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A stretched Polar Vortex and North American and Eastern Asian Cold-Air Events during January/February 2025

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Abstract

During mid-January through February 2025 the low-level stratospheric polar vortex (LSPV) at 100 mb extended from North America across the pole to east-central Asia, a stretched pattern, coinciding with a period of extended cold weather on both continents. The LSPV, and its associated tropospheric blocking projections, were a main organizing feature. Weather events were mostly contained in the tropospheric west-east wave guide. For the United States (US), cold conditions occurred in a corridor that includes Illinois, through Mississippi and Virginia. During the second half of January, a 500 mb ridge-trough was set up off the west coast of California, driving cold temperatures into the southeastern US, with record snow in New Orleans. During early February there were cold events in Korea and Eastern Asia; an intermediate timing between cold air outbreaks in the US. The end of February saw a second US cold air outbreak. Although the stretched LSPV at 100 mb had a one and a half month duration extending over the subarctic, mid-tropospheric weather events were of shorter duration in both the US and Eastern Asia. The troughing at 100 mb in the stretched LSPV pattern coincided with event-based barotropic atmospheric troughing response at lower levels. Tropospheric weather events can coexist with the LSPV and thus contribute to sub-seasonal forecasting.

1. Introduction

The relation of the lower stratospheric polar vortex (LSPV) at 100 mb to tropospheric weather patterns is an important issue as it relates to extreme weather features such as heatwaves and cold air outbreaks (CAO) [1]. While hemispheric, seasonal-mean temperatures are rising, the United States (US) and other regions of the Northern

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Hemisphere continue to experience intermittent episodes of extreme cold winter weather [2,3]. The recent January and February 2025 are a case in point. For example, the US presidential inauguration on 20 January had to be moved indoors due to cold weather with snow reaching much of the southeastern US.

The occurrence of wintertime cold spells in the midlatitudes is driven by a complex interplay of atmospheric processes, spanning both local and remote influences [4]. Extensive research has examined the impact of various factors, including modes of climate variability [5–7], planetary wave activity [8,9], and large-scale weather regimes that operate on regional to continental scales [1,10,11]. Broad meteorological patterns have been recognized for their role in shaping extreme winter weather events [12–14]. Beyond tropospheric dynamics, external drivers such as tropical atmospheric signals [15–19] and the variability of the Arctic LSPV are associated with influence on midlatitude cold extremes [20,21].

The LSPV is a fundamental factor in winter climate variability, having a role in shaping temperature patterns across midlatitudes [21,22]. The LSPV forms in autumn as Arctic temperatures decline, intensifies during winter, and weakens in spring, following seasonal shifts in stratospheric temperature gradients [2,23]. Variability in the vortex configuration and strength projects onto variability in the midlatitude tropospheric circulation [24–26] and has been linked to extreme winter weather in multiple geographical regions, including North America [23,27–30]. A strong LSPV often confines cold Arctic air to high latitudes.

When the LSPV is not centered near the north pole it is said to be disrupted. Disruptions such as stretching or displacement of the LSPV can coincide with extreme weather anomalies in midlatitude regions, including severe cold-air outbreaks [2]. [20,28], and [31] divide possible configurations of the LSPV into five or six patterns based on cluster analysis. An important disruption case is when the LSPV is stretched, i.e., when the 100 mb geopotential height field takes on an elliptical shape spanning both the North American and Asian hemispheres [2,32,33]. Such a stretched LSPV was prominent during the second half of January 2025 and through February. Such stretched events were associated with CAOs in the US and Eastern Asia. The stretched LSPV was not fixed during the period but pulsed, changing size, moved to be located more over North America or Eastern Asia, and even split into two centers. The six-week duration of the stretched feature set overall atmospheric conditions. But details of the 500 mb flow and surface temperatures provided within season variability to near surface weather.

A consequence of a stretched LSPV is its possible impact on regional temperatures. When the LSPV elongates, a stretched pattern, or shifts away from near the center of the Arctic, it influences the tropospheric jet stream, generating persistent troughs and ridges that modulate temperature patterns across North America and Eurasia [20]. For example, displacements of the LSPV toward Greenland have been associated with severe cold spells in the eastern US and concurrent anomalous warming in the western US [34,35]. Furthermore, stratospheric perturbations have been identified as factors influencing North American weather regime predictions, highlighting the need for improved forecasting models that incorporate LSPV variability [36].

This study investigates LSPV stretching and its association with midlatitude temperature variability in winter 2025. By analyzing observational data, we aim to improve understanding of how atmospheric dynamics influence midlatitude winter extremes. Our findings contribute to the broader discourse on Arctic-midlatitude interactions due to internal atmospheric variability, and have implications for improving seasonal weather forecasting in an era of ongoing change. In the next sections we cover the duration of the stretched LSPV during the second half of January 2025 through February. This is followed by discussion of associated CAO events in the US and Eastern Asia.

2. Methods and data

The data are for the ERA5 Reanalysis. A LSPV stretching index is based on an aspect ratio (AR) of the stretched ellipse long axis length divided by the ellipse width for the 15400 gpm geopotential height contour at 100 mb.

3. The Lower Stratospheric Polar Vortex (LSPV)

During early January 2025 (1–14 Jan) the LSPV was rather small in spatial extent and mostly centered near the north pole. There was a LSPV lobe partway over northeastern Asia on 9–13 January. Beginning on 15 January the LSPV began taking on a stretched configuration, extending from Asia across the pole to northeastern North America (Fig 1A). Its extent was somewhat reduced and located more over the North American side during 19–23 January, but returned to a broad extent after 26 January. Beginning on 5 February the Asian lobe reached as far south as the Korean peninsula, while in North America the 100 mb pattern became zonal over the continental US. On 11 February the stretched pattern became split. After 17 February the LSPV pattern regressed to a smaller extent on the Asian side. On 17 February the LSPV extended on the North American side and on 23 February an extensive stretched pattern returned.

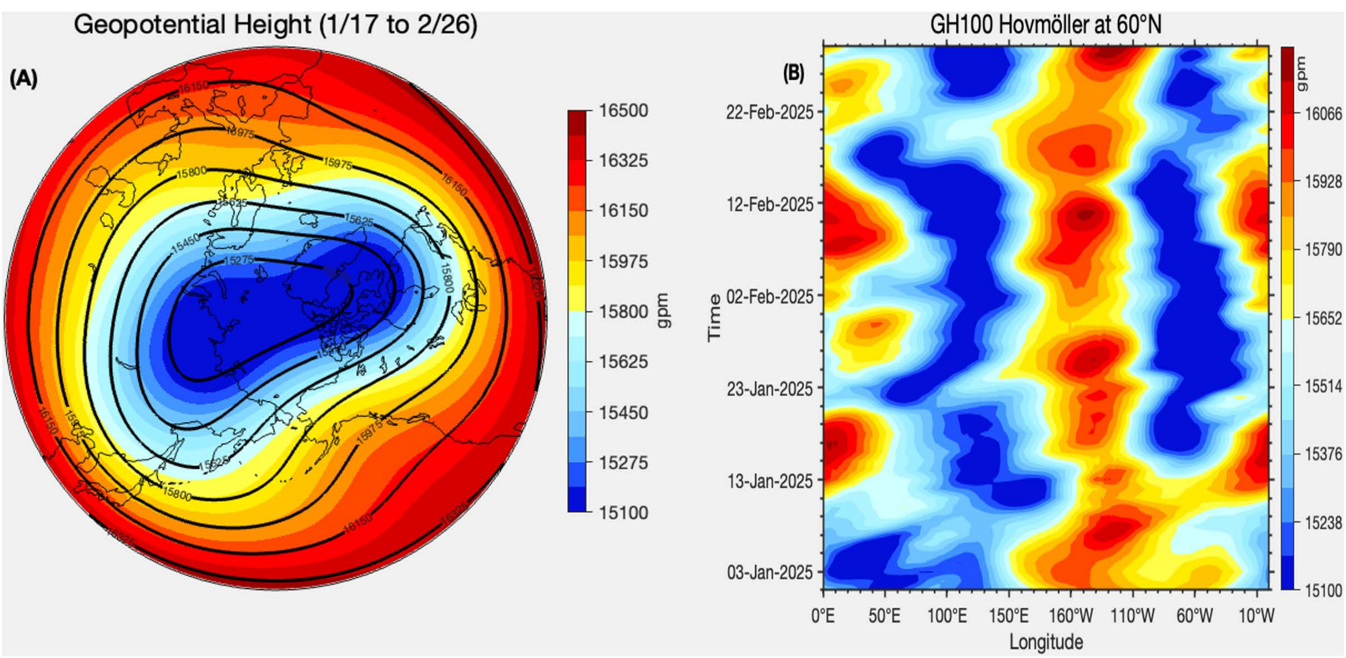

Fig 1. A. Color contours: Average of the stretched 100 mb geopotential height pattern for the period 17 January through 26 February 2025. Black contours: climatology from 17 January to 26 February for years 1979–2024. This image and following images provided by the NOAA Physical Sciences Laboratory, from their Web site at https://psl.noaa.gov/. B. A Hovmoller time/longitude plot along 60° N of 100 mb geopotential height.

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Black contours in Fig 1A show the climatology from 17 January to 26 February for years 1979–2024; in comparing the same contour height levels during 2025 versus climatology, the climatology also has an elongated shape but its spatial extend is less.

A Hovmoller time/longitude plot of January-February 2025 100 mb geopotential heights is shown in Fig 1B for 60° N. The first half of January is represented by a wave number one pattern that then shifts to a wave two pattern for the duration, with the two vertical stripes of low values shown in blue. The spatial extent of the trough is slightly greater in late January for North America and slightly greater for Eastern Asia in early February.

An index to define a stretched LSPV event is its Aspect Ratio (AR), the longest divided by the shortest elliptical dimension. The AR for the January-February 2025 LSPV period (Fig 1a) is 2.3.

A feature noted during some LSPV stretching is the vertical component of atmospheric wave energy, known as wave activity flux or Eliassen Palm (EP) flux [28,37,38].

4. The North American troposphere

January 2025 starts with a Greenland blocking pattern though 8 January. By 11 January, a strong trough is established over eastern Canada congruent with a developing LSPV. By 17 January a ridge is formed west of California and a ridge-trough pattern across the continental US is established through 29 January (Figs 2, 3). Figures for corresponding hemispheric wide fields are provided in Supplemental material matching Figs 3, 6 and 8, i.e., Fig A, Fig B, Fig C in S1 Text. The AR for the LSPV during 17–29 January is 2.2. Note that 500 mb height contours in Fig 3 lineup with the shape of the 100 mb contours. This simultaneity of 100 mb and 500 mb geopotential height pattern shapes suggests a barotropic atmospheric structure with the trough at 100 mb matching the eastern North American location of the 500 mb trough. On 1 February the 500 mb geopotential height pattern takes on a more west-east orientation across the northern US through 15 February.

Surface 2 m air temperatures in the eastern and central US had strong negative anomalies during 19–26 January (Fig 4). Eight inches of snow fell in New Orleans on 21 January, far exceeding the previous record of 3 inches in 1963. Warm anomalies were seen over northwestern Canada through 29 January. After the event a warm temperature anomaly feature propagated eastward across the US during 29–31 January.

5. Korea and Northeast Asia

While North America was having a pause with near normal temperatures during early February with zonal flow at 500 mb across the continental US, the stretched LSPV at 100 mb shifted southward over Eastern Asia. The corresponding 500 mb geopotential heights showed strong troughing reaching south to Korea during 3–10 February (Figs 5 and 6) with an AR of 2.8.

This configuration of the LSPV corresponded to spatially extensive cold air anomalies (Fig 7). In Korea, temperatures dropped significantly and persisted. Seoul experienced temperatures below -10° C for six consecutive days in February, the first such occurrence in 39 years. Japan simultaneously experienced its strongest cold wave of the season, with Obihiro city in Hokkaido recording 124 cm of snowfall within a 72-hour period—a new record. Northwesterly flow associated with the LSPV-related trough enhanced traditional lake effect snow mechanisms. As the LSPV extended southward further into East Asia, China's northern and northwestern regions experienced temperatures of more than 10° C below seasonal averages during February 7–8, with blizzard conditions disrupting travel across multiple provinces. Even subtropical Taiwan recorded temperatures below 6° C in metropolitan areas, resulting in 78 deaths [39], primarily among the elderly population.

The out-of-phase relationship between cold events in North America and Eastern Asia during early February 2025 demonstrates how the elliptical shaped, stretched LSPV may modulate hemispheric weather patterns in a coordinated manner, before shifting its influence back to North America late in February.

6. The US again

During zonal winds of 3–10 February southern Canada was cold and the continental US had positive temperature anomalies. Cold temperatures were established in northwestern US during 9–12 February. This cold region moved eastward on 13–14 February. Cold conditions and a stretched LSPV over North America return on 17 February though 26 February (Fig 8). The Hovmoller plot (Fig 1b) shows the event being particularly strong during 22–26 February.

A central and eastern continental US cold pattern was reestablished during 17–26 February, again with warm Canadian anomalies (Fig 9).

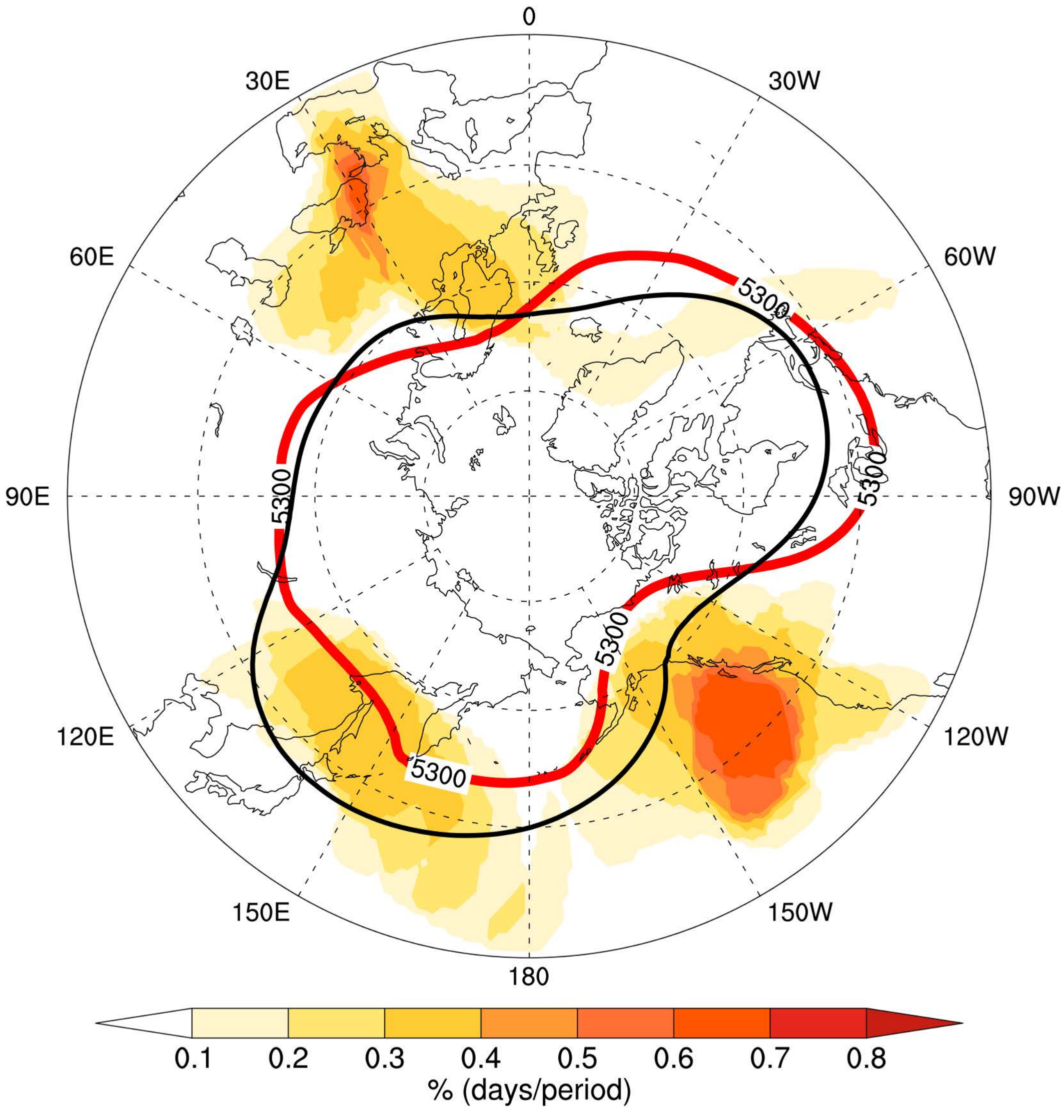

Fig 2. Blocking regions in the Northern Hemisphere during 17 to 29 January 2025 indicated by shading, which shows the percentage of days with blocking events (1 = blocking present for all 13 days). The red contour represents the mean 5300 m geopotential height at 500 mb (Z500) from 17 to 29 January 2025, while the black contour shows the winter (DJF) mean 5300 **m.**

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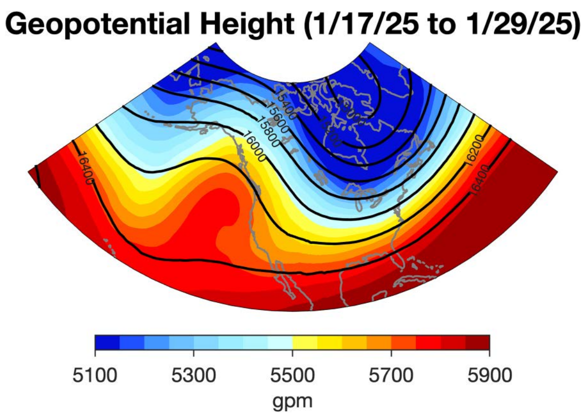

Fig 3. Late January west-east dipole 500 mb geopotential height (shaded) pattern and 100 mb geopotential height (contours), 17-29 January 2025. Figure for hemispheric wide field is provided in Supplemental material corresponding to Fig 3 is Fig A in S1 Text.

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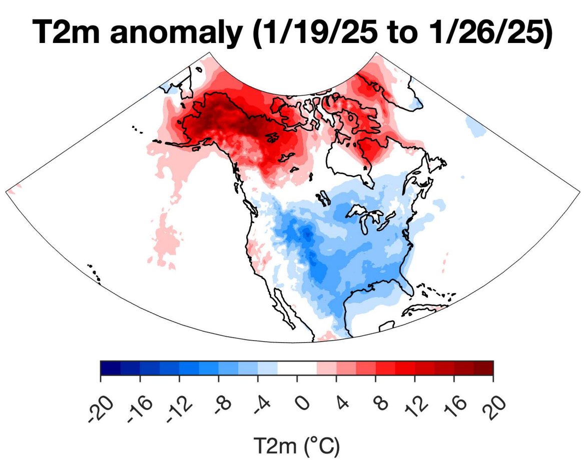

Fig 4. 2 m air temperature anomalies over southeastern US during 19–26 January 2025. Anomalies calculated based on 1991–2020 climatology.

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7. Discussion

During January-February 2025, the 500 mb trough over eastern North America often lines up with the North American half of the stretched 100 mb LSPV. A cold spell in the eastern US coincided with the 500 mb dipole pattern in the second half of January. February in the US started with a zonal 500 mb wind pattern with both warm and cold US anomalies, and ended the month with a persistent cold event. In between the two US cold events a cold pattern shifted with the LSPV into Eastern Asia.

For all cases the trough locations at 500 mb line up simultaneous with 100 mb trough locations (Figs 3,6,8). This suggests a hydrostatic barotropic vertical structure, with low geopotential heights at 100 mb being reflected in low heights in lower altitudes during LSPV stretched events. Perlwitz and Graff [40] discuss a barotropic connection of 50 mb and 500 mb based on canonical correlation for strong LSPV during winters 1958–1993. Further, lag canonical correlations [41]

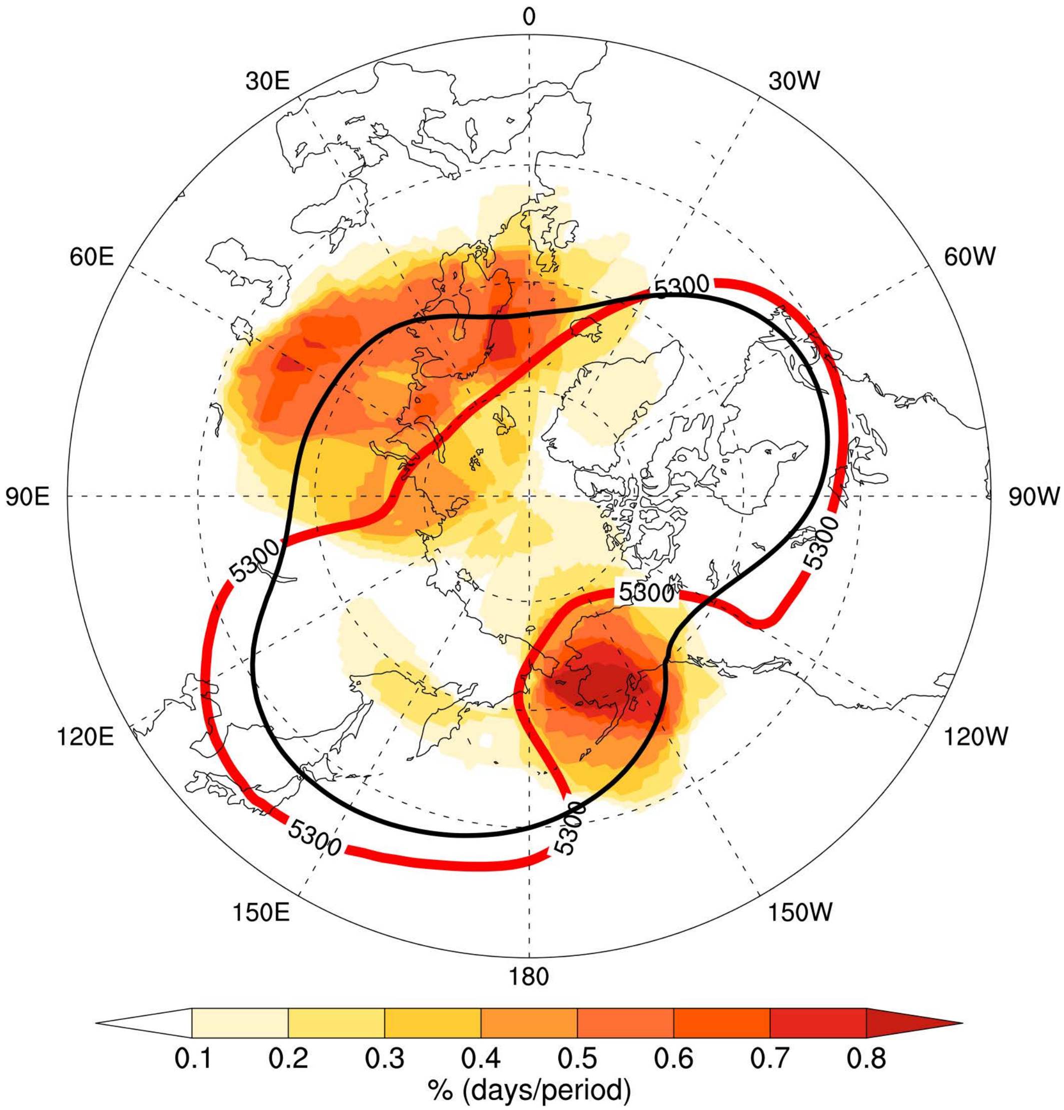

Fig 5. Blocking regions in the Northern Hemisphere during February 1 to 14, 2025 indicated by shading, which shows the percentage of days with blocking events (1 = blocking present for all 14 days). The red contour represents the mean 5300 m geopotential height at 500 mb (Z500) from February 3 to 10, 2025, while the black contour shows the winter (DJF) mean 5300 m geopotential height.

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were maximum from minus three days to plus six days, suggesting rapid vertical adjustments, as seen in Figs 3, 6, and 8. In contrast, in weak vortex sudden stratospheric warming episodes [2], vertical propagation can be on multi-week time scales [4,42].

It is interesting to know how rare were the winter 2025 events. Frequency information on historical elliptical shaped 100 mb geopotential height patterns during 1980–2021 are noted in [2]; frequencies for their patterns P2 and P4 are provide by their Figure Supplementary 3. There is considerable year-to-year variation with some years showing no events. This [2] comparison and our Fig 1a suggest that January-February 2025 are not necessarily unusual compared to some previous years with multiple events.

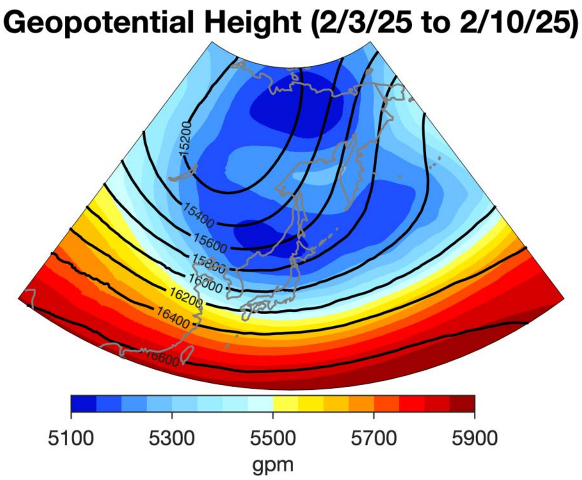

Fig 6. 500 mb (shaded) troughing over eastern Asia during early February 2025. 100 mb geopotential height (contours) overlaid. Supplemental figure corresponding to Fig 6 is Fig B in S1 Text.

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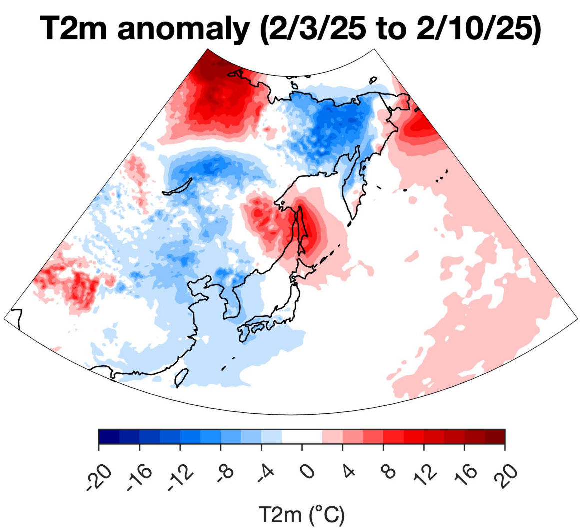

Fig 7. Long duration cold temperature anomalies over eastern Asia during early February 2025. Anomalies calculated based on 1991 – 2020 climatology.

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8. Conclusion

The lower stratospheric polar vortex (LSPV) is shown to be fundamental to winter weather variability in some years. Although the LSPV can take on multiple configurations, disruptions such as stretching can be associated with extreme weather anomalies in subarctic and midlatitude regions, including severe cold-air outbreaks. This was evident during the persistent LSPV pattern at 100 mb of January–February 2025. In the latter half of January and through February, a stretched LSPV extended from northeastern Asia across the Arctic to northeastern North America (Fig 1A and 1B), demonstrating a high latitude coincidence with midlatitude weather. Although the persistent stretched feature across two continents was the most prominent aspect, its elliptical shape fluctuated over time, shifting its extreme southern

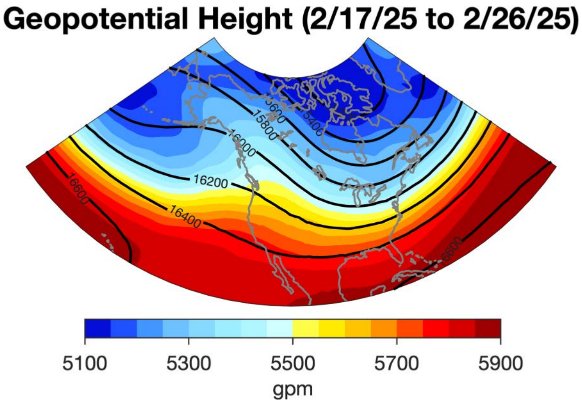

Fig 8. 500 mb geopotential height field (shaded) in late February 2025, 17 February through 26 February. Stretched 100 mb geopotential height field (contours) overlaid. Supplemental figure corresponding to Fig 8 is Fig C is S1 Text.

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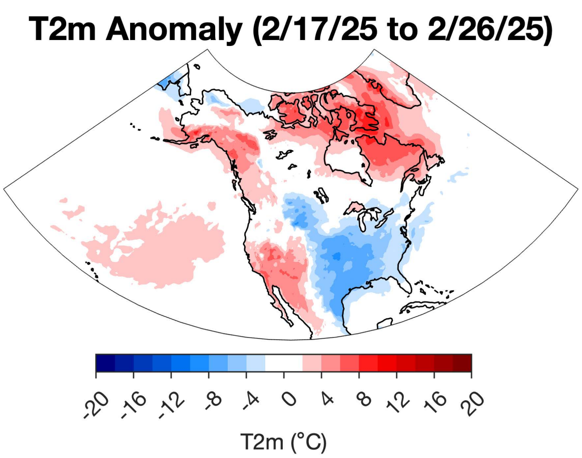

Fig 9. Late February cold 2 m air temperature anomalies in central eastern US. Anomalies calculated based on 1991 – 2020 climatology.

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boundaries between these two continents. As a result, surface and tropospheric responses varied throughout the period. Cold and snowy conditions observed in the eastern US during the latter half of January, shifted to eastern Asia in early February, and returned to the US in the later part of February. The prolonged presence of the stretched LSPV had wide-spread hemispheric impacts.

We have shown that an expanded monthly LSPVs across the Arctic and subarctic can coincide with hemispheric-wide weather events. However, the association between a stretched LSPV and cold weather is not always direct. In early February, for instance, the LSPV expanded in a west-east orientation across Canada. This expansion reinforced a strong zonal flow over the continental United States limiting the development and duration of significant cold-air outbreaks. A shifted LSPV in early February coincided with cold temperatures in Eastern Asia. Stratospheric disruptions, such as LSPV stretching and displacement, have been identified as factors influencing North American, Eastern Asia and hemispheric weather regime predictions, highlighting the need for improved forecasting models that resolve LSPV variability [2,36].

Supporting information

S1 Text. Fig A. 100 mb and 500 mb geopotential Height fields for 17–29 January 2022. Fig B. 100 mb and 500 mb geopotential Height fields for 3–10 February 2022. Fig C. 100 mb and 500 mb geopotential Height fields for 17–26 February 2022.
(DOCX)

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There were real-time following of 2025 weather events: the blog of Cohen https://published.aer.com/aoblog/aoblog.html and reports in the Washington Post. This is NOAA Pacific Marine Environmental Laboratory Contribution No 5749.

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Methodology: Varunesh Chandra, Hoyoung Ku.

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Writing – review & editing: James E. Overland, Varunesh Chandra, Baek-Min Kim, Muyin Wang, Hoyoung Ku, Edward Hanna.

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