**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 an existing 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 over northern regions of the U.S. compared to southern regions of the U.S. 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; Papritz 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 in 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, the North Atlantic, Greenland, and the 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) contributing 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 the 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 1979–2015 climatologies of TPVs and cold pools, which are compared to an existing 1979–2015 climatology of CAOs occurring in six NCEI-defined climate regions over the central and eastern U.S., and examining the climatological linkages between TPVs, cold pools, and CAOs.

 The remainder of this paper is organized as follows: Section 2 presents the data and methodology used to construct the 1979–2015 climatologies of TPVs and cold pools, and to examine the climatological linkages between TPVs, cold pools, and CAOs. Section 3 discusses the climatologies, including the locations, seasonality, and characteristics of TPVs and cold pools, and examines the climatological linkages between TPVs, cold pools, and CAOs. Section 4 summarizes the results of the paper.

**2. Data and methodology**

*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 are tracked 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, representing a candidate TPV, is defined such that there is a DT potential temperature minimum and all locations in the region possess positive values of the vertical component of DT relative vorticity. The regions are advected in space and time with use of the DT zonal and meridional winds. The extent of overlap between advected regions is used to determine which regions are connected in space and time to create TPV tracks. The location or center of a TPV is the location of the DT potential temperature minimum of the TPV. For detailed information on TPVTrack, the reader is referred to Szapiro and Cavallo (2018).

In order to track cold pools, TPVTrack is 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. The 1000–500-hPa thickness field is used because it can represent 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 represent regions of relatively cold air associated with cold pools. The 700-hPa zonal and meridional winds are used because these winds are located approximately at the midpoint of the 1000–500-hPa layer. Like TPVs, cold pools are 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, representing a candidate cold pool, is defined such that there is a 1000–500-hPa thickness minimum and all locations in the region possess positive values of 1000–500-hPa thermal vorticity. The 700-hPa zonal and meridional winds are used to advect the regions. 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 are constructed by manually following the location of the 1000­–500-hPa thickness minimum of the cold pools, are compared to their corresponding objective cold pool tracks. The manual and objective cold pool tracks are found to be very similar (not shown).

TPVs and cold pools are 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 more relaxed latitude criterion is imposed in the present study because the primary interest is on TPVs transported from high latitudes (> 60°N) to middle latitudes (30°N–60°N), where they may be associated with CAOs. Thus, TPVs and cold pools that may not spend a large portion of their lifetimes in high latitudes, but may still be associated with CAOs, can be identified.

*b. Identification of CAOs*

A climatology of CAOs occurring throughout the year over the U.S. that was constructed by Murphy (2017) is used in the present 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 relatively evenly distributed across nine climate regions defined by NCEI over the U.S. to identify CAOs for each region. Murphy used stations that have superior temporal coverage during 1948–2015, which is the period that he used to identify CAOs. 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 (Fig. 1 and Table 1), are considered in the present study, which is restricted to CAOs during 1979–2015. 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 during late December 1981 and early January 1982, 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 a tropopause fold (e.g., Reed and Danielsen 1959; Danielsen 1968; Keyser and Shapiro 1986, sections 2a,b) and 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 extending away from the core of the TPV (Fig. 3a). The large spatial overlap and temporal coincidence of the TPV and cold pool (Fig. 2a), 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 of 1500 km surrounding the cold pool center intersect with at least one grid point on a 0.5° × 0.5° grid within 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 encompasses the spatial extent 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 contains all of the regions experiencing a CAO at this time, which are the Northeast, Central, South, and Southeast (Fig. 4b), such that the January 1982 CAO qualifies as a CAO linked to a cold pool for all of these regions. Several additional cold pool circle radius thresholds are 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 of 750 km of each other for at least two consecutive days (Fig. 4c). Requiring this distance threshold for at least two consecutive days helps ensure that there is spatial overlap and temporal coincidence 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), such that 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 one cold pool and one cold pool associated with two 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 same regions in which this CAO qualifies as a CAO linked to a cold pool, which are the Northeast, Central, South, and Southeast. Several additional TPV–cold pool distance thresholds are 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 geographically confined 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 geographically confined 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 is relatively low and TPV track density is relatively high 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. The lower total number of cold pools (23045) compared to TPVs (58563) likely is a consequence of the 1000–500-hPa thickness field, from which cold pools are identified, being smoother than the DT potential temperature field, from which TPVs are identified, resulting in 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 are found over central and eastern North America and over central and eastern Eurasia (Figs. 5c,d). There are also maxima in the number of instances in which TPVs and cold pools cross into middle latitudes over central and eastern North America and over central and eastern Eurasia, and there is a minimum in the number of instances in which TPVs and cold pools cross into middle latitudes 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 may play important roles in the development of CAOs, which are prevalent in this region (e.g., Konrad and Colucci 1989; Konrad 1996; Walsh et al. 2001).

*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 across the six climate 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 the 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 is normalized by multiplying the number of CAOs by 12 (the maximum number of stations for all of the regions) and then dividing by the number of stations for the region. The normalized number of CAOs is found to vary less across regions compared to the raw number of CAOs (Table 2).

To identify CAOs that are linked to cold pools for each region, cold pool circle radius thresholds are tested from 1000 km to 2000 km, every 250 km. There is an 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 over both northern regions of the U.S. (i.e., WNC, ENC, Northeast, and Central) and southern regions of the U.S. (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 over northern regions of the U.S. (Figs. 7a,b). Thus, most candidate cold pools that contribute to CAO development are likely accounted for over northern regions of the U.S. once the cold pool circle radius threshold is large enough. An intermediate cold pool circle radius threshold of 1500 km is used for the rest of this study given that this intermediate threshold likely reduces misses that result from using too small of a threshold (e.g., 1000 km) and false alarms that result from using too large of a threshold (e.g., 2000 km). A miss may occur, for example, when a surface anticyclone and terrain channeling allow cold air from a cold pool to spread far away from the cold pool center (e.g., Shapiro et al. 1987; Colle and Mass 1995) and contribute to a CAO occurring in a region, but the CAO is not identified as being linked to the cold pool because the cold pool circle radius is too small such that the cold pool circle does not contain the region. A false alarm may occur, for example, when cold air from a cold pool does not spread far enough away from the cold pool center to contribute to a CAO occurring in a region, but the CAO is identified as being linked to the cold pool because the cold pool circle radius is too large such that the cold pool circle contains the region. Regardless of the cold pool circle radius threshold used, there is a moderate-to-high percentage of CAOs linked to cold pools over northern regions of the U.S. (e.g., 76.1–90.2% when using a 1500 km threshold), and a smaller percentage over southern regions of the U.S. (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 misses in which a cold pool spatially overlaps and temporally coincides 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 alarms 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 more than one TPV to be associated with a cold pool than for more than one cold pool to be associated with a TPV. 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 is a consequence of a larger number of TPVs transported to middle latitudes (25085) than cold pools transported to middle latitudes (8395). The lower percentage of TPVs associated with cold pools may also be a consequence of some TPVs being too small or too weak to be associated with a cold pool, and of some TPVs being associated with a thickness trough that is not trackable as a cold pool.

Now that CAOs linked to cold pools and cold pools associated with TPVs have been examined, CAOs linked to cold pools associated with TPVs can be examined. 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 this study; nevertheless, for all thresholds there is a moderate-to-high percentage of CAOs linked to cold pools associated with TPVs over northern regions of the U.S. (e.g., 67.4–87.8% when using a 750-km threshold) and a smaller percentage over southern regions of the U.S. (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 over northern regions of the U.S. compared to southern regions of the U.S. is a consequence of 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 northern regions of the U.S. compared to southern regions of the U.S.

*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 examined for all climate regions in terms of genesis density and track density. CAO TPVs most frequently form over northern Canada, the Canadian Archipelago, and the 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 the 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 form simultaneously (e.g., Fig. 2a), as some TPVs may not become associated with a cold pool until they attain sufficient strength and 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 of lower-tropospheric static stability beneath CAO TPVs forming 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 over the eastern North Pacific and western North America likely contribute to 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 are examined for each climate region in terms of track density. 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 the standardized anomaly of 1000–500-hPa thickness at tlowest are composited for the CAO cold pools impacting each region. The standardized anomaly of 1000–500-hPa thickness is calculated with respect to a 1979–2015 climatology [constructed using the methodology of Brammer and Thorncroft (2015, section 2a)]. The highest track density of CAO cold pools is found over northern areas of each region (Figs. 11a–f), indicating that CAO cold pools preferably impact these areas. 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.

There is a southward shift of the preferred areas impacted by the CAO cold pools from northern regions of the U.S. (Figs. 11a–c,e) to southern regions of the U.S. (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 over southern regions of the U.S. require that cold pools more often travel farther south compared to those over northern regions of the U.S. There is also an eastward shift of the preferred areas impacted by CAO cold pools from western regions of the U.S. (Figs. 11a,d), to central regions of the U.S. (Figs. 11b,e), and then to eastern regions of the U.S. (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. As an example of the documented eastward shift of the preferred areas impacted by CAO cold pools, 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*

Separating 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), and the highest and lowest number of all cold pools occurs during the summer and winter, respectively (Fig. 12b). Shortwave radiative heating, which may offset TPV intensification due to longwave radiative cooling (e.g., Cavallo and Hakim 2013), and which is 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 embedded in stronger horizontal thickness gradients during winter compared to summer may contribute to the lowest number of cold pools during winter and the highest number of cold pools during 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 during the winter and lowest during the summer, 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). Summer having the highest number of all cold pools (Fig. 12b) likely contributes to summer having the highest number of cold pools transported to middle latitudes when considering crossing latitudes of 60°N and 55°N (Fig. 12d). The more-poleward position of the polar jet stream and increased shortwave radiative heating over middle and high latitudes during summer relative to other seasons likely contribute to summer having the lowest number of TPVs transported to middle latitudes when considering crossing latitudes of 60°N–45°N (Fig. 12c) and lowest number of cold pools transported to middle latitudes when considering crossing latitudes of 50°N and 45°N (Fig. 12d). There is a substantial decrease in the number of TPVs and cold pools transported to middle latitudes as the crossing latitude decreases for a given season (Figs. 12c,d), suggesting that it may take an increasingly amplified flow pattern to enable TPVs and cold pools to be transported equatorward of a given crossing latitude as the crossing latitude decreases.

CAOs are 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). The greater occurrence of CAOs during winter compared to other seasons for all regions except South likely is a consequence of the lower-latitude position of the polar jet stream and decreased shortwave radiative heating during winter relative to other seasons. Thus, cold air masses are more likely to develop and spread southward across the central and eastern U.S. and contribute to CAO development during winter. There is a moderate-to-high percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs over northern regions of the U.S. (i.e., WNC, ENC, Northeast, and Central) for all seasons (Figs. 13c,d). There is a lower percentage of CAOs linked to cold pools and CAOs linked to cold pools associated with TPVs over southern regions of the U.S. (i.e., South and Southeast) compared to northern regions of the U.S. for all seasons (Figs. 13c,d), which likely is a consequence of the substantial decrease in the number of TPVs and cold pools crossing equatorward of a given crossing latitude as the crossing latitude decreases for a given season (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 is a consequence of the transport of the lowest number of TPVs and cold pools 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 examined and 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, for 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 is adapted from Torn and Hakim (2015) and 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 bootstrap test is also used for CAO cold pools and climatological cold pools, but will be described only 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 the respective 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.

The lowest standardized anomaly of DT potential temperature and of 1000–500-hPa thickness of some CAO TPVs and some CAO cold pools, respectively, overlaps with the 25th through 75th percentiles of that of climatological TPVs (Fig. 14b) and climatological cold pools (Fig. 15b), respectively, for all seasons. The aforementioned overlap indicates that some CAO TPVs and some CAO cold pools are as anomalously cold as climatological TPVs and climatological cold pools, respectively, suggesting that TPVs and cold pools that contribute to CAOs are not always exceptionally cold. Although seasonal variability exists 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), little seasonal variability exists in the lowest standardized anomaly of DT potential temperature of climatological TPVs and CAO TPVs (Fig. 14b), and in the lowest standardized anomaly of 1000–500-hPa thickness of climatological cold pools and CAO cold pools (Fig. 15b). For example, a CAO cold pool during summer may not be as cold as a CAO cold pool during winter, but the CAO cold pools may be similarly anomalously cold during both seasons.

In terms of longevity, CAO TPVs are characterized by a statistically significantly longer mean lifetime compared to climatological TPVs for all seasons (Fig. 14c and Table 4), and CAO cold pools are characterized by 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, suggests that a longer period of longwave radiative cooling may be contributing to greater cooling of CAO TPVs and CAO cold pools compared to climatological TPVs and climatological cold pools. This greater cooling of CAO TPVs and CAO cold pools compared to climatological TPVs and climatological cold pools may be contributing to CAO TPVs and CAO cold pools being statistically significantly colder than climatological TPVs (Figs. 14a,b and Table 4) and climatological cold pools (Figs. 15a,b and Table 5), respectively.

**4. Summary**

It is shown in prior studies 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). Additional evidence is provided in the present study of the linkages between TPVs, cold pools, and CAOs by comparing climatologies of TPVs, cold pools, and CAOs occurring in six NCEI-defined climate regions over the central and eastern U.S., and identifying CAOs linked to cold pools associated with TPVs for these regions.

It is shown in prior studies (e.g., Hakim and Canavan 2005; Cavallo and Hakim 2009, 2012) and in the present study that central and eastern North America, in particular northern Canada and the Canadian Archipelago, is a region of high TPV occurrence, and it is also shown in the present study that this is a region of high cold pool occurrence. It is further shown in the present study that central and eastern North America is a preferred corridor 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, the North Atlantic, Greenland, and the Arctic may allow TPVs and cold pools to move equatorward over central and eastern North America and to 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 over northern regions of the U.S. throughout the year and each season, which is higher than that over southern regions of the U.S. throughout the year and each season. The higher percentage over northern regions of the U.S. compared to southern regions of the U.S. is a consequence of 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 transported 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 elevated terrain (e.g., the Rockies), may allow cold air associated with the TPVs and cold pools to be transported 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; Papritz et al. 2019). Furthermore, a dynamical response to the intensification of a TPV may be the 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 that is documented in the present study.

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*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 (KTOP)Waco, TX (KACT) |
| Southeast(*N*=8) | Washington, DC/Reagan National (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 the number of CAOs linked to cold pools divided by the number of CAOs (given in Table 2). Percentage of CAOs linked to cold pools associated with TPVs is defined as the number of CAOs linked to cold pools associated with TPVs divided by the 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 defined in the Fig. 12 caption, where TPVs are separated into each season 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 defined in the Fig. 12 caption, where cold pools are separated into each season 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 the number of CAOs linked to cold pools divided by the 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 the number of TPVs associated with cold pools divided by the number of TPVs transported to middle latitudes (given by the value of N in Fig. 5c). Percentage of cold pools associated with TPVs is defined as the number of cold pools associated with TPVs divided by the number of cold pools transported to middle latitudes (given by the value of N 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 the number of CAOs linked to cold pools associated with TPVs divided by the 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 [given by the value of N in (a) and (c)] and CAO cold pools [given by the value of N in (b) and (d)], 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 the value of N in each panel) 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 conventional definition of meteorological seasons is adopted, where DJF (winter) denotes December, January, and February, MAM (spring) denotes March, April, and May, JJA (summer) denotes June, July, and August, and SON (autumn) denotes September, October, and November. TPVs and cold pools are separated into each season 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 the number of CAOs for that climate region and season divided by the 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 the number of CAOs linked to cold pools for that climate region and season divided by the 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 the number of CAOs linked to cold pools associated with TPVs for that climate region and season divided by the number of CAOs for that climate region and season. Seasons are defined in the Fig. 12 caption, where CAOs are separated into each season 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 defined in the Fig. 12 caption, where TPVs are separated into each season 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 defined in the Fig. 12 caption, where cold pools are separated into each season based on the month of their genesis date.

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