Stratospheric modulation of winter temperature trends in a warming climate

Amy Butler (✉ amy.butler@noaa.gov)

NOAA Chemical Sciences Laboratory <https://orcid.org/0000-0002-3632-0925>

Alexey Karpechko

Finnish Meteorological Institute

Chaim Garfinkel

Finnish Meteorological Institute <https://orcid.org/0000-0001-7258-666X>

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Stratospheric modulation of winter temperature trends in a warming climate

Amy H. Butler*, National Oceanic and Atmospheric Administration, Chemical Sciences
Laboratory, Boulder, CO, USA

Alexey Yu. Karpechko, Finnish Meteorological Institute, Helsinki, Finland

Chaim I. Garfinkel, Fredy and Nadine Herrmann Institute of Earth Sciences, Hebrew
University of Jerusalem, Israel

*Corresponding author: amy.butler@noaa.gov

Variability in the circumpolar westerly winds of the Northern Hemisphere winter polar stratosphere-- the stratospheric polar vortex-- has a known downward influence on the extratropical surface climate on sub-seasonal timescales. On longer timescales, observed trends towards a weakening stratospheric polar vortex have been linked to cooling surface temperatures over Eurasia from 1990-2009. Here, we show that 10-40 year polar vortex weakening trends occur as often as strengthening trends in large-ensemble historical climate simulations, and that decadal variability in polar vortex trends is significantly linked to decadal variability in regional surface temperature trends across the Northern Hemisphere even as the climate warms. We find that 74% of ensemble members with cooling trends over Eurasia during an 1850-2099 climate simulation also exhibit a weakening polar vortex, while 70% of members with accelerated warming over Eurasia exhibit a strengthening polar vortex. Decadal variability in the polar vortex thus modulates extratropical anthropogenically-forced warming trends.

The Northern Hemisphere stratospheric polar vortex describes the westerly circumpolar winds in the region 10-50 km above the surface that form every year in boreal winter as sunlight disappears from the pole. The strength of the polar vortex is highly variable from December to February, and is both influenced by, and in turn influences, the tropospheric circulation. This two-way coupling occurs due to interactions of large-scale atmospheric waves with the mean stratospheric flow, though aspects of the coupling mechanism remain uncertain¹. Extremes in the polar vortex strength have been linked to extremes at the surface², with implications for prediction

across timescales^{3–5}. In particular, an anomalously weak polar vortex (often associated with a “sudden stratospheric warming”) is associated with cold surface temperature anomalies in northern Europe and Asia, and warm surface temperature anomalies over eastern Canada, Greenland, and subtropical Africa and Asia^{6,7}. Opposite-signed surface temperature anomalies in those regions are observed when the vortex is anomalously strong, meaning that the polar vortex has been shown to also contribute to winter heat extremes over, e.g., Siberia⁸.

The question of how the stratospheric polar vortex will change as greenhouse gas emissions increase and whether it can exert substantial influence on wintertime weather on longer than sub-seasonal timescales has gained interest, not least because from ~1990-2009, a significant weakening of the polar vortex was observed. This vortex weakening was linked to a period of cooling surface temperatures (and thus a “hiatus” of winter warming) over Eurasia^{9,10} and colder snowier weather in other regions^{11,12}. There remains debate about whether this vortex weakening was forced by concurrent rapid Arctic sea ice loss^{13,14} or was just sampling of internal variability^{15–17}, and whether Arctic amplification will mean more winter weather extremes in the future¹⁸.

However, future projections of the strength of the Northern Hemisphere polar vortex are highly uncertain, with the number of climate models predicting a weakening vortex nearly the same as the number predicting a strengthening vortex in high greenhouse gas emission scenarios^{19–22}. This uncertainty in future trends of the vortex contributes substantially to uncertainties in the projections of Northern Hemisphere extratropical surface climate^{23,24}, contributing up to 20% of the across-model CMIP5

spread in precipitation trends over Europe and up to 50% of the across-model spread in sea level pressure trends over the Arctic²⁵.

While understanding the mechanisms that might drive a forced response of the polar vortex to climate change is important, the influence of decadal changes in the polar vortex, whether forced or due to internal variability, on future surface climate remains the underlying motivation for these studies. In this study, we seek to answer the questions: how much can decadal variability in the stratospheric polar vortex modulate surface temperature trends? Can the mid-latitudes experience decades of enhanced winter cold extremes even in a rapidly warming global climate if the polar vortex weakens? And, for how long can such a cooling trend persist?

Decadal variability in polar vortex and surface temperatures linked

The wintertime stratospheric polar vortex exhibits large variability even on decadal timescales. For example, the polar vortex weakened significantly during ~1990-2009 (**Fig 1a**). This trend was associated with an exceptionally strong and stable polar vortex in the 1990s compared to past decades²⁶, while the 2000s had a disruption of the vortex almost every year²⁷. On the other hand, during ~2001-2020 the polar vortex strengthened. The polar vortex is strongly coupled to the large-scale wintertime tropospheric circulation, of which the dominant pattern of variability is the Northern Annular Mode^{28,29} (NAM, see *Methods*) (**Fig 1b**). On interannual timescales, the polar vortex time series explains 44% ($r=-0.66$, $p<0.01$) of the variability in the NAM (for detrended DJF-mean time series, 1959-2020). The NAM also showed a negative trend from 1990-2009 and a positive trend from 2001-2020 (**Fig 1b**).

Figure 1. Indices of the stratospheric polar vortex and surface Northern Annular Mode.

DJF (a) geopotential height anomalies [m] at 50 hPa, 70-90N from JRA-55 reanalysis; (b) standardized NAM index from NOAA Climate Prediction Center. Linear trendlines for 1990-2009 (blue) and 2001-2010 (red) are shown. The y-axis in (a) is reversed (negative height anomalies mean a stronger polar vortex).

A comparison of 20-year linear trends in the wintertime tropospheric circulation and surface temperatures (**Fig. 2a,d**) shows strong Arctic surface warming and increasingly positive geopotential heights over the Arctic during both time periods. Differencing the trends (**Fig 2g**) shows that the trends from 1990-2009 were characterized by a more negative NAM-like circulation relative to the trends from 2001-2010, with stronger warming over the North Atlantic and Greenland, cooling over the mid-latitudes, and warming over subtropical Africa and Asia.

The trends during these 20-year time periods that are linearly congruent with trends in the polar vortex (**Fig 2b,e**, see *Methods*) resemble the North Atlantic Oscillation (NAO), the regional manifestation of the NAM. From 1990-2009, the polar vortex weakening trend is congruent with almost 3 times the observed cooling of surface temperatures over Eurasia, 70% of the observed warming over subtropical

Africa and Asia, and 35% of the warming over the Greenland/eastern Canadian regions (identified by the blue, red, and green boxes in **Fig 2b**, respectively; see also Supplementary **Fig S1**). From 2001-2020, the trend towards a strengthening polar vortex explains tropospheric circulation and surface trends in the opposite sense. Because the amplitude of the strengthening polar vortex trend is weaker, overall it explains a smaller fraction of the tropospheric trends, but still explains 30% of the observed warming over Eurasia and more than three times the observed cooling in the Greenland region.

Differencing the component that is linearly congruent with the polar vortex trends for the 1990-2009 and 2001-2020 periods reveals a canonical negative NAO pattern associated with stratosphere-troposphere coupling (**Fig 2h**). This pattern is spatially similar to the total trend differences between these two periods (**Fig 2g**), and indeed explains the entirety of the Eurasian cooling, most of the subtropical Eurasian/African warming, and around half of the Greenland warming. In other regions, like the Pacific sector, the total trend differences seem unrelated to trends congruent with the polar vortex, suggesting an additional role for other factors (e.g. tropical variability³⁰) to influence regional trends during these two time periods.

Figure 2. Trends in wintertime surface temperatures and circulation during two recent periods. DJF surface temperature [shading, degK/decade] and 500 hPa geopotential height [contours, m/decade] (a,d) total linear trends, (b,e) trends congruent with polar vortex trends, and (c,f) residual trends (e.g., a-b, d-e) for the (left column) 1990-2009 and (middle column) 2001-2020 period. The right column (g-i) shows the differences between the left and middle columns. All panels use JRA-55 reanalysis. The blue, green, and red outlines in (b), (e) are the Eurasia, Greenland, and subtropical Asia regions referred to in the other figures.

Removing the stratospheric contribution from the total trends (**Fig 2c,f**) shows temperature trends over much of high-latitude Eurasia for the 1990-2009 period that are *opposite* to the total temperature trends, highlighting the dominant role the polar vortex played^{9,10}. Similarly, the residual temperature trends in the mid- and subtropical latitude regions are small particularly for the 1990-2009 period, suggesting that the stratospheric contribution was substantial. In other regions, on the other hand, the stratospheric contribution was more muted. For example, there is a residual amplified warming trend over the Arctic during both time periods, particularly over the Barents-Kara sea, which is associated with an amplified positive trend in geopotential heights. Differencing the residual trends (**Fig 2i**) highlights trend differences not linearly related to the polar vortex trends, including cooling over the North Pacific and warming over the North Atlantic during 1990-2009 relative to 2001-2020, perhaps reflecting decadal variability in sea surface temperatures (SSTs).

Figure 3 shows that DJF trends in the polar vortex during the 1990-2009 period explain a significant fraction of the variability across ensemble members of the trends in surface temperatures for the regions highlighted in Fig. 2, for two large-ensemble comprehensive global climate simulations. One set of model simulations is the 29-member ensemble of the Goddard Earth Observing System Chemistry-Climate Model, Version 2 (GEOSCCM)³¹ [see *Methods*] forced by observed SSTs, sea ice, and greenhouse gas concentrations for the period from January 1980 to December 2009. The other set is the fully coupled atmosphere-ocean Max Planck Institute Grand Ensemble (MPI-GE)³² [see *Methods*], which consists of 100 ensemble members, for historical (1850-2005) and RCP-8.5 (2006-2099) simulations. In both large-ensemble

model simulations during the 1990-2009 period, there is a significant ($p < 0.05$) negative correlation between the DJF trends in the polar vortex and northern Eurasian near-surface (2m) temperatures across ensemble members (**Fig 3a,d**), consistent with previous findings⁹. Ensemble members with greater weakening trends of the stratospheric polar vortex are not only linked to stronger cooling trends over Eurasia, but also significantly ($p < 0.05$) stronger warming trends over Greenland (**Fig 3b,e**) and subtropical Asia (**Fig 3c,f**). Conversely, ensemble members with a *strengthening* trend of the stratospheric polar vortex simulate pronounced warming trends over Eurasia, and cooling trends over Greenland and subtropical Asia. These relationships between trends in the strength of the polar vortex and surface temperatures across ensemble members echo their interannual relationships (Supplementary **Fig S2**).

Interestingly, the correlations between the DJF polar vortex and both Eurasian and subtropical Asian surface temperature trends are considerably weaker in the MPI-GE, even after sub-sampling to 29-members to compare with GEOSCCM (**Fig 3g,i**), which suggests either (a) the influence of the stratosphere on the surface climate in these two regions is significantly weaker in MPI-GE, or (b) the coupled ocean in MPI-GE contributes to greater variability across ensemble members. MPI-GE also underestimates the observed interannual relationships in these two regions (Supplementary **Fig S2**). For GEOSCCM, no ensemble members capture the magnitude of the observed polar vortex weakening; however, the observed values fall within the ensemble range for MPI-GE. Notably, the magnitude of the polar vortex induced uncertainty (the range of temperature trends associated with different vortex responses) is more than a factor of two larger than the ensemble mean temperature

189 response (the forced response) for all regions and for both large ensembles over these
 190 twenty years.

191
 192 **Figure 3. Comparing trends across ensemble members of wintertime temperatures and**
 193 **the polar vortex in two model simulations.** DJF trends from 1990-2009 for (a-c) 29 ensemble
 194 members in GEOSCCM (dots) and (d-f) 100 ensemble members in MPI-GE (triangles) and 3
 195 reanalysis products (ERA5, ERA-interim, and MERRA; black plus signs), for the stratospheric
 196 polar vortex (50 hPa, 70-90N) in [m/decade] versus (a,d) Eurasian 2m-temperature (T2m)
 197 trends [degK/decade] (blue markers; land gridpoints area-weighted from 0-145E, 45-80N), (b,e)
 198 Greenland T2m trends [degK/decade] (green markers; land gridpoints area-weighted from 90W-
 199 40W, 50-80N), and (c,f) subtropical Asia/Africa (red markers, land gridpoints area-weighted from
 200 0E-90E, 15N-45N) T2m trends [degK/decade]. (g-i) Histograms of the correlations obtained
 201 when MPI-GE is subsampled to 29 randomly selected ensemble members (repeated 1000
 202 times). The vertical colored lines in (g-i) show the corresponding correlation in the 29 members
 203 of GEOSCCM (e.g., values from (a-c)).

204

Up to this point, we have focused on the 20-year time period from 1990-2009. To investigate the stationarity of the relationship, we show the correlation across MPI-GE ensemble members of the DJF trends in polar vortex strength with trends in near-surface temperatures for the 3 different regions in **Fig 4a** and Supplementary **Fig S4**. The correlation remains relatively constant for 20 year periods sub-sampled from the pre-industrial period through the end of the century in the RCP-8.5 scenario (average correlation: $r = -0.40$ for Eurasia, $r = 0.24$ for subtropical Asia, $r = 0.40$ for Greenland, $p < 0.02$ for all using Fisher-Z transformation), though there is sensitivity in the strength of the relationship to the starting/end points of the trends.

That the relationship of 20-year DJF trends between the polar vortex and surface temperature remains relatively stationary from 1850-2099 is relevant because the climate is changing rapidly in this scenario. In the MPI-GE, after 1950, the ensemble-mean 20-year temperature trends over all regions are positive (**Fig 4b,d,f**), approaching an average of 0.8 K/decade by the end of the century over Eurasia and Greenland and 0.5 K/decade over subtropical Asia/Africa. In this particular model, the polar vortex strengthens in the ensemble-mean after 2000 (Supplementary **Fig S3**); however, there are individual ensemble members for which the vortex weakens over 20-year periods even at the end of the 21st century in the RCP-8.5 scenario. We re-calculate the 20-year temperature trends for only those ensemble members that also show either polar vortex weakening or strengthening during the same 20-year period. We find that the temperature trends are on average 0.36 K/decade colder over Eurasia, 0.38 K/decade warmer over Greenland, and 0.09 K/decade warmer over subtropical Asia/Africa when the polar vortex is weakening compared to strengthening (**Fig 4b,d,f**). Thus, 20-year

Figure 4. Variations in 20-year surface temperature trends and their connection to concurrent trends in the polar vortex from 1850-2099 in historical and RCP8.5 climate change simulations. (a) Correlations between 20-year DJF trends in the polar vortex (Z50) and T2m trends over Eurasia (blue), Greenland (green), and subtropical Asia (red) across 100 MPI-GE ensemble members as a function of starting year. Dots correspond to 20-year trends starting in 1990 as shown in Figs 2-3. Grey shading shows the region of $p < 0.025$ significant correlations using a 2-tailed t-test. (b,d,f) 20-year DJF T2m trends over (b) subpolar Eurasia, (d) Greenland, and (f) subtropical Asia as a function of starting year for the ensemble-mean (solid), and for only those members also showing vortex weakening (dashed) or vortex

strengthening (dotted). Dots and crosses show trends for members with weakening vortex and those with strengthening vortex respectively, which are significantly different from each other at $p < 0.025$ (95th percentile) according to a 2-tailed t-test. (c,e,g) The total fraction (solid) of ensemble members showing negative DJF T2m trends for the 20-year period as a function of starting year for (c) Eurasia, and the total fraction showing warming trends exceeding by more than double the ensemble-mean trends for (e) Greenland and (g) subtropical Asia. The dashed (dotted) lines show the fraction of ensemble members that also show simultaneous weakening (strengthening) of the polar vortex. Dots and crosses mark fractions of members with simultaneous weakening (strengthening) and cooling (accelerated warming) trends that lie outside of the 5%-95% range of samples of members randomly drawn 10000 times from the full ensemble (see Methods).

trends in the polar vortex contribute to variability in 20-year trends in winter surface temperatures even in a warming climate, and can either temporarily amplify anthropogenic warming trends or reduce them.

Prior to 1950 roughly half of ensemble members show 20-year periods of cooling in Eurasia, and ~65% (35%) of those ensemble members also show simultaneous 20-year polar vortex weakening (strengthening) (**Fig 4c**). After 1950, the number of ensemble members showing negative 20-year Eurasian temperature trends drops significantly, but the relative fraction that show concurrent 20-year polar vortex weakening or strengthening remains the same. In other words, the decrease in negative 20-year Eurasian temperature trends is not because the relationship between the polar vortex and Eurasian temperature trends is weakening over time (**Fig 4a**, Supplementary **Fig S4**); rather, the thermodynamic response to increasing greenhouse gases is modulated by, but eventually dominates, the dynamic stratosphere-troposphere coupling influence. While 20-year periods of Eurasian cooling become increasingly less likely in a warmer climate when they do occur the majority of the time it's associated

with polar vortex weakening. Similarly, the fraction of ensemble members that show accelerated 20-year warming trends over subtropical Asia (trends more than double the ensemble-mean trend, **Fig 4g**) decreases over time as the ensemble-mean trend becomes larger and more difficult to surpass, but the relative fraction of those members that also show vortex weakening (strengthening) remains roughly the same (~60% [40%]).

While the fraction of ensemble members that show 20-year warming trends more than double the ensemble-mean trend over Greenland also decreases by the end of the 21st century (**Fig 4e**), unlike Eurasia or subtropical Asia, the relative fraction of those members that also show vortex weakening (strengthening) does change slightly from ~63% (37%) for trends beginning prior to 1950 to ~73% (27%) for trends beginning after 1950. This suggests a minor increase in the relative role of the polar vortex trends on Greenland temperature trends which also is reflected by a slight but systematic shift towards higher correlations between 20-year trends in the vortex and Greenland temperature trends after 1950 (**Fig 4a**, Supplementary **Fig S4**). Whether this is linked to the changing cryosphere over Greenland and associated stratosphere-troposphere coupling needs further exploration.

Stratospheric influence on trends exceeding 20 years

We've shown that variability in 20-year trends in the wintertime stratospheric polar vortex is significantly correlated to variability in wintertime surface temperature trends in three Northern Hemisphere regions. Do these relationships hold for longer length trends and for different periods of the record?

Figure 5. Linking Eurasian temperature trends to trends in the polar vortex as a function of trend length and start year. (a) Fraction of 100 MPI-GE ensemble members with negative DJF near-surface temperature trends over Eurasia as a function of starting year (x-axis) and length of trend (y-axis). (b) Same as (a) but for fraction of ensemble members with weakening DJF polar vortex trends. (c) The fraction of members identified in (a) as having negative DJF Eurasian surface trends that also show polar vortex weakening trends for the same time period. (d) Fraction of members with accelerated warming trends (defined as double the ensemble-mean trend) that also show polar vortex strengthening trends for the same time period (the colorbar is flipped from the other panels). In (c) and (d), only those fractions that exceeded the 95th percentile of a bootstrapping significance test are shown (see *Methods* for details).

When we calculate the fraction of ensemble members in MPI-GE that show negative Eurasian surface temperature trends as a function of start year and trend length (**Fig 5a**), we find that on average 46% of the ensemble members have negative 10-20 year temperature trends and 38% of ensemble members have negative 20-50 year temperature trends in the historical climate (starting trend years 1850-1950).

Exceptions are generally congruent with large volcanic eruptions, e.g., 1883 (Krakatoa), which is associated with a stronger polar vortex³³ and warmer wintertime temperatures over Eurasia³⁴ in the MPI-GE. After 1950, negative Eurasian temperature trends for any period greater than 10 years become less common; however, negative 10-20 year trends still occur in 21% of ensemble members even during the 21st century RCP-8.5 climate, indicating that internal climate variability can still modulate trends on timescales less than 20 years even in a strongly warming climate. On the other hand, very few members (on average 5%) show negative 50-120 year Eurasian temperature trends in the historical+RCP-8.5 climate scenario, no matter the starting year.

How many of the ensemble members that show cooling trends over Eurasia also show weakening trends of the polar vortex? Overall, 50% of members show polar vortex weakening for 10-50 year trends starting during the 1850-1950 period (**Fig 5b**), though for this particular model this number decreases to 28% for trends starting after 2000 (the ensemble-mean shows vortex strengthening in the 21st century, Supplementary **Fig S3**). While correlations between polar vortex trends and Eurasian surface temperature trends across ensemble members are fairly stationary, even for different trend lengths (Supplementary **Fig S4**), we find that on average, 74% of all negative Eurasian temperature trends from 1850-2100, regardless of trend length or start year, coincide with vortex weakening (**Fig 5c**). Strengthening trends in the polar vortex are also associated with accelerated warming trends (more than double the ensemble-mean warming) over Eurasia (**Fig 5d**). 70% of all accelerated warming trends over Eurasia during the 1850-2099 period, regardless of trend length or start year, coincide with vortex strengthening.

Discussion

There are a few important caveats to address. First, these results do not necessarily imply causality of the polar vortex trends on surface climate trends, as the stratosphere and troposphere are coupled via two-way interactions between the mean flow and atmospheric waves. For example, it's possible that trends towards certain surface climate patterns can also drive stratospheric polar vortex trends. However a quantitatively similar effect is seen on subseasonal and interannual timescales where the direction of causality is clearer (Supplementary **Fig S2**). Either way, our results suggest that decadal variability in the polar stratospheric and extratropical tropospheric wintertime circulations are closely linked, even across many decades and in a rapidly warming climate.

Second, the index for the polar vortex used in this study is a measure of its relative strength, and does not take into account, e.g. long-term shifts of the vortex off the pole³⁵ or changes in the shape of the vortex³⁶. Trends in these characteristics of the polar vortex may be relevant for future changes in extreme events such as cold-air outbreaks over North America or Europe.

Finally, the overall importance of stratospheric variability differs between the two models considered here for the 1990-2009 period, potentially associated with additional noise arising from atmosphere-ocean coupling in MPI-GE. Thus additional models should be considered for future work to better quantify the role of the stratosphere. While the quantitative details of our results may be model-dependent, the overall correlation of polar vortex trends and surface temperature trends changes little for

longer trend periods and different start and end dates even in the model with a relatively weaker stratosphere-troposphere coupling response. In addition, even in a model like MPI-GE where the polar vortex response to anthropogenic greenhouse gas emissions is a strengthening, we find that 10-50 year trends in polar vortex weakening still occur in about a third of the ensemble members during the 21st century, which means that temperature trends over Eurasia will be colder, and over subtropical Asia and Greenland will be warmer, for those scenarios compared to if the polar vortex strengthened.

Conclusions

The key result of our study is that variability of the stratospheric polar vortex is large even on decadal timescales, and this variability can significantly modulate regional extratropical surface temperature trends even in a warming climate. Decadal stratospheric polar vortex weakening trends very often coincide with trends towards Eurasian cooling, subtropical Asian/African warming, and Greenland warming, as observed during the 1990-2009 period. Likewise, trends towards stratospheric polar vortex strengthening often coincide with surface temperature trends in those regions in the opposite direction, as observed during the 2001-2020 period. In both MPI-GE and the GEOSCCM model for the 1990-2009 period, the within-ensemble uncertainty in trends associated with the stratospheric polar vortex is more than double the forced response (i.e. ensemble mean). In the MPI-GE historical and RCP-8.5 climate simulation, 74% of all negative Eurasian temperature trends coincide with vortex

weakening and 70% of all amplified Eurasian warming trends coincide with vortex strengthening.

Is the decadal variability in surface temperatures that is linked to the decadal variability in the polar vortex enough to substantially modulate anthropogenically-forced warming trends? During the 1990-2009 period, the observed Eurasian cooling associated with a weakening of the polar vortex overwhelmed the simulated forced signal associated with climate change. Additionally, MPI-GE ensemble members that show 20-year periods of polar vortex weakening exhibit temperature trends that are on average 0.36 K/decade colder over Eurasia and 0.38 K/decade warmer over Greenland compared to ensemble members exhibiting 20-year polar vortex strengthening trends. This difference is a significant fraction of the forced signal, which is on the order of 0.5-1.0 K/decade in these regions during the 21st century, suggesting that decadal polar vortex variability could contribute to decades of reduced or amplified anthropogenic warming, depending on the region.

Nonetheless, it becomes increasingly unlikely during the 21st century that decadal variability in surface temperatures related to polar vortex variability will overwhelm the anthropogenically-forced surface warming trends under the high greenhouse gas emissions (RCP-8.5) climate change scenario we have considered in this study. It is possible that in a scenario where increased greenhouse gas emissions are strongly mitigated, decadal weakening trends of the polar vortex could more readily contribute to periods of colder Eurasian winters, as observed in the pre-industrial to present-day climate.

Methods

Observational datasets

The reanalysis products used in this study are JRA-55³⁷, ERA-Interim³⁸, ERA-5³⁹, and MERRA⁴⁰. We use geopotential height anomalies at 50 hPa and near-surface (2m) temperature anomalies from all reanalyses. For JRA-55, we also use the 500 hPa geopotential height anomalies (Figure 2).

The NAM index is from the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table). It is calculated as the principal component of monthly-mean 1000 hPa geopotential height anomalies from 20-90°N.

Large-ensemble model simulations

GEOSCCM

We examine a 29 member ensemble of the Goddard Earth Observing System Chemistry-Climate Model, Version 2 (GEOSCCM)³¹ of the period from January 1980 to December 2009⁹. The model has 72 vertical layers, with a model top at 0.01 hPa, and all simulations discussed here were performed at 2° latitude × 2.5° longitude horizontal resolution. These simulations all include changing SSTs, sea ice, and greenhouse gas concentrations. We use time varying observed SSTs and sea ice up to November 2006 from the Met Office Hadley center observational database⁴¹ and from the National Climatic Data Center⁴² since then. Greenhouse gas concentrations are from observations up to 2005 and from the Representative Concentrations Pathway 4.5 after

2005⁴³. The Quasi-biennial Oscillation is spontaneously generated by the gravity wave scheme⁴⁴.

MPI-GE

The second model ensemble is the Max Planck Institute Grand Ensemble (MPI-GE)³², which consists of 100 members for the historical simulations and for four forcing scenario simulations by the Max-Planck Institute Earth System Model (MPI-ESM). MPI-GE is one of the largest available ensembles of climate simulations by an Earth system model. As such, it is perfectly suited for quantifying the role of internal variability in climate change and separating and quantifying the forced signal. The atmospheric component of the model is ECHAM-6⁴⁵ run in a T63L47 configuration. The ocean component is MPIOM⁴⁶ run on the GR15L40 grid. Approximate resolution of the ocean component is $1.5^{\circ} \times 1.5^{\circ}$ in latitude-longitude grid with increased density towards the poles, and that of the atmospheric component is $1.8^{\circ} \times 1.8^{\circ}$. MPI-ESM includes the land component JSBACH⁴⁷ which has dynamic vegetation with a fire module and accounts for land use changes, and ocean biogeochemistry component HAMOCC5.2⁴⁸. For this study we used historical (1850-2005) and RCP-8.5 (2006-2099, a high-emissions scenario) ensemble simulations concatenated to make continuous 1850-2099 timeseries.

Methodology

The polar vortex time series is calculated using monthly-mean 50 hPa geopotential heights averaged using cosine-weighting over 70-90N. The seasonal cycle

is removed and the wintertime (Dec-Feb) mean of the anomalies is then calculated. This index is a close approximation to the stratospheric annular mode⁴⁹. For the calculation of the polar vortex in the MPI-GE simulation, the global-mean 50 hPa geopotential height at each time step is first removed from the gridded monthly-mean 50 hPa height field, to account for the effects of rising heights due to anthropogenic warming⁵⁰. The results shown are not sensitive to whether this step is included.

For Figure 2, total trends in surface temperature and 500 hPa height anomalies are calculated as the linear least squares fit of the monthly-mean data across each time period. To determine the portion of the trends that can be explained by trends in the polar vortex (**Fig 2b,e**), we multiply the trend in the polar vortex time series during this period (**Fig 1a**) by the regression map of the 500 hPa height or surface temperature anomalies onto the polar vortex time series⁵¹. These regression coefficients are determined using linearly detrended time series for the full 1958-2020 period.

Statistical significance tests

Significance testing of correlation coefficient values in Figures 1, 3, and 4a is calculated using a two-tailed Student's t-test.

Significance testing for Figure 4b,d,f was done using a 2-tailed t-test comparison of slope/regression coefficients. In particular we evaluate:

$$(1) \quad t = \frac{(bw-bs)}{\sqrt{s_{bw}^2+s_{bs}^2}}$$

Where bw and bs are the regression coefficients (linear trend values) for the 20-year temperature trends for a given start year averaged over the Nw ensemble members with either weakening trends, or the $Ns=100-Nw$ members with strengthening trends,

respectively. s_{bw} and s_{bs} are the errors in the regression coefficient calculated following the uncertainty propagation rule: since $bw = (bw1 + bw2 + \dots + bwN)/Nw$ then

$$(2) \quad s_{bw} = \frac{\sqrt{s_{bw1}^2 + s_{bw2}^2 + \dots + s_{bwN}^2}}{Nw}$$

where $s_{bw1} \dots s_{bwN}$ are slopes in Nw members with weakening vortex. s_{bs} is calculated in a similar manner for the Ns members with strengthening vortex.

Significance testing for Figure 4c,e,g and Figure 5c,d was performed by first randomly drawing the number of members that exhibit cooling trends (or accelerated warming trends) for each start year. Then the fraction of polar vortex weakening and strengthening trends in this random sample is calculated. The procedure is repeated 10000 times to get a distribution. For Figures 4c,e,g and Figure 5c, where the actual fraction of members with cooling (accelerated warming) trends that show polar vortex weakening (strengthening) exceeds (falls below) the 95th (5th) percentile of this distribution, the null hypothesis that the simultaneous cooling (accelerated warming) and vortex weakening (strengthening) trends occurred by chance is rejected, and the fraction is considered unlikely to have occurred by chance. Similarly for Figure 5d, the null hypothesis is rejected where the actual fraction of members with Eurasian accelerated warming that show polar vortex strengthening exceeds the 95th percentile.

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487

488 **Author Contributions**

489 AHB did the analysis for Figs 1-2 and wrote the text. CIG provided model data for
490 GEOSCCM and did the analysis for Fig 3. AYK provided model data for MPI-GE and
491 did the analysis for Fig 3-5.

492

493 **Competing interests**

494 The authors declare no competing interests.

495

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Figure Legends

Figure 1. Indices of the stratospheric polar vortex and surface Northern Annular

Mode. DJF (a) geopotential height anomalies [m] at 50 hPa, 70-90N from JRA-55 reanalysis; (b) standardized NAM index from NOAA Climate Prediction Center. Linear trendlines for 1990-2009 (blue) and 2001-2010 (red) are shown. The y-axis in (a) is reversed (weaker height anomalies mean a stronger polar vortex).

Figure 2. Trends in wintertime surface temperatures and circulation during two

recent periods. DJF surface temperature [shading, degK/decade] and 500 hPa geopotential height [contours, m/decade] (a,d) total linear trends, (b,e) trends congruent with polar vortex trends, and (c,f) residual trends (e.g., a-b, d-e) for the (left column) 1990-2009 and (middle column) 2001-2020 period. The right column (g-i) shows the differences between the left and middle columns. All panels use JRA-55 reanalysis. The blue, green, and red outlines in (b), (e) are the Eurasia, Greenland, and subtropical Asia regions referred to in the other figures.

Figure 3. Comparing trends across ensemble members of wintertime

temperatures and the polar vortex in two model simulations. DJF trends from 1990-

2009 for (a-c) 29 ensemble members in GEOSCCM (dots) and (d-f) 100 ensemble members in MPI-GE (triangles) and 3 reanalysis products (ERA5, ERA-interim, and MERRA; black plus signs), for the stratospheric polar vortex (50 hPa, 70-90N) in [m/decade] versus (a,d) Eurasian 2m-temperature (T2m) trends [degK/decade] (blue markers; land gridpoints area-weighted from 0-145E, 45-80N), (b,e) Greenland T2m trends [degK/decade] (green markers; land gridpoints area-weighted from 90W-40W, 50-80N), and (c,f) subtropical Asia/Africa (red markers, land gridpoints area-weighted from 0E-90E, 15N-45N) T2m trends [degK/decade]. (g-i) Histograms of the correlations obtained when MPI-GE is subsampled to 29 randomly selected ensemble members (repeated 1000 times). The vertical colored lines in (g-i) show the corresponding correlation in the 29 members of GEOSCCM (e.g., values from (a-c)).

Figure 4. Variations in 20-year surface temperature trends and their connection to concurrent trends in the polar vortex from 1850-2099 in historical and RCP8.5 climate change simulations. (a) Correlations between 20-year DJF trends in the polar vortex (Z50) and T2m trends over Eurasia (blue), Greenland (green), and subtropical Asia (red) across 100 MPI-GE ensemble members as a function of starting year. Dots correspond to 20-year trends starting in 1990 as shown in Figs 2-3. Grey shading shows the region of $p < 0.025$ significant correlations using a 2-tailed t-test. (b,d,f) 20-year DJF T2m trends over (b) subpolar Eurasia, (d) Greenland, and (f) subtropical Asia as a function of starting year for the ensemble-mean (solid), and for only those members also showing vortex weakening (dashed) or vortex strengthening (dotted). Dots and crosses show trends for members with weakening vortex and those with strengthening vortex respectively, which are significantly different from each other at $p < 0.025$ (95th percentile) according to a 2-tailed t-test. (c,e,g) The total fraction (solid) of ensemble members showing negative DJF T2m trends for the 20-year period as a function of starting year for (c) Eurasia, and the total fraction showing warming trends exceeding by more than double the ensemble-mean trends for (e) Greenland and (g) subtropical Asia. The dashed (dotted) lines show the fraction of ensemble members that also show simultaneous weakening (strengthening) of the polar vortex. Dots and crosses mark fractions of members with simultaneous weakening (strengthening) and cooling (accelerated warming) trends that lie outside of the 5%-95% range of samples of members randomly drawn 10000 times from the full ensemble (see Methods).

Figure 5. Linking Eurasian temperature trends to trends in the polar vortex as a function of trend length and start year. (a) Fraction of 100 MPI-GE ensemble members with negative DJF near-surface temperature trends over Eurasia as a function of starting year (x-axis) and length of trend (y-axis). (b) Same as (a) but for fraction of ensemble members with weakening DJF polar vortex trends. (c) The fraction of members identified in (a) as having negative DJF Eurasian surface trends that also show polar vortex weakening trends for the same time period. (d) Fraction of members with accelerated warming trends (defined as double the ensemble-mean trend) that also show polar vortex strengthening trends for the same time period (the colorbar is flipped

710 from the other panels). In (c) and (d), only those fractions that exceed the 95th
711 percentile of a bootstrapping significance test are shown (see *Methods* for details).
712

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