Potential Arctic connections to eastern North American cold winters

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Abstract
Far-field temperature and geopotential height fields associated with eastern North American early winter (DEC-JAN) extreme cold events are documented since 1950. Based on 19 cases of monthly extreme cold events, two large-scale patterns emerge. First, a strong Alaskan Ridge (AR) can develop with higher 700 hPa geopotential heights and positive temperature anomalies from Alaska south along the coastal northeastern Pacific Ocean, and low eastern North American geopotential height anomalies, the well-known North American ridge/trough pattern. A second subset of cases is a Greenland-Baffin Blocking (GBB) pattern that have positive temperature anomalies centered west of Greenland with a cut off tropospheric polar vortex feature over eastern North America; cold temperature anomalies extend from southeastern United States northwestward into central Canada. Both of these historical large-scale patterns associated with eastern North American cold events (AR and GBB) have the potential for future reinforcement by sea ice loss and associated warm Arctic regional temperature anomalies. An example of a GBB case is 15-22 December 2010 and an extreme AR case is in early 4-14 December 2016. In both cases lack of sea ice and warm temperature anomalies were co-located with local maximums in the geopotential height anomaly fields. Future regional delay of fall freeze up in the Chukchi Sea and Baffin Bay regions could reinforce these geopotential height patterns once they occur, but is not likely to initiate AR and GBB type events.

Key words: jet stream, blocking, teleconnections, cold-air outbreaks

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Introduction

Global temperatures have been rising since the 1970s yet there are cooling temperature trends during winter over eastern Northern Hemisphere continents during 1990-2015 (Fig. 1). While several authors emphasize concurrent Arctic trends (Cohen et al. 2014, Lee et al. 2015, Kug et al. 2015), other authors have attributed cooling

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over eastern North America (NA) to natural variability, western equatorial Pacific teleconnections, and changes in the waviness of tropospheric jet stream related to Arctic amplification of temperatures (Ding et al. 2014, Perlwitz et al. 2015, Sun et al. 2016, Zhang et al. 2016). Inspection of winter time series in these papers shows the trend is more due to individual event years rather than a continuous increase during all years. Much interest has been given to the role of the tropospheric polar vortex during recent cold events.

This emphasis on single year contributions highlights an episodic interpretation of extreme events (Trenberth 2011, Shepherd 2014, Overland 2016, Osborne et al. 2016). This idea features year-to-year and month-to-month intermittency: that chaotic internal variability dominates atmospheric circulation dynamics, and thermodynamic aspects of change (temperature, water vapor, sea ice) reinforce existing dynamic patterns. Thus potential thermodynamic forcing of Arctic/midlatitude weather linkages are conditionally dependent based on different atmospheric circulation regimes, for example a weaker westerly wind tropospheric polar vortex in some winters (Francis et Skific 2015, Vavrus et al. 2017). The jet stream provides the bridge between Arctic thermodynamic forcing and midlatitude weather responses (Overland et al. 2015, their Fig. 2). Variability in jet stream configurations means that the bridge is not always down.

Rather than starting at the Arctic forcing end to investigate Arctic/NA cold weather linkages, we begin with determining those winter months (December-February, DJF) that had cold eastern US temperatures since 1950, a case study approach. These cases are then classified according to two associated large-scale NA temperature/geopotential height field patterns. We then document two case studies for early winter that had a potential for cold eastern US temperatures related to a long wave pattern over NA being reinforced by late freeze up for sea ice north of Alaska or in Baffin Bay. We make a case that continuing Arctic change will not cause cold NA events but can reinforce a subset of large-scale atmospheric flow patterns.

Methods: Eastern North American extreme winter cold events

We select a region for the eastern US to study cold events that is bounded by 30 - 45° N and 90° - 72° W as shown in Fig. 1. To exclude ocean areas a land-sea mask is applied to the temperature anomaly field. The limits of this domain are motivated by previous studies of eastern NA cold events (Grotjahn et al. 2016, Messori et al. 2016, Singh et al. 2016). Monthly areal average 2-meter air temperature anomalies (T_{2m}) were computed for this region from the NCEP/NCAR reanalysis beginning in 1950. As a criterion for a cold event, we selected 19 early winter months when the areal mean temperature anomaly was equal to or below one standard deviation for each month, listed for December (Dec) and January (Jan) in Table 1. As shown later, February cold cases had a more zonal flow across NA and did not show clear teleconnection patterns; thus February cases were dropped from further analysis. Bellprat et al. (2016) reached a similar conclusion for February. Overall there are both cold and not-so-cold historical periods, such as the cold events since 2000 and during the 1960s and late 1970s. A strong cold pattern was noted for the winter of 1976 (Diaz et Quayle (1978).

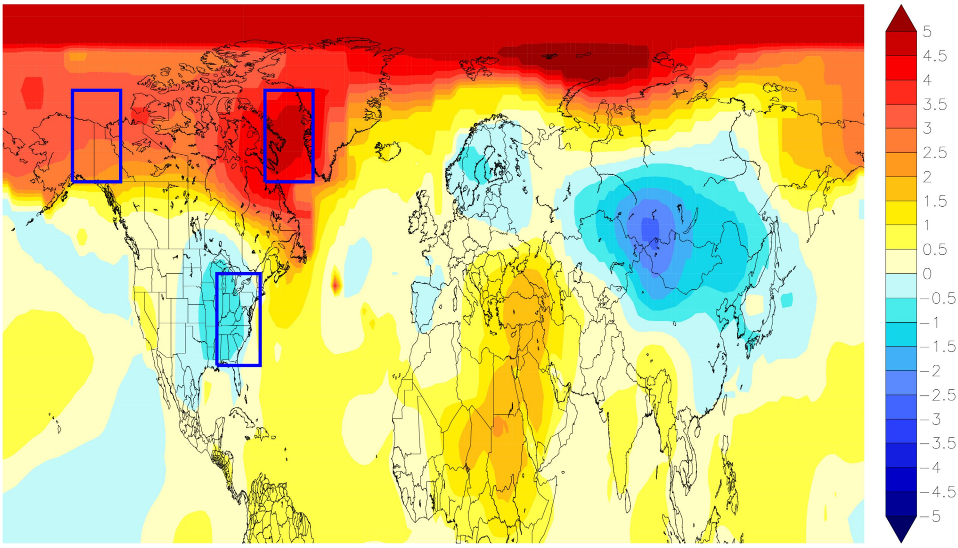

Fig. 1. Winter surface air temperature trends for 1990-2015 (based on NASA data, *see* web page: https://data.giss.nasa.gov/gistemp and similar to Cohen et al. 2014). The blue box over eastern North America outlines the domain used to compute monthly temperature anomalies. Boxes over Alaska and to the east of Greenland are the domain for calculating monthly geopotential height anomalies to assign Alaska Ridge (AR) and Greenland/Baffin Blocking (GBB) cases.

Fig. 2 (left) shows the composite pattern of near surface 925 hPa air temperatures that occurs during eastern NA cold events in each DJF month. Note the warm Arctic/cold Continent type pattern with positive temperature anomalies near southern Baffin Bay and in Alaska/east Siberia.

Fig. 2 (right) illustrates the 700 hPa geopotential height composite anomaly fields for these cold eastern NA events; a similar pattern for cold events is noted by Konrad (1996) and Messori et al. (2016). The two large geopotential height anomaly regions are nearly collocated with the two positive temperature anomaly regions, especially in December and January, supporting a surface temperature anomaly/lower atmospheric geopotential thickness connection.

By inspection of individual months, positive temperature and height anomaly maximums can occur either near Alaska, west of Greenland, or in combination. Two location boxes, (AR box 60-75° N, 150-130° W and the GBB box 60-75° N, 70-50° W) shown in Fig. 1 were based on maximum 700 hPa geopotential height anomalies from compositing December and January fields listed in Table 1. All 19 cases were then separated by their maximum height anomaly values into Alaskan Ridge (AR), Greenland-Baffin Block (GBB), or both cases (*see* Table 1). Note that the GBB months do not necessarily relate to the Greenland Blocking Index (GBI) proposed by Hanna et al. (2014) that covers a larger region. GBB lies to the west of GBI as also noted by Chen et Luo (2017). The potential for the Arctic to impact eastern NA relates to thermodynamic reinforcement of these two atmospheric long wave patterns.

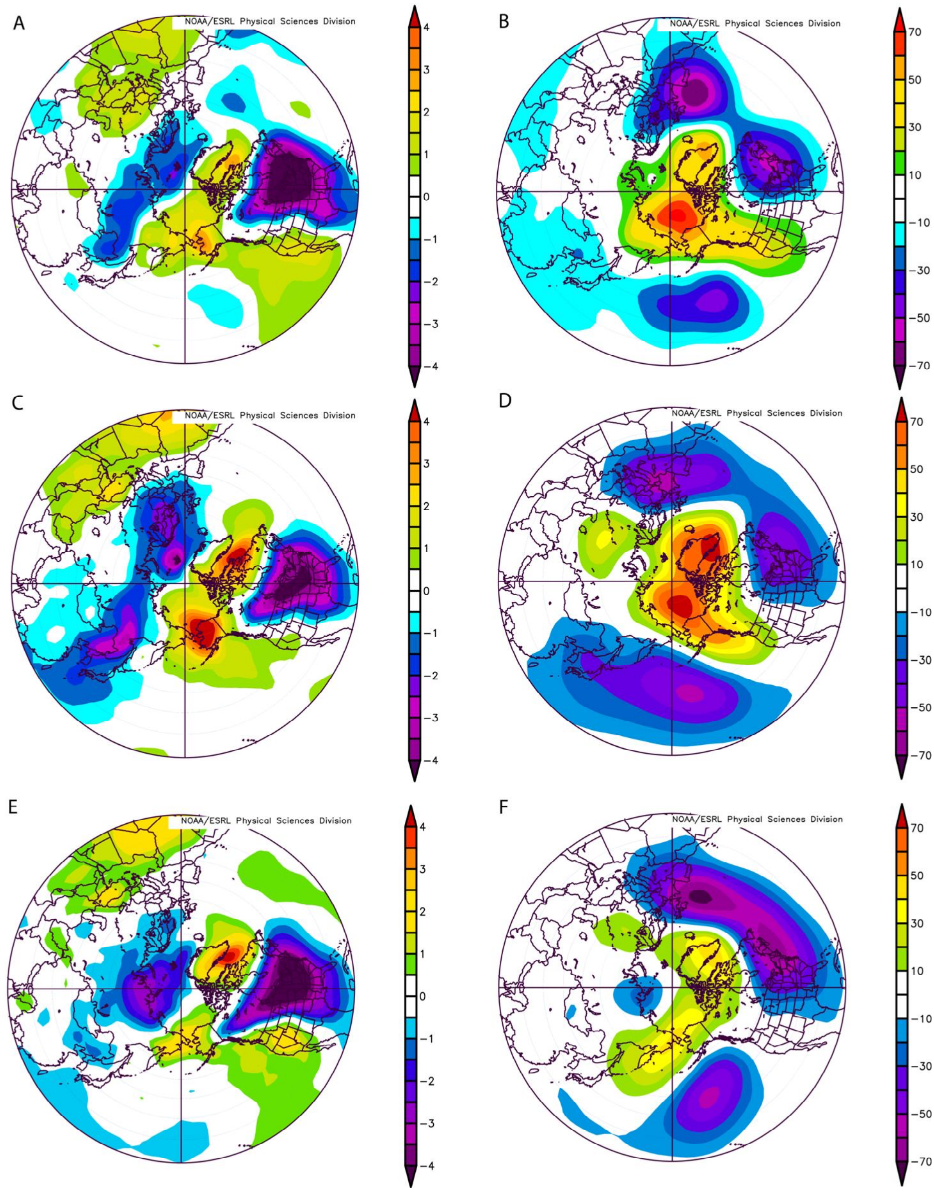

Fig. 2. Composite 925 hPa temperature anomaly (A, C, E - left panels) and 700 hPa geopotential height anomaly (B, D, F - right panels) for cold months from 1950 to 2015 divided in to December (top), January (middle) and February (bottom). Data from the NOAA/NCAR reanalysis using the NOAA/ESRL online plotting routines. Based on the weaker more zonal height anomaly fields, February is excluded from further analyses. The following years are into the composite for December: 1958, 1960, 1963, 1976, 1983, 1985, 1989, 2000, and 2010; for January: 1963, 1966, 1970, 1977, 1978, 1981, 1985, 1994, 2003, 2011, and 2014; and for February: 1958, 1963, 1967, 1968, 1978, 1979, 1980, 2003, 2007, 2010, 2014, and 2015.

Cold Years			
Dec	GBB-index	AR-index	Pattern Assigned
1958	34.74	52.75	Both
1960	-36.46	51.79	AR
1963	11.11	56.66	AR
1976	21.51	-3.22	GBB
1983	-29.18	110.18	AR
1985	48.24	68.96	Both
1989	-4.64	52.92	AR
2000	85.99	72.76	Both
2010	176.74	2.25	GBB
Jan	**GBB-index**	**AR-index**	
1963	95.15	97.75	Both
1966	142.25	29.89	GBB
1970	62.53	28.55	Both
1977	120.74	64.76	GBB
1978	-18.68	86.38	AR
1985	86.2	75.46	Both
1994	7.39	74.32	AR
2003	41.64	53.96	Both
2011	110.57	46.04	GBB
2014	9.72	42.37	AR

Table 1. Months of cold eastern North American temperatures for December and January 1950-2015. For each cold NA case, the GBB and AR regional height anomaly index (*see* regional boxes in Fig. 1) are listed. Based on comparing the indices cases are assigned to GBB, AR, or Both.

Results (Associated 700 hPa geopotential height fields) and Discussion

The combined Dec-Jan 925 hPa temperature anomaly, 700 hPa geopotential height anomaly, and 700 hPa geopotential height fields are shown for AR cases (Fig. 3A-C) and GBB cases (Fig. 3D-F). The AR pattern shows positive geopotential height anomalies spreading from north of northeastern Siberia across Alaska southward along the Pacific coast of the North America and seaward into the Pacific Ocean. The AR temperature pattern shows a region of warm temperature anomalies from northern Alaska southward along the west coast of NA supporting the ridge pattern of higher geopotential heights.

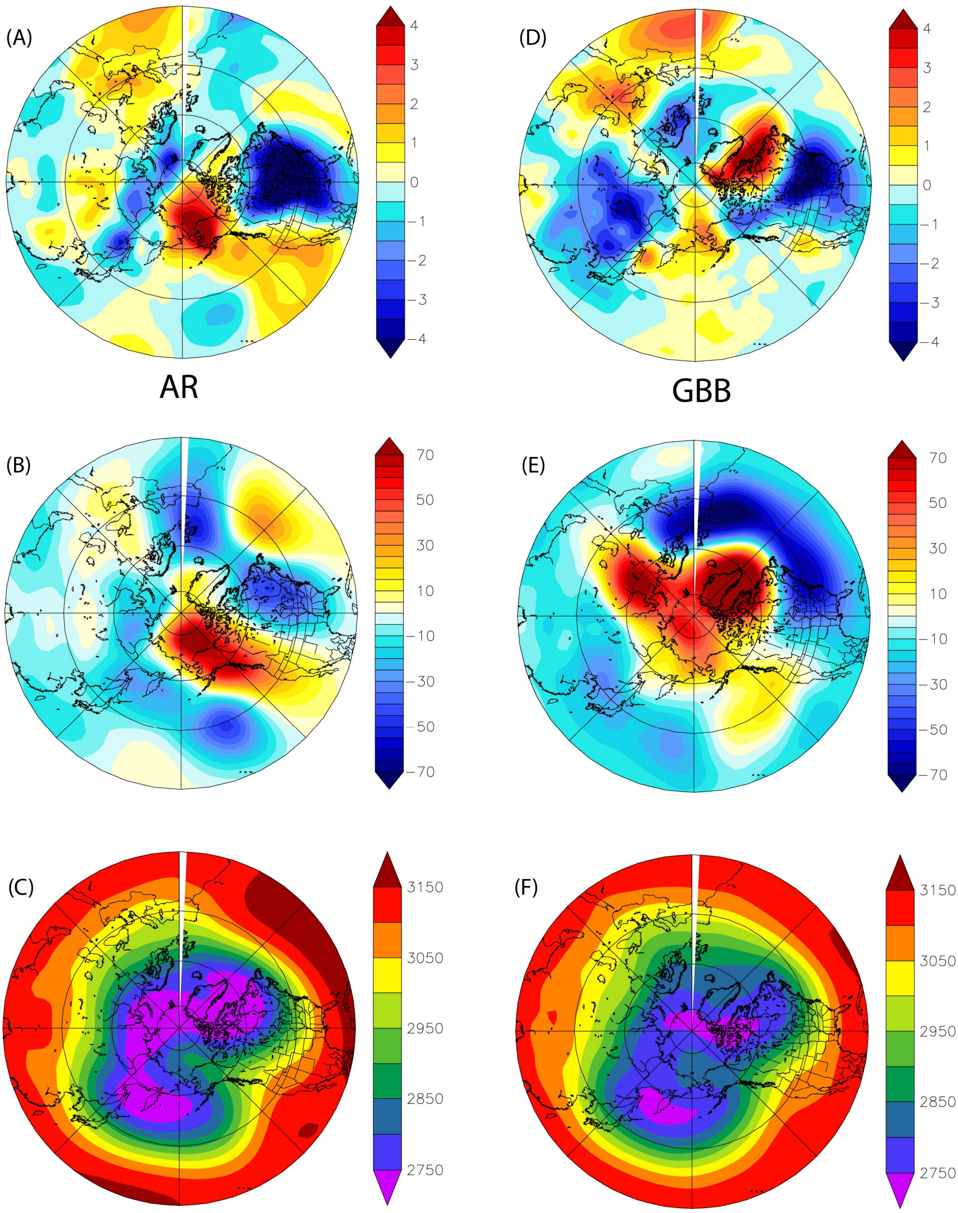

Fig. 3. Composite plots of 925 hPa temperature anomaly (top, A,D), 700 hPa geopotential height anomaly(middle B ,E), and mean 700 hPa geopotential height (bottom, C, F) associated with cold eastern North American temperature cases for an Alaskan Ridge (AR) pattern (left) and for the Greenland-Baffin Blocking (GBB) pattern (right).

The GBB pattern has positive temperatures anomalies centered over Baffin Bay and cold anomalies extending from the eastern US northwestward into central/western Canada. GBB cases have higher geopotential height anomalies over Greenland and this center extends northwestward into the central Arctic Basin. There are minimum height anomalies over the southeastern US and extending into the Atlantic. There can be positive height anomalies along the Pacific coast in GBB cases, not dissimilar to the AR cases. Also of note for GBB cases is the presence of major low geopotential height anomalies in the central Pacific Ocean southwest of the Aleutian Islands, but weaker compared to AR cases (Fig. 3B). The GBB cases have higher heights over Greenland relative to Baffin Bay as also noted by Messori et al. (2016); this creates a small vortex over eastern Canada which can be labeled as a Greenland Block feature. In the AR cases there is no Greenland Block and the tropospheric vortex extends from eastern Canada northward to the North Pole. In all cases there is a northwest wind component across central Canada and into central and eastern US. A third set of cases (not shown) labeled Both in Table 1 have characteristics simultaneously of AR and GBB.

An open question is the extent of persistence or reoccurrence of these patterns provided by thermodynamic reinforcement: by western tropical Pacific sea surface temperatures (SST) (Hartmann 2015), northeastern North Pacific SST (Baxter et Nigam 2015), hemispheric scale patterns (Harnik et al. 2016), minimum sea-ice conditions north of Alaska/east Siberian Sea (Kug et al. 2015, Lee et al. 2015), Baffin/Hudson Bay (Overland et al. 2015, Ballinger et al. 2017), or warm SSTs in the coastal North Atlantic (Hanna et al 2014). Baxter et Nigam (2015) show that notable winter climate anomalies in the Pacific–North American sector need not originate from the tropics. While the historical teleconnections in Fig. 3 do not necessarily include Arctic change, Kug et al. (2015) do suggest a recent (1980-2014) winter connection of Chukchi Sea warm temperatures to eastern NA cold events. Further, extreme sea ice loss and warm temperatures in the Chukchi in November 2016 co-occurred with an extreme northward extension of the ridge feature into the central Arctic and an eastern NA cold event in December (*see* bellow). Likewise in Baffin Bay, Ballinger et al. (2017) found variations in sea-ice freeze onset and regional SSTs linked to 500 hPa blocking patterns and years of extreme late-freeze conditions occurring since 2006. However, Ayarzagüena et Screen (2016) and Trenary et al. (2016) do not conclude an increase in eastern NA cold events in historical data or future model projections. Thus it does not appear reasonable to say that the Arctic causes eastern US cold spells, but that near future Arctic change has the potential to prolong or possibly amplify the atmospheric long wave pattern associated with such events.

The geopotential height/temperature relationship

Whether thermodynamic changes (surface energy fluxes from warm SST anomalies and sea-ice loss, or temperature advection) can be connected to atmospheric dynamics and wind systems, is given by the geopotential tendency equation (Holton 1979), which may be expressed as:

Geopotential Height Change (*is proportional to*) A (*Vorticity Advection*) + decrease with height of [B (*Temperature Advection*) + C (*Thermal Heating*)] *Eqn.* 1

Geopotential heights can change, and thus modify wind fields, by (term A) horizontal propagation of existing jet stream features that can be considered primarily a random part of atmospheric dynamics, (term B) bringing low-level warm, less dense air into a region or (term C) warming a region locally. Part of the difficulty with linkage research is determining the influence of term C from Arctic sources relative to contributions from lower latitude to geopotential height changes.

A Greenland-Baffin Blocking (GBB) case

Chen et Luo (2017) concluded that more winter cold air outbreaks should occur over the eastern NA if large sea ice declines continue in Baffin Bay and the Labrador Sea regions that co-occur during weaken westerly winds. They note potential events in 2009, 2010 and 2012. We show the example of GBB for 15-22 December 2010. A large 500-1000 hPa geopotential thickness anomaly is evident in the GBB location (Fig. 4A). This is supported though the colocation of positive low level air temperature anomalies in Baffin Bay (Fig. 4B). While surface forcing can reinforce the geopotential height pattern, (Eqn. 1), it is unclear from Chen et Luo (2017) what percentage is due to the relative magnitude of surface forcing compared to the other height change contributions.

An Alaskan Ridge (AR) case

A recent high amplitude AR case was seen in 4-14 December 2016. Fig. 4C shows the 700 hPa geopotential height field for 4-14 December 2016. A clear feature is the AR reaching well into the Arctic north of Alaska with northwest winds crossing the central US northern border. Of interest is the positive geopotential height maximum centered over the north coast of Alaska. The December 2016 height pattern is collocated with positive temperature anomalies over the Pacific Arctic (Fig. 4D) and anomalous lack of sea ice in the region for the previous November (Fig. 4E). Fig. 4D surface temperatures were above freezing as confirmed by an ocean buoy north of Alaska at (71.0° N, 162.6° W) on 12 December 2016. Lack of sea ice and warm temperatures north of Alaska support greater geopotential thicknesses in the region and thus the major 700 hPa geopotential height feature and northern location of the ridge. That the thermodynamics in the coastal Alaskan Arctic region were persistent contributed to the AR pattern, and thus gave time for cold Arctic air to be advected into the continental US and spawn secondary vortices to the east of the ridge. Although the region of average cold temperatures shown in Fig. 4D does not extend to the east coast of NA, at the end of this period a small cold closed tropospheric vortex moved from Canada into the central US and on to the east coast. Dulles Airport reported its coldest temperature for 16 December of -13°C, with the record beginning in 1963. Historical analogs for early December 2016 are rare, with the December 1983 AR case being a near match with a strong positive temperature anomaly over the Chukchi Sea.

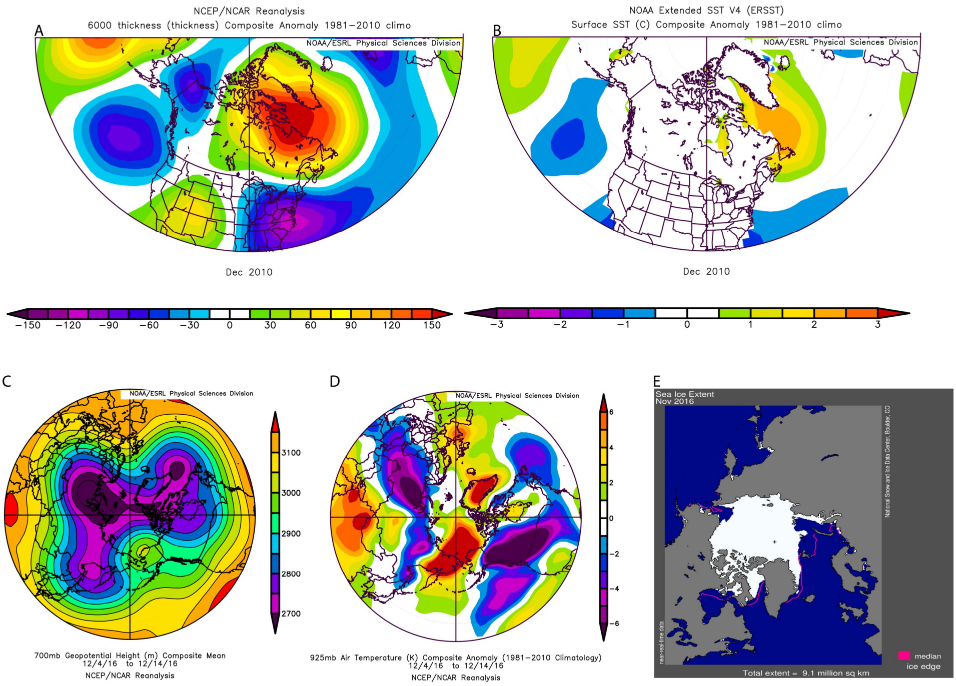

Fig. 4. A) the geopotential 1000-500 hPa thickness anomaly and B) the corresponding surface temperature anomaly for a Greenland-Baffin Blocking case during 15-22 December 2010 based on surface skin temperature from NOAA/NCAR reanalysis. C) 700 hPa geopotential height field for Alaskan Ridge case during 4-14 December 2016 and D) the corresponding 925 hPa temperature anomaly field for AR case. E) the November 2016 sea ice extent (white) and climatology (red line) from NSIDC. Note local height maximum and warm temperatures over north Alaska and lack of sea ice in the Chukchi Sea, Hudson Bay and the Barents and Kara Seas.

Summary and Conclusions

Cold temperature events have been recorded in the eastern US as long as records have been maintained over centuries. In this study cold events were defined as monthly mean temperature anomalies equal to or below one standard deviation over an eastern NA region for December and January (*see* Fig. 2, Table 1). We noted 19 major cases since 1950, with a rather uneven decadal distribution. In some but not all winters there was month-to-month persistence of cold events. Nearly all events have a west-east US temperature dipole pattern and a NA west coast ridge in the geopotential height field, as noted in Liu at al. (2015) and Singh et al. (2016). Abnormally high northeast Pacific SSTs relate to many cases of the AR pattern (Hartmann 2015, Baxter et Nigam 2015, Lee et al. 2015). The west coast ridge (AR) cases can occur with or without associated Greenland Blocking as noted in the cases that we labeled Both. For AR cases without GBB the east coast US low geopotential height anomalies can extend northward into the Arctic. In GBB cases the anomaly can be considered as a block with a cut off tropospheric vortex over eastern NA. All patterns have a warm Arctic/cold continent character.

Arctic/midlatitude weather linkages can support the North American AR or GBB patterns through reinforcing geopotential height fields by low level warm air convergence and low level heating (Eqn. 1), which increase the lower atmospheric geopotential thickness (Overland et Wang 2010, Overland 2016). Geopotential height field changes also have a chaotic or propagation component through vorticity advection that complicates assigning thermodynamic causality. Thus if we consider that the jet stream provides the bridge between Arctic thermodynamic forcing and midlatitude weather responses, variability in the jet stream pattern means that the bridge is not always down.

We note a December 2010 GBB case with collocated positive SST anomalies that reinforced the geopotential height pattern. Early December 2016 was an extreme AR case; the ridge extended well to the north of Alaska. *In situ* data, reanalysis temperature fields, and lack of November sea ice correspond in location to a local maximum in the geopotential height field centered on the north coast of Alaska. This case did not correspond to a month long cold eastern NA period, but spawned several short-term severe cold weather events over the eastern US.

Arctic connections to eastern NA cold events have been proposed based on surface temperature trends (Cohen et al. 2014, Kug et al. 2015, Chen et Luo 2017). However, some data analyses and model analyses of NA cold events do not show cooling trends, in fact some show the reverse (Screen et al. 2015, Trenary et al. 2016). We interpret such differences in conclusions to the intermittency of such events. There are short episodic examples of Arctic change reinforcing large scale atmospheric patterns associated with individual eastern NA midlatitude cold events, as in the December 2010 GBB and the December 2016 AR cases. They are conditional on the prior development of the Alaska Ridge or Greenland-Baffin Block patterns, and thus will not occur in every year with major sea-ice retreat, nor will they strongly contribute to overall climate statistics. Historically and at present, cold eastern NA events are mainly a consequence of natural variability and the Arctic does not drive the core of such events.

We concur with Bellprat et al. (2016) and Xie et al. (2017) that reduced Arctic sea ice and positive SST anomalies will contribute to sustaining anomalous meanders of the jet stream over NA, and increase the occasional persistence of extreme eastern NA cold spells.

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