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Characterizing the Northern Hemisphere Circumpolar Vortex Through Space and Time

Nazla Bushra
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CHARACTERIZING THE NORTHERN HEMISPHERE CIRCUMPOLAR VORTEX THROUGH SPACE AND TIME

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in

The Department of Oceanography and Coastal Sciences

by

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August 2021
To my husband Rubayet Bin Mostafiz…
To my princess (daughter) Nawara Ishraq…
To my son Zayeen Mostafiz…

who sacrificed a lot during this journey!
ACKNOWLEDGMENTS

I am not sure if there are enough words to describe Dr. Robert V. Rohli, who is not only an academic advisor, but also a guardian, a mentor, a friend, and a person who is always there to assist without being asked in this academic journey. When I first came to the U.S.A., I left my family and an eleven month old child in Bangladesh and still agreed to continue my academic journey to pursue a Ph.D. under Dr. Rohli’s supervision because of his unbelievably supportive attitude that allowed me to which reunite my family. I could always envision that the support would continue throughout my journey and it has. While I heard many sorrowful stories of how difficult dissertation research is to accomplish, I have been incredibly fortunate to have experienced an academic journey full of joyful memories, accomplishments, and learning. I am equally grateful to Dr. Rohli’s family, Suzanne Rohli, Kristen Rohli, Eric Rohli, and Dr. Rohli’s mother, Sharon Rohli, who always welcomed us (my family). I felt the warmth of a family whenever I visited them. While I am writing this my eyes are filled with tears because I know this is the time to officially leave the warmth, support, and wonderful memories that are built upon trust and respect.

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<td>$R_c$</td>
<td>Circularity Ratio</td>
</tr>
<tr>
<td>AMIP</td>
<td>Atmospheric Model Intercomparison Project</td>
</tr>
<tr>
<td>AMO</td>
<td>Atlantic Multidecadal Oscillation</td>
</tr>
<tr>
<td>AO</td>
<td>Arctic Oscillation</td>
</tr>
<tr>
<td>CLAC</td>
<td>CPV Centroid Location, Area, and Circularity</td>
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<tr>
<td>CMIP6</td>
<td>Coupled Model Intercomparison Project Phase 6</td>
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<td>C-O</td>
<td>Cochrane–Orcutt</td>
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<td>CPV</td>
<td>Circumpolar Vortices</td>
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<td>CSTC</td>
<td>Create Space Time Cube</td>
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<td>DOE</td>
<td>Department of Energy</td>
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<td>D-W</td>
<td>The Durbin-Watson</td>
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<td>EHSA</td>
<td>Emerging Hot Spot Analysis</td>
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<td>ENSO</td>
<td>El Niño/Southern Oscillation</td>
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<td>ERA5</td>
<td>European Reanalysis</td>
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<td>FFT</td>
<td>FAST Fourier Transform</td>
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<td>GIS</td>
<td>Geographic Information Systems</td>
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<tr>
<td>MFT</td>
<td>Multiresolution Fourier Transform</td>
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<tr>
<td>NAO</td>
<td>North Atlantic Oscillation</td>
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<td>NCAR</td>
<td>National Center For Atmospheric Research</td>
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<td>NCEP</td>
<td>National Centers For Environmental Prediction</td>
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<td>NH</td>
<td>Northern Hemisphere</td>
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<td>NVA</td>
<td>Negative Vorticity Advection</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>PCA</td>
<td>Principal Components Analysis</td>
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<td>PDO</td>
<td>Pacific Decadal Oscillation</td>
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<tr>
<td>PDO</td>
<td>Pacific Decadal Oscillation</td>
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<tr>
<td>PFJ</td>
<td>Polar Front Jet</td>
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<tr>
<td>PNA</td>
<td>Pacific-North American</td>
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<td>PVA</td>
<td>Positive Vorticity Advection</td>
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<td>QBO</td>
<td>Quasi-Biennial Oscillation</td>
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<td>SAM</td>
<td>Southern Annular Mode</td>
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<td>SH</td>
<td>Northern Hemisphere</td>
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<td>SHELDUS</td>
<td>Spatial Hazard Events and Losses Database of The U.S.</td>
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<td>SLP</td>
<td>Sea Level Pressure</td>
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<td>SO</td>
<td>Southern Oscillation</td>
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<td>SOI</td>
<td>Southern Oscillation Index</td>
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<tr>
<td>SS</td>
<td>Statistically Significant</td>
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<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>TCPV</td>
<td>Tropospheric Circumpolar Vortex</td>
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<tr>
<td>ULC</td>
<td>Upper-Level Convergence</td>
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<tr>
<td>ULD</td>
<td>Upper-Level Divergence</td>
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ABSTRACT

This hemispheric-scale, steering atmospheric circulation represented by the circumpolar vortices (CPVs) are the middle- and upper-tropospheric wind belts circumnavigating the poles. Variability in the CPV area, shape, and position are important topics in geoenvironmental sciences because of the many links to environmental features. However, a means of characterizing the CPV has remained elusive. The goal of this research is to (i) identify the Northern Hemisphere CPV (NHCPV) and its morphometric characteristics, (ii) understand the daily characteristics of NHCPV area and circularity over time, (iii) identify and analyze spatiotemporal variability in the NHCPV’s centroid, and (iv) analyze how CPV features relate to the air-sea teleconnections that are known to explain important variability in weather/climate. Daily data (1979—2017) were collected from the National Centers for Environmental Prediction at the 500-hPa geopotential height level, and processed and analyzed in Python, MATLAB, R, and ArcGIS Desktop platform.

Results suggest that the innovative method improves the calculation of NHCPV area and circularity, proven with the significant correlations between the NHCPV and teleconnection indices. At a daily scale, both correlations and principal components analysis reveal that the NHCPV is closely related to some air-sea teleconnections. The NHCPV area has expanded linearly over the 1979—2017 period and within its four subperiods, likely because of the weakened gradient of atmospheric mass over time. On the other hand, the NHCPV has alternating periods of increasing and decreasing circularity, suggesting that it may have become more unstable in its delivery of west-to-east flow. Spectrum analysis shows distinct annual and semiannual cycles for the area and circularity over all periods. While the NHCPV centroid shifts annually and intra-annually throughout the time series, probably because of the seasonality and teleconnection linkage, the linear trend analysis shows that the day-to-day distance moved by the NHCPV
centroid decreased significantly, suggesting stability in the centroid positions. Emerging hot spot analysis reveals that new and oscillating hot spots have been emerged over time. This research can be extended to understand the current and projected relationship between the full 4-D (x-y-z-t) feature-based CPV structure, ocean-air teleconnections, sea-ice forcing, and natural hazard impacts.
CHAPTER 1.
INTRODUCTION

1.1 Overview of Circumpolar Vortex (CPV)

The broad-scale steering atmospheric circulation has been an important research topic in the geoenvironmental sciences. The two tropospheric circumpolar vortices (CPVs, Waugh et al., 2017) – one surrounding each pole – represent the hemispheric-scale, steering, extratropical circulation at a given time. These belts of strong quasi-west-to-east winds circumnavigate the north and south polar regions at 5–12 km in altitude. Each CPV is situated at the steepest gradient of air temperature – at the boundary where polar air meets much warmer air at those heights. At any given time, 3 to 6 long waves (aka: Rossby waves) exist in the westerly flow at the leading edge of the CPV in each hemisphere at the core of the polar front jet. During cold periods, the CPVs expand equatorward and during warm periods they retreat poleward (Figure 1.1). The CPVs’ position changes over time interannually (as the Earth-ocean-atmosphere system warms, the cold pool and therefore the CPV theoretically retreats poleward), seasonally (toward the equator as winter approaches and the cold polar pool expands in that

Figure 1.1. CPV at the Northern Hemisphere on 3 January and 23 July in 1979. In winter the CPV expanded equatorward and in summer CPV contracted poleward.
hemisphere, and toward the poles as summer approaches), and intra-seasonally (as air masses migrate with the daily weather patterns). The waves amplify/deamplify and propagate in response to thermal and orographic forcing, and subtropical upper-level divergence (Hoskins & Karoly, 1981).

The location, extent, and shape of the CPV has great implications for surface weather and climate. Rohli et al. (2005) and Wrona and Rohli (2007) showed that temporal variability and long-term change in the monthly mean Northern Hemisphere (NH) CPV centroid location, area, and/or circularity (CLAC) are linked to temperature variability and regional-scale flow patterns around the NH. Subtropical latitudes can be sensitive to NHCPV variability because trough elongation of the NHCPV, such as in January 2014 across the eastern U.S. (Figure 1.2), generally supports equatorward intrusions of Arctic air that greatly impact society.

Surprisingly, in contrast to the results of Angell (2006) for the 300-hPa-defined NHCPV over the 1963–2001 period, Rohli et al. (2005) found little evidence of monthly temporal changes in the 500-hPa-defined NHCPV over the 1959–2001 period. But was this result because the time series did not include the warmest years of the global instrumental period of record

![Figure 1.2. 500-hPa geopotential height-based CPV for January 2014 shown by the red line. Note the strong equatorward excursion over central and eastern North America marked by the black star.](image-url)
(2002-2017)? Was it an ominous suggestion that the worst impacts of surface warming are yet to be felt, as the middle-to-upper-troposphere has a temporally lagged response to long-term surface warming? This study will introduce four major innovations made possible by available technology and datasets, which will help to address questions such as these.

Throughout this dissertation, air-sea teleconnections are considered as being potential modulators of, and being potentially moderated by, the CPV. These air-sea teleconnections include Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific-North American (PNA), El Niño/Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO). ENSO, which is a sea-saw of atmospheric mass between the tropical western and eastern Pacific Ocean, affecting the global atmospheric circulation. Another important air-sea teleconnection is the AO which consists of a cyclical expansion and contraction of the cold polar core at mid-to-upper levels of the troposphere. The NAO is a simultaneous see-saw in pressure anomalies between the Icelandic Low and Bermuda-Azores High usually yields strong west-to-east flow across the North Atlantic Ocean, and a less intense than average Icelandic Low and Bermuda-Azores High usually corresponds to weaker west-to-east flow with more north-south and south-north meanders across the North Atlantic. The PNA air-sea teleconnection consists of an alternating pattern of enhanced and weakened riding (south-to-north and north-to-south meander) in the general west-to-east flow over northwestern North America. The PDO is an oscillation in sea surface temperature anomalies between the tropical and extratropical North Pacific Ocean that is similar in some ways to the effects of ENSO, but with a stronger extratropical signal and a longer time scale.
1.2 Research Goal

The overarching goal of this research is to identify and characterize the four-dimensional \((x, y, z, t)\) feature-based NHCPV structure at a daily scale, to assist in understanding the relationship between the NHCPV properties and important air-sea teleconnections that drive surface weather and climate variability, and to assist in understanding how the NHCPV varies over space and time.

Specific objectives (O) are stated below:

O1. To identify the NHCPV and define its area and circularity using a new method.

A novel approach has been developed to represent the daily CPV using the sharpest decreasing gradient of atmospheric mass at the 500-hPa geopotential height level – the height at which approximately half of the atmospheric mass lies above and half lies below that elevation. The “sharpest decreasing gradient” delineates the leading edge of the CPV and occurs at the latitude along a given meridian of longitude where the 500-hPa geopotential height (and therefore the thermal gradient) is steepest from south to north. While previous work (e.g., Angell, 1992; Frauenfeld & Davis, 2003; Rohli et al., 2005; Ballinger et al., 2014) was effective and innovative in addressing important research questions about the CPV or a subset of it, work to date has selected a particular isohypse (i.e., a line on a map representing the same, predetermined elevation at which the 500-hPa geopotential height is assumed to occur) \(a\ priori\) to represent the CPV over the entire study period. This approach gives a reasonable approximation in many cases, but it falls short for several reasons. First, since the predetermined isohypse is used across space, it is unlikely to represent the best-approximation for where the sharpest gradient exists everywhere around the hemisphere. Second, since the predetermined isohypse is chosen to represent the sharpest gradient for monthly or even seasonal analyses, it is unlikely that the same
value would be equally valid for the first day of a month or season as for the last day. Instead, the CPV’s leading edge varies spatiotemporally to an extent that “one size doesn’t fit all” in this manner. This objective of depicting the CPV using our “sharpest gradient” approach circumvents the “one size fits all” approach and represents the CPV’s CLAC more realistically because weather systems move based on relative rather than absolute spatial distributions of geopotential height (and therefore pressure and mass).

Moreover, monthly mean data may mask extreme intramonthly CPV variations, suggesting an average value is not representative of the atmospheric properties of that month. Thus, development of a novel, daily CPV dataset through this objective makes it possible to address the question of appropriateness of using the monthly CPV for assessing hemispheric-scale climate variability and change.

O2. To determine how the NHCPV area and circularity vary intra- and inter-annually.

This objective will provide not only a tangible index of the response of atmospheric steering flow to long-term surface warming, but it will also provide a mechanism for corroborating existing work that calculated CPV area and circularity. When the CPV is circular, the high-latitude cold pool of air is restrained in the polar areas as west-to-east flow minimizes the north-south exchange of energy. By contrast, a CPV characterized by amplified ridges and troughs (i.e., an amoeba-like shape) would allow for greater meridional energy exchange (with cold air easily transported equatorward and warm air easily moved poleward). Long-term changes in the ridge-trough amplitudes could reveal important clues about the atmospheric circulation response to the observed and modeled amplified warming over the poles relative to the tropics – the so-called Arctic amplification (Holland & Bitz, 2003; Pithan & Mauritsen, 2014; Francis et al., 2017; Francis et al., 2018). The geometric properties (i.e., CLAC) will inform
future studies on extratropical severe weather that rely on the juxtaposition of tropical and polar air masses by the CPV (e.g., Overland et al., 2015).

O3. To determine how the centroid of the NHCPV varies intra- and inter-annually and shifts over time and space.

High-frequency variability in the centroid and its mean position may explain the incidence of weather pattern variability, trends, and extremes during previous decades. This objective is important because consistency in CPV area and circularity might have been misinterpreted as “no change” when in fact the positions of the ridges and troughs could have rotated longitudinally about a fixed point (i.e., representing ridge/trough positional changes including progression and retrogression and changes in the influence of air-sea teleconnection patterns), without changing the size or shape of the CPV, but affecting the locations of the environmental impacts of the CPV.

O4. To better understand the relationship between the NHCPV area and circularity and the physical mechanisms contributing to atmospheric flow variability in the form of the known tropical and extratropical air-sea teleconnections, at the daily scale.

Variability in the NHCPV’s CLAC could suggest that the CPV’s ridge/trough positional changes relate to or are influenced by the changes in teleconnection patterns. Any association between variability in the CLAC components of the CPVs and variability in teleconnection patterns would suggest that the regional-scale teleconnections fluctuate as the CPV pattern varies. By contrast, the absence of such a link would suggest that regional changes can occur in the absence of (or independently of) variation in the CPV pattern. This analysis will address the question of whether teleconnections merely represent regional-scale flow variability, or whether they holistically represent the hemispheric-scale flow.
1.3 Hypothesis (H)

H1. The “sharpest gradient approach” at the 500-hPa level delineates the NHCPV more effectively than other approaches.

H2. The NHCPV has undergone a long-term decrease in area and a long-term increase in “waviness” (or decrease in circularity, consistent with much of the current prevailing thinking regarding Arctic amplification) over the 1979–2017 period, as the surface environment (particularly that in the high latitudes) has warmed.

H3. The boreal seasonal and intra-seasonal variability notwithstanding, the NHCPV centroids have remained near the North Pole, despite the warming over the 1979–2017 period, as little convincing evidence to the contrary is apparent in the current literature.

H4. The association between the daily CLAC of the NHCPV to air-sea teleconnections provides significantly more information than the monthly mean CLAC, allowing for more detailed analyses of and comparisons with weather patterns and extreme events.

1.4 Overview

The CPVs are important indicators of the position, size, and shape of the cold pool that drives hemispheric-scale flow and affects environments. Yet relatively little specific information is known about how CPV morphometry changes affect these surface environmental features, especially via their interaction with air-sea teleconnections. Availability of longer, high-quality datasets, geospatial analytical tools, and high-performance computing ability provides a golden opportunity to improve our ability to anticipate impacts of forcing at both long and short time scales by characterizing and monitoring the CPVs. This dissertation will focus on the NHCPV, but future work can certainly focus on the Southern Hemisphere’s CPV.
While existing air-sea teleconnection indices describe regional features of the CPV, a means of characterizing daily hemispheric CPVs has remained elusive to this point. Geographic information systems (GIS) and machine learning applications offer many possibilities for ongoing and future climatological research (Kang et al., 2014), but more can be done to utilize the capabilities of GIS to characterize CPV features, including analysis of daily changes in CLAC.
CHAPTER 2.
AN OBJECTIVE PROCEDURE FOR DELINEATING THE CIRCUMPOLAR VORTEX

2.1 Introduction – the Circumpolar Vortex

The broad-scale steering atmospheric circulation is one of the most important components of the Earth-ocean-atmosphere system. Through advection of air masses and storm systems, it transfers energy, matter, and momentum between the polar and tropical parts of the Earth, thereby contributing to the energy and water balances of the planet. Therefore, delineation of both short-term fluctuations and long-term changes in this circulation is important for understanding the changing distribution of energy, matter, and momentum, both through space and time.

This hemispheric-scale steering circulation is represented by the mid-tropospheric circumpolar vortex (CPV). While distinct from the stratospheric CPV (Waugh et al., 2017), the two tropospheric CPVs (hereafter referred to as CPV) – one surrounding each pole – represent the extratropical circulation at a given time. These belts of strong quasi-west-to-east winds circumnavigate the north and south polar regions at 5–12 km in altitude. Each CPV is situated at the steepest gradient of air temperature – at the boundary where polar air meets much warmer air at those heights. Daily changes in morphology of the CPV represent altered distributions of energy, matter, and momentum that comprise the variation in daily weather, such as that which produces the media-favorite “polar vortex” extreme temperature events.

Although circulation within CPVs generally involves west-to-east flow, it bends poleward at ridges and equatorward at troughs. These ridges and troughs vary in amplitude and propagate longitudinally over time. During anomalously cold periods, the CPVs expand
equatorward, and during anomalously warm periods they retreat poleward. At times, the CPV is nearly circular and centered on the poles, while at other times the CPV contains large departures from circularity and/or may be centered some distance away from the poles. Modeling research suggests that these meanders are expected to increase into the future (Peings and Magnusdottir, 2014).

Areal extent of the Northern Hemisphere’s CPV has been the focus of several studies over the last several decades relating to broad-scale atmospheric circulation variability. For example, Angell and Korshover (1977) noted that the 300-hPa-defined annual-averaged CPV expanded from 1970 to 1975 while the winter vortex simultaneously contracted. Davis and Benkovic (1994) noticed an expansion of the 500-hPa-defined CPV over the 1970s and 1980s, which substantiated their previous observations (Davis & Benkovic, 1992) of expansion from 1966–1990. Interestingly, Angell (2006) observed a temporal shrinking of the 300-hPa-defined CPV of 1.5 percent per decade from 1963 to 2001, particularly over the Western Hemisphere. Previous work has demonstrated a link between general features of the CPV area and various environmental conditions, including air mass advection (Angell & Korshover, 1977; Diaz & Quayle, 1980; Kalnicky, 1974; Knox et al., 1988), surface temperature anomalies (Angell, 1992, 1998; Angell & Korshover, 1977, 1978, 1985; Burnett, 1993; Burnett & McNicoll, 2000; Davis & Benkovic, 1992, 1994; Frauenfeld & Davis, 2000, 2002; Markham, 1985; Rohli et al., 2005; Wrona & Rohli, 2007), sunspot activity (Angell, 2001), and precipitation (Angell, 1992; Burnett, 1993).

While some work (Thompson & Solomon, 2002) utilized vertical gradients of geopotential heights at a small number of radiosonde-based stations to index CPV behavior, most other studies described above represent the leading edge of the CPV by tracing a certain pre-
determined isohypse of geopotential height around the hemisphere. An important development in the definition of the CPV was the identification of a specific series of isohypses that define the center, poleward extreme, and equatorward extreme of the CPV, by month and vertical level (Frauenfeld & Davis, 2003). Since that time, several studies (Ballinger et al., 2014; Rohli et al., 2005; Wrona & Rohli, 2007) have utilized the recommended isohypses from Frauenfeld and Davis (2003).

CPV shape had only been analyzed in terms of the relative area within various quadrants about the pole (Angell, 1992, 1998, 2006) until Rohli et al. (2005) and Wrona and Rohli (2007) defined a circularity ratio \( R_c \) to characterize shape. More recently, by using an approach that identifies the length of the isohypse as an indicator of sinuosity, Vavrus et al. (2017) found that maximum waviness (i.e., meridional motion and enhanced probability of severe weather) occurs with weak flow in summer, and minimum waviness coincides with strong flow in winter.

2.2 Atmospheric Teleconnections and Hemispheric-Scale Flow

Regardless of the technique used to identify the CPV, the extent to which the CPV is an effective measure of circulation can be assessed by correlating the CPV area and \( R_c \) against indices of ocean-atmospheric teleconnection patterns (Barnston & Livezey, 1987) that are known to be related to the hemispheric-scale flow. For example, the atmospheric component of the El Niño/Southern Oscillation (ENSO) phenomenon – the Southern Oscillation (SO; Bjerknes, 1969) has been shown to be related to variability in the CPV’s position (Angell, 2001) and intensity of the polar front jet stream in the Pacific Ocean (Strong & Davis, 2006). El Niño events tend to be followed by shrinking of the CPV within the season (Frauenfeld & Davis, 2000) and with a three-season lag (Angell, 1992), but the eastern Pacific sector of the CPV expands during the El Niño event (Angell, 1992). Pacific variability at broader time scales, both inside and outside the
tropics, is represented by the Pacific Decadal Oscillation (PDO; Newman et al., 2003).

Frauenfeld and Davis (2002) emphasized on the PDO as a dominant mode influencing sea surface temperature (SST) variability in the Pacific at various time scales, thus modulating the ocean-atmosphere interaction and CPV properties at various temporal scales. Budikova (2005) implied that the CPV’s physical properties are influenced by the intervention of various PDO phases which modify surface air temperature and impact winter temperature over much of the United States.

Among extratropical teleconnections, the Pacific-North American (PNA) pattern (Wallace & Gutzler, 1981), Arctic Oscillation (AO; Thompson & Wallace, 1998), and North Atlantic Oscillation (NAO; Lamb & Peppler, 1987) have all been shown to be related to the CPV. Burnett (1993) suggested that the increased frequency of the positive mode of the PNA pattern, with its amplified ridge-trough configuration over the North Pacific Ocean and western North American mountain cordillera, may have caused the temporal increase in CPV area from 1964 to about the mid-1980s. Angell (2006) noted that although the AO cannot serve as a proxy for the CPV, the AO index is negatively correlated with CPV area. Piao et al. (2018) found that the long-term contraction of the CPV may be related to the May patterns of NAO-influenced variability.

2.3 Purpose

While previous research has been valuable in quantifying the mean monthly properties and long-term changes in the CPV, especially the CPV, over time, some shortcomings exist in its identification. Specifically, the use of a pre-determined isohypse of atmospheric geopotential height (and therefore atmospheric pressure and mass) \textit{a priori} to represent the CPV over the entire study period is a less-than-ideal approach because weather systems move based on relative
rather than absolute spatial distributions of atmospheric geopotential height (and therefore pressure and mass). Because high/low pressure systems are only “high” or “low” relative to the air around them, the assumption that a particular isohypse, such as 5640 m for all winter months (Frauenfeld & Davis, 2003), represents the CPV’s location invites caution, particularly on a daily time scale. At a minimum, days falling near the periphery of the month or season having a recommended isohypse would be represented by an increasingly inaccurate CPV. Furthermore, the previous work relied on the first-generation National Center for Atmospheric Research Reanalysis suite (Kalnay et al., 1996); use of the second-generation products (Kanamitsu et al., 2002) would allow improved spatial resolution from 5° to 2.5° with strengthened correlations to reanalysis data collected since 1979 (Saha et al., 2010), which coincides with the Satellite Era.

The purpose of this research is to introduce a technique for identifying the CPVs more effectively, represented by the sharpest gradient of atmospheric mass at the 500 hPa level using geospatial techniques with appropriate smoothing algorithms to simulate the upper-level atmospheric flow. The effectiveness of this technique will be assessed through comparison of the relationship between CPV diagnostic properties and atmospheric teleconnection patterns that are known to influence hemispheric-scale flow. Calculated values will also be compared with those derived by Wrona and Rohli (2007) using monthly data and the isohypse recommended by Frauenfeld and Davis (2003). The use of daily CPV data in this study makes it possible to address the question of appropriateness of the monthly mean CPV. After the approach is shown to be effective, the monthly time series is extended through 2017, and automated identification of the CPV can be performed in future work in identifying the daily mid-tropospheric CPV. Such use of the daily indices would allow for better understanding of the connection between changes
to the steering flow and response in the form of the “polar vortex” and other abrupt changes of energy, matter, and momentum in the near-surface atmosphere.

2.4 Data and Methods

2.4.1 Identifying the CPV

Daily 500-hPa geopotential height data are obtained from the National Centers for Environmental Prediction (NCEP)/Department of Energy (DOE) Reanalysis 2 project (Kanamitsu et al., 2002) for the 1979–2017 period. This temporal domain is selected to include the overlapping period of the Rohli et al. (2005) and Wrona and Rohli (2007) period of record (which ended in 2001) along with subsequent years of data. For each day of analysis (1/1/1979 through 12/31/2017), the gridded 500-hPa geopotential height dataset is imported into ArcGIS Desktop v10.5.1. At each 2.5° increment of longitude globally from 20°N to the North Pole, the latitude in the Northern Hemisphere having the steepest 500-hPa geopotential height gradient at that longitude is identified by iterative finite differencing across a given meridian of longitude. Then, a polygon is drawn to connect the flagged point at each of the 144 Northern Hemisphere longitudes analyzed. For each day, the procedure continues until the polygon is “closed” by connecting the last flagged coordinate to the first identified coordinate. This polygon represents the unsmoothed CPV for that day.

If multiple parallels of latitude for a given meridian of longitude have the same gradient, the “pyramid” approach is employed to identify the CPV’s extent. Specifically, if two latitudes along a meridian have the same sharpest gradient, then the midpoint between those latitudes is chosen; if three latitudes (A, B, and C) along a meridian have the same sharpest gradient, then the midpoint of AB and of BC is found, with the CPV demarcated at the midpoint of those two
midpoints (Figure 2.1). If four or more points are tied, the procedure continues with the CPV demarcated at the midpoint of the midpoints of the midpoints, etc.

![Figure 2.1. Schematic of approach for handling ties for the steepest gradient.](image)

To depict the CPV as accurately and precisely as possible, the polygons representing the daily CPV are then smoothed. Jekeli (2005) explained that for geopotential modeling, three types of spherical spline are generally used: 1) splines formed from polynomial and trigonometric B-splines; 2) splines constructed from radial basis functions; and 3) spherical splines based on homogeneous Bernstein-Bézier polynomials. While first two splines have implication for modeling the Earth’s geoid based on assembly of geographical coordinates and considering Earth as a spheroid, the Bernstein-Bézier polynomial splines method is most suitable for any sphere-like surface (Jekeli, 2005) and is most appropriate for representing the CPV. The Bézier curve equation can be represented as follows:

\[ B(t) = \sum_{i=0}^{n} \binom{n}{i} (1 - t)^{n-i} t^i P_i \]
where $B(t)$ is the function of parameter $t$ on a scale 0 to 1, $C$ represents the permutations and combinations where $n$ defines the degree of the Bézier curve (i.e., whether a Bézier curve is linear, cubic, quadratic, or higher orders), and $P$ is the number of anchor and control points. The cubic Bézier curve is applied here to smooth the CPV boundary. Figure 2.2 presents an example of the unsmoothed polygon, with its Bézier curve and the 500-hPa isohypse, on 7 January 2014, a day with an unusually deep trough over much of central and eastern North America commonly described in the popular media as a “polar vortex.” The centroid of the smoothed polygon barely falls inside the unsmoothed polygon.

![Figure 2.2](image.png)

**Figure 2.2.** Unsmoothed and smoothed 500-hPa geopotential height, representing the CPV on 7 January 2014, a day on which much of eastern North America experienced record low temperatures, as compared with the monthly mean value for January 2014.

The calculated daily CPV also initially included unusual shapes for a small percentage of days. These CPVs presented computational challenges, including perforations (i.e., “donuts”) of colder air surrounded spuriously by warmer air and proruptions (i.e., “snakes”) of a narrow zone of colder air wrapped spuriously equatorward of warmer air, and required further analysis. These
donuts and snakes are then identified, removed, and quality-controlled, with the revised CPV demarcated by the leading edge of the perforation, which prove in test cases to represent the CPV most realistically when compared to the temperature and atmospheric teleconnection patterns.

2.4.2 Calculating CPV Area and Circularity Ratio ($R_c$)

Once the daily 500-hPa CPVs are identified, diagnostics are calculated. To do this, the mapped polygon is projected into the Lambert’s equal area (i.e., equivalent) map projection, and the area enclosed within the polygon is calculated. Lambert’s projection has been found to be useful for areas that have near-equal north-south and east-west dimensions (Robinson et al., 1984), as is the case for the CPV. Then the mapped polygon is projected into the conformal (i.e., equal shape) polar stereographic projection, to calculate the perimeter of the CPV. As in Rohli et al. (2005) and Wrona and Rohli (2007), the “circularity ratio” ($R_c$), a measure of shape borrowed from fluvial geomorphology (Chorley et al., 1984), is used to index circularity of the CPV and is calculated as

$$R_c = \frac{A}{A_c} \tag{2.1}$$

where $A$ represents the area enclosed within the CPV and $A_c$ represents the area of the circle with the same perimeter as the CPV on that day. Thus, theoretically, $R_c$ can vary between 0 and 1, with $R_c$ being proportional to the circularity of the westerly flow in the CPV. Small values of $R_c$ suggest amplified and/or more numerous longwave ridges and troughs. Because O’Sullivan and Unwin (2003) recommended comparisons of the methods were run, with the calculation that

$$R_c = \sqrt{\frac{A}{A_c}} \tag{2.2}$$
yields the most significant Pearson product-moment correlations to six common teleconnection indices being implemented in all subsequent analyses. The teleconnection indices used are the SO Index (SOI; Bunge & Clarke, 2009; Können et al., 1998; Ropelewski & Jones, 1987) and Niño3.4 index (Bunge & Clarke, 2009; Ren & Jin, 2011) representing ENSO, along with indices representing the PNA pattern, AO, NAO, and PDO, the latter of which is only available at the monthly time scale. Teleconnection indices are downloaded from the sources listed in Table 2.1. The process of computing area and the “best” $R_c$ is repeated for the 8401 days between 1 January 1979 and 31 December 2001. Daily areas and $R_c$ are then statistically standardized (n=23) for that day, so that the CPV properties could be compared across days, months, and seasons. For comparison with Wrona and Rohli (2007), the daily-standardized area and $R_c$ are aggregated to monthly mean standardized area and $R_c$.

Table 2.1. Sources of atmospheric teleconnection indices.

<table>
<thead>
<tr>
<th>Teleconnection</th>
<th>Source</th>
</tr>
</thead>
</table>
Niño 3.4: http://www.cpc.noaa.gov/data/indices/ |
| Arctic Oscillation (daily)                    | http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml |
| Pacific Decadal Oscillation (monthly only)    | https://www.ncdc.noaa.gov/teleconnections/pdo/                          |

Because Wrona & Rohli (2007) only analyzed monthly Pearson correlations for December, January, February, April, July, and October, only those months are used for comparison. Moreover, data for the July PNA index are unavailable, as the PNA pattern is not prominent in the summer months (Barnston & Livezey, 1987). As in Wrona and Rohli (2007),
associations between the CPV properties (area and $R_c$) and regional-scale teleconnection indices are presumed to imply that the CPV ridges and troughs are forced by the relevant teleconnection. In reality, interactions exist between multiple teleconnections, including some that are not analyzed here, such as the West Pacific (Wallace & Gutzler, 1981) and Tropical Northern Hemisphere (Mo & Livezey, 1986) patterns. While such influences would remain undetected in this analysis, it is highly likely that the major influence will be captured by at least one of the indices for the six teleconnections known to produce the largest variability in Northern Hemisphere flow.

2.5 Results and Discussion

2.5.1 Validation of the Approach

Results suggest that the new approach identifies stronger relationships to the teleconnection indices, compared to those reported for the same time period by Wrona and Rohli (2007). Specifically, 12 (12) significant ($\alpha = 0.05$) correlations to the area ($R_c$) are identified, compared with 10 (6) by Wrona and Rohli (2007), for the six months analyzed (Table 2.2). In general, the similarity of the magnitudes and signs correlations in the matrix (other than being stronger in the present study) between the present study and that of Wrona and Rohli (2007) corroborates the findings.

The AO has the strongest and most significant relationship to both CPV area and $R_c$, with consistent results to those reported by Wrona and Rohli (2007), as shown in Table 2.2. Specifically, in each winter month, and also in April and July, the warm (cold) phase of the AO is linked to smaller and more circular (larger and less circular) CPV. This result supports the theoretical arguments of a smaller (larger) CPV when the mid-latitudes are warmed (cooled), as is the case in a positive (negative) AO regime. The strengthened (weakened) mid-latitude
geopotential height gradient during a positive (negative) AO (Thompson et al., 2000) also induces a more (less) circular CPV, with the thermal conditions of the warm (cold) phase tending to shrink (expand) the CPV. Likewise, with its characteristic increase in zonality (meridionality), the positive (negative) phase of the NAO is linked to smaller (larger) and more (less) circular CPV, but with fewer months displaying the significant relationship. Because the AO and NAO are related to each other (Marshall et al., 2001; Rogers and McHugh, 2002), the similarity of the correlations between the NAO and CPV also corroborates the findings.

The PNA pattern also has a strong relationship to the CPV $R_c$ but not area. As would be expected, amplification (deamplification) of the ridge-trough configuration is associated with significantly lower (higher) $R_c$ in each of the three winter months. The implication is that amplification of the Rossby wave train across a significant part of the hemisphere drives amplifications of adjacent Rossby ridge-trough configurations in response, while altering the net CPV area insignificantly. Another implication is that the smoothing algorithm introduced here performs well, because it preserves the relationship that is known with most certainty to exist; waviness (or lack thereof) in the PNA pattern should coincide with low (or high) $R_c$.

Furthermore, results again corroborate those of Wrona and Rohli (2007), but the method used by the latter allowed only the core winter month of January to display statistically significant results.

As suggested in previous research (Angell, 1992; Frauenfeld & Davis, 2003), ENSO also shows some relationship to the CPV area and $R_c$, as identified in this research. Specifically, a larger (smaller) CPV occurs during the La Niña (El Niño) phase, with significant associations occurring in December and February (as defined by the SOI, which defines the El Niño phase as
Table 2.2. Comparison of Pearson correlations of the area and circularity ratio ($R_c$) of monthly CPV vs. several atmospheric and SST indices, for the present study and Wrona and Rohli (2007). Correlations significant at $\alpha < 0.05$ are shown in italics.

<table>
<thead>
<tr>
<th></th>
<th>Present Study</th>
<th>Wrona and Rohli (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AO r value</td>
<td>NAO r value</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.454$</td>
<td>$-0.397$</td>
</tr>
<tr>
<td></td>
<td>$0.030$</td>
<td>$0.023$</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.540$</td>
<td>$-0.289$</td>
</tr>
<tr>
<td></td>
<td>$0.042$</td>
<td>$0.078$</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.678$</td>
<td>$-0.530$</td>
</tr>
<tr>
<td></td>
<td>$&lt;0.000$</td>
<td>$0.009$</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.567$</td>
<td>$0.034$</td>
</tr>
<tr>
<td></td>
<td>$0.005$</td>
<td>$0.877$</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.631$</td>
<td>$-0.466$</td>
</tr>
<tr>
<td></td>
<td>$0.001$</td>
<td>$0.027$</td>
</tr>
<tr>
<td>Area</td>
<td>$-0.221$</td>
<td>$-0.358$</td>
</tr>
<tr>
<td></td>
<td>$0.312$</td>
<td>$0.043$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.541$</td>
<td>$0.125$</td>
</tr>
<tr>
<td></td>
<td>$0.008$</td>
<td>$0.071$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.152$</td>
<td>$0.250$</td>
</tr>
<tr>
<td></td>
<td>$0.488$</td>
<td>$0.091$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.074$</td>
<td>$-0.182$</td>
</tr>
<tr>
<td></td>
<td>$0.736$</td>
<td>$0.406$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.629$</td>
<td>$0.178$</td>
</tr>
<tr>
<td></td>
<td>$0.001$</td>
<td>$0.416$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.630$</td>
<td>$0.622$</td>
</tr>
<tr>
<td></td>
<td>$0.001$</td>
<td>$0.002$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.551$</td>
<td>$0.353$</td>
</tr>
<tr>
<td></td>
<td>$0.006$</td>
<td>$0.098$</td>
</tr>
</tbody>
</table>
negative values) or February only (as defined by Niño3.4, which represents the El Niño phase through positive SST anomalies). The implication is that the polar front is shifted anomalously southward (northward) by the presence of colder (warmer) than normal winters during La Niña (El Niño). Notably, the insignificant correlations in other months are often of opposite signs.

Unlike the cases for AO, NAO, and PNA pattern, the ENSO relationships described here were undetected by Wrona and Rohli (2007); instead, they found a relationship only in July (Table 2.2), but because of the known strength of ENSO associations in winter, our results here seem more plausible.

Finally, a negative relationship between the PDO and $R_c$ is observed, but only in December (Table 2.2). This result is reasonable, because the positive (negative), or warm (cold), phase of the PDO (which is characterized by a long-term (20-30 years) periodic oscillations in the tropical central and eastern Pacific Ocean) creates greater (lesser) undulation in the ridges and troughs of the CPV and thus decreases (increases) the NHCPV’s circularity (Newman et al., 2003). Because of the long-term periodic nature of the PDO, this result should be interpreted with caution, as a 23-year study period may not represent the true nature of the PDO-induced variability. Moreover, this relationship was undetected by Wrona and Rohli (2007), who instead found a (negative) relationship only in October.

2.6.2 Extension of the Time Series

With confidence in the approach established, the time series is extended to all twelve months of the January 1979 to December 2017 period. Many, but not all, of the patterns that emerge are similar to those of the shorter time series. The AO remains the teleconnection with the most direct correlation to the CPV. In nine of the twelve months, a warm (cold) AO is linked to a smaller (larger) CPV (Table 2.3). In contrast to the 1979–2001 period, this correlation is
somewhat weaker in winter than the other months, with two of the three months lacking a significant relationship are January and February. The findings for $R_c$ also echo those for the shorter time series, as ten of the twelve months show that warm (cold) AO is linked to a more (less) circular CPV. Interestingly, again January and February are the months in which this relationship is not significant.

The linkages to the NAO also largely echo the results from the 1979–2001 period and corroborate relationships between the NAO and AO (Table 2.3). Four months (March, June, July, and October) have CPV areas with significant positive relationships to the NAO and only one month (January) shows a significant negative correlation. Three of the months showing positive relationships to area (June, July, and October) also show a positive link between the NAO and $R_c$. Thus, a positive (negative) NAO is associated with smaller (larger) and more (less) circular CPV, at least for June, July, and October.

While the PNA pattern shows no links to the CPV area in the shorter time series, expansion of the number of years of analysis causes the PNA pattern to display significantly positive relationships to area, in December, August, September, and November (Table 2.3). While at first glance, this result might suggest a possible bias in the smoothing algorithm, in which adjacent troughs might have been connected instead of separated by a ridge, the absence of such a relationship in the shorter time series, along with the presence of significant negative relationships between the PNA index and $R_c$ in eleven of the twelve months, suggests that the smoothing algorithm succeeded.

Looking to the Pacific Ocean, as was the case for the shorter time series, the PDO displays few relationships to the CPV (Table 2.3). Only November has a correlation with both area and $R_c$, with a positive (negative) PDO coincident with larger (smaller) and less (more)
circular CPV. March and April share this same PDO-\(R_c\) relationship but display no significant link between PDO and area.

ENSO shows a weaker relationship to the CPV than occurred over the shorter time series. None of the relationships between CPV area and ENSO that appeared in the 1979–2001 period are evident over the 1979–2017 period (compare Tables 2.2 and 2.3). However, the relationships to \(R_c\) are largely the same over the two time series, with only January displaying a significant link between ENSO, as defined by both the SOI and Niño3.4 indices. El Niño (La Niña) in January is associated with a less (more) circular CPV. September, which was not analyzed in the shorter time series analysis because it was not analyzed by Wrona and Rohli (2007), also shows some evidence of an ENSO link to \(R_c\), but only when ENSO is defined by SOI, and in the opposite direction as January; El Niño (La Niña) in September is associated with a more (less) circular CPV.

Table 2.3. Pearson correlations of the area and circularity ratio \((R_c)\) of all months CPV vs. several atmospheric and SST indices for the extended time period (1979–2017). Correlations significant at \(\alpha < 0.05\) are shown in italics.
<table>
<thead>
<tr>
<th>Area</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>r value</td>
<td>p-value</td>
<td>r value</td>
<td>p-value</td>
</tr>
<tr>
<td>AO</td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
</tr>
<tr>
<td></td>
<td>-0.495</td>
<td>-0.712</td>
<td>-0.398</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>&lt;0.000</td>
<td>0.055</td>
</tr>
<tr>
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<td>-0.503</td>
<td>0.175</td>
</tr>
<tr>
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<td>0.010</td>
<td>0.001</td>
<td>0.287</td>
</tr>
<tr>
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<td>0.210</td>
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</tr>
<tr>
<td></td>
<td>0.227</td>
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<td>&lt;0.000</td>
</tr>
<tr>
<td>PDO</td>
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<td>0.183</td>
<td>0.111</td>
</tr>
<tr>
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<td>0.373</td>
<td>0.266</td>
<td>0.948</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
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<td>0.150</td>
<td>0.684</td>
</tr>
<tr>
<td>NIÑO3.4</td>
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<td>0.153</td>
<td>-0.107</td>
</tr>
<tr>
<td></td>
<td>0.535</td>
<td>0.353</td>
<td>0.515</td>
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</tbody>
</table>
2.6 Summary and Conclusions

This research introduces an effective, objective method for identifying the tropospheric circumpolar vortex (CPV). Results suggest that the area of the CPV as calculated here offers improvements over those of Wrona and Rohli (2007) as evidenced by significance of correlations to the major modes of hemispheric-scale variability in the form of both tropical and extratropical atmospheric teleconnections. The technique also improves the identification of circularity of the CPV substantially. Given the demonstrated improvement of this index, it is implemented for all twelve months of the period of available data (1979–2017).

The CPV is most closely linked to variability associated with the AO and NAO, followed by the PNA pattern, ENSO, and finally the PDO. These results, while not surprising, have implications for forecasting at seasonal time scales and beyond. Now that this technique is validated by comparison to previous work at the monthly scale of analysis and the time series of the standardized CPV area and circularity has been updated, future research should investigate the practicality of delineating diurnal features of the CPV as identified herein.

The technique introduced here is a rich source of future studies of atmospheric circulation variability because it permits the consideration of multiple vertical levels, for continuous updating of the CPVs diagnostic features on a near-real-time basis. For example, such work will allow for identification of a signal of global climatic change in the upper-level flow. A warming planet should cause impacts that ripple through the troposphere. Lack of such a signal could either indicate impacts that do not resonate effectively or impacts that are yet to be felt through the troposphere. Furthermore, the technique allows future research on the identification for the identification of changes in the baroclinicity of the upper-level steering flow. Such changes could alter the vertical wind shear that would affect the development of mid-latitude storm systems.
The improved understanding of the drivers of such broad-scale flow could have important implications for protecting life and property.
CHAPTER 3.
RELATIONSHIP BETWEEN ATMOSPHERIC TELECONNECTIONS AND THE NORTHERN HEMISPHERE’S CIRCUMPOLAR VORTEX

3.1 Introduction

The circumpolar vortex (CPV) is the continuous zone of rapid winds generally flowing cyclonically aloft in the middle-to-upper troposphere circumnavigating each pole. The leading edge of the CPV is the polar front, which steers, supports, and suppresses extratropical surface weather systems by providing upper-level support (or lack thereof) for surface storms. Therefore, an improved understanding of the spatial and temporal variability associated with the CPV can enhance predictability in surface weather and its related impacts.

Chapter 2 identified a new method for identifying the CPV, with diagnostic measurements of the CPV’s area, hemispheric zonality in the form of a circularity ratio ($R_c$ – the ratio of the area enclosed within the NHCPV polygon to the area of a circle with a perimeter equal to the distance enclosed by the polygon, such that near-zero values represent more amplified ridges/troughs and values near 1.0 represent a more circular NHCPV – Rohli et al. 2005), and centroid location. The daily values from Chapter 2 were aggregated and reported at the monthly scale for direct comparison to Wrona and Rohli’s (2007) monthly mean Northern Hemispheric CPV (NHCPV) area and $R_c$ for the months included in Wrona and Rohli’s (2007) analysis (April, July, October, December, January, and February). Wrona and Rohli (2007) had used the more conventional approach of defining the NHCPV using a pre-determined 500-hPa isohypse recommended by Frauenfeld and Davis (2003), over the 1979–2001 period. Results from Chapter 2 revealed that although the previous work had represented substantial steps forward, the new technique, which delineates the CPV at the sharpest 500-hPa geopotential height gradient along each meridian of longitude, is advantageous because it reveals NHCPV
variability that is linked more strongly than the previous techniques to known modulators of monthly circulation variability in the form of atmospheric teleconnections. This result is potentially very important, because, if this result is confirmed at the daily scale, then the available daily teleconnection indices could lead to an improved understanding of sub-monthly-scale atmospheric variability, such as floods and severe weather events.

3.2 Purpose

As the new measurement technique has been validated, the purpose of this research is to address the questions of how the area and circularity of the NHCPV are linked to teleconnection variability on a daily scale. These questions are important to address because the main modes of low-frequency variability in broad-scale atmospheric flow in the form of atmospheric teleconnections are increasingly predictable at long lead times, yet their most important impacts are at the daily time scale in the form of extreme weather events that are less predictable at long lead times. While we acknowledge that geophysical impacts of the El Niño/Southern Oscillation (ENSO) phenomenon require weeks to months to materialize, with different lag times at different times of the year, we include ENSO as part of our analysis, for comparison to the representation of higher-frequency forms of variability in the form of mid-latitude teleconnections. Resolution of the research questions will represent an important step forward in using predicted or observed high-frequency shifts in the teleconnection indices to anticipate potential extreme events at short lead times.

In addition to the investigation of high-frequency (i.e., daily) variability of the teleconnection patterns taken individually, the association between some teleconnections to each other calls for an examination of the collective linkage between modes of variability in broad-scale flow and the NHCPV. Thus, a principal components analysis (PCA) is implemented to
reduce the dimensionality (number of variables) of the data set and reveal the holistic links between the teleconnections and NHCPV area and $R_c$.

### 3.3 Atmospheric Teleconnections that Influence Extratropical Flow

The identification of major modes of broad-scale atmospheric variability has a rich history, including seminal work by Walker and Bliss (1932), Horel and Wallace (1981), Wallace and Gutzler (1981), and Barnston and Livezey (1987). The most important mode of low-frequency air-sea variability is ENSO (Philander, 1990). ENSO is an oscillation between surface atmospheric pressure between the western and eastern equatorial Pacific Ocean. During times when the atmospheric sea level pressure (SLP) is anomalously high (low) in the western tropical Pacific, it is simultaneously low (high) in the eastern tropical Pacific, and this phase is known as El Niño or a “warm event” (La Niña or “cold event”). Among the many indices representing the mode of ENSO variability, the Southern Oscillation index (SOI) is one of the most commonly used, particularly in atmospheric research, since it is based on normalized SLP differences – between Tahiti and Darwin, Australia, with positive (negative) SOI representing La Niña (El Niño). A second index is more popular in oceanographic work because it relies on sea surface temperature (SST) departures; this so-called Niño3.4 index is aligned such that positive (negative) values in the so called Niño3.4 region of the east-central tropical Pacific Ocean indicate El Niño (La Niña).

Much previous work has investigated the relationship between tropical teleconnections, particularly ENSO, and the NHCPV. The tendency for El Niño to be followed by shrinking of the NHCPV with a three-season lag (Angell, 1992) and within the season (Frauenfeld & Davis, 2000), have been noted, [with the eastern Pacific sector of the NHCPV expanding during the El Niño event (Angell, 1992)]. Over the periods 1959 – 2001, Rohli et al. (2005) found that neither
the SOI nor the Niño3.4 SST index show significant correlation with either January NHCPV area or $R_c$. Although Angell and Korshover (1977) had found a tendency for the NHCPV to be contracted when the quasi-biennial oscillation (QBO) is in its westerly phase from 1963 to 1975, Angell (2001) found little evidence for a relationship between the NHCPV area and the QBO over the tropical stratosphere.

Not unexpectedly, extratropical teleconnections, which are hypothesized to be tied to CPV behavior, have also been evaluated for their influences on weather. The North Atlantic Oscillation (NAO; van Loon & Rogers, 1978; Wallace & Gutzler, 1981; Barnston & Livezey, 1987; Hurrell, 1995) modulates the atmospheric circulation that impacts winter weather conditions in western Europe and the eastern U.S.A. (Hurrell & van Loon, 1997; Kapala et al., 1998; Higgins et al., 2000). The NAO index has been used to measure the surface temperature and differences in normalized SLP (Wallace & Gutzler, 1981) between two locations: Ponta Delgado, Azores, and Akureyri, Iceland (Lamb & Peppler, 1987), or it can be derived based on empirical orthogonal function analysis of mid-tropospheric geopotential heights (e.g., Deser & Blackmon, 1993). Positive (negative) phases of the NAO correspond with a strong (weak) Icelandic Low, strong (weak) westerlies across the North Atlantic, and positive (negative) SLP anomalies near the Bermuda-Azores subtropical anticyclone (Wallace & Gutzler, 1981). The positive (negative) NAO is associated with positive (negative) temperatures departures in the eastern U.S.A. and northwestern Europe and negative- (positive-) temperature anomalies in the Greenland/Labrador area (Wallace & Gutzler, 1981). PCA has been used to identify modes of variability associated with teleconnections including the NAO (e.g., Martinez-Artigas et al., 2021).
The Arctic Oscillation (AO), characterized by a see-saw of atmospheric mass between the Arctic and the mid-latitudes, is another dominant mode of Northern Hemispheric-scale atmospheric variability (Thompson & Wallace, 1998, 2000). The winter AO pattern influences weather and climate of the vast regions of North America, Europe, and East Asia (e.g., Higgins et al., 2002; Kolstad et al., 2010; Park et al., 2011; Tomassini et al., 2012). A positive (negative) AO index indicates negative (positive) geopotential height anomalies over the Arctic and anomalously high (low) geopotential heights in lower latitudes and causes a “warm (cold) phase” particularly over northern Europe (Thompson & Wallace, 1998). Variability associated with the AO tends to occur on a multitude of time scales, including decadal, with the 1960s through the 1980s dominated by the “cold phase” and the 1990s through most of the first two decades of the present century dominated by “warm phase” conditions, with strongly fluctuating signals in recent years.

Several studies (e.g., Ambaum et al., 2001; Wanner et al., 2001; Rogers & McHugh, 2002) have shown that the AO resembles the NAO and there is a strong correlation between them, although their impacts can differ (Wang et al., 2005). The frequency-time appearance of NAO is physically more robust, consistent, and relevant to Northern Hemisphere winter climate variability than the AO (Ambaum et al., 2001). The AO and NAO indices are negatively correlated with the area of the NHCPV in winter and April (Wrona & Rohli, 2007), such that the positive or “warm” phase is linked to NHCPV shrinking.

The Pacific-North American (PNA) pattern is another important component of mid-latitude flow, consisting of anomalies in the geopotential height fields (typically at 700 or 500 hPa) observed over the western and eastern U.S.A. (Wallace & Gutzler, 1981). The positive phase consists of above-normal geopotential heights (i.e., ridging) over western North America
and below normal geopotential heights (i.e., troughing) over the eastern U.S.A., allowing cold
Canadian air to plunge southeastward, resulting in negative temperature anomalies over the
eastern U.S.A. and positive temperature anomalies over western North America (Leathers et al.,
1991, Leathers & Palecki, 1992). The negative phase features troughing or at least negative
height departures over western North America, and simultaneous ridging or positive height
departures over the eastern U.S.A., resulting in negative temperature departures in the western
mountain cordillera and positive temperature departures over the eastern U.S. (Leathers &
Palecki, 1992). The PNA pattern has been found to be strongly influenced by ENSO (Renwick &
Wallace, 1996; Straus & Shukla, 2002; Wang et al., 2020), with the positive (negative) phase of
the PNA pattern tending to be associated with Pacific warm (cold) episodes (i.e., El Niño (La
Niña). The cumulative effect of the NAO and PNA pattern acting in concert can amplify U.S.
temperature anomalies (Notaro et al., 2006; Baxter & Nigam, 2013; Ning & Bradley, 2016).
Burnett (1993) suggested that the increased frequency of the positive mode of the PNA pattern
may have contributed to the temporal increase in NHCPV area from 1964 to the mid-1980s. The
PNA pattern is negatively correlated to NHCPV $R_c$ in December, January, and to some extent,
October (Wrona & Rohli, 2007; Bushra & Rohli, 2019).

Although several studies demonstrate the relationship between variability in
teleconnection indices and atmospheric variables at climatological time scales, none have
included the CPV. Given that other studies show significant associations of teleconnections to
surface meteorological anomalies, other teleconnections are likely to be linked to NHCPV
variability. However, some may have compensating effects across longitudes, yielding no
significant net change in NHCPV area or circularity. Others, such as the Pacific Decadal
Oscillation (PDO; Newman et al., 2003) are potentially useful but do not have indices that are
readily available on a daily basis. And some indices of teleconnections, particularly those representing ENSO, are unavailable on a daily basis even though daily data exist for other indices of that teleconnection (e.g., Multivariate ENSO Index; Wolter & Timlin, 2011). Therefore, the present research is needed to ascertain whether the linkage between the NHCPV area and/or $R_c$ and the SOI, Niño3.4, NAO, AO, and PNA appear at the daily scale using the improved technique, and at all months rather than only those in winter and one representative month of each season as tested in Chapter 2. This issue is important to address because the size and shape of the CPV are inherently tied to the locations of baroclinicity and upper-level support for surface systems associated with impactful extreme weather.

3.4 Materials and Methods

Details regarding methods of obtaining the statistically standardized atmospheric teleconnection index data and calculating the CPV diagnostics of area and $R_c$ for the 1979–2017 period are provided in Chapter 2. To facilitate comparison of results with that of the previous study, NHCPV area and $R_c$ are calculated from 500-hPa geopotential height data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kanamitsu et al., 2002). Also as in Chapter 2, delineating the daily CPV based on the sharpest gradient of geopotential heights involves the computational challenges of preserving complicated shapes that appear in the daily data but get “washed out” in monthly mean data, namely perforations such as cutoff lows of colder air surrounded spuriously by warmer air and protrusions of a narrow zone of colder air equatorward of warmer air.

Daily mean teleconnection indices for the NAO, AO, and PNA pattern in the Satellite Era beginning in 1979 and for the SOI and Niño3.4 since 1991 and 1990, respectively, are used. These time periods are selected to match the periods for which the NHCPV area and $R_c$ were
computed in Chapter 2. A Pearson product-moment correlation matrix is calculated between the NHCPV area and $R_c$ with the five standardized indices representing the four teleconnections, on a daily scale for those above-mentioned periods. To ensure an adequate number of observations while still remaining true to the mission of representing daily variability accurately, the NHCPV standardization is done by day over the 1979 to 2017 period, while the teleconnection indices are standardized using all data available between 1979 and 2017. This leaves only a maximum of ten observations for 29 February. Because holistic spatio-temporal variability of the relationships between the NHCPV and the teleconnections is an important consideration (Demšar et al., 2013), PCA is applied to identify trends in the main modes of dataset variability.

PCA is one of the oldest and popular dimensionality reduction methods applied in the atmospheric sciences, operating by identifying common patterns underlying a data set by linearly transforming the original data to new dimensions that explain successively less data set variability (Jackson, 2005). As such, PCA is useful for illustrating the teleconnection/CPV relationship, in which broad-scale dynamics are inferred from inspection of patterns resulting (primarily) from PCA, through space and time simultaneously. To date, PCA has been used in atmospheric research such as in identifying and assessing analog forecasting (Grimmer, 1963), spatial variability (e.g., Kutzbach, 1967; Stidd, 1967), classification (e.g., Dyer, 1975) and regionalization (e.g., Richman & Lamb, 1985; Mallants & Feyens, 1990; Comrie & Glenn, 1998), and circulation changes (e.g., Compagnucci & Vargas, 1998).

Feldstein (2000) implemented PCA in examining the daily ENSO, NAO, PNA, and west Pacific (WP; Wallace & Gutzler, 1981; Barnston & Livezey, 1987) teleconnection variability, power spectra, and climate noise properties from the unfiltered 300-hPa geopotential height field. McCabe and Dettinger (2002) used PCA to analyze snowpack variability associated with

In this research, an input matrix consisting of seven columns (i.e., the five daily-standardized teleconnection indices and the two daily-standardized indices of the NHCPV (i.e., area and $R_c$) and 9,705 rows (i.e., month/day/year), is input into a P-mode PCA data structure (Richman, 1986). The P-mode data structure is defined such that parameters appear along the columns and time appears along the rows, with the location remaining fixed (Richman, 1986). The correlation matrix of the seven daily-standardized variables against each other is then produced, with the loadings matrix output consisting of the seven variables along the rows vs. the first seven principal components (PCs). The output component scores matrix, by PC (columns) vs. time (rows) allows for detailed analysis of the time series of changes in the atmospheric configuration consisting of the teleconnections and NHCPV properties. Data for 29 February are also standardized on a daily basis, despite having only ten observations of each variable on that day. Then, sixteen additional, separate PCAs are run on the same daily standardized data, for each of the twelve months and for each meteorological season (D-J-F, M-A-M, J-J-A, and S-O-N), to identify the extent of consistency and aid in explanation of forcing features.
While the standardization process satisfies the PCA assumption of non-stationarity in the seasonality of the atmospheric data, the Durbin-Watson (D-W) test (Savin & White, 1977) is used to assess the validity of the assumption of the absence of serial autocorrelation (Vanhatalo & Kulahci, 2016). A D-W test statistic of 0 to 4 is output, whereby values above (below) 2 suggest (negative) positive autocorrelation, mostly applicable for time series data. According to Field (2009), values below 1 or exceeding 3 could be cause for concern. The Cochrane–Orcutt (C-O) method (Montgomery et al., 2012) is used to remove any such autocorrelation.

3.5 Results

3.5.1 Pearson Correlation Analysis

More statistically significant correlations between NHCPV area and (separately) \( R_c \) vs. the teleconnection indices exist at the daily scale than Chapter 2 reported at the monthly scale. Specifically, 37 (38) significant correlations, or 61.67% (63.33%) of the pairs of variables, for CPV area (\( R_c \)) exist, respectively (Table 3.1). These numbers compare to 18 (27), or 30.0% (45.0%), as shown in Table 2.3 from Chapter 2 for the same teleconnections and study period. It should be noted that the PDO was analyzed at the monthly scale in Chapter 2, but this teleconnection was not analyzed here because daily values were unavailable. Still, however, the relatively low explained variance for some correlations invites caution in the interpretation of results and may complicate use of the results for predictive purposes.

Table 3.1 reveals many interesting patterns. As was the case at the monthly scale, the AO shows the strongest relationship among the teleconnection indices to both NHCPV area and \( R_c \). The AO is correlated significantly to both area (negatively) and \( R_c \) (positively) in 11 of the 12 months, with February having a significant correlation only to \( R_c \). Also, expectedly similar to the work at the monthly scale, the daily NAO is linked in largely the same manner as the AO, with a
Table 3.1. Pearson product-moment correlations of the area and circularity ratio ($R_c$) of the NHCPV vs. atmospheric and SST indices, at the daily time scale, for the periods of available records of teleconnection indices (January 1979 to September 2017 for the AO, NAO, and PNA pattern, January 1991 through December 2017 for the SOI, and January 1990 through December 2017 for the Niño3.4). Correlations significant at $\alpha \leq 0.05$ are shown in italics.

<table>
<thead>
<tr>
<th>Month</th>
<th>Area</th>
<th>Niño 3.4</th>
<th>AO</th>
<th>NAO</th>
<th>PNA</th>
<th>SOI</th>
<th>AO</th>
<th>NAO</th>
<th>PNA</th>
<th>SOI</th>
<th>Niño 3.4</th>
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<tbody>
<tr>
<td>Jan</td>
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<td>0.018</td>
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<td></td>
</tr>
<tr>
<td>Feb</td>
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<td>-0.047</td>
<td>0.027</td>
<td>0.049</td>
<td>0.127</td>
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<td>-0.221</td>
<td>0.006</td>
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<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.873</td>
<td>0.541</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.097</td>
<td>0.653</td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>-0.326</td>
<td>-0.181</td>
<td>0.155</td>
<td>-0.024</td>
<td>0.166</td>
<td>0.246</td>
<td>0.129</td>
<td>-0.175</td>
<td>0.066</td>
<td>-0.128</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.490</td>
<td>0.541</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.057</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>-0.237</td>
<td>0.062</td>
<td>0.448</td>
<td>-0.020</td>
<td>-0.016</td>
<td>0.202</td>
<td>-0.020</td>
<td>-0.270</td>
<td>-0.001</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>0.030</td>
<td>&lt;0.001</td>
<td>0.569</td>
<td>0.634</td>
<td>&lt;0.001</td>
<td>0.479</td>
<td>&lt;0.001</td>
<td>0.987</td>
<td>0.478</td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>-0.247</td>
<td>-0.055</td>
<td>0.227</td>
<td>0.192</td>
<td>-0.245</td>
<td>0.197</td>
<td>-0.006</td>
<td>-0.170</td>
<td>-0.152</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>0.061</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.838</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>-0.213</td>
<td>-0.139</td>
<td>0.034</td>
<td>-0.099</td>
<td>-0.048</td>
<td>0.242</td>
<td>0.117</td>
<td>-0.144</td>
<td>0.079</td>
<td>0.0286</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.233</td>
<td>0.004</td>
<td>0.161</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.022</td>
<td>0.399</td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>-0.261</td>
<td>-0.098</td>
<td>0.138</td>
<td>0.062</td>
<td>-0.088</td>
<td>0.307</td>
<td>0.179</td>
<td>-0.276</td>
<td>-0.047</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.077</td>
<td>0.010</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.180</td>
<td>0.293</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>-0.167</td>
<td>0.055</td>
<td>0.176</td>
<td>0.110</td>
<td>-0.099</td>
<td>0.170</td>
<td>-0.0155</td>
<td>-0.222</td>
<td>-0.050</td>
<td>0.040</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>0.590</td>
<td>&lt;0.001</td>
<td>0.151</td>
<td>0.241</td>
<td></td>
</tr>
</tbody>
</table>
positive NAO index associated with a significantly anomalously small and circular NHCPV, but only in seven months each for area and $R_c$. Interestingly, the NAO’s linkage to the NHCPV weakens or even reverses in winter, a finding that was largely supported in Chapter 2’s monthly-scale analysis. The daily PNA pattern has a significantly positive link to NHCPV area in eight months, with a weaker association in winter, and a negative link to $R_c$ in all months. The two ENSO indices demonstrate weaker correlations, though still statistically significant in some months, as compared to the three indices of extratropical teleconnections.

NHCPV area is inversely linked to $R_c$, and several of the daily teleconnection indices are correlated with each other (Table 3.2). For example, it is not surprising that strongly significant positive relationships exist between the AO and NAO, and between SOI and Niño3.4. Overall daily correlations across all months verify the results in Table 3.1, with even the tropical teleconnections showing evidence for linkages to the NHCPV.

Table 3.2. Pearson product-moment correlation matrix and p-values of the daily NHCPV metrics and teleconnection indices, for the available periods of record indicated in Table 3.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Area</th>
<th>$R_c$</th>
<th>AO</th>
<th>NAO</th>
<th>PNA</th>
<th>SOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_c$</td>
<td>-0.528**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>-0.141**</td>
<td>0.383**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAO</td>
<td>-0.012</td>
<td>0.210**</td>
<td>0.551**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PNA</td>
<td>0.132**</td>
<td>-0.268**</td>
<td>-0.147**</td>
<td>0.046**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOI</td>
<td>0.012</td>
<td>0.044**</td>
<td>0.048**</td>
<td>0.031*</td>
<td>-0.069**</td>
<td></td>
</tr>
<tr>
<td>Niño3.4</td>
<td>-0.028*</td>
<td>-0.049**</td>
<td>-0.016</td>
<td>0.016</td>
<td>0.066**</td>
<td>-0.469**</td>
</tr>
</tbody>
</table>

*p < 0.05  **p < 0.01

3.5.2 Principal Components Analysis (PCA)

Because teleconnections tend to change relatively slowly over time, it is not surprising that the D-W test on daily teleconnection indices (and CPV area and $R_c$ affected by them) reveals the existence of serial correlation for the first-order autoregressive process. However, much
reduced values of the D-W statistic result for the AO, NAO, and Niño3.4 after applying the C-O procedure (Table 3.3). Although the PNA pattern index and SOI did not converge (which is a continuation of an iterative approach until calculating the regression coefficients, rho) after applying the C-O adjustment, they were input into the PCA before applying the C-O procedure since the original D-W test statistics fell within the range of 1.5 to 2.5.

Table 3.3. Durbin-Watson Test and p-value for the first-order autoregressive process.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before C-O procedure</th>
<th>After C-O procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>1.91</td>
<td>1.993</td>
</tr>
<tr>
<td>Rs</td>
<td>1.974</td>
<td>1.997</td>
</tr>
<tr>
<td>AO</td>
<td>0.884</td>
<td>1.990</td>
</tr>
<tr>
<td>NAO</td>
<td>0.905</td>
<td>1.894</td>
</tr>
<tr>
<td>PNA</td>
<td>1.738</td>
<td>*Did not converge</td>
</tr>
<tr>
<td>SOI</td>
<td>1.682</td>
<td>*Did not converge</td>
</tr>
<tr>
<td>Niño3.4</td>
<td>0.351</td>
<td>2.034</td>
</tr>
</tbody>
</table>

* An iterative approach continues until there is convergence in calculating the regression coefficients.

The first PC explains nearly 29 percent of the dataset variance, while the first three components explain more normalized variance than the original variables that comprise them, as indicated by their eigenvalues exceeding 1.0 (Table 3.4). A scree plot (Jackson, 2005; Figure 3.1) suggests that the first four components, which collectively explain over 80 percent of the dataset variability, should be examined more closely. This approach accomplishes the goal of data

Table 3.4. Principal components analysis-generated eigenvalues, for the seven components, using available periods of record for the seven variables as described in Table 3.1.

<table>
<thead>
<tr>
<th>PC</th>
<th>Eigenvalue</th>
<th>Proportion</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.022</td>
<td>0.289</td>
<td>0.289</td>
</tr>
<tr>
<td>2</td>
<td>1.474</td>
<td>0.211</td>
<td>0.499</td>
</tr>
<tr>
<td>3</td>
<td>1.277</td>
<td>0.183</td>
<td>0.682</td>
</tr>
<tr>
<td>4</td>
<td>0.885</td>
<td>0.127</td>
<td>0.808</td>
</tr>
<tr>
<td>5</td>
<td>0.533</td>
<td>0.076</td>
<td>0.885</td>
</tr>
<tr>
<td>6</td>
<td>0.416</td>
<td>0.059</td>
<td>0.944</td>
</tr>
<tr>
<td>7</td>
<td>0.392</td>
<td>0.056</td>
<td>1.000</td>
</tr>
</tbody>
</table>
reduction, to identify the main modes of variability in the data set, so that intercorrelations among the different teleconnections and CPV area and $R_c$ are removed.

![Scree Plot](image)

**Figure 3.1.** Scree plot showing (a) eigenvalue and b) proportion and cumulative proportion of the explained variability, by principal component, using available periods of record for the seven variables as described in Table 3.1.

The explained variance by PC (Figure 3.2) shows that $R_c$ is the most strongly-represented variable in PC1, while PCs 2 and 5 represent the ENSO indices most effectively. PC3 best

![Percentage of total variance explained](image)

**Figure 3.2.** Percentage of total variance explained by each of the first five PCs by NHCPV area, NHCPV $R_c$, and five atmospheric teleconnection indices, for the periods of record designated in Table 3.1. The numerals in parentheses across the columns indicate the total percentage of dataset variance explained by the PCs.
represents the NAO with strong representation of both NHCPV area and the NAO-related AO. PC4 is the “PNA pattern” component. Figure 3.3 depicts these relationships graphically, for two PCs at a time, with positively correlated variables grouped together and negatively correlated variables positioned in opposite quadrants.

Figure 3.3. Variable correlation plots of the first four PCs, taken for two PCs at a time, for NHCPV area, NHCPV $R_c$, and five atmospheric teleconnection indices, for the periods of record designated in Table 3.1.
The PCA-generated eigenvalues for individual months and seasons suggest that a relatively consistent relationship among the variables across the monthly and seasonal time scales exists (Table 3.5). Moreover, similar patterns of prominence of \( R_c \), ENSO, NAO, and

Table 3.5. Proportion of variability, and cumulative percentage, explained by the first four principal components, in PCAs by month and meteorological season (D-J-F, M-A-M, J-J-A, and S-O-N), for daily NHCPV area, NHCPV \( R_c \), and the five atmospheric teleconnection indices, for the periods of record designated in Table 3.1.

<table>
<thead>
<tr>
<th></th>
<th>PC1 Eigenvalue</th>
<th>PC2 Eigenvalue</th>
<th>PC3 Eigenvalue</th>
<th>PC4 Eigenvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prop</td>
<td>Cumul</td>
<td>Prop</td>
<td>Cumul</td>
</tr>
<tr>
<td>Jan</td>
<td>2.296</td>
<td>1.481</td>
<td>1.356</td>
<td>0.767</td>
</tr>
<tr>
<td></td>
<td>0.328</td>
<td>0.328</td>
<td>0.212</td>
<td>0.540</td>
</tr>
<tr>
<td>Feb</td>
<td>2.058</td>
<td>1.633</td>
<td>1.325</td>
<td>0.912</td>
</tr>
<tr>
<td></td>
<td>0.294</td>
<td>0.294</td>
<td>0.233</td>
<td>0.527</td>
</tr>
<tr>
<td>Mar</td>
<td>1.981</td>
<td>1.725</td>
<td>1.179</td>
<td>0.886</td>
</tr>
<tr>
<td></td>
<td>0.283</td>
<td>0.283</td>
<td>0.246</td>
<td>0.529</td>
</tr>
<tr>
<td>Apr</td>
<td>2.218</td>
<td>1.448</td>
<td>1.218</td>
<td>0.753</td>
</tr>
<tr>
<td></td>
<td>0.317</td>
<td>0.317</td>
<td>0.207</td>
<td>0.524</td>
</tr>
<tr>
<td>May</td>
<td>2.224</td>
<td>1.295</td>
<td>1.152</td>
<td>0.890</td>
</tr>
<tr>
<td></td>
<td>0.318</td>
<td>0.318</td>
<td>0.185</td>
<td>0.503</td>
</tr>
<tr>
<td>Jun</td>
<td>2.413</td>
<td>1.363</td>
<td>0.993</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>0.345</td>
<td>0.345</td>
<td>0.195</td>
<td>0.540</td>
</tr>
<tr>
<td>Jul</td>
<td>2.282</td>
<td>1.414</td>
<td>1.197</td>
<td>0.736</td>
</tr>
<tr>
<td></td>
<td>0.326</td>
<td>0.326</td>
<td>0.202</td>
<td>0.528</td>
</tr>
<tr>
<td>Aug</td>
<td>2.356</td>
<td>1.569</td>
<td>1.271</td>
<td>0.649</td>
</tr>
<tr>
<td></td>
<td>0.337</td>
<td>0.337</td>
<td>0.224</td>
<td>0.561</td>
</tr>
<tr>
<td>Sep</td>
<td>2.080</td>
<td>1.502</td>
<td>1.219</td>
<td>0.835</td>
</tr>
<tr>
<td></td>
<td>0.297</td>
<td>0.297</td>
<td>0.215</td>
<td>0.512</td>
</tr>
<tr>
<td>Oct</td>
<td>2.184</td>
<td>1.573</td>
<td>1.140</td>
<td>0.878</td>
</tr>
<tr>
<td></td>
<td>0.312</td>
<td>0.312</td>
<td>0.225</td>
<td>0.537</td>
</tr>
<tr>
<td>Nov</td>
<td>2.351</td>
<td>1.434</td>
<td>1.078</td>
<td>0.895</td>
</tr>
<tr>
<td></td>
<td>0.336</td>
<td>0.336</td>
<td>0.205</td>
<td>0.541</td>
</tr>
<tr>
<td>Dec</td>
<td>1.984</td>
<td>1.664</td>
<td>1.400</td>
<td>0.765</td>
</tr>
<tr>
<td></td>
<td>0.283</td>
<td>0.283</td>
<td>0.238</td>
<td>0.521</td>
</tr>
<tr>
<td>Spring</td>
<td>2.058</td>
<td>1.499</td>
<td>1.168</td>
<td>0.843</td>
</tr>
<tr>
<td></td>
<td>0.294</td>
<td>0.294</td>
<td>0.214</td>
<td>0.508</td>
</tr>
<tr>
<td>Autumn</td>
<td>2.072</td>
<td>1.568</td>
<td>1.175</td>
<td>0.876</td>
</tr>
<tr>
<td></td>
<td>0.296</td>
<td>0.296</td>
<td>0.224</td>
<td>0.520</td>
</tr>
<tr>
<td>Summer</td>
<td>2.276</td>
<td>1.400</td>
<td>1.209</td>
<td>0.792</td>
</tr>
<tr>
<td></td>
<td>0.325</td>
<td>0.325</td>
<td>0.200</td>
<td>0.525</td>
</tr>
<tr>
<td>Winter</td>
<td>2.030</td>
<td>1.542</td>
<td>1.421</td>
<td>0.841</td>
</tr>
<tr>
<td></td>
<td>0.290</td>
<td>0.290</td>
<td>0.220</td>
<td>0.510</td>
</tr>
</tbody>
</table>
PNA in PCs 1 through 4, respectively, persist in general in each season (Figure 3.4), verifying the robustness of the results. In every case, approximately 80% of the variance is explained by

![Table and Diagram]

Figure 3.4. As in Figure 3.3, but by meteorological season (D-J-F, M-A-M, J-J-A, and S-O-N).
the four PCs, but differences from month to month for PC1 and PC2 are noteworthy, as indicated by eigenvalues that exceed 1.0 (Table 3.5). Specifically, PC1 is slightly less important in late winter/early spring than at most other times of the year while PC2 is more important, and other months have complimentary explained variance for these two components (Figure 3.5). Similar complimentary patterns are apparent between PC3 and PC4 but with less explained variability. Not surprisingly, the ENSO-dominated PC2 shows less prominence in April through July (Figure 3.5), which overlaps substantially with a time when ENSO has its weakest signature.

![Figure 3.5. Proportion of variability explained by the first four principal components, by month, for the patterns representing the interconnections between daily NHCPV area, NHCPV \( R_c \), and the five atmospheric teleconnection indices, for the periods of record designated in Table 3.1.](image)

The PCA-generated scores matrix provides a time series of influence of the various PCs. Linear tests for trend suggest that PC3 is weakening significantly over time (\( p < 0.001 \)), while PCs 4 and 5 are strengthening temporally (\( p < 0.001 \); Figure 3.6). PCs 1, 2, 6, and 7 show no significant linear temporal trend.
Figure 3.6. Significant linear temporal trends in daily PCA-generated scores for PCs 3, 4, and 5.
3.6 Discussion

3.6.1 Teleconnection Analysis

The increased number of significant correlations at the daily scale, as compared to the monthly scale in previous work, suggests that monthly analyses may “wash out” some of the sub-monthly-scale variability that links atmospheric flow and NHCPV properties. The finding that the extratropical teleconnections (NAO, AO, and PNA) can have predictive value for representing the daily NHCPV variability is important, because most impactful weather phenomena in the extratropics are related to upper-level support that is represented by CPV behavior. The observation that NHCPV area is inversely related to the daily AO index in all months except February comes as no surprise, as the “warm phase” (i.e., positive AO index) is linked to a poleward retreat of the polar front. The finding of a strongly positive link between $R_c$ and the AO in every month at the daily scale confirms that the areal retreat (expansion) is tied to zonal flow in the warm phase and meridional (i.e., wavy) flow in the cold phase. The similarity of associations between the regional expression of the AO – the NAO – and the NHCPV, with positive (negative) NAO tied to small and more circular NHCPV, corroborates these findings.

This result could shed some light in the ongoing debate over the role of Arctic amplification in driving changes to the mid-latitude steering flow (Holland & Bitz, 2003; Pithan & Mauritsen, 2014) by supporting the assertion of Cattiaux et al. (2016) and Di Capua and Coumou (2016) that increased zonality is to be expected under future warming conditions, despite the finding by Cattiaux et al. (2016) of decreased zonality in past decades associated with warming. More specifically, our result suggests, albeit indirectly, that an increasingly positive (i.e., “warm phase”) AO might affect the transfer of energy from the tropics to the poles in both the atmosphere (e.g., Cohen et al., 2014) and ocean (e.g., Rahmstorf et al., 2015; Praetorius,
2018), but perhaps with increasing severe weather frequencies (Cohen et al., 2018). But on the other hand, Arctic amplification may also impact the circularity of the NHCPV (and the Southern Hemispheric CPV) by weakening the zonal winds, including in the lower stratosphere in winter (Kretschmer et al., 2018), in part because of non-uniform warming rates by latitude, which may be connected to changes in Rossby wave activity. Francis and Vavrus (2012; 2015) suggested that amplified waviness is more likely in the future as a result of these weakened zonal winds. Despite the fact that our results here tend to favor the suggestion of Cattiaux et al. (2016), further work must be done to ascertain more clearly the most likely scenario, as Vavrus (2018) summarized the conflicting evidence and lamented the continuing lack of consensus. Our work is but one piece of a complicated puzzle.

It is also not surprising that the amplified ridge-trough configuration over mid-latitude North America captured by the positive mode of the PNA pattern is linked to an anomalously enlarged and less circular NHCPV. The implication is that an expanded pool of polar air in the Northern Hemisphere is associated with zonality over North America and a smaller pool of polar air is linked to meridionality over North America. The recent warming signal is likely tied to this latter scenario, resulting in our frequent observations of temperature extremes across the mid-latitudes of North America. However, the fact that this linkage is weaker in winter is somewhat surprising and is perhaps explained by the importance of other factors, namely the variability in extent and position of Eurasian snow cover as a driver of the winter NHCPV area and circularity. In general, these results support the findings at the monthly scale reported in Chapter 2.

3.6.2 PCA

Because the position and amplitude of the NHCPV’s ridges and troughs may not necessarily be associated with NHCPV area (i.e., the ridges and troughs could simply progress or
retrogress, or amplify in some places and dampen simultaneously in others), and because the ridges and troughs progress and retrogress temporally, it is important to identify the teleconnections that, individually or collectively, may vary coincidentally with CPV area and/or CPV $R_c$. The PCA procedure confirms the close association between the NHCPV area and the AO and NAO, through space and time. The temporal weakening of PC3 (the NAO component) may suggest that this teleconnection is becoming “lost” relative to the AO, in its influence on the NHCPV area and $R_c$. On the other hand, the increasing role of two components that explain lesser variance (the PNA pattern and the second ENSO pattern) implies that these may be becoming more prominent players in recent years, including, perhaps as drivers of the NHCPV area and $R_c$. The latter implication contradicts findings of Cohen (2016), who found weakened tropical forcing due to ENSO in recent decades.

At first glance, the complementarity of the time series between PC1 and PC2 (Figure 3.5) suggests that a near-circular NHCPV is related to the La Niña phase of ENSO, while a wavy NHCPV is linked to the El Niño phase. Nevertheless, the relatively weak association between ENSO and the NHCPV (Table 3.1) largely corroborates the results of Straus and Shukla (2002), who suggested that El Niño phase does not force the PNA pattern, and that the La Niña phase was inconclusive in its influence of the PNA pattern.

For PC1 vs. PC2, PC1 vs. PC3, and PC1 vs. PC4, $R_c$, AO, and NAO generally remain clustered while the SOI and Niño3.4 are along opposite axes. This result is expected because the ENSO phase has opposite signs in these indices. While PC1 explains the most variability, at the daily scale, CPV area appears to exert less influence on the dataset variability than CPV $R_c$, probably because the overall area of CPV does not vary much over daily scale but the undulation of the CPV boundary (i.e. ridges and troughs of the CPV) varies more notably on a daily scale,
depending on the position of the pressure gradient/jet stream flow. NHCPV area and PNA index are closely linked but usually on opposite axes due to the negative relationship (see again Figure 3.3a-c). Similar clusters of variables appear for PC2 vs. PC3, PC2 vs. PC4, and PC3 vs. PC4, though the linkages become progressively weaker (Figure 3.3d-f). Neither the SOI nor Niño3.4 cluster with CPV area or $R_c$ in any of the plots here, which suggests relatively little influence of ENSO on the NHCPV. The distance between variables and the origin measures the quality of the variables on the component map. Variables that are distant from the origin are well represented on the map.

The complementarity between PC3 and PC4 (Figure 3.5) confirms the intuitive oscillation of importance between the NAO and PNA, with zonal flow associated with the NAO tied to the negative PNA index, and meridional NAO flow linked to a positive PNA, despite the fact that this linkage is not revealed through simple correlation of the two indices (Table 3.2).

The fact that the relative influence of the PCs on dataset variability remains largely consistent throughout the year suggests that the CPV/teleconnection relationship is important in all months.

3.7 Summary and Conclusion

This research assesses the linkages between the atmospheric teleconnections and the NHCPV area and $R_c$. Results suggest that both NHCPV area and $R_c$ are more strongly correlated with the extratropical AO, NAO, and PNA teleconnections than with the tropical ENSO phenomenon. Most notably, the warm (i.e., positive) phase of the AO, which dominates the latter part of the study period, is tied to an anomalously small and circular NHCPV. The PCA suggests that NHCPV $R_c$ is closely tied to the PC dominated by the AO and NAO, acting together, and that NHCPV area is linked more closely to the component dominated by the PNA.
teleconnection, though the latter PC explains less dataset variance than the former. Variability of SOI and Niño3.4 are linked less directly to CPV area and \( R_c \).

Future work should investigate the vertical consistency of these results, so that inferences can be drawn about whether changes in height of the NHCPV over time in response to surface warming might be confounding results shown here. Furthermore, the reduced amplitudes of the Rossby waves in the Southern Hemisphere as compared to those in the Northern Hemisphere might call for a more precise and sensitive method of evaluating daily variability and long-term changes in the Southern Hemispheric CPV, such as the method proposed by Bushra and Rohli (2019) in Chapter 2 and employed here. An analysis of the degree of synchronicity of anomalies in area and circularity of the two CPVs could shed light on the cross-hemisphere influence of the teleconnections. In general, improvements in our understanding of the CPVs, at both the daily and monthly time scales, will enhance predictability and perhaps identify signatures that might provide a harbinger of abrupt, impactful weather and climate events and impacts of longer-term climatic changes.
CHAPTER 4.
NORTHERN HEMISPHERE 500-HPA CIRCUMPOLAR VORTEX TRENDS AND VARIABILITY

4.1 Introduction

The tropospheric circumpolar vortices (CPVs, Waugh et al. 2017) are the two hemispheric-scale, steering, extratropical circulation systems that circumnavigate each polar region – one in the Northern Hemisphere (NHCPV) and the other in the Southern (SHCPV), most evident at 5–12 km in altitude. The CPVs are positioned as upper-level manifestations of the surface polar front at a given time, situated at the steepest gradient of air temperature, at the fastest flow of the quasi-westerly wind belt, including the polar front jet stream.

Despite the general circular shape formed as the westerly circulation at the leading edge of the CPV proceeds eastward in the upper-tropospheric westerlies, longitudinal differences in heating cause the CPV’s area, position, and centroid to shift, at the inter-annual, seasonal, and intra-seasonal time scales. At any given time, sections of the CPV can bend poleward (at longwave ridges) or equatorward (at longwave troughs), with the ridges and troughs varying in amplitude and progression across space and time, again at all of these temporal scales, thereby creating longitudinal variability in heat and mass exchanges (Yu & Sun, 2020). Inter-annually, as the ocean-atmosphere system warms, the cold pool and therefore the CPV theoretically retreats poleward. Seasonally, the CPV expands equatorward as the cold pool grows with the onset of winter and contracts as summer approaches. Intra-seasonally, the CPV expands and contracts as air masses affecting and affected by the cold pool migrate with the daily weather patterns.

The amplitude and length of poleward (i.e., ridges) and equatorward (i.e., troughs) meanders in the Rossby waves in the CPV’s westerly flow support surface storminess (Di Capua & Coumou, 2016) through upper-level divergence (ULD) and positive vorticity advection
(PVA), and suppress surface storminess by upper-level convergence (ULC) and negative vorticity advection (NVA). Likewise, ULC and NVA (ULD and PVA), driven by the Rossby waves, support (suppress) surface anticyclones. While the changes in the CPV’s dimensions (i.e., area and “waviness” in the form of ridges/troughs) are likely to affect the degree to which surface storms or anticyclones beneath the CPV are supported, surface features may also influence the CPV properties (Angell & Korshover, 1985; Kirby et al., 2002). Variability in the strength, position, “waviness” (i.e., amplitude and length of longwave ridges/troughs aloft), and location of the CPV is well-known to be directly linked to variations in surface environmental features such as surface air temperature and wind (van den Broeke & van Lipzig, 2002; Moron et al., 2018), precipitation (Srinivas et al., 2018), sea surface temperature (Frauenfeld et al., 2005), ocean salinity (Chen et al., 2018), pollutants (Bartlett et al., 2018), air mass properties (Vanos & Cakmak, 2014), water vapor transport (Wang & Ding, 2009), storm tracks (Kidston et al., 2015), sea ice extent (Orme et al., 2017), and ozone (Glovin et al., 2016).

Several studies have evaluated trends in the NHCPV area in the form of a pre-determined isohypse. According to Angell and Korshover (1977), the 300-hPa annual-averaged NHCPV area increased from 1970 to 1975 despite simultaneously shrinking over time in winter. Davis and Benkovic (1992, 1994) noted an expansion of the 500-hPa January NHCPV from 1966 to 1990, with the expansion primarily resulting from intensified regional troughing over the North Pacific Ocean and eastern North America and concurrent warm air mass intrusion into Alaska and western Canada. Burnett (1993) found similar results for the January NHCPV after the mid-1960s, with areal growth due to expansion along the Pacific and eastern North America/Atlantic sectors, but with contraction commencing in the late 1980s. Angell (1998, 2006) found different results at 300 hPa; the NHCPV area was decreasing over the 1963–2001 period, especially in the
Western Hemisphere, at a rate of 1.5 percent per decade. Angell (1998) demonstrated that the most intense 300-hPa-NHCPV contraction began around 1990. Frauenfeld and Davis (2003) investigated temporal trends of NHCPV area at multiple geopotential-height levels over the 1949–2000 period; at all levels they found significant NHCPV expansion until 1970 and areal contraction afterward, with the primary areas of expansion/contraction over Asia, Europe, and North America, with less variability over the Northern Hemisphere oceans. Trends were more apparent in the upper troposphere than near the surface (Frauenfeld & Davis, 2003), likely because of the complexity of the surface influence.

While all of the above studies delineate the NHCPV area using a pre-determined isohypse, as recommended by Frauenfeld and Davis (2003), Thompson and Solomon (2002) applied vertical gradients of geopotential heights at the relatively coarse network of radiosonde-based stations to define the NHCPV. Bushra and Rohli (2019) delineated the CPV’s leading edge at the sharpest latitudinal gradient of 500-hPa geopotential height.

Although the NHCPV’s area has been studied for several decades, a means of characterizing CPV shape has remained elusive until recently. Analysis of CPV shape had been largely restricted to reporting the relative area within various quadrants about the pole until Rohli et al. (2005), Wrona and Rohli (2007), andBushra and Rohli (2019) borrowed from watershed hydrologists’ drainage basin metrics (Chorley et al., 1984) by using a “circularity ratio” ($R_c$), ranging from 0 (i.e., infinitely amplified ridges and troughs) to 1.0 (i.e., perfectly circular, west-to-east-flowing CPV), to characterize the NHCPV’s shape. CPV sinuosity (i.e., ratio of CPV length to the length of a particular latitude segment) has also been analyzed for the 500-hPa level in the North American sector (Vavrus et al., 2017) and at the hemispheric scale (Cattiaux et al., 2016; Di Capua & Coumou, 2016) using a fast Fourier transform (FFT) approach (Screen &
Simmonds, 2013), and for potential-vorticity-based individual Rossby wave initiation (Röthlisberger et al., 2016). However, with these and a few other exceptions (e.g., Zakinyan et al., 2016), little attention has been given to defining and interpreting holistic CPV shape.

Analyzing temporal trends in CPV and $R_c$ may reveal important features of hemispheric-scale response to surface warming. While air temperatures are increasing across Earth, the warming trend of the past several decades is most pronounced in the high latitudes, especially in the Arctic (Holland & Bitz, 2003; Pithan & Mauritsen, 2014). This “Arctic amplification” decreases the horizontal temperature gradient and affects the transfer of energy from the tropics to the poles in both the atmosphere (e.g., Cohen et al., 2014) and ocean (e.g., Rahmstorf et al., 2015; Praetorius, 2018). This phenomenon has been proposed to weaken the zonal winds, which may be connected to increased amplification of Rossby wave activity and support for severe weather by increasing areas of ULD and PVA. Model-based research has posited that these meridional meanders are expected to increase into the future (Francis & Vavrus, 2012, 2015; Peings & Magnusdottir, 2014). However, Cattiaux et al. (2016) suggested that a less sinuous NHCPV may occur as warming continues. Vavrus (2018) summarized the conflicting evidence and lamented the lack of consensus.

Cyclical variation of the broad-scale steering circulation has included analysis of the energy distribution of the atmospheric motion and waves. This recurring frequency can be explained through their linearized/non-linearized energy transfer spectra with Fourier analysis over space and time. Understanding of the relationship between wave number and frequency, and variability of magnitude and phase, could aid understanding of the dynamics of the energetics influencing surface weather. Hayashi (1974) performed space-time cross spectrum analysis to understand the effect of tropical disturbances on the general circulation. Chen et al.
(1981) simulated winter wind fields over a 90-day period to apply modified Fourier analysis to characterize the wavenumber-frequency spectra. Hayashi (1982) applied space-time spectral analysis to understand broad-scale atmospheric waves. Higuchi et al. (1999) employed multiresolution Fourier transform spectral analysis to resolve the temporal structure of the variation of the North Atlantic Oscillation (NAO), a component of the NHCPV, in terms of various frequency components. Torrence and Compo (1998) explained the implications of wavelet analysis in the atmospheric sciences using the example of the El Niño–Southern Oscillation (ENSO) time series. Pelletier (1998) explored local variability of the high-frequency component of the temperature time series using a power spectrum. Ghil et al. (2002) applied time series analysis by treating the atmosphere as a non-linear dynamic system. More recent research has included the examination of the daily 500-hPa geopotential height data of the Southern Hemisphere to analyze the space-time frequency characteristics of the expansion coefficients (Sun & Li, 2012).

However, a comprehensive analysis of the spatiotemporal cyclical nature of the NHCPV area and $R_c$ is lacking. Implications of the linear regression model provide us with the temporal trend over the time domain while the FFT extracts information on the variability of the magnitude and cyclical trend by analyzing the frequency variability. In a dynamic system, framing the CPV characteristics with these analytical tools may reveal important understanding about how the hemispheric circulation is influenced by the surface environment and impacts extreme climatic events. Although considerable progress has been made in implementing time series analysis tools in climate research and weather forecasting, the dynamism of the atmospheric circulation needs to be understood with better precision.
4.2 Purpose

The purpose of this research is to evaluate temporal trends of the NHCPV’s area and $R_c$ at the 500-hPa geopotential height level. Time-series analysis will identify the periodicity/frequency characteristics and variability over time objectively. Analysis of the intra- and inter-annual variability of the NHCPV area and $R_c$ provides a tangible index of the relationship between the atmospheric steering flow and surface warming, and it also contextualizes recent results (Bushra & Rohli, 2019). Analyzing the intra- and inter-annual variability of the NHCPV shape is important not only as a characterization of the response to Arctic amplification, but also as an indicator of the extent of baroclinic instability. Analysis of NHCPV area and $R_c$ will also inform studies on extratropical severe weather that rely on the juxtaposition of tropical and polar air masses (e.g., Overland et al., 2015).

4.3 Data and Methods

To facilitate comparison of results to Bushra and Rohli (2019), daily 500-hPa geopotential height data are obtained from the National Centers for Environmental Information (NCEI)/National Center for Atmospheric Research (NCAR) Reanalysis 2 project (Kanamitsu et al., 2002). At each 2.5° increment of longitude globally from 20°N to the North Pole, the daily 500-hPa NHCPV is delineated over the 1979–2017 period using the method described more fully in Bushra and Rohli (2019). Specifically, the NHCPV polygon is formed by connecting the dots representing the latitude of the steepest gradient of 500-hPa geopotential height for each meridian of longitude around the Northern Hemisphere. After Bézier smoothing (Jekeli, 2005), the NHCPV area is then measured, and $R_c$ is calculated as

$$R_c = \frac{A}{A_c}$$
where $A$ represents the area enclosed within the NHCPV and $A_c$ represents the area of the circle with the same perimeter as the NHCPV on that day. When $R_c = 1$, the CPV is perfectly circular (i.e., has west-to-east flow); near-zero $R_c$ implies amplified ridges and troughs (i.e., “waviness”).

Statistical regression in then used to analyze the linear trend of the NHCPV’s area and $R_c$ for the 500-hPa level for the entire time period and subperiods identified via breakpoint analysis (Muggeo, 2008). Zero padding (Borkowski & Mroczka, 2010) and Butterworth (Butterworth, 1930) low-pass filters are applied at a cutoff point of 0.01 frequency to the dataset to smoothen the output of the frequency peak and to remove the higher frequencies, before applying FFT (Welch, 1967). Spectral analysis identifies the space-time Fourier component of the NHCPV properties to evaluate the periodic characteristics of the area and $R_c$ time series data by decomposing their time series signal into frequency space (i.e., quantifying their magnitude of variations at different frequencies).

4.4 Results and Discussion

4.4.1 Long-term Trends

Linear regression analysis reveals that over the 1979–2017 time period, the area enclosed within the 500-hPa NHCPV shows, counterintuitively at first glance, a significant temporal increase ($125 \text{ km}^2 \text{ day}^{-1}$; $p < 0.001$; Figure 4.1a) despite coincident increases in global mean surface temperature. Time series breakpoints are identified at a 95% confidence level in 1986, 1994, and 2001, with NHCPV area increasing over all four segmented periods (Figure 4.1b), but with the 1979–1986 segment showing an increasing area only at a 90% confidence level (Table 1). The highest rate of NHCPV areal increase ($1305 \text{ km}^2 \text{ day}^{-1}$) occurred over the 1994–2001 period, perhaps because of the major El Niño events and eruption of Mount Pinatubo in the Philippines. The lowest rate of $188 \text{ km}^2 \text{ day}^{-1}$ occurred over the 2001–2017 period, possibly
corresponding to shifting of the Pacific Decadal Oscillation (Newman et al., 2003) phases. But all these hypotheses require further investigation.

The areal expansion contrasts with the conventional wisdom that the 500-hPa NHCPV area would decrease over time as the cold pool retreats poleward in response to surface warming and instead suggests that other factors may be driving the result. In a follow-up analysis, it is

![Diagram](image)

Figure 4.1. (a) Statistically significant \((p < 0.001)\) linearly increasing trend in NHCPV area over the 1979–2017 period. The smoothed black line, from Butterworth low-pass filtering, shows the annual cycle; and (b) Linear regressions from breakpoint analysis of four subperiods of 1979–1986, 1986–1994, 1994–2001, and 2001–2017 for NHCPV area with confidence intervals shown along the x-axis.
confirmed that the daily-averaged 500-hPa geopotential height gradient that demarcates the leading edge of the NHCPV is indeed decreasing significantly, at a rate of 0.1661 km day\(^{-1}\) (p < 0.001), over the study period. This value was calculated from the trend line \(y = 89.44 - 1.661 \times 10^{-4} x\) of the 14,245 daily mean values of the 144 daily longitudinal maximum 500-hPa daily geopotential height difference (in m) at a given longitude occurring across the horizontal distance between two data points 2.5° of latitude (or 279.23 km), to give an answer in m km\(^{-1}\) day\(^{-1}\). This weakening gradient may be a stronger symptom of Arctic amplification than the area enclosed within the NHCPV. Nevertheless, the preponderance of the evidence suggests that the NHCPV’s link to the observed surface warming has differed substantially from that of the original hypothesis.

Because the unexpected changes in NHCPV area could have been associated with simultaneous changes in “waviness,” an examination of temporal changes in the NHCPV \(R_c\) is conducted. Linear regression analysis of the 500-hPa NHCPV’s \(R_c\) reveals no significant trend \((-4.258 \times 10^{-8} \text{ day}^{-1}; p = 0.445\)\) over the entire time series (Figure 4.2a). Four time series

![Graphs showing temporal changes in NHCPV R_c](attachment:graphs.png)

Figure 4.2. (a) As in Figure 4.1, but for the statistically insignificant (p = 0.445) decreasing trend in \(R_c\); and (b) Linear regressions from breakpoint analysis of four subperiods of 1979–1988, 1988–1994, 1994–2001, and 2001–2017 for NHCPV \(R_c\).
segments are also identified for the 500-hPa NHCPV $R_c$, with breakpoints in 1988, 1994, and 2001 at a 95 percent confidence interval (Figure 4.2b; Table 4.1). These breakpoints are very similar to those for the area analysis, probably suggesting that the trend of the undulation of the ridges and troughs is related to the NHCPV area. Over the 1979–1988 and 1994–2001 segments, $R_c$ increases significantly (at 90 and 95 percent confidence levels, respectively) with the highest increasing rate of $0.02 \times 10^{-8}$ day$^{-1}$ over the latter period. However, these subperiods are interrupted by intervals of decreasing trends for 1988–1994 and 2001–2017 (at 95 and 90 percent confidence levels, respectively) with the highest decreasing rate of $-0.017 \times 10^{-8}$ day$^{-1}$ over the earlier period.

Table 4.1. Time series breakpoints of NHCPV Area and $R_c$ with confidence interval.

<table>
<thead>
<tr>
<th>Sub-periods</th>
<th>Regression line (p-value)</th>
<th>Breakpoints (Confidence Interval)</th>
<th>Sub-periods</th>
<th>Regression line (p-value)</th>
<th>Breakpoints (Confidence Interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/01/1979 – 5/26/1986</td>
<td>$y = 4.662e+13 + 5.871e+08x$ (p = 0.086)</td>
<td></td>
<td>01/01/1979 – 6/4/1988</td>
<td>$Y = 8.577e-01 + 3.135e-05$ (p = 0.061)</td>
<td></td>
</tr>
</tbody>
</table>

This result suggests that the 500-hPa NHCPV’s shape may be characterized by alternating increases and decreases in Rossby wave amplification over time. Such a feature may be expected to continue in an environment of weakening equator-to-pole gradients of 500-hPa geopotential height and weakened zonal winds, which may in turn amplify (but perhaps
simultaneously weaken) the Rossby waves. Some modes may be associated with increased frequency and magnitude of weather extremes.

4.4.2 Seasonal Cycle

Application of the power spectrum and filtering assesses the frequency and amplitudes of the 500-hPa NHCPV characteristics to identify cycles. FFT analysis shows that NHCPV area has a distinct annual cycle suggestive of the variation of solar radiation due to Earth revolution around the Sun and a semiannual cycle perhaps reflective of the cold-warm seasonal flow, over the complete study period (1979–2017). However, the magnitude of the annual cycle varies over the subperiods with an indistinct or weaker semiannual cycle (Figure 4.3a–e). The semiannual signal among these daily standardized values suggests that z-scores of the area might offer at least some degree of predictability for the z-scores of area six months into the future. FFT also reveals a high frequency intra-annual cycle of ~7.5 year\(^{-1}\) but only over the 1994–2001 period (Figure 4.3d) and may have been associated with ENSO events. This was also the subperiod that showed the strongest increasing trend in NHCPV area.

FFT analysis for the NHCPV \(R_c\) also shows a distinct annual cycle over the 1979–2017 period, but no semiannual cycle (Figure 4.4a–e). The annual signal has similar strength over the 1979–1988, 1988–1994, and 1994 subperiods (Figure 4.4b, 4.4c, and 4.4d), while the magnitude of 2001–2017 (Figure 4.4e) is higher than the rest. The smaller amplitudes in the earlier stage of the time series for the three subperiods imply that the shape of the CPV had less association to the annual cycle of solar radiation than in the 2001–2017 subperiod (i.e., the warmest decades). In addition, the 1979–1988 and 2001–2017 periods (Figure 4.4c & 4.4e) show a secondary cycle at 3 year\(^{-1}\). The reason for this cycle for only these two subperiods is unclear and deserves future research consideration.
Figure 4.3. Magnitudes of the power spectra of the daily NHCPV area over (a) 1979–2017, (b) 1979–1986, (c) 1986–1994, (d) 1994–2001, and (e) 2001–2017 periods. The peaks indicate the magnitude of the high-frequency variability. The highest peaks at 1 cycles/year indicate an annual cycle for all periods.
Figure 4.4. As in Figure 4.3, but for $R_c$. 
4.5 Summary and Conclusions

Analysis of daily variability of area and circularity (Rc) of the NHCPV defined by the sharpest gradient of the atmospheric mass at the 500-hPa geopotential height level offers potential for improved understanding of the steering circulation. However, the geopotential height gradient itself is also an important indicator of the mid-tropospheric response to surface warming.

In this research, long-term changes in area and Rc of the 500-hPa NHCPV are presented for the 1979–2017 period of record. Linear regression analysis suggests that the NHCPV area has increased significantly while Rc has changed insignificantly over 1979–2017 periods, but with subperiods showing different trends at different significance levels (i.e., 90 to 95 percent) in both variables. The gradient of atmospheric mass that separates the polar cold pool from the temperate atmosphere and delineates the leading edge of the NHCPV has weakened over time. Thus, the distinctiveness of the NHCPV has blurred over time, which may impact the trends and the NHCPV’s influence.

The NHCPV area and Rc co-exist as a low-frequency variability mode in the atmosphere. Application of the power spectrum and filtering shows that both NHCPV area and Rc have distinct annual cycles but with varying amplitude. FFT also reveals intra-annual cycles for subperiods. This result suggests that the NHCPV has become more variable in its extent and waviness.

These results are important indicators of the impact of globally changing temperatures at varying time scales on the upper-level steering circulation. Analyzing CPV characteristics reveals important clues about how hemispheric circulation may influence the surface environment and may have implications for extreme atmospheric events. Analysis of the intra-
annual variability of the NHCPV area provides a tangible index of the response of atmospheric steering flow to the observed surface warming.

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CHAPTER 5.
TRENDS IN THE CENTROID OF THE NORTHERN HEMISPHERE’S CIRCUMPOLAR VORTEX

5.1 Introduction

5.1.1 The Circumpolar Vortex

The two tropospheric circumpolar vortices (CPVs, Waugh et al., 2017) – one approximately centered on each pole – represent the hemispheric-scale, steering, extratropical circulation at a given time. These strong, quasi-west-to-east (i.e., quasi-westerly) extratropical wind belts circumnavigate the north and south high-latitude regions at altitudes of 5–12 km. The leading edge of each CPV is near the steepest gradient of air temperature at the three-dimensional boundary where polar and tropical air meet. At any given time, 3–6 long waves (aka: Rossby waves, or planetary waves) exist in the westerly flow at the leading edge of the CPV in each hemisphere, at the core of the polar front jet stream (PFJ), that amplify/deamplify and propagate in response to thermal and orographic forcing, and subtropical upper-level divergence (Hoskins & Karoly, 1981).

This broad-scale steering atmospheric circulation represented by the CPVs is an important topic in geoenvironmental sciences because of its many links to environmental features at the surface, such as air mass properties (e.g., Vanos & Cakmak, 2014), surface air temperature (e.g., Moron et al., 2018) and wind (e.g., van den Broeke & van Lipzig, 2002), sea surface temperature (SST; e.g., Frauenfeld et al., 2005), water vapor transport (e.g., Wang & Ding, 2009), precipitation (e.g., Srinivas et al., 2018), ocean salinity (e.g., Chen et al., 2018), storm tracks (e.g., Kidston et al., 2015), sea-ice extent (e.g., Orme et al., 2017), ozone (e.g., Glovin et al., 2016), and other pollutants (e.g., Bartlett et al., 2018).
Previous research (Bushra & Rohli, 2019) established the “sharpest gradient” approach to defining the CPV and correlated the area and circularity of the Northern Hemisphere’s CPV (NHCPV) to important air-sea teleconnections. Using this definition, a library of daily NHCPV area and circularity has been constructed, based on 500-hPa geopotential heights, facilitating comparisons to previous research. While the recent surface warming may be linked to a temporally shrinking NHCPV, Martin (2015) found that for winter seasons of cold years, the 850-hPa NHCPV-driven jet was expanded equatorward in both the Pacific and Atlantic sectors of the Northern Hemisphere.

The shape of the NHCPV may have also changed under the recent warming, as it becomes more or less intertwined with areas of known air-sea interactions in the form of teleconnections (Bushra & Rohli, 2019). Recent research (Bushra & Rohli, 2019) has found that the NHCPV has become wavier over time and is positively correlated most closely with the indices of the Arctic Oscillation (AO; Thompson & Wallace, 1998) and North Atlantic Oscillation (NAO; Lamb & Peppler, 1987), and negatively with Pacific/North American (PNA; Wallace & Gutzler, 1981) teleconnection pattern.

The possibility of the NHCPV changing its orientation independently of changes in areal coverage or shape (i.e., circularity) invites further analysis. A simultaneous amplification or dampening of the ridge-trough configuration on both sides of the Northern Hemisphere simultaneously could create a large change in area and circularity while leaving the centroid in a static location. Likewise, the mean daily longitudinal progression or retrogression of the ridges and troughs could occur in the absence of changes in area or circularity; in such a case, only the centroid of the polygon representing the NHCPV would change. Thus, trends in NHCPV
centroid locations may yield additional information about changes in ridge-trough location, either independently of, or in association with, areal and circularity changes.

To date, no research at the daily scale has addressed whether the NHCPV’s centroid location has drifted or shifted over time. At the monthly scale, Rohli et al. (2005) and Wrona and Rohli (2007) showed that temporal variability and long-term change in the monthly mean NHCPV centroid location (and also area and circularity) are linked to Northern Hemisphere temperature variability and regional-scale flow patterns. But questions remain about how accurately and precisely the daily NHCPV can be represented and how the NHCPV variability impacts and is impacted by surface environmental features. This question is important because even in the absence of changes in area and/or circularity of the NHCPV, shifts in its daily position could easily cause redistribution of the energy associated with severe weather, which occurs on the daily scale, and/or a host of other high-frequency atmospheric/oceanic impacts.

5.1.2 Centroids in Geospatial Analysis

In geospatial analysis, centroid may imply either the geometric center or the center of mass of an areal feature. Various methods of determining a centroid (Deakin et al., 2002), including the spatial mean, the center of mass (or center of gravity), and the center of minimum distance, may yield substantially different results. All three measures are well-explained in Levine (2002) and De Smith et al. (2007). Deakin et al. (2002) also listed several methods for defining the centroid of a polygon on the geoid; for example, “moment centroid” refers the measure of the center of mass, and “average centroid” relies on the arithmetic mean. Root mean square, harmonic mean, geometric mean, median, and mode centroids are also common, as are others including the minimum bounding rectangle centroid, the negative buffer centroid, and the circle centroid.
While in climate science, a number of studies use the concept of “centroid” in cluster analysis (Steinbach et al., 2003, Cassou et al., 2004, Esteban et al., 2005, Zhang et al., 2009), others have used centroids to characterize a natural climatic region. For example, Haskett et al. (2000) produced daily, simulated weather datasets from general circulation models, for the nine climate centroids in Iowa. Liu et al. (2012) used centroids to represent daily mean evapotranspiration zones. And Frierson & Hwang (2012) and Donohoe et al. (2013) used centroids to specify centers of precipitation. Wrona and Rohli (2007) identified the NHCPV centroid using center of mass but only at the monthly scale.

5.2 Purpose

This research uses an objective method for identifying the centroid of the NHCPV defined in Chapter 2 via geospatial techniques. The centroid position is then examined for both spatial (distribution and frequencies over places) and temporal (at both high and low frequencies) changes. Results will identify both the impact of day-to-day hemispheric-scale fluctuations and long-term changes in the steering circulation that have accompanied the changes in surface temperature over the last several decades.

5.3 Data and Methods

As described more fully in Chapter 2, gridded 500-hPa geopotential heights from the National Centers for Environmental Prediction/U.S. Dept. of Energy Reanalysis Atmospheric Model Intercomparison Project (AMIP) II (NCEP-R2; Kanamitsu et al. 2002) data set are selected here, with analysis from 1979–2017. The study period is also segmented to 1979–2001, to correspond with that used in Wrona and Rohli’s (2007) monthly analysis, and 2002–2017 subperiods. Then, the “center of mass” criterion (Deakin et al., 2002; De Smith et al., 2007) is used to identify the geographic coordinates of the centroid of each day’s NHCPV, because of its
wide acceptance and to correspond to the method used in Wrona and Rohli (2007). The North Polar Stereographic Projection (GISGeography, 2020) is used to preserve CPV shape.

5.3.1 Rationale of Using the Center of Mass

Deakin et al. (2002) noted that in a vector- (point-) based system, although the “average centroids” formulas is the easiest legitimate way of measuring the spatial central tendency, the insensitivity to the order of the vertices, and thus the shape of the polygons, can be limiting for some types of analysis. The “minimum bounding rectangle centroid” approach (Deakin et al. 2002) can be unduly influenced by the four extreme vertices of the polygon, is subject to bias by outliers in general (De Smith et al., 2007), and is insensitive to the shape. Deakin et al. (2002) also concluded that (i) the “negative buffer” and circle centroid approaches fall short in handling irregular shapes, such as a CPV with amplified Rossby waves, and are difficult to compute, (ii) the “minimum distance centroids” approach has computational drawbacks and requires sophisticated function minimization software for calculation, and (iii) neither the “momentum” nor the “center of mass” approaches have such disadvantages, and they provide a more logical and intuitive measurement of the centroid for irregular polygon shapes.

In the “center of mass” approach, the centroid is a point defined in a manner analogous to the “balance point” of the distribution of mass of a corresponding body. According to this definition, and regarding the body as a plane area \( A \) of uniformly distributed material, the centroid position is

\[
\bar{x} = \frac{M_y}{A} \quad \text{and} \quad \bar{y} = \frac{M_x}{A}
\]

(5.1)

where \( M_x \) and \( M_y \) are (first) moments with respect to the \( x \)- and \( y \)-axes respectively (Ayres, 1968).
5.3.2 Trend Analysis

Trend analysis is performed to reveal the changes in centroid location over time seasonally, intra-annually, and inter-annually. For each day in the time series, the great circle distance that the centroid moved since the previous day is computed, using a time series of vectors representing the magnitude and direction of centroid migration since the previous day.

Three techniques are widely used for measuring the great circle distance: (1) spherical law of cosines (Robusto, 1957), (2) Haversine (Sinnott, 1984), and (3) Vincenty inverse (Vincenty, 1975). The first two methods consider Earth as a sphere and the later treats Earth as an ellipsoid. Using a spherical model gives errors typically up to 0.3%. Thus, the Vincenty inverse formula is selected because it provides accuracy as close as 1 millimeter.

Linear regression analysis is then performed to identify temporal trends in the daily migration of the NHCPV’s centroid, expressed as the great circle distance moved from the centroid location on the previous day, for both the entire time series and for the two subperiods. Before applying the spectral analysis, white noise in the data series is removed by applying Butterworth (1930) low-pass filtering at a cutoff point of 0.01 to remove the higher frequencies. The effectiveness of this removal is confirmed by applying Fisher’s Exact G Test for Multiple (Genetic) Time Series, or “fisher.g.test,” and “hwwntest” (Savchev & Nason, 2018), both in R. The presence of p-values of < 0.001 in both tests supports rejection of the null hypothesis of white noise remaining in the data series. The Butterworth filter also smooths the daily NHCPV centroid distance from the previous day.

For atmospheric time series data in general, the presence of red noise indicates lag-1 autocorrelation between two successive time samples (Schulz & Mudelsee, 2002) and has a power spectrum weighted toward low frequencies (Ghil et al., 2002). The Durbin-Watson (D-W)
test (Savin & White, 1977) is performed here to identify lag-1 autocorrelation; the test statistic of 1.4 (p-value < 0.001) indicates the presence of a lag-1 positive autocorrelation in the time series. To confirm that the resultant power spectrum is not generated purely by red noise, the Cochrane–Orcutt (C-O) method (Montgomery et al., 2012) is used to remove any such autocorrelation. That test results in a D-W test statistic of 2 (p-value < 0.001), suggesting that the lag-1 autocorrelation (i.e., red noise) was removed successfully. Then, the time-series signal is decomposed into frequency space by applying spectral analysis (Koopmans, 1995) to identify variability in the magnitude and the cyclical trend. The fast Fourier transform (FFT; Welch, 1967) is run to identify whether the seasonal signal is amplifying, deamplifying, or has multiple phases of amplification/deamplification for three time periods.

In addition to the time series analysis which reveals any temporal trends in the centroid location stability, circular statistical analysis is applied to reveal temporal trends in the directional dispersion of the centroid positions around a unit circle. To apply Rao’s Spacing Test (Rao, 1972) of uniformity, Cartesian angular dispersion of the centroid positions from the previous day is calculated. The test assesses whether the angular positions of the centroids show any signs of directionality or are indicative of a random scatter. In Rao’s Spacing Test, the null hypothesis implies that data are of a uniform distribution, while the alternate hypothesis is that the data demonstrate directionality. Because the test statistic of 132.60 ($\alpha=0.05$) falls below the critical value of 136.94, the angle of direction moved has no directional trend, suggesting that a follow-up emerging hot spot analysis (EHSA) is required.

5.3.3 Centroid Patterns over Space and Time

Two components of the “Space Time Pattern Mining” toolbox in ArcGIS Pro are used to identify statistical “hot” and “cold” spots (with “hot (cold) spot” defined as a place of frequent
(infrequent) NHCPV centroid location) and temporal trends persistence in NHCPV centroid location over the simultaneous space-time dimensions. First, the “Create Space Time Cube” (CSTC) tool is used to generate three-dimensional bins and calculate annual centroid frequencies in each hexagonal-shaped bin with opposite vertices spaced 102.9 km apart and 39 layers of z-axis representing time (i.e., years). This bin size is optimized from an algorithm based on the spatial distribution of the centroids. The hexagonal shape ensures more uniform distances between neighbors than a quadrilateral, thereby minimizing distortion, making it advantageous for high latitudes.

Then, this space-time set of bins, and their corresponding NHCPV annual frequencies, is input into the “EHSA” tool, which identifies trends across space (i.e., from one bin to another across the x- and y-axes, via the Getis-Ord Gi* (pronounced “G-i-star”; i.e., “hot spot analysis”; Getis & Ord, 1992) test and time (i.e., from one bin to another over the z-axis, via Mann-Kendall rank-correlation statistics (Hamed & Rao, 1998). Significant spatiotemporal trends (i.e., hot spots or cold spots) are further characterized as persistent, increasing, or decreasing, to give 16 cluster patterns categorized as “new,” “consecutive,” “intensifying,” “persistent,” “diminishing,” “sporadic,” “oscillating,” and “historical,” each for “hot” or “cold” spots, in addition to the “no pattern detected” category. The formal definitions of these patterns are provided, with their resulting frequencies, in Table 5.1. The Getis-Ord Gi* test provides z-scores with p-values for each bin, based on neighborhood distance and neighborhood time step parameter values. The statistically significant high and low z-scores measure the intensity of the centroid clustering in comparison to its neighboring centroids. The Mann-Kendall test assesses the temporal frequency trend for each bin by assigning a +1, –1, or 0 to that bin if the frequency of centroid location for a given year is larger, smaller, or equal to (respectively) that of the previous year in the same bin.
For each bin, this value is summed for each of the 39 pairs of consecutive years, with the rank-correlation identifying significance of the temporal frequency trends in that bin.

### 5.4 Results and Discussion

#### 5.4.1 Trend Analysis

##### 5.4.1.1 Linear Trend

Linear regression reveals a significantly decreasing trend (p-value < 0.0001) for all three time periods considered. Thus, over the 1979–2017, 1979–2001, and 2002–2017 periods, the NHCPV centroid daily distance from the previous day decreased by 21.27, 20.17, and 8.402 m day\(^{-1}\), respectively (Figures 5.1 and 5.2). The decreasing trend is significant for each of the cases (p-value < 0.001) and more robust earlier than later in the study period. This implies that the NHCPV centroid position has stabilized over time, even as Northern Hemispheric mean surface temperatures have warmed abruptly over the 2002–2017 subperiod. One possible explanation is that the largely uniformly “warm-phase” Atlantic Multidecadal Oscillation (AMO; Kerr, 2000), AO, and NAO in the second subperiod would likely support a more consistent (poleward) position of NHCPV displacement over the Atlantic and (potentially) a simultaneous consistent (equatorward) displacement toward the Eastern Hemisphere. The decreasing trend in daily distance moved (i.e., increasing consistency in centroid position) would have been more noticeable in the latter half of the 1979–2001 period, leading to a stronger decrease in daily distance moved in the first sub-period, with more stabilization in the latter sub-interval.
<table>
<thead>
<tr>
<th>Pattern name</th>
<th>*Definition</th>
<th>(a) Number of bins (Total 3681)</th>
<th>(b) Number of bins (Total 1171)</th>
<th>(c) Number of bins (Total 1003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Pattern Detected</td>
<td>Does not fall into any of the hot or cold spot patterns (i.e., no significant trend)</td>
<td>2798</td>
<td>163</td>
<td>615</td>
</tr>
<tr>
<td>New Hot (Cold) Spot</td>
<td>Statistically significant (SS) hot (cold) spot for the final time step and has never been a SS hot (cold) spot before</td>
<td>5 (3)</td>
<td>0 (0)</td>
<td>10 (0)</td>
</tr>
<tr>
<td>Consecutive Hot (Cold) Spot</td>
<td>A single uninterrupted run of SS hot (cold) spot bins in the final time-step intervals. Location has never been a SS hot (cold) spot prior to the final hot (cold) spot run and &lt; 90% of all bins are SS hot (cold) spots</td>
<td>3 (1)</td>
<td>0 (57)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Intensifying Hot (Cold) Spot</td>
<td>Has been a SS hot (cold) spot for ≥ 90% of the time-step intervals, including the final time step, while the intensity of clustering of high counts in each time step is increasing significantly</td>
<td>81 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Persistent Hot (Cold) Spot</td>
<td>SS hot (cold) spot location for ≥ 90% of the time-step intervals with no discernible trend in the intensity of clustering over time</td>
<td>240 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Diminishing Hot (Cold) Spot</td>
<td>SS hot (cold) spot location for ≥ 90% of the time-step intervals, including the final time step while the intensity of clustering in each time step is decreasing significantly</td>
<td>2 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Sporadic Hot (Cold) Spot</td>
<td>An on-and-off-again hot (cold) spot location with &lt; 90% of the time-step intervals having been SS hot (cold) spots and no time-step intervals being SS cold (hot) spots</td>
<td>201 (324)</td>
<td>0 (350)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>Oscillating Hot (Cold) Spot</td>
<td>SS hot (cold) spot for the final time-step interval that has a history of also being a SS cold (hot) spot during a prior time step, with &lt; 90% of the time-step intervals having been SS hot (cold) spots</td>
<td>14 (1)</td>
<td>0 (601)</td>
<td>368 (4)</td>
</tr>
<tr>
<td>Historical Hot (Cold) Spot</td>
<td>The most recent time period is not hot (cold), but ≥ 90% of the time-step intervals have been SS hot (cold) spots</td>
<td>8 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>
Figure 5.1. Time series of the daily NHCPV centroid distance migration from 1979 to 2017. The smoothed black line, from Butterworth low-pass filtering, shows the irregular annual cycle. The line depicts a statistically significant (p<0.001) decreasing trend.

Figure 5.2. As in Figure 5.1, but for the (a) 1979–2001 and (b) 2002–2017 periods; the linear decreasing trends are statistically significant (p<0.001 in both cases).
5.4.1.2 Seasonal Cycle

Spectral analysis of the daily time series of centroid distance from the previous day reveals distinct periodicity, including intra-annual periodicities, of the centroid location, with high-frequency variability modes for all three time intervals considered. All three periods show two distinct periodic signals and two weak or indistinct intra-annual signals (Figures 5.3 and 5.4) in the FFT analysis. In the full time series (1979–2017) and 1979–2001 subperiod, the strongest signal is semi-annual, suggestive of the cold-warm seasonal flow, and the second-strongest is the annual. Two weaker intra-annual cycles of ~3 and ~6.5 cycles per year are observed (Figures 5.3 and 5.3a). The latter subperiod (2002–2017) shows stronger annual than semi-annual amplitudes in addition to weaker intra-annual signals at ~4 and ~7 cycles per year (Figure 5.3b). The full time series includes stronger annual and semi-annual amplitudes than in either sub-interval, perhaps because outliers may have a relatively smaller effect in the longer temporal period of analysis.

Figure 5.3. Magnitudes of the power spectra obtained by FFT analysis of the daily NHCPV centroid distance moved from the previous day (1979–2017). The red circles indicate the magnitude of the high-frequency variability. The left circle peaks at 1 cycle per year and the right circle peaks at 2 cycles per year.
Figure 5.4. As in Figure 5.3, but for (a) 1979–2001 and (b) 2002–2017, both with peaks at 1 and 2 cycles per year.

5.4.2 Centroid Clustering Patterns over Space and Time

The EHSA-derived frequencies of each hot/cold spot category, tabulated separately for the three time intervals, are shown in Table 5.1.

Over the 1979–2017 period, centroid hot and cold spots are distributed widely, ranging from north of the Bering Sea to south of Greenland; Figure 5.5 shows these along with their EHSA-derived categories. Of the 3681 bins, 554, or 15.05 percent (329, or 8.94 percent) show a statistically significant linear trend in their hot (cold) spot category (Table 5.1), for a total of 883 bins having a trend; the remaining 2798 bins (76.01 percent) show no pattern.

A trend for spatiotemporally increasing displacement of hot spots toward the Pacific basin over time is evident (Figure 5.5), supporting the notion of the influence of the AMO and NAO, especially in the second subperiod. Persistent (27.18 percent of the 883 bins with a trend) and Intensifying (9.17 percent) hot spots are over the Arctic Ocean basin, but mostly skewed toward the Pacific (Figure 5.5). A cluster of Oscillating hot spots (1.59 percent) is also present on the Pacific side near the Bering Strait, while three New hot spots emerge at the edge of the cluster with two other outlying New hot spots are in northeastern Canada. Three large clusters
are classified as Sporadic (22.76 percent), which fluctuates between hot and “neither hot nor cold” over time; one of these is on the Pacific side along with the main cluster, another is over eastern Greenland, and the third is over eastern Canada. Two Diminishing hot spots and eight Historic hot spot bins are barely noticeable on the southern fringe of the large cluster over the Atlantic side of the Arctic basin.

Figure 5.5 also shows the centroid cold spots over this study area. These include the Sporadic (39.64 percent of the significant bins), New (<0.01 percent), Consecutive (<0.01 percent), and Oscillating (<0.01 percent) cold spots. Note that a New cold spot and a Consecutive cold spot are found over extreme southeastern Siberia. The EHSA shows how the location and intensity of the centroid clusters change over the Pacific and the Atlantic for the 1979–2017 period. These cluster positions also support the finding from the linear regression analysis that the centroid position became increasingly static while drifting toward the Eastern Hemisphere.
Figure 5.5. Categorization of NHCPV centroid position by hexagonal bin, based on significance of linear temporal trends, using emerging hot spot analysis, 1979–2017.

Figure 5.6 shows the 1979–2017 change in intensity of hot and cold spots, by bin, according to the Mann-Kendall trend test. A total of 370 bins (of 3681, or 10.05 percent) shows a significant uptrend, with 78, 160, and 132 of these significant at the 99, 95, and 90 percent level, respectively. On the contrary, 498 bins (of 3681, or 13.53 percent) show significant downtrends, with 121, 200, and 177 of these significant at the 99, 95, and 90 percent level, respectively.

To validate at the daily scale the findings of Wrona and Rohli (2007), who suggested that, except in spring, the monthly mean centroid positions (1959–2001) tended to be displaced toward Eastern Hemisphere, the EHSA was performed over the 1979–2001 period and in segmented intervals of 1979–1984, 1985–1990, 1991–1996, and 1997–2001. This analysis is
Figure 5.6. Linear temporal trends in the NHCPV centroid hot spot location intensities by bin, according to the Mann-Kendall statistics, 1979–2017.

Also conducted to validate the suggestion of Wrona and Rohli (2007) of low circular variability for the centroid location, which implies that the centroid position moved little between 1959 and 2001.

Among the 1171 bins showing statistically significant (at a 95% confidence interval) temporal trends over 1979–2001 period, nearly all are cold spots. The Oscillating cold spot dominated these, with 601 bins, mostly over the Arctic basin with some elongation in the Atlantic (Figure 5.7a). Of the remaining trending bins, 350 are Sporadic cold spots and 57 were Consecutive cold spots (Figure 5.7a). Only 163 bins (16.17 percent) show no pattern over the 1979–2001 period, while 2798 (76.01 percent) display no pattern over the 1979–2017 period.

82
Figure 5.7. Emerging hot spot patterns showing the significant trends of centroid positions over (a) 1979–2001 and (b) 2002–2017.
This vast difference may indicate that randomness in centroid positions increased as the daily distance moved decreased. In the 2002–2017 interval (Figure 5.7b), the cold spots are virtually absent, with Oscillating hot spot (368 bins) dominating the Arctic Basin. By contrast, the Oscillating, Sporadic, and Consecutive cold spot bins decreased to 4, 5, and 0 bins, respectively. The New hot spot emerged along with the core mostly the Eastern Hemisphere with 10 bins and Sporadic hot spot has only 1 bin (Figure 5.7b). Moreover, the emergence of New and other hot spots and reduction of the cold spots indicate an overall trend toward hot spots.
Within the first half of the time series, the EHSA on segmented time periods (over 1979–1984, 1985–1990, 1991–1996, and 1997–2001; Figure 5.8a-d, respectively) suggests that the number of Persistent hot spots decreased across the four segments while the Oscillating hot spots increased suddenly in the 1997–2001 period. The number of New cold spots was high in comparison to New hot spots, especially from 1979 to 1984, with the New cold spots skewed toward the Arctic basin and north of Greenland (Figure 5.8a-d). On the contrary, the last four segmented periods (2002–2005, 2006–2009, 2010–2013, and 2014–2017; Figure 5.9a-d, respectively) show that the number of Sporadic and (to a lesser extent) Consecutive hot spots increased abruptly in 2014–2017 (Figure 5.9d), and all these patterns are situated towards the Eastern Hemisphere of the North Pole (Figure 5.9a-d). The time series of bin frequencies by segmented time periods is shown in Figure 5.10.
Figure 5.9. As in Figure 5.7, but for (a) 2002–2005, (b) 2006–2009, (c) 2010–2013, and (d) 2014–2017.
5.5 Summary and Conclusions

Studying the spatiotemporal CPV centroid characteristics is important for enhancing understanding in applications such as medium-to-long range weather forecasting, short-range climate prediction, and assessing impacts of air-sea teleconnections such as the AMO and NAO. Linear trend analysis suggests that the day-to-day distance moved by the NHCPV centroid decreased significantly over time from 1979 to 2017, while there are persistent semi-annual and quarterly cycles visible throughout the time series but with different magnitudes. While the decreasing trend indicates stability in the centroid positions, the periodic cycle may provide an indication of the causes of perturbations such as weather pattern variability and extremes.

Over the 1979–2017 period, EHSA identifies locations that are more likely (hot spots) and less likely (cold spots) for the NHCPV centroid, and temporal changes in the preference of
such locations. A strong preference for hot spots toward the Eastern Hemisphere is notable across the study period. A number of hot and cold spots emerge and weaken over the last four decades, especially in the 1979–2001 sub-interval. Over the 2002–2017 period, the emerging hot spots are sufficient in number to skew the trend, according to the Mann-Kendall trend analysis over the 1979–2017 period.

Understanding spatio-temporal changes in centroid locations is useful, as Chen et al. (2015) noted the importance of such finite-amplitude wave activity for assessing future impacts of regional climate change. Future research will proceed with identifying the variability of the CPVs centroid positions at multiple atmospheric levels to consider the baroclinicity of the steering atmospheric circulation’s response to continued surface warming, in the form of the NHCPV.
CHAPTER 6.
SUMMARY/CONCLUSIONS

6.1 Summary of Findings

The circumpolar vortex (CPV) is the continuous, permanent flow of generally west-to-east winds (i.e., the westerlies) in the middle-to-upper troposphere, more-or-less centered over each pole at a given time and separating the cold polar air from much warmer air. This important feature of the atmospheric steering circulation is linked to variability in surface environmental features. The CPV can be characterized by its centroid location, area, and circularity (or waviness; (CLAC), all of which vary over time and space.

This research uses geospatial tools and technologies to delineate the Northern Hemisphere’s circumpolar vortex (NHCPV), popularly known as the “polar vortex” and analyze the spatiotemporal variability and change in the NHCPV over the 1979–2017 period, as a mechanism that drives and (in many ways, more likely) is driven by changes in air-sea teleconnections, surface weather systems, and general environmental characteristics. Results from the delineation of the NHCPV’s CLAC allow for hypothesis testing regarding variability and long-term change in the NHCPV, likely resulting from long-term surface warming.

6.1.1 An Improved Method to Define NHCPV

Chapter 2 identified the leading edge of the NHCPV as the boundary at the 500-hPa geopotential height level (i.e., the height at which approximately half of the mass of the atmosphere lies above and half lies below it) where cold air (i.e., with greater density) meets much warmer air (i.e., with lesser density) from the temperate zones of Earth. The approach is innovative because it uses an improved, data-intensive technique that automates and objectivizes the process of identifying the NHCPV. The method offers advantages over the previous techniques, as the area and waviness of the polar vortex are shown to relate better to other known
atmospheric features, such as circulation associated with El Niño, than the area and waviness of the CPV as computed in previous research. The NHCPV area is delineated using geographic information systems technology, in which Lambert’s Equal Area projection is used to compute the area encircled within the NHCPV. The “waviness” is represented using the “circularity ratio” ($R_c$) concept (Chorley et al., 1984) in which a conformal (i.e., equal shape) polar stereographic projection is used to find the perimeter of the NHCPV, where $R_c$ is defined as the ratio of the NHCPV area to the area of a circle with the same perimeter as the NHCPV on that day. When $R_c = 1$, the NHCPV is perfectly circular (i.e., has west-to-east flow); near-zero $R_c$ implies amplified ridges and troughs. This research is valuable because improved identification and definition of the size and shape of the polar vortex at a daily scale will contribute to greater understanding of its impacts.

*Key Points:*

- The leading edge of Northern Hemisphere’s tropospheric circumpolar vortex is delineated by the steepest 500-hPa geopotential height gradient.
- The new delineation represents area and circularity of the tropospheric circumpolar vortex effectively.
- This technique facilitates further work on atmospheric circulation variability by showing that it is possible to use similar techniques to evaluate the NHCPV at multiple vertical levels beyond the 500-hPa level.

6.1.2 Correlation and Variability of NHCPV Features with Air-sea Teleconnections

While the results of Chapters 2, 4, and 5 showed that the use of predetermined isohypses to represent the NHCPV may lead to spurious results, Chapter Five showed that using monthly-averaged data to represent the NHCPV may oversimplify analyses, especially for identifying
association with the air-sea teleconnections at the daily scale. This research delineates the
NHCPV at a daily-scale and suggests that the daily NHCPVs are more closely related to the
variability in the extratropical Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and
Pacific-North America (PNA) teleconnections than with the tropical El Niño / Southern
Oscillation (ENSO) phenomenon, than those identified by Wrona and Rohli (2007) who used
preconceived isohypses on monthly mean data. A principal components analysis (PCA) reveals
the extent of the interrelationships between the air-sea teleconnections and the NHCPV. Results
generally affirm that both the individual teleconnections, especially the NAO and AO, and
interdependencies among these teleconnections and others, are strongly related to the NHCPV
area and circularity. This finding is important because low- and high-frequency variability of the
broad-scale flow influences the weather systems.

Key Points:

- High-frequency (i.e., daily) variability of the NHCPV area and circularity is linked to
  variability in air-sea teleconnection patterns, in some cases better than monthly mean
  data.
- Both NHCPV area and R_c are more strongly correlated with the extratropical AO, NAO,
  and PNA teleconnections than they are correlated to the tropical ENSO phenomenon as
  identified by the Southern Oscillation Index and the Niño3.4 index.

PCA suggests that NHCPV R_c is closely tied to the mode of variability represented by the AO
and NAO, acting together, and that NHCPV area is linked more closely to the component
dominated by the PNA teleconnection.
6.1.3 Multidecadal Linear and Cyclical Temporal Characteristics of the NHCPV

Chapter 4 revealed that at the 500-hPa level, the NHCPV area has shown a statistically significant linear temporal increase over the 1979 to 2017 period and within four of the 1979–1986, 1986–1994, 1994–2001, and 2001–2017 subperiods therein, but with area during 1979–1986 subperiod increasing only at a 90% confidence level. This result is somewhat surprising because a warming planet was hypothesized to be associated with a decrease the area of the cold pool of air contained within the NHCPV. Therefore, follow-up analysis was conducted in Chapter 4, which revealed that the result can be explained by the fact that the gradient delineating the NHCPV weakened temporally, even as the NHCPV expanded, as the air within the NHCPV warmed more than the temperate air outside the NHCPV. This result is in line with the theory of Arctic amplification (Holland & Bitz, 2003; Pithan & Mauritsen, 2014; Francis et al., 2017; Francis et al., 2018), which suggests that the high latitudes experience an even greater rate of warming than tropical areas, which would weaken the sharpest gradient of atmospheric mass at the leading edge of the NHCPV.

Chapter 4 also revealed that waviness, as represented by $R_c$, demonstrated an overall insignificant linear temporal trend over the 1979 to 2017 period, but with opposing trends during various subintervals of that period. Specifically, an increasing linear trend was observed over the 1979–1988 and 1994–2001 subperiods (90% and 95% level of significance, respectively), and a decreasing linear trend occurred over the 1988–1994 and 2001–2017 subperiods (95% and 90% level of significance, respectively).

Variability in CPV area and waviness is an important indicator of the impact of globally changing temperatures on atmospheric circulation and can have implications on surface weather/climate and their impacts. Results from Chapter 4 imply that the sharpest gradient of
atmospheric mass in the Northern Hemisphere has moved equatorward as the polar area has warming at a faster rate than the equatorial region. Moreover, the NHCPV’s shape may be characterized by alternating increases and decreases in Rossby wave amplification over time due to an environment of weakening equator-to-pole gradients of atmospheric mass and weakened zonal winds, which may in turn amplify (but perhaps simultaneously weaken) the Rossby waves. This result is consistent with suggestions from previous studies (e.g., Francis and Vavrus, 2012, 2015; Peings and Magnusdottir, 2014). It is possible that changes in the dominant modes of low-frequency variability in air-sea teleconnections may be at least partially responsible for these “regime shifts” in 1994 and 2001.

Some modes may be associated with increased frequency and magnitude of weather extremes.

Key Points:

- The Northern Hemisphere’s 500-hPa circumpolar vortex (NHCPV) has expanded linearly over time (1979–2017), but at different rates and levels of significance in the subperiods.
- The NHCPV’s “waviness” shows an insignificant trend over the 1979–2017 period, with subperiods showing alternating significantly increasing and decreasing trends.
- These conclusions are drawn cautiously, as the 500-hPa geopotential height gradient delineating the NHCPV’s boundary has weakened over time, blurring its distinctiveness.

6.1.4 Spatiotemporal Variability of NHCPVs Centroids

While Chapter 2 implemented an approach for delineating the leading edge of the boundary of the cold polar air circulation – i.e., the NHCPV, and Chapter 4 described the temporal trends in area and circularity in the NHCPV, Chapter 5 identified the position of the centroid of the NHCPV on a daily basis, from 1979 through 2017. Results suggest that the
centroid’s position has stabilized over time while maintaining a preferred position on the Eastern Hemisphere side of the North Pole. Over the 1979–2017, 1979–2001, and 2002–2017 subperiods, the NHCPV centroid daily distance shows a significantly decreasing trend (p-value < 0.0001), high-frequency variability modes of two distinct periodic signals (annual and semi-annual), and two weak or indistinct intra-annual signals (at ~3–4 and ~ 6.5–7 cycles per year). While the decreasing trend indicates increasing consistency in centroid position, the periodic cycle may indicate the causes of perturbations, such as seasonality and weather pattern variability and extremes. These results are important because they suggest that the middle weather layer in the atmosphere may responding slowly to the near-surface warming over the last few decades.

Key Points:

- Daily distance that the Northern Hemispheric circumpolar vortex centroid moves decreases linearly over time, with distinctive seasonality.
- The centroid tends to be displaced toward the Eastern Hemisphere, likely due to the influence of warm Atlantic Ocean circulations.
- These results are important because they suggest that they index the mid-tropospheric response to observed surface warming.

6.2 Intellectual Merit and Broader Impacts

Collectively, the research contained in this dissertation provides an avenue to link the capabilities of geographic information systems (GIS), computational systems, and the meteorology of air-sea interactions in a way that has not been attempted previously. Novel NHCPV metrics were developed based on improved, objective criteria and datasets. Furthermore, the use of the “circularity ratio” as an indicator of the shape of the CPV introduced
in this research allows for more efficient description of the CPV shape. This research is among the first (along with studies such as Di Capua and Coumou (2016)) to introduce daily data in CPV research, and therefore provides a means to assess the validity of monthly mean data in assessing the CPV condition. The metrics generated provide far more temporal detail about the variability of the CPV than the mean monthly approaches employed in research to date. This detail, as represented by the daily CLAC properties, improves understanding of causative physical linkages and surface-atmosphere interactions contributing to atmospheric circulation variability at higher frequencies than is currently possible using existing knowledge at the monthly-seasonal scales. Finally, the often-overlooked concept of appropriate use of map projections is promoted as an improvement in our understanding of spatial aspects of atmospheric circulation.

The research provides valuable results that informs a range of work, primarily through its derivation of an objective means of assessing the relative impact of extratropical vs. tropical teleconnections in modulating longwave extratropical hemisphere-scale flow. Such understanding at this temporal scale is useful in medium-to-long range weather forecasting, short-range climate prediction, and in assessing impacts of teleconnections including the AO, NAO, PNA pattern, Pacific Decadal Oscillation, and possibly even ENSO, which to date have been examined largely at broader time scales. Chen et al. (2015) noted the importance of such finite-amplitude wave activity for assessing future impacts of regional climate change. All of these results would further protect life and property due to weather and climate and enhance economic development, as a variety of economic sectors are influenced by weather. The results have direct benefit across the extratropical Earth and of indirect benefit globally.
The results of this research may also inform general circulation modelers as they seek to link their model output with natural and societal impacts. For instance, general circulation model results suggest future intensification of the AO (Givati & Rosenfeld, 2013), NAO (Bacer et al., 2016), and the Southern Annular Mode (SAM) – the Southern Hemisphere equivalent to the AO (Paeth & Pollinger, 2010). If this is indeed the case, then results here that quantify the relationship between the AO and NAO will help to assess future changes in NHCPV metrics and impacts.

6.3 Future Research

Future research on this theme will begin by examining the extent to which the NHCPV properties persist in similar ways as found at the 500-hPa level at other levels in the atmosphere. The hypothesis is that steering circulation response to the observed surface warming begins with the lower levels of atmospheric flow and extends upward over time. A second avenue of future research will extend the same hypotheses to the Southern Hemisphere’s CPV (SHCPV). The hypothesis is that the centroid remains centered over the South Pole, but that the area has decreased over time and the circularity increased over time, both in response to the observed multidecadal surface warming. Testing of these hypotheses will allow for evaluation of whether the unexpected temporal increase in area of the NHCPV as found in Chapter 4 is accompanied by the same trend in the Southern Hemisphere, or whether the Northern Hemisphere’s areal trend was spurious or unique to the conditions in that hemisphere. Such research would also be able to better conceptualize the impacts of the forecasted intensification of the SAM.

In a more general sense, future NHCPV and SHCPV research must continue to improve the understanding of the linkages between local-, meso-, and macro-scale air and ocean circulation, especially as integrated by land-air-sea interactions, by using machine learning
and/or related data mining techniques. Such considerations will improve understanding of latent and stochastic relationships between circulation variability and magnitude/frequency of extreme weather events across scales. Such holistic understanding of the long-term variability and expected trends and impacts of the broad-scale circulation is lacking, particularly regarding extreme weather events. As a result, the ability to harness knowledge of steering atmospheric circulation as a tool for societal impact assessment can be enhanced. Specifically, this gap can be filled by causatively linking current and model-based future 4D (x, y, z, t) hemispheric-scale circulation variability and extreme weather impacts, characterized via atmospheric hazard-related losses in the United States. Identification, quantification, and explanation of projected changes in CPV CLAC under climate change scenarios (including isolating the impact of Arctic sea-ice loss); linking these to surface extreme events; and assigning monetary values to the losses from those identified extreme events will provide valuable insight.

The tools for addressing this overarching goal will include more robust data sets, multiple vertical heights in the atmosphere, data mining, and climate model projections. Specifically, the daily CPV could be characterized using the techniques identified in this dissertation, but with the now-available, much finer-resolution (0.25° x 0.25°) European Reanalysis (ERA5) dataset, at the 700-, 500-, 300-, and 200-hPa levels, which will facilitate identification of the land-air-sea interactions. After validating results from the dissertation (which was done using data at a 2.5° x 2.5° grid), the ERA5 data and data mining approaches will provide an opportunity to isolate impacts of short waves in addition to the Rossby waves identified in this dissertation. Then, the important patterns could be analyzed in relation to output from the latest state-of-the-art climate model projections of the Coupled Model Intercomparison Project Phase 6 (CMIP6). Economic
impacts could be identified using the freely-available Spatial Hazard Events and Losses Database of the U.S. (SHELDUS). Figure 6.1 shows some of the many long-term possibilities.

Figure 6.1. Schematic of future research interests related to variability in CPV associated with land-sea-air interaction over various spatiotemporal scales. Dashed outlines highlight areas of specific research goals, with double-headed arrows indicating two-way relationships.
APPENDIX.
CHAPTER 2 PERMISSION


Dear Editor Benoît Pirenne,

In 2019, I authored the following manuscript [Paper #2019EA000590R] that is published in Earth and Space Science:

**Bushra, N., & Rohli, R. V. (2019). An objective procedure for delineating the circumpolar vortex. Earth and Space Science, 6(5), 774-783.**

I am writing to request permission for this publication to appear as a chapter in my upcoming dissertation. Please let me know if I have your permission to:

1) reprint the manuscript as is;
2) make changes to it, particularly if requested by my dissertation committee members; and
3) renumber figures to conform to guidelines by my Graduate School (for instance, renumbering Figure 1 as Figure 3.1, etc.).

I must provide the draft to my committee at the beginning of February, so I look forward to your reply. Thank you.

Sincerely,

**Nazla Bushra**
Ph. D. Candidate
Department of Oceanography and Coastal Sciences
College of the Coast and Environment
Louisiana State University
Baton Rouge, LA 70803, USA

Dear Dr. Bushra,

AGU does allow for use of published manuscripts for academic purposes:

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Best,

Brian Sedora
LIST OF REFERENCES


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VITA

Nazla Bushra was born in 1985, in Dhaka, Bangladesh. She completed her Bachelor of Science degree in 2009 and Master of Science degree in 2012 in Geography and Environment from the University of Dhaka, Bangladesh. She received a Dean’s Award, University Grants Commission Award, and Academic Merit Scholarship for her results. During her studies and afterwards she worked as a project coordinator, GIS analyst, and research officer for various government and non-government organizations. In October 2009, she was named as an International Climate Champion and expanded her network to the International level. She also obtained a Post Graduate Diploma in Water Resource and Flood Management in 2013 from the Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, under a South Asian Water (SAWA) fellowship. She joined the faculty at the University of Chittagong in March 2012 and later at the University of the Dhaka in November 2012. She showed courage to leave her family to pursue her second Master of Science degree in Geography from the Louisiana State University, U.S.A., in 2014 under the Fulbright Program. After receiving her second M.S. degree, she received an Economic Development Assistantship and Dissertation Year Fellowship to pursue her doctorate degree in Oceanography and Coastal Sciences under the supervision of Dr. Robert V. Rohli in the Department of Oceanography & Coastal Sciences of College of Coast & Environment at Louisiana State University. She is also a Louisiana Sea Grant Graduate Research Scholar. During her Ph.D. program she was able to reunite with her family. She is also a mother of two wonderful children and a wife of a devoted husband. Her research expertise also includes drought severity index accuracy assessment, combined risk modeling from hurricane-induced storm surge and wind, climate hazard variability and their associated impacts on the landscape and human communities, and risk estimation due to extreme weather events.