$ is the horizontal wind. Therefore, we simulated the effects of precipitation variations by modifying the 3-dimensional Q_1 profile within the model. In the sensitivity simulations, a value of 1.5 times the observed July–August Q_1 anomaly in the TP region (22–42°N, 65–105°E) in the abnormal TP precipitation years (2006, 2010, 2013, 2016, 2019, and 2022; selected based on a threshold of 0.5 times the standard deviation) between 2001 and 2023 was added to the model. Therefore, the spatial distribution of the Q_1 difference between the sensitivity experiment and the control experiment is consistent with that in Supplementary Fig. 9c, with the values amplified by a factor of 1.5. The purpose of magnifying anomalies is to highlight the results driven by specified forcings. The total atmospheric apparent heat source during high PC1 years, and normal years, as well as their differences, were displayed in Supplementary Fig. 8. The only difference between the sensitivity simulations and the control simulations lies in the non-adiabatic heating profile over the key region of the TP precipitation. Therefore, the ensemble difference between the sensitivity and control experiments was taken as the simulation result, which indicates the atmospheric circulation response to the identified precipitation pattern.

Data availability

The observed active fire data was accessible via <https://firms.modaps.eosdis.nasa.gov/>. The GPCC and CRU precipitation data were available from the <https://psl.noaa.gov/data/gridded/data.gpcc.html> and https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.09/, respectively. The ERA5 reanalysis products were available from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=form>. The GFED5 dataset can be obtained from <https://www.globalfiredata.org/>.

Code availability

The code of the CESM1 model used here is available from (<http://www.cesm.ucar.edu/models/cesm1.2/>). Other codes used in the present study are available from the corresponding author on request.

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Author contributions

X.Y. performed this study, plotted the figures, and wrote the preliminary manuscript. H.L. and Z.Z. participated in the revision and partial writing. C. H., G. Z., H.-W. L., T.O., and W. W. provided valuable suggestions and discussions on the improvement of this manuscript. D.C. supervised this study. All the authors contributed to the writing and reviewing of the manuscript.

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Competing interests

The authors declare no competing interests.

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