**A climatological analysis of the linkages between tropopause polar vortices, cold pools, and cold air outbreaks over the central and eastern United States**

*By*

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**ABSTRACT**

Coherent vortices in the vicinity of the tropopause, referred to as tropopause polar vortices (TPVs), may be associated with tropospheric-deep cold pools. TPVs and associated cold pools transported from high latitudes to middle latitudes may play important roles in the development of cold air outbreaks (CAOs). The purpose of this study is to examine climatological linkages between TPVs, cold pools, and CAOs occurring in the central and eastern U.S. To conduct this study, 1979–2015 climatologies of TPVs and cold pools are constructed using the ERA-Interim dataset and an objective tracking algorithm, and are compared to a 1979–2015 climatology of CAOs occurring in six NCEI-defined climate regions over the central and eastern U.S. The climatologies of TPVs and cold pools indicate that central and eastern North America is a preferred corridor for their equatorward transport to middle latitudes, and that northern regions of the U.S. are more susceptible to the occurrence of TPVs and cold pools than southern regions of the U.S. Correspondingly, there is a higher percentage of CAOs linked to cold pools associated with TPVs in the northern regions (67.4–87.8%) compared to the southern regions (24.7–26.4%). TPVs and cold pools contributing to CAOs most often form over northern Canada and the Canadian Archipelago, and move southeastward toward southern Canada and the northern U.S. These TPVs and cold pools contributing to CAOs tend to be statistically significantly colder and longer-lived when compared to all TPVs and cold pools transported to middle latitudes.

**1. Introduction**

TPVs are cold-core, coherent tropopause-based cyclonic vortices and material features, characterized by a local minimum of dynamic tropopause (DT) potential temperature, a lowered DT, an upper-level cyclonic potential vorticity (PV) anomaly, and parcel trapping (e.g., Hakim 2000; Pyle et al. 2004; Hakim and Canavan 2005; Cavallo and Hakim 2009, 2010). Pyle et al. (2004) referred to TPVs as coherent tropopause disturbances (CTDs), which dynamically represent the same features as TPVs, except that TPVs are typically required to spend a portion of their lifetimes in high latitudes (e.g., Cavallo and Hakim 2009, 2010), while CTDs are not. TPVs are generally characterized by radii of 100–1000 km and lifetimes of days to months (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2012). Longwave radiative cooling has been shown to be an important mechanism for the maintenance and intensification of TPVs (e.g., Cavallo and Hakim 2009, 2010, 2012, 2013). Cavallo and Hakim (2010, 2012, 2013) show that longwave radiative cooling is enhanced near the DT at the location of TPVs because of enhanced vertical gradients of water vapor between relatively moist tropospheric air beneath TPVs and relatively dry stratospheric air within TPVs. Resulting enhanced positive vertical gradients of longwave radiative heating within TPVs can contribute to the production of cyclonic PV within TPVs that helps maintain and intensify TPVs (e.g., Cavallo and Hakim 2010, 2012, 2013).

TPVs have been shown to be dynamically important precursors to the development and intensification of extratropical cyclones (e.g., Hoskins et al. 1985, section 6e; Uccellini et al. 1985; Hakim et al. 1995; Bosart et al. 1996; Simmonds and Rudeva 2012). Interactions between TPVs and the jet stream may lead to the formation and intensification of jet streaks (e.g., Pyle et al. 2004), which may further support the development and intensification of extratropical cyclones (e.g., Uccellini and Kocin 1987). TPVs may also be dynamically important precursors to the development of CAOs, since TPVs are cold-core features and are associated with anomalously cold air throughout the depth of the troposphere (e.g., Cavallo and Hakim 2010). Several studies show evidence of tropospheric-deep cold pools located within and beneath TPVs and upper-level cyclonic PV anomalies (e.g., Defant and Taba 1957; Boyle and Bosart 1983; Shapiro et al. 1987; Hakim et al. 1995; Papritiz et al. 2019). Papritz et al. (2019) show that cooling air parcels trapped throughout the troposphere within and beneath TPVs can contribute to the formation of these cold pools, and, along with Shapiro et al. (1987), show that these cold pools can contribute to the development of CAOs. Longwave radiative cooling from surface snow and ice cover, and from ice crystals, condensate, and low-level clouds often found in the troposphere within cold air masses (e.g., Gotaas and Benson 1965; Curry 1983; Emanuel 2008), may contribute to the cooling of these cold pools (e.g., Turner and Gyakum 2011; Turner et al. 2013; Papritz et al. 2019).

Central and eastern North America has been shown to be susceptible to the occurrence of TPVs (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2009, 2010, 2012; Szapiro and Cavallo 2018), 500-hPa cyclones (e.g., Bell and Bosart 1989) and troughs (e.g., Sanders 1988; Lefevre and Nielsen-Gammon 1995), in which TPVs may be embedded (e.g., Shapiro et al. 1987), and CAOs (e.g., Dallavalle and Bosart 1975; Konrad and Colucci 1989; Hartjenstein and Bleck 1991; Colle and Mass 1995; Konrad 1996; Walsh et al. 2001; Cellitti et al. 2006; Westby and Black 2015). TPV track frequency is particularly high over northern Canada and the Canadian Archipelago (e.g., Cavallo and Hakim 2009, 2010, 2012; Szapiro and Cavallo 2018), where TPVs often may meander slowly and intensify via longwave radiative cooling (e.g., Cavallo and Hakim 2009, 2010). Walsh et al. (2001) show that cold air trajectories associated with CAOs over the central and eastern U.S. originate over high latitudes and also often move slowly over northern Canada, where longwave radiative cooling contributes to the cooling of these trajectories.

Upper-level ridging and ridge amplification over the eastern North Pacific, western North America, North Atlantic, Greenland, and Arctic may contribute to the equatorward transport of TPVs and cold pools over central and eastern North America (e.g., Namias 1978; Shapiro et al. 1987; Alberta et al. 1991; Colle and Mass 1995; Hakim et al. 1995; Bosart et al. 1996; Konrad 1996; Colucci et al. 1999; Waugh et al. 2017). Between an upper-level ridge and a TPV may be a region of anticyclonic vorticity advection and sinking motion (e.g., Hakim 2000; Cavallo and Hakim 2010) that may contribute to surface anticyclogenesis (e.g., Dallavalle and Bosart 1975; Shapiro et al. 1987; Jones and Cohen 2011). Surface anticyclones accompanying TPVs and cold pools may advect cold air associated with the TPVs and cold pools far equatorward into the U.S. (e.g., Dallavalle and Bosart 1975; Boyle and Bosart 1983; Colucci and Davenport 1987; Shapiro et al. 1987; Konrad and Colucci 1989; Rogers and Rohli 1991; Colle and Mass 1995). The equatorward transport of cold air may be enhanced by a terrain-tied northerly component of strong low-level flow in the vicinity of a strong SLP gradient associated with a surface anticyclone (e.g., Bell and Bosart 1988; Colle and Mass 1995). For example, cold air may be channeled on the eastern side of the Rockies as far equatorward as Mexico (e.g., Colle and Mass 1995). In addition, Papritz et al. (2019) show that the cyclonic circulation associated with TPVs can contribute to the advection of cold air masses over far distances (e.g., from Siberia to the Fram Strait).

Research on the climatological linkages between TPVs and CAOs has recently gained attention. Papritz et al. (2019) examine linkages between CAOs occurring just south of the Fram Strait and TPVs, finding that 40% and 29% of the top 40 and 100 CAOs, respectively, are associated with TPVs. Lillo et al. (2020) show that a CAO occurring over the U.S. during 29 January–1 February 2019 is linked to an intense TPV, and show that CAOs over the U.S. during winter are often linked to TPVs. The present study provides a complementary analysis of climatological linkages between TPVs and CAOs by additionally exploring climatologies of cold pools, and the climatological linkages between TPVs, cold pools, and CAOs occurring over different regions of the central and eastern U.S. throughout the year.

The remainder of this paper is organized as follows. The data and methodology used to identify 1979–2015 climatologies of TPVs, cold pools, and CAOs, and linkages between TPVs, cold pools, and CAOs, are described in section 2. Results of the climatologies of TPVs, cold pools, and CAOs, and of the linkages between TPVs, cold pools, and CAOs, are discussed in section 3. A summary and conclusions of the results are presented in section 4.

**2. Data and methods**

*a. Identification of TPVs and cold pools*

All data used in this study for identifying TPVs and cold pools are from the ERA-Interim (Dee et al. 2011), downloaded at 0.5° × 0.5° horizontal resolution. TPVs were tracked objectively poleward of 30°N every 6 h during 1979–2015 utilizing an objective TPV tracking algorithm developed by Szapiro and Cavallo (2018) called TPVTrack. TPVTrack uses potential temperature, zonal and meridional winds, and the vertical component of relative vorticity on the DT (2-PVU surface) as input variables. At each time step, the DT potential temperature field is segmented into watershed basins. Each watershed basin is associated with either a DT potential temperature minimum or maximum, with locations in watershed basins associated with a DT potential temperature minimum and maximum possessing positive and negative values of the vertical component of DT relative vorticity, respectively. Watershed basins associated with a DT potential temperature minimum, which represent possible TPVs, are advected in space and time with use of the DT zonal and meridional winds. The degree of horizontal and vertical overlap of these advected watershed basins is used to connect watershed basins in space and time to create TPV tracks. The location or center of a TPV is the location of the minimum of DT potential temperature of the TPV. For detailed information on TPVTrack, see Szapiro and Cavallo (2018).

In order to track cold pools, TPVTrack was modified by only changing the input variables, such that DT potential temperature was changed to 1000–500-hPa thickness, DT zonal and meridional winds were changed to 700-hPa zonal and meridional winds, and the vertical component of DT relative vorticity was changed to 1000–500-hPa thermal vorticity, which is calculated by subtracting the vertical component of 1000-hPa relative vorticity from the vertical component of 500-hPa relativity vorticity. Like TPVs, cold pools were tracked poleward of 30°N every 6 h during 1979–2015. With the modified TPVTrack for cold pool tracking, each watershed basin is associated with either a 1000–500-hPa thickness minimum or maximum, with locations in watershed basins associated with a 1000–500-hPa thickness minimum and maximum possessing positive and negative values of the 1000–500-hPa thermal vorticity, respectively. The 1000–500-hPa thickness field is used because it is a rather smooth field with distinct minima representative of cold pools, and can encapsulate the structure of the thermal field throughout the troposphere within and beneath TPVs, which often extend downward to 500 hPa or lower (e.g., Cavallo and Hakim 2010). The 1000–500-hPa thermal vorticity is used because positive values of 1000–500-hPa thermal vorticity can encapsulate regions of relatively cold air associated with cold pools. The 700-hPa zonal and meridional winds are used to advect the watershed basins because these winds are located roughly in the middle of the 1000–500-hPa layer. The location or center of a cold pool is the location of the 1000–500-hPa thickness minimum of the cold pool. To test the modified TPVTrack for cold pool tracking, several manual cold pool tracks, which were created by manually following the location of the 1000­–500-hPa thickness minimum of the cold pools, were compared to their corresponding objective cold pool tracks. The manual and objective cold pool tracks were found to be very similar (not shown).

TPVs and cold pools were filtered by requiring them to last at least two days and spend at least 6 h poleward of 60°N. Cavallo and Hakim (2009) require that TPVs last at least two days and spend at least 60% of their lifetimes poleward of 65°N. A less strict latitude criterion is imposed in this study because the primary interest is on TPVs transported from high latitudes (> 60°N) to middle latitudes (30°N–60°N), where they may contribute to CAOs. The latitude criterion imposed in this study is more similar to a genesis latitude criterion tested by Szapiro and Cavallo (2018), which requires TPVs to just form poleward of 60°N. Szapiro and Cavallo (2018) find similar and increased TPV track frequencies over the Arctic and middle latitudes, respectively, when using their genesis latitude criterion over the latitude criterion of Cavallo and Hakim (2009). In this study, TPVs are not required to form poleward of 60°N, as some TPVs may form in the middle latitudes, then move poleward of 60°N, and then move back into the middle latitudes to potentially play important roles in CAO development.

*b. Identification of CAOs*

A climatology of CAOs occurring throughout the year over the U.S. that were identified by Murphy (2017) are used in this study. Murphy used daily minimum temperature data extracted from stations within the Global Historical Climatology Network (GHCN)-Daily dataset (Menne et al. 2012) that are distributed across nine climate regions defined by NCEI over the U.S. to identify CAOs for each region. Only regions over the central and eastern U.S., which include West North Central (WNC), East North Central (ENC), Northeast, Central, South, and Southeast, and their associated stations, are considered in this study (Fig. 1 and Table 1). The stations chosen by Murphy were based on their relatively even distribution across the U.S. and superior temporal coverage during 1948–2015, which is the period used by Murphy to identify CAOs. For this study, only CAOs during 1979–2015 are considered. According to Murphy, a CAO is defined to occur within a region whenever two or more stations within the region experience three or more consecutive days where daily minimum temperatures are less than or equal to the 31-day centered moving average of the 5th percentile minimum temperature for those days and share at least one overlapping day.

*c. Identification of linkages between TPVs, cold pools, and CAOs*

All CAOs during 1979–2015, and all TPVs and cold pools transported to middle latitudes, i.e., TPVs and cold pools that move equatorward of 60°N after being located poleward of 60°N, during 1979–2015 are considered when identifying linkages between TPVs, cold pools, and CAOs. A CAO that occurred during 9–14 January 1982 is used to illustrate how these linkages are identified. The January 1982 CAO was identified as a CAO for the Northeast, Central, South, and Southeast regions. This CAO is linked to a TPV and cold pool that spend much of their lifetimes meandering in tandem with each other over Canada during late December 1981 and early January 1982, before moving equatorward into and then eastward across the northern U.S. (Fig. 2a). The TPV and cold pool concomitantly intensify over Canada, with the TPV obtaining a minimum DT potential temperature value of ~249 K on 9 January 1982 and the cold pool obtaining a minimum 1000–500-hPa thickness of ~463 dam on 7 January 1982 (Figs. 2a,b). A meridional cross section through the TPV and cold pool at 0000 UTC 10 January 1982 (Figs. 3a–c) shows that the TPV extends downward to ~750 hPa and is associated with tropopause folding (e.g., Reed and Danielsen 1959; Danielsen 1968; Keyser and Shapiro 1986) as it interacts with an intense jet streak (Figs. 3a,b). There is a notable upward bowing of isentropes throughout the troposphere within and beneath the TPV (Fig. 3a), illustrative of the cold pool (Fig. 3c) associated with the TPV, with low surface potential temperature values spreading away from the core of the TPV (Fig. 3a). The large spatial overlap and temporal coincidence of the TPV and cold pool (Fig. 2a; Figs. 3a–c), and the concomitant intensification of the TPV and cold pool (Fig. 2b), suggest that the TPV and cold pool are dynamically linked.

The January 1982 CAO is clearly linked to a cold pool associated with a TPV. To identify all CAOs linked to cold pools associated with TPVs, CAOs linked to cold pools are first identified. CAOs linked to cold pools are identified by requiring that a cold pool circle of a specified radius (i.e., 1500 km) surrounding the cold pool center intersect with at least one grid point (using a 0.5° × 0.5° grid) of a region experiencing a CAO for at least one 6-h time step during the CAO (Figs. 4a,b). A cold pool circle with a radius of 1500 km generally encapsulates the spatial scale of the cold pool shown in Fig. 4a at 0000 UTC 10 January 1982, as well as at other times (not shown). Furthermore, this cold pool circle overlaps with all of the regions experiencing a CAO at this time, which are the Northeast, Central, South, and Southeast (Fig. 4b), and thus, the January 1982 CAO qualifies as a CAO linked to a cold pool for all of these regions. Several cold pool circle radius thresholds were tested, and the sensitivity of the identification of CAOs linked to cold pools to the cold pool circle radius threshold will be discussed in section 3b.

Once the CAOs linked to cold pools are identified, cold pools associated with TPVs and TPVs associated with cold pools are identified by requiring that the center of a TPV and the center of a cold pool be located within a specified TPV–cold pool distance threshold (i.e., 750 km) for at least two consecutive days (Fig. 4c). Requiring this distance threshold for at least two consecutive days helps insure that there is spatial and temporal overlap between TPVs and cold pools, while accounting for the fact that the centers of TPVs and cold pools are not always exactly collocated (e.g., Fig. 4c). The TPV and cold pool involved in the January 1982 CAO are within 750 km of each other at 0000 UTC 10 January 1982 as well as throughout much of their lifetimes (Fig. 4c), and thus the TPV and cold pool are associated with each other. The number of TPVs associated with cold pools and the number of cold pools associated with TPVs may not be the same because it is possible for one TPV to be associated with more than one cold pool and for one cold pool to be associated with more than one TPV. For example, if two TPVs are within the TPV–cold pool distance threshold of one cold pool for at least two consecutive days, then there are two TPVs associated with a cold pool and one cold pool associated with TPVs in this situation. Once cold pools associated with TPVs are identified, CAOs linked to cold pools associated with TPVs can be identified. Since the cold pool involved in the January 1982 CAO is a cold pool associated with a TPV, this CAO qualifies as a CAO linked to a cold pool associated with a TPV for the Northeast, Central, South, and Southeast regions. Several TPV–cold pool distance thresholds were tested, and the sensitivity of the identification of TPVs associated with cold pools, cold pools associated with TPVs, and CAOs linked to cold pools associated with TPVs to the TPV–cold pool distance threshold will be discussed in section 3b.

**3. Results**

*a. Locations of TPVs and cold pools*

In terms of track density of all TPVs during 1979–2015, TPVs occur most frequently over northern Canada, the Canadian Archipelago, Eurasia, and the Arctic (Fig. 5a), which are also regions of high TPV track density shown in Hakim and Canavan (2005), Cavallo and Hakim (2009, 2010, 2012), and Szapiro and Cavallo (2018). In terms of track density of all cold pools during 1979–2015, cold pools occur most frequently over the same aforementioned regions as TPVs (Fig. 5b). However, the regions of high cold pool track density are more restricted than those of high TPV track density (compare Fig. 5a and Fig. 5b), which may be due to a greater influence of land surface type on cold pools compared to TPVs. For example, regions of high cold pool track density are more restricted than regions of high TPV track density to land surfaces and surfaces that are typically covered with snow and ice throughout the year (e.g., the central Arctic), from which longwave radiative cooling would aid in cold pool production (e.g., Emanuel 2008; Turner and Gyakum 2011). Furthermore, cold pool track density and TPV track density is relatively low and high, respectively, over the open waters of the Norwegian Sea, from which surface sensible heating may weaken or destroy cold pools (e.g., Papritz et al. 2019), but may have little to no influence on TPVs. Reduced cold pool track density also occurs over the Rockies (Fig. 5b), as cold air is often channeled on the lee side of the Rockies (e.g., Colle and Mass 1995). The lower total number of cold pools (23045) compared to TPVs (58563) likely relates to the 1000–500-hPa thickness field, from which cold pools are identified, being a smoother field than the DT potential temperature field, from which TPVs are identified, and thus there being fewer trackable minima of 1000–500-hPa thickness than minima of DT potential temperature.

If considering TPVs and cold pools transported to middle latitudes, as defined at the beginning of section 2c, maxima of track density of these TPVs and cold pools are found over central and eastern North America, and central and eastern Eurasia (Figs. 5c,d). There are also maxima in the number of instances in which TPVs and cold pools cross equatorward of 60°N into middle latitudes over central and eastern North America, and central and eastern Eurasia, and a minimum in the number of these instances over the eastern North Pacific and western North America (Figs. 6a,b). Upper-level ridging over the eastern North Pacific and western North America, which may prevent the equatorward transport of TPVs and cold pools in these regions, may aid in the equatorward transport of TPVs and cold pools downstream over central and eastern North America (e.g., Shapiro et al. 1987; Colle and Mass 1995; Hakim et al. 1995; Konrad 1996). TPVs and cold pools transported equatorward over central and eastern North America, and central and eastern Eurasia, may play important roles in the development of CAOs, which are prevalent in these regions (e.g., Chang and Lau 1980; Konrad and Colucci 1989; Konrad 1996; Walsh et al. 2001; Chen et al. 2002, 2004). There is also high track density of TPVs and cold pools, and of TPVs and cold pools transported to middle latitudes, on the poleward side of the North Atlantic and North Pacific jet streams (Figs. 5a–d). Possible interactions of TPVs and cold pools with the North Atlantic and North Pacific jet streams, and regions of tropospheric-deep baroclinicity that may accompany these jet streams, may support the development of strong jet streaks (e.g., Pyle et al. 2004) and extratropical cyclones (e.g., Uccellini et al. 1985).

*b. Linkages between TPVs, cold pools, and CAOs*

Linkages between TPVs, cold pools, and CAOs are now examined, where only TPVs and cold pools transported to middle latitudes, as defined at the beginning of section 2c, are considered. Starting with the 1979–2015 climatology of CAOs, regional variability in the number of CAOs is found amongst the six regions over the central and eastern U.S. (Table 2). Differences in the number of stations in each region used to identify CAOs (Table 1) likely contribute to this regional variability, as regions with fewer stations have fewer CAOs than regions with more stations (Tables 1 and 2). To illustrate the impact of the number of stations on the number of CAOs for each region, the number of CAOs for each region was normalized by taking the number of CAOs for the region, multiplying by 12, which is the maximum number of stations of all the regions, and dividing by the number of stations of the region. The normalized number of CAOs is found to be more similar between regions compared to the raw number of CAOs (Table 2).

To identify CAOs that are linked to cold pools for each region, several cold pool circle radius thresholds were tested from 1000 km to 2000 km, every 250 km. For both northern regions (i.e., WNC, ENC, Central, and Northeast) and southern regions (i.e., South and Southeast), there is a relatively linear increase in the number and percentage of CAOs linked to cold pools when the cold pool circle radius threshold is increased from 1000 km to 1500 km, but only for the northern regions is there a smaller increase in this number and percentage when the cold pool circle radius threshold is increased from 1500 km to 2000 km (Figs. 7a,b). Thus, once the cold pool circle radius threshold is large enough (i.e., 1500 km), most possible cold pools that contribute to CAO development are likely accounted for in the northern regions. The 1500-km cold pool circle radius threshold is used for the rest of this study given that this intermediate threshold likely reduces miss scenarios from using too small of a threshold (e.g., 1000 km), in which a region experiencing a CAO is not identified as being linked to a cold pool because the region is too far from the cold pool center, but, for example, a surface anticyclone allows cold air from the cold pool to spread far away from the cold pool center (e.g., Shapiro et al. 1987) and impact the region. Furthermore, this intermediate threshold likely reduces false alarm scenarios from using too large of a threshold (e.g., 2000 km) in which a region is identified as being linked to a cold pool, but the cold air from the cold pool does not spread far enough away from the cold pool center to impact the region. Regardless of cold pool circle radius threshold used, there is a moderate-to-high percentage of CAOs linked to cold pools for the northern regions (e.g., 76.1–90.2% when using a 1500 km threshold), but a much smaller percentage for the southern regions (e.g., 28.4–35.2% when using a 1500 km threshold) (Fig. 7b and Table 3).

There is sensitivity in the number and percentage of TPVs associated with cold pools and cold pools associated with TPVs to the TPV–cold pool distance threshold as this threshold is increased from 250 km to 1000 km, every 250 km (Figs. 8a,b). Too small of a TPV–cold pool distance threshold may result in miss scenarios in which a cold pool spatially and temporally overlaps with a TPV, but the centers of the cold pool and TPV may temporarily be spaced too far away from each other to meet the small distance threshold. Too large of a TPV–cold pool distance threshold may result in false alarm scenarios in which a cold pool and TPV are identified as being associated with each other, but may be distinct features that minimally overlap. For TPV­–cold pool distance thresholds of ≥ 500 km, there is a larger number of TPVs associated with cold pools compared to cold pools associated with TPVs (Fig. 8a), suggesting that it is more likely for cold pools to be associated with more than one TPV during their lifetimes than for TPVs to be associated with more than one cold pool during their lifetimes. For all TPV–cold pool distance thresholds, there is a moderate-to-high percentage of cold pools associated with TPVs (e.g., ~75% when using a 750-km threshold), but a lower percentage of TPVs associated with cold pools (e.g., ~26% when using a 750-km threshold) (Fig. 8b). The lower percentage of TPVs associated with cold pools likely relates to there being a larger total number of TPVs transported to middle latitudes (25085) compared to cold pools transported to middle latitudes (8395). The lower percentage of TPVs associated with cold pools may also relate to some TPVs possibly being too small or too weak to be associated with a cold pool, and to some TPVs possibly being associated with a thickness trough that is not trackable as a cold pool.

In terms of CAOs linked to cold pools associated with TPVs, for all regions, as the TPV–cold pool distance threshold is increased from 250 km to 1000 km, every 250 km, the number and percentage of CAOs linked to cold pools associated with TPVs increases, but at a decreasing rate, such that there is little to no increase in this number and percentage when increasing the threshold from 750 km to 1000 km (Figs. 9a,b). The intermediate TPV–cold pool distance threshold of 750-km is used for the rest of the study, but regardless, for all thresholds, there is a moderate-to-high percentage of CAOs linked to cold pools associated with TPVs for the northern regions (e.g., 67.4–87.8% when using a 750-km threshold), but a smaller percentage for the southern regions (e.g., 24.7–26.4% when using a 750-km threshold) (Fig. 9b and Table 3). The higher percentage of CAOs linked to cold pools associated with TPVs for the northern regions compared to the southern regions is related to the large meridional gradient of TPV and cold pool track density over southern Canada and the northern U.S. (Figs. 5c,d), which indicates that the northern regions are more susceptible to the occurrence of TPVs and cold pools than the southern regions. Other features, such as troughs without an embedded trackable cold pool and TPV, may contribute to CAOs not linked to cold pools associated with TPVs for all regions.

*c. Locations of TPVs and cold pools involved in CAOs*

For CAOs linked to cold pools associated with TPVs, the locations of the TPVs (hereafter CAO TPVs) and cold pools (hereafter CAO cold pools) are now examined for all regions. CAO TPVs most often form over northern Canada, the Canadian Archipelago, and adjacent Arctic, but also form over Siberia and the North Pacific (Fig. 10a). The Canadian Archipelago was also shown by Cavallo and Hakim (2009) to be a region of particularly high occurrence of TPV genesis. CAO cold pools also most often form over northern Canada, the Canadian Archipelago, and adjacent Arctic (Fig. 10b), but less often form over Siberia and the North Pacific compared to CAO TPVs (compare Fig. 10a and Fig. 10b). CAO TPVs and CAO cold pools do not always simultaneously form (e.g., Fig. 2a) as some TPVs may need to strengthen before being associated with a cold pool, and for TPVs forming over open water areas like the North Pacific, cold pools may not simultaneously form, as there may be surface sensible heating from the open waters that may initially inhibit the development of cold pools. CAO TPVs and CAO cold pools follow a similar preferred pathway once over Canada, generally moving southeastward toward southern Canada and the northern U.S., and then eastward toward the North Atlantic (Figs. 10c,d). Upper-level ridging and ridge amplification, for example over the eastern North Pacific and western North America, likely support the equatorward transport of these TPVs and cold pools across Canada (e.g., Shapiro et al. 1987; Colle and Mass 1995; Hakim et al. 1995; Konrad 1996).

In terms of CAO cold pools impacting each region, northern portions of each region experience the highest percentage of these CAO cold pools (Figs. 11a–f). Given the large meridional gradient of CAO cold pool track density over southern Canada and the northern U.S. shown in Fig. 10d, northern portions of any region are closer to the center of CAO cold pools compared to southern portions of any region. Going from northern regions (Figs. 11a–c,e) to southern regions (Figs. 11d,f), there is a southward shift in the preferred locations impacted by the CAO cold pools, indicating that CAOs in southern regions more often require that cold pools travel farther south compared to those in northern regions. Going from western regions (Figs. 11a,d), to central regions (Figs. 11b,e), and then to eastern regions (Figs. 11c,f), there is an eastward shift in the preferred locations impacted by CAO cold pools. For example, it may be inferred that CAO cold pools impacting the Northeast (Fig. 11c) more often track east of the Great Lakes compared to CAO cold pools impacting ENC, which more often track over or west of the Great Lakes (Fig. 11b). Cold pools located farther east and any accompanying surface anticyclone and associated northerly flow of cold air are less likely to pass over and be modified by the warmer Great Lakes (e.g., via surface sensible heating) than those located farther west, and thus are more likely to be colder upon reaching the Northeast.

*d. Seasonality of TPVs, cold pools, and CAOs*

Breaking down the climatology of TPVs and cold pools by season, it is found that the highest and lowest number of all TPVs occurs during the winter and summer, respectively (Fig. 12a), with the opposite result true for cold pools (Fig. 12b). Shortwave heating, which may offset TPV intensification due to longwave radiative cooling (e.g., Cavallo and Hakim 2013), being smallest and largest during winter and summer in high latitudes, respectively, may contribute to winter and summer having the highest and lowest number of TPVs, respectively. Cold pools possibly being embedded in stronger horizontal thickness gradients during winter compared to summer may contribute to the lower number of cold pools during winter compared to summer, as cold pools embedded in strong horizontal thickness gradients may appear as thickness troughs that are not trackable as cold pools.

The highest and lowest number of TPVs transported to middle latitudes occurs during the winter and summer, respectively, when considering TPVs transported equatorward of crossing latitudes ranging from 60°N to 45°N, every 5° (Fig. 12c). For cold pools transported to middle latitudes, if considering crossing latitudes of 60°N and 55°N, the highest number occurs during the summer, but considering crossing latitudes of 50°N and 45°N, the lowest number occurs during the summer (Fig. 12d). The more-poleward position of the polar jet stream during summer relative to winter (not shown) likely facilitates fewer TPVs and cold pools being transported equatorward of 50°N and 45°N during summer relative to winter. As the crossing latitude is decreased for a given season, there is a substantial decrease in the number of TPVs and cold pools (Figs. 12c,d), suggesting it may take an increasingly anomalously amplified flow pattern to enable TPVs and cold pools to be transported equatorward of a given crossing latitude as the crossing latitude decreases.

For all regions except the South, CAOs were most often identified during the winter, and for all regions, CAOs were least often identified during either spring or summer (Figs. 13a,b). Winter having a greater occurrence of CAOs compared to other seasons for most regions likely relates to the polar jet stream being at lower latitudes during the winter compared to other seasons, and there concomitantly being more opportunity for cold air masses to spread southward across the central and eastern U.S. and contribute to CAO development during the winter. The northern regions (i.e., WNC, ENC, Northeast, and Central) are associated with a moderate-to-high percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs for all seasons (Figs. 13c,d), indicating that cold pools and TPVs can play important roles in CAO development throughout the year in the northern regions. The southern regions (i.e., South and Southeast) have a lower percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs compared to the northern regions for all seasons (Figs. 13c,d), which likely relates to the substantial decrease in the number of TPVs and cold pools crossing equatorward of a given crossing latitude as the crossing latitude is decreased (Figs. 12c,d). The lowest percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs occurs during summer for all regions, except WNC and ENC (Figs. 13c,d), which likely relates to there being the fewest TPVs and cold pools being transported equatorward of 50°N and 45°N during summer (Figs. 12c,d).

*e. Characteristics of TPVs and cold pools*

Characteristics of CAO TPVs and CAO cold pools for all regions are now compared to those of the full climatology of TPVs transported to middle latitudes and cold pools transported to middle latitudes (hereafter climatological TPVs and climatological cold pools), respectively, each season. The characteristics of the TPVs (cold pools) that are examined are 1) lowest minimum DT potential temperature (1000–500-hPa thickness) during the lifetime of the TPVs (cold pools), 2) lowest standardized anomaly of DT potential temperature (1000­–500-hPa thickness) at the TPV (cold pool) center during the lifetime of the TPVs (cold pools), and 3) lifetime of the TPVs (cold pools). Standardized anomalies of DT potential temperature and 1000–500-hPa thickness are calculated with respect to a 1979–2015 climatology of these variables using the methodology of Brammer and Thorncroft (2015). The aforementioned characteristics will illuminate whether there are differences in the coldness and longevity between CAO TPVs and climatological TPVs, and between CAO cold pools and climatological cold pools.

A bootstrap resampling with replacement test adapted from Torn and Hakim (2015) is used to determine if there are statistically significant differences between the mean value of each characteristic for each season between that of the CAO TPVs (CAO cold pools) and that of the climatological TPVs (climatological cold pools). For each characteristic and each season, a sample of the climatological TPVs (climatological cold pools) of size N, where N is equal to the number of CAO TPVs (CAO cold pools) for that season, is randomly sampled, and the mean value of that characteristic for that sample is determined. This process is repeated 10000 times to yield a distribution of the mean value of that characteristic for the climatological TPVs (climatological cold pools). If the mean value of that characteristic for the CAO TPVs (CAO cold pools) falls outside of the 95% confidence bounds of the distribution of the mean value of that characteristic for the climatological TPVs (climatological cold pools), the difference between these mean values is said to be statistically significant.

Compared to climatological TPVs, CAO TPVs are associated with a statistically significantly lower mean value of lowest minimum DT potential temperature during the lifetime of the TPVs for all seasons (Fig. 14a and Table 4), and a statistically significantly lower mean value of lowest standardized anomaly of DT potential temperature at the TPV center during the lifetime of the TPVs for all seasons (Fig. 14b and Table 4). Compared to climatological cold pools, CAO cold pools are associated with a statistically significantly lower mean value of lowest minimum 1000–500-hPa thickness during the lifetime of the cold pools for all seasons (Fig. 15a and Table 5), and a statistically significantly lower mean value of lowest standardized anomaly of 1000–500-hPa thickness at the cold pool center during the lifetime of the cold pools for all seasons (Fig. 15b and Table 5). Thus, CAO TPVs and CAO cold pools are statistically significantly colder than climatological TPVs and climatological cold pools, respectively, each season. Longwave radiative cooling likely contributes to the cooling of the CAO TPVs and CAO cold pools (e.g., Curry 1983; Emanuel 2008; Tuner and Gyakum 2011; Cavallo and Hakim 2013; Papritz et al. 2019), especially as they move across high-latitude regions, including Siberia, the Arctic, and Canada (Figs. 10c,d).

For all seasons, the lowest value of standardized anomaly of DT potential temperature and of 1000–500-hPa thickness of some CAO TPVs and some CAO cold pools, respectively, is between the 25th and 75th percentiles of that of climatological TPVs (Fig. 14b) and climatological cold pools (Fig. 15b), respectively. Thus, for all seasons, some CAO TPVs and some CAO cold pools are similarly anomalously cold as climatological TPVs and climatological cold pools, respectively, indicating that TPVs and cold pools do not always need to be exceptionally cold to contribute to CAOs. Although there is an expected seasonal variability in the lowest DT potential temperature of climatological TPVs and CAO TPVs (Fig. 14a), and in the lowest 1000–500-hPa thickness of climatological cold pools and CAO cold pools (Fig. 15a), each of these types of TPVs and cold pools tend to be similarly anomalously cold each season (Figs. 14b and 15b). For example, although a CAO cold pool during summer may not be as cold as a CAO cold pool during winter, the CAO cold pools may be similarly anomalously cold during both seasons.

In terms of longevity, CAO TPVs are associated with a statistically significantly longer mean lifetime compared to climatological TPVs for all seasons (Fig. 14c and Table 4), and CAO cold pools are associated with a statistically significantly longer mean lifetime compared to climatological cold pools for winter and autumn (Fig. 15c and Table 5). The tendency for statistically significantly longer lifetimes of CAO TPVs and CAO cold pools compared to climatological TPVs and climatological cold pools, respectively, may suggest a longer period of longwave radiative cooling to contribute to more cooling of CAO TPVs and CAO cold pools compared to climatological TPVs and climatological cold pools. However, some CAO TPVs and CAO cold pools are relatively short-lived (Figs. 14c and 15c), as they may, in some cases, break off from previously existing TPVs and cold pools, or, in the case of cold pools, may not be trackable until they become cold enough to have a distinct 1000–500-hPa thickness minimum (e.g., a thickness trough becomes a cold pool).

**4. Summary and conclusions**

It has been shown that TPVs are cold-core features, associated with anomalously cold air throughout the depth of the troposphere within and beneath the TPVs (e.g., Cavallo and Hakim 2010), and that there is evidence of linkages between TPVs, cold pools, and CAOs (e.g., Boyle and Bosart 1983; Shapiro et al. 1987; Hakim et al. 1995; Papritz et al. 2019; Lillo et al. 2020). This study provides additional understanding of the linkages between TPVs, cold pools, and CAOs by linking together climatologies of TPVs, cold pools, and CAOs occurring in six regions over the central and eastern U.S., and identifying CAOs linked to cold pools associated with TPVs for these regions.

Central and eastern North America, in particular northern Canada and the Canadian Archipelago, is shown in this study and in past studies (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2009, 2010, 2012; Szapiro and Cavallo 2018) to be a region of high TPV occurrence, and in this study to be a region of high cold pool occurrence. This study further shows that central and eastern North America is a favorable region for the equatorward transport of TPVs and cold pools to middle latitudes. Upper-level ridging and ridge amplification over the eastern North Pacific, western North America, North Atlantic, Greenland, and Arctic may allow TPVs and cold pools to move equatorward over central and eastern North America and contribute to the development of CAOs over the central and eastern U.S. (e.g., Namias 1978; Shapiro et al. 1987; Alberta et al. 1991; Colle and Mass 1995; Hakim et al. 1995; Konrad 1996; Colucci et al. 1999; Waugh et al. 2017).

There is a moderate-to-high percentage of CAOs linked to cold pools associated with TPVs in the northern regions of the U.S. throughout the year (67.4–87.8%) and each season, which is higher than that for the southern regions of the U.S. throughout the year (24.7–26.4%) and each season. The higher percentage for the northern regions of the U.S. compared to the southern regions of the U.S. is related to the large meridional gradient of TPV and cold pool track density over southern Canada and the northern U.S. TPVs and cold pools contributing to CAOs most frequently form over northern Canada and the Canadian Archipelago before traveling southeastward across Canada and then eastward across southern Canada and the northern U.S. Thus, northern regions of the U.S. are more often in closer proximity to TPVs and cold pools than southern regions. Although the center of a cold pool may not reach a region experiencing a CAO, the cold air may be advected away from the cold pool center and contribute to a CAO in that region. For example, northerly flow of cold air associated with surface anticyclones accompanying TPVs and cold pools, and terrain-channeling, may allow cold air associated with the TPVs and cold pools to be advected well equatorward (e.g., Shapiro et al. 1987; Bell and Bosart 1988; Colle and Mass 1995).

TPVs and cold pools contributing to CAOs are statistically significantly colder each season and statistically significantly longer-lived each season (except spring and summer for cold pools) than climatological TPVs and cold pools, respectively. It is anticipated that longwave radiative cooling plays an important role in the cooling of TPVs and cold pools contributing to CAOs (e.g., Curry 1983; Emanuel 2008; Turner and Gyakum 2011; Cavallo and Hakim 2013; Turner et al. 2013; Papritz et al. 2019). Furthermore, a dynamical response to an intensification of a TPV may be an intensification of the cold pool beneath the TPV (e.g., Papritz et al. 2019), as is suggested by the concomitant intensification of the TPV and cold pool involved in the January 1982 CAO.

Cold pools associated with TPVs can play an important role in CAO development, and so improved understanding of cold pools associated with TPVs may lead to improved understanding of CAOs. Case studies and composite analyses of CAOs linked to cold pools associated with TPVs occurring in different regions of the central and eastern U.S. may be used to better understand the formation and intensification of these TPVs and cold pools, the equatorward transport of these TPVs and cold pools, the development of possible surface anticyclones accompanying these TPVs and cold pools, and the equatorward advection of the cold air associated with these TPVs and cold pools.

*Data Availability Statement*

The ERA-Interim data used in this study was downloaded from the ECMWF. CAO cases were obtained from Murphy (2017), who used daily minimum temperature data extracted from the GHCN-Daily dataset, which is available from NOAA NCEI. TPV and cold pool tracks, and data pertaining to the linkages between TPVs, cold pools, and CAOs, are available from the first author upon request.

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**TABLES**

TABLE 1. GHCN-Daily stations used in Murphy (2017) for each NCEI climate region over the central and eastern U.S.

|  |  |
| --- | --- |
| Regions | Stations |
| WNC | Billings, MT  Bismarck, ND  Cheyenne, WY  Great Falls, MT  North Platte, NE  Pierre, SD |
| ENC | Des Moines, IA  International Falls, MN  Milwaukee, WI  Minneapolis, MN |
| Northeast | Albany, NY  Boston, MA  Caribou, ME  Erie, PA  New York City, NY  Pittsburgh, PA |
| Central | Chicago, IL  Cincinnati, OH  Nashville, TN  St. Louis, MO |
| South | Amarillo, TX  Corpus Christi, TX  Dodge City, KS  El Paso, TX  Little Rock, AR  Meridian, MS  New Orleans, LA  Oklahoma City, OK  Port Arthur, TX  San Angelo, TX  Topeka, KS  Waco, TX |
| Southeast | Arlington, VA  Atlanta, GA  Charleston, SC  Miami, FL  Norfolk, VA  Raleigh, NC  Tallahassee, FL  Tampa, FL |

TABLE 2. Number and normalized number of CAOs for each climate region during 1979–2015. The normalized number of CAOs is rounded to the nearest whole number.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | WNC | ENC | Northeast | Central | South | Southeast |
| Number of CAOs | 99 | 41 | 67 | 46 | 162 | 91 |
| Normalized number of CAOs | 198 | 123 | 134 | 138 | 162 | 137 |

TABLE 3. Count and percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs, using a 1500-km cold pool circle radius threshold and a 750-km TPV–cold pool distance threshold.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | WNC | ENC | Northeast | Central | South | Southeast |
| Count (percentage) of CAOs linked to cold pools | 84 (84.8) | 37 (90.2) | 58 (86.6) | 35 (76.1) | 46 (28.4) | 32 (35.2) |
| Count (percentage) of CAOs linked to cold pools associated with TPVs | 73 (73.7) | 36 (87.8) | 53 (79.1) | 31 (67.4) | 40 (24.7) | 24 (26.4) |

TABLE 4. A comparison between climatological TPVs and CAO TPVs each season of the count of the TPVs and of the mean value of the following characteristics of the TPVs: 1) lowest minimum DT potential temperature (θ; K) during the lifetime of the TPVs, 2) lowest standardized anomaly of DT θ (σ) at the TPV center during the lifetime of the TPVs, and 3) lifetime of the TPVs (days). For each of the characteristics and each season, the mean value for the climatological TPVs is statistically significantly different from the mean value for the CAO TPVs at the 95% confidence level. Seasons are as described in Fig. 12, where TPVs are separated into these seasons based on the month of their genesis date.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | DJF | | MAM | | JJA | | SON | |
| Climo | CAO | Climo | CAO | Climo | CAO | Climo | CAO |
| Count | 7423 | 113 | 6135 | 51 | 5210 | 31 | 6317 | 71 |
| Lowest min. DT θ (K) | 284.2 | 268.3 | 290.8 | 278.1 | 307.8 | 297.1 | 293.7 | 275.8 |
| Lowest min. stnd. anom. of DT θ (σ) | −2.24 | −3.38 | −2.34 | −3.20 | −2.27 | −3.17 | −2.28 | −3.49 |
| Lifetime (days) | 6.2 | 10.7 | 6.7 | 11.3 | 7.1 | 12.0 | 6.6 | 14.4 |

TABLE 5. A comparison between climatological cold pools and CAO cold pools each season of the count of the cold pools and of the mean value of the following characteristics of the cold pools: 1) lowest minimum 1000–500-hPa thickness (dam) during the lifetime of the cold pools, 2) lowest standardized anomaly of 1000–500-hPa thickness (σ) at the cold pool center during the lifetime of the cold pools, and 3) lifetime of the cold pools (days). For each of the characteristics and each season, the mean value for the climatological cold pools is statistically significantly different from the mean value for the CAO cold pools at the 95% confidence level, except where indicated by an asterisk. Seasons are as described in Fig. 12, where cold pools are separated into these seasons based on the month of their genesis date.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | DJF | | MAM | | JJA | | SON | |
| Climo | CAO | Climo | CAO | Climo | CAO | Climo | CAO |
| Count | 1907 | 97 | 2040 | 46 | 2436 | 28 | 2012 | 62 |
| Lowest min. thickness (dam) | 490.5 | 479.8 | 508.8 | 496.3 | 535.9 | 529.0 | 512.4 | 499.8 |
| Lowest min. stnd. anom. of thickness (σ) | −1.95 | −2.54 | −2.15 | −2.54 | −2.26 | −2.93 | −2.14 | −2.67 |
| Lifetime (days) | 6.4 | 9.0 | 6.4\* | 7.6\* | 6.6\* | 8.5\* | 6.1 | 9.0 |

**FIGURES**

FIG. 1. NCEI climate regions (color shading) and GHCN-Daily stations (red dots) over the central and eastern U.S. used in Murphy (2017).

FIG. 2. (a) Tracks of TPV (red) every 6 h from 0600 UTC 15 December 1981 to 0000 UTC 13 January 1982 and cold pool (blue) every 6 h from 1800 UTC 20 December 1981 to 1800 UTC 13 January 1982 for January 1982 CAO case. Stars denote locations of genesis, crosses denote locations of lysis, and red and blue dots denote 0000 UTC positions of TPV and cold pool, respectively, every 48 h. Numbers pointing toward dots denote dates of the 0000 UTC positions of the TPV and cold pool. (b) Time series of minimum DT potential temperature of TPV (K, red) and minimum 1000–500-hPa thickness of cold pool (dam, blue) every 6 h for same respective time periods as in (a).

FIG. 3. (a) Cross section along line AA’ of PV (PVU, shading), potential temperature (K, black), and wind speed (dashed white contours every 10 m s−1, beginning at 50 m s−1); (b) DT (2-PVU surface) potential temperature (K, shading), wind speed (black contours every 10 m s−1, beginning at 50 m s−1), and wind (m s−1, flags and barbs); and (c) 1000–500-hPa thickness (dam, shading) and 700-hPa wind (m s−1, flags and barbs). Yellow line in (b) and (c) denotes transect of cross section AA’. Labels “TPV” and “CP” denote locations of TPV and cold pool, respectively. Analyses shown in (a)–(c) are for 0000 UTC 10 January 1982. Data source: ERA-Interim.

FIG. 4. (a) 1000–500-hPa thickness (dam, shading), 700-hPa wind (m s−1, flags and barbs), cold pool track (yellow line), and 1500-km radius circle (blue circle) surrounding cold pool center (yellow dot) at 0000 UTC 10 January 1982. (b) NCEI climate regions (color shading) and same circle as in (a) surrounding cold pool center (blue dot) at 0000 UTC 10 January 1982. (c) DT (2-PVU surface) potential temperature (K, shading) and wind (m s−1, flags and barbs), TPV and cold pool tracks (green and yellow lines, respectively), position of TPV center and cold pool center (green and yellow dots, respectively), and 750-km radius circle (black circle) surrounding TPV center at 0000 UTC 10 January 1982. Data source: ERA-Interim.

FIG. 5. Track density of (a) all TPVs, (b) all cold pools, (c) TPVs transported to middle latitudes (equatorward of 60°N), and (d) cold pools transported to middle latitudes (equatorward of 60°N), shaded according to the average number of these features passing within 500 km of a given grid point (using a 0.5° grid) each year during 1979–2015. Also shown is the 1979–2015 mean DT wind speed (m s−1, black contours).

FIG. 6. Histograms showing the total number of instances in which (a) TPVs and (b) cold pools cross equatorward of 60°N (black line on map) for each 30° longitudinal bin globally during 1979–2015. An individual TPV and an individual cold pool can be counted more than once if it crosses equatorward of 60°N after returning poleward of 60°N.

FIG. 7. (a) Count and (b) percentage of CAOs linked to cold pools for each climate region and for cold pool circle radius thresholds of 1000 km to 2000 km, every 250 km.

FIG. 8. (a) Count and (b) percentage of TPVs associated with cold pools (red) and cold pools associated with TPVs (blue) for TPV­–cold pool distance thresholds of 250 km to 1000 km, every 250 km.

FIG. 9. (a) Count and (b) percentage of CAOs linked to cold pools associated with TPVs for each climate region and for TPV–cold pool distance thresholds of 250 km to 1000 km, every 250 km. A 1500-km cold pool circle radius threshold is used.

FIG. 10. Genesis density of (a) CAO TPVs and (b) CAO cold pools for all climate regions, shaded according to the number of CAO TPVs and CAO cold pools, respectively, forming within 500 km of a given grid point (using a 0.5° grid). Track density of aforementioned (c) CAO TPVs and (d) CAO cold pools, shaded according to the number of CAO TPVs and CAO cold pools, respectively, passing within 500 km of a given grid point (using a 0.5° grid). If a CAO TPV or CAO cold pool impacts multiple regions, that CAO TPV or CAO cold pool is only counted once.

FIG. 11. Track density of CAO cold pools for the (a) WNC, (b) ENC, (c) Northeast, (d) South, (e) Central, and (f) Southeast regions, shaded according to the percentage of cold pools passing within 1500 km of a given grid point (using a 0.5° grid) when normalized by the number cold pools for each climate region. States in each climate region are outlined in thick black. The same CAO cold pool can impact multiple regions, and thus the same CAO cold pool can be included in the count for multiple regions.

FIG. 12. Total number of (a) TPVs and (b) cold pools each season during 1979–2015. Number of (c) TPVs and (d) cold pools transported equatorward of crossing latitudes ranging from 60°N to 45°N, every 5°, each season during 1979–2015, where each bar is colored according to the crossing latitude. The seasons are DJF (winter), which denotes December, January, and February, MAM (spring), which denotes March, April, and May, JJA (summer), which denotes June, July, and August, and SON (autumn), which denotes September, October, and November. TPVs and cold pools are separated into these seasons based on the month of their genesis date.

FIG. 13. (a) Count of CAOs for each climate region and season. (b) Percentage of CAOs for each climate region occurring each season. (c) Percentage of CAOs linked to cold pools and (d) percentage of CAOs linked to cold pools associated with TPVs for each climate region and season. Seasons are as described in Fig. 12, where CAOs are separated into these seasons based on the month of their first date of occurrence.

FIG. 14. Box and whisker plots showing a comparison between climatological TPVs (gray) and CAO TPVs (red) each season for the following characteristics: (a) lowest minimum DT potential temperature (K) during the lifetime of the TPVs, (b) lowest standardized anomaly of DT potential temperature (σ) at the TPV center during the lifetime of the TPVs, and (c) lifetime of the TPVs (days). Boxes extend from 25th to 75th percentiles, with median values denoted by solid line within each box. Whiskers extend to 5th and 95th percentiles. Circles denote the mean values and stars denote the minimum and maximum values. Mean values are given in Table 4. The number of TPVs for each box and whiskers plot is indicated. Seasons are as described in Fig. 12, where TPVs are separated into these seasons based on the month of their genesis date.

FIG. 15. Box and whisker plots showing a comparison between climatological cold pools (gray) and CAO cold pools (blue) each season for the following characteristics: (a) lowest minimum 1000–500-hPa thickness (dam) during the lifetime of the cold pools, (b) lowest standardized anomaly of 1000–500-hPa thickness (σ) at the cold pool center during the lifetime of the cold pools, and (c) lifetime of the cold pools (days). Boxes extend from 25th to 75th percentiles, with median values denoted by solid line within each box. Whiskers extend to 5th and 95th percentiles. Circles denote the mean values and stars denote the minimum and maximum values. Mean values are given in Table 5. The number of cold pools for each box and whisker plot is indicated. Seasons are as described in Fig. 12, where cold pools are separated into these seasons based on the month of their genesis date.

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