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European Heatwaves Aggravated by Recent Summer Arctic Changes

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Abstract

European heatwaves have dramatically escalated in both duration and severity. The cumulative intensity of European heatwaves has surged by over 50% in the recent decade. Recent studies have reported accelerating Arctic warming and associated mid-latitude circulation changes, while its summer impacts remain uncertain. Here we provide evidence that the recent summer changes in the Arctic play critical roles in the escalation of European heatwaves. The Arctic has experienced unprecedented regional changes in summer since 2010. The Barents-Kara Seas have warmed by 2.3°C per decade, while western Greenland has cooled by 0.6°C per decade. The temperature changes in these two regions influenced European weather through two different pathways: 1) Norwegian-Barents-Kara Sea warming weakened daily weather activities, thereby promoting persistently hot weather over Northeastern Europe; 2) western Greenland cooling shifted the North Atlantic jet poleward, which allowed easy invasion of subtropical and Saharan air to Southwestern Europe. Both pathways have emerged substantially since 2010, exacerbating heatwave risks in Europe. Climate model experiments establish the direct causal pathways from Arctic change to European heatwaves, demonstrating independent amplification of heatwave intensity by 59% and 27% over Northeastern and Southwestern Europe, respectively. Given the wide-ranging consequences of heatwaves on health, food, and energy, closer attention to the Arctic and subarctic oceans is required.

Main

Intensified heat extremes are direct consequence of climate change, with broad implications for human health[1–3], quality of life, economic productivity[4,5], and social costs for climate adaptation[6,7]. The World Health Organization estimates that climate change claims over 150,000 lives annually through heat-related mortality and diseases[1]. Current climate conditions already subject approximately 30% of the global population to potentially deadly heat for at least 20 days annually, with projections estimating that 74% of the population will be exposed by 2100[2]. European regions exhibit particularly pronounced intensification of heat extremes, with record-breaking heatwave events occurring every few years in recent decades[8–12]. Given their concentrated socioeconomic infrastructure, these regions face heightened vulnerability to heat extremes.

Warming climate has caused summer temperatures to increase worldwide, with Europe witnessing most pronounced effects of heatwaves (Fig. 1). This change in weather characteristics cannot be simply attributed to the rising mean temperature. Changes in circulation pattern can also be critical in generating more frequent and persistent heatwaves[9,13–15]. Notable examples include the 2010 western Russia heatwave, which is recognized as the most intense and long-lasting event (33 consecutive hot-and-dry days above 30°C) in historical record; and the successive northern Europe heatwaves of 2014 and 2018[9,12,16,17]. In 2024, Eastern Europe experienced 63 days of heatwave conditions throughout the boreal summer, accounting for approximately 70% of the entire season[18]. These frequent events demonstrate that European heatwaves are getting worse in terms of persistence and frequency. The

intensification far exceeds the IPCC multi-model mean projections accounting for historical forcing[19], suggesting that there are unresolved processes contributing to this observed intensification[20,21].

Recent studies have established a connection between Arctic warming and mid-latitude weather and climate extremes[20,22,23]. The baseline ideas are jet stream weakening and reduced poleward temperature gradient due to amplified Arctic warming[20,24–26], leading to decreased synoptic weather activity[27] and more persistent weather patterns[20]. Arctic warming has also been associated with the emergence of dipole-like atmospheric circulation patterns[20,28] that favor prolonged heat events. While those studies have primarily focused on the cold-season (autumn and winter) linkage between Arctic warming and mid-latitude weather[22,23,29], an analogous mechanism may also apply to summer months. Summer Arctic warming was historically considered weaker than the cold season warming because of the weak oceanic heat fluxes[30]. Consequently, it was assumed to have no significant impact on mid-latitude weather variance until 2014[31]. However, recent observations reveal unprecedented summer Arctic warming due to the extensive sea-ice loss[28,32,33] (Supplementary Fig. 1a-c) and Arctic Atlantification[34–36] (Supplementary Fig. 1d-f) over the last two decades. This accelerated warming could have activated physical processes imposing heat stress over Europe[27,28].

In this study, we examine recent summer Arctic changes to identify key factors and mechanisms influencing European heatwaves. Our results reveal that recent Arctic changes contribute to European heatwave intensification through two distinct mechanisms. First, cold and low-pressure anomalies over western Greenland shift the Atlantic jet poleward, facilitating the intrusion of hot subtropical air into western Europe. Second, warm and high-pressure anomalies over Barents-Kara Seas suppress synoptic eddy activity, promoting persistent hot extreme conditions over eastern Europe. The detailed features of the Arctic changes and physical evidence that links the Arctic changes to European heatwaves are further described in the following sections.

Recent state of European heatwaves

European heatwaves exhibited a gradual increase during recent decades. The observed cumulative intensity (see Heatwave identification in Methods) of heatwave (Fig. 1) reveals widespread intensification over the continent, with cumulative intensity increasing by 10–15°C (60–70%) per decade across most European regions (Fig. 1a and Supplementary Fig. 2). The probability density distribution revealed that European heatwave trends have shifted markedly toward higher values compared to other midlatitude regions (Fig. 1b), indicating the continent's particular vulnerability to extreme heat events. This intensification is mainly reflected in the number of heatwave days, with many cities experiencing increases exceeding 5 days (50%) per decade (Supplementary Fig. 2a, 3b). By contrast, the increase in heatwave intensity is moderate compared to the heatwave days (Supplementary Fig. 2c, 3c). Our inspection of decadal trend variations (Fig. 1c) demonstrates that the heatwave duration plays an

increasingly dominant role in recent decades. In particular, European heatwave events have increased markedly in duration across the continent since 2010.

We also investigated changes in heatwave persistence, which simply presents the mean duration of individual heatwave events. The heatwave persistence demonstrated a similar pattern of year-to-year changes as the heatwave cumulative intensity (Supplementary Fig. 4a). The probability density distribution of heatwave persistence revealed a marked shift after 2010 (Supplementary Fig. 4b, 4c). These results demonstrate a noticeable change in summer heatwave characteristics in recent decades, transitioning to more frequent and prolonged heatwaves across Europe. This growing dominance of duration over intensity[14,21] indicates a shift in European summer atmospheric circulation patterns.

Summer Arctic change as a potential cause

The recent dramatic heatwave changes in Europe are linked with the modification of broader atmospheric circulation. This includes a weakened mid-latitude jet stream[20,25] and shifts in Atlantic-European summer circulation patterns, including more frequent blocking anticyclones and altered storm track activity[37,38]. The Arctic has undergone unprecedented regional warming since 2010, with two distinct anomalous atmospheric patterns over the Norwegian-Barents-Kara Seas (NBK) and western Greenland. The NBK region experienced dramatic lower tropospheric warming of 2.3°C per decade, while western Greenland exhibited pronounced cooling of -0.64°C per decade since 2010 (Fig. 2a). The Greenland cooling appears also with the North Atlantic (NA) warming, forming a dipole structure. Such temperature changes in summer were not apparent in the preceding three decades (Supplementary Fig. 5). These changes project onto atmospheric pressure changes, with high pressure trends noted over the NBK region and low pressure trends centered over western Greenland[23] (Fig. 2a). The temperature and pressure timeseries clearly demonstrate this change after 2010, with both the regions showing a clear transitioning trends not previously recorded (Fig. 2b, c).

These Arctic temperature and pressure changes could affect mid-latitude circulation[20,23–27,29]. Regional changes in temperature gradients can modify atmospheric circulation patterns, including the jet stream and storm tracks, potentially increasing the frequency and persistence of conditions favorable for heat extremes. Detail mechanisms are described in following section.

Detailed physical mechanisms linking heatwaves

To elucidate the effects of Arctic changes on European heatwaves, we examined synoptic eddy (e.g., mid-latitude migratory cyclones and anticyclones) activity. These eddies evolve on time scales spanning a week with relatively fast eastward movement and cause day-to-day variability[27,39]. The weather variability provides continental-scale ventilation and heat relief, thereby inhibiting prolonged heatwaves.

Figure 3 presents regional trends of synoptic eddy activity during 2010–2024 in terms of upper tropospheric kinetic energy (Fig. 3a) and lower tropospheric heat flux (Fig. 3b). These parameters

indicated noticeable decrease in the activities over northern Eurasia but increase over the North Atlantic, aligning with the poleward temperature gradient changes (e.g. Supplementary Fig. 6). The longitudinal structure, averaged over mid-latitudes from 50°N to 70°N, clearly reveals these contrasting regional responses, with significant reductions in both metrics over western Eurasia (30°E-100°E) and enhancements over the Atlantic sector (60°W-0°). These contrasting changes lead to two different processes through which the Arctic change affects European heatwaves.

A. Stagnant weather pattern (Northeastern Europe): The declining synoptic cyclone activity (Fig. 3) and weak polar-front jet[25] (Supplementary Fig. 7b, 7f) over Eastern Europe have resulted in slower atmospheric flow and a reduction in weather variability over short time scales[27,40]. This weakening is clearly observed in surface temperature variation pattern over Eastern Europe after 2010 (Supplementary Fig. 8). This series of changes further indicates that poor atmospheric ventilation due to suppressed weather variability and persistent weather patterns would be frequent in this region. Our analysis reveals that the heatwave persistence is clearly anticorrelated with synoptic cyclone activity over Eastern Europe (Fig. 4a and 4b). This relationship supports the proposed physical mechanism linking the NBK warming to stagnant weather and prolonged heat extremes in Eastern Europe.

B. Enhanced subtropical influences (Southwestern Europe): The activity of the synoptic cyclone exhibits a more complex pattern in the North Atlantic, with decreased activity south of the polar-front jet (~ 40°N) and increased activity to the north (~ 60°N). This dipole pattern drives a northward shift of the Atlantic polar-front jet, resulting in a disconnection with the subtropical Eurasian jet (c.f. Supplementary Fig. 9a). This split jet structure, more commonly observed in the recent decade[25,26], promotes the northeastward expansion of an anomalous high over inland Europe[24,26] (Supplementary Fig. 9). The high-pressure conditions over Europe trap hot air, contributing to long-lasting heatwaves[21] (Fig. 4c and 4d). In addition, this condition facilitates the intrusion of hot and dry Saharan air into Southern Europe, aggravating heatwaves[41–43].

To verify the proposed mechanisms, we conducted sensitivity experiments using CESM2 with temperature nudging applied to the NBK and NA regions, using 50-member ensembles under present-day climatological conditions to isolate the atmospheric responses. The NBK experiment successfully reproduced the observed atmospheric circulation changes over Northern Eurasia, including weakened mid-tropospheric westerlies (Supplementary Fig. 10a, 10c) and reduced synoptic eddy activity (Supplementary Fig. 10e). The NA experiment captured the northward shift of the Atlantic jet stream (Supplementary Fig. 10b, 10d), consistent with the observed jet displacement and altered storm track patterns. These circulation responses closely matched the observed changes, confirming the proposed pathways linking regional Arctic warming to mid-latitude circulation modifications.

The simulated circulation changes led to substantial intensification of European heatwaves (Fig. 5). The NBK experiment enhanced heatwave cumulative intensity over Northeastern Europe by approximately 59%, while the NA experiment increased intensity over Southwestern Europe by 27%. The probability distributions reveal not only increased mean intensity but also broader tails toward extreme values,

indicating more frequent occurrence of severe heatwave events in both experiments. These results confirm that the observed Arctic temperature changes drive European heatwaves intensification through the proposed pathways.

These mechanisms may work synergistically to amplify their effects over Europe. One manifestation of these combined effects is the increased anticyclonic blocking frequency over Europe, particularly over western and central regions (Supplementary Fig. 11). Blocking is a typical representative of persistent weather that supports long-lasting heatwave events. While detailed interaction processes require in-depth research, the continued Arctic warming is likely worsening European heatwaves by allowing persistent high-pressure patterns.

Discussion and Summary

The linkage between the escalating European heatwaves and the summer Arctic changes has become increasingly apparent since 2010. The dramatic summer Arctic warming around the NBK region enhanced through local feedback processes[30,44]. The Norwegian Sea is experiencing ocean warming[34–36] that leads to increased heat and moisture contents in the lower atmosphere[45–47], strengthening downward longwave feedback (Supplementary Fig. 12). Concurrently, the high-pressure system over the Barents-Kara Sea suppresses cloud cover (Fig. 2a), allowing enhanced solar radiation (Supplementary Fig. 13). Surface energy budget analysis also reveals that downward longwave/shortwave radiation dominates Norwegian Sea/Barents-Kara Sea warming (Supplementary Fig. 14). Since 2010, these local radiative feedback processes have intensified markedly, suggesting that Arctic ocean is now actively contributing to the amplification of regional warming.

The western Greenland cooling (and NA warming) is likely associated with the recent North Atlantic SST changes, which shows a similar dipole structure (Supplementary Fig. 15). Since 2010, a pronounced SST dipole has emerged across the North Atlantic, characterized by continued warming over the midlatitude basin and concurrent cooling over the subpolar gyre south of Greenland (Supplementary Fig. 15a, 15b). This intensified meridional SST gradient could be projected to low-troposphere temperature[48,49], causing the northward shift of the polar-front jet (Supplementary Fig. 15c, 15d). Yet, the recent cooling over western Greenland may partly be induced by remote teleconnection from tropical ocean[50–52]. A recent study suggested that the Greenland cooling is caused by the teleconnection pattern originated from the warming of eastern subtropical Pacific[52], while the remote influences are relatively uncertain, as they could be modulated by inter-decadal climate variability or even natural variability.

Regardless of the cause of the Arctic changes, the dynamical linkage between the Arctic changes and European heatwaves is quite robust. In summary, the accelerated Arctic changes are now causing substantial weather impacts across Europe and neighboring regions in summer through two different atmospheric pathways: Norwegian-Barents-Kara Sea warming weakens synoptic activity over northern Eurasia, which contribute to more stagnant weather patterns in Northeastern Europe; The western Greenland cooling (along with North Atlantic warming) cause northward shift of the Atlantic jet, which

allows intrusion of hot subtropical and Saharan air into Southwestern Europe. These compounding mechanisms are expected to aggravate heat stress across Europe. The weakening of synoptic eddy activity over northern Eurasia could be persistent because of the ongoing Arctic sea ice loss[53], whereas the northward shift of the Atlantic jet could persist for years to a decade, though its underlying mechanisms remain uncertain as they are related to inter-decadal natural variability. Enhanced Arctic monitoring will be beneficial for projection and mitigation of summertime heatwaves in Europe.

Declarations

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Author contributions

E.N. and J.K. conceived and designed the study. E.N. conducted the observational and reanalysis data analyses, performed the climate model experiments, and created the figures. S.-Y.J., M.M., and J.-H.K. provided technical advice on model experiment design and implementation. Y.K., S.-W.Y., S.-W.S., B.-M.K., D.C., W.M. and K.K. contributed to the interpretation of results and development of key scientific insights through extensive discussions. E.N. and J.K. wrote the manuscript with contributions from all co-authors. All authors discussed the results and commented on the manuscript.

Competing interests

Additional information

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Methods

Data

The observed station data were obtained from the Met Office Hadley Centre Integrated Surface Database[54,55] (HadISD). HadISD is a global sub-daily dataset based on the ISD dataset from NOAA's NCEI (National Centers for Environmental Information, https://www.ncei.noaa.gov/), providing quality-controlled hourly surface meteorological observations from approximately 8,000 stations worldwide. We applied stringent quality control criteria to ensure data reliability: maximum temperature analysis required stations with at least 8 observations per day (3-hourly data), while average temperature calculations used stations with a minimum of 4 observations per day (6-hourly data). Stations with data gaps exceeding 10% during summer months (June-August) were excluded from the analysis.

We also employed the European Centre for Medium-Range Weather Forecasts Reanalysis version 5[56] (ERA5) dataset, regridded to a 1.5×1.5° longitude/latitude grid. ERA5 provides comprehensive atmospheric variables, including geopotential height, specific humidity, air temperature, and radiation components at multiple pressure levels with hourly temporal resolution. For Arctic Sea ice and sea surface temperature analysis, we employed the Hadley Centre Sea Ice and Sea Surface Temperature dataset[57] (HadISST). All reanalysis datasets were processed at daily intervals to match the observational temporal resolution and facilitate consistent comparison across data sources. We limited our analysis to the satellite-covered period (1979–2024) to minimize the effects of changes in the observing system and ensure temporal consistency.

Heatwave identification

We applied the T_{max} heatwave definition following Perkins and Alexander (2013)[58], which identifies heatwave events when daily maximum temperature exceeds the 90th percentile threshold for at least three consecutive days. The 90th percentile thresholds were calculated using a 15-day centered window for each calendar day based on the 1981–2010 reference period. This approach accounted for the seasonal cycle while maintaining statistical robustness across different climatic regions.

Heatwave characteristics were quantified using multiple metrics: (1) heatwave duration (total length of heatwave events in days), (2) heatwave intensity (average temperature excess above the threshold during heatwave days), and (3) cumulative heatwave intensity (sum of daily temperature exceedances above the threshold for all heatwave days in a year). Furthermore, we calculated heatwave persistence as the ratio of total heatwave days to the number of heatwave events per year, effectively capturing the tendency for individual events to become longer-lasting. All heatwave metrics were computed for the summer season (June-August) when European heatwaves reach their peak intensity and societal impact.

Activity of synoptic eddy

We computed the synoptic-scale eddy activity by applying a 10-day high-pass filter to 6-hourly ERA5 data[39,59]. To isolate changes in eddy activity from those caused by latitudinal shifts in zonal winds (jet

streams), we examined v'^2 (meridional wind variance) representing baroclinic wave activity and $v'T'$ (meridional eddy heat flux) indicating baroclinic wave energy sources[39,60].

Model experiments

To isolate the causal impacts of regional Arctic temperature changes on European heatwaves, we conducted targeted sensitivity experiments using the Community Earth System Model version 2 (CESM2). The experiments were performed in atmosphere-only mode with prescribed sea surface temperatures based on observed climatology. We first performed 50 equilibrium climate simulations under present-day climate conditions, which served as our ensemble control runs. Building on this ensemble, we conducted two sets of sensitivity experiments by applying temperature nudging to specific regions: (1) the Barents-Kara Sea (BKS) warming experiment and (2) the North Atlantic (NA) dipole change experiment.

The nudging technique constrains model temperature toward prescribed target values while allowing other atmospheric variables to respond dynamically. The temperature nudging follows the CAM6 implementation based on a relaxation tendency:

$$F_{nudge} = \frac{\alpha}{\Delta t_{nudge}} (T_{target} - T_{model})$$

where T_{target} and T_{model} are the target and current model temperatures, respectively, α is a normalized strength coefficient ($0 \leq \alpha \leq 1$), and Δt_{nudge} is the relaxation timescale. For each sensitivity experiment, we applied the observed 2010-2024 temperature changes (15-year trends shown in Fig. 2) as the nudging target. We set Δt_{nudge}= 5 days to allow sufficient time for synoptic-scale atmospheric variability to respond to the imposed temperature changes while maintaining the regional temperature anomalies. This relatively weak nudging strength was deliberately chosen to examine changes in synoptic eddy activity and associated circulation patterns rather than imposing overly rigid constraints. Each sensitivity experiment consisted of 50 ensemble members corresponding to the 50 control runs, enabling robust statistical comparison of regional climate responses.

Data availability

The ERA5[56] data used in this article are freely available from the Copernicus Climate Data Store (CDS) at https://cds.climate.copernicus.eu/cdsapp#/dataset/reanalysis-era5-single-levels. The HadISD[54,55] dataset is available from the Met Office Hadley Centre observations datasets at https://www.metoffice.gov.uk/hadobs/hadisd/index.html. The HadISST[57] dataset is available at https://www.metoffice.gov.uk/hadobs/hadisst/.

Methods References

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Figures

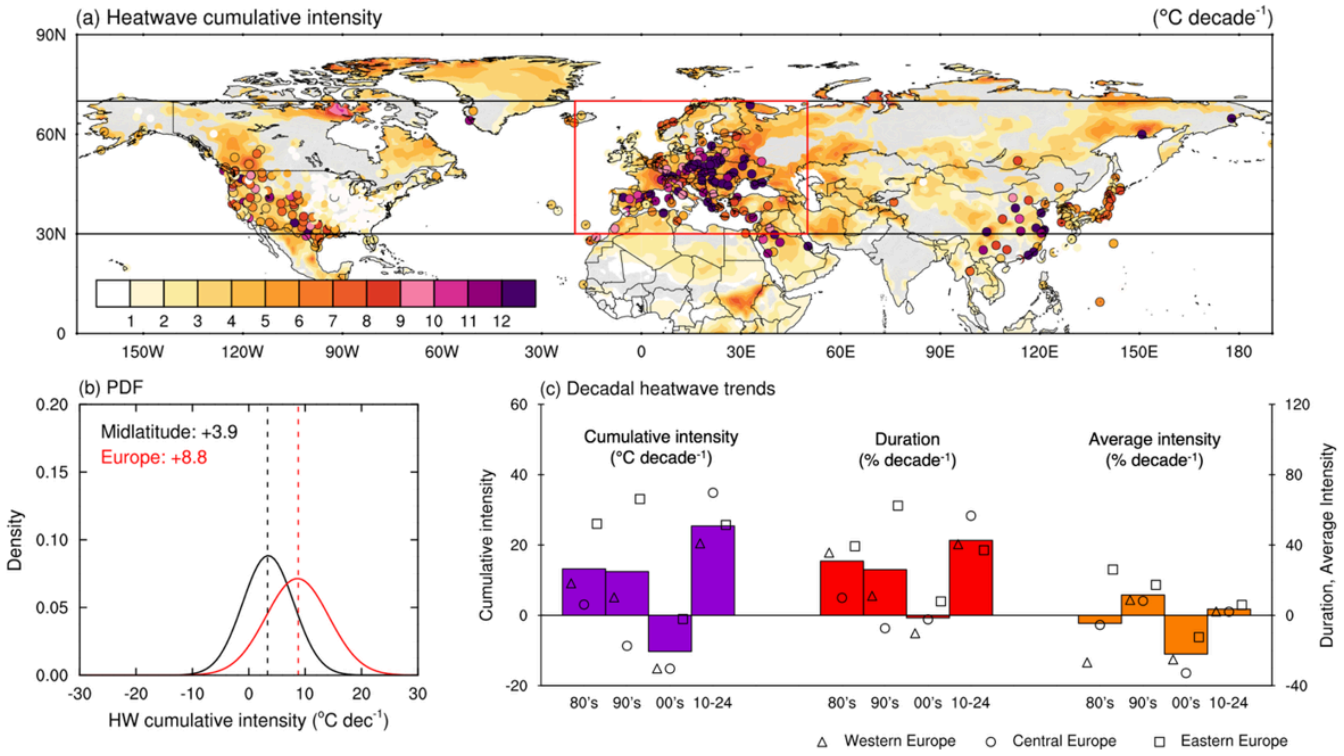


Figure 1

Trends and characteristics of European summer heatwaves

Spatial distribution of decadal trends from 1979 to 2024 in (a) heatwave cumulative intensity (°C decade^{-1}) during boreal summer (June–August). Shading represents trends derived from ERA5 reanalysis, with gray masking indicating regions where trends are not statistically significant at the $p = 0.05$ level. Colored circles represent trends from HadISD observation stations, with the black outlines denoting $p < 0.05$. (b) Probability distribution function of decadal trend of heatwave cumulative intensity of all observation stations for Europe (in red, as the region included in red box of a) and the midlatitude lands excluding Europe (in black). (c) Regional comparison of decadal heatwave trends across European subregions for different decades (1980s, 1990s, 2000s, 2010–24). Left: cumulative intensity trends (°C decade⁻¹), middle: duration trends (% decade⁻¹), and right: average intensity trends (% decade⁻¹). The different symbols represent western Europe (triangle), central Europe (circle), and eastern Europe (square).

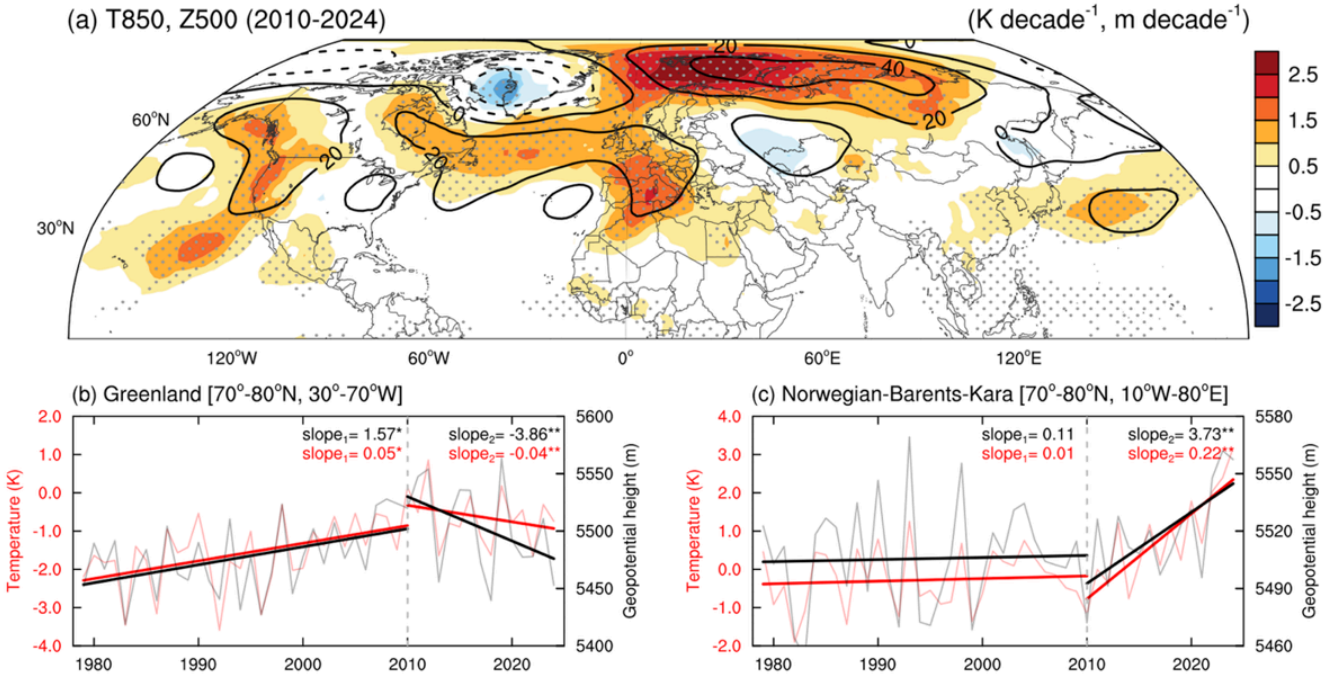


Figure 2

Recent summer Arctic changes

(a) Spatial distributions of decadal trends during boreal summer (June–August) in 850-hPa temperature (shading, K decade⁻¹) and 500-hPa geopotential height (contour, m decade⁻¹, 20-m intervals) for 2010–2024. (b, c) Time series of 850-hPa temperature (red line, left axis) and 500-hPa geopotential height (black line, right axis) averaged over (b) western Greenland [70°-80°N, 30°-70°W] and the (c) Norwegian-Barents-Kara Sea [70°-80°N, 10°W-80°E], respectively. Translucent lines indicate annual values; thick lines denote segmented linear trends, highlighting changes in slope across different periods.

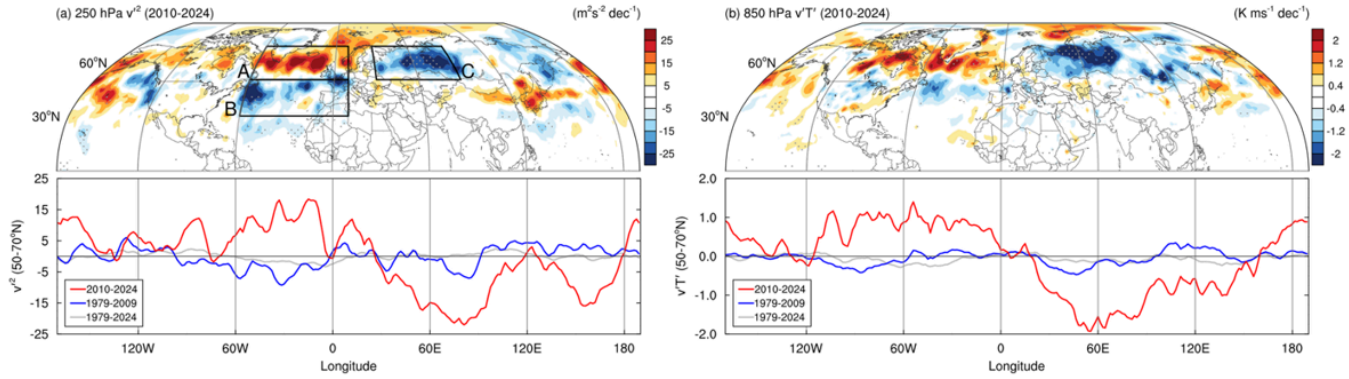


Figure 3

Synoptic eddy activity changes in response to Arctic changes

Decadal trends during boreal summer (June–August) from 2010–2024 in (a) 250-hPa meridional wind variance (v'^2, m² s⁻² decade⁻¹) and (b) 850-hPa heat flux ($v'T'$, K m s⁻¹ decade⁻¹) associated with synoptic eddies. Gray dots indicate regions where trends are statistically significant at $p < 0.05$. The bottom panel indicates the longitudinal distributions of decadal trend in v'^2 and $v'T'$ averaged over midlatitudes (50°–70°N) for three time periods: 1979–2024 (black), 1979–2009 (blue), and 2010–2024 (red).

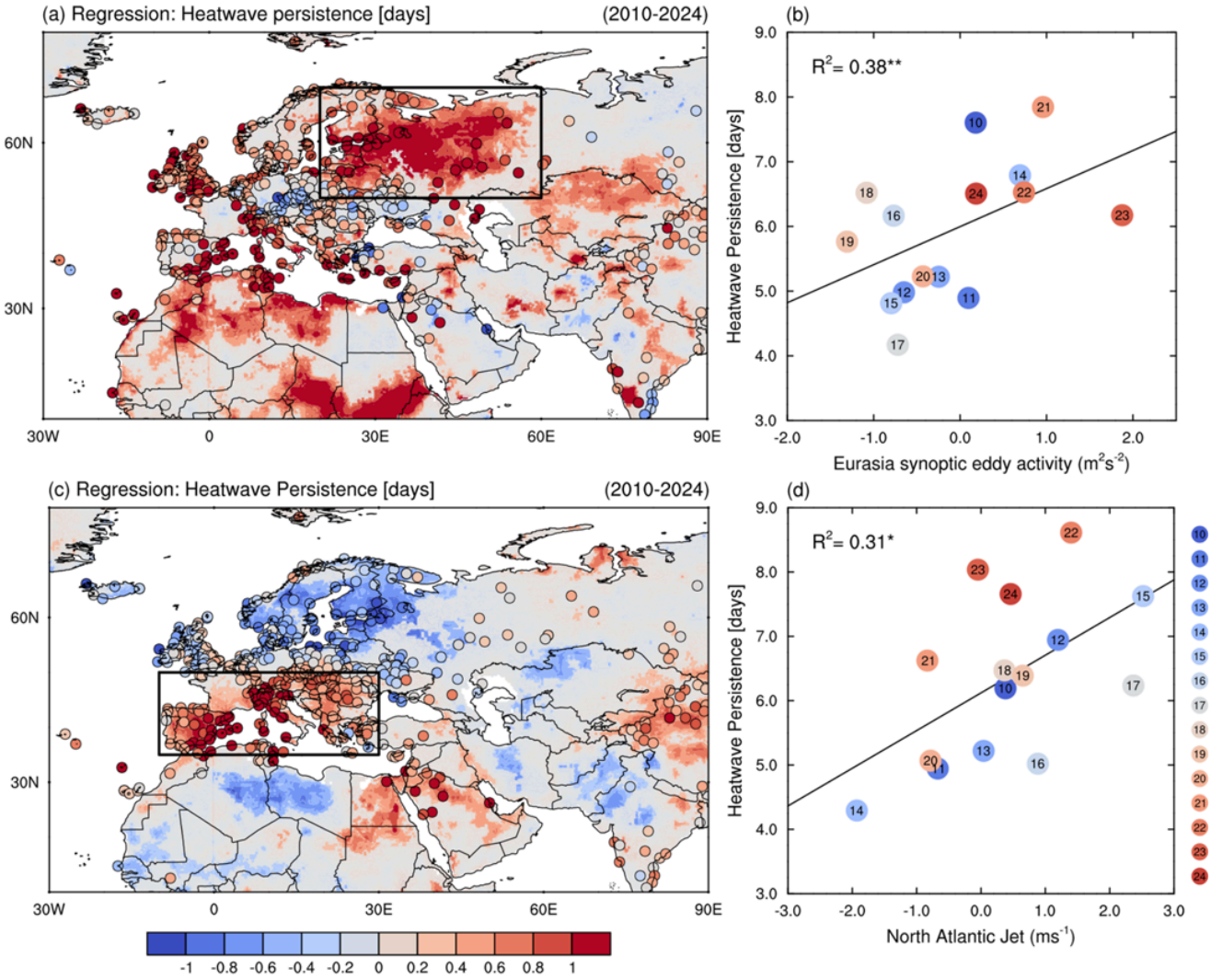


Figure 4

Heatwave persistence related to circulation changes

(a, c) Spatial patterns of heatwave persistence (days) regressed onto (a) the negative standardized time series of Eurasia synoptic eddy activity [region C in Fig. 3a; C (50-70°N, 30-60°E)] and (c) the North

Atlantic jet shift index, calculated as the difference in zonal wind between North and South regions [region A and B in Fig. 3a; A (50-70°N, 60°W-10°), B (30-50°N, 60°W-10°)]. Gray areas indicate regions where regression coefficients are not statistically significant at p = 0.05 level. (b, d) Scatter plots showing the relationship of European heatwave persistence with (b) Eurasia synoptic eddy activity, and (d) North Atlantic jet index, respectively. Colored dots represent values observational station data (HadISD) averaged over the black box regions shown in panels (a) and (c). Correlation coefficients (R^2) and statistical significance levels are indicated in the upper left of each scatter plot, where a single and double asterisks denote significance at $p < 0.05$ and $p< 0.01$, respectively. Numbers represent individual years from 2010 (labeled as 10) to 2024 (labeled as 24).

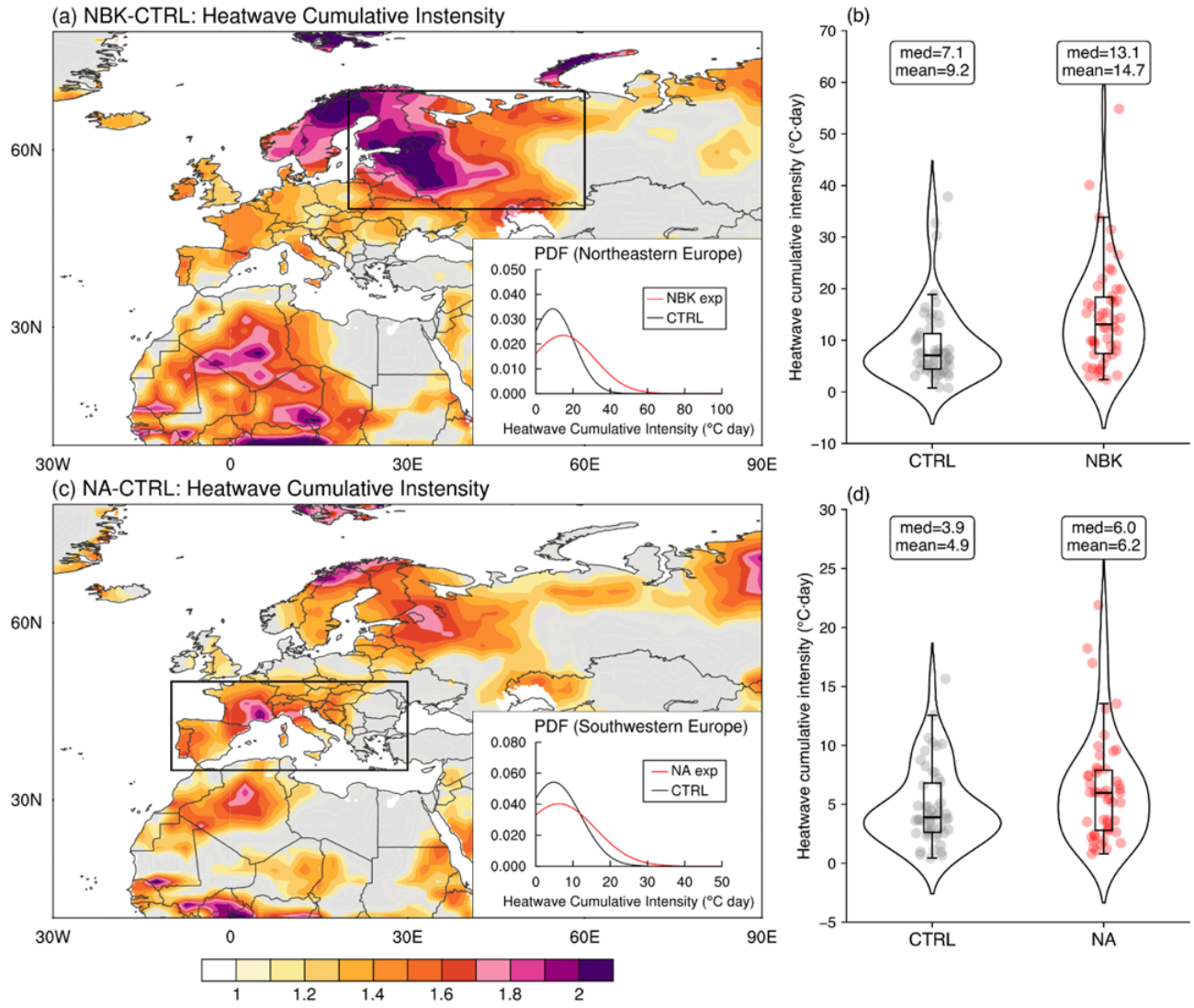


Figure 5

Response of European heatwave to recent Arctic changes

(a, c) Ensemble mean (50 members) ratio of heatwave cumulative intensity between control run and sensitivity experiments for (a) Norwegian-Barents-Kara Sea warming experiment and (c) North Atlantic

dipole experiment. Insets show probability density functions (PDFs) of heatwave cumulative intensity (°C·day) over the black box regions for the sensitivity experiments (red) and control run (black). (b, d) Violin plots showing the distribution of heatwave cumulative intensity (°C·day) averaged over the black box regions in (a) and (c), representing (b) Northeastern Europe and (d) Southwestern Europe. The violin shape represents the probability density distribution, individual dots show each of the 50 ensemble members (gray for CTRL, red for BKS/NA experiments), and the box plot inside indicates the median (center line), interquartile range (box edges, 25th-75th percentile), and whiskers (10th-90th percentile).

Supplementary Files

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