**5. Discussion, Conclusions, and Suggestions for Future Work**

5.1 Discussion and Conclusions

The goals of this research were to improve understanding of 1) the equatorward transport of TPVs and cold pools to middle latitudes and 2) dynamical linkages between TPVs, cold pools, and CAOs. Although previous studies have examined CAOs linked to cold pools and have discussed upper-level features that may play a role in CAOs, no previous study has examined the linkages between TPVs, cold pools, and CAOs from a climatological perspective. Climatologies of TPVs and cold pools were constructed to gain insight on regions favorable for the equatorward transport of TPVs and cold pools. A climatology of CAOs over the central and eastern U.S. that are linked to cold pools associated with TPVs was then constructed to gain understanding on the dynamical linkages between TPVs, cold pools, and CAOs. Case study investigations of two CAOs that are linked to cold pools associated with TPVs were preformed to gain further understanding on the equatorward transport of TPVs and cold pools to middle latitudes and the dynamical linkages between TPVs, cold pools, and CAOs.

*5.1.1 Climatologies*

*5.1.1.1 Climatologies of TPVs and Cold Pools*

Many of the results of the TPV climatology are in agreement with past studies on TPVs. TPV track density is highest over the high latitudes, especially over the Canadian Archipelago and northern Siberia (Fig. 3.1a), in agreement with the results of Cavallo and Hakim (2009, 2012). Cavallo and Hakim (2009, 2010, 2012, 2013) have shown that TPVs are common over high latitudes because longwave radiative cooling, which may maintain and intensify TPVs, dominates latent heating processes that may act to weaken or destroy TPVs. In addition, as shown by Cavallo and Hakim (2012), the regions of high TPV track density over the Canadian Archipelago and northern Siberia coincide with climatological troughs. TPVs may spend a lot of time meandering around within these troughs, which may contribute to high TPV track density in these regions. Similar to TPVs, regions of high cold pool track density are found over the high latitudes, especially over the Canadian Archipelago and northern Siberia and the adjacent Arctic Ocean (Fig. 3.4a). Longwave radiative cooling over these regions from surface snow and ice cover over these regions as well as from ice crystals, condensate, and low-level clouds often found in the cold air over the Arctic (e.g., Curry 1983; Emanuel 2008) may support the maintenance and intensification of cold pools (e.g., Turner and Gyakum 2011; Turner et al. 2013).

The climatologies of TPVs and cold pools transported to middle latitudes indicate that central and eastern North America and Siberia and eastern Asia are favorable corridors for the equatorward transport of TPVs (Figs. 3.1b and 3.2) and cold pools (Figs. 3.4b and 3.5) to middle latitudes. Ridge amplification over the eastern North Pacific and western North America may lead to the downstream equatorward transport of TPVs and cold pools over central and eastern North America, as illustrated in the case studies in chapter 4 as well as in past studies including Hakim et al. (1995, 1996) and Bosart et al. (1996). Since central and eastern North America is a region favored for CAOs (e.g. Konrad and Colucci 1989; Colle and Mass 1995; Walsh et al. 2001), TPVs and cold pools transported equatorward over central and eastern North America may play important roles in the development of CAOs. The TPVs and cold pools that frequently track over Siberia and eastern Asia may be involved in cold surges over eastern Asia (e.g., Chang and Lau 1980; Boyle 1986; Chen et al. 2002). For example, Boyle (1986) showed that cold air ushered in by synoptic scale shortwaves passing through the longwave trough over eastern Asia may result in cold surges over eastern Asia. TPVs and associated cold pools over Siberia and eastern Asia may similarly result in cold surges over eastern Asia.

In addition, it was suggested in Figs. 3.1b and 3.4b that TPVs and cold pools transported to middle latitudes, respectively, frequently track near the entrance regions and along the poleward sides of the North Atlantic and North Pacific jet streams. TPVs and cold pools tracking near these jet streams may contribute to the development and intensification of jet streaks. TPVs may contribute to the development and intensification of jet streaks via TPV–jet interaction (e.g., Pyle et al. 2004) and cold pools may contribute to the development and intensification of jet streaks by contributing to increases in lower-tropospheric baroclinicity (e.g., Sanders and Davis 1988). The development and intensification of jet streaks may support the development of strong ECs (e.g., Uccellini et al. 1985; Uccellini and Kocin 1987). Furthermore, TPVs themselves can be precursors to the development of strong ECs (e.g. Hakim et al. 1995, 1996; Bosart et al. 1996), and the movement of cold pools over strong SST gradients associated with the Gulf Stream and Kuroshio current may support strong sensible and latent heat fluxes and a reduction of static stability, which may provide favorable conditions for the development of strong ECs (e.g., Sanders and Gyakum 1980).

*5.1.1.2 Climatology of CAOs that are linked to Cold Pools Associated with TPVs*

As discussed in section 3.3 and as shown in Fig. 3.7, there is a much larger percentage of CAOs that are linked to cold pools in northern regions of the U.S., comprising the WNC, ENC, and Northeast regions (~85–90%) compared to the southern regions of the U.S., comprising the South and Southeast regions (~28–36%), which is likely related to the large meridional gradient of track density of cold pools transported to middle latitudes over southern Canada and the northern U.S. (Fig. 3.4b). Thus, there is likely is more opportunity for northern regions of the U.S to be impacted by cold pools compared to the southern regions of the U.S. For example, a cold pool that moves across southern Canada may only impact northern regions of the U.S., especially if the flow pattern over the U.S. is fairly zonal, and cold air cannot penetrate far equatorward. For cold pools that impact both the northern and southern regions of the U.S., although the core of the cold pool may only move over the northern regions of the U.S., the cold air associated with the cold pool may still spread far away and impact southern regions of the U.S. For example, as shown in the case studies in chapter 4 and in past studies (e.g., Boyle and Bosart 1983; Colle and Mass 1995), a cold pool may be accompanied by a strong surface anticyclone on the east side of the Rocky Mountains. The strong SLP gradient associated with the surface anticyclone and a terrain-tied northerly component of low-level motion east of the Rocky Mountains may allow cold air from the cold pool to advect far equatorward.

Past studies have shown that upper-level features may be associated with cold pools. For example, Boyle and Bosart (1983) showed that a maximum of PV was found above a cold pool leading to a CAO over North America during November 1969, and Shapiro et al. (1987) showed that a midlevel cyclone or “polar vortex” feature was associated with a cold pool that played an important role in the development of the January 1985 CAO. As shown in chapter 4, this “polar vortex” feature is related to a TPV. This thesis expands upon these past studies by providing a climatological understanding of the relationship between TPVs and cold pools. As discussed in section 3.3, it has been found that 6,288 out of the total 8,395 cold pools transported to middle latitudes, or 74.9%, match with at least one TPV transported to middle latitudes. Also, 6,510 out of the total 25,085 TPVs transported to middle latitudes, or 26.0%, match with at least one cold pool transported to middle latitudes. Although a large percentage of cold pools transported to middle latitudes (74.9%) are associated with TPVs, a large percentage of TPVs (74%) are not associated with cold pools. In many instances, TPVs may be too small or weak to be associated with a cold pool. For example, when the TPV in the January 1982 CAO case is relatively small and weak (Figs. 4.7a,b), it is not associated with an identifiable cold pool (Fig. 4.7c). Regardless, Figs. 4.7a,c illustrate that such a TPV may still be associated with cold air throughout the troposphere. Furthermore, a TPV may be robust, but may be associated with a 1000–500-hPa thickness trough that is not trackable, if for example, a region of relatively low 1000–500-hPa thickness air associated with the TPV is embedded in a strong horizontal thickness gradient.

After comparing the climatologies of TPVs, cold pools, and CAOs, it was found that ~74–88% of CAOs are linked to cold pools associated with TPVs over northern regions of the U.S., while ~24–28% of CAOs are linked to cold pools associated with TPVs over southern regions of the U.S. (Fig. 3.7). Thus, while cold pools associated with TPVs may contribute to CAO development over the entire central and eastern U.S., they are more likely to cause CAO development over northern regions of the U.S. The large percentage of CAOs over northern regions of the U.S. that are linked to cold pools associated with TPVs suggests that TPVs may play an important role in CAO development and that improved understanding of TPVs may lead to improved understanding of CAOs. This climatology of CAOs that are linked to cold pools associated with TPVs complement and extend existing studies of CAOs discussed to be linked to cold pools and upper-level features (e.g., Shapiro et al. 1987) by providing climatological context for the linkages between TPVs, cold pools, and CAOs.

5.1.2 Case Studies

Similar to past studies showing the equatorward transport of TPVs (e.g., Hakim et al. 1995, 1996; Bosart et al. 1996) and cold pools (e.g., Namias 1978), ridge amplification over the eastern North Pacific and western North America appears to play an important role in the equatorward transport of the TPV and cold pool in both the January 1982 CAO case and January 1985 CAO case, with ridge amplification over the northwestern North Atlantic also playing an important role in the equatorward transport of the TPV and cold pool in the January 1985 CAO case. Poleward fluxes of warm, moist air and diabatically driven upper-tropospheric divergent outflow associated with ECs appear to play important roles in ridge amplification in both cases. The importance of ridge amplification for the equatorward transport of TPVs and cold pools suggests that improved understanding of precursor disturbances and processes responsible for ridge amplification may lead to improved understanding of the equatorward transport of TPVs and cold pools.

In both case studies in chapter 4, the large spatial overlap and temporal coincidence of the TPV and cold pool throughout much of their lifetimes (Fig. 4.1 for January 1982 CAO case and Fig. 4.11 for January 1985 CAO case) suggests that the TPV and cold pool are dynamically linked. The composite cross section of TPVs from Cavallo and Hakim (2010; Fig. 1.3a in this thesis), which shows anomalously cold air throughout the troposphere, within and beneath the TPV, also suggests that there may be a dynamical linkage between TPVs and cold pools. Cross sections of the TPV and cold pool in each case were examined to better understand the linkages between TPVs and cold pools. In the January 1982 CAO case, as the TPV becomes a stronger and deeper feature, there becomes a more pronounced upward bowing of the isentropes within and beneath the TPV (compare Figs. 4.7a,b to Figs. 4.8a,b), corresponding to the development of an intense cold pool (compare Figs. 4.7c to Fig. 4.8c). In the January 1985 CAO case, early in the life cycle of the cold pool, although the TPV has yet to develop, there is still a broad region of relatively low DT potential temperature air (Fig. 4.17b) and concomitantly a broad region of depressed DT (Fig. 4.17a) associated with the cold pool (Fig. 4.17c). As the TPV in the January 1985 becomes established and strengthens (compare Fig. 4.18b to Fig. 4.19b), there become a more pronounced upward bowing of the isentropes throughout the troposphere (compare Fig. 4.18a to Fig. 4.19a). Concomitantly, the cold pool is stronger after the formation of the TPV compared to prior to the formation of the TPV (compare Figs. 4.18c and 4.19c to Fig. 4.17c). There thus appears to be dynamical linkage between the TPV and cold pool in each case. The dynamical linkage demonstrates that the influence of TPVs can extend throughout the depth of the troposphere and cover a widespread geographical area.

In both cases, a jet streak over western North America strengthens as TPV–jet interaction occurs, and a strong surface anticyclone over western North America concomitantly strengthens and expands equatorward in the left entrance region of the jet streak (Figs. 4.10a,d,g,j for January 1982 CAO case and Figs. 4.20a,d,g,j for January 1985 CAO case). A composite analysis of strong surface anticyclones occurring over western North America from Jones and Cohen (2011) suggests that the composite surface anticyclone also strengthens in the left entrance region of a jet streak, where there is Q-vector divergence and thus QG forcing for descent near the composite anticyclone. In both cases examined in chapter 4, there an enhancement of **Q**n forcing decent in the left entrance region of the jet streak as the jet streak strengthens during TPV–jet interaction (e.g., compare Figs. 4.10g,h to Figs. 4.10d,e for January 1982 CAO case and compare Figs. 4.20d,e to Figs. 4.20a,b for January 1985 CAO case). In addition, the TPV in each case is associated with a shortwave trough, with **Q**s forcing for descent found upstream of the shortwave trough, as anticipated from Sanders and Hoskins (1990). As the TPV interacts with the jet streak in each case, the **Q**s forcing for the descent is found the left entrance region of the jet streak, augmenting the **Q**n forcing for descent in the left entrance region of the jet streak (e.g., Figs. 4.10g–i for January 1982 CAO case and Figs. 4.20g–i for January 1985 CAO case). The **Q**s forcing for descent is stronger and more organized in the January 1982 CAO case compared to in the January 1985 CAO case, possibly due in part to the shortwave trough associated with the TPV in the January 1982 CAO case being sharper compared to that in the January 1985 CAO case (e.g., compare Figs. 4.10i to 4.20i). In both cases, the enhanced regions of **Q**n and **Q**s forcings for descent in the left entrance region of the jet streak related to the TPV and TPV–jet interaction may support the strengthening and expansion of the surface anticyclone in the left entrance region of the jet streak. Therefore, TPV–jet interaction may play an important role in the strengthening and expansion of surface anticyclones.

As the TPV and cold pool move into the U.S., and the surface anticyclone expands southward on the east side of the Rocky Mountains, an expected terrain-tied northerly component of strong low-level flow (e.g., Colle and Mass 1995) in the vicinity of the strong SLP gradient associated with the surface anticyclone likely helps allow cold air from the cold pool associated with the TPV to rapidly advect equatorward (Figs. 4.5e,f for January 1982 CAO case and Fig. 4.15e,f for January 1985 CAO case). The strong surface anticyclone thus likely plays an important role in CAO development in each case, consistent with past studies on CAO development including Dallavalle and Bosart (1975), Boyle and Bosart (1983), Colucci and Davenport (1987), Konrad and Colucci (1989), Colle and Mass (1995), Walsh et al. (2001), and Jones and Cohen (2011).

The cases studies in chapter 4 illustrate that TPVs may play a crucial role in CAO development given that 1) the TPV is associated with a cold pool that moves directly along with the TPV into the U.S. during the time of the CAO and 2) the TPV via TPV–jet interaction may help to strengthen a strong surface anticyclone that helps transport cold air from the cold pool associated with the TPV far away from the core of the cold pool. Therefore, the case studies in chapter 4 complement and extend existing studies of cold pools and strong surface anticyclones linked to CAO development by illustrating the role of TPVs. Also, the January 1985 CAO case showcases that the midlevel cyclone or “polar vortex” feature examined by Shapiro et al. (1987) to play an important role in the development of the January 1985 CAO is related to a TPV, suggesting that shortwave troughs and midlevel cyclones identified to play important roles in CAO development in past studies may be related to TPVs. For example, it may be possible that there are linkages between the cold pool discussed by Boyle and Bosart (1983) and a TPV, especially given that Boyle and Bosart (1983) discuss the existence of an upper-level PV maximum collocated with the 1000–500-hPa thickness minimum of the cold pool. If there is a TPV linkage, the degree to which TPV–jet interaction plays a role in the evolution of the surface anticyclone discussed by Boyle and Bosart (1983) could be examined, especially given that the surface anticyclone in this case moves equatorward along with a jet streak.

5.2 Suggestions for Future Work

A remaining research issue is whether and how CAOs that are linked to cold pools associated with TPVs may differ from CAOs that are not linked to cold pools associated with TPVs. To address this research issue, composites of CAOs that are linked to cold pools associated with TPVs for different regions comprising the central and eastern U.S. could be constructed and compared to similar composites of CAOs that are not identified to be linked to cold pools associated with TPVs. In addition, idealized modeling could be use to further understand the dynamical linkage between TPVs and cold pools. For example, the strength and structure of an idealized TPV could be modified in order to better understand how changes in the strength and structure of the TPV impact a cold pool associated with the TPV. Furthermore, in both cases in chapter 4, processes hypothesized to play a role in intensity changes of the TPV and cold pool in each case such as longwave radiative cooling, latent heating, and sensible heating could be quantified in in order to better understand the impact of these processes on TPV and cold pool intensity in each case. For example, a thermodynamic budget similar to that used by Turner et al. (2013) could be used to quantify the influence of radiative cooling on the intensity of each cold pool.

In addition, the TPV and cold pool climatologies presented in this thesis indicate that Siberia and eastern Asia are favored regions for the equatorward transport of TPVs and cold pools. A climatology of CAOs that are linked to cold pools associated with TPVs could be constructed for Siberia and Eastern Asia, and the role of TPVs and cold pools on the development of cold surges over eastern Asia (e.g., Chang and Lau 1980; Boyle 1986) could be examined. Furthermore, it has been shown that cold surges over eastern Asia may potentially impact the state and structure of the North Pacific jet stream (e.g., Chang and Lau 1982; Handlos and Martin 2016), which may impact the downstream synoptic-scale flow (e.g., Griffin and Martin 2017). Therefore, it is possible the changes in the state and structure of the North Pacific jet stream in response to upstream precursor disturbances like TPVs, cold pools, and associated cold surges over eastern Asia may impact the synoptic-scale flow over the eastern North Pacific and western North America, which may influence whether TPVs and cold pools are transported to middle latitudes over North America. Thus, climatological, composite, predictability, and case studies of the impact of TPVs, cold pools, and associated cold surges over eastern Asia on the state and structure of the North Pacific jet stream, and subsequent impact on the structure of the downstream synoptic-scale flow and equatorward transport of TPVs and cold pools over North America could be carried out.