STRATOSPHERIC POLAR VORTEX TRENDS OF THE TWENTIETH AND TWENTY-FIRST CENTURIES AND AN ASSESSMENT OF THE CMIP5 HISTORICAL ENSEMBLE

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ABSTRACT

The state of the Northern Hemisphere (NH) stratospheric polar vortex is an indicator of NH wintertime weather. As such, its projected trends provide insight into the nature of future winters. Stratospheric vortex trends since 1980 have been studied in detail, but the trends of the entire twentieth century and of the twenty-first century have been studied very little. Previous work (Zhang et al. 2016) has explored connections between vortex trends and climate change impacts, implying that climate change has the potential to impact stratospheric polar vortex trends. We determine the polar vortex trends projected for the twenty-first century under conditions of increasing carbon dioxide emissions using the CMIP5 RCP8.5 emission scenario climate models. In addition, we use reanalysis data to explore the polar vortex trends of the twentieth century to better understand how it has behaved in the past. Also, we assess the CMIP5 Historical ensemble's ability to reproduce the past polar vortex trends, thereby putting the ensemble's future projections into context. Analysis of polar cap height (PCH) during the twentieth century reveals high internal variability, which must be taken into account when assessing the role of climate change on these trends. The CMIP5 Historical ensemble does not adequately reproduce the polar vortex trends of past; there is high spread among the ensemble members. However, certain individual models perform well. For the twenty-first century, the CMIP5 RCP8.5 ensemble projects a vortex shift toward Northeast Asia, with inconclusive results regarding future polar vortex strength.

1. INTRODUCTION

The stratospheric polar vortex is a low pressure circulation in the polar regions in the stratosphere that impacts winter weather in the middle and high latitudes. The stratospheric polar vortex exists over the Northern polar region as well as the Southern polar region, but it only exists during the winter season of each respective hemisphere. There also exists a tropospheric polar vortex in each hemisphere, the boundary of which is the polar jet stream (Waugh et al. 2017). This study focuses on the stratospheric polar vortex in the Northern Hemisphere. Hereafter, the terms "polar vortex" and "vortex" refer to the stratospheric polar vortex in the Northern Hemisphere.

Though the stratospheric polar vortex is distinct from the tropospheric polar vortex, the two are not isolated from one another. Tropospheric Rossby waves propagate up into the stratosphere, weakening the stratospheric polar vortex and distorting its shape (Waugh et al. 2017). The stratospheric polar vortex affects the tropospheric polar vortex as well; stratospheric annular mode anomalies tend to precede tropospheric annular mode anomalies of the same sign (Baldwin & Dunkerton 2001). Positive annular mode anomalies are associated with strong vortex conditions, while negative annular mode anomalies are associated with weak vortex conditions. Thus, a strong stratospheric vortex tends to precede a strong tropospheric vortex, and a weak stratospheric vortex tends to precede a weak tropospheric vortex. Furthermore, stratospheric polar vortex strength is an indicator of the frequency of extreme cold events in the Northern Hemisphere middle and high latitudes. Specifically, extreme cold events are more frequent at the middle and high latitudes during weak polar vortex conditions than during strong vortex conditions (Thompson et al. 2002).

Previous studies have examined the stratospheric polar vortex trends of the recent past. Zhang et al. (2016) and Seviour (2017) each found a positive trend in the fractional area of the polar vortex over the Eurasian continent from 1980-2016, suggesting a directional shift in the

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vortex's location toward Eurasia. Zhang et al. (2016) explored the connections between this directional shift and a reduction in sea-ice concentration, as well as increased snow cover over the Eurasian continent. Because Arctic sea-ice loss and increased snow cover over the Eurasian continent are impacts of climate change, these connections suggest that climate change has the potential to impact polar vortex trends.

In addition to the vortex shift toward Eurasia, Seviour (2017) found a positive trend in the polar cap area-averaged 50 hPa geopotential height, and negative trends in the latitudes of the potential vorticity (PV) maximum and of the vortex centroid from 1980-2016. These trends are indicative of an equator-ward vortex shift or a possible weakening of the vortex.

A previous study by Mitchell et al. (2012) examined the polar vortex trends of the twenty-first century under climate change conditions. The projected trends include a weakening of the vortex, as well as a climatological equatorward shift of the vortex centroid, implying more frequent vortex displacement events in the future. However, sudden stratospheric warming events, which are associated with a breakdown of the polar vortex, are not projected to increase in frequency during the twenty-first century.

This study expands upon the research of Zhang et al. (2016) and Seviour (2017) on stratospheric polar vortex trends of the past by expanding the time period studied to the entire twentieth century. Additionally, an ensemble of climate models within the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2011) is assessed by comparing the vortex trends found in their historical runs to the trends determined from reanalysis data from the same time periods. Next, the same ensemble of models within CMIP5 are used to determine the expected polar vortex trends for the twenty-first century. The polar vortex trends are projections within the context of climate change. Because the vortex trends are an indicator of winter weather at the middle and high latitudes, these expected trends give clues about winter weather under the worst-case-scenario climate change conditions.

2. DATA AND METHODS

This study examines the expected stratospheric polar vortex trends from 2005-2100 using the fifth phase of the Coupled Model Intercomparison Project (CMIP5) climate models (Taylor et al. 2011). Like the study by Mitchell et al. (2012), the Representative Concentration Pathway 8.5 (RCP8.5) ensemble of climate models is used (Vuuren et al. 2011). But, this study uses different vortex diagnostics than those used by Mitchell et al. (2012). The RCP8.5 pathway uses the steepest increase in carbon dioxide emissions out of all of the CMIP5 ensembles; it roughly doubles carbon dioxide emissions by the year 2100. The RCP8.5 pathway was chosen in order to determine the stratospheric polar vortex trends under the most extreme climate change scenario. Before studying the expected trends for the future, stratospheric vortex trends of the past are explored using the ERA-Interim reanalysis data set (1979-2016; Dee et al. 2011), which was used by both Seviour (2017) and Zhang et al. (2016) and has grid spacing 1.5° x 1.5° and 23 pressure levels. The ERA-20C reanalysis data set (1900-2010; Poli et al. 2016), which has grid spacing 1° x 1° and 37 pressure levels, is used for comparison with the ERA-Interim reanalysis data set during their shared time period, as well as to determine the polar vortex trends of the more distant past. To put the future model projections into context, we also analyze the CMIP5 Historical ensemble during the time period 1900-2005. The trends are then compared to the ERA-20C trends during the same period to assess the CMIP5 Historical ensemble's ability to reproduce the polar vortex trends of the past. Data from the CMIP5 climate models have 17-18 pressure levels and 0.9375°-2.022° x 1.25°-3.75° grid spacing, but are re-gridded to 1°x 1°grid spacing. Because the stratospheric polar vortex is a winter phenomenon, only data from winter months November-March (NDJFM) are used. All reanalysis and model data are monthly-mean geopotential height data at the 50 hPa level. The 50 hPa level is chosen because it is representative of stratospheric polar vortex variability, and for direct comparison with Seviour (2017).

The stratospheric polar vortex is characterized by low geopotential heights at the stratospheric levels. Based on this characteristic, a few measures of the polar vortex's location and strength were chosen. These measures are similar to those used by Zhang et al. (2016) and Seviour (2017) to determine the polar vortex trends of the recent past. One way to imagine the center of the stratospheric polar vortex is the minimum geopotential height across all grid points at a given

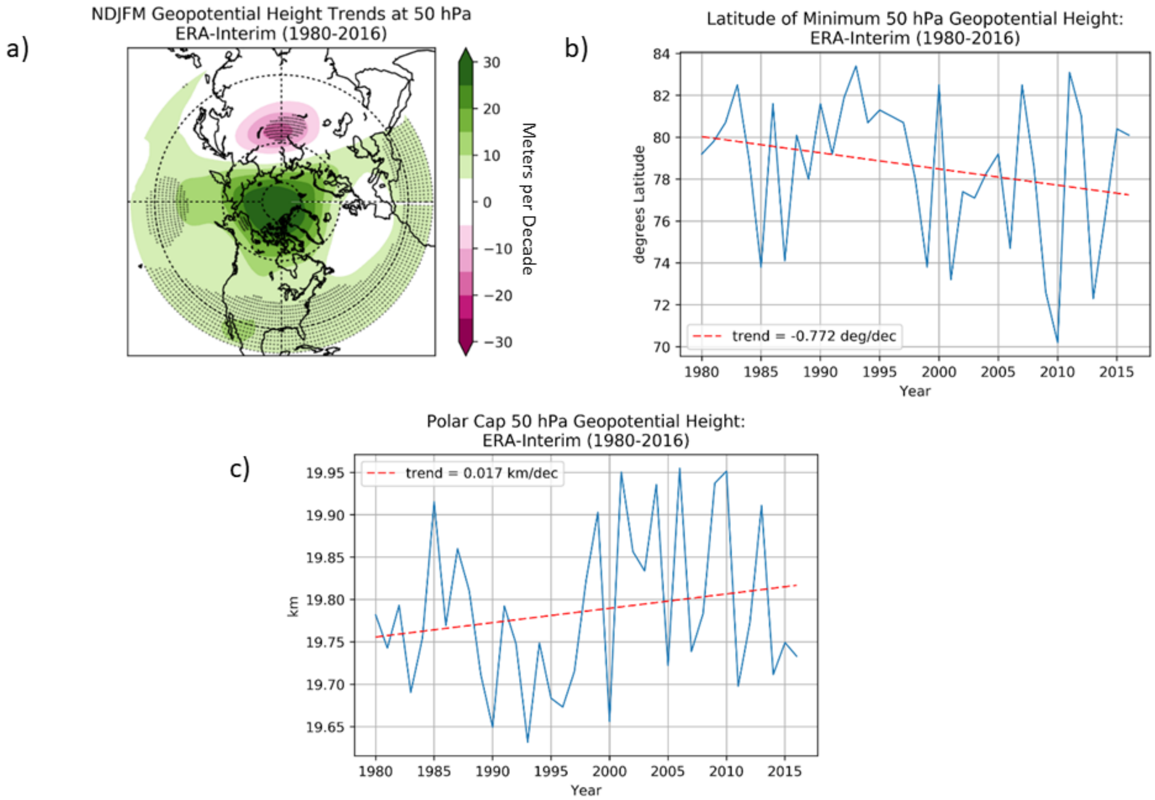

Figure 1. ERA-Interim (1980-2016) results. a) Trends in the winter-average (NDJFM) geopotential height at 50 hPa by grid point. b) Winter-average (NDJFM) latitude of the minimum 50 hPa geopotential height. c) Winter-average (NDJFM) area-averaged geopotential height at 50 hPa poleward of 60° N.

stratospheric pressure level. Therefore, one metric we use is to plot the average latitude of the center during each winter season. Another useful measure determines the geopotential height trend at each grid point at a given stratospheric pressure level. Through this, we see whether the geopotential heights have risen or fallen at each grid point, which clues us into the movement of the vortex over a long time period. For this measure, statistical significance at the 90% level is evaluated at each grid point using a two-tailed *t*-test. Finally, we measure the polar cap height, which is the area-averaged geopotential heights at 50 hPa poleward of 60° N, and plot it for each winter season. This measure was chosen for direct comparison with Seviour (2017). The polar cap height is a measure that is reflected in the trend maps, as the trend map includes the polar cap region. However, this measure allows a higher time-resolution, in that we can see the changes for each winter season, rather than only the average trend over an entire time period. The area - averaged polar cap height trend over each time period is calculated as well.

3. RESULTS

a. Reanalysis and CMIP5 Historical

Analysis of vortex trends in the ERA-Interim reanalysis data set yields similar results to Zhang et al. (2016) and Seviour (2017). Each of these studies found a directional shift in the polar vortex toward the Eurasian continent during the time period 1979-2016. Figure 1a depicts the geopotential height trends at each grid point. The positive geopotential height trend over the polar cap combined with the negative geopotential height trend over Asia suggest a shift of the polar vortex away from the pole and toward Asia. The stippling denotes statistical significance at the 90% level. Almost none of the positive geopotential height trends in the polar region are statistically significant, yet much of the negative trends over Asia are statistically significant. This suggests an expansion of the vortex toward Asia in addition to

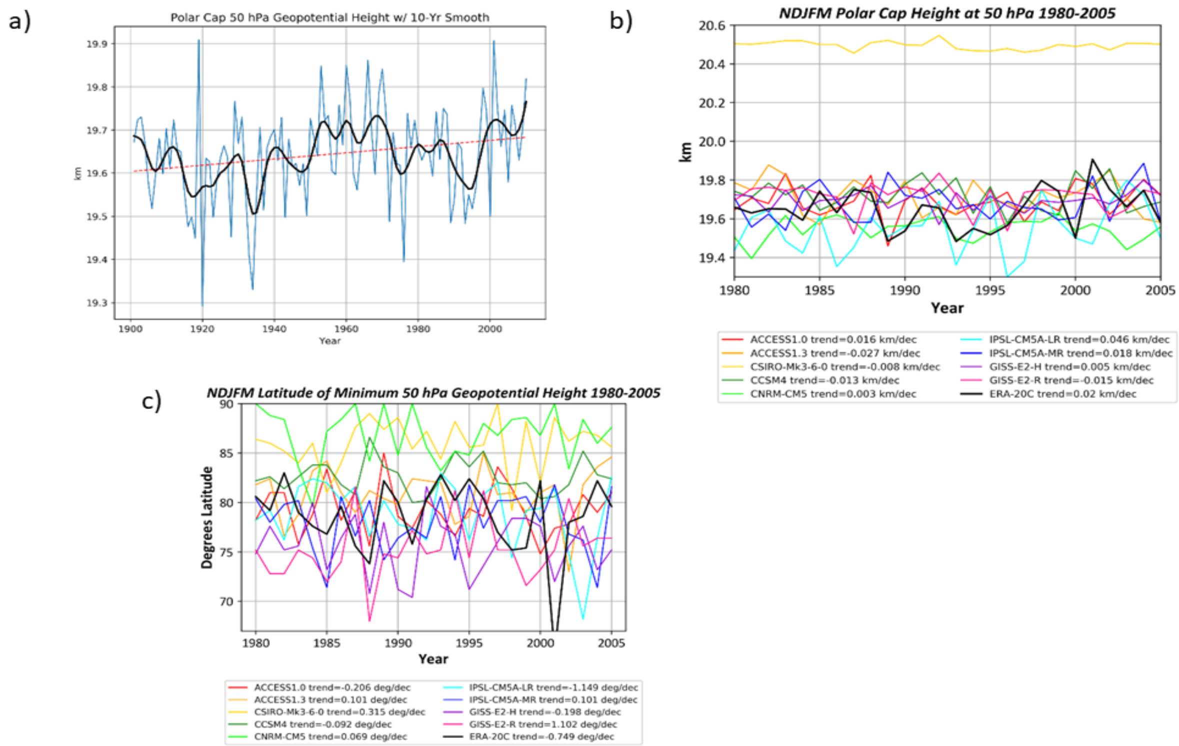

Figure 2. a) Winter-average (NDJFM) area-averaged geopotential height at 50 hPa poleward of 60° N from ERA-20C (1900-2010) in blue with 10-year smoothing line in black and trend line in red. b) Winter-average (NDJFM) area-averaged geopotential height at 50 hPa poleward of 60° N from ERA-20C (1980-2005) in black and ensemble members in colors. c) Winter-average (NDJFM) latitude of the minimum 50 hPa geopotential height from ERA-20C (1980-2005) in black and ensemble members in colors.

a slight shift of the vortex toward Asia. Figure 1b shows a negative trend of -0.772 degrees per decade in the latitude of the minimum geopotential height, which indicates an equatorward shift of the vortex. The positive geopotential height trend over the polar region is also shown in Figure 1c. The area-averaged polar cap height has a positive trend of 0.017 kilometers per decade over the time period. In addition to the positive trend, this figure shows high variability in the seasonal-average polar cap height from winter to winter.

Analysis of the ERA-20C reanalysis data set is used to determine polar vortex trends for the century. Figure 2a depicts the winter-average (NDJFM) area-averaged polar cap geopotential heights from the ERA-20C reanalysis data set during the time period 1900-2010. Polar cap heights display high variability throughout the twentieth century. The addition of a 10-year smoothing line reveals multi-decade time periods sustaining high PCH, and multi-decade time periods sustaining low PCH. This suggests that the polar vortex can go through long time periods of strong conditions, and then return to long time periods of weak conditions, and vice versa. Furthermore, because the twentieth century experienced climate change conditions, this result suggests that the polar vortex could go through long periods of strong and weak conditions under climate change of the twenty-first century as well. That is, the stratospheric polar vortex contains significant internal variability that must be taken into account when assessing any role of climate change on those trends.

Figure 2b,c compares CMIP5 Historical model vortex trends to the ERA-20C reanalysis vortex trends during 1980-2005. In Figure 2b, the ERA-20C polar cap height trend is positive at 0.02 kilometers per decade. Only about half of the models correctly reproduce a positive polar cap height trend. All but one of the models reproduce polar cap heights similar to those observed in the reanalysis data. Model CSIRO-Mk3-6-0 produces polar cap heights much higher than those observed and will be discounted from further analyses.

Figure 2c shows a negative trend, -0.749 degrees per decade, in the latitude of the minimum geopotential height given by the ERA-20C reanalysis data, which appears to be heavily influenced by the small latitude value in 2001. Again, roughly half of the models correctly reproduce a negative trend. More importantly, some models (e.g. CSIRO-Mk3-6-0 and CNRM-CM5) show the minimum latitude remaining closer to the pole than was observed, indicating a tendency for those models to underestimate equatorward movement of the vortex.

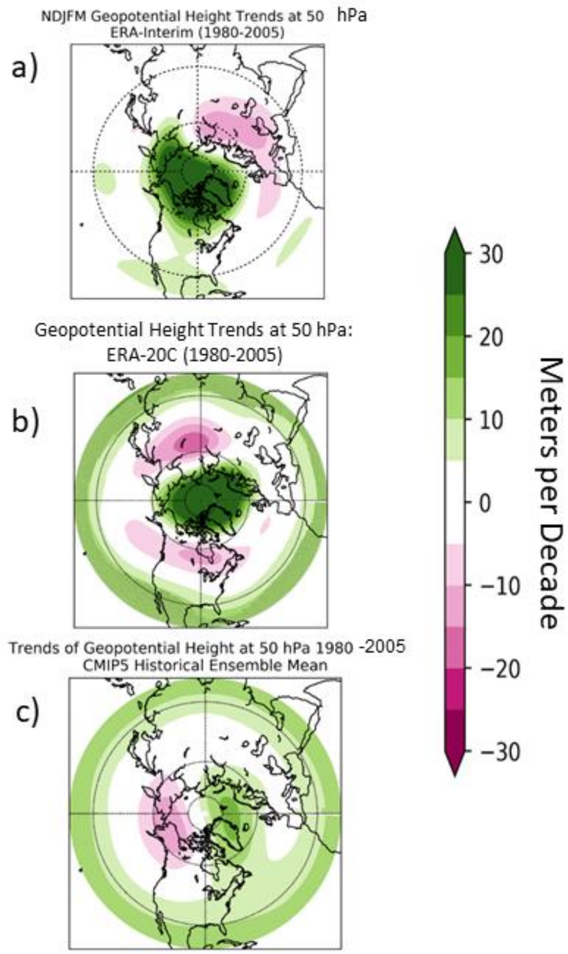

Figure 3. Trends in the winter-average (NDJFM) geopotential height at 50 hPa by grid point (1980-2005). a) ERA-Interim. b) ERA-20C. c) CMIP5 Historical ensemble mean.

Figures 3a,b depict the geopotential height trends from 1980-2005 of the ERA-Interim and ERA-20C reanalysis data sets, respectively. Both of these trend maps show a positive geopotential height trend over the pole and a negative geopotential heights trend over the Eurasian continent. Note that Figure 3a looks slightly different than Figure 1a due to the fact that it covers a shorter time period. We notice an eastward shift of the area with negative trends from Figure 3a to Figure 1a, indicating that the vortex may have shifted slightly eastward during the time period 2006-2016. Figure 3c depicts the CMIP5 Historical ensemble mean of the geopotential height trends during the same time period. This map does not resemble the other two maps. The CMIP5 ensemble mean shows positive geopotential height trends over Greenland and the Barents-Kara seas (BKS), and negative trends over Alaska and Northeast Asia, indicating a vortex shift from Greenland and BKS to Alaska and Northeast Asia. In this case, the CMIP5 Historical ensemble mean fails to reproduce the polar vortex trends from the past.

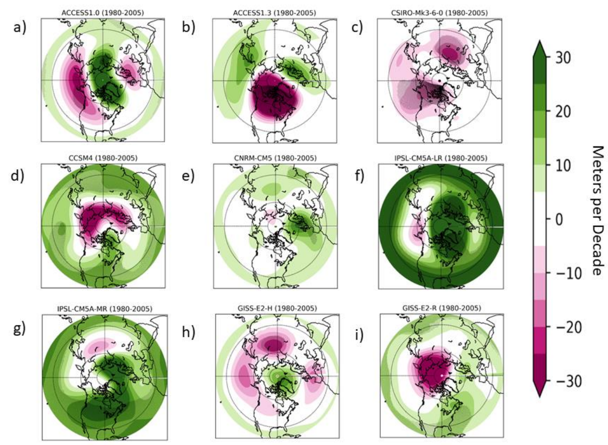

Figure 4. Trends in the winter-average (NDJFM) geopotential height at 50 hPa by grid point (1980-2005) by individual CMIP5 Historical ensemble members.

Individual models, however, correctly reproduce the geopotential height trends from 1980-2005. The key characteristics of the trend maps for this time period are a positive trend over the pole and a negative trend over the Eurasian continent. The IPSL-CM5A-MR (Figure 4g) and GISS-E2-H (Figure 4h) models each show those trends. All of the other models failed to reproduce the correct trends. Three of them (e.g. ACCESS1.3, CCSM4, and GISS-E2-R) show strong negative trends over the polar region, and a few of them show strong negative trends over Alaska, Northeast Asia, and the Northern Pacific Ocean as well.

b. CMIP5 RCP8.5

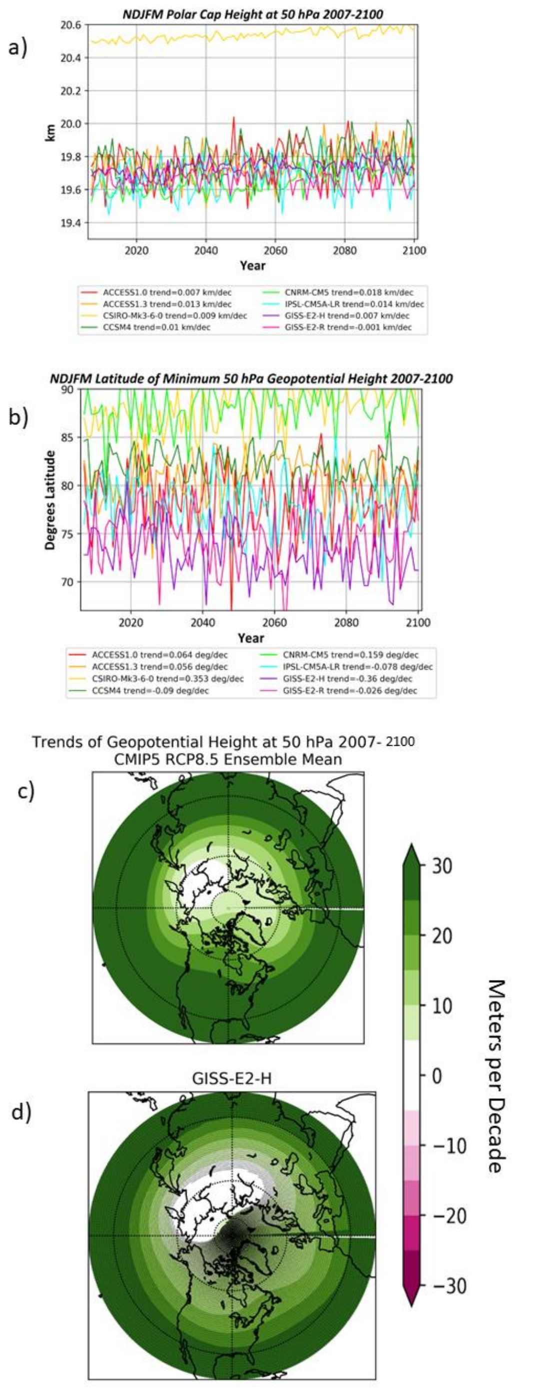

Figure 5. CMIP5 RCP8.5 Projections (2007-2100). a) Winter-average (NDJFM) area-averaged geopotential height at 50 hPa poleward of 60° N with individual ensemble members in each color. b) Winter-average (NDJFM) latitude of the minimum 50 hPa geopotential height with individual ensemble members in each color. c,d) Trends in the winter-average (NDJFM) geopotential height at 50 hPa by grid point by c) CMIP5 RCP8.5 ensemble mean and d) ensemble member GISS-E2-H.

The CMIP5 RCP8.5 ensemble projects an increase in area-averaged polar cap height from 2007 to 2100 almost unanimously (Figure 5a). All but one of the models (GISS-E2-R) project a positive trend in polar cap height. Increasing polar cap height is an indication of either a weakening of the polar vortex, a shift of the polar vortex away from the polar region, or a combination of both. Just as in the historical simulations, model CSIRO-Mk3-6-0 produces polar cap heights that are much higher than those of the other models. Other than that, most of the models project similar polar cap heights.

There is high variability among the CMIP5 RCP8.5 ensemble members on their projections for latitude of the minimum geopotential height during the twenty-first century (Figure 5b). Half of the models project a positive trend in the latitude, indicating a movement of the vortex toward the pole, while the other half project a negative trend, indicating a movement of the vortex away from the pole. Furthermore, the models differ in their projections of the latitude values. Some maintain high latitude values, indicating that the vortex will remain near the pole, while others maintain low latitude values, indicating that the vortex's position during the twenty-first century will remain away from the pole.

The projected positive trend in polar cap height is also evident in the CMIP5 RCP8.5 ensemble mean trend map (Figure 5c). The projected trends from the CMIP5 RCP8.5 ensemble depict positive geopotential height trends at the mid-latitudes as well as at the polar cap. Additionally, the positive geopotential height trends at the mid-latitudes are of a greater magnitude than are those at the polar cap, which may suggest a strengthening of the vortex. While this does not rule out the possibility of a weakening vortex, it indicates that some other process must be involved.

Because model GISS-E2-H accurately reproduced the key geopotential height trends during the time period 1980-2005, provided in Figure 5d is a map of the geopotential height trends projected by GISS-E2-H for the time period 2007-2100. (The other model that accurately reproduced the geopotential height trends during the time period 1980-2005 is IPSL-CM5A-MR. The geopotential height data for future runs of this model is missing, preventing the model's inclusion in our analysis of future polar vortex trends.) The GISS-E2-H trend map (Figure 5d) shares key characteristics with the ensemble mean map (Figure 5c), including large positive geopotential height trends at the mid-latitudes and near-zero geopotential height trends over Northeast Asia. One key difference between the two maps, however, lies over the pole. The ensemble mean map shows a small positive geopotential height trend over the pole, while the GISS-E2-H map shows a large positive geopotential height trend over the pole. This distinction between the two projections could be the difference between suggesting a shift of the vortex off of the pole and suggesting a weakening of the vortex.

4. CONCLUSIONS

The polar vortex trends of the twentieth century have been examined using two reanalysis datasets. Consistent with previous studies, we found that the polar vortex has shifted toward Asia near the end of the century. Further, analysis of statistical significance of geopotential height trends reveals that there may not only have been a shift of the vortex toward Asia, but also an expansion of the vortex toward Asia. Analysis of polar cap height during the entire twentieth century reveals high variability throughout the century, with multi-decade time periods sustaining high polar cap heights, and multi-decade time periods sustaining low polar cap heights. This suggests that the polar vortex can go through long strong-vortex regimes, and then return to long weak-vortex regimes, and vice versa. And, because the twentieth century experienced climate change conditions, this result suggests that the polar vortex could go through long periods of strong and weak conditions under climate change of the twenty-first century as well.

The CMIP5 Historical ensemble's ability to reproduce the polar vortex trends of the past has been assessed. Only two models out of nine in the ensemble reproduce the directional shift of the stratospheric polar vortex toward the Eurasian continent. Additionally, there is high spread among the model results for area-averaged polar cap height and the latitude of the minimum geopotential height. Given these results, we conclude that the CMIP5 Historical ensemble does not adequately reproduce the polar vortex trends of the past. That being said, a couple of models (GISS-E2-H and IPSL-CM5A-MR) successfully reproduce the correct polar vortex trends.

Expected polar vortex trends of the twenty-first century under the RCP8.5 carbon dioxide emission scenario have been explored. With low variability among the models, stratospheric geopotential heights are projected to rise in both the middle and high-latitudes during the twenty-first century. The steep increase in geopotential heights at the mid-latitudes indicates that another process besides a weakening vortex must be involved. Also, it leaves projections of polar vortex strength unclear. In the past, rising polar cap heights have been associated with a weakening vortex. However, if mid-latitude heights rise at an even steeper rate, the vortex could potentially strengthen. Further analysis is needed to determine the projected polar vortex strength trends for the twenty-first century. Regarding the position of the polar vortex, a shift of the vortex toward Northeast Asia is projected for the twenty-first century. The CMIP5 ensemble mean, as well as the GISS-E2-H model, both project this shift. This shift would translate to a trend of cold wintertime temperatures in Northeast Asia. Future work should include analysis of future tropospheric conditions in the middle and high-latitudes in relation to tropospheric interactions with the stratospheric polar vortex.

5. ACKNOWLEDGMENTS

We thank Dr. Daphne LaDue for providing the opportunity with the National Weather Center Research Experience for Undergraduates, as well as Matthew Green and Yujia You for their help with coding. This material is based upon work supported by the National Science Foundation under Grant No. AGS-1560419.

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