Non-Gaussian Cold-Side Temperature Distribution Tails and Associated Synoptic Meteorology

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ABSTRACT

Non-Gaussian cold side temperature distribution tails occur in spatially coherent patterns in winter and summer across the globe. Under such conditions, future changes in extreme cold temperature exceedances may be manifested in more complex ways than if the underlying distribution were Gaussian. For example, under a uniform warm shift, locations with shorter- or longer-than-Gaussian cold side tails would experience a more or less rapid decrease in the number of extreme cold threshold exceedances, respectively, compared to if the tail were Gaussian. In many places in the mid- to high latitudes, shorter-than-Gaussian cold tails occur where there is a climatological limit on the magnitude of cold air to be transported by synoptic flow. For example, some high-latitude regions are already among the coldest in the hemisphere, thus limiting the availability of extremely cold air, in an anomalous sense, that can be transported to the region. In other short tail regions, anomalously cold air originates from or travels over large water bodies, which limits the magnitude of the cold anomaly. Long tails are often present when the cold source region is downstream of the climatological flow, requiring a highly anomalous circulation pattern to transport the cold air. The synoptic evolution of extreme cold days at several short- and long-tailed weather stations are presented to help diagnose the mechanisms behind extreme cold temperatures under conditions of non-Gaussianity. This provides a mechanistic view of how extreme cold occurs at each location, as well as an explanation for the notable deviations from Gaussianity.

1. Introduction

Extreme cold temperature anomalies are associated with a multitude of impacts on society and the environment. For example, extreme cold winter temperatures can pose threat to human life and safety (Conlon et al. 2011), damage infrastructure and disrupt transportation (Doll et al. 2014), and substantially increase energy demand for heating. During the growing season, extreme cold can damage crops, especially if temperatures fall below freezing (Gu et al. 2008). Conversely, in some regions, exceeding certain cold thresholds may provide benefit by controlling the growth and

geographic spread of native and invasive pests such as the pine bark beetle (Bentz et al. 2010; Carroll et al. 2003; Safranyik et al. 2010) or the *Aedes albopictus* mosquito (Caminade et al. 2012; Rochlin et al. 2013). However, anthropogenic climate warming is broadly projected to decrease the frequency of days exceeding current-climate extreme cold thresholds (Kirtman et al. 2013), although the rate and magnitude of this change will vary regionally. A comprehensive understanding of the climatological characteristics and driving mechanisms behind extreme cold is therefore of critical importance to best make projections of future change at regional scales.

Observational evidence supports a decrease in the frequency and severity of extreme cold days over the past several decades at global and regional scales (e.g., Wang et al. 2017; Sheridan and Lee 2018; Zwiers et al. 2011; Morak et al. 2013) with further evidence provided by a well-documented decrease in the number of

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extreme cold records broken compared with that expected in a stationary climate (Finkel and Katz 2018; Rowe and Derry 2012). Cold extremes have also been documented to be warming at a faster rate than the mean in many places (Gross et al. 2018). These changes are often statistically attributable to anthropogenic forcing (Min et al. 2013; Kim et al. 2016; Yin and Sun 2018). However, while consistent with and often attributable to global warming, these changes have been more pronounced in some regions of the extratropics than others with the mechanisms behind these heterogeneous trends an area of active research (Ogawa et al. 2018). For example, while extreme cold events may be less likely to occur in a warmer world (Screen et al. 2015; Ayarzagüena and Screen 2016; Christiansen et al. 2018), some studies suggest that a more disproportionately rapidly warming Arctic may influence Northern Hemisphere winter climate dynamics such that poleward excursions of extremely cold air could remain common even under warming (e.g., Francis and Vavrus 2015; Kretschmer et al. 2018; Wegmann et al. 2018).

Extreme cool events in the extratropics are often associated with anomalous large-scale meteorological patterns (LSMPs) and identifying and describing these patterns can help diagnose the physical mechanisms behind the anomalous temperatures. Because extreme negative temperature anomalies are most severe in the cool season, most studies describing the LSMPs associated with extreme cold focus on winter extremes (Smith and Sheridan 2018; Westby and Black 2015; Krueger et al. 2015; Loikith et al. 2017; Grotjahn and Zhang 2017; Risbey et al. 2019) while the LSMPs associated with extreme cold events in the warm season have received less attention. Midlatitude cold extremes tend to be primarily associated with LSMPs that promote the transport of anomalous cold air masses to the region experiencing the extreme, with positive sea level pressure (SLP) anomalies associated with the low-level cold air and an upper-level trough often centered downstream (Loikith and Broccoli 2012).

While the source region for extremely cold air is often poleward of any given location, the direction and distance of the coldest air available to be transported to a given location varies considerably at the regional scale (Fig. 1). For example, over much of Europe in the winter, the extreme cold air is usually transported westward from the interior of Eurasia while over the central United States extreme cold air originates from the north (Walsh et al. 2001). Both the distance and direction to the cold air source region for a location can therefore have a substantial impact on local extreme cold climatology including frequency and magnitude of cold anomalies. LSMPs can therefore provide valuable information

FIG. 1. Mean 2-m temperature values, in $^{\circ}\text{C}$, for DJF and JJA as labeled at the upper left. Contours are every 4°C . Magenta stars are locations for composites in Figs. 5–10 and magenta crosses are locations for composites in the online supplemental material.

on the behavior of extreme cold climatology at locally and regionally specific scales.

It is well documented that marked departures from Gaussianity are common in daily surface temperature distributions (Cavanaugh and Shen 2014; Perron and Sura 2013; Loikith et al. 2013; Linz et al. 2018). Furthermore, these departures often occur in spatially coherent regions, which suggests a prominent role of large-scale climatological forcing (Stefanova et al. 2013; Garfinkel and Harnik 2017). This presence of non-Gaussian temperature distributions carries potentially substantial implications for future changes in extreme temperatures as such changes will be manifested in more complex ways compared to if the distribution were normal (Sardeshmukh et al. 2015; Guirguis et al. 2018). For example, Ruff and Neelin (2012) demonstrated that under a uniform warm shift, the simplest prototype of future warming, a longer-than-Gaussian warm side temperature distribution tail would result in a smaller increase in the frequency of exceedances of a fixed extreme warm threshold than if the distribution were Gaussian. Loikith and Neelin (2015) demonstrated the opposite effect for shorter-than-Gaussian warm tails, resulting in a larger increase in the number of days exceeding the fixed threshold compared with shifting a Gaussian by the same amount. This effect is illustrated in the schematic in Fig. 2.

FIG. 2. A schematic illustrating the effect of non-Gaussian tails on changes in the frequency of exceeding a fixed extreme temperature threshold under a uniform warm shift. Solid curves are the temperature frequency distributions for the preshifted climate while dotted curves are the temperature frequency distributions after the warm shift. Solid vertical yellow lines are the preshifted mean and dotted vertical yellow lines are the mean after the warm shift. The red shaded area represents temperatures above the 95th percentile of the preshifted distribution while the blue shaded area represents the 5th percentile. Illustrations are for (top) a Gaussian distribution, (middle) a distribution with a shorter-than-Gaussian warm tail and a longer-than-Gaussian cold tail, and (bottom) a distribution with a longer-than-Gaussian warm tail and a shorter-than-Gaussian cold tail.

To date, most research on the interaction between temperature distribution tail shape and extremes has focused on the warm side of the temperature distribution or on the overall distribution asymmetry (e.g., Huybers et al. 2014; Loikith and Neelin 2015; Guirguis et al. 2018). Loikith et al. (2018) identified several “hotspots” of regional warming where shorter-than-Gaussian warm side tails are projected to lead to much

more rapid than Gaussian increases in the frequency of exceeding a fixed extreme warm temperature threshold. This conclusion carries notable implications for relatively near-term change in warm extremes in regions with short warm tails. However, change in extreme cold exceedances also carries substantial implications for society and the environment. Therefore, here we focus on regions of non-Gaussian cold side temperature distribution tails where short and long tails result in a larger and smaller decrease in extreme cold exceedances compared to a Gaussian under uniform warming across the distribution, respectively. We further investigate the LSMPs associated with anomalous cold in a selection of locations representing regions that exhibit strong departures from Gaussian as a way to diagnose the underlying meteorological reasons for the long or short cold tail.

2. Data

Gridded 2-m temperature, SLP, 500-hPa geopotential height (Z500), and cloud fraction data are from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA2) reanalysis. MERRA2 is the latest generation of atmospheric reanalysis from the U.S. National Aeronautics and Space Administration (NASA) and is provided at hourly temporal resolution on a 0.5° latitude by 0.625° longitude grid (Gelaro et al. 2017). Here we construct daily means from the hourly data. MERRA2 data are provided globally, but here we only analyze temperature over land. Daily mean 2-m temperatures for select locations are from the Global Historical Climatology Network–Daily dataset (Menne et al. 2012). All stations analyzed had complete or nearly complete data coverage for the analysis period during the season analyzed. While reanalysis temperature data carry uncertainty (e.g., Gross et al. 2018), the inclusion of station data aids in the validation of the departures from Gaussian calculated in the reanalysis data. Furthermore, previous work using reanalysis to identify regions of non-Gaussian warm tails suggests that the principal patterns of non-Gaussianity are generally consistently represented within reanalysis (Loikith and Neelin 2015; Loikith et al. 2018).

3. Methodology

All analysis is performed using the 30-yr period 1980–2009, matching Loikith and Neelin (2015). Anomalies are computed by subtracting the daily climatological mean, calculated for the entire 30-yr record, from each day. The linear trend in the temperature reanalysis anomalies is removed at each grid point, separately for

FIG. 3. (a),(c) Shift ratios, plotted on a log scale, for DJF and JJA as labeled at top left. Values less than one have a shorter-than-Gaussian cold tail while values greater than one have a longer-than-Gaussian cold tail. Only grid cells where the cold tail deviates from Gaussian with statistical significance at the 5% confidence level are shaded. The individual locations presented in subsequent figures are indicated by the red and blue symbols. Red symbols are examples with long tails and blue are examples with short tails. Stars indicate examples in the main manuscript and crosses are in the online supplemental material. (b),(d) The standard deviation of temperature in $^{\circ}\text{C}$ with the 2° contour highlighted in red.

each season. Normalized anomalies are computed by dividing the daily anomalies by the temporal standard deviation of the entire seasonal anomaly time series. Seasons are defined as the standard meteorological 3-month season, here focusing on December–February (DJF) and June–August (JJA).

Following the approach used for warm tails in [Loikith et al. \(2018\)](#), non-Gaussian temperature distribution cold side tails are identified via the following process. First, the 5th percentile of the temperature distribution is identified. The distribution is then shifted uniformly by 0.5 standard deviations (σ). A uniform shift in σ is chosen over a fixed value (such as one degree) so that the shift magnitude is proportional to the variance of the distribution. Next, the percent of days exceeding (colder than) the 5th percentile after the uniform shift is tabulated. If the percent of days exceeding the 5th percentile after the shift is greater or less than that expected from shifting a Gaussian by 0.5σ , which is approximately 1.61% of the time, then that cold tail is deemed longer or shorter than Gaussian, respectively. This value is expressed as a ratio of the percent of days exceeding the 5th percentile after the 0.5σ shift to that expected from shifting a Gaussian and referred to herein as a shift ratio. Significance is assessed by applying this shift process to a randomly generated Gaussian distribution of length equal to the number of days 10 000 times to create a distribution of exceedance percentages. If the actual

number of days exceeding the preshifted 5th percentile is greater than the 95th or less than the 5th percentile of the 10 000-member synthetic Gaussian shift distribution (1.25% of days and 1.93% percent of days, respectively), the cold tail is deemed significantly non-Gaussian. This approach to identifying short tails and testing for significance is pragmatic in that it shows the influence non-Gaussian tails can have on changes in cold extremes under warming while also being an application of a variant of the Kolmogorov–Smirnov test for normality [see [Loikith and Neelin \(2015\)](#) for details].

For construction of the LSMPs, extreme cold days are defined as those falling below the 5th percentile of the temperature anomaly distribution for each station. LSMPs are computed as composites of 2-m temperature, SLP, and Z500 for all extreme cold days as well as two and four days prior to the extreme. Because extreme cold events often last multiple days, the same day may contribute to more than one composite; however, we assessed the sensitivity of the LSMPs to this feature by building composites with only unique days and found that the overall synoptic patterns and associated conclusions remained unchanged.

4. Non-Gaussian cold tails spatial patterns

[Figures 3a and 3c](#) show the shift ratios for each of the four seasons using MERRA2 reanalysis. Values less

than one indicate shorter-than-Gaussian while values greater than one indicate longer-than-Gaussian cold tails. Note that regions of long tails tend to also exhibit negative skewness while areas of short tails exhibit positive skewness (not shown). However, while the shift ratio maps would look qualitatively similar to maps of skewness in most places, we focus only on the cold tail to isolate departures from Gaussian in the tail rather than across the entire distribution as in skewness. [Figures 3b and 3d](#) show the standard deviation of the temperature anomalies with the 2°C contour in red to highlight regions with narrow temperature distributions where the importance of tail length diminishes and the importance of distribution width increases with respect to changes in extremes under warming. In places with very narrow temperature distributions, which are primarily in low latitudes, a relatively modest shift will result in a large portion of the narrow distribution exceeding an extreme temperature threshold, regardless of tail shape ([Fischer and Knutti 2015](#); [Fischer et al. 2012](#)). Here, a standard deviation of 2° is provided as a reference for where distributions become notably narrow; however, it is not an exact delineation of where distribution width becomes dominant. This also emphasizes the motivation behind focusing on extratropical examples in this study.

Both DJF and JJA exhibit several spatially coherent areas of long and short tails. In DJF, short tails are common in northern North America while long tails are common in a band stretching from the panhandle of Alaska to the Great Lakes. In some parts of the short tail region, after a uniform 0.5σ warm shift, only half as many days would be colder than the preshifted 5th percentile than if the distribution were Gaussian. On the other hand, some portions of the long tail region show shift ratio values as high as two, meaning twice as many days would exceed the 5th percentile compared to if the distribution were Gaussian. In other words, under a uniform shift paradigm, the high latitudes of North America would see a rapid decrease in the number of days colder than the 5th percentile while in parts of the North American Pacific Northwest, extreme cold exceedances would continue to be relatively common under warming due to the underlying longer-than-Gaussian cold tails. Much of Europe and the western three-quarters of Asia are also characterized by long tails, while eastern Russia is mostly characterized by short tails. In the Southern Hemisphere, short cold tails are found across Patagonia and the southern coast of Australia.

Short tails are common in JJA across the Northern Hemisphere, with much of the Arctic coast characterized by notable short cold tails. The area of short tails over the northwestern U.S. coast and British Columbia in JJA tends to replace long tails in this region seen in

DJF. Short tails are also prominent across the northern two-thirds of Europe, La Plata basin, and most of Australia. A substantial region of long cold tails is found in central South America in JJA extending at an angle roughly from Bolivia toward São Paulo; long cold tails are also found over portions of the Sahara, India, and southeastern China.

In some cases, an explanation of the presence of regions of non-Gaussian tails may be offered by the position of the region within the temperature climatology as shown in [Fig. 1](#). For example, the area of short tails in northern North America in DJF lies in or near the climatologically coldest air in the hemisphere, resulting in an absence of a source region of anomalously cold air, and therefore limiting the magnitude of cold tail excursions. On the other hand, the area of long tails found to the south of this region lies to the west and southwest of this region of climatologically cold air. This puts the cold air source region upstream of the westerly climatological flow, which suggests that rare meteorological conditions would be required to transport this relatively extreme cold air to this region. This would lead to large cold tail excursions relative to the climatology, when such conditions are favorable. Similar relationships are present across Eurasia, where long cold tails are prominent upstream (to the west) of the coldest air in Siberia, whereas in the vicinity of that cold air short tails are common. During JJA, the region of prominent long tails over South America is north of a relatively strong temperature gradient. In this case, rare equatorward excursions of cold air could lead to high-magnitude negative temperature anomalies. Such Andean cold surge events are documented in detail in [Prince and Evans \(2018\)](#).

In other cases, non-Gaussian tails may be influenced by proximity to other features, such as moderating bodies of water. In DJF, for example, southern Australia exhibits notable short cold tails, even though there is climatologically colder air to the south. Here, however, the open ocean would act to limit how cool the air can get, prohibiting large cold side excursions of the temperature distribution. A similar effect may be at play for the Atlantic coast of northwestern Africa in JJA. In JJA the region of short tails in British Columbia and the northwestern United States likely results from the lack of a highly anomalous cold air source region altogether, as the interior warms faster than the ocean. In this case, air trajectories from any direction would not bring especially cold air, limiting cold tail excursions.

5. Individual cases

In this section, the LSMPs associated with extreme cold days at six locations (three with short and three with

FIG. 4. Temperature frequency distributions for the six cities used as case studies. PDFs are constructed using station observation for the indicated city. Distributions on the left have significant short cold tails while distributions on the right have significant long cold tails. The dotted blue vertical line is the distribution mean and the dotted black vertical line is the 5th percentile. Bin counts below the 5th percentile are indicated with open circles. A Gaussian fit to the core is provided to highlight tail departures from Gaussianity. Frequency is provided on a log scale to highlight the tails.

long tails) are presented. Extreme cold temperature days are defined using GHCN-D station data with the geographic location of each station indicated in both Figs. 1 and 3 and on the location-specific composite maps. Figure 4 shows the temperature anomaly distributions for each of the six locations using station observations from the indicated city with a Gaussian fit to the core of each distribution provided to highlight the departures from normality. The prominent non-Gaussian tails for each city agree qualitatively well with the MERRA2 reanalysis within these non-Gaussian regions.

In choosing stations to present as examples, we aim to select a set of places representing a diverse range of geographies within the extratropics. Focus on the extratropics was motivated by the importance of synoptic scale dynamics on the occurrence of temperature extremes as well as the larger influence of tail shape on changes in extreme exceedances under warming

compared with the tropics. Station selection was also constrained by availability of high-quality data spanning the entire analysis time range, which prohibited station-based analysis in some regions of non-Gaussianity. Given these considerations, we present three short-tailed (Yellowknife, Adelaide, and Rennes) and three long-tailed (Pendleton, North Platte, and Berlin) locations with two local summer cases and four local winter cases. While this provides a reasonably inclusive set of examples, we acknowledge that these six cases may not represent the synoptic dynamics associated with extreme cold in all extratropical regions of non-Gaussianity. While our presentation focuses on the six cases, we further provide three additional local summer cases in Figs. S1–S3 in the online supplemental material for Seattle (United States), Bergen (Norway), and Berlin (Germany), respectively. We also show one tropical location in local summer for Indore, India, in Fig. S4 where nonbaroclinic

FIG. 5. Composites for (top) days below the 5th percentile of the temperature distribution at Yellowknife, Canada (magenta star), during DJF (local winter). Composites are for (left) 2-m temperature in units of $^{\circ}\text{C}$, (center) SLP in units of mb, and (right) Z500 in units of m. Dashed contours for 2-m temperature and Z500 are standardized anomalies. SLP values are contoured every 1 mb.

summer monsoon dynamics are prominent, to provide contrast with the extratropical examples where baroclinic processes are key.

a. Short tail cases

1) YELLOWKNIFE, CANADA, DJF

The DJF temperature distribution for Yellowknife, Canada, exhibits a shorter-than-Gaussian cold tail (Fig. 4) and sits within a large region of short tails (Fig. 3). Figure 5 shows composites of total field and standardized anomalies in temperature (left column), SLP (middle column), and Z500 (right column) for days falling below the 5th percentile of the DJF temperature anomaly distribution (referred to as cold days herein) at Yellowknife (top row), two days prior to the cold day (middle row; $t - 2$), and four days prior to the cold day (bottom row; $t - 4$). At $t - 4$, temperatures are generally around 0.5σ below the climatological average across much of central Canada, with temperatures around -30°C in the vicinity of Yellowknife. Slightly colder air is present to the north and east of the city, with warmer temperatures elsewhere. An area of high pressure is present over the Arctic Ocean north of Alaska, extending east/southeastward toward Yellowknife where the SLP gradient is weak. At Z500, a broad trough is centered to the east of Yellowknife, with an anomalous ridge over western Alaska.

At $t - 2$, temperatures are considerably lower over and to the north and east of Yellowknife than at $t - 4$. These cold temperatures, around -40°C , are confined to a band, with warmer temperatures to the north over the Arctic Ocean. An area of temperature anomalies exceeding 1σ has developed in the vicinity of Yellowknife. The area of high pressure has strengthened and extended farther east and southeastward, with SLP values increasing over Yellowknife. The city sits within a weak SLP gradient, suggesting light surface winds; however, the SLP gradient just to the east suggests some northerly flow, which would act to locally transport the coldest air that has formed near and to the north of Yellowknife. The Z500 trough has strengthened by $t - 2$ but has not changed position appreciably.

On the cold day, the composites show Yellowknife within a broad area of below average temperatures, with negative anomalies exceeding 1.5σ in and around the city. Temperatures below -40°C are common in a band stretching northwestward from Hudson Bay to the Arctic Coast, in the same geographic location as the coldest temperatures at $t - 2$. There is no evidence of cold air being transported from elsewhere, but rather the coldest temperatures apparently develop mostly in place. SLP values have increased substantially by the cold day as the high pressure center has moved east and expanded southward, with the highest SLP values near Yellowknife. With high pressure at the surface and a

FIG. 6. As in Fig. 5, but for Adelaide, Australia, during DJF (local summer).

weak pressure gradient and minimal winter insolation, ideal radiational cooling conditions are present, likely the primary contributing factor to the development of the anomalous cold. This is supported by composites of cloud fraction and cloud fraction anomalies in Fig. S5, showing anomalously clear conditions over Yellowknife concurrent with cold days. At Z500, the trough is stronger than in $t - 2$, and shifted slightly southward. Together, this synoptic progression indicates that the coldest temperatures within this area of short tails are not primarily the product of transport of air from much colder places, but rather conditions that promote the development of anomalously cold air. This is consistent with expectations from the climatological temperature gradient in Fig. 1, as Yellowknife sits near the coldest temperatures in the hemisphere. This limit on advection of highly anomalous cold air therefore helps explain the short tails in this region.

2) ADELAIDE, AUSTRALIA, DJF

Figure 6 shows the composites for Adelaide, Australia, during the summer months. The southern coast of Australia is characterized by short cold tails during DJF (Fig. 3). The composites for $t - 4$ at Adelaide show temperatures within 0.5σ of the mean across the region. The SLP pattern shows an area of high pressure centered over the Indian Ocean with higher pressure along the southern coast of Australia and lower pressure to the north. The pressure gradient over Adelaide would promote southerly flow, but no evidence of anomalous

temperature advection is apparent. At Z500, a wave train pattern with a trough centered near Adelaide is present. At $t - 2$, cold temperature anomalies have developed, with the strongest anomalies of greater than -1σ southwest of the city. The area of high pressure is stronger at $t - 2$ than $t - 4$ with its influence extending eastward, increasing the SLP gradient over Adelaide and to the west. This strong pressure gradient also coincides with the negative temperature anomalies, suggesting transport of cold air from higher latitudes toward Adelaide. The wave train at Z500 has amplified considerably relative to $t - 2$ with the trough centered just south of Adelaide.

The cold day composite at Adelaide shows the area of cold anomalies centered over the city and surrounding region. This area of negative temperature anomalies appears to have moved from the southwest to the northeast. This advancement of the anomalously cold air coincides with a further extension of the surface high to the east with a SLP gradient that would continue to promote southerly flow at Adelaide. The city sits just to the west of the Z500 trough center on cold days. This synoptic setup suggests the advancing area of high SLP advects cool air from the south; however, because this air is of marine origin and must travel over open ocean to arrive at Adelaide, the magnitude of the anomalies is limited, contributing to the short tails along the southern Australia coast.

3) RENNES, FRANCE, JJA

Figure 7 shows the composites for Rennes, a city in western France, during the summer months of JJA.

FIG. 7. As in Fig. 5, but for Rennes, France, and for JJA (local summer).

Rennes is within an area of short tails that extends from western Europe through Scandinavia and into western Russia. The temperature composites for $t - 4$ show an area of modest cold anomalies to the northwest of Rennes, but temperatures in the vicinity of the city are within 0.5σ of the mean. An area of high SLP values is centered over the Azores, with a SLP gradient over Rennes that would promote westerly flow, which would be generally coming from the direction of the negative temperature anomalies. This SLP gradient is enhanced by low SLP over Scandinavia. At Z500, Rennes is on the southern end of a trough, with a ridge present over the North Atlantic Ocean. At $t - 2$, temperatures have cooled across the British Isles and France, with Rennes within an area of temperature anomalies between -0.5 and -1σ . The strongest cool anomalies are to the north-northwest. At $t - 2$, the area of high pressure has expanded northward toward Iceland, while the low pressure is centered over southern Norway. This has turned the SLP gradient such that winds near the surface would be more northwesterly and originate from the region with the highest-magnitude cool anomalies. The Z500 wave train is more amplified at $t - 2$, with the trough center considerably farther south than at $t - 4$.

The composites for cold days show a broad area of cool anomalies greater than -1σ centered over France. This area of anomalously cool temperatures has progressed southeastward over time and has increased in magnitude since $t - 4$. This is suggestive of transport of cool air by the low level SLP gradient. The cold day

SLP composite shows a northeastward expansion of the Azores-centered high into France and the British Isles, while the Scandinavia-centered low has remained nearly stationary. This SLP gradient is favorable for transporting cool air from the northwest into the region. The Z500 trough has moved south compared with $t - 2$ and is now centered over the Germany/France border. While this pattern is relatively highly amplified near the surface and the midtroposphere, cool anomalies are relatively modest. This is due primarily to the marine origin of the cold air. This limits the magnitude of cool anomalies here and contributes to the short tail.

b. Long tail individual cases

1) PENDLETON, UNITED STATES, DJF

Pendleton, located in the Columbia River basin of the U.S. state of Oregon is within a large region of long cold tails in DJF. Pendleton is located to the southwest of the coldest air in North America, which puts this cold air downstream of the climatological flow at Pendleton. Additionally, Pendleton is often protected from Arctic cold surges by the Rocky Mountains, which act as a barrier to the often shallow cold air mass that more commonly occur across the eastern half of the United States. Combined, these features make highly anomalous cold air outbreaks relatively rare in Pendleton; however, under some conditions, transport of highly anomalous high-latitude continental air can result in large excursions from the mean, which in turn would

FIG. 8. As in Fig. 5, but for Pendleton, United States, for DJF (local winter).

result in the long cold tail observed here. Figure 8 illustrates the highly anomalous flow pattern required to transport extreme cold air south and west across the mountains to bring cold anomalies to the Pendleton region. At $t - 4$, Pendleton is within a large region of cold temperature anomalies that encompasses much of western North America. The coldest temperatures are to the north and east of the city over the Rocky Mountains with even colder air farther to the north and northeast. Concurrently, high SLP values are found to the north and northwest of Pendleton with lower SLP to the south. This causes a pressure gradient that promotes easterly flow near the surface, which would act to inhibit the moderating influence from westerlies of Pacific origin while helping transport colder continental air. A highly amplified Z500 pattern is also present at $t - 4$, with a strong anomalous ridge centered over the Gulf of Alaska, a trough extending from Hudson Bay southwest beyond Hawaii and another ridge centered over the Bahamas.

At $t - 2$, the magnitude of the cold anomalies is stronger than at $t - 4$, with a large area exceeding -1.5σ . The coldest air over Canada has also clearly moved southwest compared with $t - 4$. The area of high pressure that was present largely over northwestern Canada at $t - 4$ is stronger at $t - 2$ and has expanded south and southeastward. This acts to strengthen the SLP gradient in the vicinity of Pendleton, promoting transport of the coldest air from the east and northeast. There is little apparent change in the Z500 pattern between $t - 4$ and $t - 2$. The cold day composites show much of the

western three-quarters of the United States and much of southern Canada encompassed by negative temperature anomalies. The strongest anomalies are in the Pendleton area and the coldest surface temperatures have expanded farther southwest. The area of high pressure has moved south and southeast compared with $t - 2$, with relatively low pressure south of Pendleton, high pressure to the north, and even higher pressure to the east over the Great Plains. Furthermore, while subtle, a smaller area of locally high SLP north of Pendleton may be the result of enhancement of cold air over the Columbia River basin and surrounding region under calm winds and limited winter insolation. This acts to strengthen the pressure gradient over Pendleton and could provide a local enhancement of the cold air. The highly amplified Z500 pattern is similar to $t - 2$, with the trough extending southwest from northeast Canada, the climatologically coldest part of North America.

This highly amplified, relatively persistent circulation pattern strongly deviates from climatology and results in a large perturbation in the climatological synoptic flow. As a result, this setup is rare, but capable of transporting highly anomalous interior Arctic air to a region not typically under the influence of such an air mass. The result is large deviations from the mean and a longer-than-Gaussian cold tail. LSMPs are consistent with those found to be associated with extreme cold across much of the Pacific Northwest region of the United States in Loikith et al. (2017).

FIG. 9. As in Fig. 5, but for North Platte, United States, for DJF (local winter).

2) NORTH PLATTE, UNITED STATES, DJF

North Platte (Fig. 9), in the U.S. state of Nebraska, is located on the eastern side of the long tail region that also includes Pendleton. The two locations also share some commonalities in the LSMPs associated with extreme cold and the synoptic progression of these patterns over time, although North Platte does not have topography as a barrier to anomalous cold. At $t - 4$, regional temperature anomalies are relatively weak but widespread across a large portion of central Canada and the north-central to northwestern United States. A strong surface high is evident in the SLP composite, centered over northwest Canada with weak SLP gradients in the vicinity of North Platte. At Z500, a wave train pattern that somewhat resembles that for the Pendleton example is present, with a trough centered to the north of the city. At $t - 2$, cold anomalies are of a higher magnitude than $t - 4$ across the western United States and southwestern Canada; however, the strongest anomalies are northwest of North Platte. The migration of the coldest air from central Canada has moved south and southwestward, indicating central and northeastern Canada as the source of the advancing cold air. The high pressure area is stronger at $t - 2$ and has expanded southward toward North Platte. The high SLP values push up against the Rocky Mountains as the coldest, densest air is prevented from expanding west of the topography. The most anomalous temperatures at $t - 2$ align with a SLP gradient that promotes transport of air clockwise around the surface high from central and northeastern Canada

and up the slope of the High Plains. At $t - 2$, the Z500 pattern has amplified, but the ridge and trough centers have only moved slightly compared with $t - 4$.

The composites for cold days at North Platte show the most negative temperature anomalies over the city and extending northwest and southeast. The coldest temperatures, exceeding -30°C , have pushed south and southwest into the northern United States to the north and northeast of North Platte. The highest SLP values are just to the north of the city with a pressure gradient indicating a flow pattern that transports the coldest air from central and northeastern Canada into the U.S. Midwest and westward up the slope of the Great Plains to North Platte. The very high SLP values are evidence of this very cold air mass with an associated flow pattern transporting very cold high latitude air into the U.S. Great Plains. The northeast to southwest elongation of the Z500 trough is further evidence of the cold air mass extending southwestward into the United States. While North Platte is not as far removed from the extreme cold air as Pendleton, this relatively highly anomalous setup that draws extreme cold air from the northeast and up the slope of the Great Plains allows very extreme cold anomalies in this region on rare occasion, contributing to the long cold tail here.

3) BERLIN, GERMANY, DJF

Much of northern and central Europe is characterized by long cold tails in DJF. The source region for

FIG. 10. As in Fig. 5, but for Berlin, Germany, for DJF (local winter).

anomalously cold air for the region is far to the east, placing highly anomalous cold air climatologically downstream. The composites for $t - 4$ in Fig. 10 show most of Europe under the influence of cold anomalies with the coldest air extending eastward from Finland through Russia. A relatively weak area of high pressure is present to the north of Berlin, with lower pressure to the south, resulting in a SLP gradient that would promote easterly flow. The Z500 setup resembles a blocking pattern with anomalously high heights centered north of Iceland and anomalously low heights extending across all of mainland Europe. At $t - 2$, temperatures have cooled across central Europe with the coldest air extending into eastern Europe. The surface high to the north of Berlin is stronger at $t - 2$ compared with $t - 4$, enhancing the SLP gradient and promoting stronger easterly winds. The blocking pattern is more amplified at Z500 with the Z500 high extending farther east over northern Scandinavia and the Z500 low in a similar position. This flow pattern is indicative of a southwestward displacement of very cold air from the interior of Russia.

Cold days at Berlin show an area of cold anomalies exceeding -2σ along with a strong high pressure to the north and a relatively unchanged low pressure to the south compared with $t - 2$ and $t - 4$. The blocking pattern at Z500 remains relatively unchanged compared to the composites from days prior. This highly anomalous pattern allows extremely cold air, in an anomalous sense, from central Russia to be transported westward,

opposing the climatological westerlies and resulting in large deviations from the mean and contributing to the long cold tail in Berlin.

6. Summary of mechanisms

Non-Gaussian cold tails commonly occur throughout the globe and are often present in coherent spatial patterns. Here we investigate the LSMPs associated with extreme cold at three cities located within shorter-than-Gaussian regions and three located in longer-than-Gaussian regions in the midlatitudes where synoptic flow is key to temperature variability. Figure 11 summarizes these mechanisms for each city examined with the background seasonal temperature climatology provided for reference. Yellowknife (Fig. 11a) is just to the southeast of the climatologically coldest air in the region, with a relatively weak climatological temperature gradient between the city and the coldest air. Cold days in Yellowknife occur when an area of high SLP builds southeastward into the region. The counterclockwise circulation associated with the high likely ensures that the coldest air from the north and northeast is in place. Then, the calm winds and clear skies (Fig. S5) under the center of the high promote radiational cooling, resulting in the extreme cold anomaly. This all suggests that the short tail that characterizes the temperature distribution at Yellowknife, and the surrounding region, exists primarily because highly anomalous cold air is not available for transport since this region is the coldest in the hemisphere.

FIG. 11. Summary illustrations depicting the meteorological patterns and physical mechanisms associated with extreme cold at each of the six select cities. Results are for (left) short tail cities and (right) long tail cities for the given season. Background shading is the climatological mean temperature for the indicated season. A blue H indicates a surface high pressure center; arrows connecting Hs indicate progression of the high pressure. Purple vectors represent low-level airflow. Thick blue arrows illustrate flow at Z500.

Cold days during summer in Adelaide require the climatologically coldest air to travel over open ocean before reaching the city (Fig. 11b). Cold days occur with high SLP to the west and low SLP to the east, with the resulting gradient promoting flow from the south and southwest. The marine moderation of this cold air limits the cold anomalies that are possible, contributing to the short tail here. A similar effect is present during summer cold days in Rennes, which exhibits a short cold tail along with much of mainland Europe. Figure 11c shows a weak climatological temperature gradient in this region with the coldest air to the northwest. Cold days are characterized by a notable SLP gradient that promotes flow from the northwest; however, cold air has a marine origin and is therefore limited in how cold it can get, contributing to the short tail here.

Pendleton (Fig. 11d) is within a large region of long tails in DJF and largely upwind of the climatologically coldest air available for transport. Cold days therefore require a highly anomalous synoptic situation and a cold air mass that is able to cross the mountains to the east. This occurs when a strong area of high SLP moves southeast from Canada, along the Rocky Mountains, and the resulting SLP gradient promotes easterly flow at Pendleton. In conjunction, a large, elongated, positively tilted Z500 trough is indicative of the southwestward displacement of this cold air. A similar setup is present for North Platte (Fig. 11e), which is at the eastern end of the same long tail region as Pendleton. Here, cold days are associated with a southward migration of a strong SLP high, which helps to transport low-level cold air from north and northeast Canada, around the high, and

up the slope of the Great Plains to North Platte. Like at Pendleton, the Z500 flow pattern is highly anomalous with an elongated positively tilted trough. This pattern also results in a flow pattern that opposes climatology, with cold air moving south and west, contributing to the long tail at North Platte.

Much of Europe exhibits long tails in DJF with the climatologically coldest air to the east. Cold days at Berlin (Fig. 11f) are associated with a blocking pattern at Z500 with a ridge to the north and a trough to the south of Berlin. At the surface, Berlin is between a high SLP center to the north and a low center to the south, promoting easterly flow near the surface. Together, these features reverse the climatological westerlies and transport highly anomalous cold air westward from Russia, resulting in rare but extremely cold anomalies, and contribute to the long cold tail.

7. Discussion and conclusions

While non-Gaussian cold tails may occur for a variety of reasons across the globe, results here suggest that a primary driver of deviations from Gaussian is the meteorological availability of and accessibility to highly anomalous cold air. Long cold tails tend to occur when the source of very cold air, relative to local climatology, is generally located downstream of the location. This makes variations in climatological flow unlikely to “tap” into this source of cold air unless the patterns are highly anomalous. This is evident in all three long tail cases examined in this study. On the other hand, large excursions on the cold side of the temperature distribution tend to be limited when the source region of the coldest air, relative to local climatology, is constrained in magnitude. This constraint may be due to marine moderation of the low-level air as in Rennes and Adelaide, or by simply being within the coldest region as in Yellowknife. These are, however, just a sampling of locations within non-Gaussian regions and are all within the mid- to high latitudes. It is likely that other physical processes and mechanisms are at play in some other non-Gaussian geographies, especially in lower latitudes. For example, downward vertical motion has been associated with anomalous cold (e.g., Risbey et al. 2019) and is not directly evident from the fields analyzed here. Last, some regions of non-Gaussianity do not obviously fit into this generalization and may have influence from other processes. For example, eastern South Africa exhibits long tails in DJF even though the coldest air available for advection to this region is over the ocean. More targeted analysis for exceptional cases like this would aid in fully diagnosing the entire range of physical reasons for non-Gaussianity.

The existence of non-Gaussian cold tails, as well as their driving mechanisms, provides substantial implications for future change in extreme cold under global warming. Under the simplest prototype for future warming, a uniform warm shift across the distribution, places with short cold tails would see a more rapid decrease in the number of days falling below a fixed extreme cold threshold (as in Fig. 3). The opposite would be true for long cold tails. However, amplified warming in the Arctic compared with lower latitudes acts to disproportionately warm the source regions of anomalously cold air (Screen et al. 2015). Given the primary importance of equatorward transport of anomalous cold air in the occurrence of days in the tails, particularly in the midlatitudes, this could contribute to deviations from expectations based on the shift paradigm. So, while changes in extreme cold will be manifested in more complex ways in the presence of non-Gaussian tails, compared with a Gaussian distribution, other changes in dynamics, advection strength, and temperature at high latitudes could further complicate change pathways for cold extremes in areas of non-Gaussianity.

Physical explanations of non-Gaussian behavior provided in this study take a regional perspective, describing the dynamics for a particular non-Gaussian location, which are influenced by the local and regional geography of the location. This includes the surface over which cold air is being transported, where the location is in relation to influential terrain features such as mountain ranges, and the accessibility of the location to highly anomalously cold air. It is worth underlining that the advection arguments in each case are not purely local, but require consideration of how the temperature gradient changes in the region from which cold air is transported into the given location. Related advection-based perspectives have also been applied to understanding deviations from Gaussianity in situations with simple, large-scale temperature gradients. For example, Garfinkel and Harnik (2017) demonstrate that equatorward propagation of Rossby waves along the storm track distort the zonal temperature gradient, resulting in equatorward advection of high-latitude air. Linz et al. (2018) use a two-dimensional advection–diffusion model to explain how large-scale dynamics lead to non-Gaussian temperature distributions in the midlatitudes. This model also proves useful in understanding the fundamentals of how global warming can change distribution shape through changes in latitudinal temperature gradients. Tamarin-Brodsky et al. (2019) also demonstrate the importance of advection in 850-hPa cold extremes and temperature distribution asymmetry in the Southern Hemisphere and how this influences projection of future change. Future work

aiming to bridge the local and regional scales of perspective may offer more comprehensive understanding of the role large-scale circulation in the presence of horizontal temperature gradients play in current temperature distribution symmetry as well as future change in extremes.

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