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Stratospheric Polar Vortex Variability in the Northern Hemisphere:
The Effects of Climate Change on Polar Vortex Trends and Future Projections

by

John Earl Rogers

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geography

Thesis Committee:
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Portland State University
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Abstract

Regions that have experienced recent successive cold winters such as the Northeast of North America and Siberia have endured critical social and economic impacts from anomalous low temperatures in recent years, despite warming global temperatures. It is well known that the Tropospheric Polar Vortex (TPV), or jet stream, is a primary influence on many mid-latitude winter weather patterns. However, the strong circumpolar westerlies that maximize at around 60° latitude just above the tropopause, known as the Stratospheric Polar Vortex (SPV), can affect tropospheric circulation and thus winter weather in the Northern Hemisphere. Strong upward propagating waves can affect the geographic extent and strength of the SPV resulting in a weakened polar vortex state, which can in turn bring persistent weather events to the mid-latitudes. Here, an index of SPV spatiotemporal variability is presented using observation based analysis of zonal wind and geopotential height to show changes in SPV behavior at a seasonal scale from 1950-2018. Utilizing the CMIP5 suite of global climate models, historical and projected simulations of the SPV's climatological extent and strength are analyzed from 1915 to the end of this century, taking into account models with enhanced stratospheric representation. Simulated results are largely consistent with trends in the observational data, which suggest continued increases in average SPV size throughout this century. If future SPV disturbances increase in frequency, there could be negative impacts in ecosystem and agricultural health, infrastructure damage, and to human safety. A more advanced understanding of SPV trends and anomalous events could improve forecasts of cold air outbreaks (CAOs) and severe or persistent winter weather.

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Table of Contents

Abstract	i
Acknowledgements	ii
List of Tables	v
List of Figures	vi
Chapter 1: Introduction and Review of Relevant Literature	1
1.1: Importance, Overview and Research Objectives	1
1.1.2: Observational Studies on Polar Vortex Trends.....	3
1.1.3: SPV Anomalies and Resulting Surface Expressions	4
1.1.4: CMIP5 Model Configuration and Simulating the SPV	6
Chapter 2: Data	9
2.1: NCEP/NCAR Reanalysis.....	9
2.2: The CMIP5 Global Climate Model Suite	9
Chapter 3: Methodology.....	12
3.1: Dataset Intercomparison - NCEP/NCAR and the CMIP5 Model Suite	12
3.2: Polar Vortex Identification Methods	13
3.3: CMIP5 Multimodel Projections.....	15
Chapter 4: Results.....	17
4.1: Polar Vortex Changes in the Observational Period	17

4.2: Identifying Polar Vortex Events	18
4.3: CMIP5 Simulations, Trends, and Statistical Significance	20
Chapter 5: Summary and Discussion.....	24
References	44

List of Tables

Table 1. The main characteristics of the CMIP5 models included in the historical (1915-2005) and projected (2010-2090) model simulations. Models highlighted in bold include a well-resolved stratosphere and are analyzed in the high-top composites (Data Source: https://esgf-node.llnl.gov/projects/esgf-lln).....	30
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List of Figures

Fig. 1. A generalized schematic of the SPV and TPV (Jet Stream) in the Northern Hemisphere.....	31
Figure 2. Conceptual maps displaying an average winter extent of the SPV (a), a vortex displacement event (b), and a vortex split event (c) in the middle atmosphere.....	32
Figure 3. The SPV edge (black) identified by interpolating the maximum zonal wind during a displaced to splitting event in January 2014 using (left.) The maximum gradient geopotential height gradient aligns with the maximum zonal winds at 50 hPa from NCEP reanalysis.....	33
Figure 4. A generalized GIS-based workflow for identifying the SPV edge.....	34
Figure 5. An example of a high polar vortex aspect ratio during the SSW on January 11 th , 2013/2014 that split into two separate low pressure vortices in the middle of the polar night jet season	35
Figure 6. An example of simulations from the six CMIP5 models excluded from this study. Projected period 1 (2010-2040) Stratospheric Polar Vortex zonal winds (m/s) at 50 hPa	36
Figure 7. Decadal Stratospheric Polar Vortex and increasing in extent from the 1950's-2010 and recent decreasing mean zonal wind velocity.....	37
Figure 8. Decadal Stratospheric Polar Vortex consistently shifting towards Eurasia and increasing in extent from the 1950's-2010 with their respective centroids showing an equatorward migration	38

Figure 9. Winter of 1990s anomalous SPV and the resulting persistent COA (left) compared to a stronger and more typical vortex winter (right).....	39
Figure 10. Temperatures departures in the 45 days after the Feb. 2018 SSW event (middle) compared to days after all recorded SSW events (left) compared to a map of February 2018 SPV (right, white). Source: NOAA. Data: NCEP/NCAR.....	39
Figure 11. Comparison of the CMIP5 high-top ensemble composite from 1975-2005 compared to the NCEP/NCAR reanalysis composite.....	40
Figure 12. Individual historical and projected model simulations for each 30-year simulation and the composite average.....	41
Figure 13. Individual high-top model simulations of historical and projected 30-year simulations and their multi-model composite (black) show a consistent increase in polar vortex size, although the geography of the model simulations are quite variable. A Student's T-test show a p-value of 0.048 at the 95% confidence level in significant change in size from the most recent historical period and the projection for the end of this century (projection 3).....	42
Figure 14. Comparison and trends for the CMIP5 29-model and 14 model high-top simulations of SPV extent.....	43

Chapter 1: Introduction and Review of Relevant Literature

1.1 Importance, Overview and Research Objectives

The northeast of North America, Northern Europe, and Siberia have experienced recent successive cold winters with substantial impact on social and economic systems. Anomalously low air temperature and elevated precipitation events have occurred in recent years, despite a global warming trend (Kim et al., 2014). It has been a challenge for scientists to agree on the mechanisms behind regional cooling amidst global warming; and whether or not these cold winters will persist (Cohen et al. 2014; McCusker et al. 2016; Kretschmer et al. 2018; Screen et al. 2015). Explanations of these trends and events point to the most prominent feature of the polar stratosphere; the Stratospheric Polar Vortex (SPV). Although the SPV is separated from the TPV (Jet Stream), the SPV can play a role in surface weather events (Fig. 1). The TPV is much larger than its stratospheric counterpart and exists and influences weather year round, whereas the SPV forms in fall but dissipates in spring each year. Both vortices can affect weather events at the surface, such as CAOs or persistent winter patterns, but such events are not always the result of either the existence or variability of one or the other (Waugh et al. 2016).

This Arctic connection implicates the movement of extremely cold air masses from the SPV to the mid-latitudes at the surface, known as a cold air outbreak (CAO). It has been well-documented in the literature that the likelihood of CAOs increases during periods following a breakdown or weakening of the SPV (Kolstad et al., 2010). Perturbations can be caused by a displacement of the SPV away from the pole, a split of

the cohesive vortex into two vortices, or an anomalous equatorward elongation induced by a Sudden Stratospheric Warming event (SSW). A SSW event is a rapid disturbance of the stratospheric wintertime circulation such that anomalously large vertically propagating Rossby waves of tropospheric Arctic origin that break into the stratosphere and marked by dramatic heat flux anomalies above 100 hPa (O’Callaghan 2014). These vertically propagating waves produce frictional drag on the stratospheric zonal winds causing them to slow down, commonly inducing a splitting of the polar vortex into two smaller vortices (Butler 2018). As the zonal winds slow or reverse, air parcels sink and rapidly warm adiabatically with the potential to propagate into the troposphere following the weakening gradient of the SPV edge (Baldwin and Dunkerton, 2001). After the onset of a particularly strong SSW event, CAOs can migrate equatorward from Arctic high pressure systems to the mid-latitudes. Rapid decreases in air temperature and resulting persistent winter conditions can negatively affect agriculture, power and transportation infrastructure with significant economic impacts. Although correlations have been identified between weak SPV events and CAOs at the surface (O’Callaghan 2014, Mitchell et al. 2013, Kolstad et al., 2010), the relationships between the two are not always well understood and remain an area of active research. The known complexities of interannual SPV variability, stratospheric-tropospheric coupling, and uncertainty of future polar vortex behavior is imperative and clearly deserves further research. Towards this need for research, this thesis examines the observational record to assess the historical changes in geography and strength of the SPV. Additionally, although not a large portion of this study, the utility of the methods in identifying polar anomalous SPV

events and their possible impacts at the surface are demonstrated. Motivated by the general dearth of research on projected SPV behavior in response to anthropogenic climate forcing, the main objective of this research is to utilize the CMIP5 suite to create multimodel simulations of polar vortex strength and extent, in both historical and future periods. Simulations from the CMIP5 climate model suite are analyzed to determine whether changes in the strength and size of the Northern Hemisphere's SPV are expected to change due to global warming. Additional objectives are to evaluate whether CMIP5 can replicate polar vortex characteristics and to statistically assess future CMIP5 simulations of the SPV under the global warming scenario (RCP8.5).

1.2.2: Observational Studies on Polar Vortex Trends

This research is motivated in part by Zhang et al. (2016) that proposed an observable geographical shift in the SPV since the 1980's, and from the research of Seviour (2017) that addresses SPV shifts and considers both internal variability and forced response; both prompting questions pertaining to a fuller understanding of past trends. The association between temperature anomalies in the Northern Hemisphere and the weak SPV states have been identified in other previous studies that have identified resulting CAOs in northern Asia, Europe and North America (Kolstad et al. 2010; Zhang et al. 2016). Whether such decadal trends are SPV events related to tropospheric CAOs or whether they exhibit a geographical tendency is unclear. Some studies have addressed the SPV's geographical shift over time, however, ignoring years with SSWs which in turn removes much of the inter-annual vortex variability from the linear trend (Seviour 2017). This motivated a different approach for this thesis research, in which all SPV winters

from 1950 to 2010 were included in the analysis. More recently, Kretschmer et al. (2018) identify patterns of more-persistent weak vortex states that are dynamically linked to a Eurasian cooling trend in response to Arctic sea ice decline and increased frequency of vertical wave activity. However, some researchers' claims that solely Arctic sea ice loss may increase the risk of midlatitude cold extremes are primarily based on hypothetical statements on increases in the latitudinal extent of north-south excursions of the jet stream. These types of hypotheses leave out the crucial factor that the midlatitudes are warming (and are expected to continue to warm), meaning that it takes a larger-magnitude cold anomaly to cause an extreme than in a previously cooler climate. Additionally, due to the factor of disproportionate warming of the high-latitudes compared to the mid-latitudes, this reduces the overall temperature gradient between the two regions (Screen et al. 2015).

1.1.3: SPV Anomalies and Resulting Surface Expressions

Many studies (Kretschmer, 2018; Serra et al. 2017; Cohen 2011; Kuttippurath and G. Nikulin 2012) have linked stratospheric-tropospheric coupling to persistent CAOs that coincide geographically with the southern meander of the SPV. It is known that the variability of the SPV has increased since the 1990s with more frequent weak states. (Kretschmer et al. 2018). For instance, the sudden weakening of the SPV that quickly follows a SSW occurred relatively infrequently during the 1990s according to the World Meteorological Organization, and since have occurred nearly every year since 2000 (Kuttippurath and G. Nikulin 2012). SSWs will weaken the polar vortex by initiating a “pinched” (Fig. 5), displaced (Fig. 2b) or even “split” (Fig. 2c) vortex state causing the

SPV to extend equatorward, contrary to the more typical circumpolar westerly around the North Pole (Fig. 2a). Kretschmer et al. (2018) show more frequent SSWs and weak polar vortex states since the end of the 1990s linking 60% of observed cold extremes in mid-latitude Eurasia to mid to late winter weak vortex states. This agrees with (Zhang et al. 2016) that show an average weakening decadal trend, which is pronounced in the 2000s when SSWs occurred nearly every winter. When the SPV is less variable and more conformal around the pole, it tends to be colder, stronger, and less likely to interact with the troposphere. During a “split” vortex event the stratospheric temperature anomalies tend to be high with equatorward vortex migration. When the winds slacken during such events, this can allow extremely cold polar air to propagate downward through the tropopause with nearly double the surface temperature impact compared to a displaced vortex event (O’Callaghan et al. 2014; Seviour et al. 2017).

There are some researchers that combine model evidence with observational data to link a warming Arctic with a weakening SPV and increasing cold weather anomalies (Cohen et al. 2007, Kim et al., 2014, Zhang et al. 2016) or high snow cover inducing a weak polar vortex (Cohen 2011), however, many link projected sea ice loss to projections of reduced cold extremes in the midlatitudes (Screen et al., 2015). Additionally, some research argues that the presence or absence of stratospheric circulation extremes in winter contribute a nontrivial role in determining seasonal sea ice extent when combined with other factors (Smith et al. 2018). It remains unclarified whether observed mid-latitude cold weather events are related to stratospheric variability (Sun et al. 2016), tropical (Palmer 2014) or Arctic (Cohen et al. 2012; Cohen 2011) warming trends and

teleconnections, or whether these relatively brief trends will eventually cease due to a decrease in cold weather anomalies in response to a future decrease in the mid-latitude-Arctic temperature gradient (Screen et al. 2015). Many question if the location of the polar vortex has also experienced a consistent change in response to Arctic amplification. Francis and Skific (2015) show that as emissions of greenhouse gasses continue unabated, amplification of Arctic warming should favor an increased occurrence of persistent weather patterns that can cause extreme winter weather events. Studies on the mechanisms of stratospheric and tropospheric circulation response to projected sea ice loss has been investigated (Sun et al. 2015) using models with a well-resolved stratosphere such as the Whole Atmosphere Community Climate Model (WACCUM). From these model simulations, results show a wintertime stratospheric weakening and surface climate impacts that resemble the negative phase of the North Atlantic Oscillation, a subtropical-subpolar index that can explain changes in mid-latitude pressure, temperature and precipitation patterns. Although there has been a recent influx of relevant research on these topics, consensus in the literature on the issue remains indistinct.

1.1.4: CMIP5 Model Configuration and Simulating the SPV

Although there are recent studies that utilize the CMIP5 climate model suite for analyzing SPV behavior and characteristics (Seviour et al. 2016; Lee and Black 2014), there is limited research regarding future projections of SPV trends. Depending on the behavior and frequency of near-future perturbations in the atmosphere, outcomes are unknown regarding the degree of impact of CAOs to a warming troposphere, however,

the variable SPV should have some influence on wintertime hemispheric circulation during anomalous vortex events. Research efforts to analyze CMIP5 simulations from a 20 model member study have been considered (Lee and Black 2015, Charlton-Perez et al. 2013) in order to analyze the temporal variability of the SPV and its associated tropospheric footprint. Such results show reduced variability in stratospheric planetary wave activity and low polar vortex variability signifying poor representation of vertical dynamical coupling in low-top models, which often simulate atmospheric circulation with less accuracy than models with a higher vertical resolution (high-top models). Additionally, considering that SSWs are a contributing part of a gamut of wintertime SPV variability (Seviour 2017) and that historical and climate change simulations computed by Butler et al. (2015), who consider a variety of SSW definitions, show projected increases in SSWs while demonstrating the importance of analyzing ensembles with a well-resolved stratosphere. While the many possible model biases may reduce confidence in future projections, the benefits of multimodel composites are clear in that they are an effective tool to best project the behavior of large-scale atmospheric circulation over the next century (Barnes and Polvani 2015).

Although providing a comprehensive solution for answering the issues regarding the physical mechanisms behind the stratosphere's influence on anomalous winter weather at the surface may not be entirely possible in this thesis work, it is expected that this research and discussion will provide some insight to addressing them. To better understand how SPV variability can affect the troposphere, comparisons of SPV behavior with anomalous winter weather that may be connected to stratospheric vortex events are

presented. This thesis discusses modeled, observed and hypothetical statements regarding the SPV and its possible impact on surface weather. Here, insights to analyzing polar vortex winters throughout the observational period, methods for identifying location and extent during anomalous stratospheric events, and metrics for use in global climate model simulations through the 21st century are presented. This research aims to simulate whether or not the SPV is projected to undergo change in strength and size by the end of this century with continued anthropogenic climate forcing and global tropospheric warming. Although not yet documented in the literature, this type of study could inspire the climate science community to create more robust statistics and projections of polar vortex variability as well as more accurate medium to long range weather forecasts if vortex trends and projections are better understood.

Chapter 2: Data

2.1: NCEP/NCAR Reanalysis

The NCEP/NCAR's Reanalysis 1 zonal wind data is used to define the SPV 'edge' and strength in the historical monitoring portion of this research. Reanalyses combine model fields with observations (satellite, ship, land station data, balloon soundings, etc.) distributed irregularly in space and time into a spatially complete gridded meteorological dataset, with an unchanging model system spanning the historical data record, allowing multiple measurements to be easily compared (Kalnay et al. 2011). This creates a dynamically continuous best estimate of the state of the climate at various time steps at a spatial scale of $2.5^{\circ} \times 2.5^{\circ}$ with 17 vertical levels since 1948. The reanalysis datasets analyzed function as an ideal reference to compare with the historical CMIP5 multimodel results presented in the second portion the results of this study. Here, like Kolstad et al. (2010), Karpetchko et al. (2005) and Limpasuvan et al. (2005), NCEP/NCAR data is chosen to analyze 70 winters (DJFM) of monthly mean zonal wind and geopotential height reanalysis as this dataset agrees well with the other widely used reanalyses such as ERA-40 and is an effective dataset to represent both SSWs and the polar vortex (Kozubek et al. 2016) For understanding relationships between geographically distinct CAOs and SPV events and trends, NCEP/NCAR surface temperature reanalysis data is analyzed.

2.2: The CMIP5 Global Climate Model Suite

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) is an ensemble of coordinated global climate model simulations with data that are made freely

available to researchers and the public through integrated data nodes from modeling institutes around the world. The CMIP5 suite produces a state-of-the-art multimodel dataset that is designed with the purpose of advancing scientific knowledge of climate variability and climate change with historical simulations of twentieth-century climate and projections for the twenty-first century and beyond (Taylor, K. 2012).

29 CMIP5 global climate models are assessed to examine stratospheric zonal wind in order to represent possible future trends in SPV variability. Representative Concentration Pathway 8.5, the “business as usual” radiative forcing scenario, is used to analyze how strength and variability of polar vortex simulations from 2010-2100 differ from historical CMIP5 simulations and NCEP/NCAR reanalysis results. This scenario was chosen over mitigation scenarios primarily because it is most similar to the current rate of global carbon emissions and it shows the largest change signal. Historical CMIP5 simulations are observed in this analysis which account for climate forcing’s such as changes in land use, GHG’s, volcanic and anthropogenic aerosols, and ozone variability in order to equate to the observed reanalysis period in this study. Some models provide multiple simulations produced with different initial conditions, however, here only the first ensemble member from each model is used. In considering the differences in model configurations in all institution’s GCM’s, especially when noting the differences of the strength of the polar vortex across all models (Butchart et al. 2011) and the range of horizontal resolutions between all, an ensemble of strictly high-top models are analyzed. Abundant research with the CMIP5 suite has shown a stark contrast between low-top and high-top models (which have a vertical resolution beyond the stratopause) in their ability

to resolve stratospheric variability including SSW events, zonal wind tendency, and other vortex diagnostics (Butler et al. 2015, Charlton-Perez et al. 2013, Seviour et al. 2016). When analyzing simulations from the CMIP5 suite to reproduce stratospheric dynamics, some low-top models members may underestimate most proxies as their model tops are generally below the stratopause, which means they may not effectively simulate troposphere-stratosphere coupling or upper stratospheric circulation. In contrast, high-top models resolve data to 0.1 hPa allowing more effective modeling of the stratosphere (Charlton-Perez et al. 2013). In consideration of low-top and high-top biases, here, model simulations and composites for both a 29 member ensemble alongside a 14 model ensemble of “high-top only” composites that exceed 1 hPa or higher are analyzed. A summary of the CMIP5 models (Table 1) that are used in both the multimodel composites as well as the high-top model composites (highlighted in bold).

Chapter 3: Methodology

3.1: Dataset Intercomparison - NCEP/NCAR and the CMIP5 Model Suite

Identifying the spatial extent of and strength of the winter SPV ‘edge’ is the primary determinate of the severity, location and annual size of the ozone hole in the Southern Hemisphere, and can have implications on displacements of cold air at the surface in the Northern Hemisphere (Serra et al. 2017). As winter begins, a rise in circumpolar wind velocities in the stratosphere result in a vortical motion delineated by a sharp pressure gradient containing cold polar air in the main vortex, while it’s enclosing gradient barrier is known as the vortex ‘edge’. Methods of identifying the SPV ‘edge’ include interpolating the maximum zonal winds at the same pressure level, which is closely aligned with the maximum geopotential height gradient (Fig. 3). As the extent and strength of the SPV edge has spatiotemporal implications on ozone breakdown, snow cover gain or loss, and possible increases in persistent cold winter weather in the mid-latitudes, it is important to accurately identify the main vortex and its enclosing outer edge (Serra et al. 2017). Motivated by the ability to apply these standard variables to climate model ensembles, a straightforward method to identify the SPV ‘edge’ is chosen that requires only interpolating maximum zonal winds at 50 hPa from NCEP/NCAR reanalysis data. Additionally, due to anthropogenic forcing's effects on changes in geopotential height, zonal wind data serves as a more appropriate method for identifying polar vortex climatological extents over any temporal scale. The Northern Hemisphere’s polar vortex winter is defined here as December-March (DJFM) in order to capture the stratosphere’s polar night jet season from buildup to breakdown. As zonal wind at 50 hPa

for the Northern Hemisphere's SPV winter is a commonly used variable in previous studies and is an integral height in terms of stratospheric-tropospheric coupling, the same parameters for analyzing the SPV's variability and climatologies were chosen for both the dataset intercomparison portion of the historical period as well as for the projected periods in the CMIP5 model intercomparison and validation.

3.2: Polar Vortex Identification Methods

Using ArcGIS as a tool for database management, visual display and as a platform for SPV identification and statistical analysis, the 'Multidimensional Toolkit' is used to process and analyze the NCEP/NCAR reanalysis data in a NetCDF format. The toolkit converts the NetCDF to a raster grid at the specified temporal scale, chosen pressure level (50 hPa), at a hemispheric scale in its native grid of 2.5°x2.5°.

ArcMap's spline interpolation method is a mathematical function that creates a line that passes through the nearest input points while minimizing the total curvature of the surface. Spline interpolation is applied to the centroid of each grid cell of reanalysis data to show the path of the maximum zonal wind at 50 hPa in the stratosphere, marking the SPV's 'edge'. Interpolations were computed with a North Pole Lambert Azimuthal Equal Area projection to reduce the distortion of area in the Arctic as much as possible. The generalized polar vortex identification methodology is summarized (Fig. 4) as follows:

- i. Importing NCEP/NCAR reanalysis datasets into ArcGIS using the Multidimensional toolkit to specify desired latitude, longitude, pressure level, and temporal dimensions.
- ii. To identify the vortex extent, a single path of 50 hPa maximum zonal wind is interpolated from NCEP/NCAR reanalysis data (1948-2018) using ArcGIS' spline interpolation method. This shows the maximum zonal wind values of the DJFM mean for each polar vortex winter.
- iii. The gridded vortex 'edge' is used to identify vortex geometry and vortex moments as the strength (velocity), extent and geographic location, centroid latitude, centroid clustering, and aspect ratio in addition to further statistics.

From the polar vortex extent produced at the temporal scale in question, extraction from each interpolated cell value of zonal mean wind generates statistics and locations of maximum velocity, attributing to the seasonal averages calculated. The benefit of considering geometry diagnostics such as centroid location and aspect ratio are in understanding variability over time and to make inferences on the underlying dynamics of the polar vortex (Fig. 5) and in defining SSW's (Butler et al. 2015, Mitchell et al. 2011). The centroid location is an important indicator of the geographic location of the polar vortex, inter-annual trends, and to the many SSW definitions and vortex moment diagnostics. The representative centroid of each polar vortex winter is calculated in GIS from averaging distances from each of the polygon's vertices and the results are converted to polar coordinates. Seviour et al. (2013) define thresholds of 66°N in centroid latitude and an aspect ratio of 2.4 to define anomalous vortex excursion events. The aspect ratio is geometrically calculated from length over width of the polar vortex.

3.3: CMIP5 Multimodel Projections

In order to better understand future behavior of the SPV under continued anthropogenic forcing, these identification methods are applied to the CMIP5 multimodel outputs to compare trends in observed SPV changes to projections of vortex strength, location and extent. Initially, multimodel composites are analyzed for six 30-year periods (spanning from 1915-2100) in order to account for natural climate variability. Although the historical CMIP5 periods between 1915-1945 and 1945-1975 are presented, only 1975-2005 period is compared to the observational SPV climatology.

While the CSIRO, INM-CM4, and GISS models (Fig. 6) were excluded from this study due to either an inability to detect SSWs (CSIRO, INM-CM4) or lack of interactive chemistry, poor stratospheric simulations (GISS), or overrepresentation of the wintertime average polar vortex, also noted by Lee and Black (2015), the CMIP5 experiments assessed here include a 29 member model ensemble. Many stratospheric modeling efforts have chosen a small ensemble group that is known to resolve the stratosphere in simulations better than others for varying model configurations (Seviour 2017), while some studies value a large multimodel ensemble and others consider only high-top models for stratospheric event classification (Charlton-Perez et al. 2012, Seviour et al. 2016).

A 29 model composite, discarding the aforementioned models, provides a robust multimodel average with less bias from poor stratospheric resolve. Following suit of Seviour et al. (2016), we also distinguish between the models that have an uppermost lid which is in the upper mesosphere (0.1 hPa), while including CanESM2 that has a lid

height near 50 km which is higher than the “low-top” models. While even this selection of high-top models still possess biases, it is currently an effective tool to project the behavior of stratospheric events and hemispheric-scale circulation patterns over the next century. This study shows composites with an equally weighted 29 model and a 14 member “high-top only” ensemble simulating projections of SPV location, strength and extent. All model outputs were re-gridded to a common horizontal resolution of $2.5^\circ \times 2.5^\circ$ by performing a bilinear interpolation which determines the new value of a cell based on a weighted distance average of the four nearest input cell centers. The benefit of this common resolution in the composite plots is for the purpose of comparison to the reanalysis climatologies and to retain the spatial data between the various resolutions of the models.

In order to determine if the results of the CMIP5 multimodel composite projections are statistically significant in regards to change in vortex size and strength in the high-top models, the Student’s two-tailed t-test is computed. Significance in the difference of polar vortex size and velocity at the end of the century is compared to the most recent historical composite. Additionally, linear regression trend analyses are evaluated for both the 29-model and high-top model ensemble simulations in order to indicate overall changes in polar vortex climatologies from the historical period to the end of the 21st century.

Chapter 4: Results

4.1: Polar Vortex Changes in the Observational Period

Analysis of polar vortex trends in stratospheric zonal wind from the NCEP/NCAR reanalysis data set shows an increasing trend in the geographic area of the SPV and a decreasing latitudinal extent in both the geographic centroids and southernmost SPV edge since the 1950s (Fig. 8). While prominent interannual variability of size and strength in the last 70 year is observed in the reanalysis, a decreasing trend in the strength and average wind speed of the decadal climatologies since the 1980s (Fig. 7).

The 1990's, which had a stronger average vortex (a decade that lacked SSW events) and in the 2000's that contrastingly experienced increasingly weaker vortex winters along with more common major SSW events. The shift from a mostly positive phase of NAO in the 1990s to more negative phases in the 2000s suggest that the long strong/weak vortex regimes in the stratosphere may exert some influence on the troposphere, or vis-versa (Kolstad and Charlton-Perez, 2010). Although using varying reanalysis datasets and different measures of stratospheric polar vortex identification, results of this study are consistent with those of Seviour et al. (2017) and Zhang et al. (2016) in the findings of consistent decadal directional shift in the polar vortex away from the pole and towards Eurasia. Like the findings from Zhang et al. (2016) the SPV extent averages from the 1980s, 1990s, and 2000s show similar results in vortex location over Eurasia, while all decadal composites from the 1950s-2000s show consistent Eurasian migration and a general increasing trend in vortex size (Fig. 8).

4.2: Identifying Polar Vortex Events

Recent studies show that extreme stratospheric events such as SSWs and equatorward excursions can be followed by anomalous weather at the surface that can persist for up to two months (Baldwin and Dunkerton 2001, Thompson et al., 2002). With the goal to better understand the relationship between weak vortex events and tropospheric CAOs, this research compares methods of SPV identification to the modeling approach of Kolstad et al. (2010) that shows such relationships between the southern meander of the SPV and resulting temperature anomalies. For example, the winter of 1989/1990 in North America experienced anomalous CAOs, record freezes east of the Rockies and as far south as Florida that persisted for up to two months. The SPV edge (Fig. 9, left) during this event migrated with an extraordinary southern meander which contributed to the record cold conditions throughout the eastern portion of North America. In contrast, an example of a more typical vortex winter is evident in the winter of 1982/1983 (Fig. 9, right) with a more circumpolar flow of the SPV and a colder Arctic with more mild mid-latitudes.

The 1989/1990 example shows and elongation that was a result of a major SSW which split the SPV into two separate parts, known as a wave-2 pattern. A physical mechanism behind the formation of a SSW and the likely result of a split or southern meander of the SPV occur from the event of tropospheric waves entering the lower stratosphere (Charney and Drazin, 1961). Recently in February of 2018 (Fig. 10), a large amount of wave energy transferred between the troposphere and stratosphere preceding a SSW that exceeded measurements previously seen in the observational record. Following

a typical SSW pattern, changes in sea level pressure can induce a negative phase of the North Atlantic Oscillation (NAO), which creates a disturbance of the typical synoptic-scale surface pressure patterns across the Arctic and mid-latitudes, resulting in milder weather over Arctic and more wintry weather over the mid-latitudes (Cohen, 2011).

Results from February's SPV interpolation (Fig. 10, right) shows an unusual displaced polar vortex that meandered equatorward over North America as a result of the SSW and the splitting of the main vortex. Additionally, SPV extent and strength results align very closely to NOAA's model of temperature departures following February's SSW event which was caused by a record-breaking movement of large-scale eddy heat fluxes into the stratosphere. The temperature pattern (Fig. 10, middle) following this SSW event closely resembled the typical negative phase of the NAO, similar to the average patterns that follow these events (Fig. 10, left). Within two of weeks of this SSW, multiple severe winter storms hit the United Kingdom and most of Western Europe, bringing snow as far south as Rome. Additionally, regions in the NE United States received several feet of snow while many regions experienced persistent cold and snowy weather along the East Coast throughout March (Butler, 2018). The uses of these methods can be applied to vortex events and perhaps in understanding the spatial structure of stratosphere-troposphere coupling. Although it is unlikely that simple mechanisms are the sole cause of coupling in the atmosphere, perhaps an increased understanding of the modes of variability at play are required when considering the nature of anomalous vortex events that induce such excitations of the barotropic mode.

4.3: CMIP5 Simulations, Trends, and Statistical Significance

Utilizing both a 29 model ensemble and a 14 model high-top ensemble with historical and projected 30-year experiments, composite results are compared and validated with the NCEP/NCAR reanalysis data (Fig. 11). Consistent with other studies, the high-top model ensemble reproduces reanalysis averages more closely than ensembles that include low-top model heights. The average area, centroid location and latitudinal extent all compare well with the historical period, indicating that the CMIP5 high-top composites may be a close estimation of polar vortex variability, which would remain consistent with past comparison studies (Butler et al. 2015; Charlton and Polvani 2007) that show a similar number of SSW events per year in historical CMIP5 simulations. Initial interesting findings in projections of polar vortex size are the commonalities to most all of the model composites that simulated an increase in size, decreases in latitudinal extent, or significant displacements towards Europe, NE North America, Siberia and NE Asia.

Individually, most model members rarely replicate polar vortex trends of the past in the historical CMIP5 model simulations. With the goal of overcoming such limitations in model biases, the method of selecting the more skillful high-top models is analyzed in attempt to reduce the uncertainty of the models and to achieve the highest skill in the projections. Although the high-top model spread in geography is quite variable, a positive linear trend among the models in increasing vortex size is notable. The multimodel composites from the three historical to the projections at the end of 21st century show a linear trend with notable upticks through the 21st century.

Each 30-year high-top simulation of area and average velocity was compared to the most recent 30-year historical period (1975-2005). The similarity of the slope of increasing vortex size in the 30-year timescales both model groups indicates that this trend in simulations is robust and that we may be able to use the multimodel composite slope to quantify the link to projected stratospheric variability. When comparing the change in size among the multimodel averages between the historical period and each of the three 30-year projected periods under the RCP 8.5 scenario, period 3 (2070-2100) was found to significantly increase in size at the 95% confidence level ($p\text{-value} = 0.048$). This is an increase of 20.1 percent from the most recent 30-year observational average. The change in the difference of polar vortex size for the 2010-2040 and 2040-2070 runs were not found to be statistically significant, although the simulations showed an expansion of 3.9 and 11.3 percent, respectively, compared to recent observational composite. Interestingly, although a consistent increase in vortex size and southerly excursion in latitude throughout the projections is evident, the average vortex zonal wind velocity shows no trend and remains relatively similar in to the most recent historical velocity average.

Similar to the geographic shift over the Eurasian continent that has been observed in reanalysis, both CMIP5 ensemble groups show not only a shift towards Eurasia, but an expansion of the polar vortex over NE Asia. Further in-depth analysis is needed to make inferences on whether or not this projected expansion could be from the possibility of increases in major SSWs that typically split the vortex into separate vortices over Eurasia, North America or Europe. Although the relative impact on surface weather from different

types of splits and displacements vary, the projected expansion into NE Asia and Siberia could indicate the possibility of increased surface signal of stronger negative pressure anomalies over these regions.

The linear regression trend (Fig. 14, bottom) shows an expanding polar vortex climatology for high-top composites is at 97% from the first historical run to the end of the 21st century, while the 29 model trend is also a linear fit at 95%. It is important to note that the 29-model composites could underestimate projected variability and/or frequency SSWs as some model members lack realistic stratospheric variability (i.e., with a low top) which could underestimate the likelihood of such events, and hence, the outputs from these models should be interpreted with caution. The climatological difference in vortex area and geographical location between the high-top (solid extents) and 29 model composites (dashed extents) and the linear trends of both the high-top and the 29 model ensembles are similar in expanding geography (Fig. 14, top). Notably, the 2070-2100 high-top composite shows an equatorward push of the SPV gradient over most landmasses.

Although the 29 model ensemble simulations show a lower estimate of polar vortex size of nearly 3 million square kilometers in some 30-year simulations, both ensemble groups show a high r^2 value in the linear trend line, with a notable uptick towards the end of the 21st century. While there is high variability among the CMIP5 ensemble members on their projections for minimum latitude of the polar vortex edge throughout the 21st century, the simulated high-top composites remain a robust best estimate and show a general agreement in expanding extent, suggesting future increases

in zonal wind variability in the stratosphere are likely. Considering the CMIP5 suite's ability to replicate vortex climatologies of the past and assuming that the high-top model simulations statistical significance in change of size are representative of future atmospheric variability, these results could indicate a large changes in SPV climatology. Most models maintain low latitude values in the projections, indicating that the vortex's position during the 21st century should remain away from the pole, suggesting future increases in seasonal variability and likely increases in the frequency of polar vortex splitting or displacement events towards the end of the century. If the SPV is expected to increase in variability, the necessity for more skillful seasonal forecasts of interannual vortex variability will become more imperative

Chapter 5: Summary and Discussion

Trends in the Northern Hemisphere's Stratospheric Polar Vortex have been examined using reanalysis datasets to assess both strength and size in the 20th century. Consistent with previous studies, it is clear that vortex size has been increasing with a shift equatorward towards Eurasia over the observational period. The association between a weak polar vortex and CAOs that coincide with regions of southerly excursions of the SPV and the link between SPV shifts over Eurasia and North America that can induce cooling deserves further attention to better understand the future of wintertime climates. Initially this study has found that the decadal average size of the polar vortex has historically increased while shifting equatorward over Eurasia, which prompted the main research question regarding whether or not the affects of future climate warming on the strength, size, and geographic position of the polar vortex will be projected to undergo significant change in response to the RCP 8.5 emissions scenario. These findings are interesting as questions can be raised as to whether or not this trend in increasing extent is attributed to anthropogenic climate forcing, natural climate variability, Arctic amplification or a combination of many. Although the size of the decadal averages of the SPV extent have been increasing since the 1950s, a more pronounced weakening is observed from the 1980s onward, possibly suggesting that anthropogenic climate forcing or rapid Arctic tropospheric warming are likely a key mechanisms of perturbation in the Arctic stratosphere. The influence of the polar vortex position on the Northern Hemisphere's surface climate resulting from the shift of the SPV towards the Eurasian continent can contribute to increased regional potential vorticity. In turn, this can produce

Rossby wave trains from Eurasia to North America which can affect winter surface temperatures in both Eurasia and North America (primarily the Northeast North America) in February and March (Baldwin and Dunkerton 2001, Zhang et al. 2016). There is clearly a need for more advanced modeling and forecasting in this complex coupled system.

This study addressed the need for analyzing changes in polar vortex projections in location and strength throughout the 21st century. The 30-year multimodel mean projections of zonal wind at 50 hPa should account for natural climate variability by the end of the century. The significant change in polar vortex size and location simulated by a robust multimodel ensemble toward the end of the century suggests that anthropogenic forcing should play a role in the polar vortex variability rather than solely internal variability. Reanalysis data reveals high polar vortex variability throughout the 20th century with multi-decade periods of both strong and weak vortex regimes. As the 20th century has experienced fairly dramatic climate change, this suggests that the polar vortex over the 21st century should go through both strong and weaker regimes as well. The significant trend among the high-top models in increasing extent and the uptick toward the end of the 21st century suggest that changes in radiative forcing from emissions contribute in some way to the changes in stratospheric wintertime variability in the Northern Hemisphere's polar vortex. Change in strength of the polar vortex was found to be insignificant, suggesting that even under continued warming, the polar vortex could continue to go through multi-decadal periods of strong vortex regimes, and again return to long weak periods with large expansions. Although this study finds no clear

trends in projections of polar vortex strength, further in-depth analysis of projected strength is needed to better understand possible future vortex behavior and associated impacts. The projected geographic shifts and expansion of the polar vortex could potentially translate to cold wintertime events in certain regions of NE Asia, Europe and North America, although the likelihood of persistent cooling trends in most regions is unlikely considering the outlook of reduction in the Arctic-midlatitude tropospheric temperature gradient in addition to most model projections of global warming and reduced ice and snow toward the end of the century.

Future projections of SSW frequency would improve understanding of the casual mechanisms that may expand the polar vortex in a warmer climate. As a result of a warm Arctic and SST anomalies in the high latitudes during early winter months, Kim et al. (2014) show that upward propagation of planetary-scale waves with both wave numbers 1 and 2 to be enhanced during these periods, which in turn can weaken the polar vortex in mid-winter. More recently, the wavenumber-2-like pattern has been found to be the most likely type to cause a SSW event that can contribute to anomalously low temperatures over Eurasia (Mitchell et al. 2013). As Arctic temperatures are expected to continue to increase under global climate change, it is a logical hypothesis that SSW events, which occur directly over the Arctic Ocean and are driven by such heat-flux activity, will increase in frequency under future warming scenarios as the amount of heat and moisture exchanged between the troposphere and stratosphere undergoes future changes. As a weakened polar vortex can induce a negative phase of the NAO at the surface, often resulting in lower temperatures in the mid-latitudes, it will be important to further

research on these interactions as the complexities between the impacts of weak polar vortex events during a warming Arctic-midlatitude temperature gradient remain unclear.

One of the more striking results from the 2010-2100 CMIP5 multimodel composite shows large southerly excursions of the SPV, which are located above highly populated areas of Europe, Eurasia and the eastern United States. Consistent with the reanalysis, the model composites show expanding size, and more interestingly show not only a shift towards Eurasia, but an expansion of the polar vortex over NE Asia. These observations raise questions regarding the behavior of future polar vortex expressions into the troposphere, as well as to what extent a projected increase in vortex variability could have an impact on surface weather in the age of a globally warming troposphere. Although the high-top composites may be an effective tool to simulate large-scale atmospheric circulation over this century, there is a high spread among model projections due to individual configurations and how some models replicate trends of the past better than others. The advantage in analyzing the high-top ensembles for projections in the polar vortex's response to radiative forcing is that with lid tops well into and above the stratosphere, the models are more capable of resolving stratospheric variability. For future research into SPV variability, improved model resolution of the stratosphere and higher lid tops will be advantageous in increasing model skill in future projections when resolving SSW event frequency and polar vortex trends. Models such as the MPI-ESM-MR in the CMIP5 suite are currently being replaced in CMIP6 to match our best understanding of the 21st century climate with major technical optimizations with

additions that offer a higher resolution in the atmosphere component, improved soil carbon and nitrogen cycle model, among other model improvements.

In conclusion, the results of this study reveal that the Stratospheric Polar Vortex has on average increased in size while shifting equatorward over Eurasia and away from the pole since the 1950s. These recent trends of decreasing strength and increasing size could be a major contributor to the recent hiatus of Eurasian warming during the winter season and deserve further modeling and analysis. The recent weakening of the polar vortex has been notable since the 1980s along with the relative increase in SSWs in the 2000s prompted the research objectives to analyze climate model simulated polar vortex climatologies to the end of the 21st century in order to observe whether or not the CMIP5 models project increases in size and/or decreases in strength. The significant change in the vortex mean state (linearly increasing size) towards the end of the 21st century should result in a more disturbed or variable average vortex state, which could implicate more frequent occurrences of SSWs or more simply increased polar stratospheric wintertime variability. Although the multimodel composites show a robust increase in size, the mean velocity of the polar vortex edge simulated shows no significant increase or decrease, leaving more questions regarding the future variation in behavior of the SPV.

A better understanding of precursors to SSWs and associated polar vortex events (splits/displacements) and future changes in variability will aid medium-long range winter weather forecasts. Further analysis of future tropospheric conditions in the middle to high-latitudes in relation to tropospheric-stratospheric coupling is needed.

Additionally, a more accurate understanding of expectations of hemispheric circulation

patterns will contribute to the knowledge and planning for both Arctic and regional mid-latitude climate resiliency. In time, improvements in modeling skill from the CMIP Phase 6 and coupled chemistry-climate models in addition to advances in observationally based data collection may contribute to a more appropriate approach to increasing model forecasting and simulation skill in the years to come.

Institute	Model	Spatial Resolution	Lid Height (km)	Reference
Centre for Australian Weather and Climate Research	ACCESS1-0	1.25 x 1.875	39 km	Collier and Uhe 2012
Centre for Australian Weather and Climate Research	ACCESS1-3	1.25 x 1.875	39 km	Collier and Uhe 2012
Beijing Climate Center	BCC-CSM1	2.7906 x 2.8125	2.97 hPa	Wu et al. 2012
Beijing Normal University	BNU-ESM	2.7906 x 2.8125	2.19 hPa	Ji et al. 2014
Canadian Earth System Model	CanESM2	2.8125 x 2.8125	48.1 km	Chylek et al. 2011
Community Climate System Model	CCSM4	0.9424 x 1.25	2.19 hPa	Collins et al. 2004
Centro Euro-Mediterraneo per i Cambiamenti Climatici	CMCC-CESM	3.4431 x 3.75	80.6 km	Folgt and Iovino 2014
Centro Euro-Mediterraneo per i Cambiamenti Climatici	CMCC-CM	0.7484 x 0.75	10 hPa	Scoccimarro et al. 2011
Centro Euro-Mediterraneo per i Cambiamenti Climatici	CMCC-CMS	3.7111 x 3.75	80.6 km	Scoccimarro et al. 2011
Centre National de Recherches Meteorologiques	CNRM-CM5	1.4008 x 1.40625	10 hPa	Voldoire et al. 2012
EC-EARTH Consortium	EC-EARTH	1.1215 x 1.125	5 hPa	Hazeleger et al. 2012
Geophysical Fluid Dynamics Laboratory	GDCL-CM3	2 x 2.5	76.3 km	Donner et al. 2011
Geophysical Fluid Dynamics Laboratory	GFCL-ESM2G	2.0225 x 2	3 hPa	Dunne et al. 2013
Geophysical Fluid Dynamics Laboratory	GFCL-ESM2M	2.0225 x 2.5	3 hPa	Dunne et al. 2013
Met Office Hadley Centre	HadGEM2-AO	1.25 x 1.875	40 km	Baek et al. 2013
Met Office Hadley Centre	HadGEM2-CC	1.25 x 1.875	84.1 km	Collins et al. 2011
*Met Office Hadley Centre	HadGEM2-ES	1.25 x 1.875	40 km	Collins et al. 2011
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	1.8947 x 3.75	70.4 km	Dugense et al. 2013
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	1.2676 x 2.5	70.4 km	Dugense et al. 2013
Institut Pierre-Simon Laplace	IPSL-CM5B-LR	1.8947 x 3.5	70.4 km	Dugense et al. 2013
Atmosphere and Ocean Research Institute	MIROC-ESM	2.7906 x 2.8125	0.0036 hPa	Watanabe et al. 2010
Atmosphere and Ocean Research Institute	MIROC-ESM-CHEM	2.7906 x 2.8125	87.8 km	Watanabe et al. 2010
Max Planck Institute for Meteorology	MPI-ESM-LR	1.8653 x 1.875	80.6 km	Stevens et al. 2013
Max Planck Institute for Meteorology	MPI-ESM-MR	1.8653 x 1.875	80.6 km	Stevens et al. 2013
Meteorological Research Institute	MRI-CGCM3	0.562 x 0.5625	80.6 km	Yukimoto et al. 2012
Meteorological Research Institute	MRI-ESM1	1.12148 x 1.125	80.6 km	Yukimoto et al. 2012
Norwegian Climate Centre	NorESM1-M	1.8947 x 2.5	3.54 hPa	Bentsen et al. 2013
Norwegian Climate Centre	NorESM1-ME	1.8947 x 2.5	3.54 hPa	Bentsen et al. 2013

Table 1: The main characteristics of the CMIP5 models included in the historical (1915-2005) and projected (2010-2090) model simulations. Models highlighted in bold include

a well-resolved stratosphere and are analyzed in the high-top composites (Data Source: <https://esgf-node.llnl.gov/projects/esgf-lln>)

Fig. 1. A generalized schematic of the SPV and TPV (Jet Stream) in the Northern Hemisphere.

Fig. 2. Conceptual maps displaying an average winter extent of the SPV (a), a vortex displacement event (b), and a vortex split event (c) in the middle atmosphere.

Fig. 3: The SPV edge (black) identified by interpolating the maximum zonal wind during a displaced to splitting event in January 2014 using (left.) The maximum gradient geopotential height gradient aligns with the maximum zonal winds at 50 hPa from NCEP reanalysis.

Fig 4: A generalized GIS-based model for identifying the SPV edge.

NCEP/NCAR Analysis
Geopotential Height
Jan. 11th - 50 hPa

Fig. 5. An example of a high polar vortex aspect ratio during the SSW on January 11th, 2013/2014 that split into two separate low pressure vortices in the middle of the polar night jet season.

Fig. 6: An example of simulations from the six CMIP5 models excluded from this study. Projected period 1 (2010-2040) Stratospheric Polar Vortex zonal winds (m/s) at 50 hPa.

Fig. 7: Decadal Stratospheric Polar Vortex and increasing in extent from the 1950's-2010 and recent decreasing mean zonal wind velocity.

Fig 8: Decadal Stratospheric Polar Vortex consistently shifting towards Eurasia and increasing in extent from the 1950's-2010 with their respective centroids showing an equatorward migration.

Fig. 9: Winter of 1990s anomalous SPV and the resulting persistent COA (left) compared to a stronger and more typical vortex winter (right).

Fig. 10: Temperatures departures in the 45 days after the Feb. 2018 SSW event (middle) compared to days after all recorded SSW events (left) compared to a map of February 2018 SPV (right, white). Source: NOAA. Data: NCEP/NCAR.

Fig. 11: Comparison of the CMIP5 high-top ensemble composite from 1975-2005 compared to the NCEP/NCAR reanalysis composite.

Fig. 12: Individual historical and projected model simulations for each 30-year simulation and the composite average.

Fig. 13: Individual high-top model simulations of historical and projected 30-year simulations and their multi-model composite (black) show a consistent increase in polar vortex size, although the geography of the model simulations are quite variable. A Student's T-test show a p-value of 0.048 at the 95% confidence level in significant change in size from the most recent historical period and the projection for the end of this century (projection 3).

Fig. 14: Comparison and trends for the CMIP5 29-model and 14 model high-top simulations of SPV extent.

References

- Baldwin, M. and Dunkerton, T. 1999. Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *Journal of Geophysical Research: Atmospheres*. 104: 30937-30946.
- Barnes, E. A. and Polvani, L.M. 2015. CMIP5 Projections of Arctic Amplification, of the North American/North Atlantic Circulation, and of Their Relationship. *Journal of Climate*. 28 (13):5254–5271.
- Butler, A. 2015. Defining Sudden Stratospheric Warmings. *Bulletin of the American Meteorological Society*. 96 (11)
- Butler, A. 2018. February and March madness: How winds miles above the Arctic may have brought wintry weather to mid-latitudes | NOAA Climate.gov. *Climate.gov*. <https://www.climate.gov/news-features/blogs/enso/february-and-march-madness-how-winds-miles-above-arctic-may-have-brought> (last accessed 26 May 2018).
- Charlton-Perez, A.J., M.P. Baldwin, T. Birner, R.X. Black, A.H. Butler, N. Calvo, N.A. Davis, E.P. Gerber, N. Gillett, S. Hardiman, J. Kim, K. Krüger, Y.-Y. Lee, E. Manzini, B.A. McDaniel, L. Polvani, T. Reichler, T.A. Shaw, M. Sigmond, S.-W. Son, M. Toohey, K. Wilcox, S. Yoden, B. Christiansen, F. Lott, D. Shindell, S. Yukimoto, and S. Watanabe, 2013: On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models. *J. Geophys. Res. Atmos.*, 118, no. 6, 2494-2505, doi:10.1002/jgrd.50125.
- Charney, J.G. and Drazin, P.G., 1961. Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *Journal of Geophysical Research*, 66(1), 83–109. doi: 10.1029/JZ066i001p00083.
- Cohen, J. 2011. Eurasian Snow Cover Variability and Links with Stratosphere-Troposphere Coupling and Their Potential Use in Seasonal to Decadal Climate Predictions. *Science and Technology Infusion Climate Bulletin*, NOAA, 1-6.
- Cohen, J. and Jones, J. 2011. Tropospheric precursors and stratospheric warmings. *Journal of Climate*. Vol. 25: 1780-1790.
- Cohen, J., J. Furtado, M. Barlow, V. Alexeev, and J. Cherry. 2012. Arctic warming, increasing snow cover and widespread boreal winter cooling. *Environmental Research Letters* 7 (1):014007.

- Francis, J., and Vavrus, S. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters* 39 (6):n/a-n/a.
- Garfinkel, C., D. Waugh, and E. Gerber. 2013. The Effect of Tropospheric Jet Latitude on Coupling between the Stratospheric Polar Vortex and the Troposphere. *Journal of Climate* 26 (6):2077-2095.
- Karpechko, A., E. Kyrö, and B. Knudsen. 2005. Arctic and Antarctic polar vortices 1957–2002 as seen from the ERA-40 reanalyses. *Journal of Geophysical Research* 110 (D21).
- Kim, B., S. Son, S. Min, J. Jeong, S. Kim, X. Zhang, T. Shim, and J. Yoon. 2014. Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nature Communications* 5:4646.
- Kolstad, E. W., and A. J. Charlton-Perez. 2010. Observed and simulated precursors of stratospheric polar vortex anomalies in the Northern Hemisphere. *Climate Dynamics* 37 (7-8):1443–1456.
- Kolstad, E., Breiteig, T., Scaife, A. 2010. The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere. *Royal Meteorological Society*. 1366: 886-893.
- Kozubek, M., P. Krizan, and J. Lastovicka. 2017. Comparison of the long-term trends in stratospheric dynamics of four reanalyses. *Annales Geophysicae* 35 (2):279–294.
- Kretschmer, M., D. Coumou, L. Agel, M. Barlow, E. Tziperman, and J. Cohen. 2018. More-Persistent Weak Stratospheric Polar Vortex States Linked to Cold Extremes. *Bulletin of the American Meteorological Society* 99 (1):49–60.
- Kuttippurath, J., and G. Nikulin. 2012. A comparative study of the major sudden stratospheric warmings in the Arctic winters 2003/2004- 2009/2010. *Atmospheric Chemistry and Physics* 12 (17):8115-8129.
- Lee, Y., and R. Black. 2015. The Structure and Dynamics of the Stratospheric Northern Annular Mode in CMIP5 Simulations. *Journal of Climate* 28 (1):86-107.
- Limpasuvan, V., D. Hartmann, D. Thompson, K. Jeev, and Y. Yung. 2005. Stratosphere-troposphere evolution during polar vortex intensification. *Journal of Geophysical Research* 110 (D24).

- McCusker, K. E., J. C. Fyfe, and M. Sigmond, 2016: Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic sea-ice loss. *Nat. Geosci.*, 9, 838–842, <https://doi.org/10.1038/ngeo2820>.
- McKenna, C., T. Bracegirdle, E. Shuckburgh, P. Haynes, and M. Joshi. 2018. Arctic Sea Ice Loss in Different Regions Leads to Contrasting Northern Hemisphere Impacts. *Geophysical Research Letters* 45 (2):945-954.
- Overland et al. 2016 Overland, J. E., and Coauthors, 2016: Nonlinear response of mid-latitude weather to the changing Arctic. *Nat. Climate Change*, 6, 992–999, <https://doi.org/10.1038/nclimate3121>. View Full Reference List).
- Palmer, T. 2014. Record-breaking winters and global climate change. *Science*. 344 (6186):803-804.
- Reinecker et al. 2011. MERRA: NASA’s Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*. 24: 3624-3648.
- Serra, M., Sathe, P., Beron-Vera, F., Haller, G. 2017. Uncovering the Edge of the Polar Vortex. *Journal of Atmospheric Physics*. 10: 1175.
- Seviour, W., L. Gray, and D. Mitchell. 2016. Stratospheric polar vortex splits and displacements in the high-top CMIP5 climate models. *Journal of Geophysical Research: Atmospheres* 121 (4):1400-1413.
- Sun, L., C. Deser, and R. Tomas. 2015. Mechanisms of Stratospheric and Tropospheric Circulation Response to Projected Arctic Sea Ice Loss. *Journal of Climate* 28 (19):7824-7845.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012). An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, 93, 485–498, doi:10.1175/BAMS-D-11-00094.1.
- Waugh, D., Sobel, A., Polvani, L. 2016. What is the polar vortex and how does it influence weather? *American Meteorological Society*. 1: 37-44.
- Zhang, J., Tian, W., Chipperfield, M., Xie, F., Huang, J. 2016. Persistent shift of the Arctic polar vortex towards the Eurasian continent in recent decades. *Nature Climate Change*. 6: 1094-1099.
- Screen, J. A., C. Deser, and L. Sun. 2015. Reduced Risk of North American Cold Extremes due to Continued Arctic Sea Ice Loss. *Bulletin of the American Meteorological Society* 96 (9):1489–1503.

Smith, K. L., L. M. Polvani, and L. B. Tremblay. 2018. The Impact of Stratospheric Circulation Extremes on Minimum Arctic Sea Ice Extent. *Journal of Climate* 31 (18):7169–7183.