**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 the frequency of the occurrence of TPVs and cold pools is higher over northern regions of the U.S. compared to 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 form most frequently over northern Canada and the Canadian Archipelago, and generally move southeastward toward southern Canada and the northern U.S. 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, a cyclonic potential vorticity (PV) anomaly, radii of 100–1000 km, and lifetimes of days to months (e.g., Hakim 2000; Pyle et al. 2004; Hakim and Canavan 2005; Cavallo and Hakim 2009, 2010, 2012). 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. Longwave radiative cooling has been shown to be important for the maintenance and intensification of TPVs (e.g., Cavallo and Hakim 2009, 2010, 2012, 2013). Cavallo and Hakim (2010, 2012, 2013) show that there is a region of enhanced longwave radiative cooling on and just below the DT at the location of TPVs resulting from enhanced vertical gradients of water vapor between relatively moist tropospheric air beneath TPVs and relatively dry stratospheric air within TPVs. There is a decrease in longwave radiative cooling above the region of enhanced longwave radiative cooling. As a result, there is a positive vertical gradient in radiative heating within TPVs that can contribute to an increase in static stability and the concomitant 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) and jet streaks (e.g., Pyle et al. 2004). TPVs may also be dynamically important precursors to the development of CAOs, which are incursions of cold air masses into a region that result in an episode of anomalously low surface temperatures (e.g., Konrad 1996; Walsh et al. 2001; Cellitti et al. 2006). 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-tropospheric 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 cold pools, and, along with Shapiro et al. (1987), show that exceptionally cold air that may be associated with these cold pools can contribute to the development of CAOs. Longwave radiative cooling from surface snow and ice cover (e.g., Curry 1983), and from ice crystals (e.g., Gotaas and Benson 1965; Curry 1983), liquid water droplets (e.g., Curry 1983), and low-level clouds (e.g., Curry 1983; Emanuel 2008) often found in the troposphere within cold air masses, may contribute to the cooling of cold pools (e.g., Turner and Gyakum 2011; Turner et al. 2013; Papritz et al. 2019). Although TPVs are not necessary for the development of CAOs, so long as the air mass associated with a CAO is cold enough, the exceptionally cold air that may be found beneath TPVs suggests that TPVs may be effective at triggering CAOs.

TPVs (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2009, 2010, 2012; Szapiro and Cavallo 2018), and 500-hPa cyclones (e.g., Bell and Bosart 1989) and 500-hPa troughs (e.g., Sanders 1988; Lefevre and Nielsen-Gammon 1995), in which some TPVs may be embedded (e.g., Shapiro et al. 1987), have been shown to frequently occur over central and eastern North America. Similarly, CAOs have been shown to frequently occur over central and eastern North America (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 through longwave radiative cooling (e.g., Cavallo and Hakim 2009, 2010). Walsh et al. (2001) use a trajectory analysis to show that cold air parcels associated with CAOs over the central and eastern U.S. originate over high latitudes and often move slowly over northern Canada, where longwave radiative cooling contributes to the cooling of these air parcels.

Upper-tropospheric ridges 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). A region of differential anticyclonic vorticity advection and sinking motion (e.g., Colucci and Davenport 1987; Hakim 2000; Cavallo and Hakim 2010) that may contribute to surface anticyclogenesis (e.g., Dallavalle and Bosart 1975; Colucci and Davenport 1987; Jones and Cohen 2011) may exist on the downstream side of an upper-tropospheric ridge and upstream side of a TPV. Northerly flow associated with 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). The equatorward transport of cold air may be enhanced by a terrain-tied northerly component of strong lower-tropospheric flow in the presence of a strong sea level pressure 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; Schultz et al. 1997; Steenburgh et al. 1998).

Research on the climatological linkages between TPVs and CAOs has been a topic of recent interest. 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 late January and early February 2019 is linked to an intense TPV, and also 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 constructing climatologies of cold pools, and examining 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 these climatologies and linkages are discussed in section 3. A summary 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 regions. Each region is associated with either a DT potential temperature minimum or maximum, with locations in regions associated with a DT potential temperature minimum and maximum possessing positive and negative values of the vertical component of DT relative vorticity, respectively. Regions 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 regions is used to connect these regions 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 to 1000–500-hPa thickness, 700-hPa zonal and meridional winds, and 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, the 1000–500-hPa thickness field is segmented into regions. Each region is associated with either a 1000–500-hPa thickness minimum or maximum, with locations in regions associated with a 1000–500-hPa thickness minimum and maximum possessing positive and negative values of 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 field 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 regions 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. Thus, TPVs and cold pools that may not spend a large percentage of their lifetimes in high latitudes, but may still contribute to CAOs, can be identified.

*b. Identification of CAOs*

A climatology of CAOs occurring throughout the year over the U.S. that was created by Murphy (2017) is 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) of each other 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 and 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 cold pools associated with TPVs, TPVs associated with cold pools, 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*

Areas of high track density of all TPVs (Fig. 5a) and all cold pools (Fig. 5b) during 1979–2015 are found over northern Canada, the Canadian Archipelago, Eurasia, and the Arctic, 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). However, areas of high cold pool track density are more spatially restricted than areas 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, areas of high cold pool track density are more spatially restricted than areas 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 heat fluxes 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 is also found 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.

Maxima of track density of TPVs and cold pools transported to middle latitudes (defined at the beginning of section 2c) 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). Climatologically favored upper-tropospheric 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).

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

Linkages between TPVs, cold pools, and CAOs are now examined. Only TPVs and cold pools transported to middle latitudes 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 multiplying the number of CAOs by 12 (the maximum number of stations of all the regions) and then 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. 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 for both northern regions (i.e., WNC, ENC, Central, and Northeast) and southern regions (i.e., South and Southeast) (Figs. 7a,b). There is a smaller increase in this number and percentage when the cold pool circle radius threshold is increased from 1500 km to 2000 km only for northern regions (Figs. 7a,b). Thus, most possible cold pools that contribute to CAO development are likely accounted for in the northern regions once the cold pool circle radius threshold is large enough (i.e., 1500 km). 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) and false alarm scenarios from using too large of a threshold (e.g., 2000 km). A miss scenario may occur, for example, when 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 a surface anticyclone and terrain channeling allows cold air from the cold pool to spread far away from the cold pool center (e.g., Shapiro et al. 1987; Colle and Mass 1995) and impact the region. A false alarm scenario may occur, for example, when 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 the 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 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 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, 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 for all regions, 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 frequency of occurrence of TPVs and cold pools is higher over the northern regions compared to 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) for all regions in terms of genesis density and track density are examined. CAO TPVs most frequently 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 frequently 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. In addition, surface sensible heat fluxes from the open waters of the North Pacific may initially inhibit the development of cold pools beneath CAO TPVs forming over the North Pacific. Such surface sensible heat fluxes are suggested by low values lower-tropospheric static stability beneath these CAO TPVs when located over the North Pacific (not shown). 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-tropospheric ridges and ridge amplification, for example over the eastern North Pacific and western North America, likely support the equatorward transport of the CAO TPVs and CAO cold pools across Canada (e.g., Shapiro et al. 1987; Colle and Mass 1995; Hakim et al. 1995).

Preferred areas impacted by CAO cold pools for each region in terms of track density are now examined. In addition, for each CAO cold pool and region, the time period during which the 1500-km cold pool circle surrounding the cold pool center intersects the region during the CAO is determined, and the time during this period at which the 1000–500-hPa thickness averaged across the region is lowest (hereafter tlowest) is identified. The 1000–500-hPa thickness and standardized anomaly of 1000–500-hPa thickness fields at tlowest for the CAO cold pools impacting each region are composited. The standardized anomaly of 1000–500-hPa thickness field is calculated with respect to a 1979–2015 climatology [constructed using methodology of Brammer and Thorncroft (2015), section 2a]. The highest track density of CAO cold pools is found over northern areas of each region, indicating that CAO cold pools preferably impact these areas (Figs. 11a–f). However, the composite negative values of standardized anomaly of 1000–500-hPa thickness for each region show that anomalously cold air is found across the entire region (Figs. 11a–f), suggesting that anomalously cold air associated with the CAO cold pools can spread across the entire region from the areas of highest track density.

In addition, there is a southward shift of the preferred areas impacted by the CAO cold pools going from northern regions (Figs. 11a–c,e) to southern regions (Figs. 11d,f), as indicated by a southward shift of the highest values of track density, and as suggested by a southward shift of the composite 540-dam contour of 1000–500-hPa thickness and of the composite negative values of standardized anomaly of 1000–500-hPa thickness. The southward shift of the preferred areas impacted by the CAO cold pools indicates that CAOs in southern regions more often require that cold pools travel farther south compared to those in northern regions. There is also an eastward shift of the preferred areas impacted by CAO cold pools going from western regions (Figs. 11a,d), to central regions (Figs. 11b,e), and then to eastern regions (Figs. 11c,f), as indicated by an eastward shift of the highest values of track density, and as suggested by an eastward shift of a composite 1000–500-hPa thickness trough and of the composite negative values of standardized anomaly of 1000–500-hPa thickness. 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 heat fluxes) 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 climatologies 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 number of TPVs transported to middle latitudes is highest and lowest 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). The number of cold pools transported to middle latitudes is highest during summer when considering crossing latitudes of 60°N and 55°N, but lowest during summer when considering crossing latitudes of 50°N and 45°N (Fig. 12d). The more-poleward position of the polar jet stream and increased solar radiation during summer relative to winter likely contributes to fewer TPVs and cold pools transported to middle latitudes during summer when considering crossing latitudes of 50°N and 45°N. There is also a substantial decrease in the number of TPVs and cold pools transported to middle latitudes as the crossing latitude is decreased for a given season (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.

CAOs were most often identified during the winter for all regions except South, and least often identified during either spring or summer for all regions (Figs. 13a,b). Winter having a greater occurrence of CAOs compared to other seasons for most regions likely relates to solar radiation being decreased and the polar jet stream being at lower latitudes during the winter compared to other seasons. Thus, there concomitantly is likely more opportunity for cold air masses to develop and 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 that are examined are 1) lowest DT potential temperature during the lifetime of the TPVs, 2) lowest standardized anomaly of DT potential temperature at the TPV center during the lifetime of the TPVs, and 3) lifetime of the TPVs. The characteristics of the cold pools that are examined are 1) lowest 1000–500-hPa thickness during the lifetime of the cold pools, 2) lowest standardized anomaly of 1000­–500-hPa thickness at the cold pool center during the lifetime of the cold pools, and 3) lifetime of the cold pools. Standardized anomalies are constructed as described in section 3c. 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 and that of the climatological TPVs. The test is also used for CAO cold pools and climatological cold pools, but will just be described for TPVs. For each characteristic and each season, a sample of the climatological TPVs of size N, where N is equal to the number of CAO TPVs 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. If the mean value of that characteristic for the CAO TPVs falls outside of the 95% confidence bounds of the distribution of the mean value of that characteristic for the climatological TPVs, 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 DT potential temperature (Fig. 14a and Table 4) and of lowest standardized anomaly of DT potential temperature at the TPV center (Fig. 14b and Table 4) during the lifetime of the TPVs for all seasons. Compared to climatological cold pools, CAO cold pools are associated with a statistically significantly lower mean value of lowest 1000–500-hPa thickness (Fig. 15a and Table 5) and of lowest standardized anomaly of 1000–500-hPa thickness at the cold pool center (Fig. 15b and Table 5) during the lifetime of the cold pools for all seasons. Thus, CAO TPVs and CAO cold pools are statistically significantly colder than climatological TPVs and climatological cold pools, respectively, for all seasons. 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), especially as they move across high-latitude regions, including Siberia, the Arctic, and Canada (Figs. 10c,d).

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, for all seasons. Thus, 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**

It has been shown that TPVs are associated with anomalously cold air throughout the depth of the troposphere (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, 2012) 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-tropospheric ridges 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).

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 generally traveling southeastward across Canada toward southern Canada and the northern U.S. Thus, the frequency of occurrence of TPVs and cold pools is higher over northern regions of the U.S. compared to southern regions of the U.S. 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 associated with surface anticyclones accompanying TPVs and cold pools, and terrain channeling east of higher terrain (e.g., the Rockies), 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). In addition, as the Coriolis parameter decreases as latitude decreases, the cold air may spread more quickly equatorward independent of terrain channeling effects.

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; 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.

TPVs and associated cold pools can play an important role in CAO development, and so improved understanding of these TPVs and cold pools may lead to improved understanding of CAOs. Case studies and composite analyses of CAOs linked to cold pools associated with TPVs may be used to better understand the formation, intensification, and equatorward transport of 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 were 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 (identifier in parentheses) |
| WNC  (*N*=6) | Billings, MT (KBIL)  Bismarck, ND (KBIS)  Cheyenne, WY (KCYS)  Great Falls, MT (KGTF)  North Platte, NE (KLBF)  Pierre, SD (KPIR) |
| ENC  (*N*=4) | Des Moines, IA (KDSM)  International Falls, MN (KINL)  Milwaukee, WI (KMKE)  Minneapolis, MN (KMSP) |
| Northeast  (*N*=6) | Albany, NY (KALB)  Boston, MA (KBOS)  Caribou, ME (KCAR)  Erie, PA (KERI)  New York, NY/LaGuardia (KLGA)  Pittsburgh, PA (KPIT) |
| Central  (*N*=4) | Chicago, IL/Midway (KMDW)  Cincinnati, OH (KCVG)  Nashville, TN (KBNA)  St. Louis, MO (KSTL) |
| South  (*N*=12) | Amarillo, TX (KAMA)  Corpus Christi, TX (KCRP)  Dodge City, KS (KDDC)  El Paso, TX (KELP)  Little Rock, AR (KLIT)  Meridian, MS (KMEI)  New Orleans, LA (KMSY)  Oklahoma City, OK (KOKC)  Port Arthur, TX (KBPT)  San Angelo, TX (KSJT)  Topeka, KS (KFOE)  Waco, TX (KACT) |
| Southeast  (*N*=8) | Washington, D.C. (KDCA)  Atlanta, GA (KATL)  Charleston, SC (KCHS)  Miami, FL (KMIA)  Norfolk, VA (KORF)  Raleigh, NC (KRDU)  Tallahassee, FL (KTLH)  Tampa, FL (KTPA) |

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. Number and percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs for each climate region, using a 1500-km cold pool circle radius threshold and a 750-km TPV–cold pool distance threshold. Percentage of CAOs linked to cold pools is defined as number of CAOs linked to cold pools divided by number of CAOs (given in Table 2). Percentage of CAOs linked to cold pools associated with TPVs is defined as number of CAOs linked to cold pools associated with TPVs divided by number of CAOs (given in Table 2).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | WNC | ENC | Northeast | Central | South | Southeast |
| Number (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) |
| Number (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 for each season of the number of TPVs and of the mean values of the following characteristics of the TPVs: 1) lowest 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 respective seasons based on the month of their genesis date.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | DJF | | MAM | | JJA | | SON | |
| Climo | CAO | Climo | CAO | Climo | CAO | Climo | CAO |
| Number | 7423 | 113 | 6135 | 51 | 5210 | 31 | 6317 | 71 |
| Lowest DT θ (K) | 284.2 | 268.3 | 290.8 | 278.1 | 307.8 | 297.1 | 293.7 | 275.8 |
| Lowest 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 for each season of the number of cold pools and of the mean values of the following characteristics of the cold pools: 1) lowest 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 respective seasons based on the month of their genesis date.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | DJF | | MAM | | JJA | | SON | |
| Climo | CAO | Climo | CAO | Climo | CAO | Climo | CAO |
| Number | 1907 | 97 | 2040 | 46 | 2436 | 28 | 2012 | 62 |
| Lowest thickness (dam) | 490.5 | 479.8 | 508.8 | 496.3 | 535.9 | 529.0 | 512.4 | 499.8 |
| Lowest 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 adjacent to arrows 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 location 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. TPV and cold pool tracks are repeated from Fig. 2a from the respective times of genesis of the TPV and cold pool to 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 percentage of these respective features passing within 500 km of a given grid point (using a 0.5° grid) during 1979–2015 when normalized by the total number of these respective features. An individual TPV and an individual cold pool can only be counted once for the track density at a given grid point.

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 may be counted more than once if they cross equatorward of 60°N after returning poleward of 60°N.

FIG. 7. (a) Number 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. Percentage of CAOs linked to cold pools is defined as number of CAOs linked to cold pools divided by number of CAOs (given in Table 2).

FIG. 8. (a) Number 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. Percentage of TPVs associated with cold pools is defined as number of TPVs associated with cold pools divided by number of TPVs transported to middle latitudes (given in Fig. 5c). Percentage of cold pools associated with TPVs is defined as number of cold pools associated with TPVs divided by number of cold pools transported to middle latitudes (given in Fig. 5d).

FIG. 9. (a) Number 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. Percentage of CAOs linked to cold pools associated with TPVs is defined as number of CAOs linked to cold pools associated with TPVs divided by number of CAOs (given in Table 2).

FIG. 10. Genesis density of (a) CAO TPVs and (b) CAO cold pools for all climate regions, shaded according to the percentage of CAO TPVs and CAO cold pools, respectively, forming within 500 km of a given grid point (using a 0.5° grid) when normalized by the total number of CAO TPVs and CAO cold pools, respectively. Track density of aforementioned (c) CAO TPVs and (d) CAO cold pools, shaded according to the percentage of CAO TPVs and CAO cold pools, respectively, passing within 500 km of a given grid point (using a 0.5° grid) when normalized by the total number of CAO TPVs and CAO cold pools, respectively. If an individual CAO TPV or individual CAO cold pool impacts multiple regions, that CAO TPV or CAO cold pool is only counted once in the total count of CAO TPVs and CAO cold pools (given by N), respectively. An individual CAO TPV and an individual CAO cold pool can only be counted once for the genesis density and track density at a given grid point.

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 CAO cold pools passing within 1500 km of a given grid point (using a 0.5° grid) when normalized by the total number CAO cold pools for each climate region. Composite 1000–500-hPa thickness (every 20 dam, dashed blue contours) and composite negative values of standardized anomaly of 1000–500-hPa thickness (every 0.5 σ, solid cyan contours) at tlowest (defined in text in section 3c). 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 total count of CAO cold pools (given by N) for multiple regions. An individual CAO cold pool can only be counted once for the track density at a given grid point.

FIG. 12. Number of (a) all TPVs and (b) all 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°, for 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 respective seasons based on the month of their genesis date.

FIG. 13. (a) Number of CAOs for each climate region and season. (b) Percentage of CAOs for each climate region occurring each season, where this percentage is defined as number of CAOs for that climate region and season divided by number of CAOs for that climate region (given in Table 2). (c) Percentage of CAOs linked to cold pools for each climate region and season, where this percentage is defined as number of CAOs linked to cold pools for that climate region and season divided by number of CAOs for that climate region and season. (d) Percentage of CAOs linked to cold pools associated with TPVs for each climate region and season, where this percentage is defined as number of CAOs linked to cold pools associated with TPVs for that climate region and season divided by number of CAOs for that climate region and season. Seasons are as described in Fig. 12, where CAOs are separated into these respective 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 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 respective 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 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 respective seasons based on the month of their genesis date.

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