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Prevailing Synoptic Patterns for Persistent Positive Temperature Anomaly Episodes in the United States

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장기간 지속되는 이상고온기의 종관패턴: 미국을 사례로

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Abstract : This study examines the prevailing synoptic-scale mechanisms favorable for long-lived summer Persistent Positive Temperature Anomalies (PPTAs) as well as winter PPTAs in the United States. Such long-lived PPTAs usually occur in the south-central region of the United States in summer, but in the southwestern part of the United States in winter. Composite analyses of surface and pressure level data demonstrate that the formation of both winter and summer PPTAs is closely related to the movement of subtropical high pressure systems in the Pacific Ocean and Atlantic Ocean, respectively. The occurrence of long-lived summer PPTAs usually coincides with an extremely stable atmospheric condition caused by persistent blocking by mid- to upper-tropospheric anticyclones. Significant surface forcing is also easily identified through relatively high Bowen ratios at the surface. Warm air advection is, however, weak and appears to be an insignificant element in the formation of long-lived summer PPTAs. On the other hand, synergistic warming effects associated with adiabatic heating under an anticyclonic blocking system as well as significant warm air advection characterize the favorable synoptic environments for long-lived winter PPTAs. However, the impact of surface forcing mechanisms on winter PPTAs is insignificant.
Key Words : persistent positive temperature anomaly, synoptic patterns, United States

요약 : 본 연구는 미국 지역을 사례로 겨울철 및 여름철에 장기간 지속되는 이상고온기 발생에 유리한 종관 규모의 매커니즘을 밝힌다. 여름철 이상고온기는 주로 미국의 남중부 지역에서 발생하는 반면, 겨울철 이상고온기는 미서부 지역에서 발생한다. 지상 및 상층 기압장 자료 분석 결과, 이러한 이상고온기는 태평양과 대서양의 아열대 고기압들의 활동과 밀접하게 관련되어있다. 장기간 지속되는 여름철 이상고온기는 중층 및 상층 블러킹 고기압의 활동에 의해 형성되는 매우 안정된 대기 조건하에서 주로 발생한다. 또한 이 시기에는 지표강제력으로 상대적으로 높은 보웬비(Bowen ratio)가 나타나지만, 따뜻한 공기의 이류의 영향은 크지 않다. 반면, 장기간 지속되는 겨울철 이상고온기는 블러킹 고기압에 의한 단열 기온 상승뿐만 아니라 따뜻한 공기의 이류의 복합적인 작용에 의해 나타난다. 그러나 이 시기의 지표 강제력의 영향은 약하다.
주요어 : 이상고온기, 종관패턴, 미국

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1. Introduction

Recently it has been more important to monitor extreme weather events associated with climatic variation and to assess their impacts, since they often lead to serious environmental and human consequences. In the United States, heatwaves, episodes of recurring extremely high surface air temperatures, have also caused considerable attention because of an apparently increasing number of more intense and prolonged events in recent years and their relationship with "global warming" (Blair, 1997; Choi and Meentemeyer, 2002; Meehl and Tebaldi, 2004).

Many studies have dealt with the general synoptic mechanisms and meteorological characteristics of severe summer heatwaves. Early studies by Klein (1952) and Namias (1955, 1966) found that hot months are enhanced by surface anticyclones and upper-level ridges over both the Pacific Ocean and Atlantic Ocean, as well as a deeper-than-normal upper-level trough along the west coast of North America. Later findings proved that the most prominent feature in the development of extensive, long-lived summer heatwaves, and potential drought conditions, is a mid-tropospheric ridge from a continental scale anticyclone (Namias, 1982; Chang and Wallace, 1987; Wolfson *et al.*, 1987; Trenberth and Guillemot, 1996; Henderson and Muller, 1997). In the United States, summer heatwaves usually coincide with an extremely stable atmosphere caused by persistent blocking of mid- to upper-tropospheric anticyclones over the North Atlantic Ocean. This particular circulation pattern can strengthen to form large "warm core high" type thermal structures. Under certain conditions, prevailing large upper-level anticyclones can also grow to quasi-permanent blocking anticyclones, also known as an "Omega High" such as the Bermuda High (Davis *et al.*, 1997). This pattern often persists for several days to weeks in the same general location. Surface temperatures are likely to become much above average beneath the upper-level ridge (Namias, 1962, 1982; Kunkel, 1989). These subtropical highs are very tall, often extending vertically from the surface to the stratosphere, while covering several thousand kilometers horizontally (Djuric, 1994).

Surface conditions are also important for the formation of summer heatwaves in the United States. A dry surface can act as a component of positive feedback to intensify heatwaves. Several previous studies found that surface conditions including soil moisture were responsible for the decay of summer heatwaves, usually associated with a shift in the storm track and the occurrence of significant rainfall in the affected area (Shukla and Mintz, 1982; Wolfson *et al.*, 1987; Namias, 1991). Walsh *et al.* (1985) stated that high surface temperatures could induce and intensify upper-level anticyclones. Chang and Wallace (1987) found that heatwaves were usually associated with upper-level anticyclones and dry surface conditions. Trenberth and Branstator (1992) and Trenberth *et al.* (1988) demonstrated links between the 1988 heatwave and Sea Surface Temperature (SST) anomalies, which disrupted atmospheric heating patterns and displaced circulation across North America northward.

It is commonly accepted that heatwaves usually occur in summer, can cause stress, and may also involve droughts. There is, however, a broader issue, namely persistent positive temperature anomalies (PPTAs). Choi and Meetemeyer (2002) defined a "PPTA" to be a run of three or more days at 1.0 SD above the true daily mean for the daily maximum temperature. Thus, PPTAs, from a climatological point of view, can occur at any time during a diurnal cycle, in any season, and in any region. PPTAs can occur in winter as well as summer.

As described earlier, many studies have

identified typical synoptic patterns of remarkable PPTAs, primarily extensive summer PPTAs, across the United States. PPTAs in other seasons have been, however, rarely studied. This study aims to determine the prevailing surface and upper-level synoptic-scale mechanisms that produce and sustain the most prominent and severe PPTAs across the contiguous United States. Emphasis will be on seasonal comparisons between summer and winter PPTAs. To do this, the synoptic conditions common to long-lived summer as well as winter PPTAs are "reconstructed". These analyses are based on composite maps which were created by averaging synoptic patterns of selected groups of similar PPTA events identified in the 46-year climatology record from 1950-1995 (Choi and Meentemeyer, 2002). These maps provide a basis for understanding regional and seasonal patterns and synoptic environments that produce PPTAs.

2. Data and Methods

Based on the previous work by Choi and Meentemeyer (2002), seven long-lived summer PPTAs (16 to 31 days in length) and the six longest winter PPTAs (ranging from 19 to 36 days) were selected to analyze favorable synoptic environments leading to extensive summer and winter PPTAs. Table 1 lists selected PPTA events

Table 1. Selected long-lived summer and winter PPTAs and their durations for the period, 1950-1995

Event	Summer	Winter
1	06/03/52-07/02/52 (30 days)	12/07/50-12/25/50 (19 days)
2	06/01/53-06/25/53 (25 days)	12/13/55-01/17/56 (36 days)
3	06/23/54-07/23/54 (31 days)	02/25/59-03/15/59 (19 days)
4	08/03/56-08/18/56 (16 days)	11/19/59-12/08/59 (20 days)
5	06/28/78-07/22/78 (25 days)	12/13/80-01/15/81 (34 days)
6	06/22/80-07/20/80 (29 days)	11/11/95-11/30/95 (20 days)
7	07/27/88-08/18/88 (23 days)	

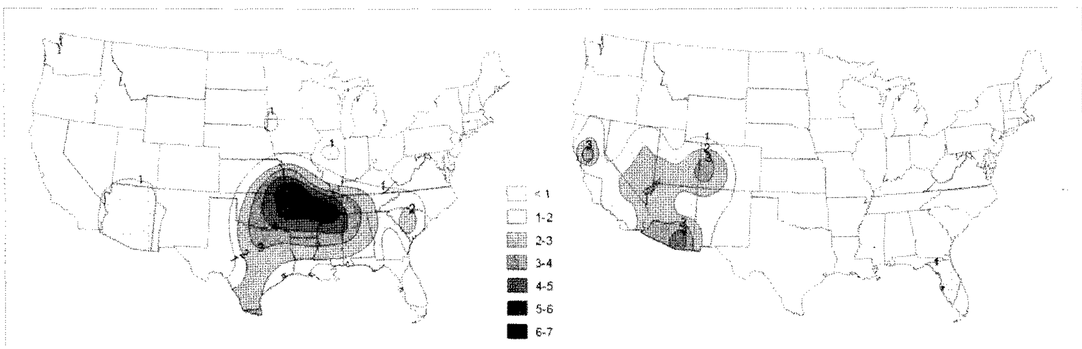

Figure 1. Frequency of PPTAs of 15 or more days in a run in a warm season (left) and a cool season (right) for the period, 1950-1995 (Choi and Meentemeyer, 2002)

that lasted 15 or more consecutive days for the period of record at three or more contiguous weather stations. The average duration of selected summer and winter PPTAs is 25.6 days and 24.7 days, respectively. Such long-lived, intense, and extensive PPTAs usually occurred in the south-central region of the United States in summer, but in the southwestern part of the United States in winter (Figure 1).

Data used for synoptic analyses include pressure level data and surface data that were obtained from the online database maintained by the Climate Diagnostics Center (CDC). Upper-air circulation analyses and surface flux maps were constructed using the reanalysis gridded data from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR).

These reanalysis data include daily average values of pressure level and surface conditions. Pressure level data consist of 2.5° latitude×2.5° longitude grids, whereas surface reanalysis data covers a 1.88° latitude×1.87° longitude surface using a Gaussian grid network. These data were obtained in NetCDF format and converted to General Meteorological Package ($GEMPAK_{TM}$) format for further analyses. Temperature, specific humidity, u and v wind vectors, and geopotential height were obtained for the mandatory pressure levels (1000hPa, 850hPa, 700hPa, 500hPa and 300hPa). Vertical moisture and thermal structure including thermal and moisture advection, vorticity advection, and subsidence were calculated. From the surface Gaussian grids, Bowen ratios (β), which indicate the partitioning of surface energy between sensible and latent heat, were determined from latent heat and sensible heat fluxes.

The surface-to-850hPa fields help to describe the lower-atmospheric environment including surface temperature and vertical temperature gradients during PPTA events (Djuric, 1994). In this study, an estimate of thermal advection at the surface and 1000hPa levels was acquired because of its potential effects on PPTA. At the 850hPa level, both thermal advection and moisture transport fields were calculated and mapped. The 500hPa-level data reveal the geopotential heights and absolute vorticity for the mid-troposphere, which can reveal areas of subsidence that may enhance adiabatic heating. The composite 300hPa-divergence field is used to diagnose upper-level support for anticyclogenesis, upper-level convergence. The 300hPa geopotential heights and isotachs allow for identification of corridors of higher wind speeds at upper-levels of the troposphere and suggest the presence of jet streaks that may cause intensified vertical motion and induce mechanical air subsidence (Djuric, 1994).

For a better understanding of favorable synoptic mechanisms which in general produce PPTAs, this study uses a "composite method". This method averages the synoptic data fields for selected groups of similar PPTAs on the basis of season and geographic region. This approach has been proven to be an efficient and objective approach when the analysis of a large number of temporally or geographically similar events is difficult (Winkler, 1988). Compositing a large number of cases into one helps to identify processes common to each of the cases (Achtor and Horn, 1986). For analysis purposes, the maps of the departure of selected variables listed above from "normals" were also derived. NCEP/NCAR reanalysis dataset provides these normals based on mean values of each variable for a 29-year period (1968-1996). These departures and the degree of departure from normal are excellent indicators of the unusual atmospheric conditions which prevail during PPTAs.

3. Results

1) Summer PPTAs

The development of anticyclones is highly reliant on planetary waves in the global circulation. Karl and Quayle (1981) found that high pressure systems which affect weather conditions in the United States are parts of wave trains consisting of high pressure areas over the Northeastern Pacific Ocean and North Atlantic Ocean. Along these propagating Rossby Waves, a prevailing ridge often develops in summer over the central Great Plains with two troughs located over the Pacific and Atlantic coastal regions (Figure 2a). This pattern results in steep meridional flows which induce positive temperature departures over the central United States. Figure 2a and 3a shows that the Bermuda High has expanded during all of the seven longest summer PPTA events. Most of the southern and eastern states as well as Mexico and the Caribbean are affected by this high pressure system. This expanded high pressure system greatly shifts storm tracks poleward along the western margin, with the flow veering from southwest to northeast (Zishka and Smith, 1980). This pattern leads to clear skies and decreased precipitation throughout the eastern half of the United States and often persists until cyclones become more frequent over the central United States.

Figure 3a shows the composite of 500hPa geopotential heights of the seven summer PPTAs. This composite map shows great agreement with the upper-level flow patterns that cause PPTAs and/or accompanying droughts, as found in other studies (Namias, 1982; Chang and Wallace, 1987; Wolfson *et al.*, 1987; Kunkel, 1989; Henderson and Muller, 1997). The map also reveals characteristic of extreme summer PPTAs. Positive departures of the geopotential height develop over the central United States centered in Iowa, Illinois, and Missouri (Figure 3a). The warm core is centered on eastern Oklahoma for these seven extreme events. These large, tall air domes, exceeding 5880 geopotential meters (gpm), are

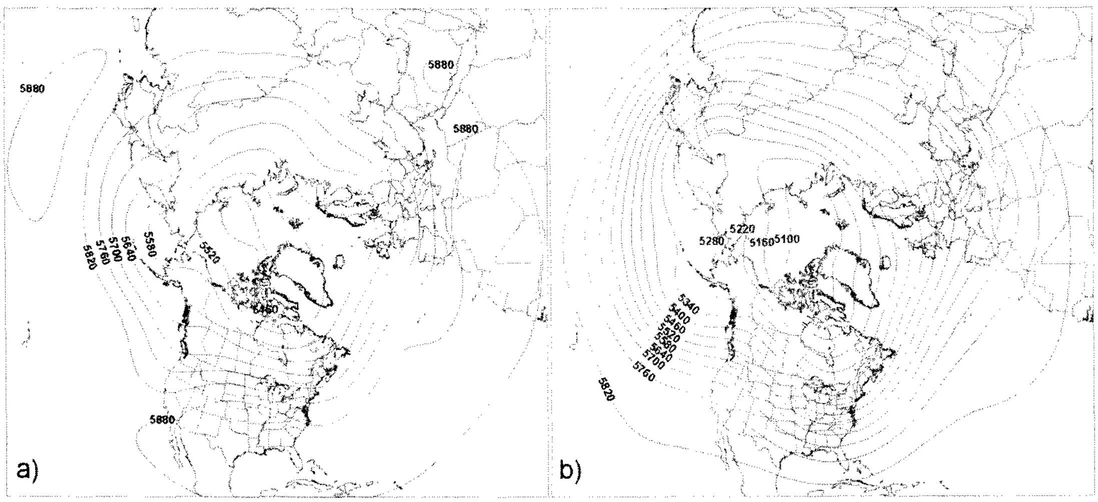

Figure 2. a) Composite of 500hPa geopotential heights (gpm) for selected seven longest summer PPTAs. b) As in a) but for selected six winter PPTAs

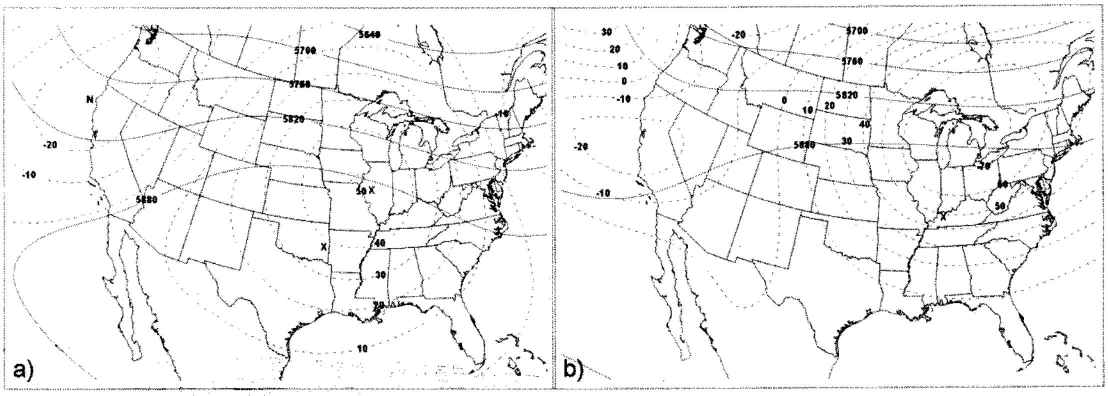

Figure 3. a) Composite 500hPa Geopotential heights (gpm, solid lines) and departures (dashed lines) from climatic normal for the seven longest summer (left) and the six longest winter (right) PPTAs. The "X" in eastern Oklahoma is the highest point for average geopotential height and the "X" in Illinois represents the peak for the deviation which occurred during the seven PPTAs. b) As in a) but during the 1988 summer PPTA

associated with a large ridge in the upper-level airflow over the central United States Among the seven longest summer PPTAs, the largest monthly departure (>70gpm) in the geopotential height occurred mainly in June prior to the 1988 PPTA episode (Figure 3b).

Figure 4a shows a composite map of sea level pressure and surface thermal advection during the seven longest summer PPTAs. The "Bermuda High" takes on the shape of a semi-permanent oceanic anticyclone. The United States is located in the western flank of the Bermuda High. Warm air advection at the surface along with southerly and southeasterly flow from the Bermuda High is observed over more than three-fourths of the United States. This warm air advection strengthens PPTAs. The intensity of this warm air advection is, however, weak, indicating that it may not be a dominating factor in producing summer PPTAs.

At 1000hPa, warm air advection associated with clockwise motion around the Bermuda High is more evident during PPTAs (Figure 4b). Warm air is "squeezed" into the central and southern United States by the anticyclonic flow off the western flank of the Bermuda High. The average wind speed at 1000hPa is less than 5 ms-1, indicative of very weak surface thermal advection. On the other hand, strong cold air advection is observed during PPTAs across most of the western United States, which is under an upper-level trough as previously described.

Figure 5a illustrates 850hPa thermal advection. Average extreme PPTAs are associated with warm air advection which develops downstream at the 850hPa ridge axis, a place where anomalies of geopotential height also reach maximum values. Thermal advection from the Atlantic Ocean and Gulf of Mexico is driven by the Bermuda High which causes a southerly wind, part of the flow regime of a typical Bermuda High. The Bermuda subtropical high pressure system also expands substantially and occupies much of the Atlantic basin.

The 500hPa composite chart for vorticity shows a broad longwave ridge over the Midwest (Figure 5b). Maximum negative vorticity advection at 500hPa occurs over Missouri, where the highest geopotential height anomalies usually occur. The center of the PPTA region is usually located

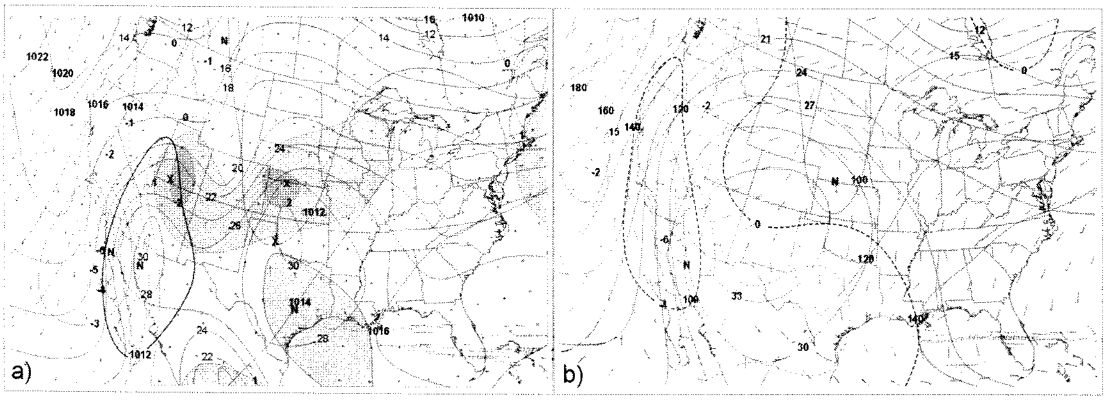

Figure 4. a) Composite of sea level pressure (hPa, bold), air temperature (°C), and surface thermal advection (x10^{-1}°C hr^{-1}, bold characters and dashed lines; shaded represents warm air advection) for the seven longest summer PPTAs. b) Composite of 1000hPa thermal advection (x10^{-1}°C hr^{-1}, dashed lines; shading represents warm air advection), heights (gpm, solid lines), air temperature (°C) and wind (m·s^{-1}) for the seven longest summer PPTAs

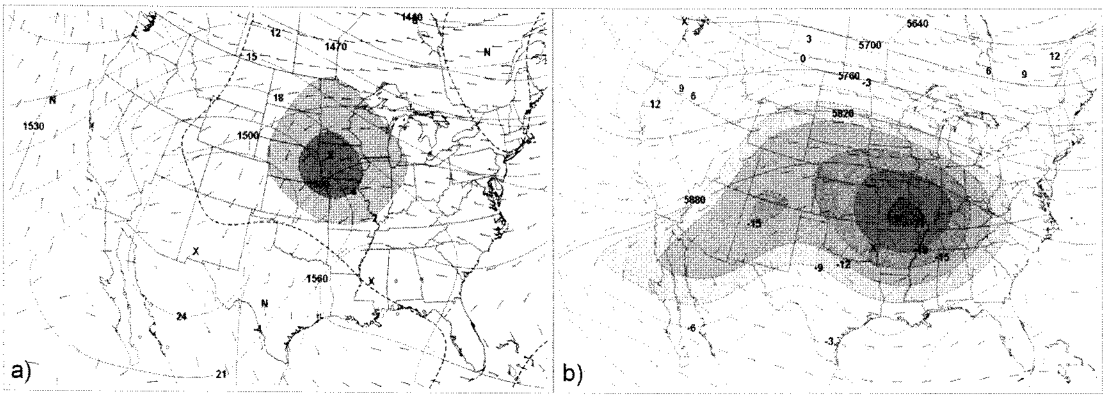

Figure 5. a) Composite of 850hPa thermal advection (x10^{-1}°C day^{-1}, dashed lines; shaded represents warm air advection), heights (gpm, solid lines), air temperature (°C) and wind (m·s^{-1}) for the seven longest summer PPTAs. b) Composite of 500hPa vorticity advection (x10^{-5}·s^{-1}, dashed lines; shaded is negative vorticity), heights (gpm, solid lines), and winds (m·s^{-1}) for the seven longest summer PPTAs

downstream at the mid-level ridge axis. Adiabatic heating then causes prolonged PPTAs over this large area in the United States

Meanwhile, upper-level flow patterns are favorable for sustaining positive surface temperature anomalies. A consistent, intense convergence at 300hPa reinforces the sinking motion related to the adiabatic heating process (Figure 6a). Similar to the mid-level flow orientation, PPTAs form downstream in the ridge of 300hPa height field. All PPTA events are then observed on the eastern side of upper-level ridges. This larger-scale dynamic forcing provides enough upper-air convergence to enhance subsidence which initiates surface heating and reduces soil moisture. Thus, once intense summer PPTAs are established, they can persist longer than PPTAs in other seasons.

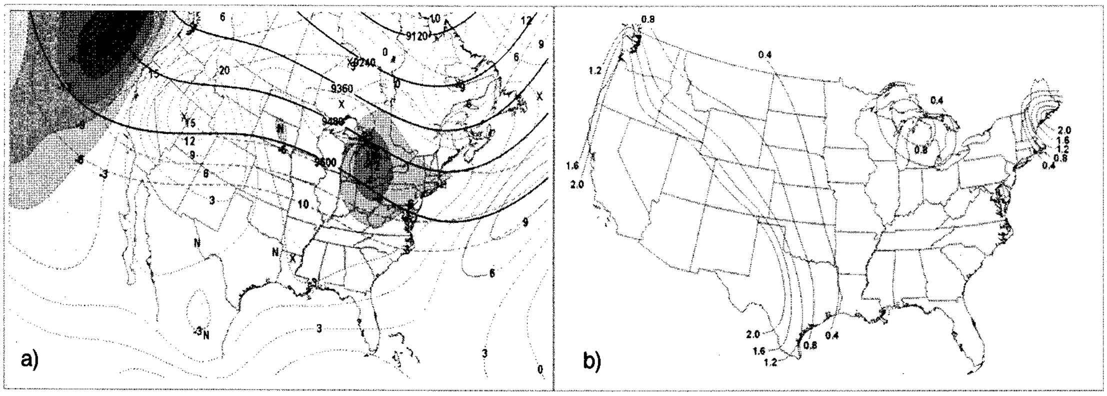

Figure 6. a) Composite of 300hPa divergence (x10^{-6}day^{-1}, dashed lines; shaded represents convergence), height (gpm, solid lines), and isotachs (m·s^{-1}) for the seven longest summer PPTAs. b) Composite of Bowen ratio for the seven longest summer PPTAs

Bowen ratios greater than 1.0 extend from southern Texas up to the Pacific Northwest (Figure 6b). Reduced cloudiness and a lack of precipitation under the extensive high pressure as well as adiabatic heating make sufficient energy available to evaporate surface moisture and to maintain a dry surface (higher Bowen ratio) which is favorable for anomalously high surface temperatures. In long-lived summer PPTAs, once this positive feedback mechanism between surface and upper-level conditions is initiated, it can perpetually self-amplify and induce unusually high temperatures. During the selected summer PPTAs, significant surface forcing can be easily identified through relatively high Bowen ratios.

2) Winter PPTAs

Synoptic patterns which cause long-lived winter PPTAs are somewhat different from those for long-lived summer PPTAs. During long-lived winter PPTAs, a wave train of westerlies in the western part of the United States is characterized by a stronger-than-normal Aleutian Low which is displaced to the south and east of its normal position (Figure 2b). With the development of two troughs over the eastern Pacific Ocean and eastern United States, anticyclonic vorticity advances northward. Along this wave train, steep meridional flow amplifies the ridge over the west coast of North America. This stationary anticyclonic blocking pattern displaces storm tracks northward and accompanies such intense winter PPTAs attributable to the growth of the high pressure system across much of the western United States (Figure 2b).

All long-lived winter PPTA events appear at the center of maximum anomalies in the upper-level ridge centered in the west-central states. This pattern is consistent with earlier findings (Dickson, 1981; Taubensee, 1981; Wagner, 1981). Figure 7a depicts composite 500hPa geopotential heights and anomalies for six long-lived winter PPTAs. Across the United States, normal mid to upper-level circulation patterns in winter are characterized by a ridge over the west coast of the United States and a trough over the eastern part of the country. A large ridge found in the composite of six winter PPTAs is displaced further northward, and it is much steeper than normal. The maximum positive anomaly from the long-term average is 97gpm above normal in the

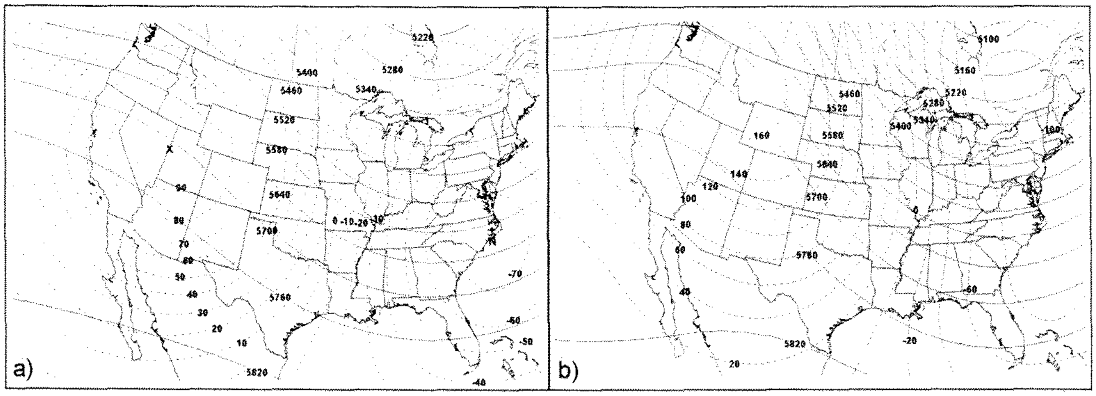

Figure 7. a) Composite 500hPa Geopotential heights (gpm, solid lines) and departures (dashed lines) from climatic normal for the six longest winter PPTAs. b) As in a) but during the 1980-81 winter PPTA

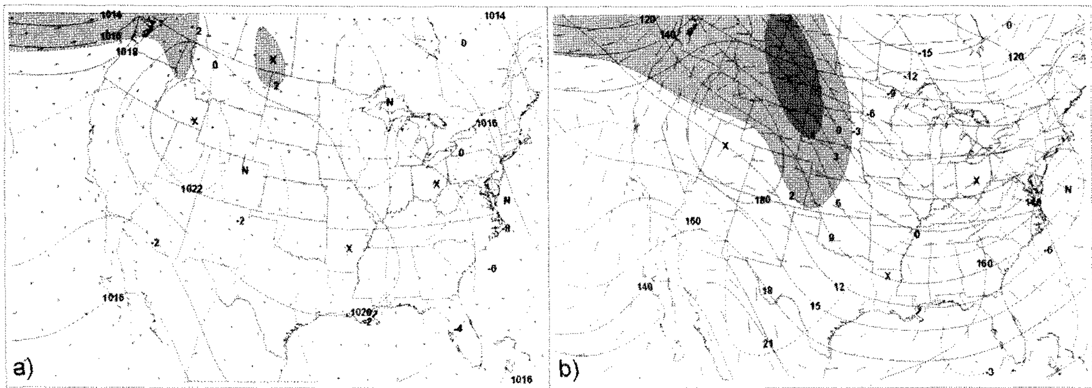

Figure 8. a) Composite of sea level pressure (hPa, bold), air temperature (°C), and surface thermal advection (x10^{-1}°C hr^{-1}, bold characters and dashed lines; shaded represents warm air advection) for the six longest winter PPTAs. b) Composite of 1000hPa thermal advection (x10^{-1}°C hr^{-1}, dashed lines; shading represents warm air advection), heights (gpm, solid lines), air temperature (°C) and wind (m·s^{-1}) for the six longest winter PPTAs

500hPa geopotential height (Figure 7a). A trough, about 80gpm below normal, is also related to this steep meridional flow. This flow pattern induces above-normal temperatures over the west-central United States and below-normal temperatures in the eastern United States. As an example, the 1981 winter PPTA was typical with the 500hPa geopotential height field with more than 170gpm above normal (Figure 7b).

Intense winter PPTAs also coincide with meridional flow in the upper-level field. The displacement of pressure pattern resembles the positive Pacific/North America (PNA) pattern in winter found over North America (Bernett, 1994). An anomalous strong ridge associated with an extensive anticyclone system over the Pacific West Coast provides a favorable upper air pattern to maintain winter PPTAs. In conjunction with the growth of the upper-level ridge, the surface high pressure system which develops in the west-central region centered on Utah and Idaho (Figure 8a) during winter PPTA events persist until the upper-level ridge either moves away or weakens. Circulation around these surface anticyclones shifts the direction of the prevailing westerlies such that warm air is transported into the western United States off the Pacific Ocean from the west and southwest. These patterns are illustrated nicely by the surface and 850hPa thermal transport vector fields shown in Figures 8a, 8b, and 9a. During the six longest winter PPTAs, southerly and westerly warm air advection (WAA) into the western United States is significant.

Low-level forcing (surface high pressure) and mid- and upper-level dynamics (primarily ridging and negative vorticity advection coincident with jet stream) appear to enhance the positive surface temperature anomalies. In conjunction with the surface high pressure pattern in the west-central United States, southwesterly flow is predominant in the northwestern United States, while westerly winds prevail across the north-central United States during winter PPTAs (Figure 8a). These winds bring warm air into the western part of the country. A similar wind pattern is observed in the 1000hPa height field (Figure 8b). In this case, much stronger WAA is visible extending from the northwestern United States into the northern and south-central plains States. The WAA occurs around the northern portion of the center of high pressure located in Utah. The strongest advection (>0.4°C/hr) is found from eastern Alberta and Saskatchewan extending southeast into eastern Montana and the western Dakotas (Figure 8b). The average 1000hPa air temperature is 12°C at the center of high pressure where the long-lived PPTAs occur. Over the west-central United States, air temperature of westerly flow is often considerably warmer than surface temperature in place. The westerly flow originates over the relatively warmer waters of the Pacific Ocean, and is modified as it crosses two western mountain ranges, the Cascade Range and the Rockies further east. Modified maritime polar air sharply contrasts with cold, dry continental polar air masses of Canadian origin that often dominate conditions east of the mountains and the continental divide. Downslope adiabatic warming contributes to the WAA pattern. Any existing snow cover in the region could also result in colder surface temperatures, enhanced by the

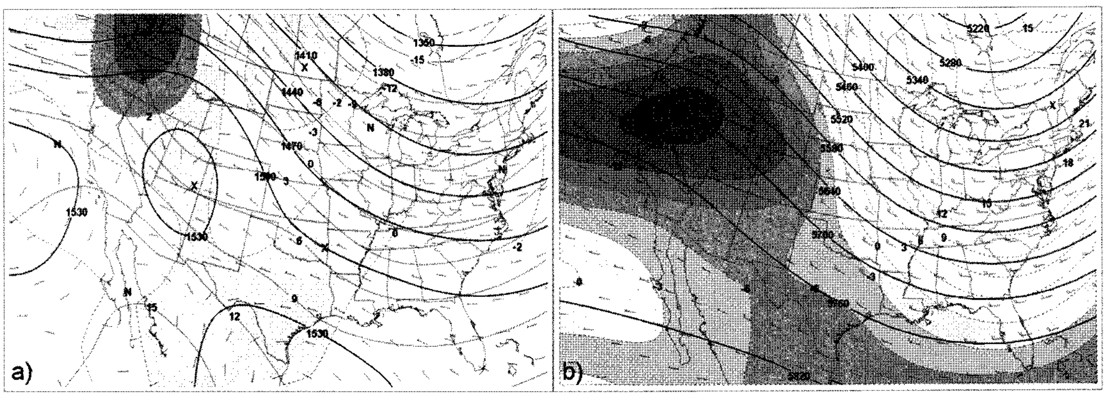

Figure 9. a) Composite of 850hPa thermal advection (x10^{-1}°C day^{-1}, dashed lines; shaded represents warm air advection), heights (gpm, solid lines), air temperature (°C) and wind (m·s^{-1}) for the six longest winter PPTAs. b) Composite of 500hPa vorticity advection (x10^{-5}·s^{-1}, dashed lines; shaded is negative vorticity), heights (gpm, solid lines), and winds (m·s^{-1}) for the six longest winter PPTAs

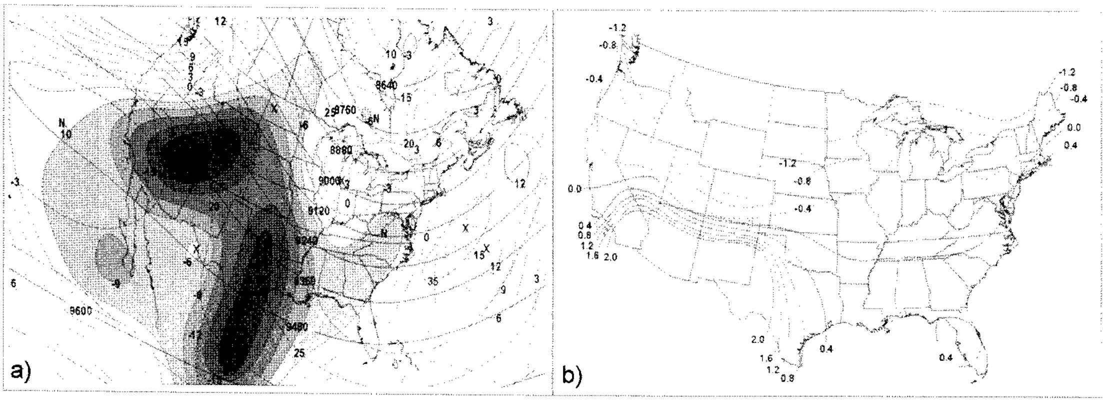

Figure 10. a) Composite of 300hPa divergence ($\times 10^{-6}$ day^{-1}, dashed lines; shaded represents convergence), height (gpm, solid lines), and isotachs ($m \cdot s^{-1}$) for the six longest winter PPTAs. b) Composite of Bowen ratio for the six longest winter PPTAs

effect of continentality, elevation and limited amounts of insolation in winter. The importance of warm advection in winter PPTAs is quite significant. In much the same manner, WAA also occurs upstream of the ridge axis along anticyclonic flow from the eastern Pacific Ocean in the 850hPa geopotential height field (Figure 9a). The average 850hPa air temperature amounts to 6°C at the center of PPTAs.

The mid-level composite of 500hPa vorticity for winter PPTAs is characterized by atmospheric stability that coincides with negative vorticity advection (Figure 9b). Subsidence is found downstream of the ridge axis at the 500hPa level. An examination of the composite 300hPa divergence field shows that strong convergence is found at the center of winter PPTAs (Figure 10a). This convergence provides sufficient mechanical momentum to trigger atmospheric subsidence and consequently initiate abnormally high surface temperatures.

Bowen ratios greater than 1.0 during winter PPTAs retreat to the deep southwest as seasons progress from summer to winter (Figure 10b). In this region, there is sufficient energy to evaporate surface moisture and maintain a dry surface in winter. This pattern is substantially different from that of summer PPTAs. Unlike dry surface conditions during summer PPTAs that increase surface temperature and intensify PPTAs, surface conditions are not favorable for the formation of winter PPTAs because the absolute flux of sensible heat from the surface is greatly diminished by cooler winter conditions. During long-lived winter PPTAs episodes, at best, Bowen ratios in this region amount to 1.0.

In winter, warm air advection into regions that are normally cold, often associated with cyclonic activity, can often produce positive temperature anomalies over much of the United States.

However, since cold fronts immediately follow cyclonic warm air advection, long-lived winter PPTAs do not occur. Warm air advection from a Föehn event may help intensify PPTAs in some regions in winter, but it is not likely that they are the main causal factor. In California, when high pressure is located over the Great Basin region, anticyclonic "offshore flow" carries hot, dry air from the California deserts west toward coastal regions. Westerlies on the leeward side of the eastern Rocky Mountains also induce positive temperature anomalies with warm air advection generated by adiabatic heating. Föehn-induced warm air advection may help intensify PPTAs in both summer and winter. In this regard, the degree of intensification needs to be determined in future studies.

In summary, long-lived winter PPTAs are characterized by synoptic environments including positive PNA type mid to upper-level flow patterns, intense adiabatic heating, warm air advection from the southwest and lower Bowen ratios than in summer. Compared to summer PPTAs, warm air advection plays a significant role in developing winter PPTAs. In particular, when warm air advection is combined with other synoptic mechanisms favorable for winter PPTAs, synergistic warming effects from advected warm air and adiabatic heating under an upper-level anticyclone often result in significant winter PPTAs in the western United States.

4. Summary and Conclusion

This study determines the prevailing synoptic-scale mechanisms favorable for long-lived summer PPTAs as well as winter PPTAs in the United States. The formation of both winter and summer PPTAs is closely related to the movement of subtropical high pressure systems in the Pacific and Atlantic Oceans. It also appears that these anticyclones shift the direction of the westerlies and transport warm air into affected geographic locations.

An idealized synoptic pattern favorable for long-lived summer PPTAs is warm air masses driven by southerly flow and/or upper-level ridges formed by stagnant blocking and surface high pressure. Summer PPTAs are usually located downstream from the upper-level ridge axis, where subsiding vertical motion is typically found. The occurrence of this unusual string of large-scale surface temperature anomalies usually coincides with an extremely stable atmosphere caused by persistent blocking by mid- to upper-tropospheric anticyclones operating at a continental scale. Long-lived winter PPTAs occur over the west-central to southwestern United States centered on Nevada and Arizona. Winter PPTAs develop under somewhat different synoptic conditions from those for summer. The formation of an anticyclonic blocking system associated with a large positive PNA pattern is a typically favored synoptic conditions for long-lived winter PPTAs. With the development of an anomalously strong ridge, warm air advection directed into the western United States from the California coast appears to be a significant mechanism to maintain these winter PPTAs. Southwesterly winds prevail over the northwestern United States while westerly winds are dominant over the north-central United States. Synergistic warming processes caused by advected warm air and adiabatic heating develop the long-lived winter PPTAs. However, surface forcing mechanisms (a shrinking Bowen ratio) may not be as significant as the synoptic pattern. It is possibly because insolation is not sufficient in winter to cause excessive sensible heat flux from the surface. In addition, winter PPTAs happen only if upper-level flow patterns persist long enough to lead to extensive surface heating.

This study provides a better understanding of the synoptic patterns which develop PPTA events in both summer and winter in the United States. Thus, these analyses are potentially useful in identifying the climatic dynamics of PPTAs. Further research is recommended to explore interrelationships between the development of PPTAs and teleconnection indices, as well as to forecast the emergence of potentially extreme PPTAs.

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