Examining variability in model skill during the 7 January 2013 sudden stratospheric warming event

Jonathan Lee Blufer

University at Albany, State University of New York, jblufer@albany.edu

The University at Albany community has made this article openly available. Please share how this access benefits you.

Follow this and additional works at: https://scholarsarchive.library.albany.edu/legacy-etd

Part of the Atmospheric Sciences Commons

Recommended Citation
https://scholarsarchive.library.albany.edu/legacy-etd/1787

This Master's Thesis is brought to you for free and open access by the The Graduate School at Scholars Archive. It has been accepted for inclusion in Legacy Theses & Dissertations (2009 - 2024) by an authorized administrator of Scholars Archive. Please see Terms of Use. For more information, please contact scholarsarchive@albany.edu.
EXAMINING VARIABILITY IN MODEL SKILL DURING THE 7 JANUARY 2013
SUDDEN STRATOSPHERIC WARMING EVENT

by

Jonathan L. Blufer

A Thesis
Submitted to the University at Albany, State University of New York
in Partial Fulfillment of
the Requirements for the Degree of
Master of Science

College of Arts & Sciences
Department of Atmospheric and Environmental Sciences
2017
ABSTRACT

Recent analyses of numerical weather prediction models have shown that stratospheric regime changes (e.g. strong and weak vortex events) are not skillfully predicted at medium-range lead times. Motivated by these recent analyses, this thesis investigates the sources of variability in stratospheric forecast skill amongst several operational models initiated at different lead times prior to the 7 January 2013 sudden stratospheric warming (SSW). This study extends upon a previous analysis by the Stratospheric Network for the Assessment of Predictability (SNAP), which concluded that a change in forecast lead-time from 15 to 10 days increased model skill in predicting the 2013 SSW by roughly 50 percent. The sources of such variability in predictive skill are investigated further in this thesis.

Coordinated reforecasts from the SNAP dataset are used to examine model variability and forecast skill in six medium-range operational ensemble forecast models. Both elliptical diagnostics of the polar vortex that quantify the vortex eccentricity, center longitude and latitude, and area, as well as zonal mean metrics are used to assess model errors and biases in the stratosphere. Ensemble skill is categorized into low and high error composite groups according to two separate metrics: the strength of the 10-hPa zonal mean zonal wind at 60˚N and the center latitude of the 10-hPa vortex ellipse. Analysis reveals that ensemble members forecasting an ellipse center located equatorward of 70°N prior to 7 January 2013 had greater skill in predicting an easterly 10-hPa zonal mean zonal wind regime at the time of verified SSW onset.

It is hypothesized that model error in forecasting thermodynamic processes linked to the SSW precursor tropospheric blocking in the N. Atlantic resulted in systematic biases and variability in dynamical forcing (e.g. upward wave activity flux) into the polar stratosphere in forecasts of the 7 January 2013 SSW event. Results indicate that errors in maintaining a
blocking ridge in the N. Atlantic associated with an intensifying cyclone off the northeast coast of the United States produced deviations in ensemble forecasted wave activity flux into the lower stratosphere one week prior to the 7 January 2013 SSW event.
ACKNOWLEDGEMENTS

I would like to thank Dr. Andrea Lang and Dr. Lance Bosart for advising me while I worked on completing my master’s degree. Entering the Department of Atmospheric and Environmental Sciences in Fall 2015 with an undergraduate degree in Biological Sciences, I was unsure of how my background would allow for me to succeed while completing my degree at the University at Albany. Yet with the advisement of Dr. Andrea Lang and Dr. Lance Bosart, I was able to quickly develop and refine my meteorological skills and grow immensely as a scientist and as a student. Now working as a marine meteorologist, I am grateful that they have shown me how research can be applied to operations in a plethora of ways. I am incredibly thankful for the insight they have given me over the previous 2.5 years, and I am confident that working with them will show in my future endeavors.

I am exceedingly thankful for the enthusiastic professors and staff of the Department of Atmospheric and Environmental Sciences at the University at Albany. Under their guidance and teachings, I have received an amazing education in so many aspects of atmospheric sciences. I would like to thank the professors who guided me as a graduate teaching assistant – with their mentorship, I have greatly developed my skills as a leader. I would also like to thank the professors who instructed me as an undergraduate at Cornell University, particularly the professors in the atmospheric sciences and biological sciences departments. While my background in biology might not be directly applicable to the atmospheric sciences, my undergraduate education taught me how to continuously push myself and pursue what I truly desire, which is a career in meteorology.
I would like to thank my fellow students at the University at Albany, who created a welcoming, collaborative environment from the day I moved to Albany. I am especially grateful for the emotional and professional support from Zachary Murphy, Michaela Rosenmayer, Erin Dougherty, and Colleen McHugh, who entered graduate school with me and made my experience run as smoothly as I ever could have hoped. I would also like to thank my officemates in ES 234 for were always willing to help with coding and coursework. Of special note, I am so thankful for my family, boyfriend, and friends who always support me and push me to succeed as a meteorologist.

J.L.B.

New York

November 2017
# TABLE OF CONTENTS

Abstract........................................................................................................................................... ii  
Acknowledgements....................................................................................................................... iv  
Table of Contents ......................................................................................................................... vi  
List of Tables................................................................................................................................... ix  
List of Figures ................................................................................................................................... x  
1. Introduction................................................................................................................................. 1  
1.1 Motivation ............................................................................................................................... 1  
1.2 Literature Review ................................................................................................................... 2  
1.2.1 Defining the Polar Vortex and Sudden Stratospheric Warmings................................. 2  
1.2.2 Troposphere-Stratosphere Coupling.............................................................................. 5  
1.2.2.1 The Breakdown of the Polar Vortex........................................................................... 5  
1.2.2.2 Tropospheric Blocking............................................................................................... 6  
1.2.3 Stratosphere-Troposphere Coupling and Impacts near the Surface ......................... 10  
1.2.4 SSW Predictability ........................................................................................................ 11  
1.2.5 Previous Work on the 7 January 2013 SSW Event ...................................................... 13  
1.3 Research Goals and Thesis Structure ................................................................................. 14  
2. Data and Methodology.............................................................................................................. 21  
2.1 SNAP Dataset......................................................................................................................... 21  
2.1.1 CAWCR AGREPS.......................................................................................................... 21  
2.1.2 MRI-AGCM ................................................................................................................... 22  
2.1.3 NOGAPS ....................................................................................................................... 22  
2.1.4 MET Office Unified Model............................................................................................. 22
2.1.5 ECMWF System 4 .................................................................................. 23
2.1.6 Korea Air Force Global/Regional Integrated Model system .............. 23
2.2 Verification Dataset .................................................................................. 24
2.3 Model Categorization: Zonal Mean Zonal Wind ..................................... 24
2.4 Model Categorization: Elliptical Diagnostics ........................................... 25
2.5 Troposphere-Stratosphere Coupling Analysis ......................................... 25
3. Zonal Mean Metrics .................................................................................... 28
  3.1 Lead Time Variability ........................................................................... 28
  3.2 Tropospheric Forcing ........................................................................... 35
    3.2.1 PV Waveguide Progression ............................................................. 35
    3.2.2 Blocking Regime Variability ............................................................ 41
4. Elliptical Metrics ......................................................................................... 62
  4.1 Polar Vortex Tracking ........................................................................... 62
  4.2 Vortex Ellipse Centers .......................................................................... 67
    4.2.1 Vortex Ellipse Ensemble Variability .............................................. 67
    4.2.2 Vortex Ellipse Latitude Clustering .................................................. 68
      4.2.2.1 Relationship to Zonal Mean Metrics ....................................... 68
      4.2.2.2 Tropospheric Forcing ............................................................... 69
  4.3 Summary ............................................................................................... 75
5. Summary, Discussion, and Suggestions for Future Work ......................... 92
  5.1 Summary ............................................................................................... 92
  5.2 Discussion ............................................................................................. 96
    5.2.1 Zonal Mean Metrics ..................................................................... 97
5.2.2 Elliptical Metrics ..................................................................................99
5.3 Suggestions for Future Work .................................................................101
References .....................................................................................................103
LIST OF TABLES

Table 2.1. A synopsis of the six NWP ensembles used to analyze the 7 January 2013 SSW event. Ensemble name, abbreviation, number of members, vertical resolution, and horizontal resolution are provided, with additional information on the SNAP dataset found in Tripathi et al. (2016).

Table 3.1. Ensemble mean and standard deviation of forecasted 10 hPa 60°N zonal mean zonal wind at 00 UTC 07 January 2013 for all six SNAP models at 15- and 10-day lead times. Verified CFSR value at 00 UTC 07 January 2013 included.
LIST OF FIGURES

Fig. 1.1 Climatological zonal-mean zonal wind in Jan and Jul. The diamonds mark the hemispheric maximum of the zonal wind at each pressure level and the approximate edge of the polar vortex for that hemisphere. Figure and caption adapted from Waugh et al. (2016).

Fig. 1.2. (a) A displacement-type SSW event on 21 Jan 2006 and (b) a split-type SSW event on 24 Jan 2009, for the average of (left) 8-15 days prior to the event, (middle) 7 days prior to the event, and (right) 1-8 days following the event. ERA-Interim temperature anomalies (based on 1979-2012 climatology) at 10 hPa (K) are shaded. The black solid line marks the 7-PVU contour (1 potential vorticity unit = 10⁻⁶ K kg⁻¹ m² s⁻¹) at 10 hPa and indicates the shape of the polar vortex. The arrows indicate the full zonal and meridional wind fields at 10 hPa (arrows with a westerly zonal component are black; arrows with an easterly zonal component are blue). The 60°N latitude band is dashed. Figure and caption adapted from Charlton and Polvani (2016).

Fig. 1.3. (left) Anomalous zonal-mean zonal wind, (middle) zonal-mean temperature, and (right) EP flux with its divergence during the composite life cycle of SSWs. Negative contours are given as blue dashes. Zero contours are given as bold solid lines. The wind (temperature) contour interval is 1 m s⁻¹ (1 K). The EP flux divergence (Divided by ρ₀a cosθ, where ρ₀ is basic density, a is the earth’s radius, and θ is latitude) is contoured in the right column every 0.25 m s⁻¹ day⁻¹ with deceleration in blue. The vector lengths in the right column are referenced with respect to the top figure in the column. Gray shading indicates areas with a 95% confidence level (based on t statistics). Figure and caption adapted from Limpasuvan et al. (2004).

Fig. 1.4. Geopotential height fields, zonal wave number 1 in blue and 2 in red, composited for the period – 10 to 0 days prior to (top) vortex displacement events and (bottom) vortex splitting events, at 500, 200, 100, 50, and 10 hPa, from left to right, respectively. Contour levels shown are: 100, 130, 160, 190, 220, 250, 300, 350, 400, 500, 600k, 700, 800 and 900 m, solid contours indicate positive values. Gray shading shows blocking frequency greater than 0.4. Figure and caption adapted from Martius et al. (2009).

Fig. 1.5. Schematic representation of ridge amplification and jet streak intensification associated with the divergent outflow of a TC impinging upon an upper-tropospheric jet stream/waveguide. Vectors represent the upper-tropospheric irrotational wind (i.e. divergent outflow) associated with the TC. Shading denotes negative PV advection by the irrotational wind. Figure and caption adapted from Archambault et al. (2013).

Fig. 1.6. Composites of time-height development of the northern annular mode for (A) 18 weak vortex events and (B) 30 strong vortex event. The events are determined by the dates on which the 10-hPa annular mode values cross -3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between -0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and stratosphere. Figure and caption adapted from Baldwin and Dunkerton (2001).

Fig. 1.7. Zonal-mean zonal wind at 10 hPa and 60°N from ERA-Interim (thick black lines) and model ensemble members (thin gray lines). The thick colored line denotes the ensemble mean. The initialization dates are (left) 23 Dec 2012 (D – 15) and (right) 28 Dec 2012 (D – 10).
Vertical date ticks are drawn at 0000 UTC. Figure and caption adapted from Tripathi et al. (2016).

Fig. 3.1. KAF ensemble forecast of 10 hPa 60°N zonal mean zonal wind (m s$^{-1}$), 60°-90° area-weighted temperature (K), and 60°-90° area-weighted geopotential height (m), initialized 23 December 2012.

Fig. 3.2. KAF ensemble forecast of 10 hPa 60°N zonal mean zonal wind (m s$^{-1}$), 60°-90° area-weighted temperature (K), and 60°-90° area-weighted geopotential height (m) initialized 28 December 2012.

Fig. 3.3. As in Fig. 3.1 but for the NOGAPS model.

Fig. 3.4. As in Fig. 3.2 but for the NOGAPS model.

Fig. 3.5. As in Fig. 3.1 but for the ECMWF model.

Fig. 3.6. As in Fig. 3.2 but for the ECMWF model.

Fig. 3.7. As in Fig. 3.1 but for the METO model.

Fig. 3.8. As in Fig. 3.2 but for the METO model.

Fig. 3.9. As in Fig. 3.1 but for the MRI model.

Fig. 3.10. As in Fig. 3.2 but for the MRI model.

Fig. 3.11. As in Fig. 3.1 but for the CAWCR model.

Fig. 3.12. As in Fig. 3.2 but for the CAWCR model.

Fig. 3.13. 1000-hPa geopotential height (black contours; m), 500-1000-hPa thickness (colored contours; purple denotes 540 dam thickness; m), and 200-300-hPa jet (fill; m s$^{-1}$) for CFSR data. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.

Fig. 3.14. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s$^{-1}$), and precipitable water (fill; mm) for CFSR data. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.

Fig. 3.15. 1000-hPa geopotential height (black contours; m), 500-1000-hPa thickness (colored contours; purple denotes 540 dam thickness; m), and 200-300-hPa jet (fill; m s$^{-1}$) for KAF data; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.

Fig. 3.16. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s$^{-1}$), and daily-averaged precipitation (fill; mm) for KAF; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC
06 January 2013.

Fig. 3.17. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s\(^{-1}\)), and daily-averaged precipitation (fill; mm) for CAWCR; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.

Fig. 3.18. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), wind speed (fill; m s\(^{-1}\)), and meridional heat flux (red contours: positive; K m s\(^{-1}\), blue contours: negative; K m s\(^{-1}\)) for (a) CFSR, (b) KAF, and (c) CAWCR; forecasts initialized 23 December 2012. All values averaged from 00 UTC 31 December 2012 through 00 UTC 07 January 2013.

Fig. 4.1. 10-hPa geopotential height field (black; km), 10-hPa 29.5 km geopotential heights (blue; km), ellipse(s) fitted to 10-hPa 29.5 km geopotential heights (red; km), using CFSR dataset valid at (a) 0000 UTC 23 December 2012, (b) 0000 UTC 28 December 2012, (c) 0000 UTC 02 January 2013, (d) 0000 UTC 07 January 2013, (e) 0000 UTC 12 January 2013, (f) 0000 UTC 17 January 2013, (g) 0000 UTC 22 January 2013, and (h) 0000 UTC 21 February 2013.

Fig. 4.2. Ensemble mean 10-hPa geopotential height field (black; km) and ensemble member ellipse(s) fitted to 10-hPa 29.5 km geopotential heights (blue; km) using KAF dataset; forecast initialized 23 December 2012 valid at (a) 0000 UTC 23 December 2012, (b) 0000 UTC 28 December 2012, (c) 0000 UTC 02 January 2013, (d) 0000 UTC 07 January 2013.

Fig. 4.3. As in Fig. 4.2 but for the NOGAPS model.

Fig. 4.4. As in Fig. 4.2 but for the ECMWF model.

Fig. 4.5. As in Fig. 4.2 but for the METO model.

Fig. 4.6. As in Fig. 4.2 but for the MRI model.

Fig. 4.7. As in Fig. 4.2 but for the CAWCR model and valid at (a) 1800 UTC 23 December 2012, (b) 1800 UTC 28 December 2012, (c) 1800 UTC 02 January 2013, (d) 1800 UTC 07 January 2013.

Fig. 4.8. 10-hPa polar vortex ellipse centers valid at 0000 UTC 06 January 2013 categorized by SNAP ensemble; forecasts initialized 23 December 2012. Red: CAWCR; Black: KAF; Magenta: NOGAPS; Green: ECMWF; Orange: METO; Blue: MRI.

Fig. 4.9. 10-hPa polar vortex ellipse centers valid at 0000 UTC 06 January 2013 categorized by latitude band; forecasts initialized 23 December 2012. Red: 60-69.9°N; Green: 70-79.9°N; Blue: 80-90°N.

Fig. 4.10. Boxplot of SNAP forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 07 January 2013 vs forecasted 10-hPa polar vortex ellipse latitude at 0000 UTC 06 January 2013, categorized by latitude band of ellipse center; initialized 23 December 2012. Boxes represent 10-hPa 60°N zonal mean zonal wind values between the first and third quartiles, with the median value represented by a solid line. Lowest and highest values in each latitude band denoted by solid black lines at the edge of the whiskers.
Fig. 4.11. SNAP forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 07 January 2013 vs forecasted 10-hPa polar vortex ellipse latitude at 0000 UTC 06 January 2013; forecasts initialized 23 December 2012. Linear regression denoted by solid black line. p-value calculated via a two-tailed Student’s t-test.

Fig. 4.12. 1000-hPa geopotential height (black solid contours; m), 1000-500-hPa thickness (colored dashed contours; m), and 300-200-hPa jet (fill; m s\(^{-1}\)) for NOGAPS Member 1; forecasts initialized 23 December 2012. 1000-500-hPa thickness values greater (less) than 540 dam are red (blue) dashed contours, every 6 dam. The 540 dam 1000-500-hPa thickness values are represented by the purple dashed contour. Analysis every two days at (a) 0000 UTC 31 December 2012, (b) 0000 UTC 02 January 2013, (c) 0000 UTC 04 January 2013, and (d) 0000 UTC 06 January 2013.

Fig. 4.13. 300-200-hPa layer-averaged potential vorticity (black contours; PVU), 300-200-hPa layer-averaged irrotational wind (vectors; m s\(^{-1}\)), and daily-averaged precipitation (fill; mm) for NOGAPS Member 1; forecasts initialized 23 December 2012. PV contoured every 1 PVU beginning at 1 PVU. Analysis every two days at (a) 0000 UTC 31 December 2012, (b) 0000 UTC 02 January 2013, (c) 0000 UTC 04 January 2013, and (d) 0000 UTC 06 January 2013.

Fig. 4.14. As in Fig. 4.12 but for the METO Member 10.

Fig. 4.15. As in Fig. 4.13 but for the METO Member 10.

Fig. 4.16. 300-200 hPa layer-averaged potential vorticity (black contours; PVU), 300-200 hPa layer-averaged wind speed (fill; m s\(^{-1}\)), and 300-200 hPa layer-averaged meridional eddy heat flux (red contours: positive; K m s\(^{-1}\), blue contours: negative; K m s\(^{-1}\)) for (a) NOGAPS Member 1 and (b) METO Member 10; forecasts initialized 23 December 2012. PV contoured every 1 PVU beginning at 1 PVU. Wind speed contoured every 10 m s\(^{-1}\) beginning at 40 m s\(^{-1}\). Meridional eddy heat flux with magnitudes exceeding 30 K m s\(^{-1}\), contoured every 10 K m s\(^{-1}\). All values averaged from 00 UTC 31 December 2012 through 0000 UTC 07 January 2013.
1. Introduction

1.1 Motivation

Sudden stratospheric warmings (SSWs) are extreme weather events in which the climatological westerlies of the stratospheric polar vortex reverse to an easterly regime (Waugh et al. 2017). While these events occur tens of kilometers above Earth’s surface, they are known to provide forcing for extreme weather in the troposphere through the downward propagation of momentum and energy anomalies (Baldwin and Dunkerton 2001; Limpasuvan et al. 2004; Charlton et al. 2004). SSWs have been associated with cold air outbreaks and extreme precipitation patterns, particularly over Europe and eastern North America, in part a result of an equatorward shift in the polar jet stream. An SSW event in February 1984 was linked to anomalous high latitude ridging in east Siberia and the North Atlantic and extreme precipitation in the northeast United States (Quiroz 1984), while an SSW in 2013 was associated with persistent cold spells over eastern North America (Schreck et al. 2015). These cold spells can have immense societal impacts, such as large increases in natural gas prices during periods of increased demand.

Of particular note is the 7 January 2013 SSW event. This major warming was the strongest event in the 1979-2009 Climate Forecast System Reanalysis (CFSR) climatology when using the 10-hPa zonal mean zonal wind at 65°N as a metric, with especially prolonged easterly zonal flow for a period of over one month beyond the event’s onset (Attard et al. 2016). Associated with the downward propagation of stratospheric momentum anomalies following the 7 January 2013 SSW event, an anomalous cold surge persisted over northern Europe for the
month of March 2013 (Tripathi et al. 2016). Due to the extreme characteristics of the 7 January 2013 SSW and its associated surface impacts, this event will be the focus for this thesis.

1.2 Literature Review

1.2.1 Defining the Polar Vortex and Sudden Stratospheric Warmings

With the term polar vortex beginning to pervade everyday vocabulary, it is important to provide a distinction between the tropospheric and stratospheric polar vortex. The most commonly used definition describes the circumpolar vortex, a band of planetary-scale westerly flow that encircles the pole, often reaching from high to mid latitudes (Waugh et al. 2017). While both the tropospheric and stratospheric vortices encircle the pole, they are separate features. The periphery of each vortex can be seen at the latitude of strongest zonal mean winds, with a clear separation around 100 hPa (Fig. 1.1). The stratospheric polar vortex is smaller spatially and has large seasonal variability – the stratospheric vortex exists only from fall to spring, while the tropospheric vortex can be seen throughout the year.

Westerlies associated with the stratospheric vortex maximize near 60°N, and are strongest between 10-hPa and 1-hPa (Waugh et al. 2017). In addition to the zonal wind, the stratospheric polar vortex can be defined based on several other metrics, e.g. based on a circumpolar region of low geopotential heights or based on a region of high potential vorticity (PV) near the pole. The stratospheric polar vortex forms during the winter months, when large meridional temperature gradients form over the poles due to the loss of solar heating. This vortex then breaks down when radiative heating returns in the spring, bringing weak easterlies to the polar region (Waugh and Polvani 2010).
With greater land-sea contrasts and topography in the Northern Hemisphere, upward-propagating planetary-scale waves are able to penetrate more easily into the stratosphere (see more in section 1.2.2), providing for a weaker and more distorted vortex in the Northern Hemisphere than in the Southern Hemisphere (Waugh and Randel 1999). With enhanced upward wave activity in the Northern Hemisphere, events known as sudden stratospheric warmings (SSWs) are able to occur, in which the stratospheric polar vortex breaks down and provides forcing for rapid and intense rises in temperature (>30-40K in one day) in the region where the vortex was previously located (Butler et al. 2015). In extreme cases, known as major sudden stratospheric warmings, a reversal in the climatological westerly zonal mean winds circling the pole is observed, and the stratospheric polar vortex either displaces itself off the pole or splits into two separate vortices.

While the zonal mean metric has been the standard for identifying SSWs (McIntruff 1978), there are many definitions in the literature. 10-hPa zonal mean winds at 60°N and 65°N (Labitzke and Naujokat 2000; Christiansen 2001) and polar cap-averaged zonal mean zonal winds poleward of 60°N (Andrews et al. 1987) are examples of the commonly used zonal mean zonal wind identifier. Due to SSWs strong association with rapid increases in polar temperatures, Labitzke (1981) defined SSW events based on the reversal of the meridional zonally-averaged temperature gradient north of 60°N. Polar cap-averages of geopotential height anomalies at 10-hPa have also been shown to have a similar correlation to warming events (Thompson et al. 2002). Teleconnections based on empirical orthogonal functions (EOFs) of geopotential height anomalies, such as the Northern Annular Mode (NAM), have been used and show a significant connection between SSWs and downstream tropospheric impacts (Baldwin and Dunkerton 2001). Waugh and Randel (1999) introduced variations in polar vortex geometry as an entirely
separate metric to categorize SSW events, and this definition has continued to be an area of interest amongst other researchers (Taguchi 2016,).

With so many definitions circulating in stratospheric literature, is one better than the rest? Butler et al. (2015) investigated nine SSW classifications using NCEP-NCAR and ERA-Interim Reanalysis data, and found that all classifications produced one warming event approximately every two years. However, there was substantial inter-decadal variability amongst the nine definitions, with the zonal mean zonal wind at 60°N classification producing no warmings during most of the 1990s, and other definitions producing two to five during that same time period. This variability could be due certain definitions being based on a specific latitude band compared to an entire latitude range (e.g. polar cap temperature), revealing the potential sensitivity of the most commonly-used definition: 10-hPa zonal mean zonal wind at 60°N.

Charlton and Polvani (2007) used the 10-hPa zonal mean zonal wind at 60°N metric to create a climatology of SSW events, with the central date of each event defined as the day in which the zonal mean zonal wind shifted to an easterly regime. Using this criterion and utilizing NCEP-NCAR and ECMWF Reanalysis (ERA-40), 31 SSWs were identified from January 1958 to February 2002. While the World Meteorological Society (WMO) definition also includes a meridional temperature gradient reversal, Charlton and Polvani found little difference in their climatology when including this metric. Once SSWs were identified, the authors classified each event as a displacement or split by computing the number of cyclonic vortices at 10-hPa near the central date of the warming (Fig. 1.2). 46% of warming events were identified as splitting SSWs, although there were slight differences in classification based on the reanalysis dataset. The 31 events observed by Charlton and Polvani (2007) were also identified by Butler et al. (2017), who used six reanalysis datasets to classify SSWs. Only one additional event from January 1958
through February 2002 was identified by Butler et al. (6 February 1981), but this event was only resolved by the Japanese Reanalysis dataset. Beyond February 2002, nine further SSWs were identified through 2013, the first occurring in January 2003 and the last in January 2013.

1.2.2 Troposphere-Stratosphere Coupling

1.2.2.1 The Breakdown of the Polar Vortex

With several established climatologies of major sudden stratospheric warmings in the literature, it is imperative to understand the forcings for the breakdown of the polar vortex and reversal of the stratospheric polar jet. SSWs have been associated with interactions between the troposphere and stratosphere in what is called troposphere-stratosphere coupling. When upward propagating planetary-scale waves, mostly of wavenumbers 1 and 2, reach the stratospheric polar jet in N.H. winter, they impart a westward-directed zonal mean acceleration through wave transience and/or dissipation, creating an easterly flow anomaly (Andrews et al. 1987). The momentum tendency created by these vertically propagating Rossby waves acts to weaken the strong westerly belt of winds encircling the pole. Through the thermal wind balance, the weaker westerlies produce a weaker meridional temperature gradient, which can give rise to the sudden increases in temperature seen during an SSW. While upward wave forcing from the troposphere is a necessary condition for an SSW to occur, the stratospheric polar vortex must also be preconditioned through a focusing of wave activity flux toward the pole (McIntyre 1983).

Limpasuvan et al. (2004) established a life cycle for an average SSW event, with five distinct stages that illustrate the impact of the troposphere on the polar stratosphere and vice-versa (Fig. 1.3). Five stages were identified: onset, growth, mature, decline, and decay. Each stage was divided into 15-day periods, with the onset stage occurring 37-23 days prior to the
SSW onset. During onset, stratospheric zonal flow is particularly strong north of 70°N, signifying the polar vortex is constrained near the pole and preconditioned for upward wave forcing. Zonal mean meridional heat flux anomalies in the mid to upper stratosphere are persistent, in part an indication of vertically propagating waves along the periphery of the vortex. These vertically propagating waves propagate in the direction of the wave activity flux (WAF), in which the vertical component is proportional to the eddy heat flux. The convergence of WAF, or in a zonal mean sense the convergence of EP flux, provides for easterly forcing above 100-hPa. In the upper stratosphere above 30-hPa, weak positive temperature anomalies exist over the pole.

EP flux convergence and weakening zonal flow near the polar region persist into the growth stage and begin to descend into the middle and lower stratosphere. Warm temperature anomalies strengthen and descend, increasing in magnitude as the event enters the mature stage. At the peak of the SSW, or the mature stage, the easterly zonal wind anomalies are at their greatest magnitudes, as well as are the highest positive temperature anomalies. This polar warming is strongest near 50-hPa as it continues to descend through the stratosphere. EP flux convergence, still near the pole, begins to shift downward near 60°N, suggesting a reduction of wave activity in the stratosphere. Temperature, zonal wind, and momentum anomalies continue to descend through the stratosphere and into the troposphere through the decline and decay stages, which will be further explained in Section 1.2.3.

1.2.2.2 Tropospheric Blocking

While vertical propagation of planetary scale waves provides forcing for the breakdown of the strong westerly flow of the wintertime N.H. polar vortex, is there a particular phenomena
providing forcing for this upward wave propagation? Julian and Labitzke (1965) found a link between high latitude blocking in the troposphere and an SSW event that occurred in January 1963. The authors discovered that a blocking event transpired five to ten days prior to the stratospheric warming and persisted beyond the vortex breakdown. The block’s persistence beyond SSW onset can be attributed to the perturbed (easterly) zonal flow in the stratosphere acting in tandem with the slowly progressing flow in the upper troposphere (Woollings and Hoskins 2008). The energy released and transferred into the stratosphere from the January 1963 tropospheric blocking event was much greater than the energy exchanged exclusively in the stratosphere, suggesting a substantial connection between the troposphere and stratosphere (Julian and Labitzke 1963).

This link between tropospheric blocking and SSWs has been studied ever since Julian and Labitzke’s (1965) finding. Labitzke (1965) analyzed SSW events from 1953-1964 and found that the majority of events were preceded by a blocking pattern over central and eastern Europe ten days prior. By analyzing momentum and heat budgets between the troposphere and stratosphere, O’Neill and Taylor (1979) suggested that blocks might be the primary triggers that initiate the vertical propagation of planetary scale Rossby waves. Quiroz (1986) compared tropospheric blocking to SSWs from 1981-1985 and came to the conclusion that blocking events precede SSWs by an average of 3.5 days, with the hypothesis that the potential forcing and linkage between the two was the amplification of planetary waves in the troposphere.

Since blocking events are often short-lived compared to the life cycle of an SSW (81 days in Limpasuvan et al. (2004)), troposphere-stratosphere coupling prior to a warming event can provide for large errors in numerical weather prediction (NWP) model forecasts (Mukougawa and Hirooka 2004). To investigate sources of forecast errors, Martius et al. (2009)
analyzed the primary causes for the onset of SSW events, particularly the link between tropospheric blocking and the breakdown of the stratospheric polar vortex. Using the ERA-40 dataset, the authors studied 27 SSW events that were identified using the methodology of Charlton and Polvani (2007). Martius et al. (2009) found that 25 of the 27 warmings were associated with precursor tropospheric blocking events. Vortex displacement and vortex splitting events were then separated and linked to the location of blocking in the troposphere. Displacements of the polar vortex were often preceded by high-latitude blocking in the Atlantic Ocean, while splits of the polar vortex were preceded by blocking events only in the Pacific Ocean or in both the Atlantic and Pacific basins (Fig. 1.4). The stratification between displacement and splitting events was also linked to wavenumber. Displacement events were dominated by wavenumber-1 activity, while splitting events were associated with both wavenumber-1 and wavenumber-2, aligning well with the location of precursor blocking events and their associated SSWs.

There are several factors that can promote the amplification of synoptic and planetary scale flow patterns associated with blocking regimes. Archambault et al. (2007) described how the recurvature of tropical cyclone (TC) Oscar provided forcing for an amplified flow pattern and high latitude ridge/block downstream. During stage 1, the TC’s interaction with extratropical flow intensifies an upper-level jet streak and amplifies a downstream ridge. Extratropical cyclogenesis then occurs during stage 2 in the poleward-exit region of the strengthened jet streak, further amplifying the downstream ridge. During the final stage, the strengthening ridge dynamically forces a robust anticyclone over North America. Similar results of ridge amplification forced by extratropical and TC interactions were obtained via a climatological study (Archambault et al. 2013). The strength of the phasing between the TC and extratropical
flow was key in providing forcing for amplified flow and downstream ridge building. Negative potential vorticity (PV) advection via the irrotational wind was able to capture the phasing between the synoptic and planetary scale features, providing a proxy for upper-level diabatic outflow (Fig. 1.5).

Pfahl et al. (2015) was able to expand upon the importance of diabatic processes and their importance in ridge amplification by examining latent heat release associated with blocking patterns. Now extended to purely North Atlantic extratropical systems, the authors found that during a 21-year climatology of blocking, nearly 70% of 7-day parcel trajectories entering high-latitude ridges were heated by more than 2K. Two key processes were essential prior to ridge building: horizontal advection of low PV air and latent heating associated with ascent from low levels of the troposphere. Bosart et al. (2017) analyzed the warm conveyor belt processes associated with moist diabatic processes and found that trajectories originating near TC Kajiki in October 2007 coincided with a specific humidity decrease of roughly 14 g kg\(^{-1}\). During the 72 hour poleward ascent from TC Kajiki to near 250 hPa, parcels underwent anticyclonic motion associated with ridge building, and in addition to the moisture loss, saw a \(\theta\) increase of approximately 39 K linked to diabatic heating via condensation. This \(\theta\) increase coincided well with Madonna et al. (2014), in which the change in potential temperature was calculated based on expected diabatic heating and latent heat release along trajectories. Using the equation for potential temperature change in Madonna et al. (2014), parcels associated with a 14 g kg\(^{-1}\) decrease in specific humidity would see a \(\theta\) increase of near 40 K, similar to the 39 K value depicted in Bosart et al. (2017). With thermodynamic processes providing a strong link to ridge building, and with blocking regimes providing forcing for SSWs, it is therefore crucial that NWP models are able to capture the diabatic processes that promote tropospheric blocking.
1.2.3 Stratosphere-Troposphere Coupling and Impacts near the Surface

In addition to upward forcing from the troposphere into the stratosphere prior to a warming event, the stratosphere can have a substantial influence on the troposphere following an SSW. During the decline stage of a stratospheric warming, wind and temperature anomalies descend into the lower stratosphere and upper troposphere, where the magnitude of the anomalies weakens (Limpasuvan et al. 2004). EP flux convergence is directed downward at this point, signifying the descent of momentum and thermal anomalies from the stratosphere into the troposphere. During the decay stage, EP flux continues to converge in the troposphere, while the stratospheric polar vortex recovers and is characterized by EP flux divergence. Easterly zonal wind anomalies are present through the depth of the polar atmosphere and negative temperature anomalies upward of 5 K in the mid-upper stratosphere begin to emerge.

Anomalous downward wave activity flux from the stratosphere into the troposphere has been shown to have impacts on sub-seasonal to seasonal timescales (two weeks to two months). Baldwin and Dunkerton (2001) characterized the strength of the polar vortex by its 10-hPa Northern Annular Mode (NAM) value and created composites of 18 weak vortex events (e.g. SSWs) and 30 strong vortex events. The NAM is the first empirical orthogonal function (EOF) of 90-day low-pass filtered geopotential height anomalies north of 20°N and acts as a measure for the vertical coupling between the stratosphere and troposphere. Out of 18 weak vortex events, positive NAM anomalies (e.g. high polar cap geopotential heights) descend from the upper stratosphere near the day of a warming event and into the troposphere in a lagged fashion (Fig. 1.6). These anomalies extend to the surface and persist for up to 80 days beyond SSW onset. Surface impacts were seen through negative surface pressure anomalies collocated with the North Atlantic wintertime storm track, providing evidence that SSWs can provide forcing that
shifts storm tracks significantly further south in the North Atlantic and North Pacific basins. With a substantial shift in storm tracks, Baldwin and Dunkerton were able to provide evidence for a significant connection between SSWs and extreme surface weather, particularly over central and southern Europe. Similar equatorward shifts in tropospheric storm tracks were seen following the 2002 Southern Hemispheric SSW (Charlton et al. 2004), providing additional evidence for the dynamical influence that the stratosphere can have on the troposphere.

1.2.4 SSW Predictability

With a plethora of evidence in the literature regarding the stratosphere’s impact on the troposphere and the troposphere’s influence on the stratosphere, it has become clear that stratospheric conditions should be considered in numerical weather prediction (NWP) models. In early NWP models (and some used today), the top modeled atmospheric level was located in the middle to upper stratosphere (e.g. 50- or 10-hPa) in an effort to limit the extraneous use of computational resources (Tripathi et al. 2015). These “low top models” were used as it was assumed (prior to recent literature) that the stratosphere did not have a significant impact on the troposphere, and therefore did not enhance predictability in the troposphere. Using a simple convective model, Lorenz (1963) was the first to attempt increasing upper boundaries to higher altitudes. Lorenz’s efforts were an attempt to decrease biases and errors in initial conditions due to the complexity of Earth’s atmospheric system. Solar radiation, for instance, can have a substantial impact on the skill of NWP models at and above tropospheric levels because of its effect on Earth’s temperature profile, which through complex thermodynamic processes, drives surface weather (Gerber et al. 2012). If variables at levels above what the low top models provide are not integrated into current NWP models, model skill could be reduced.
In recent decades, several studies have investigated the predictability of the troposphere-stratosphere coupled system, particularly surface and upper-tropospheric flow patterns. Smith et al. (2012) was able to link SSWs to enhanced skill in long-range forecasts of cold waves in eastern North America and Europe. Garfinkel et al. (2013) performed a modeling study to interrogate the dependence of the state of the stratospheric polar vortex on the latitude of the tropospheric jet stream. The authors found that the troposphere’s response to an identical polar vortex is weakest when the mid-latitude jet is located at either 30°N or 50°N, but is three times stronger when the jet is centered near 40°N. Dynamical stratospheric influences, including eddy phase speed and planetary wave refraction, were shown to have little impact on the tropospheric jet stream’s response to the polar vortex. Purely tropospheric forcing mechanisms, however, such as the longevity and persistence of the jet (e.g. during blocking regimes), were able to explain the substantial jet shift centered around 40°N observed during weak stratospheric vortex regimes. Garfinkel et al. (2013) highlights that while the troposphere-stratosphere system is coupled and has a substantial impact on NWP model variability, the internal tropospheric processes are at the crux of what determines the tropospheric outcome.

A review paper on the quantifiable predictability of the extreme stratospheric vortex events revealed that forecast errors in predicting extreme vortex events can change tropospheric forecast skill by 5-7% on sub-seasonal (two weeks-two months) time scales (Tripathi et al. 2015). With such a significant impact on NWP skill, it is essential that the limits of stratospheric predictability be reduced through further investigations of planetary-scale wave activity in the troposphere. Taguchi (2014) studied stratospheric vortex weakening and strengthening conditions by comparing Japan Meteorological Agency (JMA) one-month hindcast data to JMA Reanalysis. The authors found that the greatest errors in forecasting SSWs were derived from
forecasted errors in predicting planetary-scale wave forcing from the troposphere. Planetary wave amplification was shown to have lower skill in hindcast forecasts of weak vortex events than in strong vortex events, providing further evidence that SSW predictability in NWP models requires further study. Taguchi (2016) expanded upon his 2014 study and expressed that errors in major SSW splitting events at medium range (2 week) time scales depended not only on planetary-scale wave activity ascending from the troposphere, but also on vortex geometry, as JMA hindcast errors were largest when the polar vortex was elongated and when the wavenumber-2 component was amplified.

1.2.5 Previous Work on the 7 January 2013 SSW Event

The 7 January 2013 SSW event will be analyzed in this paper to extend upon the previous work on SSW predictability explained in section 1.2.4. On 7 January 2013, the 10-hPa zonal mean zonal wind at 60°N reversed to easterly after anomalous upwardly propagating planetary-scale wave activity from the troposphere forced for a deceleration of the stratospheric polar jet and a split of the polar vortex (Tripathi et al. 2016). Evidence for lagged surface impacts were seen, as dynamical coupling from the stratosphere to the troposphere provided forcing for an equatorward shift in the mid-latitude storm track and anomalously-cold surface conditions in northern Europe in March 2013. The Stratospheric Network for the Assessment of Predictability (SNAP) analyzed five NWP model ensembles over the course of this major SSW event. With a 15-day lead time, none of the ensemble means were able to capture an easterly zonal mean zonal wind regime on 7 January, and only a few members amongst all models were able to predict such a large deceleration of the polar vortex (Fig. 1.7). At a 10-day lead time, model skill increased by roughly 50%, with further improvements in skill seen at 5- and 0-day lead times.
Attard et al. (2016) analyzed the tropospheric state prior to the 7 January 2013 SSW event and found that several high-latitude tropospheric blocks occurred in the North Pacific basin in December 2012. These blocks were associated with two distinct decelerations of the 10-hPa zonal mean zonal wind 1-3 weeks prior to the SSW, preconditioning the stratosphere for a vortex split. This vortex preconditioning was forced by enhanced upward WAF associated with the persistent blocking pattern in the N. Pacific. Coy and Pawson (2015) found that the preconditioning of the polar vortex was seen through a displacement of the vortex off the center of the pole in late December 2012. This displacement made additional tropospheric forcing possible prior to the vortex split by enabling high values of poleward PV advection into the polar stratosphere. While the authors noted that upward WAF was dominant in the Pacific, a rapidly deepening cyclone in the North Atlantic brought upward planetary wave forcing into the polar stratosphere in the week leading up to the SSW event.

1.3 Research Goals and Thesis Structure

This thesis will extend upon preliminary results of the 7 January 2013 SSW event provided for by the SNAP research efforts to better understand the impacts of tropospheric forcing on the troposphere-stratosphere coupled system. NWP skill will be analyzed using several metrics, particularly zonal mean zonal wind and vortex geometry (Waugh and Randel 1999). It is hypothesized that model error in forecasting thermodynamic processes linked to precursor tropospheric blocking in the N. Atlantic (Coy and Pawson 2015) resulted in systematic biases in forecasted WAF into the polar stratosphere.
Following the introduction, the data and methodology used to examine the 7 January 2013 SSW event will be explained in chapter 2. Results will be separated based on which metric was used to analyze the stratospheric state: zonal mean metrics will be examined in chapter 3 and elliptical metrics in chapter 4. Chapter 5 will conclude the paper with a discussion or results, conclusions, and suggestions for future work.
Fig. 1.1 Climatological zonal-mean zonal wind in Jan and Jul. The diamonds mark the hemispheric maximum of the zonal wind at each pressure level and the approximate edge of the polar vortex for that hemisphere. Figure and caption adapted from Waugh et al. (2016).

Fig. 1.2. (a) A displacement-type SSW event on 21 Jan 2006 and (b) a split-type SSW event on 24 Jan 2009, for the average of (left) 8-15 days prior to the event, (middle) 7 days prior to the event, and (right) 1-8 days following the event. ERA-Interim temperature anomalies (based on 1979-2012 climatology) at 10 hPa (K) are shaded. The black solid line marks the 7-PVU contour (1 potential vorticity unit = $10^{-6}$ K kg$^{-1}$ m$^2$ s$^{-1}$) at 10 hPa and indicates the shape of the polar vortex. The arrows indicate the full zonal and meridional wind fields at 10 hPa (arrows with a westerly zonal component are black; arrows with an easterly zonal component are blue). The 60°N latitude band is dashed. Figure and caption adapted from Charlton and Polvani (2016)
Fig. 1.3. (left) Anomalous zonal-mean zonal wind, (middle) zonal-mean temperature, and (right) EP flux with its divergence during the composite life cycle of SSWs. Negative contours are given as blue dashes. Zero contours are given as bold solid lines. The wind (temperature) contour interval is 1 m s$^{-1}$ (1 K). The EP flux divergence (Divided by $\rho_0 a \cos \theta$, where $\rho_0$ is basic density, $a$ is the earth’s radius, and $\theta$ is latitude) is contoured in the right column every 0.25 m s$^{-1}$ day$^{-1}$ with deceleration in blue. The vector lengths in the right column are referenced with respect to the top figure in the column. Gray shading indicates areas with a 95% confidence level (based on $t$ statistics). Figure and caption adapted from Limpasuvan et al. (2004).
Fig. 1.4. Geopotential height fields, zonal wave number 1 in blue and 2 in red, composited for the period – 10 to 0 days prior to (top) vortex displacement events and (bottom) vortex splitting events, at 500, 200, 100, 50, and 10 hPa, from left to right, respectively. Contour levels shown are: 100, 130, 160, 190, 220, 250, 300, 350, 400, 500, 600k, 700, 800 and 900 m, solid contours indicate positive values. Gray shading shows blocking frequency greater than 0.4. Figure and caption adapted from Martius et al. (2009).

Fig. 1.5. Schematic representation of ridge amplification and jet streak intensification associated with the divergent outflow of a TC impinging upon an upper-tropospheric jet stream/waveguide. Vectors represent the upper-tropospheric irrotational wind (i.e. divergent outflow) associated with the TC. Shading denotes negative PV advection by the irrotational wind. Figure and caption adapted from Archambault et al. (2013).
Fig. 1.6. Composites of time-height development of the northern annular mode for (A) 18 weak vortex events and (B) 30 strong vortex event. The events are determined by the dates on which the 10-hPa annular mode values cross -3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between -0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and stratosphere. Figure and caption adapted from Baldwin and Dunkerton (2001).
Fig. 1.7. Zonal-mean zonal wind at 10 hPa and 60°N from ERA-Interim (thick black lines) and model ensemble members (thin gray lines). The thick colored line denotes the ensemble mean. The initialization dates are (left) 23 Dec 2012 (D – 15) and (right) 28 Dec 2012 (D – 10). Vertical date ticks are drawn at 0000 UTC. Figure and caption adapted from Tripathi et al. (2016).
2. Data and Methodology

2.1 SNAP Dataset

Data analysis was performed using the SNAP dataset (sparcsnap.org). This dataset is comprised of six NWP ensembles with vertical resolution well into the stratosphere, with model tops ranging from 1 hPa to 0.009 hPa, a key feature in this study of the stratospheric polar vortex. Below is a synopsis of each model and its specifications, all provided for in Tripathi et al. (2016), with the Korea Air Force (KAF) model specifications provided for in Hong et al. (2013). A summary of model data can be found in Table 1.

2.1.1 CAWCR AGREPS

The Centre for Australian Weather and Climate Research (CAWCR) is a branch within the Australian Bureau of Meteorology (BoM). CAWCR developed the ACCESS Global and Regional short range Ensemble Prediction System (AGREPS) for use in a research environment prior to operational utilization. The current AGREPS model uses the Met Office Unified Model finite-difference non-hydrostatic dynamical core in the horizontal framework, and in the vertical, the Charney-Phillips scheme. Horizontal grid spacing is approximately 60 km, or 0.555° and 0.833° (Table 1). Model vertical resolution spans 70 vertical levels, with a model top of roughly 80 km, or at the 0.009 hPa level. The AGREPS ensemble consists of 24 members, initialized from the BoM operational analyses and observations. Initial conditions are perturbed via the Kalman filter, primarily influenced by the stochastic kinetic energy backscatter scheme. The following schemes are used:

- Convection: modified mass flux scheme
- Radiation: scheme developed by Edwards and Slingo (1996)
• Microphysics: Wilson and Ballard (1999) single-moment bulk scheme

2.1.2 MRI-AGCM

The Meteorological Institute (MRI) Atmospheric General Circulation Model (AGCM) was developed by the Japanese Meteorological Agency (JMA) through the expansion of their currently operational 1-month NWP ensemble. Initial conditions are obtained from ERA-Interim data, and perturbations are created with a breeding of growing mode (BGM) tactic, comprising 51 members. Horizontal grid spacing is roughly 110 km, or 1.125° by 0.55°. Vertical resolution spans 60 levels, with a model top of 0.1 hPa. Schemes used in this model are identical to the operational JMA model, other than a new cumulus parameterization scheme developed by Yoshimura et al. (2015) and a cloud scheme from Tiedtke (1993).

2.1.3 NOGAPS

The Navy Operational Global Atmospheric Prediction System (NOGAPS) model is a 20 member ensembles that uses a finite-difference approximation in a hybrid sigma and pressure vertical coordinate, with 42 vertical levels reaching up to 0.04 hPa. Horizontal resolution is approximately 82 km, or 0.75° by 0.75°. Initial conditions are created via a nine-banded local ensemble transform scheme developed by McLay et al. (2010), which produces perturbations from the Naval Research Laboratory Atmospheric Variational Data Assimilation System-Accelerated Representer. The following schemes are used:

• Shallow Convection: Tiedtke (1984)
• Deep Convection: Emanuel (1991)
• Radiation: Harshvardhan et al. (1987)

2.1.4 Met Office Unified Model
The Met Office Unified Model (METO) ensemble consists of 22 members that are run on a 0.83° longitude by 0.55° latitude grid, with 85 levels in the vertical that extend to a model top of 85 km (Davies et al. 2005). The METO is a global model that solves the nonhydrostatic, compressible deep-atmosphere equations of motion using semi-implicit, semi-Lagrangian methods.

2.1.5 ECMWF System 4

ECMWF reforecasts were created using the ECMWF long-range System 4, which is based on the Integrated Forecast System (IFS) (https://www.ecmwf.int/en/research/modelling-and-prediction). The IFS runs on 80 km horizontal grid spacing that is coupled to a 1° global ocean model, the Nucleus for European Modelling of the Ocean (NEMO). Vertical resolution spans 91 levels, with a model top of 0.01 hPa. Atmospheric initial conditions for this 25-member ensemble come from operational analysis (rather than ERA-Interim), and initial conditions for the ocean are derived from the Ocean Reanalysis System 4 (ORAS4).

2.1.6 Korea Air Force Global/Regional Integrated Model system

The five member Korea Air Force (KAF) Global/Regional Integrated Model System (GRIMs) consists of 37 vertical levels up to 1 hPa and horizontal grid spacing of approximately 50 km. GRIMs’ dynamical core is based on spherical harmonics, with the regional model program used for local downscaling. A few examples of the GRIMs physics package include:

- Shortwave radiation: 4-albed, 12 bands, Chou and Lee (2005)
- Longwave radiation: Chou et al. (1999)
- Deep convection: SAS, Han and Pan (2011)
- Shallow convection: Hong et al. (2013)
• Microphysics: WSM1 (Hong et al. (1998))

Further details on model physics and other parameterizations can be found in Hong et al. (2013).

2.2 Verification Dataset

The NCEP Climate Forecast System Reanalysis (CFSR) dataset is used for verification purposes in the analysis of the 7 January 2013 SSW event (Saha et al. 2014). The CFSR dataset is chosen for its high model top of 0.26 hPa, making it a full stratosphere resolving dataset. The CFSR is composed of an atmosphere-ocean-land-ice coupled model with a horizontal resolution of approximately 100 km and 64 sigma-pressure hybrid levels. The CFSR model output consists of 6-hourly forecasts interpolated to a 0.5° latitude by 0.5° longitude grid and isobaric surfaces up to 1 hPa.

2.3 Model Categorization: Zonal Mean Zonal Wind

Three zonal mean metrics at 10 hPa were calculated for verification and each of the six ensembles in the SNAP dataset at both 15- and 10-day lead times: zonal mean zonal wind at 60°, polar cap (60°-90° area-weighted) temperature, and polar cap (60°-90° area-weighted) geopotential height. To be consistent with previous SSW studies (e.g. Charlton and Polvani 2007), the 10 hPa zonal mean zonal wind at 60° was used to categorize each ensemble according to their skill in forecasting the 7 January 2013 SSW event. Ensemble means of the 10 hPa zonal mean zonal wind at 60° were calculated and compared to CFSR at 00 UTC 7 January 2013 to
rank each model based on their skill, with the most easterly ensemble mean being the high skill model and the most westerly ensemble being the low skill model (see section 3.1).

2.4 Model Categorization: Elliptical Diagnostics

The location, shape, and size of the stratospheric polar cortex will be quantitatively measured by fitting an ellipse to the stratospheric polar vortex in CFSR and SNAP ensemble data. While Waugh and Randel (1999) and others have determined the location of vortex ellipse based on a PV contour, this analysis will use the 10 hPa 29.5 km geopotential height contour to calculate a best fit ellipse to the stratospheric polar vortex. The 29.5 km contour was chosen for this study because it falls within the climatology characterized by the stratospheric polar night jet during the winter season. The 29.5 km contour was also found empirically to best represent the split of the polar vortex within the SNAP dataset for the 7 January 2013 event. Once the best-fit ellipse has been calculated, the vortex ellipse center location will be determined. The latitude of the vortex center at 00 UTC 6 January 2013 will be compared to the forecasted zonal mean zonal wind at 00 UTC 7 January 2013 to look for a correlation between elliptical metrics and zonal mean metrics. A linear regression was performed between the two aforementioned metrics to quantify any sort of correlation, and a two-tailed Student’s $t$ test was used to determine statistical significance of the linear regression.

2.5 Troposphere-Stratosphere Coupling Analysis
To analyze the synoptic and planetary scale forcing in the troposphere prior to the 7 January 2013 SSW event, the PV waveguide was studied in an effort to link forecasted precursor tropospheric blocking to skill in predicting the onset of the stratospheric warming. The 300-200-hPa layer-averaged PV waveguide was time-averaged over the week prior to verified SSW onset (00 UTC 31 December 2012 thru 00 UTC 7 January 2013) to qualitatively depict a blocking pattern and were superimposed with the time-averaged 300-200-hPa layer-averaged jet. The 300-200-hPa layer-averaged meridional eddy heat flux for the aforementioned time period was calculated and used as a proxy for vertical wave activity flux as the two quantities are directly proportional.

Once a blocking pattern or zonal pattern has been established, the forcings for the development of the PV waveguide were studied. To discern the link and forcings between the synoptic and planetary scales, the zonal and meridional winds were deconstructed into their non-divergent and irrotational components. The irrotational wind was used and dissected at daily time steps to analyze upper-tropospheric divergent outflow related to diabatic heating, with the daily-averaged model derived precipitation rate also used as a proxy for diabatic processes throughout the depth of the troposphere.

The troposphere-coupling analyses described in this section will be utilized in both the zonal mean metrics and elliptical metrics chapters. Chapter 3’s analysis will study the tropospheric forcing from an ensemble mean perspective, while Chapter 4’s analysis will study individual members across the range of SNAP ensembles.
Table 2.1. A synopsis of the six NWP ensembles used to analyze the 7 January 2013 SSW event. Ensemble name, abbreviation, number of members, vertical resolution, and horizontal resolution are provided, with additional information on the SNAP dataset found in Tripathi et al. (2016).

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Ensemble Name</th>
<th># of members</th>
<th>Vertical Resolution</th>
<th>Horizontal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAF</td>
<td>Korea Air Force</td>
<td>5</td>
<td>37 (1hPa)</td>
<td>≈50 km</td>
</tr>
<tr>
<td>NOGAPS</td>
<td>Navy Operational Global Atmospheric Prediction System</td>
<td>20</td>
<td>42 (0.04 hPa)</td>
<td>0.75°x0.75°</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
<td>25</td>
<td>91 (0.01 hPa)</td>
<td>80 km</td>
</tr>
<tr>
<td>METO</td>
<td>Met Office Unified Model</td>
<td>22</td>
<td>85 (=85 km)</td>
<td>0.833°x0.555° (60 km)</td>
</tr>
<tr>
<td>MRI</td>
<td>Meteorological Research Institute</td>
<td>51</td>
<td>60 (0.1 hPa)</td>
<td>1.125°x0.555°</td>
</tr>
<tr>
<td>CAWCR</td>
<td>Centre for Australian Weather and Climate Research</td>
<td>24</td>
<td>70 (0.009 hPa)</td>
<td>0.833°x0.555° (60 km)</td>
</tr>
</tbody>
</table>
3. Zonal Mean Metrics

3.1 Lead Time Variability

Analysis of the 7 January 2013 SSW event by Tripathi et al. (2016) revealed an approximately 50% increase in model skill for forecasts initialized 28 December 2012 (10-day lead time) compared to forecasts initialized 23 December 2012 (15-day lead time) when investigating the 10 hPa zonal mean zonal wind at 60°N. This study will expand upon the results of Tripathi et al. (2016), with the addition of the KAF ensemble and analyses of two additional zonal mean metrics at 10 hPa: the 60-90°N area-averaged (polar cap) temperature and the polar cap geopotential height. In all, these three zonal mean metrics will be interrogated for six ensembles derived from the SNAP dataset to assess model variability.

Beginning 00 UTC 23 December 2012, verification (CFSR) showed an initial deceleration of the 10-hPa zonal mean zonal wind at 60°N from approximately 24 m s⁻¹ to roughly 12 m s⁻¹ by 00 UTC 27 December 2012 (Fig. 8). The zonal mean zonal wind then accelerated to near 28 m s⁻¹ at 00 UTC 31 December 2012 before decelerating to the major warming event, in which the zonal mean zonal wind reversed to easterly between 6 and 7 January 2013. The polar cap 10-hPa temperature remained steady near 200 K from 23 December 2012 thru 30 December 2012 before rapidly increasing to approximately 232 K by 00 UTC 7 January 2013. The 10-hPa polar cap geopotential height began near 29.2 km at 00 UTC 23 December 2012 and gradually rose to 29.4 km by 00 UTC 26 December 2012. 10-hPa polar cap heights began to rise by 00 UTC 31 December 2012 and shot up to roughly 30.4 km at 00 UTC 7 January 2013.
Trends in the 10-hPa zonal mean zonal wind at 60°N for the 23 December 2012 initialization of the KAF ensemble closely match verification throughout the fifteen day forecast period (Fig. 8). From 23 December 2012 thru 27 December 2012, all five members of the KAF model decelerated the flow from approximately 24 m s\(^{-1}\) to roughly 12 m s\(^{-1}\) before slowly accelerating the flow until 30 December 2012. All five members then transitioned into an easterly zonal mean zonal wind regime by 00 UTC 7 January 2013. While similar to CFSR, the final deceleration began roughly 24 hours earlier in the KAF model runs. 10-hPa polar cap temperature and geopotential heights were less skillfully forecasted at a 15-day lead time as both variables were underpredicted by all five KAF members. Both heights and temperature saw a more steady increase over the forecast period than verification. By 00 UTC 7 January 2013, 10-hPa polar cap temperatures fell 3-12 K below the observed value of 232 K, while 10-hPa polar cap heights were predicted to be 0.5-0.8 km below the observed value of 30.4 km.

While all five members forecasted an easterly 10-hPa 60°N zonal mean zonal wind by 00 UTC 7 January 2013 in KAF runs initialized 28 December 2012, the shift to easterlies was overpredicted (Fig. 9). One ensemble member predicted an easterly zonal mean zonal wind of near 18 m s\(^{-1}\), and all five members forecasted a more easterly zonal mean zonal wind than what verified, with values ranging from -7 m s\(^{-1}\) to -18 m s\(^{-1}\). The forecasted increase in 10-hPa polar cap temperatures were initiated 48-72 hours prior to verification in KAF runs at the 10-day lead time, although the polar cap temperatures steadied out to values near that of CFSR at 00 UTC 7 January 2013, with zero members deviating more than 3 K from verification. The 10-day KAF forecasts of 10-hPa polar cap geopotential height were fairly skillful through 5 January 2013, with predicted values ranging from a mere 0.2-0.4 km below the observed value of 32.4 km.
While there were discrepancies in KAF forecasts at both 15- and 10-day lead times, intra-model variability was low. NOGAPS forecasts, particularly those initialized 23 December 2012, showed considerably greater spread than KAF forecasts (Fig. 10). At a 15-day lead time, model spread of the 10-hPa 60°N zonal mean zonal wind increased throughout the forecast period, with forecasted values between approximately -2 m s\(^{-1}\) and 30 m s\(^{-1}\) by 00 UTC 7 January 2013. While variability was substantial, the overall trend of an initial deceleration, followed by a gradual and then more rapid acceleration leading up to the SSW that was seen in verification, was also seen in a majority of member in the NOGAPS ensemble. At this 15-day lead time, 10-hPa polar cap temperature was overpredicted by as much as 13 K throughout the entire forecast period (as spread increases with time), with initial conditions actually 2-3 K above what verified. 10-hPa polar cap geopotential height matched closely with CFSR for the first 7-10 days of the forecasts, but as forecasted values begin to diverge within the ensemble, the geopotential height was underpredicted by 0.1-1.0 km by 00 UTC 7 January 2013.

As seen in Tripathi et al. (2016), skill increased from the 15- to 10-day lead times for NOGAPS (Fig. 11). Spread decreased for all three 10-hPa zonal mean metrics, though it still increased throughout the forecast period. The deceleration of the 10-hPa 60°N zonal mean zonal wind was initially overforecasted, though in terms of ensemble mean, matched closely the verified value of near -6 m s\(^{-1}\) by 00 UTC 7 January 2013, with some members overpredicting the eastward shift and some underpredicting it. As with the 15-day forecasts, the increase in 10-hPa polar cap temperature was overpredicted, with values by 00 UTC 7 January 2013 ranging from roughly 233 K to 242 K, while the verified value was closer to 232 K. The NOGAPS predicted 10-hPa polar cap geopotential heights at a 10-day lead time were fairly accurate, though 0.2-0.3 km higher than what verified from 1 January 2013 thru 5 January 2013.
Much like NOGAPS, model spread was substantial in ECMWF forecasts of the 7 January 2013 SSW event. ECMWF forecasts of zonal mean zonal wind initialized 23 December 2012 were fairly accurate through 28 December 2012, but the following 10 day period of the 15 day forecast period greatly underpredicted the shift to an easterly 10-hPa 60°N zonal mean zonal wind regime (Fig. 12). None of the 25 members forecasted an easterly zonal mean zonal wind by 00 UTC 7 January 2013, with values at that time ranging from approximately 10 m s\(^{-1}\) to 48 m s\(^{-1}\). At a 15-day lead time, 10-hPa polar cap temperatures increased throughout the forecast period, though values were underpredicted upwards of 25K, and with considerable spread. 10-hPa polar cap geopotential heights fell below values seen in verification through much of the 15 days, with all values 0.3 km to 1.4 km below CFSR by the SSW onset.

Model skill of the ECMWF forecasts initialized on 28 December 2012 substantially increased compared to forecasts initialized on 23 December 2012, with values of all three 10-hPa zonal mean metrics matching closely to verification (Fig. 13). Spread was minimal throughout the 10 day forecast period. Ensemble mean 10-hPa polar cap temperatures and geopotential heights were predicted with great skill and little variability. Zonal mean zonal wind, while similar to verification, was underpredicted. By 00 UTC 7 January 2013, zonal mean zonal wind values ranged from roughly -3 m s\(^{-1}\) to 6 m s\(^{-1}\), which corresponds to an error of approximately 3-9 m s\(^{-1}\).

Similar to ECMWF, 15-day METO forecasts of the 7 January 2013 SSW event showed considerable spread in all three 10-hPa zonal mean metrics (Fig. 14). By 00 UTC 7 January 2013, none of the 22 ensemble members predicted an easterly 10-hPa 60°N zonal mean zonal wind, with values ranging from roughly 1 m s\(^{-1}\) to approximately 56 m s\(^{-1}\). Forecasted values of the zonal mean zonal wind began to diverge near 00 UTC 30 December 2012. This is the time in
which verification showed the initiation of vortex weakening as the westerlies encircling the pole decelerated from that point until SSW onset. Unlike previously mentioned ensembles, three members of the METO ensemble forecasted 10-hPa polar cap temperatures higher than what verified at a 15-day lead time. Yet, as with the zonal mean zonal wind, spread was large, with values at SSW onset ranging from roughly 205 K to 241 K. While METO-predicted 10-hPa polar cap geopotential heights near that of CFSR through 30 December 2012, they generally remained several tenths of a km below verification for the rest of the duration of the forecast period, with errors between 0.3-1.4 km by 00 UTC 7 January 2013.

Divergence in solutions was greatly reduced within the METO ensemble for forecasts initialized on 28 December 2012 as compared to forecasts initialized on 23 December 2012 (Fig. 15). Forecasted 10-hPa 60°N zonal mean zonal wind followed a similar trend to what verified, though the deceleration leading up to the SSW event was underforecast. By 00 UTC 7 January 2013, zonal mean zonal wind values ranged from -3 m s\(^{-1}\) to 14 m s\(^{-1}\), corresponding to an error of roughly 4-21 m s\(^{-1}\). Forecasts of 10-hPa polar cap temperatures and geopotential heights performed with considerable skill at this 10-day lead time. Polar cap temperature values diverged from the verified value by 4-7 K at 00 UTC 7 January 2013, with all members forecasting an increase in temperature throughout the 10-day period. Polar cap geopotential height values tended to lie below verification, though by 0.4 km at the greatest.

At a 15-day lead time, the 51-member MRI ensemble was unable to converge upon an easterly 10-hPa 60°N zonal mean zonal wind or increase in 10-hPa polar cap temperature/geopotential height (Fig. 16). While the verified polar stratospheric westerlies began to decelerate on 30 December 2012, the majority of MRI members predicted a continued acceleration though approximately 01 January 2013, at which point most members started to
decelerate. By 00 UTC 7 January 2013, forecasted values ranged from near 0 m s\(^{-1}\) to roughly 48 m s\(^{-1}\), an error upwards of 55 m s\(^{-1}\). Despite zero members forecasting an easterly 10-hPa 60°N zonal mean zonal wind, six members overpredicted the increase in 10-hPa polar cap temperature (by up to 6 K), though the majority of members were 5 K to 20 K below verification by SSW onset. 10-hPa polar cap geopotential heights were not predicted skillfully at a 15-day lead time, with the verified value of 30.4 km at 00 UTC 7 January 2013 lying above all 51 MRI predicted values, with forecasted heights ranging from 29.1 km to 30.3 km. While four members trended toward increasing values of 10-hPa polar cap geopotential heights beginning 31 December 2012, 47 members remained fairly steady.

As variability was reduced from 15-day MRI forecasts to 10-day MRI forecasts (initialized on 28 December 2012), trends in all three 10-hPa zonal mean metrics matched CFSR (Fig. 17). As with NOGAPS, ECMWF, and METO, the easterly shift in 10-hPa 60°N zonal mean zonal wind was underforecast, with errors up to 12 m s\(^{-1}\), though two members did forecast stronger easterly zonal flow than what verified. 10-hPa polar cap temperature was overpredicted in all 51 members, with two members overpredicting temperatures by roughly 9 K. 10-hPa polar cap geopotential heights showed fairly even spread around verification, with values ranging from 30.1 km to 30.6 km.

Most notable of 15-day zonal mean forecasts was the CAWCR ensemble. All 24 members predicted an acceleration of the 10-hPa 60°N zonal mean zonal wind beginning 28 December 2012 and through the date of SSW onset, compared to verification, which began a rapid deceleration starting on 30 December 2012 (Fig. 18). By 00 UTC 7 January 2013, forecasted zonal mean zonal wind span from 23 m s\(^{-1}\) to 47 m s\(^{-1}\), with a large cluster on the lower end of this range. These zonal mean zonal wind values correspond to a minimum error of
30 m s$^{-1}$. The 15-day forecasts of 10-hPa polar cap temperature and 10-hPa polar cap geopotential height were greatly underpredicted, with polar cap temperatures 7-22 K below verification and polar cap geopotential heights 0.5-1.0 km below verification.

Similar to NOGAPS, ECMWF, METO, and MRI, forecasted 10-hPa 60°N zonal mean zonal winds at a 10-day lead time were more westerly than verification (with errors between 1-22 m s$^{-1}$), though the decelerating trend seen in CFSR was also seen in the CAWCR ensemble (Fig. 19). Predicted 10-hPa polar cap temperature and 10-hPa polar cap geopotential heights were similar to observed values, though there was some spread in solutions. 10-hPa polar cap temperatures ranged from 228 K to 237 K (compared to 232 K observed), and polar cap geopotential heights spanned from 30.1 km to 30.5 km (compared to 30.4 observed).

To determine agreement with previous SSW climatologies (e.g. Charlton and Polvani 2007; Butler et al. 2017), the 10 hPa zonal mean zonal wind at 60°N was further analyzed and used to assess forecast skill amongst all six SNAP ensembles. Ensemble mean zonal mean zonal winds were calculated, and those that were closest to the observed value of $-6.164$ m s$^{-1}$ at 00 UTC 7 January 2013 were classified as low error ensemble members while those that deviated greatest from the verified value were classified as high error ensemble members. At a 15-day lead time, only KAF converged to an easterly zonal flow regime, while NOGAPS, ECMWF, METO, MRI, and CAWCR (from least to most westerly) predicted westerly zonal flow (Table 2). Spread was considerable. KAF and CAWCR, the most easterly and westerly, respectively, had the lowest spread while METO and MRI had the greatest spread. 10-day forecasts all shifted to a more easterly zonal mean zonal wind, with KAF still the lowest error ensemble as it was closest to the verified value of $-6.164$ m s$^{-1}$ at 00 UTC 7 January 2013. Spread was reduced in all ensembles other than KAF, though spread was still with a standard deviation of 4.451 m s$^{-1}$.
CAWCR remained the highest error ensemble for forecasts initialized 28 December 2012, though in terms of ensemble mean, was roughly only 10 m s\(^{-1}\) above the observed value, compared to the 15-day lead time, in which CAWCR was approximately 35 m s\(^{-1}\) above the observed value.

With such large spread in solutions at the 15-day lead time, the focus of the remainder of chapter 3 will be on SNAP forecasts initialized on 23 December 2012. As KAF was the only ensemble to converge to an easterly zonal flow regime (e.g. lowest error ensemble), and CAWCR was the only ensemble to strictly see an acceleration in westerly zonal winds leading up SSW onset (e.g. highest error ensemble), KAF and CAWCR will be the investigated further to examine why substantial variability existed between the two NWP models.

3.2 Tropospheric Forcing

3.2.1 PV Waveguide Progression

As Coy and Pawson (2015) suggested, the North Atlantic was a substantial source of upward WAF into the stratosphere the week prior to the 7 January 2013 SSW event. The authors found that a rapidly deepening cyclone off the northeast coast of the United States played a key role in forcing for this upward WAF. In an effort investigate the synoptic- and planetary-scale tropospheric forcing prior to the onset of the SSW event, lower- and upper-tropospheric analyses were performed over the Atlantic basin from 31 December 2012 through 06 January 2013.

At 00 UTC 31 December 2012, one week prior to SSW onset, verification shows a 1000-hPa geopotential height minimum of -180 m (further known as Disturbance 1) east of Nova
Scotia, located in the poleward exit region of an 80 m s\(^{-1}\) 200-300-hPa jet streak (Fig. 20a). Ahead of Disturbance 1, a 500-1000-hPa thermal ridge has formed (Thermal Ridge 1), as higher thickness values are advected from lower latitudes. Strong diabatic outflow associated with Disturbance 1 in the western North Atlantic is seen through the “starburst” pattern of 200-300-hPa layer-averaged irrotational winds (Fig. 21a). A plume of high precipitable water (PW), with values up to 44 mm, associated with these diabatic processes is being horizontally advected into the system from subtropical latitudes. As negative 200-300-hPa layer-averaged PV is advected via the irrotational wind ahead of the system, an upper-level PV ridge (referred to as PV Ridge 1) is seen downstream south of Greenland, with PV values of 1 PVU reaching latitudes of 55°N.

By 00 UTC 02 January 2013, Disturbance 1 has deepened as the 1000-hPa geopotential height minimum has lowered to -240 m, and Disturbance 1 remains in the poleward exit region of an intensifying 80+ m s\(^{-1}\) 200-300-hPa jet streak (Fig. 20b). Downstream of Disturbance 1, Thermal Ridge 1 has amplified, as thickness values of 552 dam are advected northward towards Iceland. Collocated with Thermal Ridge 1, 200-300-hPa layer-averaged irrotational winds of near 5 m s\(^{-1}\) form a weak starburst pattern of upper-level outflow (Fig. 21b). Weaker, but still considerable, PW values up to 32 mm are being advected ahead of the disturbance and reaching latitudes as high as 63°N. PV Ridge 1 has amplified, with 1 PVU values reaching 65°N. A frontal feature has formed upstream, as seen through a tightening 500-1000-hPa thickness gradient, situated across the northern United States and into the western Atlantic, with irrotational wind vectors upwards of 30 m s\(^{-1}\) advecting high PV air upwards of 7 PVU southward.

The frontal feature previously over North America strengthens as the 500-1000-hPa thickness gradient tightens, while it pushes into the central Atlantic by 00 UTC 04 January 2013.
1000-hPa geopotential heights associated with Disturbance 1 have decreased to near 320 m. Disturbance 1 loses eastward progression as an 80 m s$^{-1}$ jet streak located in the western North Atlantic begins to couple to a 60 m s$^{-1}$ jet streak over the central North Atlantic. Downstream of the coupled jet structure and Disturbance 1, Thermal Ridge 1 has slowed its eastward zonal progression and has started to tilt negatively. In the poleward exit region of the 80 m s$^{-1}$ jet and equatorward entrance region of the 60 m s$^{-1}$ jet, upper-level divergence amplifies as evidenced by an increase in magnitude of the 200-300-hPa irrotational wind vectors, with wind speeds approaching 10 m s$^{-1}$ (Fig. 21c). PV Ridge 1 gains a negative tilt and loses eastward progression, while horizontal moisture advection from the tropics and subtropics is evident, with a long, narrow plume of >38 mm PW values present downstream of the starburst pattern of 200-300-hPa irrotational winds.

By 00 UTC 6 January 2013, Disturbance 1 weakens as the 1000-hPa geopotential height minimum increases to -80 m (Fig. 20d). The coupling of the 200-300-hPa jet streaks has diminished as Thermal Ridge 1 has amplified further, with the 540 dam line approaching 77$^\circ$N. As the 500-1000-hPa thickness gradient tightens upstream in the western and central North Atlantic, PW values >35 mm are advected from the Gulf of Mexico and subtropical central Atlantic (Fig. 21d). 200-300-hPa irrotational winds weaken in the mid-latitudes upstream of PV Ridge 1, though 200-300-hPa irrotational wind vectors still approach 7 m s$^{-1}$ in the subtropical central Atlantic, advecting PV values upwards of 4 PVU below 30$^\circ$N upstream of PV Ridge 1.

As seen in verification (Fig. 20a-d), at a 15-day lead time, KAF forecasted a disturbance (Disturbance 2) in the northwest Atlantic at 00 UTC 31 December 2012, located in the poleward exit region of a >80 m s$^{-1}$ 200-300-hPa layer-averaged jet streak (Fig. 22a). A 1000-hPa geopotential height minimum associated with Disturbance 2 approached -160 m just east of
Nova Scotia. Ahead of Disturbance 2, a weak thermal ridge has formed (Thermal Ridge 2), advecting 500-1000-hPa thickness values of 534 dam into the 1000-hPa geopotential height minimum. Collocated with Thermal Ridge 2 is a 200-300-hPa layer-averaged PV ridge (PV Ridge 2), with PV values of 2 PVU reaching 50°N in the central North Atlantic (Fig. 23a). Diabatic processes associated with Disturbance 2 can be inferred through ensemble mean daily-precipitation totals of over 40 mm located near the eastern extent of the tightened 500-1000-hPa thickness gradient. Positive PV advection was predicted directly over the region of precipitation, advecting high PV air down to subtropical latitudes behind the system.

By 00 UTC 02 January 2013, Disturbance 2 forecasted by the KAF ensemble has progressed east into the central North Atlantic, located south of Greenland and east of Newfoundland (Fig. 22b). The 1000-hPa geopotential height minimum has remained near -160 m, still located in the poleward exit region of a >80 m s⁻¹ jet streak that has extended into the central North Atlantic. Thermal Ridge 2 has amplified downstream of Disturbance 2, with 540 dam 500-1000-hPa thickness values approaching 57°N. Upper-level outflow as seen through the 200-300-hPa irrotational wind has decreased, though 200-300-hPa irrotational wind vectors up to 7 m s⁻¹ were positively advecting high PV air (approaching 5 PVU) southward into subtropical latitudes (Fig. 23b). Moisture associated with Disturbance 2 has decreased in intensity, as daily precipitation totals south of the 1000-hPa geopotential height minimum were maximized near 23 mm – approximately a 20 mm decrease from 31 December 2012.

By 00 UTC 04 January 2013, Disturbance 2 remained in the poleward exit region of a >70 m s⁻¹ jet streak extending into the central Atlantic and has slowed, having moved a mere 5° east in longitude to 30°W (Fig. 22c). The 1000-hPa geopotential height minimum associated with Disturbance 2 remained near -160 m and grew in spatial extent. Thermal Ridge 2 continued
to amplify, with the 540 dam line reaching 62°N. PV Ridge 2 has also slowed, amplified, and continued to tilt negatively, with its apex encroaching upon 75°N (Fig. 23c). Disturbance 2 and PV Ridge 2 have begun to translate zonally at a slower pace by 00 UTC 04 January 2013. Daily precipitation totals up to 30 mm were forecast to continue in an area of tightened 500-1000-hPa thickness gradients to the south of disturbance B. Positive PV advection via the 200-300-hPa irrotational wind continued to advect high PV air up to 5 PVU southward, above the area of heightened precipitation.

By 00 UTC 06 January 2013, the 1000-hPa geopotential height minimum associated with Disturbance 2 remained near -160 m, with negative 1000-hPa geopotential heights extending from just east of Newfoundland to Ireland (Fig. 22d). Disturbance 2 had retrograded westward, with the 1000-hPa geopotential height minimum located near 32°W, as Thermal Ridge 2 stalled and amplified, with 534 dam heights approaching 70°N. The 200-300-hPa jet streak continued to extend through the Atlantic basin, with a belt of >40 m s⁻¹ 200-300-hPa winds forecasted from eastern North America to western Europe. As the 500-1000-hPa thickness gradient collocated with the 200-300-hPa jet weakened, daily precipitation was reduced, with scattered precipitation to the south and east of Disturbance 2 (Fig. 23d). In the area of positive 200-300-hPa PV advection upstream of PV Ridge 2, a PV trough descended to 30°N, with weak 200-300-hPa irrotational winds continuing to pull high PV high up to 5 PVU southward. PV Ridge 2 had a considerable negative tilt and lost any eastward progression as a blocking pattern had been established.

With such disparity in 10-hPa zonal mean zonal wind forecasts between KAF and CAWCR at a 15-day lead time, did CAWCR predict a high-latitude PV ridge similar to that seen in verification and KAF? While a lower tropospheric analysis was unable to be performed due to
errors in interpolation of lower level geopotential heights, an upper-tropospheric analysis was performed. At 00 UTC 31 December 2012, the CAWCR ensemble mean forecasted daily precipitation up to 26 mm southeast of Nova Scotia, (Fig. 24a). Collocated with this disturbance was a starburst pattern of upper-level divergent outflow, as seen through the 200-300-hPa layer-averaged irrotational wind. Weak negative PV advection via the 200-300-hPa irrotational wind (e.g. irrotational wind values near 7-8 m s\(^{-1}\) was predicted over the region of precipitation, as a 200-300-hPa PV ridge appeared downstream, with 1 PVU values reaching 44°N (PV Ridge 3).

As precipitation, with values up to 20 mm, translated east through 00 UTC 02 January 2013, CAWCR continued to forecast a starburst pattern of 200-300-hPa irrotational winds (Fig. 24b). While the starburst pattern of outflow remained present, it was weak, with maximum 200-300-hPa irrotational wind magnitudes of approximately 8 m s\(^{-1}\). PV Ridge 3 was forecast to amplify, with 1 PVU values approaching 56°N south of Iceland.

By 00 UTC 04 January 2013, PV Ridge 3 translated over Europe, and 200-300-hPa irrotational winds associated with it have diminished (Fig. 24c). Upstream over the central North Atlantic, a broad region of precipitation developed, and flow appeared to remain fairly zonal, as seen through the 200-300-hPa PV field. Upper-level divergent outflow over the central North Atlantic was dominated by positive PV advection, with 200-300-hPa irrotational wind values reaching 12 m s\(^{-1}\) and directed primarily southward.

By 00 UTC 06 January 2013, the 200-300-hPa PV waveguide was forecasted to remain mostly zonal from eastern North America through the Atlantic basin (Fig. 24d). Several areas of weak precipitation (daily precipitation values maximized near 20 mm) pervade the Atlantic,
though PV advection via the 200-300-hPa irrotational wind was minimal, with 200-300-hPa irrotational wind values remaining below 8 m s$^{-1}$ through the entirety of the Atlantic basin.

### 3.2.2 Blocking Regime Variability

With such considerable variability in skill in predicting stratospheric zonal mean metrics at a 15-day lead time, it is important to investigate tropospheric forcing prior to the split of the polar vortex on 7 January 2013. As noted in chapter 1, meridional eddy heat flux is directly proportional to upward WAF, and as such, blocking and associated meridional heat flux over the Atlantic basin was investigated for CFSR, KAF (low error ensemble) and CAWCR (high error ensemble).

CFSR data shows that from 00 UTC 31 December 2012 through 00 UTC 7 January 2013, a persistent 200-300 hPa layer-averaged high-latitude ridge/block (PV Ridge 1) formed in the N. Atlantic, centered west of Scandinavia and north of Ireland (Fig. 25a). The apex of PV Ridge 1 associated with this blocking pattern extended to roughly 75°N. In the poleward exit region of a 200-300-hPa 70 m s$^{-1}$ jet streak and just upstream of PV Ridge 1, a broad region of positive, poleward 200-300-hPa layer-averaged heat flux extends from 45°N to 68°N and between 50°W and 22°W. 200-300-hPa meridional heat flux values peak above 180 K m s$^{-1}$, and positive heat flux values dominate the Atlantic basin, with little to no negative values present.

Much like what was observed, the KAF (e.g. low error ensemble) ensemble mean, initialized 23 December 2012, forecasted a high-latitude 200-300-hPa ridge (PV Ridge 2) and blocking pattern in the N. Atlantic the week leading up to SSW onset, with its apex centered west of Scandinavia and extending to roughly 75°N (Fig. 25b). Upstream of PV Ridge 1 and located in the poleward exit region of a broad 200-300-hPa 70 m s$^{-1}$ jet streak is an area of 200-
300-hPa poleward heat flux with values over 30 K m s\(^{-1}\). Greater values of 200-300-hPa poleward heat flux upwards of 80 K m s\(^{-1}\) are seen northwest of the ridge over Greenland. This region of high meridional heat flux values is collocated with a large upper-level 200-300-hPa PV cutoff, which is more pronounced than that seen in verification.

Unlike CFSR and the KAF, the CAWCR (e.g. high error ensemble) ensemble mean, initialized 23 December 2012, predicted fairly zonal 200-300-hPa flow over the Atlantic (Fig. 25c). With little 200-300-hPa PV ridging and a 200-300-hPa jet of merely 50 m s\(^{-1}\), minimal meridional 200-300-hPa heat flux values were forecasted, though an area of 30-40 K m s\(^{-1}\) was seen south of Greenland. Yet west of Greenland, a substantially broader region of negative, equatorward 200-300-hPa heat flux, with values upwards of -60 K m s\(^{-1}\) was collocated with an upper-level 200-300-hPa PV cutoff feature. However, CAWCR’s forecasted upper-level cutoff was weaker than that seen in the KAF ensemble, as 200-300-hPa PV values were greater than 0.5 PVU below that seen in KAF.
Fig. 3.1. KAF ensemble forecast of 10 hPa 60°N zonal mean zonal wind (m s⁻¹), 60°-90° area-weighted temperature (K), and 60°-90° area-weighted geopotential height (m), initialized 23 December 2012.
Fig. 3.2. KAF ensemble forecast of 10 hPa 60°N zonal mean zonal wind (m s$^{-1}$), 60°-90° area-weighted temperature (K), and 60°-90° area-weighted geopotential height (m) initialized 28 December 2012.
Fig. 3.3. As in Fig. 3.1 but for the NOGAPS model.
Fig. 3.4. As in Fig. 3.2 but for the NOGAPS model.
Fig. 3.5. As in Fig. 3.1 but for the ECMWF model.
Fig. 3.6. As in Fig. 3.2 but for the ECMWF model.
Fig. 3.7. As in Fig. 3.1 but for the METO model.
Fig. 3.8. As in Fig. 3.2 but for the METO model.
Fig. 3.9. As in Fig. 3.1 but for the MRI model.
Fig. 3.10. As in Fig. 3.2 but for the MRI model.
Fig. 3.11. As in Fig. 3.1 but for the CAWCR model.
Fig. 3.12. As in Fig. 3.2 but for the CAWCR model.
<table>
<thead>
<tr>
<th>Ensemble</th>
<th>Avg Zonal Mean Zonal Wind (m/s)</th>
<th>Std. Deviation (m/s)</th>
<th>Avg Zonal Mean Zonal Wind (m/s)</th>
<th>Std. Deviation (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15-day Lead Time</td>
<td>10-day Lead Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAF</td>
<td>-1.592</td>
<td>3.599</td>
<td>-10.678</td>
<td>4.451</td>
</tr>
<tr>
<td>NOGAPS</td>
<td>9.173</td>
<td>8.683</td>
<td>-2.177</td>
<td>4.714</td>
</tr>
<tr>
<td>ECMWF</td>
<td>25.913</td>
<td>9.776</td>
<td>0.286</td>
<td>2.802</td>
</tr>
<tr>
<td>METO</td>
<td>26.615</td>
<td>12.523</td>
<td>4.280</td>
<td>3.924</td>
</tr>
<tr>
<td>MRI</td>
<td>27.940</td>
<td>12.333</td>
<td>2.178</td>
<td>4.818</td>
</tr>
<tr>
<td>CAWCR</td>
<td>29.174</td>
<td>5.702</td>
<td>4.667</td>
<td>4.871</td>
</tr>
<tr>
<td>CFSR</td>
<td>-6.164</td>
<td>N/A</td>
<td>-6.164</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 3.1.** Ensemble mean and standard deviation of forecasted 10 hPa 60°N zonal mean zonal wind at 00 UTC 07 January 2013 for all six SNAP models at 15- and 10-day lead times. Verified CFSR value at 00 UTC 07 January 2013 included.
Fig. 3.13. 1000-hPa geopotential height (black contours; m), 500-1000-hPa thickness (colored contours; purple denotes 540 dam thickness; m), and 200-300-hPa jet (fill; m s\(^{-1}\)) for CFSR data. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.
Fig. 3.14. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s$^{-1}$), and precipitable water (fill; mm) for CFSR data. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.
Fig. 3.15. 1000-hPa geopotential height (black contours; m), 500-1000-hPa thickness (colored contours; purple denotes 540 dam thickness; m), and 200-300-hPa jet (fill; m s\(^{-1}\)) for KAF data; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.
Fig. 3.16. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s$^{-1}$), and daily-averaged precipitation (fill; mm) for KAF; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.
Fig. 3.17. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), 200-300 hPa layer-averaged irrotational wind (vectors; m s\(^{-1}\)), and daily-averaged precipitation (fill; mm) for CAWCR; forecasts initialized 23 December 2012. Data provided at two-day time steps: (a) 00 UTC 31 December 2012, (b) 00 UTC 02 January 2013, (c) 00 UTC 04 January 2013, and (d) 00 UTC 06 January 2013.
Fig. 3.18. 200-300 hPa layer-averaged potential vorticity (black contours; PVU), wind speed (fill; m s\(^{-1}\)), and meridional heat flux (red contours: positive; K m s\(^{-1}\), blue contours: negative; K m s\(^{-1}\)) for (a) CFSR, (b) KAF, and (c) CAWCR; forecasts initialized 23 December 2012. All values averaged from 00 UTC 31 December 2012 through 00 UTC 07 January 2013.
4. Elliptical Metrics

4.1 Polar Vortex Tracking

While the 10-hPa 60°N zonal mean zonal wind pervades the literature as a useful metric for analyzing and forecasting SSWs (e.g., Charlton and Polvani 2007; Butler et al. 2017), metrics that quantify the polar vortex geometry has gained ground as a viable alternative (e.g., Waugh and Randel 1999; Taguchi et al. 2015b). Waugh and Randel (1999) introduced a novel approach using the stratospheric PV field to locate the polar vortex and ascertain its geometry by quantifying best-fit ellipse metrics. For this study, the 10-hPa geopotential height field was used to fit the polar vortex to an ellipse, with the 29.5 km 10-hPa geopotential height contour describing the edge of the vortex. The 29.5 km contour was used because it was in the group of height contours that were collocated with the polar height jet. The 15-day lead time forecasts from all six SNAP ensemble models were utilized in the examination of the variability in forecasting the split of the polar vortex on 07 January 2013.

At 0000 UTC 23 December 2012, the stratospheric polar vortex as represented by the 29.5 km 10-hPa geopotential height contour best-fit ellipse was displaced off the center of the North Pole, with its center over the Barents Sea (near 72°N and 45°E) (Fig. 4.1a). The 10-hPa vortex ellipse center remained near its location over the Barents Sea while decreasing in area through 0000 UTC 02 January 2013 (Fig. 4.1b,c). By 0000 UTC 07 January 2013, the amplification of ridges over the Bering Sea and the North Atlantic was accompanied by the split of the 10-hPa polar vortex into two separate ellipses, one over eastern Europe and one over northern Canada (Fig. 4.1d). At 0000 UTC 12 January 2013, height rises over the polar region caused the 10-hPa 29.5 km geopotential height contour representing the vortex over eastern
Europe to disappear, while the 10-hPa vortex ellipse over North America translated westward, its center located near 67°N and 100°W (Fig. 4.1e). The North American 10-hPa vortex ellipse progressed southward as heights continued to rise over the extratropical regions of the Northern Hemisphere (Fig. 4.1f), with the vortex dissipating by 0000 UTC 22 January 2013 (Fig. 4.1g). The core of the stratospheric polar vortex, as seen through the 29.5 km 10-hPa geopotential height contour, did not reform until a month later, 0000 UTC 21 February 2013, located near 78°N and 65°E (Fig. 4.1h).

Which, if any, SNAP ensemble forecasts initialized at 0000 UTC 23 December 2012 were able to predict the splitting of the 10-hPa polar vortex? All five members of the KAF ensemble were able to resolve the SSW and associated split. At 0000 UTC 23 December 2012, KAF forecasted the center of the 10-hPa polar vortex ellipse to be displaced off the pole near 72°N and 40°E, though there was some variability of a few degrees latitude and longitude in initial conditions (Fig. 4.2a). Five days into the forecast at 0000 UTC 28 December 2012, all five members forecasted the center of the 10-hPa polar vortex ellipse to translate west to near 70°N and 25°E, with little variability in location (Fig. 4.2b). The predicted 10-hPa polar vortex ellipses remained centered over the Barents Sea region and elongated by the 10-day forecast period valid at 0000 UTC 02 January 2013 (Fig. 4.2c). By the 15-day forecast period, or time of observed SSW onset at 0000 UTC 07 January 2013, variability in KAF 10-hPa vortex ellipse location increased, with members ranging in locations from 30°E to 70°E with no splits yet to occur in any of the ensemble members forecasts (Fig. 4.2d).

NOGAPS was less skillful in predicting the vortex split in that none of 20 members predicted a split in the 29.5 km 10-hPa geopotential height field by 0000 UTC 07 January 2013. Beginning at 0000 UTC 23 December 2012, the predicted NOGAPS centers of the 29.5 km 10-
hPa geopotential height field were located near 72°N and 45°E, all displaced off the pole into the Barents Sea region (Fig. 4.3a). Five days into the forecast at 0000 UTC 28 December 2012, like CFSR and KAF, all 20 NOGAPS ensemble members predicted the 10-hPa polar vortex ellipse center to translate west, with the cluster located at approximately 68°N and 35°E (Fig. 4.3b). Ten days into the forecast and five days prior to SSW onset at 0000 UTC 02 January 2013, 10-hPa vortex ellipse eccentricity decreased in all NOGAPS members to an ensemble mean value of 1.11 as the centers of the ellipses progressed north and westward into the Barents and Kara Seas (Fig. 4.3c). While most 10-hPa vortex ellipses elongated 15 days into the forecast valid at 0000 UTC 07 January 2013, 21 out of 22 vortex centers were located in the eastern Northern Hemisphere (Fig. 4.3d). As variability in 10-hPa vortex ellipse center, size, and eccentricity increased by SSW onset, all 20 members predicted an intact singular 29.5 km 10-hPa geopotential height contour, with the SSW event more characteristic of a displacement type event and not a splitting event.

As with the verification, KAF, and NOGAPS, the ellipse centers of the ECMWF 10-hPa polar vortex were forecasted to be displaced off the North Pole, located in the Barents Sea near 72°N and 45°E at 0000 UTC 23 December 2012 (Fig. 4.4a). Five days into the forecast at 0000 UTC 28 December 2012, the ensemble variability in location, size, and eccentricity of the 10-hPa polar vortex ellipses was small, with centers remaining further east than KAF and NOGAPS at approximately 40°E (Fig. 4.4b). By 10 days into the forecast, valid at 0000 UTC 02 January 2013, all 25 ECMWF members predicted a 10-hPa polar vortex nearly oriented parallel to the Prime Meridian as the 10-hPa ellipse centers of the 29.5 km 10-hPa geopotential height fields migrated toward the western Northern Hemisphere (Fig. 4.4c). Unlike KAF and NOGAPS, the 15-day ECMWF forecast valid at 0000 UTC 07 January 2013 predicted five members’ best-fit
ellipse centers to be located in the western Northern Hemisphere, with great spread in vortex ellipticity ratio and center locations, with center locations ranging from 40°W and 45°E, and 70°N to 84°N (Fig. 4.4d). None of the 25 ECMWF members forecasted a split of the 10-hPa polar vortex by the date of observed SSW onset, and the SSW event resembled that of a SSW displacement with an amplified stratospheric Aleutian ridge.

As with previously analyzed SNAP ensembles, the METO ensemble forecasted 10-hPa polar vortex ellipse centers to be located in the Barents Sea near 72°N and 45°E at 0000 UTC 23 December 2012, with the greatest extent of vortex area in the eastern Northern Hemisphere (Fig. 4.5a). In the five day forecast valid at 0000 UTC 28 December 2012, METO ensemble variability in 10-hPa polar vortex ellipse center longitudes increased, with centers translating east from 42°E to 58°E, while center latitudes remained near 70°N (Fig. 4.5b). As with the NOGAPS and ECMWF, the METO predicted eccentricity to decrease (by 0.27 for the METO ensemble) by 0000 UTC 02 January 2013 (Fig. 4.5c). The ensemble spread in the 10-hPa polar vortex ellipse center locations increased as forecasted vortex shifted poleward. In the 15-day forecast valid at 0000 UTC 07 January 2013, the variability in forecasted 10-hPa vortex ellipse center location greatly increased, as centers spanned locations from the Greenland Sea to the central Arctic, with center latitudes ranging from 70°N to 85°N and longitudes from 70°W to 90°E (Fig. 4.5d). While 29.5 km 10-hPa geopotential heights spread into the western Northern Hemisphere, none of the 22 members predicted a split of the 10-hPa polar vortex.

Forecasts valid between 0000 UTC 23 December 2012 and 0000 UTC 28 December 2012 in the MRI forecasted 10-hPa vortex ellipse centers to remain near 72°N and 45°E, as ensemble mean 10-hPa vortex eccentricity increased from 1.43 to 1.58 (Fig. 4.6a,b). In the 10-day forecast valid at 0000 UTC 02 January 2013, the ensemble mean 10-hPa vortex ellipse
eccentricity decreased to 1.35, while variability in ellipse center location increased over the eastern portion of the Kara Sea region (Fig. 4.6c). The 10-hPa vortex ellipse centers tended to increase in latitude, between 74°N and 81°N, and translated both west and east, between 50°E and 100°E. By the time of observed SSW onset in the 15-day forecast valid at 0000 UTC 07 January 2013, the locations of the MRI forecasted 10-hPa polar vortex gained considerable spread (Fig. 4.6d). Unlike previously discussed SNAP ensemble 10-hPa vortex ellipses from the KAF, NOGAPS, and ECMWF, the majority of MRI members predicted the vortex center to migrate to the western Northern Hemisphere, rather than remain in the Greenland/Canadian archipelago. The 10-hPa vortex ellipse eccentricity increased to an ensemble mean of 1.86 as the forecasted vortices elongated but did not split.

Similar to the five other SNAP ensembles, the CAWCR forecast of 10-hPa vortex ellipses were centered over the Barents Sea, located at roughly 72°E and 43°E valid at 1800 23 December 2012 (Fig. 4.7a). In the five day forecast valid at 1800 UTC 28 December 2012, the ensemble mean 10-hPa vortex ellipse eccentricity decreased from 1.46 to 1.39 as the center location of the vortex ellipse translated slightly east, located between 40°E and 55°E, while remaining near 71°N (Fig. 4.7b). The variability in predicted 10-hPa vortex center location increased by the 10-day forecast valid at 1800 UTC 02 January 2013, ranging from 72°N to 78°N and 40°E to 80°E within the Kara Sea region (Fig. 4.7c). The 15-day forecast valid at 1800 UTC 07 January 2013 predicted ensemble mean 10-hPa vortex ellipse eccentricity increased to 1.45 as the vortex elongated parallel to the Prime Meridian in eastern Europe and Siberia (Fig. 4.7d). The locations of forecasted 10-hPa vortex ellipse centers greatly varied, mainly in the Barents/Kara Seas and Arctic Ocean regions, all remaining in the eastern Northern Hemisphere.
None of the 24 members forecasting a split of the 10-hPa polar vortex, or a rotation angle that matched the verification.

4.2 Vortex Ellipse Centers

4.2.1 Vortex Ellipse Ensemble Variability

Due to such large variability in 15-day forecasts of 10-hPa vortex ellipse center locations amongst the six SNAP ensemble models, ellipse centers were further analyzed in this study. Ensemble member 10-hPa vortex ellipse center locations were interrogated at 0000 UTC 06 January 2013, as at that time, none of the 147 ensemble members in the SNAP dataset had predicted a split 10-hPa polar vortex.

At 0000 UTC 06 January 2013, there was considerable variability in the 10-hPa vortex ellipse center location, with 10-hPa vortex ellipse centers spanning from Eastern Europe, through the Barents/Kara Seas, and to the Arctic and Northern Canadian Maritime region (Fig. 4.8). MRI predictions of 10-hPa vortex ellipse centers showed the most substantial ensemble spread compared to KAF, CAWCR, ECWMWF, NOGAPS, and METO, with greater than 50% of forecasted ellipse centers in the region of the Canadian Archipelago and spanning 66°N to 89°N. ECMWF and METO also showed considerable meridional spread in 10-hPa vortex ellipse center location, though only one member of METO and three members of ECMWF were forecasted in the Western Hemisphere. The 10-hPa vortex ellipse centers forecasted by CAWCR, NOGAPS, and KAF were more tightly clustered over the Arctic coastal regions of Eurasia. CAWCR forecasted 10-hPa vortex ellipse centers to primarily be located within a narrow latitude band between 73°N and 82°N, and between 34°E and 89°E. NOGAPS predicted that 15 of 20 members’ 10-hPa vortex ellipse center would be located south of 70°N, with the other five
members south of 80°N. KAF was most tightly clustered in terms of latitude, with forecasted 10-hPa vortex ellipse center latitudes ranging from 61°N to 69°N. 4 of 5 KAF members were centered between 36°E and 46°E, with one member near 71°E.

4.2.2 Vortex Ellipse Latitude Clustering

4.2.2.1 Relationship to Zonal Mean Metrics

As it was evident that the KAF, NOGAPS, and CAWCR10-hPa vortex ellipse center clustered in terms of latitude, the 10-hPa vortex ellipse center latitude was further examined. Forecasted 10-hPa vortex ellipse centers were categorized into three latitude bands: 60-69.9°N (low latitude), 70-79.9°N (middle latitude), and 80-90°N (high latitude; Fig. 4.9). The categorization reveals that 13.6% (n=20) of the 147 members were located in the low latitude band, 51.7% (n=76) in the middle latitude band, and 34.7% (n=51) in the high latitude band.

The forecasted 10-hPa vortex ellipse center valid at 0000 UTC 06 January 2013 were correlated with the corresponding forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 07 January 2013 (e.g., time of observed SSW onset). A substantial decrease (more easterly component) in the 10-hPa zonal mean zonal wind was evident within the low latitude band compared to the middle and high latitude bands (Fig. 4.10). The predicted median 10-hPa 60°N zonal mean zonal wind for vortex ellipses in the low latitude band was 1.89 m s⁻¹, while the median values for the middle and high latitude bands were 26.40 m s⁻¹ and 28.46 m s⁻¹, respectively.

When the forecasted 10-hPa 60°N zonal mean zonal wind was treated as a continuous variable and compared to the forecasted 10-hPa vortex ellipse center latitude, a considerable positive correlation was noted, with a correlation coefficient of 0.44 (Fig. 4.11). A two-tailed
Student’s t-test was performed, and this linear regression was found to be statistically significant, with a p-value of 3.20E-8.

4.2.2.2 Tropospheric Forcing

In a method similar to that in 3.2, lower- and upper-tropospheric analyses were performed to investigate precursor tropospheric forcing in the Atlantic basin (e.g. Coy and Pawson 2015) prior to the onset of the 07 January 2013 SSW event. The SNAP member that forecasted the lowest latitude 10-hPa vortex center latitude (NOGAPS Member 1) and the SNAP member that forecasted the highest latitude 10-hPa vortex center latitude (METO Member 10) valid at 0000 UTC 06 January 2013 were the focus of this analysis. This analysis focuses on documenting the common tropospheric forcing between models categorized by the large and small values of the 10-hPa 60°N zonal mean zonal wind and those categorized by the minimum and maximum of 10-hPa vortex ellipse center latitude.

Initialized at a 15-day lead time, NOGAPS Member 1 forecasted a disturbance in the western North Atlantic (Disturbance A), with an associated 1000-hPa geopotential height minimum of -160 m over Newfoundland valid at 0000 UTC 31 December 2012 (Fig. 4.12a). Disturbance A was located in the poleward exit region of a >70 m s\(^{-1}\) 300-200-hPa layer-averaged jet streak that extended from the eastern United States to the western North Atlantic. Downstream of Disturbance A was a forecasted thermal ridge (Thermal Ridge A), with a narrow ridge of 540 dam 1000-500-hPa thickness values reaching 57°N. Collocated with Thermal Ridge A was a 300-200-hPa layer-averaged PV Ridge (PV Ridge A), with PV values less than 2 PVU approaching 54°N (Fig. 4.13a). Diabatically generated upper-tropospheric outflow associated
with Disturbance A could be seen through a starburst pattern of 300-200-hPa layer-averaged irrotational winds, with daily-precipitation values greater than 60 mm evident at the surface.

In the forecast valid at 0000 UTC 02 January 2013, Thermal Ridge A amplified and gained a positive tilt, with 540 dam 1000-500-hPa thicknesses reaching 67°N east of Greenland (Fig. 4.12b). Disturbance A was forecast to translate northeastward, located near the southern Greenland, with a 1000-hPa geopotential height minimum still near -160 m. Disturbance A was located in the poleward exit region of a 300-200-hPa layer-averaged jet streak of >60 m s⁻¹. A second 1000-hPa geopotential height minimum of -160 m (Disturbance B) was located in Northern Canada, upstream of a 1000-500-hPa thickness trough (Thermal Trough A) centered over northeastern Canada. Collocated with Thermal Trough A was a shortwave 300-200-hPa layer-averaged PV trough (PV Trough A), with 5 PVU values being advected south to the north Central United States (Fig. 4.13b). Near Disturbance A was a region of greater than 70 mm daily-precipitation, with a second region of greater than 70 mm daily-precipitation to the south, associated with a frontal feature that can be inferred in the region of the large 1000-500-hPa thickness gradient over the central North Atlantic. While weaker than forecasted at 0000 UTC 31 December 2012, a 300-200-hPa layer-averaged irrotational winds starburst pattern of diabatically driven upper-level outflow was collocated with Disturbance A, with irrotational wind speeds up to 6 m s⁻¹. PV Ridge A amplified and gained a positive tilt, with PV values <1 PVU reaching 69°N.

The forecast valid at 0000 UTC 04 January 2013 revealed that Disturbance A had translated east, with its associated 1000-hPa geopotential height minimum of -80 m located over Iceland (Fig. 4.12c). Thermal Ridge A, now located in the eastern North Atlantic, gained a negative tilt as 540 dam 1000-500 thicknesses extended to 63°N. Downstream of Thermal
Trough A, Disturbance B had progressed southeastward, located in the western North Atlantic, and was associated with an 1000-hPa geopotential height minimum of less than 0 m. A broad region of daily-precipitation values greater than 70 mm was predicted between Disturbance B and a 1000-hPa geopotential height maximum of 300 m located in the North Central Atlantic, south of Greenland (Fig. 4.13c). Daily-precipitation totals up to 40 mm were also forecasted in the region under Disturbance B. Collocated with these two areas of substantial precipitation and a 300-200-hPa layer-averaged PV maximum of 7 PVU was a starburst pattern of 300-200-hPa layer-averaged irrotational winds, with wind speeds approaching 15 m s\(^{-1}\). PV Ridge A had gained a negative tilt downstream of Disturbance A, with PV values <1 PVU extending north to 64°N.

By 0000 UTC 06 January 2013, Thermal Tough A continued to translate eastward, with a substantial negative tilt, and was located upstream of Disturbance B and its associated -160 m 1000-hPa geopotential height minimum (Fig. 4.12d). Disturbance B was located in the poleward exit region of a >50 m s\(^{-1}\) 300-200 hPa layer-averaged jet streak over the central North Atlantic, while a second thermal ridge (Thermal Ridge B) amplified downstream, with 534 dam 1000-500-hPa thicknesses reaching as far north as 66°N near Greenland. Thermal Ridge A had weakened and progressed over Europe as Disturbance A maintained its -160 m 1000-hPa geopotential height minimum over eastern Northern Europe. Collocated with Thermal Ridge B was a 300-200-hPa layer-averaged PV ridge (PV Ridge B), with 2 PVU values approaching 73°N. Scattered precipitation, with daily values of over 70 mm, was forecasted in association with both Disturbance B and the 300-200-hPa layer-averaged PV maximum of 4 PVU to the southwest of Disturbance B. Associated with these two areas of precipitation was weak upper-
level divergent outflow as seen through the 300-200-hPa layer-averaged irrotational wind, advecting low values of PV north, west, and east of high-latitude PV Ridge B.

To investigate the similarities and differences in synoptic- and planetary-scale tropospheric forcing for blocking between the lowest and highest 10-hPa vortex ellipse center latitude members, the tropospheric evolution from the highest latitude member (METO Member 10) was also analyzed. At 0000 UTC 31 December 2012, a 1000-hPa geopotential height minimum of -160 m (Disturbance C) was forecasted by METO Member 10, collocated with a cut-off 522 dam 1000-500-hPa thickness contour in the western North Atlantic (Fig. 4.14a). Disturbance C was located in the poleward exit region of a >60 m s⁻¹ jet streak and upstream of a high-latitude thermal ridge (Thermal Ridge C), with >540 dam 1000-5000-hPa thickness values extending northward, encroaching upon 62°N. Diabatically driven upper-level outflow was predicted, as seen through the starburst pattern of 300-200-hPa layer-averaged irrotational winds over Disturbance C (Fig. 4.15a). This diabatic outflow region corresponded to daily-precipitation up to 40 mm and irrotational wind with speeds up to 20 m s⁻¹ advecting high PV air southward (Fig. 4.15a). Downstream of Disturbance C was a 300-200-hPa layer-averaged PV ridge (PV Ridge C), with <2 PVU values extending northward 55°N.

Disturbance C had translated east into the central North Atlantic by 0000 UTC 02 January 2013, with an associated 1000-hPa geopotential height minimum of -160 m (Fig. 4.14b). Thermal Ridge C weakened, with the 540 dam contour of 1000-500-hPa thicknesses extending to only 55°N. A second lower-level disturbance (Disturbance D), with a 1000-hPa geopotential height minimum of -80 m, was located upstream in the western North Atlantic in the poleward exit region of a >80 m s⁻¹ jet streak. Collocated with Disturbance D was a broad region of 15-30 mm daily-precipitation and 300-200-hPa layer-averaged irrotational wind vectors up to 13 m s⁻¹.
The irrotational wind advected relatively higher values of PV southward into the subtropics upstream of PV Ridge C (Fig. 4.15b). PV Ridge C amplified and progressed east into the eastern North Atlantic as the 3 PVU contour reached 62°N, gaining a negative tilt.

By 0000 UTC 04 January 2013, Disturbance C dissipated over Northern Europe as the 1000-hPa geopotential height minimum associated with Disturbance D deepened to -160 m in the western North Atlantic (Fig. 4.14c). Disturbance D was located downstream of a thermal trough that extended into eastern North America and in a strengthening >80 m s⁻¹ 300-200-hPa layer-averaged jet streak. An amplifying thermal ridge (Thermal Ridge D) was located downstream of Disturbance D, with 534 dam 1000-500-hPa thicknesses extending northward to 61°N in the central North Atlantic. A broad region of >40 mm daily-precipitation was predicted associated with a frontal feature located south of Disturbance D, as evidenced by the tightening of the 1000-500-hPa thickness gradient in the western North Atlantic (Fig. 4.15c). The 300-200-hPa layer-averaged irrotational winds up to 15 m s⁻¹ advected high PV (up to 5 PVU) air southward in this broad region of frontal precipitation. Downstream of Disturbance D, a 300-200-hPa layer-averaged PV Ridge (PV Ridge D) developed with a negative tilt as the 3 PVU contour extended northward to 59°N.

By 0000 UTC 06 January 2013, Thermal Ridge D amplified downstream of Disturbance D, with the 540 dam contour of 1000-500-hPa thicknesses approaching 62°N (Fig. 4.14d). Disturbance D, which was located in the poleward exit region of a weakening >60 m s⁻¹ jet streak, was associated with a -160 m 1000-hPa geopotential height minimum and a 522 dam closed 1000-500-hPa thickness contour. A thermal trough, with <540 dam 1000-500-hPa thickness values being advected southward to 39°N over the central North Atlantic, was predicted upstream of Disturbance D and Thermal Ridge D. Diabatically driven upper-level
outflow was evident from the starburst pattern of 300-200-hPa layer-averaged irrotational winds up to 25 m s\(^{-1}\) that was collocated with Disturbance D (Fig. 4.15d). Upstream of Disturbance D, a 300-200-hPa layer-averaged PV trough continued to advect high PV air (>5 PVU) southward to 38°N. Daily-precipitation up to 40 mm extended along a frontal feature that could be seen through a tightened 1000-500-hPa thickness gradient south of Disturbance D, with daily-precipitation above 70 mm also located north and east of Disturbance D. PV Ridge D had gained a positive tilt downstream of Disturbance D, with the 1 PVU contour reaching 58°N in the eastern North Atlantic.

As in Section 3.2.2, tropospheric blocking regime variability and its associated meridional eddy heat flux was interrogated for the lowest and highest 10-hPa vortex ellipse center latitude members, as meridional eddy heat flux is directly proportional to the vertical component of the vector WAF. NOGAPS Member 1 (lowest latitude member) forecasted that in a 7-day average from 0000 UTC 31 December 2013 through 0000 UTC 07 January 2013, a high-latitude 300-200-hPa layer-averaged PV ridge pattern would develop over the eastern North Atlantic, associated with PV Ridges A and B (Fig. 4.16a). The apex of the high-latitude time-mean ridge extended north to 74°N, with a broad region of positive 300-200-hPa layer-averaged meridional eddy heat flux values from upstream of the time-mean ridge at 44°N, through the Labrador Sea region to Arctic latitudes of 85°N. Positive, or poleward, 300-200-hPa layer-averaged meridional eddy heat flux up to 80 K m s\(^{-1}\) dominated the Atlantic Basin, with few negative values present.

The corresponding 7-day average from 0000 UTC 31 December 2012 through 0000 UTC 07 January 2013 in the METO Member 10 (highest latitude member) forecasted a time-mean 300-200-hPa layer-averaged PV ridge over the eastern North Atlantic, though it was less
amplified than that predicted by NOGAPS Member 1 (Fig. 4.16b). The apex of the time-averaged PV Ridge forecasted by METO reached 64°N, which was 11° south of that forecasted by NOGAPS Member 1. While positive 300-200-hPa layer-averaged meridional eddy heat flux up to 80 K m s\(^{-1}\) was present in the western North Atlantic, the region it encompassed was smaller spatially than predicted by NOGAPS Member 1 and did not extend north of 59°N. A region of negative 300-200-hPa layer-averaged meridional eddy heat flux up to -80 K m s\(^{-1}\) was also present east of Iceland, a feature not predicted by the lowest latitude member.

4.3 Summary

The elliptical metrics used in this chapter have illustrated a few key points regarding model ensemble variability in forecasting the 7 January 2013 SSW event. (1) By 0000 UTC January 2013, none of the six SNAP ensemble forecasts had predicted a split of the 10-hPa polar vortex, with a minor displacement event predicted in many of the ensemble members. (2) There was a statistically significant correlation between forecasted 10-hPa best-fit ellipse center latitude and its corresponding zonal mean zonal wind, suggesting that elliptical metrics (particularly ellipse center latitude) are a viable alternative for forecasting SSWs as compared to zonal mean metrics. (3) The tropospheric forcings associated with the SNAP member that forecasted the most equatorward 10-hPa ellipse center latitude were similar to that seen in the KAF ensemble, which represented the most easterly 10-hPa 60°N zonal mean zonal wind, with time-mean ridging and primarily poleward meridional eddy heat flux in the North Atlantic. (4) The tropospheric forcings associated with the SNAP member that forecasted the most poleward 10-hPa ellipse center latitude were similar to that seen in the CAWCR ensemble, which
represented the most westerly 10-hPa 60°N zonal mean zonal wind, with little time-mean poleward meridional eddy heat flux and ridging primarily in mid-latitudes rather than polar latitudes.
(a) 0000 UTC 23 December 2012

(b) 0000 UTC 28 December 2012

(c) 0000 UTC 02 January 2013

(d) 0000 UTC 07 January 2013
Fig. 4.1. 10-hPa geopotential height field (black; km), 10-hPa 29.5 km geopotential heights (blue; km), ellipse(s) fitted to 10-hPa 29.5 km geopotential heights (red; km), using CFSR dataset valid at (a) 0000 UTC 23 December 2012, (b) 0000 UTC 28 December 2012, (c) 0000 UTC 02 January 2013, (d) 0000 UTC 07 January 2013, (e) 0000 UTC 12 January 2013, (f) 0000 UTC 17 January 2013, (g) 0000 UTC 22 January 2013, and (h) 0000 UTC 21 February 2013.
Fig. 4.2. Ensemble mean 10-hPa geopotential height field (black; km) and ensemble member ellipse(s) fitted to 10-hPa 29.5 km geopotential heights (blue; km) using KAF dataset; forecast initialized 23 December 2012 valid at (a) 0000 UTC 23 December 2012, (b) 0000 UTC 28 December 2012, (c) 0000 UTC 02 January 2013, (d) 0000 UTC 07 January 2013.
Fig. 4.3. As in Fig. 4.2 but for the NOGAPS model.
Fig. 4.4. As in Fig. 4.2 but for the ECMWF model.
Fig. 4.5. As in Fig. 4.2 but for the METO model.
Fig. 4.6. As in Fig. 4.2 but for the MRI model.
Fig. 4.7. As in Fig. 4.2 but for the CAWCR model and valid at (a) 1800 UTC 23 December 2012, (b) 1800 UTC 28 December 2012, (c) 1800 UTC 02 January 2013, (d) 1800 UTC 07 January 2013.
Fig. 4.8. 10-hPa polar vortex ellipse centers valid at 0000 UTC 06 January 2013 categorized by SNAP ensemble; forecasts initialized 23 December 2012. Red: CAWCR; Black: KAF; Magenta: NOGAPS; Green: ECMWF; Orange: METO; Blue: MRI.

Fig. 4.9. 10-hPa polar vortex ellipse centers valid at 0000 UTC 06 January 2013 categorized by latitude band; forecasts initialized 23 December 2012. Red: 60-69.9°N; Green: 70-79.9°N; Blue: 80-90°N.
Fig. 4.10. Boxplot of SNAP forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 07 January 2013 vs forecasted 10-hPa polar vortex ellipse latitude at 0000 UTC 06 January 2013, categorized by latitude band of ellipse center; initialized 23 December 2012. Boxes represent 10-hPa 60°N zonal mean zonal wind values between the first and third quartiles, with the median value represented by a solid line. Lowest and highest values in each latitude band denoted by solid black lines at the edge of the whiskers.

Fig. 4.11. SNAP forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 07 January 2013 vs forecasted 10-hPa polar vortex ellipse latitude at 0000 UTC 06 January 2013; forecasts initialized 23 December 2012. Linear regression denoted by solid black line. p-value calculated via a two-tailed Student’s t-test.
Fig. 4.12. 1000-hPa geopotential height (black solid contours; m), 1000-500-hPa thickness (colored dashed contours; m), and 300-200-hPa jet (fill; m s\(^{-1}\)) for NOGAPS Member 1; forecasts initialized 23 December 2012. 1000-500-hPa thickness values greater (less) than 540 dam are red (blue) dashed contours, every 6 dam. The 540 dam 1000-500-hPa thickness values are represented by the purple dashed contour. Analysis every two days at (a) 0000 UTC 31 December 2012, (b) 0000 UTC 02 January 2013, (c) 0000 UTC 04 January 2013, and (d) 0000 UTC 06 January 2013.
Fig. 4.13. 300-200-hPa layer-averaged potential vorticity (black contours; PVU), 300-200-hPa layer-averaged irrotational wind (vectors; m s\(^{-1}\)), and daily-averaged precipitation (fill; mm) for NOGAPS Member 1; forecasts initialized 23 December 2012. PV contoured every 1 PVU beginning at 1 PVU. Analysis every two days at (a) 0000 UTC 31 December 2012, (b) 0000 UTC 02 January 2013, (c) 0000 UTC 04 January 2013, and (d) 0000 UTC 06 January 2013.
Fig. 4.14. As in Fig. 4.12 but for the METO Member 10.
Fig. 4.15. As in Fig. 4.13 but for the METO Member 10.
Fig. 4.16. 300-200 hPa layer-averaged potential vorticity (black contours; PVU), 300-200 hPa layer-averaged wind speed (fill; m s\(^{-1}\)), and 300-200 hPa layer-averaged meridional eddy heat flux (red contours: positive; K m s\(^{-1}\), blue contours: negative; K m s\(^{-1}\)) for (a) NOGAPS Member 1 and (b) METO Member 10; forecasts initialized 23 December 2012. PV contoured every 1 PVU beginning at 1 PVU. Wind speed contoured every 10 m s\(^{-1}\) beginning at 40 m s\(^{-1}\). Meridional eddy heat flux with magnitudes exceeding 30 K m s\(^{-1}\), contoured every 10 K m s\(^{-1}\). All values averaged from 00 UTC 31 December 2012 through 0000 UTC 07 January 2013.
5. Summary, Discussion, and Suggestions for Future Work

5.1 Summary

Using a multi-model perspective, this study examined model ensemble variability of the 7 January 2013 Sudden Stratospheric Warming Event. The analysis was motivated by previous work on this event which revealed that 10-day forecasts had approximately 50% greater skill in predicting the reversal of the 10-hPa 60°N zonal mean zonal wind compared to 15-day forecasts (Tripathi et. al 2016). The SNAP dataset used in Tripathi et al. (2016) was utilized for its six high-top models: KAF, CAWCR, NOGAPS, MRI, ECMWF, and METO. Analysis of variability and skill was performed via two separate metrics: zonal mean metrics and elliptical metrics. Once model skill was determined via these metrics, the precursor tropospheric forcings were studied to determine if there were any key similarities or differences amongst the best and worst performing ensembles or ensemble members.

The following key conclusions were derived via analysis of the zonal mean metrics:

1. SSW onset occurred near 0000 UTC 7 January 2013, with an easterly 10-hPa 60°N zonal mean zonal wind of -6.2 m s\(^{-1}\) observed using the CFSR dataset (Table 3.1).

2. Only one of six models initialized 15-days prior to SSW onset, KAF, forecasted an ensemble mean easterly 10-hPa 60°N zonal mean zonal wind by 0000 UTC 7 January 2013 as observed, with the other five of the ensemble mean forecasts predicting a westerly zonal mean zonal wind.

3. Initialized 10-days prior to SSW onset, two of six ensembles forecasted an easterly ensemble mean 10-hPa 60°N zonal mean zonal wind, though a more easterly 10-hPa 60°N zonal mean zonal wind was predicted in all six models and with less spread.
Given the substantial variability observed in 15-day SNAP model forecasts, ensembles were categorized according to skill as determined by the error in the ensemble mean forecast of the 10-hPa 60°N zonal mean zonal wind at 0000 UTC 7 January 2013, with KAF determined to have the greatest skill and CAWCR the lowest skill. All five members of the KAF ensemble were able to converge to an easterly zonal mean wind regime, with a steady deceleration observed the week prior to SSW onset (Fig. 3.1). CAWCR, however, predicted a steady acceleration of the 10-hPa 60°N zonal mean zonal wind over the week prior to observed SSW onset, with a 29.2 m s\(^{-1}\) ensemble mean by 0000 UTC 7 January 2013 (Fig. 3.11). With such considerable divergence in solutions between the KAF and CAWCR, tropospheric forcings were then investigated to identify sources of model error.

Motivated by previous research on the January 2013 SSW by Coy and Pawson (201?), the analysis focused on the North Atlantic region where high amplitude tropospheric flow associated with a rapidly deepening cyclone and a blocking high were determined to be major contributors to the upward WAF in the week before the SSW. The goal of the analysis was to determine if model error in forecasting thermodynamic processes linked to precursor tropospheric blocking in the N. Atlantic resulted in systematic biases in WAF into the stratosphere.

The verification (CFSR) revealed that a rapidly-intensifying cyclone off the U.S. Northeast Coast one week prior to SSW onset and its associated diabatic processes provided for strong negative PV advection via the irrotational wind, forcing a high-latitude ridge in the N. Atlantic (Fig. 3.13 and 3.14). This ridge persisted through 7 January 2013, and this resultant blocking pattern provided forcing for primarily positive/poleward meridional eddy heat flux and upward WAF into the polar stratosphere (Fig. 3.18).
Similar findings presented themselves in the KAF (high skill) 15-day forecasts. The diabatically generated upper level divergence associated with a strengthening Nor’easter off the U.S. Northeast Coast negatively eroded PV downstream in the North Atlantic, providing forcing a high-latitude ridge. In the case of the KAF, positive PV advection via the irrotational wind resulted in higher PV values on the equatorward-upstream side of the cyclone (Fig 3.15 and 3.16). Positive PV advection via the irrotational wind upstream of the cyclone then helped maintain the ridge. A blocking pattern and predominately upward WAF into the polar stratosphere was predicted the week prior to SSW onset, similar to CFSR (Fig. 3.18).

Notable differences in precursor tropospheric forcings were observed in the CAWCR (low skill) 15-day forecasts of the event. While negative PV advection via the irrotational wind did aid in producing a ridge in the N. Central Atlantic one week prior to 7 January 2013, the PV waveguide was more transient (Fig. 3.17). The ridge that did develop translated east and over Europe by 0000 UTC 4 January 2013, in part a result of less positive PV advection upstream of the ridge as seen in the KAF 15-day forecast. A blocking pattern therefore did not set up, and primarily equatorward meridional eddy heat flux was forecasted in the mid-high latitudes the week prior to SSW onset (Fig. 3.18).

The results of this section of the analysis provide evidence to support the hypothesis that predicting the tropospheric blocking pattern in the North Atlantic and associated upward WAF produced better forecasts of SSW as quantified via zonal mean metrics by 7 January 2013. The next section of the analysis used the elliptical metrics and provided similar evidence with the following key conclusions:
1. The 7 January 2013 SSW event was extreme not only in terms of a rapid deceleration to an easterly zonal mean zonal wind region, but also in terms of the duration of the 10-hPa polar vortex split (as seen through the 10-hPa 29.5 km best-fit ellipses). The vortex split on 7 January 2013 into two separate vortices, one over Eastern Europe and one over North America (Fig. 4.1). Once these two vortices broke down, the polar vortex did not re-emerge until over mid-February.

2. Only the KAF ensemble was able to forecast a 10-hPa polar vortex split, though this did not occur until after 7 January 2013, with the predicted distribution of upward WAF displaced further north and west than verification (Fig. 4.2). Four of the five other ensembles, with CAWCR being the exception, primarily predicted either a minor displacement event or no SSW event at all. (Fig. 4.3-4.6) The CAWCR ensemble predicted no SSW event in all 24 members at a 15-day lead time (Fig. 4.7).

3. Large spread was observed in the locations of the 10-hPa 29.5 km best-fit ellipse centers amongst all six SNAP model ensembles at 0000 UTC 6 January 2013 (Fig. 4.8). When the 10-hPa ellipse center latitude of each SNAP ensemble member (n = 148) was compared to its corresponding forecasted 10-hPa 60°N zonal mean zonal wind at 0000 UTC 7 January 2013, there was a statistically significant correlation – the members that forecasted a lower ellipse center latitude also predicted a more easterly zonal mean wind (Fig. 4.11).

With a strong correlation observed between 10-hPa ellipse center latitude and corresponding zonal mean zonal wind, precursor tropospheric forcing was studied for the SNAP ensemble member which forecasted the lowest latitude ellipse center (NOGAPS No. 1) and the member which forecasted the highest latitude ellipse center (METO No. 10). This analysis was
done in an effort to note any similarities between the low and high error ensembles when using zonal mean metrics as compared to elliptical metrics.

The 15-day low latitude member forecast (NOGAPS No. 1) was able to resolve a deep cyclone off the U.S. Northeast Coast at 0000 UTC 31 December 2012 (Fig. 4.12). Negative PV advection by the irrotational wind associated with the rapidly deepening cyclone contributed to the amplification of a ridge over the North Atlantic (Fig. 4.13). A second cyclone at 0000 UTC 4 January 2013 then provided additional forcing for further amplification of the PV waveguide, where a second high-latitude ridge formed in the Eastern N. Atlantic by 0000 UTC 6 January 2013. With two high-latitude ridges forming in this NOGAPS No. 1 forecast, a time-mean ridge was able to form in the Eastern N. Atlantic over the week prior to SSW onset, with values of poleward meridional eddy heat flux greater than that observed (CFSR) predicted (Fig. 4.16).

The 15-day forecast produced by the high latitude member (METO No. 10) predicted a cyclone off the U.S. Northeast coast at 0000 UTC 31 December 2012 as well, though primarily positive PV advection via the irrotational wind forced a more equatorward waveguide over the Atlantic (Fig. 4.14 and 4.15). As a series of disturbances developed along this waveguide, the waveguide amplified and the resulting highly perturbed flow translated across the Atlantic basin at a more progressive zonal pace than verification, NOGAPS No. 1, and KAF. With a more equatorward regime, a time-mean balance between both equatorward and poleward meridional eddy heat flux was forecast the week prior to SSW onset, providing little forcing for a warming event (Fig. 4.16).

5.2 Discussion
Analyses of zonal mean metrics in this study are consistent with results produced in Tripathi et al. (2016), with SNAP 15-day forecasts of the 7 January 2013 event being approximately 50% less skillful than 10-day forecasts produced by the same ensembles. At a 15-day lead time, the intensity of the reversal of the 10-hPa 60°N zonal mean zonal wind was only captured by the KAF ensemble, with the other five SNAP models predicting either a weaker deceleration than verification, no deceleration, or an acceleration to a more westerly 10-hPa 60°N zonal mean zonal wind regime.

Forecasts of the 10-hPa polar cap temperature and geopotential height proved to be more variable than the often used 10-hPa 60°N zonal mean zonal wind metric, and therefore a less useful predictor of the 7 January 2013 SSW event (e.g., Charlton and Polvani 2007). However, as Butler et al. (2015) revealed when examining various SSW definitions, the 10-hPa 60°N zonal mean zonal wind metric is particularly sensitive to a specific event since only one latitude band is used. Because the 10-hPa polar vortex was previously displaced off the pole during two preconditioning events (Attard et al. 2016), it is plausible that the maximum 10-hPa zonal mean winds were near or below 60°N in the 7 January 2013 event. In events in which the 10-hPa polar vortex is more symmetric around the pole, polar cap zonal mean metrics (temperature and geopotential height) could viably be a more skillful metric than seen in this study. Therefore, the choice of verification metric is seen to be sensitive to the behavior of the polar vortex, i.e., how far off the North Pole the vortex moves.

Once skill was determined by the 10-hPa 60°N zonal mean zonal wind metric, it was evident that precursor tropospheric blocking was important in forcing for upward wave
propagation and the breakdown of the polar vortex. These results support the conclusions of Quiroz (1986), in which a brief climatology of blocking events from 1981-1985 revealed that blocking events precede SSWs by an average of 3.5 days. Both the verification and 15-day KAF ensemble mean forecasts produced a high-latitude ridge and time-mean blocking event in the N. Atlantic by 0000 UTC 4 January 2013, or approximately 3.25 days before SSW onset. These blocks persisted through SSW onset, providing forcing for the vortex split via amplification of planetary scale waves into the stratosphere as seen through large values of poleward meridional eddy heat flux upstream of these time-mean ridges. Yet the 15-day CAWCR ensemble mean forecasts lacked the production of a blocking pattern in the N. Atlantic, largely in association with reduced forcing for wave amplification from a deepening cyclone in the Western N. Atlantic. Consequently, with less poleward meridional eddy heat flux than in verification and KAF, no SSW event was forecasted, and the 10-hPa 60°N zonal mean zonal wind accelerated to a more westerly regime.

While many previous studies have linked precursor tropospheric blocking to SSW onset (e.g., Julian and Labitzke 1965; Quiroz 1986; Martius et al. 2009), these studies presented their findings from a planetary scale perspective. Motivated by the need to understand the role of the synoptic scale in SSWs (e.g., Gerber et al. 2012), this study investigated how the synoptic scale was linked to this enhanced planetary scale wave activity. The study expands upon the findings of Coy and Pawson (2015), which revealed that the N. Atlantic was a key source of planetary scale wave activity the week prior to the 7 January 2013 SSW event. Verification and 15-day KAF and CAWCR forecasts produced a deep cyclone off the U.S. Northeast Coast by 0000 UTC 31 December 2012. Noteworthy, however, was how this synoptic feature impacted the upper-tropospheric planetary scale waveguide that produced variations in the upper WAF forcing seen
in KAF and CFSR but not in CAWCR. Following the method used by Achambault et al. (2007), 300-200-hPa layer-averaged PV advection via the irrotational wind was studied as a proxy for diabatic forcing for amplification of the aforementioned PV waveguide. Enhanced diabatic heating and negative PV advection via the irrotational wind associated with TC Oscar provided forcing for a high-latitude PV ridge downstream in the N. Pacific (Archambault et al. 2007). Similarly, negative PV advection via the irrotational wind associated with the aforementioned 31 December 2012 cyclone provided forcing for a PV ridge in the Central N. Atlantic in KAF and CFSR. One notable difference in this study is that positive PV advection via the irrotational wind also played a key role in downstream ridge building in the 15-day KAF forecast. For example, upstream positive PV advection by the irrotational wind forced a low-latitude trough upstream of the surface cyclone and high-latitude PV ridge. Continuous positive PV advection by the irrotational wind then helped maintain this ridge and allow for a blocking pattern to set up the week prior to SSW onset. 15-day CAWCR forecasts, however, produced little positive PV advection via the irrotational wind upstream of the surface cyclone. The PV waveguide consequently was more progressive, with no blocking pattern and little upward planetary scale wave activity.

5.2.2 Elliptical Metrics

Variability in the predictability of the 7 January 2013 SSW event using elliptical metrics largely supported the work of Taguchi (2014; 2016). Taguchi (2016) found that errors in predicting major SSW splitting events on medium to sub-seasonal time scales was largely dependent on vortex geometry, with an elongated vortex ellipse producing more spread and variability than a more compact, less eccentric ellipse. Likewise, analysis of the 7 January 2013 event found that by 23 December 2012 (15 days prior to SSW onset), the vortex was elongated to
an eccentricity of 1.40 while over the Barents Sea (Fig. 4.1). This preconditioned polar vortex was likely forced by two blocking events in the N. Pacific in mid-December, which had provided for two minor decelerations of the 10-hPa 60°N zonal mean zonal wind 1-3 prior to the final major deceleration on 7 January 2013 (Attard et al. 2016). With the vortex in a weakened, displaced state weeks prior to the SSW event, it is plausible that such large variability in the six 15-day SNAP ensemble forecasts was in part due to a preconditioned vortex that deviated from model climatology at the time of forecast initialization.

Substantial spread can also be attributed to planetary scale tropospheric wave forcing (2014). Taguchi (2014) showed that forecasts of planetary scale wave amplification were found to have lower skill in weak stratospheric vortex events (e.g., SSWs) than in events in which the polar vortex remained strong and intact. Similar to verification and to the low error ensemble (KAF) studied utilizing the 10-hPa 60°N zonal mean zonal wind as a metric, the 15-day forecast by NOGAPS No. 1 (lowest 10-hPa 29.5 km best-fit ellipse latitude) predicted time-mean high-latitude blocking and large values of upward WAF into the polar stratosphere. Verification and these two forecasts support the claims of Martius et al. (2009) that precursor tropospheric blocking can be linked to over 90% of major SSW events.

Similar to the high error zonal mean wind ensemble (CAWCR), the high latitude member (METO No. 10) further substantiates the Martius et al. (2009) claims, with little forecasted time mean ridging and a balance between equatorward and poleward meridional eddy heat flux. While ridging was predicted in the METO No. 10 15-day forecast, it remained in the mid-latitudes, largely a consequence of less forcing via negative PV advection via the irrotational wind and a more transient waveguide. This result calls to question the importance of the spatial location of upward WAF – while upward WAF was predicted in the N. Atlantic, it remained equatorward of
60°N. The upward propagating planetary waves were therefore less likely to impart their momentum and energy anomalies into the polar stratosphere, providing little forcing for the breakdown of the polar vortex. Furthermore, the polar vortex, as seen through the 10-hPa best-fit ellipse center latitude, was centered closer to the pole than any other SNAP member, providing for greater spatial disparity between the location of the upward WAF forecasted by METO NO. 10 and the forecasted location of the belt of stratospheric polar westerlies.

The study not only substantiated the claim that improving synoptic and planetary scale forecast skill is imperative for resolving stratospheric forecast skill, but it was also found that ensemble members that predicted an ellipse center location equatorward of 70°N had significant skill in forecasting an easterly 10-hPa 60°N zonal mean zonal wind. With similar precursor tropospheric blocking forecasted in KAF and NOGAPS No. 1, the lack of blocking forecasted in CAWCR and METO No. 10, and the correlation observed between ellipse center latitude and 10-hPa 60°N zonal mean zonal wind, this study concludes that elliptical metrics can be a valuable tool used in forecasting SSWs when used in combination with the traditional 10-hPa 60°N zonal mean zonal wind.

5.3 Suggestions for Future Work

While analysis of the 7 January 2013 SSW event provided evidence that ellipse center latitude is an important metric in studying ensemble skill and variability as compared to the 10-hPa 60°N zonal mean zonal wind, future work could be done on this SSW event using other elliptical metrics. Taguchi (2016) found that polar vortices that were more elongated prior to vortex splits reduced model skill and increased model variability. The SNAP dataset could be
used to expand upon Taguchi’s (2016) work by correlating each ensemble member’s 10-hPa best-fit ellipse eccentricity to its forecasted 10-hPa 60°N zonal mean zonal wind, similar to the methods used in this study with ellipse center latitude. Other metrics that could be further examined include ellipse size and rotation. Further work on this case study could also be done through a downstream impact analysis on how the SNAP model ensembles predicted downward WAF to the surface following the SSW event since this study focused on the precursor model skill and variability.

While the scope of this thesis was limited to one case study due to current limitations of the SNAP dataset, a composite analysis of all major SSW events using the same six ensembles could be done to help verify the validity of the results presented in chapters 3 and 4. If the SNAP dataset were expanded to reflect all major SSWs as noted in the climatologies of Chartlon and Polvani (2007) and Butler et al. (2017), composite studies could be performed using both zonal mean and elliptical metrics in a similar method used in this study. While the KAF model forecasted a majority of its 10-hPa best-fit ellipses in the lowest latitude band (equatorward of 70°N) and was the most skillful ensemble in terms of the 10-hPa 60°N zonal mean zonal wind metric, it would be interesting to examine if this would be the case in other SSW events or from a composite study. Such an analysis could also highlight the model configuration and setups that produce the most skillful SSW forecasts, e.g., number and location of vertical levels, convection and microphysics parameterization schemes, and gravity wave drag schemes. Further work could also analyze the differences in model skill and variability between vortex splitting and vortex displacement events. The 7 January 2013 SSW event was a case for substantial variability and low skill (at a 15-day lead time) for a splitting event, though would such variability occur with forecasts for a displacement event?
REFERENCES


