The Circumglobal North American wave pattern and its relation to cold events in eastern North America

Nili Harnik1,2, Gabriele Messori2,3, Rodrigo Caballero2,3, and Steven B. Feldstein4

1 Geosciences Department, Tel Aviv University, Tel Aviv, Israel, 2 Department of Meteorology, Stockholm University, Stockholm, Sweden, 3 Bolin Center for Climate Research, Stockholm University, Stockholm, Sweden, 4 Department of Meteorology and Atmospheric Sciences, Pennsylvania State University, Philadelphia, Pennsylvania, USA

Abstract

Extreme large-scale North American cold events are associated with strong undulations in the tropospheric jet stream which bring cold polar air southward over the continent. Here we propose that these jet undulations are associated with the North American part of the Circumglobal Teleconnection Pattern—a pair of zonally oriented waves of zonal wave number 5 which are in zonal quadrature with each other. While the Pacific/North American pattern is associated with the first circumglobal wave pattern, North American extreme cold events are associated with the second pattern. The 300 hPa meridional wind and surface temperature anomalies associated with the Circumglobal North American wave packet are similar to those associated with the strongest eastern U.S. cold events. Both types of events are associated with a wave packet propagating all the way from Asia across the Pacific and across North America, with cold temperature anomalies spreading southeastward from Canada over the continent.

1. Introduction

The tropospheric polar vortex has gained unprecedented media attention during the past few winters, when large undulations in the jet stream formed over North America along with extreme winter conditions. This was most notable not only during the winter of 2013–2014 [e.g., Wallace et al., 2014; Baxter and Nigam, 2015; Davies, 2015; Lee et al., 2015; Yu and Zhang, 2015; Waugh et al., 2016; Watson et al., 2016; Seager and Henderson, 2016] but also during winter 2014–2015. The occurrence of such severe cold events during recent years which are globally amongst the warmest on record points to the difference between regional and global climate change; specifically, it highlights the need to fully understand the physical drivers of the events and their representation in climate models in order to robustly predict possible future changes in their frequency and intensity.

The dynamical drivers of cold events over North America have been studied extensively, using a diverse range of definitions for the cold events themselves [e.g., Konrad, 1996; Walsh et al., 2001; Portis et al., 2006; Loikith and Broccoli, 2012; Grotjahn et al., 2015; Messori et al., 2016, and references therein]. A robust finding of these studies is the association of North American cold events with large-scale circulation anomalies which advect very cold air equatorward, typically from the northwest. A common finding is also that these large-scale circulation anomalies are similar in scale and structure to the Pacific/North American (PNA) pattern, but the two patterns are zonally shifted and thus project weakly onto each other [e.g., Walsh et al., 2001; Cellitti et al., 2006; Grotjahn et al., 2015; Messori et al., 2016] (also Davies [2015] for winter 2013–2014). On the other hand, Linkin and Henderson [2008] noted a relation between North American cold air outbreaks and the North Pacific Oscillation (NPO) [Walker and Bliss, 1932] and its associated upper level West Pacific (WP) teleconnection pattern.

Here we propose that the large-scale circulation anomalies which drive cold events over North America east of the Rockies are associated with the Circumglobal Teleconnection Pattern (CTP) introduced by Branstator [2002]. Branstator [2002] obtained the CTP from the first two empirical orthogonal functions (EOFs) of monthly mean seasonal anomalies of December–February 300 hPa nondivergent meridional wind. The two patterns together represent a zonally oriented medium-scale wave train of zonal wave 5 with arbitrary zonal phasing. Feldstein and Dayan [2008] showed that on daily time scales, these patterns appear as localized wave packets which propagate downstream with an eastward group speed and near zero phase speed...
These yield a circumglobal wave pattern when averaged over time [Feldstein and Dayan, 2008].

The zonal scale of the CTP is similar to the jet stream undulations as seen in the 2013–2014 winter (the longitudinal span of the North American landmass is roughly zonal wave number 5), and we may expect its quasi-stationary nature to allow for persistent advection of cold polar air across the continent. It is therefore plausible that the CTP may play a role in driving North American extreme cold events. The CTP has been associated with extreme weather during summer [Schubert et al., 2011; Teng et al., 2013] and with winter precipitation over Israel [Feldstein and Dayan, 2008] but has not been studied in the context of North American winter weather. Recently, Messori et al. [2016] composited persistent eastern U.S. cold spells and showed a zonally oriented wave pattern with a wavelength corresponding roughly to zonal wave number 5 and a phasing similar to the second CTP pattern, which propagates from the Pacific over North America to the Atlantic (see their Figure 2). In this paper, we explicitly examine the relation of this wave pattern to the second CTP, by comparing surface temperature and upper level flow fields during times when the flow projects strongly onto the North American part of the CTP and during extreme cold events over the eastern U.S. The linking of the two phenomena has possible implications for predictability [Teng et al., 2013; Grazzini and Vitart, 2015], which we will briefly explore by examining the upstream origins and precursors of the North American part of the CTP.

2. Data and Analysis Methods

We use daily anomalies, defined by removing a smoothed daily climatology (using a 21 day running mean). The events are calculated using daily mean and monthly mean gridded fields from ERA-Interim [Dee et al., 2011] for 1979–2014. Much of the analysis for the CTP based events was repeated using National Centers for Environmental Prediction (NCEP) I reanalysis [Kalnay et al., 1996] from 1958 to 2015, and except where noted, the results are similar.

The statistical significance of the composites is calculated both using a 1000 member bootstrap method and a sign test which indicates where a certain percentage of composite members have the same sign as the composite mean. The chances for a given percentage of events to have the same sign as the composite mean are determined using a binomial formula, assuming equal chances for positive and negative anomalies. Spatial correlations between two patterns are calculated after weighting each by square root of cosine latitude, and the statistical significance is estimated by correlating one of the patterns with the corresponding field from 1000 randomly chosen days. We define several kinds of events as follows.

2.1. The Circumglobal North American (CNA) Wave Pattern

To obtain a regional CTP index, we begin by calculating the global CTP patterns using a method similar to Branstator [2002]. The global CTPs are the first two EOFs of the winter anomalies of monthly mean 300 hPa meridional wind, calculated by removing each season’s December–February mean fields from the monthly mean meridional wind fields. A square root of cosine latitude weighting is used for the analysis (so that the variance is weighted by a cosine latitude). Unlike Branstator [2002], we use the full meridional wind, rather than nondivergent meridional wind, since the two give very similar results. We note that without removing the seasonal mean anomalies, the first EOF has a planetary scale, and using daily fields gives a pair of zonal wave number 6 patterns for the first EOFs.

Using monthly ERA-Interim data, the first two EOFs (shading, Figure 1) are a pair of quasi-zonal wave number 5 patterns which explain 13.3 and 11.5% of the variance and are not well separated according to the North et al. [1982] criterion, suggesting that they span a continuum of zonal wave number 5 patterns with arbitrary phase. The robustness of these patterns is examined using NCEP reanalysis data and discussed in the supporting information (Figure S1). Following Yuan et al. [2011], we obtain daily regional CTP indices by projecting the daily 300 hPa meridional wind anomalies onto specific zonal sectors of the global CTPs (see supporting information for details). For the North American region, we choose the domain 180–324°E, 10–85°N (see the boxes in Figures 2c and 2d), where the longitudinal span of 144° was chosen to capture two full wavelengths of zonal wave 5. We then project the daily data onto the second CTP pattern in this region. We refer to this pattern as the Circumglobal North American (CNA) pattern, and to its normalized projection as the CNA index.

To define positive CNA events, we find the days on which the 5 day running mean of the CNA index exceeds its mean by one standard deviation. We define the peak value to be the event center, with events being separated
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.

by at least 1 day in which the index drops below one half a standard deviation above the mean. We find 78 positive events for ERA-Interim data (and 123 events for NCEP data). We do not impose any additional time separation but find that the vast majority of events are separated by 7 or more days.

2.2. The Circumglobal Eurasian Wave Pattern

To examine the possibility of precursor patterns, we repeat the procedure done for CNA events, using a Eurasian region: 0–144°E, 10–85° (see the box in Figure 4a), and define events in a similar manner. We find 79 events using ERA-Interim data and 139 events using NCEP data.

2.3. Eastern United States Cold (USC) Events

We rank eastern United States Cold (USC) events based on the area-weighted 2 m temperature anomaly over the region 100–70°W, 30–45° (see box in Figure 3f). The normalized area-weighted temperature time series is referred to as the USC index. To choose USC events, we smooth the temperature anomalies using a 5 day running mean and choose the days with the largest negative temperature anomaly. We discard events which are closer than 7 days to another event, keeping the colder event of the two. For comparison with the CNA event composites, we choose the 78 coldest events, which consist of an area-weighted anomaly below −4.7 K.

2.4. Daily Pacific-North American (PNA) Pattern

We calculate a daily Pacific-North American (PNA) index by combining the standardized 500 hPa geopotential height anomalies at (20°N, 160°W), (45°N, 165°W), (55°N, 115°W), and (30°N, 85°W), following Wallace and Gutzler [1981] and Cellitti et al. [2006], and normalizing the resulting index to have unit standard deviation. Positive events are defined by the index exceeding 1.0.
3. Results

Figure 1 shows the first two CTP patterns of anomalous 300 hPa meridional wind, along with the anomalous 300 hPa meridional wind composites for day 0 positive PNA events and day −3 USC events. We note that the first CTP in its positive phase corresponds to anomalous poleward flow over Alaska, with anomalous equatorward flow on its sides. This pattern fits the positive phase of the PNA (compare the shading and contours in Figure 1a). The meridional wind anomaly associated with the coldest 78 USC events, on the other hand, is in phase with the second CTP pattern (compare shading and contours in Figure 1b). This motivates us to further examine the relation between USC events and times when the flow projects strongly onto the second CTP over North America (which we have defined as CNA events). Before doing so, we note that the two CTPs are roughly in quadrature over the Pacific-North American region. Since the PNA projects strongly onto the first CTP while USC events project onto the second CTP, we expect the simultaneous correlation between the PNA and USC indices to be weak (as was found by Cellitti et al. [2006], Grotjahn et al. [2015], and Messori et al. [2016]). Indeed, the correlation between the PNA and USC indices reaches only −0.26 (at lag 0), compared to a correlation of 0.74 between the PNA and an index similar to the CNA but based on the first, rather than the second CTP.

Figure 2 shows the time lagged composites of 300 hPa meridional wind anomaly overlain on the full CTP EOF2, for CNA and USC events. The black boxes show the projection region used for defining the CNA events. The highest spatial correlation between the CNA and USC composites, with a value of 0.86 (statistical confidence...
Figure 3. (a, d, and g) Time lagged composite of surface temperature anomalies (contours, red positive and blue negative) for positive CNA events at lags −2, 3, and 7 days. Contour interval is 2K with the ±1K contours added. Thick contours mark values with a 95% statistical confidence level, green shading marks regions where 67% of the composite members have the same sign as the composite itself (chances of this happening randomly are well below 5%). (b, e, and h) The percent of positive CNA composite members (in Figures 3a, 3d, and 3g, respectively) which have the same sign as the composite. Contours mark 65%, 75%, and 85% (marked by increasing thickness), with red/blue marking regions where the composite mean is positive/negative. (c, f, and i) Same as Figures 3a, 3d, and 3g but for USC events at lags −5, 0, and 4 days. The black rectangle in Figure 3f shows the region used to define the USC events.

above the 99.9% level), is found when USC events lag the CNA events by 3 days; thus, we show the composites with a 3 day offset. We see a very clear similarity between the meridional wind pattern for both types of events. The patterns show a localized wavy pattern, with the wave packet amplitude propagating in time from Asia, over the Pacific, and onto North America, but individual positive and negative centers being quasi-stationary. In both cases, we see a precursor wave packet over Asia with a clear branch along the subtropical jet and another more northward branch. The wave packets span roughly three full wavelengths at CNA day 0, their amplitude peaks shift eastward with a group speed of about 20° longitude per day corresponding to about 1 week to travel from the Western Pacific to the Atlantic, and they have an almost zero eastward phase speed. This yields an equatorward flow over the North American continent, which is strong and significant for more than 1 week, making these quasi-stationary wave packets efficient in driving negative temperature anomalies.

Figure 3 shows the surface temperature composites for both kinds of events (Figures 3c, 3f, and 3i and 3a, 3d, and 3g), with the USC fields shifted 3 days earlier than the CNA events. We see a strong similarity between the two types of events with the peak cold anomaly covering most of North America and a warm anomaly over Alaska and the Bering Sea, at USC lag 0 and CNA lag 3. At these times, both anomalies reach their coldest values over North America, and the spatial correlation between the two fields is maximal (0.85, statistical confidence above the 99.9% level). The time evolution is also quite similar, with the peak USC cold anomaly starting from...
Figure 4. Precursor wave packet time lagged composites: (a, c, and e) 300 hPa meridional wind anomalies at days 0, 4, and 7 (contours, interval 5 m/s with the ±2.5 m/s contours added); (b, d, and f) surface temperature anomalies at lags 7, 9, and 11 days (contours, interval 2 m/s with the ±1 m/s contours added). The composites are for events when the 300 hPa meridional wind projects maximally onto the Euro-Asian sector (marked by the black rectangle in Figure 4a), using 79 events. Also shown in Figures 4a, 4c, and 4e are the 300 hPa meridional wind anomalies corresponding to the second CTP pattern (same as in Figure 2). For contours and shadings, red is positive and blue is negative. Thick contours mark values with a 95% statistical confidence level, and the darker shading in Figures 4a, 4c, and 4e and green shading in Figures 4b, 4d, and 4f mark regions where 67% of the composite members have the same sign as the composite itself (chances of this happening randomly are well below 5%).

the northwest, spreading over most of the continent and shifting toward the East Coast. We note that while the northerly flow is located over the western-central part of the continent, the cold anomalies are over the central-eastern part. This eastward shift is due to the contribution by zonal advection (see Figure S2). The CNA cold anomalies do not shift meridionally in time as much as the USC events, and they are preceded by stronger anomalies over the Pacific Ocean and over Asia at early time lags, suggesting the Asian wave packet precursor temperature signal is more robust for CNA events. We note that the NCEP 2 m temperature, which is derived differently for ERA-Interim reanalysis, shows slightly weaker and shorter lasting cold anomalies for the CNA events (Figure S3), and the ocean 2 m temperature anomalies are absent. An examination of the 500 hPa geopotential height fields for these two events (Figure S4) shows that in addition to the similarity of the fields in midlatitudes, USC events are associated with an additional polar planetary scale geopotential height anomaly. The examination of a possible contribution of the polar anomalies is left for a future study.

We also show (Figures 3b, 3e, and 3h) the number of CNA composite members which have the same sign as the composite mean at each grid point (the hit-rate). Looking at the regions where the composite mean cold anomalies are statistically significant (based on a bootstrap method, thick lines in Figures 3a, 3d, and 3g), cold anomalies are found for more than 65% of the individual CNA events. At the peak of the composite mean cold anomaly, more than 75% and even 85% of the individual CNA events have a cold anomaly.
The chances of this happening randomly are much less than 1%. Consistently, the CNA index probability distribution function is shifted to larger values preceding USC events (see Figure S5). The time correlation between the daily December-January-February (DJF) USC and CNA indices peaks at $-0.45$ when the U.S. cold conditions lag the CNA pattern by 3 days (statistical confidence of 99.99%, assuming a conservative $3^\circ$ of freedom per winter). Explicitly examining the cooccurrence of USC and CNA events, we find that 30 of the CNA events are followed within 7 days by one of the 78 coldest spells identified here, and 44 are followed by a cold event with temperatures below the 5th percentile of the full wintertime distribution, both exceeding the 95% statistical confidence level obtained from random sampling. During the 2013–2014 winter there was a succession of periods with a strong positive projection onto the CNA pattern, followed by extreme cold anomalies and negative USC values (Figure S6). Explicitly, the DJF mean normalized USC index was $-0.6$ with 37 days (41%) having a USC index below $-1.0$ standard deviation, compared to 5.9% of all 1980–2014 winter (DJF) days. The DJF mean normalized CNA index was 0.74 with 32 days (36%) having a CNA index larger than 1.0 standard deviation, compared to 5.3% of all 1980–2014 winter days.

The precursor Asian wave packet found in Figure 2 suggests a predictability pathway on a 7–10 day timescale for eastern North American cold events. To check this further, we examine composites based on Eurasian CTP2 events, defined by the black rectangular region marked in Figure 4a. We see a clear Eurasian wave packet at day zero, with corresponding statistically significant temperature anomalies being cold over the Middle East and Siberia, and warm over Central Asia (not shown). There is a clear downstream group propagation over the Pacific and onto North America, leading to persistent and significant northerly flow anomalies over eastern North America, in phase with CTP2. Consistently, after lag 7 we see a gradual development of significant cold anomalies over the eastern U.S., reaching a peak around day 11, in some regions occurring in more than 67% of composite members (these anomalies are also found in NCEP data though in a smaller more poleward region, Figure S7). Additional indications of a robust statistical relation between Eurasian CTP2 events and subsequent CNA and USC events are presented in the supporting information. We further count how many Eurasian wave packet events were followed by one of the 78 coldest USC events, 8–12 days later. This choice of range of lags is made in order to include both day 9, when the spatial correlation with the corresponding surface temperature anomalies over the CNA area is highest (0.7, statistical confidence of 99%), and day 11, when the strongest temperature anomalies (Figure 4f) take place. We find this happens for nine of the Eurasian wave packet events, which is exactly the 90th percentile statistical confidence level.

4. Discussion

We have shown that a large number of the extreme North American cold events have been driven by jet stream undulations similar to the CNA pattern. The statistical link between the CNA and North American cold events is significant and robust, though not all days with a strong projection onto the CNA lead to an extreme USC event a few days later, and not all extreme USC events are preceded by a strong projection onto the CNA. It does point, however, to a potential predictability pathway on 7–10 days, resulting from downstream propagation of the waves from Asia, and identifies potential precursor patterns. Grazzini and Vitart [2015] used an objective wave packet tracking algorithm and a forecast verification database and found increased predictability for long-lasting wave packets originating in the West Pacific. They did not differentiate, however, between synoptic scale propagating waves and medium-scale quasi-stationary waves like the CTP, but it is very probable that these different types of wave packets affect predictability differently.

Bao and Wallace [2015] recently performed a cluster analysis of Northern Hemisphere 10 day low-pass filtered 500 hPa geopotential heights. They found four reproducible patterns, three of which they related to the NAO and PNA phases. Their second pattern, which was suggestive of Alaska blocking with a downstream wave train extension over North America, is similar to the positive CNA pattern. Further examination is required to establish this connection robustly, but it suggests that the CNA may be a dominant recurring pattern of variability of the Northern Hemisphere wintertime flow.

An explicit examination of the 2013–2014 winter shows that the projection onto the positive phase of the CNA was strong during many of the days that winter, suggesting that the cold events were associated with this flow pattern. This is consistent with Wang et al. [2014] and Davies [2015] who also noted a wave train propagating from the Pacific, resulting in a strong trough-ridge anomaly over the Gulf of Alaska-Great Lakes. Baxter and Nigam [2015; see also Yu and Zhang, 2015] associated the anomalous trough-ridge during the winter of 2013–2014 with the NPO/ WP pattern, which Linkin and Nigam [2008] earlier related to...
North American cold air outbreaks. A comparison of the NPO/WP pattern [see, e.g., Figure 3a of Linkin and Nigam, 2008] with the CNA suggests that they project strongly onto each other in some regions, but the two are not the same.

A few recent studies of the extreme North American winter of 2013–2014 have suggested that the anomalous ridge-trough pattern was forced by the anomalous Pacific sea surface temperature (SST) anomalies during that winter [Wang et al., 2014; Baxter and Nigam, 2015; Hartmann, 2015; Lee et al., 2015; Seager et al., 2015; Yu and Zhang, 2015; Watson et al., 2016; Seager and Henderson, 2016]. In particular, Seager and Henderson [2016] found a zonal wave 5 pattern similar to the CNA over the Pacific-North American sector to be involved in the response to an optimized tropical SST driving pattern. Watson et al. [2016] obtained an improved forecast of the anomalous circulation over North America when the tropics were relaxed to ERA-Interim observations, suggesting that the forcing of divergent flow by SST anomalies plays a central role. This raises the possibility that the CNA is excited or enhanced by SST anomalies and points to the need for a better understanding of CNA drivers and of its possible interactions with SSTs and climate change.

Acknowledgments
The work was supported by the Israeli Science Foundation grant 1537/12. The work was done when NH was on sabbatical at Stockholm University, supported by a Rossby Visiting Fellowship from the International Meteorological Institute of Stockholm University. S.B.F. was supported by National Science Foundation grant AGS-1401220. Many of the calculations presented here were performed using GOAT (Geophysical Observation Analysis Tool), a freely available MATLAB-based tool for retrieval, analysis, and visualization of geophysical data (http://www.goat-geo.org). ECMWF ERA-Interim data used in this study have been obtained from the ECMWF Data Server http://data-portal.ecmwf.int/data/d/interim/daily/. NCEP Reanalysis data (http://www.goat-geo.org) were used in the study. MATLAB-based tool for retrieval, analysis, and visualization of geophysical data (http://www.goat-geo.org). ECMWF ERA-Interim data used in this study have been obtained from the ECMWF Data Server http://data-portal.ecmwf.int/data/d/interim/daily/. NCEP Reanalysis data were obtained from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/.

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