Arctic and Pacific Ocean Conditions Were favourable for cold extremes over Eurasia and North America during Winter 2020/21

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ABSTRACT
A sequence of extreme cold events occurred across Eurasia and North America during winter 2020/2021. Here, we explore the causes and associated mechanisms for the extremely cold temperatures using both observations and large-ensemble simulations. Experiments were conducted with observed ocean surface boundary conditions prescribed globally, and regionally to discern the specific influence of Arctic, tropical Pacific and North Pacific drivers. Increased likelihood of daily cold extremes in mid December to mid January are found in Eurasian midlatitudes in response to reduced Arctic sea ice. Tropical sea surface temperature anomalies, more specifically the La Niña pattern, increased probability of extreme cold over high-latitude Eurasia in early January to early February. Both reduced Arctic sea ice and La Niña increased the probability of daily cold extremes over western North America in late January to late February. We conclude that a combination of reduced Arctic sea ice, La Niña, and a sudden stratospheric warming in January 2021 were factors in the February 2021 extreme cold-wave that caused huge societal disruptions in Texas and the Southern Great Plains. Although the magnitude of the simulated cold extremes are relatively small when compared with observed anomalies, the Arctic and Pacific Ocean surface conditions in winter 2020/21 increased the probability of cold days as cold or colder than observed by approximately 17%~43%.

CAPSULE
Extreme cold events occurred across Eurasia and North America during winter 2020/21 were made more likely by a combination of reduced Arctic sea ice, La Niña, and a sudden stratospheric warming.
1. Introduction

Large swathes of the Northern Hemisphere continents experienced record, or near-record, cold spells and heavy snowfall during winter 2020/21. Severe cold extremes were most pronounced over midlatitude Eurasia during December 2020 and early January, over high latitude Eurasia during January and February 2021, and over western North America in February 2021 (e.g., Cohen et al. 2021; Doss-Gollin et al. 2021; Zhang et al. 2021; World Meteorological Organization: https://public.wmo.int; Fig. 1). These cold events resulted in loss of life, disruption to energy supply and transport, and economic losses. Although atmospheric intrinsic variability has been implicated as the primary cause for the midlatitude cold events (e.g., Blackport et al. 2019), ocean surface conditions, namely sea-ice cover and sea surface temperatures, may change the likelihood of cold events occurring. Winter 2020/21 and the preceding months featured below-average Arctic sea-ice cover and La Niña SST anomalies in the Pacific Ocean (Fig. S1). Another notable feature of winter 2020/21 was the sudden stratospheric warming (SSW) in January 2021 (Lu et al. 2021), which might increase the probability of North American cold spells (e.g., Cohen et al. 2021; Domeisen and Butler 2020), especially in the presence of low Barents–Kara Sea ice (Cohen et al. 2021; Kim et al. 2014; Zhang et al. 2020; Zhang et al. 2021).

It has been suggested that Arctic sea-ice loss may increase the probability of severe winter weather events (e.g., Cohen et al. 2018; Kug et al. 2015; Mori et al. 2019; Zhang et al. 2018). However, this possible connection is uncertain due to divergent conclusions between modeling and observation studies (Cohen et al. 2020), and between models (Screen et al. 2018; Screen and Blackport 2019). Such divergence may reflect model errors (e.g., Mori et al. 2019) and difficulty in determining causality (Blackport et al. 2019; Blackport and Screen 2021; Li et al. 2021; Luo et al. 2019; Overland et al. 2021; Screen et al. 2014; Screen and Blackport 2019). Furthermore, the atmospheric effects of reduced sea ice appear to depend on the spatial pattern (Screen 2017; Levine et al. 2021), seasonality and magnitude (Zhang and Screen 2021) of sea-ice loss, as well as on concomitant SST anomalies (Osborne et al. 2017; Rudeva and Simmonds 2021; Screen and Francis 2016), which makes it very hard to generalize how distinct sea ice (and SST) anomalies at a specific time (e.g., winter 2020/21) might have affected midlatitude weather.

La Niña has been invoked as another potential driver of winter coldness in northwestern North America and mid-to-high latitude Eurasia (e.g., Brönnimann 2007; Garfinkel et al. 2019; Luo et
al. 2021; Wang et al. 2000; Zhang et al. 2021), and enhanced probability of an SSW in observations, although this is not replicated in models (e.g., Domeisen et al. 2019). Various pathways have been identified for linking La Niña to midlatitudes through teleconnections. For instance, La Niña is generally associated with a northward displacement of the Pacific storm track (Seager et al. 2010) and the negative phase of Pacific-North America (PNA) teleconnection. Furthermore, La Niña induces a weakening of the Aleutian low and destructive linear interference with the climatological wave pattern, leading to a stronger and colder than normal polar vortex (Iza et al. 2016).

Whilst any of, or the combination of, reduced Arctic sea-ice cover, a warmer than average North Pacific, and tropical La Niña-like SST anomalies may have increased the probability of extreme cold events across northern Eurasia and western North America during winter 2020/21, it is unwise to generalize past work to this specific winter. Here, we perform large-ensemble atmospheric general circulation model (AGCM) experiments to assess whether the distinct ocean surface conditions in winter 2020/21 were favourable for the frequent occurrence of extreme cold events and to discern the relative influences from the Arctic and Pacific Oceans.

2. Data and Methodology

We use the daily surface air temperature (SAT), sea level pressure (SLP), geopotential height, and horizontal wind for 1979–2021 from the Fifth generation of ECMWF atmospheric reanalyses of the global climate (ERA5; Hersbach et al. 2020), and the monthly SIC and SST datasets from Hadley Centre for 1979–2021 (HadISST).

A high-top model, the Whole Atmosphere Community Climate Model (WACCM; Marsh et al. 2013), is used to investigate the response to ocean surface boundary conditions. This model configuration has a horizontal resolution of 1.98° latitude and 2.58° longitude, and 66 vertical levels extending from the surface to 5×10^-6 hPa. There are 48 pressure levels above 100 hPa, which is representative of a more realistic stratosphere. A control run and eight perturbation experiments were conducted. The perturbation experiments were prescribed with different combinations of observed Arctic sea-ice concentration (SIC) and/or Pacific SST anomalies (Table S1). A smoothing of 5° longitude and 5° latitude was applied to the imposed fields to avoid strong artificial SST gradients. The control experiment was run for 210 years prescribed with the annually repeating climatology (1979–2010) of monthly-mean SIC and SST, with the first 10 years
discarded for spin up. The perturbation experiments were analogous to the control experiment, but with observed SIC and SST anomalies from 1 Aug 2020 to 28 Feb 2021.

First, we conducted an experiment with observed Arctic SIC and SST (named SICSST) to isolate Arctic forcing. The premise for SICSST is to include the effects of SST warming directly related to sea-ice loss (Screen et al. 2013). Next, we conducted three experiments to isolate Pacific Ocean forcing over different latitude domains: 20ºS–60ºN (named IPO), 20º–60ºN (named NPDO), and 20ºS–20ºN (named LaNina). The premise for NPDO and LaNina experiments was to separate the northern extratropical and tropical components, respectively. Further, we conducted three experiments with various combinations of the above-mentioned SIC and SST anomalies: SICSST+IPO, SICSST+NPDO, SICSST+LaNina. The motivation for these experiments was to consider possible nonlinear responses to combined Arctic and Pacific Ocean forcing.

Each perturbation experiment consists of 200 members to ensure the robustness of diagnosed responses, with each member integrated from a different atmospheric initial condition (1 Aug) from the control experiment. The response is estimated by the difference between the ensemble mean from each perturbation experiment compared to the ensemble mean from the control experiment.

We primarily focus on the simulated changes in daily cold extremes. For each of the three studied cold events observed in winter 2020/21, we select a 30-day window centred on the date of the coldest observed daily temperature anomaly. Within these 30-day windows, we identify the simulated 1% coldest daily anomalies across all ensemble members, as well as the simulated coldest daily anomaly in each ensemble member, relative to daily climatology of the control experiment. We then average the temperature (and 500 hPa geopotential height) anomalies for these coldest days across ensemble members. We also show Generalized Extreme Value (GEV) distributions of daily temperature anomalies for the selected 30-day windows. GEV distributions are widely used in extreme value analysis due to their quasi-universal applicability (e.g., Coles 2001; Karin and Zwiers 2005; Karin et al. 2007; Zhang et al. 2017). To estimate the distribution of probability density function (PDF), a GEV distribution is fitted to the daily temperature anomalies in the 30-day window and across the 200 ensemble members. The skewness and kurtosis parameters are also calculated to verify if the simulated anomalies fit a normal distribution. Where normality is a reasonable assumption (significant if skewness parameter <1.96 and kurtosis
parameter <1.96), statistical significance was calculated using a two-sided Student's \( t \)-test with 95% confidence. If not, the variables are generally normalized by logarithmic function to conduct Student's \( t \)-test. As a further, and arguably more stringent test of robustness, the consistent discovery rate (CDR) test proposed by Peings et al. (2021) is also applied, using 30-member means for the bootstrap resampling. The null hypothesis for these significance tests is the significant difference between the average of extremes across ensemble members or ensemble-means in the perturbation and control experiments.

3. Results

3.1 Observed temperature and circulation anomalies

December 2020–early January 2021 was anomalously cold over midlatitude Eurasia (MEU), up to 5 °C below the monthly average in places (Fig. 1b). The most severe cold event occurred in early January, with a regionally-averaged temperature anomaly during 3–6 January of -6.7 °C, more than two standard deviations below the climatological average (Fig. 1a–c). The cold anomaly was on the southern and eastern side of a blocking ridge, which advected cold air from the Arctic into Eurasia (Fig. 1a). To evaluate the intensity of cold extreme compared with all historical temperature anomalies, Fig. 1c shows a PDF analysis of the regionally-averaged daily temperature anomalies during a 30-day window centered on the cold event for the past 42 years. The 4-day mean temperature anomaly (3–6 January 2021) during this cold event is found in the cold tail of the historical daily temperature anomaly distribution, approximately equalling to the 1% percentile. Whilst not unprecedented in the historical record, the 3-6 January 2021 cold extreme was a rare event, as also noted by Zhang et al. (2021).

Later in the winter 2020/21, through mid January to early February, cold conditions shifted to high latitude Eurasia (HEU; Fig. 1d). A second notable cold event occurred during 21–24 January (Fig. 1e), dynamically linked to northeasterly winds (Fig. 1d). The regionally-averaged temperature anomaly of -13 °C during 21–24 January is close to the 1% percentile of daily historical anomalies during the 30-day window centred on the observed event (Fig. 1f).

A third extreme cold event occurred over western North America, in a band from Alaska to Texas, during February 2021 (Fig. 1g), with maximum severity of 11.7 °C below average for the region on 7–9 February (Fig. 1h), far below the 1% percentile of historical daily anomalies (Fig. 1i).
emphasizing the rarerity of the event. The temperature anomalies are dynamically connected to the anomalously high pressure in the North Pacific, reflect a weakened Aleutian low and the negative PNA pattern (Fig. 1i), which is favorable for the intrusion of cold air southward into western and central North America (Leathers et al. 1991; Ning and Bradley 2016).

As introduced earlier, these temperature and circulation anomalies were concurrent with, and preceded by, reduced Arctic sea-ice cover, anomalously warm North Pacific SST, and cold SST anomalies in the tropical Pacific (Fig. S1). Sea ice was especially low in the Barents Sea in autumn and early winter, with a record monthly low in October 2020 (Simmonds and Li 2021). The North Pacific warm SSTs and tropical cool SSTs were present throughout winter 2020/21 and their magnitudes didn’t change much over that time. In the following sections, we use the WACCM experiments to determine the atmospheric response to these ocean surface conditions, starting with early January 2021 cold event in midlatitude Eurasia, then the late January 2021 event in high latitude Eurasia and then, the early February 2021 event over western North America. Last, we consider the role of boundary forcing in the observed SSW in early January 2021, which may have contributed to the observed cold events later in the winter (e.g., Cohen et al. 2021). As noted above, our focus is on daily temperature extremes rather than monthly or seasonal means.
Fig. 1 (a) Observed average of daily near-surface air temperature anomalies (SAT; shading; °C; relative to the daily climatology from 1979/80–2010/11) overlaid with 500-hPa geopotential height (Z500; contour interval of 50 m) during 3–6 Jan 2021. (b) Daily time-series of SAT anomalies averaged over the midlatitude Eurasia (MEU; 40°–56°N, 50°–128°E; red rectangle in a) and one standardized deviation below average (gray line) in winter 2020/21, with the gray band indicating the 30-day window (22 Dec 2020–20 Jan 2021) centered on the extreme cold event. (c) Probability density function (PDF; %; histograms and the GEV fitting) of historical daily SAT anomalies averaged over MEU during the 30-day window. (d–f) As (a–c) but for the extreme cold event occurred in high-latitude Eurasia (HEU; 55°–70°N, 50°–128°E; red rectangle in d) during 21–24 Jan 2021, daily SAT anomalies averaged over HEU, and PDF of daily SAT anomalies during the 30-day window of 9 Jan–7 Feb 2021. (g–i) As (a–c) but for the extreme cold event occurred in western North America (WNA; red contour in g with SAT anomalies lower than –8 °C) during 7–9 Feb 2021, daily SAT anomalies averaged over WNA, and PDF of daily SAT anomalies during the 30-day window of 25 Jan–23 Feb 2021. The vertical solid and dashed lines in (c, f, i) show mean SAT anomalies during the three cold events and both 5% and 1% percentiles of the historical daily anomalies during the 30-day window, respectively.
3.2 Early January 2021 cold event over midlatitude Eurasia

During winter, Arctic sea-ice anomalies in combination with Arctic SST anomalies (i.e., SICSST) cause more severe cold days (Fig. 2a) and higher severity of coldest day (Fig. S2a) over Eurasian midlatitudes. This cooling of the coldest days is connected to a strengthening of the Siberian High and East Asian Trough (Fig. 2a; Fig. S3a), which favour southward advection of cold air into midlatitude Eurasia, and closely resembles the observed circulation anomalies in early January 2021 (Fig. 2h). The persistence of winter Ural Blocking has been considered a link between Arctic warming and Eurasian extreme cold events (Luo et al. 2016; Yao et al. 2017). The PDF of midlatitude Eurasian daily temperature anomalies in SICSST is shifted towards colder anomalies compared to the control (Fig. 2i), with a higher frequency of extremely cold anomalies (as cold or colder than observed in early January 2021; Fig. 2j). In addition, there is a statistically significant increase in the frequency of cold days. The NPDO and SICSST+LaNina experiments also show cooling of the coldest day (Fig. 2c and 2j), albeit more regionally confined than in SICSST and less clear in the regionally-averaged temperature anomalies distributions (Fig. 2i–j).

The Eurasian temperature responses do not appear linearly additive; for example, the cooling response in SICSST+NPDO is less than the sum of the responses in SICSST and NPDO. Neither the IPO or LaNina experiments show a significant response of extreme cold temperatures (Fig. 2b, d, and e). In fact, fewer cold extremes are seen in the regionally-averaged temperature distribution from these experiments compared to the control (Fig. 2j).

In all experiments, the observed extreme temperature anomalies in early January 2021 lie within the daily range in all ensemble members, but towards the cold tail. In the experiments with statistically significant extreme cooling - SICSST, NPDO, and SICSST+LaNina - the simulated likelihood of temperature response as cold or colder than observed is approximately 6.2%, 4.8%, and 5.3%, respectively. The change in likelihood relative to the control run is 38%, 7%, and 18%, respectively. In summary, the midlatitude Eurasian coldness during early January 2021 was made more likely by the SICSST.
Fig. 2 Simulated extreme cold SAT anomalies (shading; °C; defined as the average of 1% coldest daily SAT anomalies regionally-averaged over the MEU) and 500-hPa geopotential height (contour interval of 30 m) during the 30-day window of 22 Dec 2020–20 Jan 2021 in the WACCM perturbation experiments, relative to those in the control run (a–h): SICSST, IPO, SICSST+IPO, NPDO, SICSST+NPDO, LaNina, and SICSST+LaNina, and observation. The magnitude of contours and shadings in observation (h) is one-third of simulation to facilitate comparison. White cross (black stippling) denotes statistical significance for SAT difference between perturbation and control run at the 95% confidence level of CDR test (t-test). Red rectangles denote the MEU region. (i) shows the PDFs (the GEV fitting) of the daily SAT anomalies averaged over MEU during the 30-day window in 200 ensemble members of the perturbation experiment (color lines) and control run (gray shade). The corresponding ensemble- and time-means are shown by circles, with cross indicating mean changes significant at the 95% confidence level of t-test. The observed four-day mean anomaly from 3–6 Jan 2021 is shown by the vertical line. (j) shows the cold tails of CDFs as cold or colder than observed, with percentage numbers next to experiment labels denoting change in probability of cold days relative to the control run.
3.3 Late January 2021 cold event over high-latitude Eurasia

Looking at all the combinations of boundary conditions, the largest cooling response of the coldest days is found in the LaNina and SICSST+LaNina experiments (Fig. 3d and g; Fig. S4b and g). Averaging over high-latitude Eurasia, days as cold or colder than observed, occur with greater frequency in the LaNina, IPO and SICSST+LaNina experiments, and to a lesser degree, the NPDO experiment, all compared to the control (Fig. 3j). In contrast, little change in the probability of cold days is simulated in the SICSST and SICSSST+IPO, and decreased probability of cold days is simulated in SICSSST+NPDO (Fig. 3j). Broadly speaking, the experiments with tropical Pacific SST anomalies show the greatest changes in cold extremes. The temperature changes are in association with the raised 500-hPa geopotential height over the Arctic and reduced geopotential height over the zonal belt extending from Europe to northern Siberia (Fig. 3; Fig. S3b). On the surface level, the Siberian high is significantly strengthened (figure not shown). The maximum probability of cooling response is found in the LaNina experiment, which again equates for approximately 1.6% as cold or colder than observed, and the change in likelihood of cold extremes relative to the control run is roughly 43% (Fig. 3j). It suggests a robust role of LaNina in the change in probability and severity of cold extremes in high-latitude Eurasia.
Fig. 3. As Fig. 2, but for extreme cold SAT and Z500 anomalies and the PDFs and CDFs of daily SAT anomalies area-averaged over HEU during the 30-day window of 9 Jan–7 Feb 2021.
3.4 Early February cold event over western North America

An increase in the frequency of cold days over western North America is simulated in the LaNina, SICSST, and SICSST+LaNina experiments (Fig. 4; Fig. S5). In the LaNina and SICSST+LaNina experiments, simulated cooling is dynamically connected to the anomalously high pressure over the North Pacific, reflecting a weakened Aleutian low (Iza et al. 2016) and the negative PNA pattern in the mid-troposphere (Fig. 4d and 4g; Fig. S3c). The anomalous high over the Aleutian region and the anomalous low over Northwest Canada facilitate cold-air outbreaks from the Arctic to North America (Leathers et al. 1991; Ning and Bradley 2016). The commonality between these experiments is the tropical Pacific SSTs, indicating that La Niña is crucial in driving the negative PNA pattern and associated cooling over western North America (Seager et al. 2010). Furthermore, the SICSST experiment also simulated a cooling over northwestern North America (Fig. 4a), with a weakened Aleutian low which may strengthen the wave-2 activities and facilitate cold surges (Zhang et al. 2020). However, the spatial patterns of western North American responses are slightly different from those in observation, with the simulated cooling more limited to western Canada and the Northeast Pacific. The Texas cold wave that caused huge societal disruption (Doss-Gollin et al. 2021) is regionally simulated in the SICSST+LaNina experiment, but not well simulated in other experiments, at least across the ensemble members (Fig. 4) and in the ensemble means (Fig. S5). As will be discussed later, ensemble members that feature an SSW also display cooling over Texas in some experiments. The SICSST may play an secondary role in the severity of cold extremes over western North America (Fig. 4a), while the NPDO-related experiments display insignificant temperature responses (Fig. 4c and f), suggesting a minimal role for North Pacific forcing in the February 2021 cold event. In summary, our simulations suggest that the observed February cooling in western North America was partly driven by La Niña and Arctic sea ice loss and the associated negative PNA.
3.5 Causes and surface effects of January 2021 sudden stratospheric warming

We next consider the possible role of ocean boundary conditions in modulating the observed SSW in early January 2021, which may have influenced observed cold events later in the winter. Here, we define an SSW as a reversal of 60°N zonal-mean zonal wind at 10 hPa during November to February (Butler et al. 2017), with the first and last day with zonal wind reversal identified, respectively, as the start and end date of SSW. The observed SSW can be seen in polar-cap-averaged geopotential height (PCH; averaged north of 65°N), starting in early January 2021 with the stratospheric disturbance persisting until early February 2021 (Fig. 5a). There is evidence of
downward propagation of the disturbance over this time period, with near-surface PCH anomalies at a maximum during late January to mid-February. Positive PCH responses in the lower stratosphere are simulated in all experiments, suggesting a weakened SPV, through much of the cold season (Fig. 5b–h). The strongest and most vertically extensive PCH responses are seen in the IPO, LaNina, SICSST+IPO and SICSST+LaNina experiments, suggesting that tropical Pacific forcing in winter 2020/21 was favorable for a weakened polar vortex. These three experiments also simulate an increased occurrence of an SSW compared to the control run.

It is not immediately obvious why La Niña would weaken the polar vortex and increase the frequency of SSWs, as this is opposite to the expected response (e.g., Domeisen et al. 2009; Iza et al. 2016). We note the weakened Aleutian Low (Fig. 4) is consistent with expectations and there is evidence of a strengthened polar vortex in late winter in the LaNina experiment (Fig. 5e), which again is consistent with prior understanding of ENSO teleconnections to the polar vortex. Ayarzagüena et al. (2018) argue that the response to La Niña differs between early and late winter, with the pathway from a weakened Aleutian Low to a strengthened polar vortex only active in late winter. Our simulations appear to support this, and the weakened polar vortex in early winter likely occurs through a different pathway. We speculate that enhanced Ural blocking, associated with anomalously high SLP in this region in the La Niña-related experiments, may be one pathway, consistent with understanding of the influence of Ural blocking on the polar vortex (Cohen et al. 2007; Luo et al. 2016, 2017; Peings 2019; Yao et al. 2017).

Albeit of weaker magnitude than the IPO- and LaNina-related experiments, in the SICSST experiment, there is a pattern reflecting upward propagation of PCH anomalies before early January and subsequently downward propagation in the following weeks (Fig. 5b), broadly consistent with that observed (Fig. 5a; Lu et al. 2021). This pattern, also apparent in SICSST+NPDO, could reflect the so-called stratospheric pathway through which autumn sea-ice loss can weaken the stratospheric polar vortex and favour cold extremes in late winter (e.g., Kim et al. 2014; Zhang et al. 2018). Although the timing of PCH anomalies do not match exactly with that observed, in any of the experiments, this is to be expected due to internal variability. In summary, our simulations suggest that Arctic and especially tropical Pacific Ocean forcing increased the likelihood of an SSW in early winter 2020/21.
Fig. 5. Observed (a) and simulated (b–h) daily polar-cap height (PCH; averaged north of 65ºN) anomalies. Black lines in (a) denote onset and end dates of the observed SSW event in winter 2020/21. Magnitude in (a) is one-third of that in simulation to facilitate comparison. White line (black stippling) denotes statistical significance at the 95% confidence level of CDR test (t-test). The numbers provided in the top right corner denote the change in the number of sudden stratospheric warming events (SSW; reversal of zonal wind at 60ºN and 10 hPa for 3 days or longer).

Regardless of the cause of the January 2021 SSW, it is possible that the subsequent downward propagation and surface cooling effect were modulated by the background state (i.e., boundary conditions). For example, Zhang et al. (2020) indicated that, in the presence of reduced Barents–Kara sea ice, SSWs favour the occurrence of surface cold events over North America in the following several weeks. The SICSST, IPO, NPDO, LaNina, and SICSST+LaNina experiments simulate cooling in western North America, extending further south and stronger than shown earlier, when we subsample the ensemble members that feature a SSW (Fig. 6). Looking at the probability of cold extremes, only the SICSST, LaNina, and SICSST+LaNina experiments display increased likelihood of cold days in SSW cases relative to noSSW cases in perturbation runs. Noting also the lower frequency of cold days in SSW cases relative to noSSW cases in the control run (Fig. 6i–o), this can also be found in the maps of Fig. 7a, consistent with Zhang et al. (2020). The SICSST+LaNina experiment shows the most commonality of spatial pattern and probability with observed (Fig. 6g). This suggests that the combination of an SSW, reduced sea ice and La
Niña is favorable for the extreme cooling from Alaska to Southern Great Plains, as observed in February 2021.

Fig. 6 (a–g) Differences in the extreme cold SAT anomalies (defined as the average of 1% coldest daily SAT anomalies) and 500-hPa geopotential height anomalies (interval of 75 m) during the 30-day window of 25 Jan–23 Feb 2021 between SSW and noSSW cases in perturbation experiments, relative to the differences between SSW and noSSW cases in the control run. Number of ensemble members with SSW events is shown in topright. (h) As Fig. 4h but with magnitude halved to facilitate comparison. (i–o) show the cold tails of cumulative PDFs (CDFs) of daily SAT anomalies during the 30-day window in SSW cases (CTL_SSW; solid gray line) and noSSW cases (CTL_noSSW; dashed gray) in control run, and in SSW cases (e.g., SICSST_SSW; solid color line) and noSSW cases (e.g., SICSST_noSSW; dashed color line) in perturbation experiments. (p) shows the CDFs of observed daily SAT anomalies during the 30-day window in SSW years (ERA5_CTL_SSW; solid gray line) and noSSW years (ERA5_CTL_noSSW; dashed gray line) and in Jan–Feb 2021 (ERA5_2021_SSW; solid black line).
We next consider whether the effects of the SSW and boundary forcings act independently and are superimposed, or whether the boundary conditions modulate the surface effects of SSWs. In the control run, the extreme cold surface temperature difference between cases with and without SSWs shows robustly extreme cooling over high latitude Eurasia and eastern and middle North America, and warming over northwestern North America (Fig. 7a; Fig. S6a), consistent with Domeisen and Butler (2020). In contrast, in the SICSST+LaNina experiment, the SSW is associated with stronger cooling over eastern and middle North America (Fig. 7b; Fig. S6b). The difference between the estimated effect of SSW in the control case compared to with observed Arctic and tropical Pacific Ocean boundary conditions in 2020/21 is shown in Fig. 7c and Fig. S6c. It shows an intensified cold extreme over North America from Alaska to Texas and extends eastward to eastern North America. The western North American cooling is similar to observed, suggesting that the boundary conditions in winter 20/21 modulated the surface effect of the SSW and amplified its cooling influence. In the control experiment, following an SSW, there is downward propagation of PCH anomalies, which reach the surface in late February (Fig. 7d) and approximately 10-50 days later (Fig. 7g). In comparison, in the SICSST+LaNina experiment, there appears to be stronger coupling between the stratosphere and troposphere and faster downward propagation of positive PCH anomalies (Fig. 7e and 7h). The largest surface cooling over North America occurs approximately 27–32 days after the onset of SSWs, and the differences between control and SICSST+LaNina conditions are significant (Fig. 7f and 7i; Fig. S7), in good consistency with Zhang et al. (2020). The delay in the surface temperature response has important implications for the timing of cold events and intraseasonal predictions (Zhang et al. 2022). In summary, our results suggest that reduced sea ice and La Niña together modulate the surface temperature response to SSWs, leading to colder temperatures over North America (and East Asia) than in the absence of these boundary conditions.
Fig. 7 Differences in the extreme cold SAT anomalies and 500-hPa daily geopotential height anomalies during the 30-day window of 25 Jan–23 Feb 2021 between SSW and noSSW cases in control run (a), SICSST+LaNina experiment (b), and their difference (c; b minus a). (d–f) As (a–c) but for differences in the daily evolution of PCH responses from 1 Nov 2020–28 Feb 2021. (g–i) As (a–c) but for differences in the post-SSW evolution of daily PCH responses. White line (black stippling) denotes statistical significance at the 95% confidence level of CDR test ($t$-test).
4. Discussion and Conclusions

Comparing large-ensemble WACCM simulations prescribed with observed sea ice and/or Pacific Ocean SST to analogous simulations with climatological values, we estimate the role of ocean surface boundary conditions in altering the likelihood of extreme cold events observed in winter 2020/21. More specifically, we consider the extreme cold events in early January 2021 over midlatitude Eurasia, late January 2021 over high-latitude Eurasia, and early February over western North America. It is important to reiterate that although the AGCM experiments reproduce many aspects of observed extreme cold events during winter 2020/21, the magnitude of severity is smaller than observed. This implies, perhaps unsurprisingly, a large role for unforced internal variability. Nevertheless, our result suggest the Arctic and Pacific Ocean surface conditions in winter 2020/21 increased the likelihood of the observed cold events by approximately 17%–43% relative to the control run.

A potential caveat of this study is that it makes use of an atmosphere-only climate model to conduct AMIP-type boundary-condition sensitivity experiments and, therefore neglect coupling between the atmosphere and ocean. Considering the nature of the atmospheric-only framework, the preclusion of ocean feedbacks may have a broad range of complex influences (e.g., Peings and Magnusdottir, 2015) and present a distorted picture of the importance of large-scale drivers (e.g., Smith et al., 2017; Screen et al., 2018). The present study examines the potential for a simultaneous and lagged winter response to surface conditions from autumn to winter, coupling to the ocean may allow for additional mechanisms for delayed responses, such as feedbacks with the ocean and sea ice. Although these limitations of AMIP runs, the Northern Hemisphere extratropical responses to the uncoupled cases are largely consistent with the coupled cases, but slightly damped in magnitude (Deser et al. 2016; Screen 2017). For a thorough investigation of the Arctic sea-air interaction and associated influence on midlatitude cold events, coupled models are under consideration in the future to compare with the present uncoupled ones.

Notwithstanding the caveats above, we conclude that reduced Arctic sea ice (and less likely warm North Pacific SSTs) were favourable for extreme cold conditions over midlatitude Eurasia during early January 2021. Both cold events in late January 2021 over high latitude Eurasia and early February 2021 over western North America were favoured by La Niña conditions. The extremely cold high-latitude Eurasia was largely caused by the combination of warm North Pacific
and cold eastern tropical Pacific SSTs. We relate the North American cold wave to the negative PNA pattern, partly a response to La Niña, and also to the SSW in early January 2021. Though Davis et al. (2022) have conducted forecasts with scrambled troposphere at one month lead (initialized on January 4th) to show a limited effect of SSW on this North American cold wave, we notice that the cold event was better simulated by the forecasts with scrambled stratosphere at one week lead (initialized on February 1st and 8th), since the SSW has already occurred and its effects have been imprinted in the troposphere. In addition, the reduced Arctic sea ice seems to induce weakened Aleutian low, contributing to the North American cold wave. The combination of reduced Arctic sea ice, La Niña, and a SSW were especially favourable for cold conditions stretching from Alaska to the Southern and eastern Great Plains, as observed in February 2021. The Arctic sea ice and La Niña base state play critical roles in modulating the SSW impacts.

The last issue worthy of discussion is the plausible linkage between Eurasian cold waves weeks prior and the North American cold wave in February 2021. Actually, the cold spells that occurred in Eurasia was dynamically associated with the strengthening of the Ural high, which was supposed to weaken the stratospheric polar vortex and then contribute to cold-air outbreaks in North America (Lu et al., 2021). Such phenomenon can be seen in the SICSST experiment in which melting sea ice caused an upward propagation of Rossby waves into stratosphere in January (Fig. 2a). The ensemble members that captured the Eurasian cold wave do have better representation of the North American cold wave than the ensemble-mean, particularly in the SICSST, IPO, LaNiña, SICSST+IPO, and SICSST+LaNiña experiments (Fig. S8). It appears that the early winter Eurasian cold wave might have an influence on the North American cold outbreaks in late winter. Our results have implications for projections of future midlatitude climate, particularly in the context of ongoing declined sea ice, and changes in ENSO variability and teleconnections (e.g., Butler et al. 2016; Zhang R. et al. 2020).

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Data Availability Statement

All data used in this study are publicly available: SIC and SST datasets from UK Met Office Hadley Centre of (https://www.metoffice.gov.uk/), and ERA5 reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (https://cds.climate.copernicus.eu/).

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INTRODUCTION


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