UNDERSTANDING THE DRIVERS OF NORTH AMERICAN COLD SPELLS IN PRESENTS AND FUTURE CLIMATES

MASTER THESIS, 30 HP, IN ATMOSPHERIC SCIENCES, OCEANOGRAPHY, AND CLIMATE

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Abstract

Cold wintertime extreme events over North America have substantial impact on major sectors of society. These events are characterized by southward propagation of cold air from the polar regions to lower latitudes. In this study, I analyse ERA-Interim reanalysis and CMIP5 model data on monthly timescales in order to analyse the link between the cold spell events over North America (USC) and the North American sector of the Circumglobal Teleconnection Pattern (CNA). This is a circum-hemispheric quasi-stationary wave packets of zonal wavenumber 5 that was found to be a driver of these extreme events in past studies. The analysis is based on 2-meter surface temperature, 500 hPa geopotential height, and 300 hPa wind. Based on reanalysis output, the extreme CNA events are closely related to USC events, with spatial correlation in 2-metre temperature fields over North America of 0.68 over the period 1979 to 2005. The atmospheric anomaly patterns associated with these two classes of events are very similar, albeit with local differences. I also evaluate the performance of eight individual CMIP5 models in order to test the reliability of the models. Among the selected models, the CCSM4 model performs best in reproducing the USC-CNA link. Model simulations for future climate under an RCP8.5 scenario suggest that climate change affects the surface temperature and geopotential height anomalies associated with CNA events relative to the historical period.
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1. Introduction

During recent winters, extreme weather conditions with cold spells over North America gained media attention and impacted widely the region’s society and economic sector (e.g., Scholer, 2014; Weisenthal, 2014). Several studies have shown that severe cold events over North America are related to persistent large-scale circulation anomalies which bring cold air equatorward from the Arctic region (Konrad and Colucci, 1989; Walsh et al., 2001; Loikith and Broccoli, 2012). Recently, it has been suggested that a driver of the recurrent cold spell episodes might be a hemisphere-wide teleconnection pattern consisting of zonal wavetrain that propagates from Pacific, over North America and into the Atlantic (Messori et al., 2016). The existence of this wave train during boreal winter leads to the appearance of strong negative temperature anomalies over eastern North America several days later. The zonal scale of this wave pattern closely resembles that of the so-called Circumglobal Teleconnection Pattern (CTP): a pair of circum-hemispheric quasi-stationary wave packets of zonal wavenumber 5, which was proposed by Bransator (2012). Harnik et al. (2016) examined the relation between CTPs and cold spells over North America using reanalysis data. They concluded that the large-scale circulation anomalies which drive the severe North American/United States cold events are associated with the regional projection of the second CTP pattern over North America (CNA).

In addition to the above, a number of other studies, such as that by Grazzini and Vitart (2015), have attempted to track and predict wave-packet patterns that originate from the West Pacific. Similarly, (Seager & Henderson, 2016) showed how a zonal wave pattern similar to the CNA pattern is influenced by SST anomalies over the tropical Pacific. However, little research has been carried out in testing these mechanisms in the CMIP5 models and in verifying how the CNA-cold spells link may respond to climate change. Further studies are therefore needed to gain a better understanding of the ability of climate models to reproduce the CNA-Cold spells link and how this may change under future climates.

The aim of this project is to test the extent to which climate models reproduce the link between the large-scale atmospheric wave pattern known as CNA and North American cold events under the present climate and how this link may change under future climates. Furthermore, I will verify whether the results of Harnik et al. (2016) and Messori et al. (2016), obtained with daily data, also hold when considering monthly timescales. In the first part of the study, the CNA-cold spell link will be analyzed in the ERA-Interim reanalysis data using monthly-mean values of several parameters such as surface temperature, wind and geopotential height. The result will then be used to verify whether the historical simulations of the CMIP5 models correctly reproduce the CNA-cold spells link. Finally, the impact of future climate change on the CNA pattern will be analyzed using CMIP5 model data under the RCP8.5 scenario. Some theoretical background regarding US cold spells and the CTP will be provided in Section 2. The data and methodology used in this project are briefly described in Section 3, followed by the analysis and discussion of the results in Section 4.
2. Background and theory

2.1. Dynamics governing the US Cold Events (USC)

Extreme wintertime cold spells over North America, or US Cold Events (USC), are commonly characterized by the existence of polar anticyclones originating in the northwestern Canada-Alaska region and moving south towards United States several days before the lowest temperatures are reached (Dallavalle & Bosart, 1975; Walsh et al., 2001). Cold air advection, mass convergence, and diabatic cooling are believed to be the main dynamical drivers of polar anticyclone formation (Wexler, 1951). According to Wexler (1951), the presence of snow and ice fields leads to higher surface albedo and radiative cooling over the polar region. Furthermore, oceans and big lakes have a larger heat capacity than land and so absorb a large amount of radiation and release less heat, causing radiative cooling over the surface. Surface cooling in restricted areas vertically lowers isobaric surfaces, causing upper level mass convergence, and affects the surface layer of air. As a result, polar anticyclones are formed.

Many believe that cold spells are associated to the large-scale hemispheric circulation since there must be a mechanism that allows cold air from high pressure system over the Arctic region to penetrate into North America and propagate into Atlantic region. Several studies have been carried out during the past decades to find a holistic point of view, especially on the drivers of cold events. These studies have used different cold spell definitions, sub-domains and timescales (cf. Walsh et al., 2001; Portis et al., 2006; Wang et al., 2010; Messori et al., 2016; Harnik et al., 2016). The canonical modes of climate variability, such as North American Oscillation (NAO), Arctic Oscillation (AO), and Pacific/North American (PNA) pattern, can have a strong footprint on the surface temperatures over the North American continent, but are likely not associated to the severe cold events (Walsh et al., 2001; Loikith & Broccoli, 2012; Grotjahn et al., 2015; Messori et al., 2016). Recently, it has been suggested that a driver of the recurrent cold spell episodes might be a hemisphere-wide teleconnection pattern. According to Messori et al. (2016), there is a wave train of zonal wave number 5 that propagates from the Pacific, over North America and into the Atlantic over several days before the lowest temperature anomalies appear over eastern North America. According to Harnik et al. (2016), the zonal scale of this wave pattern closely resembles that of North American part of Circumglobal Teleconnection Pattern (CTP) which was proposed by Bransator (2012) and will be described in Section 2.2 below.

2.2. The Circumglobal Teleconnection Pattern and its correlation to USC

The CTPs are a pair of circum-hemispheric quasi-stationary wave packets of zonal wavenumber 5. They are diagnosed as the first two Empirical Orthogonal Function (EOFs) of the mean seasonal anomalies of nondivergent meridional wind at 300 hPa during the boreal winter. EOFs analyses are examined by projecting data onto the orthogonal set of vectors. An area-weighted anomaly covariance matrix of a field consists of eigenvalues and eigenvectors. Eigenvalues
provide the fractional variance of each spatial pattern while the eigenvectors are defined as orthogonal set of vectors. EOFs thus describe orthogonal variance patterns of data, where the dominant variance mode is represented by the first EOFs. The successive EOFs account for progressively lower proportions of the variances. Therefore, EOFs analysis is an effective tool for determining spatial climate variability patterns (Zhang & Moore, 2015). One of the applications of EOFs is to investigate the correlation between the regional climate variability and global hemispheric teleconnection patterns. For instance, Thompson and Wallace (1998) proved that the NAO is correlated to a hemispheric teleconnection pattern called Arctic Oscillation.

![Figure 1](image)

Figure 1: (a) The first empirical orthogonal function (EOF) of monthly mean seasonal anomalies of 300 hPa meridional winds (shading) and the meridional wind composite of positive PNA events (red-blue contours) using December–February data. (b) The second EOF of monthly mean seasonal anomalies of 300 hPa meridional winds (shading) and the day -3 meridional wind composite of eastern U.S. cold events (78 coldest events, red-blue contours). The contour interval is 3 m/s with thick lines denoting the 95% confidence level. The EOFs are plotted to represent one standard deviation of the principal component time series, with a contour interval of 1 m/s. For all fields red is positive, and blue is negative. (Figure and caption from: Harnik et al., 2016)

Branstator (2002) conducted an EOF analysis to assess whether zonally oriented waveguide disturbances trapped in the South Asian jet stream are related to a teleconnection pattern. The EOF analysis is used to verify the result of a one-point correlation method implemented by computing the correlation between 300 hPa meridional ($v$) wind variability during the December – February (DJF) season at a given location on the globe (base point), with the variability of the remaining grid points. The study concluded that these waveguide disturbances form part of a
circumglobal waveguide pattern. It is also pointed out that this pattern is correlated to NAO variability in the Northern Hemisphere.

Figure 2: Time lagged composite of 300 hPa meridional wind anomalies (contours) for (a, c, and d) positive CNA events at lags -4, 0, and 3 days. (b, d, and f) USC events at lags -7, -3, and 0, all plotted over the 300 hPa meridional wind anomalies corresponding to the second CTP pattern (shading). The projection region used to define the CNA events is marked by the black rectangle in Figures 2c and 2d. Contour interval is 5 m/s, with the ±2.5 m/s contours added, and the shading is similar to Figure 1b. For contours and shading, red is positive, and blue is negative. Thick contours mark 95% statistical confidence, and dark brown shading marks regions where 67% of the composite members have the same sign of the composite (chances of this happening randomly are well below 5%). (Figure and caption from Harnik et al., 2016)

Based on Branstator’s (2002) work, the relation between CTPs and cold spells over North America was examined by Harnik et al. (2016). In Figure 1, their results showed that North American cold events (USC) are associated with the second CTP pattern (see Figure 1.b), while the first CTP pattern fits more closely with the Pacific/North American (PNA) pattern (see Figure 1.a). In particular, the authors found a systematic link between USC and the regional sector of the CTP2 over the North American domain, called CNA pattern. In Figure 2, it is shown that the USC is highly correlated to CNA events (R² of 0.86) when the CNA events precede the USC events by 3 days. From this work, it can be concluded that the large-scale
circulation anomalies which drive the severe cold events over North America correspond to the CNA pattern and that the onset of this pattern can be traced to a zonal wavepacket propagating from Asia across the Pacific Ocean. The emergences of the Asian wave packet were often followed by USC events at lags of 8 – 12 days, thus providing a robust pathway to medium-range predictability.

2.3. Empirical Orthogonal Function Analysis

The approach for performing EOF analysis (following Hannachi et al. (2007)) is the following: Firstly, let us take the data matrix of an observable, consisting of gridded data \( x_{ij} \) (e.g. temperature, geopotential height, etc.) at discrete times \( t_i \) and grid point \( s_j \) where \( i=1, \ldots, n \) and \( j=1, \ldots, p \), written as

\[
X = (x_1, x_2, \ldots, x_n)^T = 
\begin{pmatrix}
x_{11} & x_{12} & \cdots & x_{1p} \\
x_{21} & x_{22} & \cdots & x_{2p} \\
\vdots & \vdots & \ddots & \vdots \\
x_{n1} & x_{n2} & \cdots & x_{np}
\end{pmatrix}
\]  

(1)

where \( x_t = (x_1, x_2, \ldots, x_n)^T. t = 1, \ldots, n \), are the values of the field time \( t \). In order to observe meaningful patterns, the anomaly field (\( X' \)) should be computed following Equation 2.

\[
X' = X - 1_n\bar{x} = \left(I_n - \frac{1}{n}1_n1_n^T\right)X =HX
\]  

(2)

where \( 1_n = (1, \ldots, 1)^T \) is a vector of ones of length \( n \), \( \bar{x} \) is the climatology field of \( x_t \), \( I_n \) is the identity matrix of \( n \times n \), and \( H \) is the centering matrix. Below, the anomaly matrix is written as \( X \) instead of \( X' \).

The next step is to determine the covariance of the field \( s_{ij} \) at grid points \((s_i, s_j)\) with \( i, j = 1, \ldots, p \) along the observation period, using Equation 3 and applying Equation 4 to build a covariance matrix.

\[
s_{ij} = [S]_{ij} = \frac{1}{n} \sum_{t=1}^{n} x_{ti}x_{tj}
\]  

(3)

\[
S = \frac{1}{n}X^TX
\]  

(4)

The basic principle of EOF analysis is to determine the largest variance of \( Xu \), as the uncorrelated linear combination from several variables with \( u = (u_1, \ldots, u_p)^T \) as a unit-length direction:

\[
max(u^TSu), s.t. u^Tu = 1
\]  

(5)

The eigenvalue solution is then:

\[
Su = \lambda^2 u
\]  

(6)
Based on Equation 6, if we define \( k = 1, \ldots, p \), the \( k \)'th of EOF corresponds to the \( k \)'th eigenvector \( u_k \). The eigenvalue \( \lambda_k^2 \) describes the variance of the data in the \( u_k \) direction and can be obtained as below:

\[
\lambda_k^2 = u_k^T S u_k = \frac{1}{n} \| X u_k \|^2
\]  

(7)

The variances are arranged in descending order and usually presented in percentages. The dominant features of the data are described by the largest variance. For analysis purposes, \( a_k = X u_k \) is defined as the anomaly field \( X \) that is commonly projected onto the \( k \)'th EOF \( u_k = (u_{k1}, \ldots, u_{kp})^T \) using:

\[
a_{tk} = \sum_{j=1}^{p} x_{tj} u_{kj}
\]  

(8)

Therefore, the \( k \)'th eigenvalue \( \lambda_k^2 \) is the variance of the \( k \)'th projected anomaly field \( a_k = (a_{1k}, a_{2k}, \ldots, a_{nk})^T \).

2.4. Definitions of the USC, CNA and Circumglobal Eurasian Patterns

2.4.1. The Circumglobal North American (CNA) pattern

The regional CTP for North America (CNA) can be obtained from the global CTP index following Harnik et al. (2016). First, the seasonal mean anomalies of the monthly mean 300 hPa meridional wind for wintertime (December-February) are computed. The global CTP2 index is defined as the second EOF of these winter anomalies. Next, the monthly 300 hPa meridional wind fields are projected onto the CTP2 index over the North American region (180-324°E and 10-85°N, following Yuan et al., 2011). The CNA index is the normalized projection on the CNA pattern. The months when the monthly running mean of the CNA index exceeds its mean by more than one standard deviation are defined as positive CNA events. The CNA indices for the NCEP/NCAR reanalysis and all the historical and RCP8.5 CMIP5 model simulations were already available for analysis from previous work (D. Sandler and N. Harnik, personal communication).

2.4.2. North American/Eastern United States Cold Spell (USC) events

Based on the work of Messori et al. (2016) and Harnik et al. (2016), the cold spell events are determined by computing the 2-meter air temperature anomalies over the eastern part of North America (100-70°W, 30-45°N) and ranked based on the area-weighted temperature anomaly. However, instead of using daily timescales as in the two previous works, the monthly mean anomalies of 2-meter air temperature are used to determine the cold extreme events in this project. The USC index is obtained from the time series of these normalized area-weighted temperature anomalies.
3. Methods and Data

3.1. Data

In this study, reanalysis and model data are used to understand the drivers of North American cold spells in past and future climates.

3.1.1. Reanalysis Data

Reanalysis data assimilates the available observational climate data into a numerical model (Kalnay, 1996). The gridded fields from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (Dee et al., 2011) over 1979 to 2005 (historical period) is used as the “ground truth” dataset to which the CMIP5 model results will be compared. ERA-Interim, has an approximately 80 km native horizontal resolution which corresponds to a T255 spectral truncation. Here, data interpolated to a regular 83km/0.75° grid is used. Surface temperature, 300 hPa zonal and meridional wind, and 500 hPa geopotential height are the three variables that are analysed. The dataset can be downloaded from ECMWF’s website at [http://apps.ecmwf.int/datasets/](http://apps.ecmwf.int/datasets/).

In this study, monthly mean anomalies are used for the analysis. These are computed by removing the December–February climatological mean from monthly mean fields. The next step is selecting the extreme events by ranking the coldest months with lowest area-weighted 2-meter temperature over the USC domain (defined in Section 2.4.2). The top 16 months, corresponding to the top 20 percentiles, are selected. The 16 months with the highest CNA index are also analysed by ranking the CNA Index that is computed as described in Section 2.4.1.

3.1.2. CMIP5 Models

The climate model data are taken from the Coupled Model Intercomparison Project Phase 5 (CMIP5). These are used to obtain regional Circumglobal Teleconnection Pattern (CTP) indices for the historical period (1979 – 2005) and for future (2006-2099) under the Representative Concentration Pathway (RCP) 8.5 scenario.

RCPs are scenarios of greenhouse gas concentrations and emissions designed to investigate the possible future impacts and responses to climate change (Riahi, et al., 2011). The RCPs are described in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and consist of four pathways: RCP2.6, RCP4.5, RCP6, and RCP8.5. Every pathway number corresponds to the radiative forcing at the top of atmosphere in Wm⁻² that will be generated by the scenario. RCP8.5 is associated to a continuous increment of greenhouse gas emissions and concentration over time that leads to radiative forcing of 8.5 Wm⁻² by 2100. This scenario makes several assumptions: high population, lack of technology changes, low rate of GDP growth, high energy consumption and GHG emissions (van Vuuren et al., 2011).
Table 1: CMIP5 model configurations used in this study (Adopted from Tian et al. (2013) and http://cmip5.whoi.edu/?page_id=339)

<table>
<thead>
<tr>
<th>Modelling Center</th>
<th>Institution ID</th>
<th>Model</th>
<th>Horizontal Resolution (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commonwealth Scientific and Industrial Research</td>
<td>CSIRO-BOM</td>
<td>ACCESS1.0</td>
<td>1.25 1.875</td>
</tr>
<tr>
<td>Organization (CSIRO) and Bureau of Meteorology (BOM), Australia</td>
<td></td>
<td>ACCESS1.3</td>
<td>1.25 1.875</td>
</tr>
<tr>
<td>Beijing Climate Center, China Meteorological Administration, China</td>
<td>BCC</td>
<td>BCC-CSM1.1</td>
<td>2.8 2.8</td>
</tr>
<tr>
<td>National Center for Atmospheric Research, USA</td>
<td>NCAR</td>
<td>CCSM4</td>
<td>0.9 1.25</td>
</tr>
<tr>
<td>Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy</td>
<td>CMCC</td>
<td>CMCC-CESM</td>
<td>3.4 3.75</td>
</tr>
<tr>
<td>Meteorological Research Institute, Japan</td>
<td>MRI</td>
<td>MRI-CGCM3</td>
<td>1.1 1.1</td>
</tr>
<tr>
<td>Norwegian Climate Center, Norway</td>
<td>NCC</td>
<td>NorESM1-M</td>
<td>1.9 2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NorESM1-ME</td>
<td>1.9 2.5</td>
</tr>
</tbody>
</table>

CMIP5 promotes a multi-model comparison in order to understand the factors responsible for model differences in some key feedbacks such as clouds and the carbon cycle, projecting future climate change, and also assessing the reliability of the models in simulating the past (World Climate Research Programme, 2008). CTP indices are available for 32 individual CMIP5 models (D. Sandler and N. Harnik, personal communication), however only 8 individual CMIP5 models are used in this project (see Table 1). The selection of models is based on computational constraints and consideration on how each of the selected models represents one of three categories of models. In some models, the loading pattern of the EOF describing CTP2 is strongest over North America; in others over Eurasia and in others still it shows no preference. In this study, there are two models belonging to the Asian group, two models in the North American group and two with no geographical preference. Monthly mean anomalies of surface temperature, 500 hPa geopotential height, 300 hPa zonal and meridional wind data for the 8 CMIP5 models are regridded to the resolution of the coarsest model considered here (3.4°x3.75°) for analysis of multi-model means.
I use monthly mean anomalies of each variable for the analysis using a similar method as for ERA-Interim data. However, I limit my analysis to the 16 months with the largest CNA Index values.

3.2. Methods

There are several methods that are used in this study to analyze the dynamics of North American cold spells during historical and future periods and to evaluate the models’ performance in reproducing these. The computation and analysis have been conducted using MatLab and Climate Data Operators (CDO).

3.2.1. Composite Analysis

Multi-model mean and composite analysis imply computing the average value of data anomalies from different sources (i.e. models) and/or time periods. Composite analysis is a very useful method to construct climatologies of extreme phenomena and teleconnection patterns, including USC and CNA. The multi-model mean is defined as the average of the total monthly mean anomalies output from 8 models. The composite analysis is used to identify how the models reproduce the link between CNA and cold events relative to on ERA-Interim output.

3.2.2. Verification and Validation of models

In order to evaluate each model’s performance, deviations are computed by subtracting the area-weighted monthly mean anomalies from reanalysis. This is applied to two regions that, in ERA-Interim, correspond to warm and cold centers associated with the CTPs. The warm center is defined as the area with the highest 2-meter air temperature anomalies, while the cold center is defined as the opposite. The same approach is also applied to the 500 hPa geopotential height.

3.2.3. Significance testing

There are two significance tests that were performed in this study in order to assess whether the composites are statistically significant: the Monte Carlo and bootstrap methods. These two tests can effectively handle large amounts of multi-dimensional data. According to Metropolis and Ulam (1949), Monte Carlo testing is a statistical approach that uses some quantity of random samples from a large number of data. The random samples are used to represents those large data in several numbers of calculation or trials. One random sample may not represent the whole data, but the probability increases with the number of trials. In this project, 1000 random samples are examined. The 5th and 95th percentiles are then used as significance bounds. For example, if the monthly mean anomalies of the selected 16 most extreme CNA events are significant, then the
mean value of the anomalies should be more (less) than the 95th (5th) percentile of the means of the 1000 random samples. The Monte Carlo approach is used in every composite analysis.

The bootstrap method is applied to examine how significantly the RCP8.5 scenario will affect CNA events in the future. Bootstrapping tests the accuracy and sensitivity of the models under certain inputs (Efron & Tibshirani, 1993). In this work, the mean of the 16 most extreme positive CNA index values and their area-weighted monthly-mean 2-meter surface temperature anomalies over the domains described in Section 2.4.2 for historical and future periods are calculated for each model. The next step is determining the deviation of future CNA indices and surface temperature anomalies relative to the historical output. Bootstrapping is performed by resampling the 16 most extreme CNA events for historical data and taking the mean of those distributions only. Resampling is repeated for 1000 times and it yields one set of data containing 1000 means. Based on the distribution of these resampled means, the 95th and 5th percentiles of the distribution are determined. The significance of the mean future CNA indices and surface temperature anomalies under the RCP8.5 scenario are assessed relative to these limits.

3.2.4. Spatial Correlation

In this study, the spatial correlation is used in order to determine how well two different composites are correlated each other. The computation of 2-D correlation coefficient is performed using the MatLab command corr2, based on Equation 9 below:

\[ r = \frac{\sum_{m} \sum_{n} (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\sum_{m} \sum_{n} (A_{mn} - \bar{A})^2 \sum_{m} \sum_{n} (B_{mn} - \bar{B})^2}} \]  

where \( A \) and \( B \) are two different coefficient or m x n matrices, \( \bar{A} \) and \( \bar{B} \) are the averages of matrix elements \( A_{mn} \) and \( B_{mn} \), respectively.

4. Results and Discussion

4.1. USC variability and correlation with the CNA during the Historical Period

4.1.1. A comparison of CNA and USC events in reanalysis data

The comparison of 2-meter temperature anomalies between the 16 strongest positive CNA episodes and the 16 coldest wintertime temperature events from 1979 to 2005 for reanalysis data is presented in Figure 3. The aim is to understand how CNA and USC events are related to each other. The CNA and USC index values are obtained as described in Sections 2.4.1 and 2.4.2. In Figures 3.a and 3.b, it is interesting to see that both the USC and the most positive CNA events display significant cold and warm anomalies over continental North America and the Alaska-Siberia region, respectively. The most prominent distinction between the two is the areal coverage of the cold and warm pools. The cold anomalies for the CNA events cover a wider part
of North America than for the USC. However, the surface temperature anomalies are slightly lower (colder) during USC events, reaching as low as -4.5K on average (vs. -4.2 K for the CNA). The warm pool for the USC events reaches average anomalies of up to +4.8K and extends from the High Arctic and the northern part of Canada to the Bering Sea. For the CNA events, the warm anomalies are weaker (up to around +3.7K) and cover a smaller domain from eastern Siberia to western Alaska.

The distribution of CNA index values during the observational period is depicted in Figure 4. The average value is 0.48, while the mean values for the 16 coldest USC events is 75.2, corresponding to the 73rd percentile of the distribution. The 16 selected CNA events correspond to a mean value of 137.5, well beyond the 80th percentile of the distribution. Relative to the spread shown by the distribution, the difference between the two average values is small.
4.1.2. Geopotential height and wind variability during CNA events in reanalysis data during the historical period

The analyses of 500 hPa geopotential height and 300 hPa wind anomalies aim to illustrate the dynamical processes leading to the appearance of cold anomalies during CNA events. Geopotential height is the height of a given pressure level in meters. The geopotential height anomalies of the 500 hPa pressure level are broadly used to diagnose the large-scale atmospheric circulation. For the wind analysis, the focus is on the 300 hPa level, which is indicative of the upper-level jet stream structure.

Figure 5 presents the composites of 500 hPa geopotential height and wind anomalies during the USC events and the positive CNA events in order to compare the dynamical development of the two sets of events. It can be seen from Figure 5.a that significant positive geopotential height anomalies span the Arctic region and a large part of Greenland during the USC events, with the largest values exceeding 77.8 meters. These match the large-scale anticyclonic flow seen over the Arctic Ocean and Gulf of Alaska (Figure 5.c). On the other hand, negative geopotential height anomalies are found over the eastern part of North America and extend to the British Isles, the western part of Africa, and cover the whole of Scandinavia. These lead to polar winds bringing cold air to the south and the jet stream over the North Atlantic being shifted further south than its climatological location. This configuration is consistent with the characteristic structure of cold spells over North America [e.g., Walsh et al., 2001; Loikith and Broccoli, 2012; Messori et al., 2016; Harnik et al., 2016] and explains the development of cold anomalies over the mid-latitude North American continent (see Section 2.1). The large-scale wind anomalies reach across the Atlantic Ocean to the European Continent. The maximum value of wind speed
anomaly (5.23 m/s) is reached over the region upstream of the trough system (along 110°-60°W centered at 45°N) and it extends over the ridge area.

The positive CNA events display a similar pattern (Figure 5.b), with even stronger positive geopotential height anomalies over Gulf of Alaska, locally exceeding 100 meters. Another high pressure system appears across Greenland and over the Atlantic Ocean, with lower values of the anomaly field. Unlike for the USC, the negative geopotential height anomalies that stretch across the Atlantic Ocean cover a smaller area and do not extend as far north-eastwards. However, as for the USC events, the jet stream is intensified, with peak anomalies of 7.9 m/s (see Figure 5.d). Other than some relatively limited regional differences, the two sets of events are therefore very similar. The spatial correlations of the two patterns are 0.65 and 0.66 for the wind and geopotential height fields, respectively.

4.2. Multimodel Analysis and comparison to ERA-Interim

4.2.1. Large-Scale Atmospheric Fields

The comparison between monthly-mean surface temperature anomalies of the positive CNA events for reanalysis and CMIP5 models is shown in Figure 6 for the historical period. Figure 6.a
corresponds to Figure 3.b, but with a different range to match that used for model output. The latter is shown in Figure 6.b (multi-model mean). The most prominent difference between reanalysis and the multi-model mean is that the latter has smaller range of values than the former (-1K to 1.5K compared to -4.3K to 3.7K). It is clear that the negative anomalies over North America from reanalysis output are much colder than those of the multi-model mean. Similarly, the warm anomalies are weaker and do not appear over Alaska but are instead limited to eastern Siberia. While there is still a clear association between CNA events and cold temperatures over North America, this is therefore much weaker than in the reanalysis. I further note that the anomalies shown in Figure 6.b are not statistically significant over North America. The multi-model mean may be affected by some models that fail to capture this link.

Figure 6: Surface temperature anomaly (K) composites of positive CNA events during DJFs over the period 1979-2005 for (a) ERA-Interim data, and (b) multi model mean of CMIP5 model data. White contours indicate 95% Monte Carlo confidence bounds. Warm and cold domains used to calculate the deviations of the models from reanalysis data are marked by the two thick black boxes over East Siberia and central North America.
RESULTS AND DISCUSSION

Geopotential height and wind composites for the CMIP5 multi-model mean are presented in Figure 7. Geopotential height anomalies over western Canada are slightly lower than the climatology by around 2.27 meters and result in a weak cyclonic flow over the region. Similar to surface temperature analysis, the composites of geopotential height and wind are not statistically significant over North America and do not reproduce the strong link between CNA and USC events seen in the reanalysis. Due to the shift in the location of the geopotential height anomalies, the winds from the polar region penetrate the Gulf of Alaska and only reached as far east as the Great Lakes. It is therefore understandable that the cold anomalies remain limited to Canada instead of extending over the whole of North America. In contrast to reanalysis output, no clear Atlantic-wide anomaly in the jet stream can be seen; this is again linked to the weaker geopotential height anomalies found. A tripole pattern of significant geopotential heights spanning from the Norwegian Sea to the Mediterranean region brings warm air to Greenland and the Norwegian Sea.

Figure 7: CMIP5 multi-model mean anomaly composites of positive CNA events during DJFs over the period 1979-2005 for (a) 500 hPa geopotential height (m), and (b) 300 hPa wind (vectors) and wind speed (shading, m/s). White contours indicate 95% Monte Carlo confidence bounds.
4.2.2. A statistical comparison for individual models

In order to determine which models show the best match to the reanalysis, a test is performed to verify how much the results of individual models deviate from reanalysis over two domains selected over the warm (East Siberia, 154-180°E, 58–72°N) and cold (Central North America, 70-103°W, 43–58°N) anomaly regions. As described in Section 2.4.2, this analysis is performed by calculating the area-weighted average of the variable of interest over the domain and subtracting each individual model result from the reference ERA-Interim value. The two domains are selected based on mediation between the ERA-Interim and CMIP5 temperature anomalies. Table 2 lists the deviations of individual CMIP5 models from reanalysis data for surface temperature and 500 hPa geopotential height over two domains. It can be seen that all models underestimate the magnitude of the anomalies for both domains and fields. Many models even have anomalies of the wrong sign. For example, the ACCESS1.3, CMCC-CESM, and MRI-CGCM3 surface temperature anomalies deviate from reanalysis output over the warm box by 1.486, 1.484, and 1.431 K, and all three models display on average negative anomalies there. These models also have a higher deviation than other models for the geopotential height anomalies, which are again of the wrong sign. On the contrary, CCSM4 and ACCESS1.0 have the lowest deviation for surface temperature and geopotential height anomalies, respectively, followed by NorESM1-M.

<table>
<thead>
<tr>
<th>SURFACE TEMPERATURE</th>
<th>GEOPOTENTIAL HEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WARM CENTER</td>
</tr>
<tr>
<td>ERA-INTERIM MODELS</td>
<td>AREA WEIGHTED (K)</td>
</tr>
<tr>
<td>ACCESS1.0</td>
<td>0.194</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td>-0.109</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>0.465</td>
</tr>
<tr>
<td>CCSM4</td>
<td>1.219</td>
</tr>
<tr>
<td>CMCC-CESM</td>
<td>-0.106</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>-0.054</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>1.199</td>
</tr>
<tr>
<td>NorESM1-ME</td>
<td>0.426</td>
</tr>
</tbody>
</table>

Table 2: Deviation of CMIP5 model output from ERA Interim data over the selected warm and cold domains.
Among the selected models, NorESM1-M is the model with the coldest area-weighted surface temperature over the cold box and CCSM4 ranks second. CMCC-CESM has the largest temperature deviation, followed closely by ACCESS1.3 and BCC-CSM1.1. For the geopotential heights, CCSM4 deviates the least from reanalysis data while BCC-CSM1.1 has the largest deviation. The above therefore suggests that CCSM4 and NorESM1-M consistently provide the best results for the geopotential height and surface temperature anomalies linked to positive CNA events relative to the ERA-Interim reanalysis.

### 4.2.3. CMIP5 models under the RCP8.5 scenario

Figure 8 presents multi-model mean composites for the historical and future periods. The surface temperature and geopotential height composites that have been presented in Figures 6.b and 7.a are repeated in Figures 8.a and 8.b in order to help the reader to observe how future climate change may alter the anomaly patterns associated with positive CNA events. In the RCP8.5 scenario, the climatological surface temperature over the USC domain increases by over 5K compared to the present day. In parallel with this, it can be seen from Figures 8.a and 8.c that the magnitude of the surface temperature anomalies associated with the positive CNA events increases significantly relative to the mean climate over the whole of North America. These are related to stronger geopotential height anomalies, which increase locally by over 25 meter, except over Norwegian Sea that has anomalies of opposite sign from historical period.
Figure 8: CMIP5 multi-model mean anomaly composites of surface temperature and 500 hPa geopotential height during DJFs over the period 1979-2005 are presented in panel (a) and (b), respectively, to be compared with the composites under the RCP8.5 scenario in the panels (c) and (d). White contours indicate 95% Monte Carlo confidence bounds.

The impact of the RCP8.5 scenario on CNA events is further examined by comparing the CNA index of the historical and future periods for each of the selected CMIP5 models. Table 3 shows the mean CNA Index values for the historical and future periods, together with the differences between the two periods for each individual model. In order to understand how the change of CNA Index mean may affect model output, the difference between historical and future surface temperature anomalies over USC domain are presented in Table 4. From Table 3, it is obvious that majority of the models experience lower CNA Index values under the RCP8.5 scenario, except for CCSM4 and NorESM1-ME. The CNA index of the latter model significantly increases by 0.057. This increment corresponds to a non-significant decrease of the surface temperature anomalies by 0.326 K over the USC domain.

In addition, there are several models that experience non-significant changes of future CNA Index mean values. The CCSM4 model shows a higher CNA Index in the future, although the value is not significant and does not correspond to a significant change in surface temperature anomalies. ACCESS1.0 and NorESM1-M also display non-significant changes in the CNA Index, but the latter model has significantly colder temperature anomalies. The mean CNA Index is significantly decreased for the other four models, which also display significantly lower surface temperature anomalies under RCP8.5 scenario. On average, the CNA Index decreases by 0.039, together with a temperature decrease of around 0.81 K. Significant changes in both the average CNA Index and the surface temperature suggest that the RCP8.5 scenario may affect the
dynamics and intensity of cold US spells in the future. The link between these two changes is discussed in Section 4.3.

Table 3: Changes in CNA Index of positive CNA extreme events for each CMIP5 model during the historical and future periods. Parentheses indicate that differences are not statistically significant based on a bootstrap analysis.

<table>
<thead>
<tr>
<th>MODELS</th>
<th>HISTORICAL</th>
<th>RCP8.5</th>
<th>DIFFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1.0</td>
<td>0.465</td>
<td>0.456</td>
<td>(-0.010)</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td>0.443</td>
<td>0.307</td>
<td>-0.137</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>0.531</td>
<td>0.435</td>
<td>-0.096</td>
</tr>
<tr>
<td>CCSM4</td>
<td>0.459</td>
<td>0.474</td>
<td>(0.014)</td>
</tr>
<tr>
<td>CMCC-CESM</td>
<td>0.494</td>
<td>0.437</td>
<td>-0.057</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>0.554</td>
<td>0.504</td>
<td>-0.050</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>0.544</td>
<td>0.508</td>
<td>(-0.036)</td>
</tr>
<tr>
<td>NorESM1-ME</td>
<td>0.581</td>
<td>0.638</td>
<td>0.057</td>
</tr>
<tr>
<td>MEAN</td>
<td></td>
<td></td>
<td><strong>-0.039</strong></td>
</tr>
</tbody>
</table>

Table 4: Changes in mean monthly surface temperature of positive CNA extreme events for each CMIP5 model during the historical and future periods over the USC domain. Parentheses indicate that differences are not statistically significant based on a bootstrap analysis.

<table>
<thead>
<tr>
<th>MODELS</th>
<th>HISTORICAL</th>
<th>RCP8.5</th>
<th>DIFFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1.0</td>
<td>-0.500</td>
<td>-0.950</td>
<td>(-0.451)</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td>-0.224</td>
<td>-0.981</td>
<td>-0.757</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>0.221</td>
<td>-0.752</td>
<td>-0.973</td>
</tr>
<tr>
<td>CCSM4</td>
<td>-0.569</td>
<td>-1.421</td>
<td>(-0.852)</td>
</tr>
<tr>
<td>CMCC-CESM</td>
<td>0.196</td>
<td>-0.629</td>
<td>-0.826</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>-0.040</td>
<td>-1.046</td>
<td>-1.006</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>0.221</td>
<td>-1.061</td>
<td>-1.282</td>
</tr>
<tr>
<td>NorESM1-ME</td>
<td>0.157</td>
<td>-0.169</td>
<td>(-0.326)</td>
</tr>
<tr>
<td>MEAN</td>
<td></td>
<td></td>
<td><strong>-0.809</strong></td>
</tr>
</tbody>
</table>

4.3. Discussion

The extreme North American cold events are characterized by the existence of an elongated high pressure system over the Arctic region and Alaska in parallel with a low pressure system over North America. This leads to southward advection of cold polar air to North America and is also associated with an intensification of the jet stream across the North Atlantic. Generally, this
pattern is consistent with previous work by Messori et al. (2016) and Harnik et al. (2016), which examined USC events in North America on daily timescales. Messori et al. (2016) further identified an intensified jet stream, as found here. In Harnik et al. (2016), it is concluded that the CNA events lead to USC events with a lag of a few days. This link between USC and CNA events is robust, with a correlation of 0.86 taking into account a 3-day lag. In this study, I use monthly timescales; I still find that USC and CNA events are related to each other, with large-scale patterns that are very similar to the daily ones. The atmospheric patterns associated with the positive CNA events reproduce some key features of the USC events, although they are distinct in several points.

Figure 9: 300 hPa meridional wind anomaly composites during DJFs over the period 1979-2005 for the extreme USC (shading, m/s) and positive CNA events (contours, m/s). Thick contours indicate 95% Monte Carlo confidence bounds. The contour interval is set to 2 m/s. The domain used to define CNA events is marked by the thick black box.

Figure 9, shows a comparison of the 300 hPa meridional wind for USC and CNA events in ERA-Interim, which can be compared to the prior study by Harnik et al. (2016). The 300 hPa meridional wind composite shows that the CNA pattern closely resembles the USC pattern, especially over the Pacific Ocean and the North American region. The spatial correlation between these two patterns over the CNA domain (shown by the black box) is 0.68. This is slightly lower than what found in Harnik et al. (2016). This is not surprising, since the use of monthly timescales implies one cannot record the exact time at which the USC-CNA patterns have the strongest correlation. The monthly mean composites lead to much lower temperature anomaly values than the daily composites, since the CNA and USC extreme events persist only for several days to weeks within a month. As consequence, the coldest (warmest) temperature anomalies of the USC events in this study is only half or less of the lowest (highest) temperatures in Harnik et al. (2016, see their Figure 3). A similar result is found for the positive CNA events. As a result of the monthly analysis, precursor wave-packets to the USC events that originated from Asia cannot be tracked here.
The performance of eight selected CMIP5 models is examined in this study by evaluating which climate models best reproduce the CNA pattern as seen in ERA-Interim data during the historical period. CCSM4 and NorESM1-M are two models that consistently present the lowest deviation from reanalysis output for surface temperature and geopotential height fields over selected North American/Siberian domains. CCSM4 is the model with the highest spatial resolution in this study, but this is not the case for NorESM1-M. Several studies demonstrate the reliability of the CCSM4 model for observing regional climate in North America. According to Sheffield et al. (2013b), CCSM4 is one of the top 5 models from more than 27 climate models considered in evaluating North American hydroclimatology. The model has the smallest biases relative to observations or reanalysis output for 14 of the variables considered in the study (which include sea surface temperature, precipitation in winter and summer, etc.). In addition, Yuan and Quiring (2017) evaluated 17 individual CMIP5 model, of which five are included in this study, for their performance in simulating soil moisture over the United States. They found that CCSM4 consistently performs best. However, several studies (e.g., Sheffield et al., 2013a; 2013b; Lombardo et al., 2015) show that there are other CMIP5 models that perform well over North America but that were not included in this study. This presents a clear opportunity for future work on this topic.

Future climate changes under the RCP8.5 scenario remarkably affect the CNA pattern in CMIP5 models and generally reduce the CNA Index. The latter change is significant for five of the eight models that have been examined in this study. The reduction of the CNA Index is associated with an increase in the magnitude of the surface temperature anomalies relative to the climatology. I find that the USC events will be much colder relative to climatology than in the historical period or, in other words, more extreme. From a climatological point of view, the area weighted average surface temperature over the USC domain will increase by 5.37K. This agrees with Maloney et al. (2014), who found that the climatological surface temperature was projected to increase by 4-9K over the US during wintertime and by about 12K over the Arctic. Another study showed an increment of surface temperature over the contiguous United States by almost 5K in 2100 relative to 1901-1930 under the RCP8.5 scenario (Karmalkar & Bradley, 2017). The intensification of surface temperature and geopotential height anomalies associated with CNA events are clearly seen in the multimodel mean (see Figure 8). This may seem counterintuitive, as the CNA index weakens as does the equator-to-pole temperature gradient (Manabe & Wetherald, 1987; Tang & Weaver, 1995). However, I note that larger temperature anomaly deviations may be due to an increased land-sea contrast and the stronger geopotential height anomalies found here. The land-sea contrast refers to the fact that a forcing generally drives larger thermal anomalies over land than over the oceans; a fact which holds also for future climate change (Joshi & Gregory, 2008). The enhanced contrast and stronger geopotential height anomalies may lead to a more vigorous and persistent meridional advection of comparatively colder air, which in the end balances the decrease in CNA Index. There is also the possibility that the very large change in the future USC-CNA links in the multi-model mean is overestimated, due to the models’ clear inability to capture the link during the historical period.
For future studies, a daily timescale analysis for CMIP5 models under both the historical and RCP8.5 scenarios would be valuable in gaining a deeper insight of the dynamics driving the USC.

5. Ethical and Societal Aspect

In this section, I discuss the relevance of cold spells to ethical and societal aspects. Cold extreme weather impacts North American society both in the health and economic sectors. Several studies found increased mortality during cold winters for several countries including the United States (Sakamoto, 1977; Bull & Morton, 1978). The main reasons behind a higher rate of mortality in cold US winters include seasonal diseases such as cardiovascular, cerebrovascular and respiratory disease (Feinstein, 2002; Rosenwaike, 1966; Rau, 2007). A study about the impact of the unusually cold winter in 2013-2014 on economic activity shows that the weather has a remarkable albeit temporary impact on utilities, customer services, construction and the trading sector (Bloesch & Gourio, 2015). It is predicted that climate change will increase the impact of winter weather on the economy by up to 20 percent.

This study raises no specific ethical concerns nor has any ethical relevance.
6. Conclusion

In this thesis, the author investigated the link between the atmospheric wave pattern known as CNA and wintertime North American cold spells under present and future climates. Cold extreme events over North America are driven by a pair of circunhemispheric quasi-stationary wave packet of zonal wavenumber 5 called the Circumglobal Teleconnection Pattern (CTP). The relation between US cold spells (USC) and regional sector of CTP over North America (CNA) has been investigated on daily timescale by Harnik et al. (2016). Some conclusions that can be drawn from the statistical and dynamical analysis are the following:

- The analysis of monthly surface temperature, geopotential height and wind anomalies composites, based on ERA-Interim reanalysis output, shows that extreme positive CNA episodes are related to the coldest USC events during winter months. The atmospheric anomalies associated to these two events show similar characteristics, with some local differences. The large-scale patterns are generally consistent with that seen on daily timescales from previous work, but as may be expected with much lower anomaly values. However, due to the monthly timescale precursor wave-packets of USC over Eurasia cannot be resolved.

- From the evaluation of eight CMIP5 models it can be concluded that the CCSM4 model performs best in reproducing the CNA-cold spell link over North America during historical period, as seen in ERA-Interim reanalysis. NorESM1-M follows closely. Specifically, these two models capture well the location and magnitude of the geopotential height and surface temperature.

- The RCP8.5 scenario, taken to be a representation of a possible future climate, leads to an increase in the climatological surface temperature of more 5K relative to historical values over the selected North America domain in CMIP5. However, surface temperature anomalies during positive CNA events relative to climatology are larger in magnitude compared to the historical period. Similarly, geopotential height anomalies are intensified in the future. The larger temperature anomalies may be linked to the impact of the land sea temperature contrast, and stronger geopotential height anomalies leading to a more intense and persistent meridional air-mass advection.

- For furthering our understanding of the USC-CNA link, it will be important to extend this study by examining daily timescales for CMIP5 models during both the historical and future periods. Furthermore, it is important to analyse more models in order to thoroughly assess our ability to model USC-CNA events.
Acknowledgements

All praise is to Allah, Lord of the worlds, the Entirely Merciful, the Especially Merciful, for the opportunity, strengths, knowledge, and endless blessing for me in this life journey. I would like to also express my sincere gratitude to my supervisor Gabriele Messori not only for giving me the opportunity to work with the project but also for his guidance, help, and encouragement in completing this master thesis.
References


