

<https://doi.org/10.1038/s41612-024-00611-7>

# From peak to plummet: impending decline of the warm Arctic-cold continents phenomenon

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Yungi Hong<sup>1</sup>, S.-Y. Simon Wang<sup>2</sup>, Seok-Woo Son<sup>3</sup>, Jee-Hoon Jeong<sup>4</sup>, Sang-Woo Kim<sup>3</sup>, Baekmin Kim<sup>5</sup>, Hyungjun Kim<sup>6</sup> & Jin-Ho Yoon<sup>1</sup>✉

This study assesses the projected trajectory of Warm Arctic-Cold Continent (WACC) events in East Asia and North America through large ensemble simulation for the upcoming decades. It analyses the evolution of the geographical boundaries of threshold cold temperatures, revealing a significant northward shift as a sign of global warming's impact on the southward advancement of Arctic cold air. While validating the intensification of the WACC phenomenon until the 2020s, echoing earlier studies, the findings indicate a marked decrease beginning in the 2030s. If warming is not curbed, this shift suggests a critical modification in the WACC pattern, prompting a re-evaluation of existing theories and models for extreme winter weather events. The results have major implications, spurring communities impacted by WACC to anticipate future changes and encouraging the climate forecasting community to update conceptual models for improved adaptation and mitigation approaches.

Over the past decades, the puzzling juxtaposition of increasing global temperatures with anomalous cold winters and associated cold extremes in specific mid-latitude regions has captured much attention of climate scientists. This anomaly, encapsulated within the Warm Arctic-Cold Continents (WACC) paradigm, has sparked rigorous debate on the influence of Arctic warming on mid-latitude weather patterns. As the Arctic experiences rapid sea-ice decline, particularly in regions like the Barents-Kara seas, speculations have arisen suggesting a potential link between this decline and the severe winters witnessed in parts of East Asia and North America<sup>1-7</sup>. A recent review of the comprehensive dynamics of early 21st-century East Asia cooling highlights the balance between thermodynamic and dynamic processes in shaping this phenomenon<sup>8</sup>. While the dynamics, primarily driven by internal variability and to a lesser extent by sea ice, contribute to East Asia cooling, sea-ice retreat induces warming that can offset the cooling<sup>8</sup>.

Despite the prevailing arguments and evidence from the previous decade, closer scrutiny of evolving climatic data presents an intriguing proposition: as time progresses and warming intensifies, the WACC phenomenon might begin to wane and eventually dissipate<sup>9,10</sup>. The association

between Arctic sea-ice decline and its cascading impacts on mid-latitude weather is neither linear nor uniform<sup>1,11,12</sup>. Distinct influences have been reported for regions like East Asia and North America, indicating the multifaceted nature of the Arctic's role in global weather dynamics in the warmer climate<sup>3,9,13</sup>. Some studies have even proposed that the continued loss of Arctic Sea ice may reduce the risk of North American cold extremes<sup>10</sup>. Given this complex tapestry of findings, a pressing question emerges: Is the WACC paradigm a transient phenomenon, and if so, when might we expect a shift in its influence? The goal of this research is to elucidate this intricate connection and explore the potential timeline of the WACC's changing influence on global weather patterns.

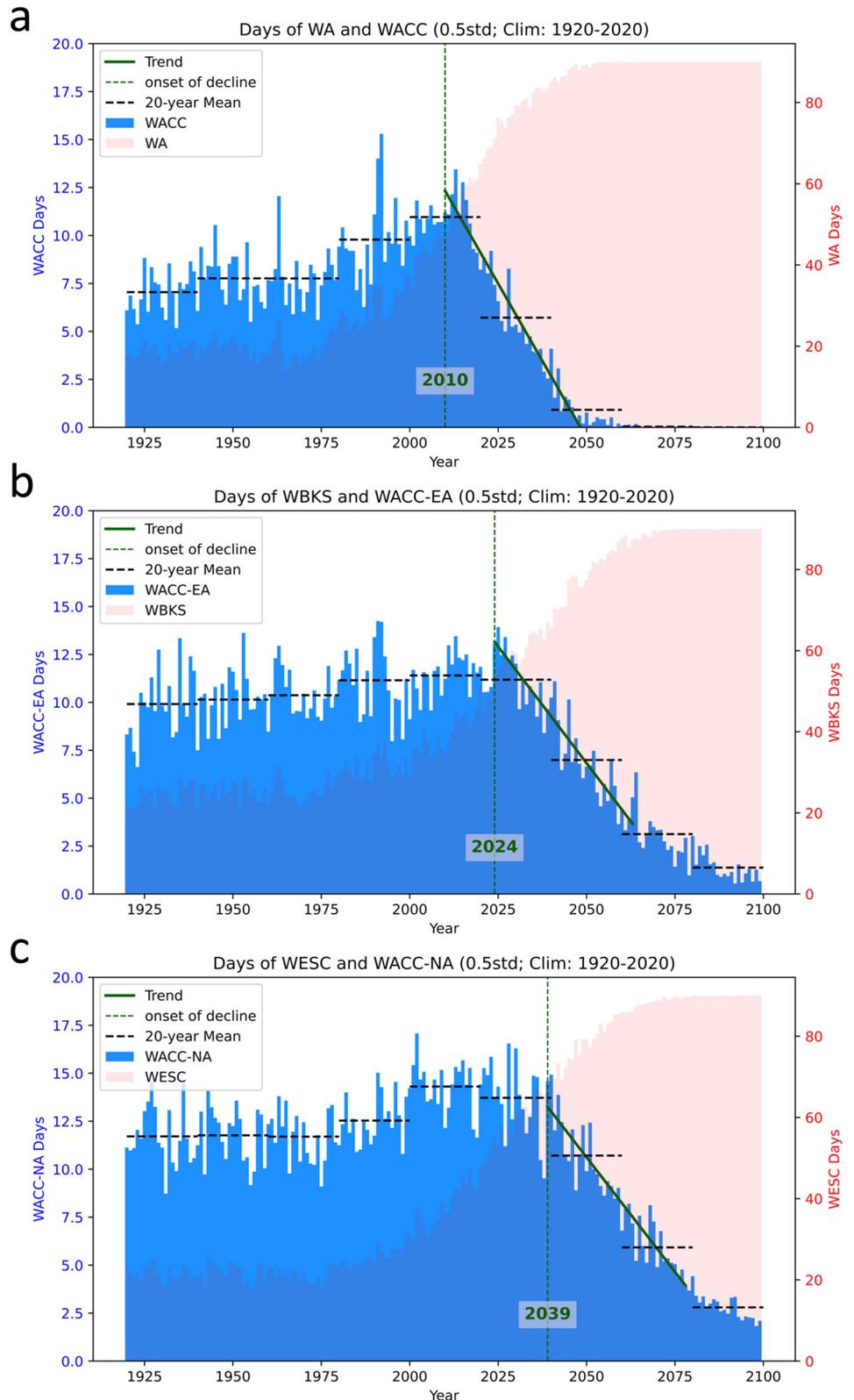
## Results

We employed the CESM1 large ensemble dataset for our analysis, encompassing 40 ensemble members under the aggressive RCP8.5 emission scenario. Warm and cold days were identified based on deviations exceeding or falling below the climatological mean by  $\pm 0.5$  standard deviations, respectively, as was defined by Hong et al.<sup>14</sup> (see "Methods" section). Figure 1a displays the number of warm Arctic (WA) and WACC days, which

<sup>1</sup>School of Earth Sciences and Environmental Engineering, Gwangju Institute of Science and Technology, Gwangju, South Korea. <sup>2</sup>Department of Plants, Soils, and Climate, Utah State University, Logan, UT, USA. <sup>3</sup>School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea. <sup>4</sup>Faculty of Earth and Environmental Sciences, Chonnam National University, Gwangju, South Korea. <sup>5</sup>Department of Environmental Atmospheric Sciences, Pukyong National University, Busan, South Korea. <sup>6</sup>Moon Soul Graduate School of Future Strategy, Korea Advanced Institute of Science and Technology, Daejeon, South Korea.

✉e-mail: [yjinho@gist.ac.kr](mailto:yjinho@gist.ac.kr)

**Fig. 1 | Number of days per winter from 1920 to 2100. a** displays Warm Arctic (WA) and Warm Arctic Cold Continent (WACC). The left and right axes indicate the number of WACC and WA days, respectively. Similar to a–c display warm Barents-Kara Sea (WBKS) and WACC-EA, and warm East Siberian Chukchi Sea (WESC) and WACC-NA, respectively. The green line and text show the linear trend and the year of decline onset.



combine both East Asia (EA) and North America (NA), measured each winter from 1920 to 2100. These days are identified across all members and then averaged. Up until 2020, WACC days consistently increased almost in sync with the Arctic warming trend, an uptrend that aligns with the observations (Supplementary Figs. 1 and 2). However, the WACC days show a rapid and permanent decline afterward.

To quantify the extent to which the plummeting WACC events start and last, we conducted an analysis to determine the timing of a decline in WACC frequency. For each year, we computed a subsequent 40-year trend. The year that showed the most pronounced negative linear trend was identified as the onset of the WACC frequency decline. This trend, confirmed across various ensembles, is depicted by the green line in Fig. 1a,

indicating a sharp decline in WACC events after 2010, following immediately their recent peak. Cohen et al.<sup>2</sup> highlighted that as the Arctic transitions from a relatively cold state to a warmer one, the frequency of severe winter weather in mid-latitudes increases, especially in the eastern US. Similarly, Kim et al.<sup>15</sup> noted that significant Arctic sea-ice losses, particularly over the Barents–Kara seas, enhanced planetary-scale wave propagation that initiated a predominantly negative Arctic Oscillation phase, intensifying WACC occurrences. The post-2000 peak of WACC agrees with recent findings.

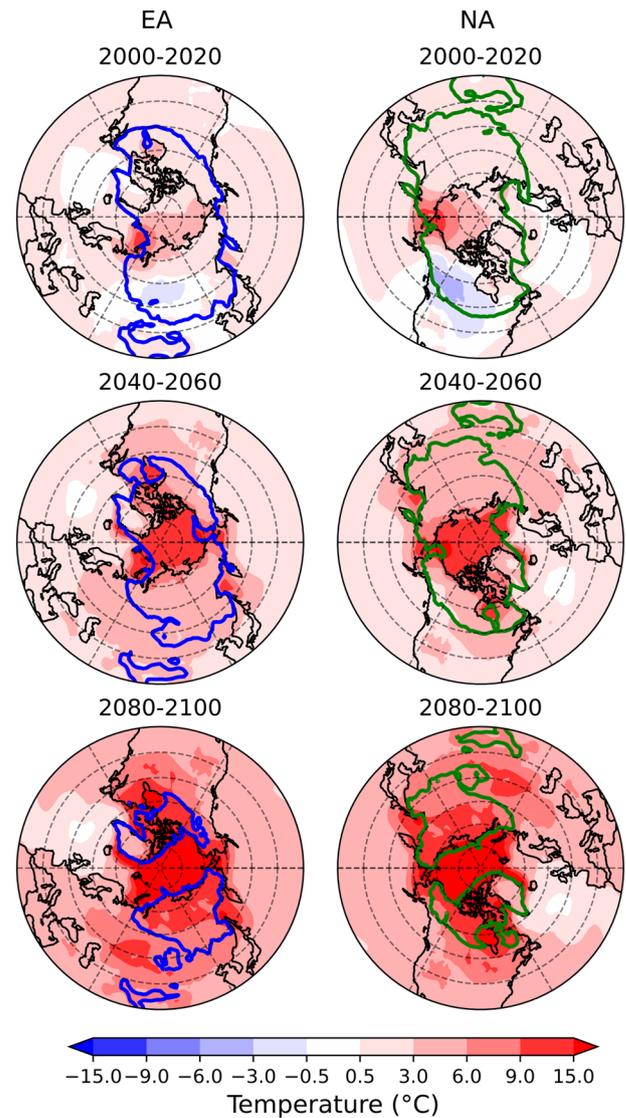
To examine further, we repeat the analysis separately for East Asia (EA) and North America (NA). Figure 1b illustrates the number of WACC-EA days, revealing a prolonged consistency in WACC frequency from 1920 to 2040. Nevertheless, a swift decline is evident in the period after 2024, where the declining trend of 40 consecutive years becomes significant. Similarly, Fig. 1c presents the number of WACC-NA days, in which a persistent decline starts in 2039. Furthermore, the duration and intensity of WACC, as well as those of WACC-EA and WACC-NA, are also projected to decline in the future (figures not shown). Throughout all periods, the frequency of WACC events is higher in NA than in EA, while the 2000–2020 period generally marks the peak frequency of all WACC events. The different timing of the declining trends between EA and NA (i.e., 2024 versus 2039) implies that, as global warming continues, the teleconnection between warm Arctic and cold continent may become inconsequential<sup>14</sup>. Whereas in the RCP4.5 scenario, the WACC phenomenon in recent years has persisted further into the future (figures not shown). This also highlights the sensitivity of the WACC trend to different emission scenarios and underscores the importance of considering a range of potential future greenhouse gas concentrations in our analyses. Nevertheless, the decline in the frequency of the extreme projection of global warming suggests that human-induced climate warming, by initiating the WACC effect in the mid-latitudes, can eventually offset this effect if left unchecked.

In light of the projected decline in WACC event frequency (Fig. 1), we conducted an analysis of the evolving temperature patterns for the warm Barents–Kara Sea (WBKS) and warm East Siberian Chukchi Sea (WESC) to track the changing geographical extent of the advancing cold air intrusion over time. Figure 2 illustrates the composite of temperature anomalies for WBKS and WESC events. In the early 21st century, both events display Arctic warming coupled with mid-latitude cooling. By the mid-21st century, the Arctic as a whole experienced accelerated warming, outpacing other regions. Heading into the late 21<sup>st</sup> century, the mid-latitudes would experience notable warming. Yet, there is a critical shift observed: the threshold lines of WACC for both East Asia and North America are seen to move northward. Specifically, the EA threshold line transitions from 40°N to 50°N, and the NA threshold line advances northward by approximately 5–10°N compared to the period of 2000–2020. This pronounced northward shift is a critical indicator that global warming is constraining the southward expansion of “cold air” in today’s definition, thereby mitigating the coldness associated with WA, a tendency that is projected to start emerging as soon as 2040. The perplexing trend where WACC initially rises and then sharply declines might be due to winter warming trends on both continents, pushing temperature thresholds northward.

One may argue that the methodology defining WACC would impact the rate and timing of the decline. To validate this point, we experimented with different criteria for the base period (e.g., 1920–1970 vs. 1970–2020) and the threshold temperature (e.g., mean ± 0.5std vs. mean ± 1.0std). While the number of days does change, the timing and rate of decline do not exhibit substantial differences, i.e. within ±5 years. Nonetheless, we call for further analysis to incorporate different definitions of WACC to offer insights.

## Discussion

The intriguing findings from this research have elucidated a significant evolution in the WACC phenomenon: a pronounced increase from the 1990s to the present, which echoes a wealth of recent research, but the narrative takes a dramatic turn as projections indicate that a sharp decline in



**Fig. 2 | Near-surface temperature anomaly map.** The left column displays the WBKS, while the right column displays the WESC. The thick blue and green lines denote the threshold of temperature mean for cold events:  $-15.73^{\circ}\text{C}$  for WACC-EA and  $-13.36^{\circ}\text{C}$  for WACC-NA.

the WACC pattern is anticipated around the 2030 s (Fig. 1). This anticipated paradigm shift, characterized by a tangible cessation in the historically observed trend, necessitates a recalibration in how we perceive the future of the WACC events. In other words, the WACC phenomenon as we know it could start to dissipate or have significantly less impact on climate after the mid-21st century.

Although the CESM1 model provides valuable insights, extending this analysis to multiple climate models could refine the predicted timeline and offer a more comprehensive understanding of the impending shift in WACC patterns. While WACC has been associated with human activities in past studies, the majority view is that WACC is also significantly influenced by internal climate variability<sup>1,16,17</sup>. Therefore, reducing the bias of internal variability between observations and the model will be a necessary future task to establish a more precise prediction of the WACC timeline. In this study, the noise from internal variability is eliminated by averaging over large ensembles and suggest that, as future warming escalates, cold days over the mid-latitudes would decrease leading to a reduction or even disappearance of WACC days. Nevertheless, further model experiments and different sets of analyses would be essential to comprehensively evaluate the

WACC timeline. Moreover, the definition of the WACC phenomenon, typically based on temperature trends or extreme<sup>1,17</sup>, is highly sensitive to the chosen climatological period. Hence, adopting different definitions of WACC could provide a more quantitative assessment of the phenomenon.

As the imminent change in the WACC trajectory looms closer, taking cognizance of its dynamics becomes essential for both societal adaptation and for the continuous refinement of global climate strategies. On one hand, they underscore the necessity for society at large, especially regions historically impacted by the WACC, to recognize and prepare for a shift in extreme winter weather occurrences. On the other hand, it becomes paramount for the climate forecasting community to realign their predictions in light of this emergent understanding. Adjusted climate predictions can lead to more targeted and efficient adaptation and mitigation strategies.

## Methods

### CESM1 Large Ensemble Community Project (LENS)

This study utilized data from the Community Earth System Model Large Ensemble Project (CESM1 LENS). All simulations were conducted using the 1-degree latitude/longitude version of the CESM1 with CAM5.2 as its atmospheric component. The project includes a 40-member ensemble of fully coupled simulations spanning 1920 to 2100, with each member subjected to identical radiative forcing scenarios (historical up to 2005 and RCP8.5 post-2005) but starting from slightly divergent atmospheric conditions achieved by minimal temperature perturbations. Detailed information about these simulations and their configurations can be found in Kay et al.<sup>18</sup>.

### Defining warm/cold frequency and identifying onset of declines

In this study, we defined six geographical regions: the Arctic (0°–360°E, 70°–90°N), mid-latitude (0°–360°E, 40°–60°N), Barents-Kara Sea (BKS; 30°–70°E, 70°–80°N), East Asia (EA; 80°–130°E, 35°–50°N), East Siberian Chukchi Sea (ESC; 160°–200°E, 65°–80°N), and North America (NA; 240°–280°E, 40°–55°N). The climatology period is set from 1920 to 2020, with anomalies calculated by subtracting the period's mean from the data. Warm and cold days were identified based on deviations exceeding or falling below the climatological mean by  $\pm 0.5$  standard deviations, respectively, as was defined by Hong et al.<sup>14</sup>, with a modification from their original use of 1.0 standard deviation. Thus, we defined the threshold line as the temperature equal to the climatological mean  $-0.5$  standard deviation in each region. The threshold lines for East Asia (EA) and NA are set at  $-15.73$  °C and  $-13.36$  °C, respectively. WACC is defined as the day when the Arctic overs the climatological mean by  $+0.5$  standard deviation and mid-latitude below the climatological mean by  $-0.5$  standard deviation (Supplementary Fig. 3). Same way, WACC-EA is defined as the concurrent warm conditions in the BKS region and cold conditions in East Asia, while WACC-NA describes the simultaneous warm conditions in the ESC and colder conditions in North America.

To determine the onset of a significant decline in WACC, WACC-EA, and WACC-NA, we conducted a 40-year linear regression analysis for each year from 1920 to 2060. For each window, the linear regression modeled the frequency trend over time, with a negative slope of the regression line indicating a decline in frequency over that period. For the significance test, we employed the Student's  $t$  test. This test was used to determine if the slope of the regression line was significantly different from zero. We identified the year with the most pronounced negative linear trend that met the  $p < 0.01$  level of significance as the beginning of the decline. This process was executed for all ensembles, and the mean of the year marking the beginning of the decline represents the robust onset year of the WACC frequency decline.

### Data availability

The meteorological data is retrieved from the ERA-interim by the European Center for Medium-Range Weather Forecast (ECMWF) at <http://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim/>. The CESM1 LENS is available at <http://earthsystemgrid.org>. Derived data

supporting the findings of this study are available from the corresponding author upon reasonable request.

### Code availability

The source codes for the analysis of this study are available from the corresponding author upon reasonable request.

Received: 29 November 2023; Accepted: 27 February 2024;

Published online: 11 March 2024

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## Acknowledgements

This research is funded by the National Research Foundation of Korea (NRF-2021R1A2C1011827, NRF-2020M1A5A1110578, and 2021H1D3A2A03097768). And SYSW acknowledges funding from the U.S. Department of Energy Award Number DE-686 SC0016605, and NSF P2C2 award number 1903721.

## Author contributions

Yungi Hong: investigation, visualization, analysis, writing-original draft, reviewing, and editing. Shih-Yu (Simon) Wang: conceptualization, writing, reviewing, editing, and supervision. Seok-Woo Son: methodology, writing, reviewing, and editing. Jee-Hoon Jeong: writing, reviewing, and editing. Sang-Woo Kim: writing, reviewing, and editing. Baekmin Kim: writing, reviewing, and editing. Hyungjun Kim: data, writing, reviewing, and editing. Jin-Ho Yoon: conceptualization, investigation, writing, reviewing, editing, supervision, and funding acquisition.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41612-024-00611-7>.

**Correspondence** and requests for materials should be addressed to Jin-Ho Yoon.

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