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A Climatology of Cold Air Outbreaks in Montana

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1. INTRODUCTION

Cold air outbreaks (CAOs), the sudden equatorward movement of cold air masses from high latitudes, commonly occur east of the Rocky Mountains in North America during the winter (DJF) season. Some of these CAOs have been cited for loss of human life (e.g., Changnon 1979) as well as significant economic losses (e.g., Kunkel et al. 1999). Among other states, CAOs impact Montana during each winter, where they present a forecast challenge to the National Weather Service Weather Forecast Offices (WFOs).

Synoptic-scale features that have been regularly observed with CAOs include rapid surface anticyclogenesis prior to the onset of an outbreak (e.g., Colucci and Davenport 1987) and near-surface cyclogenesis following the onset of an outbreak (e.g., Konrad and Colucci 1989). Some previous studies suggest that the frequency of CAO occurrences in portions of North America is well-correlated to modes of global teleconnection patterns, such as the Arctic Oscillation (AO) pattern (Thompson and Wallace 2001) and the Pacific North American (PNA) pattern (Rogers and Rohli 1991). Specifically, the positive phase of the PNA pattern is well-correlated with CAOs occurring at a relatively high frequency east of the Rocky Mountains. To establish the validity of this finding in Montana, a substantial goal of the present work is to develop a CAO climatology specifically for Montana.

Over a larger scale, Konrad (1996) developed a synoptic climatology of CAOs in North America based on synoptic-scale anomalies. His study suggests that forecast negative 500 hPa geopotential height, negative surface temperature, and positive surface pressure anomalies are well correlated to the occurrence of CAOs up to the day-4 forecast period.

Portis et al. (2006) identified the 30 strongest 5-day CAOs for a handful of locations in the central and southeast United States during the period 1948-2001. The top 30 CAOs from the Portis et al. study correspond to the 30 coldest 5-day mean temperatures throughout the period of record used, but were not necessarily linked to any synoptic-scale features present. Based on available literature, there appears to be no consensus concerning the method of objectively identifying and characterizing CAOs.

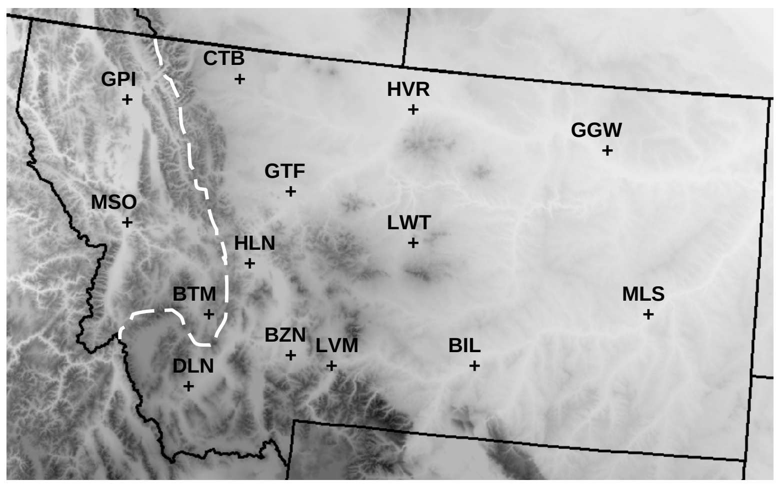

Figure 1. Montana physiographic features and ASOS sites. Terrain elevation ranges from roughly 550m (lightest shading) to 3900m (darkest shading). White dashed line represents approximate location of the Continental Divide.

Arising from the challenge of forecasting CAOs, the present study examines CAOs that have occurred in Montana using historical surface temperature data. The relationship between CAO occurrence during a 34-year period and composites of synoptic-scale features, as well as modes of the PNA pattern, is established here as well.

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2. DATA AND METHODOLOGY

Winter CAOs have been identified during the period 1973-2007 using hourly and daily temperature records from the 14 Automated Surface Observation Sensor (ASOS) sites in Montana (Fig. 1). Hourly surface temperature data were gathered from the National Climatic Data Center (NCDC) Global Integrated Surface Hourly database (DS-3505), while daily surface temperature data were obtained through the local XMClimate application in the Advanced Weather Interactive Processing System (AWIPS) at WFO Great Falls, MT. The entire Butte (BTM) hourly temperature and portions of the Dillon (DLN) hourly and daily temperature (1991-1996) datasets have been omitted from this study due to missing records. Hourly winter CAO identification has been presented here in terms of percentage of all available observations in order to account for occasionally missing hourly observations. Historical monthly-averaged teleconnection indices for the study period were obtained from the NOAA Climate Prediction Center (CPC). NCEP Global Reanalysis (Kalnay et al. 1996) composite data have been provided by the NOAA Earth System Research Laboratory (ESRL) Physical Sciences Division (PSD).

The sensitivity of Montana winter CAO occurrence to surface temperature criteria of 0° F (-17.8° C) or less, -10° F (-23.3° C) or less, and -20° F (-28.9° C) or less have been evaluated here (0 degree, -10 degree, and -20 degree CAOs respectively hereafter). Hence, no attempt has been made to distinguish surface temperatures that were at or below CAO thresholds due to local effects, such as cold pool buildup within valleys, from those due to synoptic scale features present. During much of winter, these temperature constraints are at least one standard deviation below the daily NCDC 1971-2000 average low temperature for the ASOS sites used in this study. The year of a given winter corresponds to the year that climatological winter began.

3. CAO CLIMATOLOGY

The annual number of winter days and percent of winter hours where the surface temperature CAO criterion were met varied greatly among Montana ASOS sites on an annual basis (Figs 2 and 3). At Glasgow (GGW), for example, the number of winter days with 0 degree CAOs ranged from 5 in 1986 to 67 in 1978 while percent of winter hours with 0 degree CAOs ranged from 2% in 1986 and 1991 to 43% in 1978. In contrast, the number of winter days with 0 degree CAOs at Livingston (LVM) varied between 0 in 1999 and 20 in 1983. However, the occurrence of 0 degree CAOs at LVM reached a maximum of roughly 16% of winter hours in 1978 and a minimum of 0% of winter hours in both 1991 and 1999.

Winter CAO occurrence varied greatly over short distances in some cases. For example, LVM and Bozeman (BZN), located approximately 55km apart, had very dissimilar numbers of CAO days during each winter. During winter 2000, 0 degree CAOs occurred on 36 days at BZN and only 5 days at LVM. Similarly during winter 1978, -20 degree CAOs occurred on 17 days at BZN and only 2 days at LVM. On the other hand, both BZN and LVM recorded only 2 days when -10 degree CAOs occurred during winter 1993.

Winter CAO occurrence varied greatly between ASOS sites west and east of the Continental Divide as well. For example, Missoula (MSO) and Kalispell (GPI), located west of the Continental Divide, had far fewer winter days and lower percentages of winter hours meeting any of the three CAO criteria annually than practically all ASOS sites east of the Continental Divide. Despite BTM and BZN being located on opposite sides of the Continental Divide (roughly 105km apart), both ASOS sites recorded a similar number of CAO days during each winter. Cut Bank (CTB) and GPI are also located on opposite sides of the Continental Divide (142km apart), however compared to GPI, 0 degree CAOs were present at CTB during nearly twice as many winter days and four times as many hours throughout the period of record.

4. CAO SALIENT FEATURES AND TELECONNECTIONS

The monthly PNA pattern is well correlated with salient weather features present in Montana during all winters 1973-2006. A strong relationship exists between the mean winter 500 hPa geopotential height pattern and the PNA pattern, with positive correlation coefficients ranging from roughly 0.55 in extreme southeast Montana to 0.75 in extreme north central Montana (Fig. 4). A somewhat weaker, positive relationship exists between surface air temperature and the PNA pattern during the period of study as well, with correlation coefficients ranging from 0.45 in eastern Montana to 0.55 in western Montana (Fig. 5).

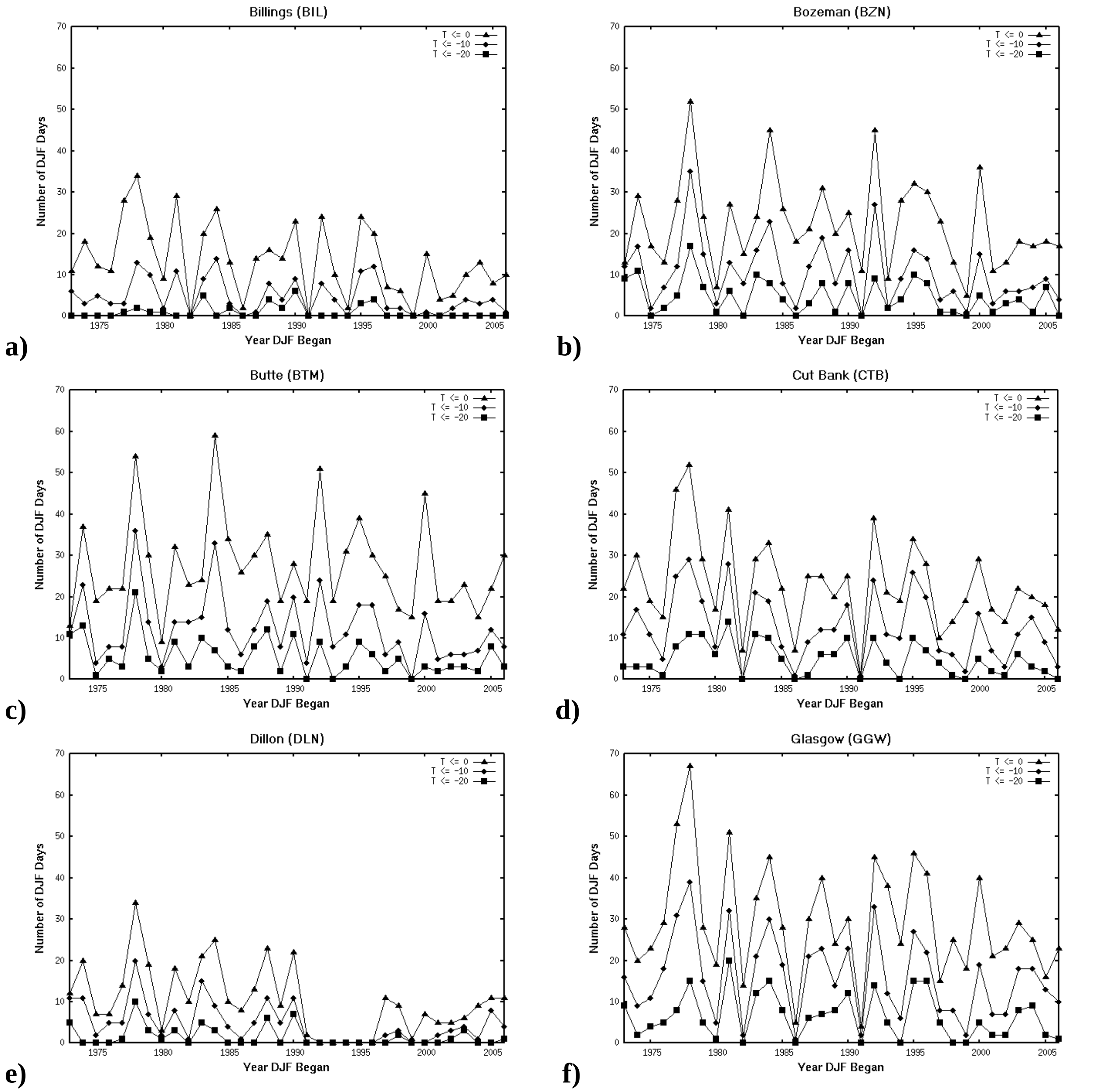
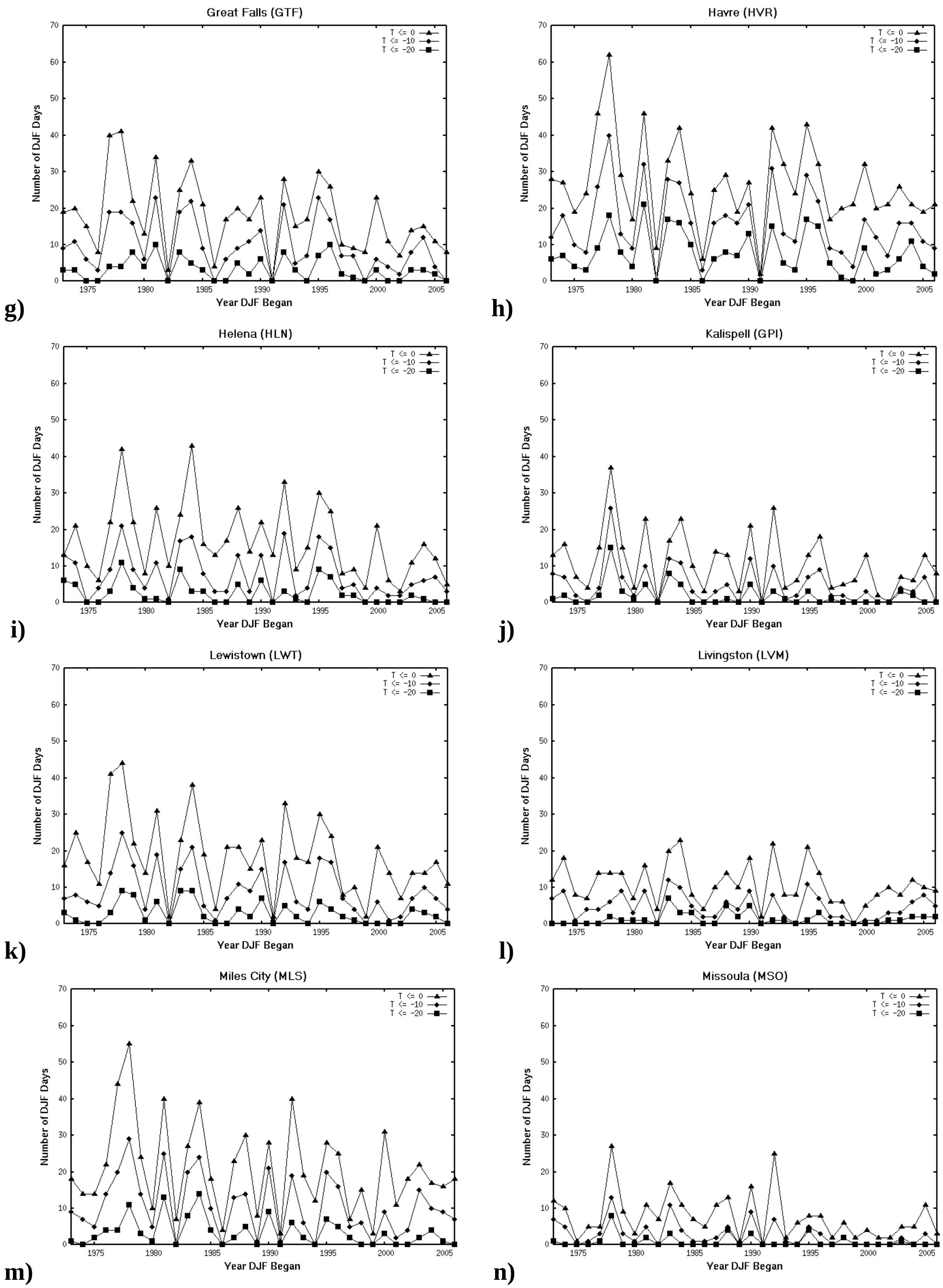


Figure 2. Number of days per winter (1973-2006) when 0 degree CAOs (triangles; top line), -10 degree CAOs (diamonds; middle line), and -20 degree CAOs (squares; bottom line) were observed at (a) Billings, (b) Bozeman, (c) Butte, (d) Cut Bank, (e) Dillon, (f) Glasgow, (g) Great Falls, (h) Havre, (i) Helena, (j) Kalispell, (k) Lewistown, (l) Livingston, (m) Miles City, and (n) Missoula ASOS sites.



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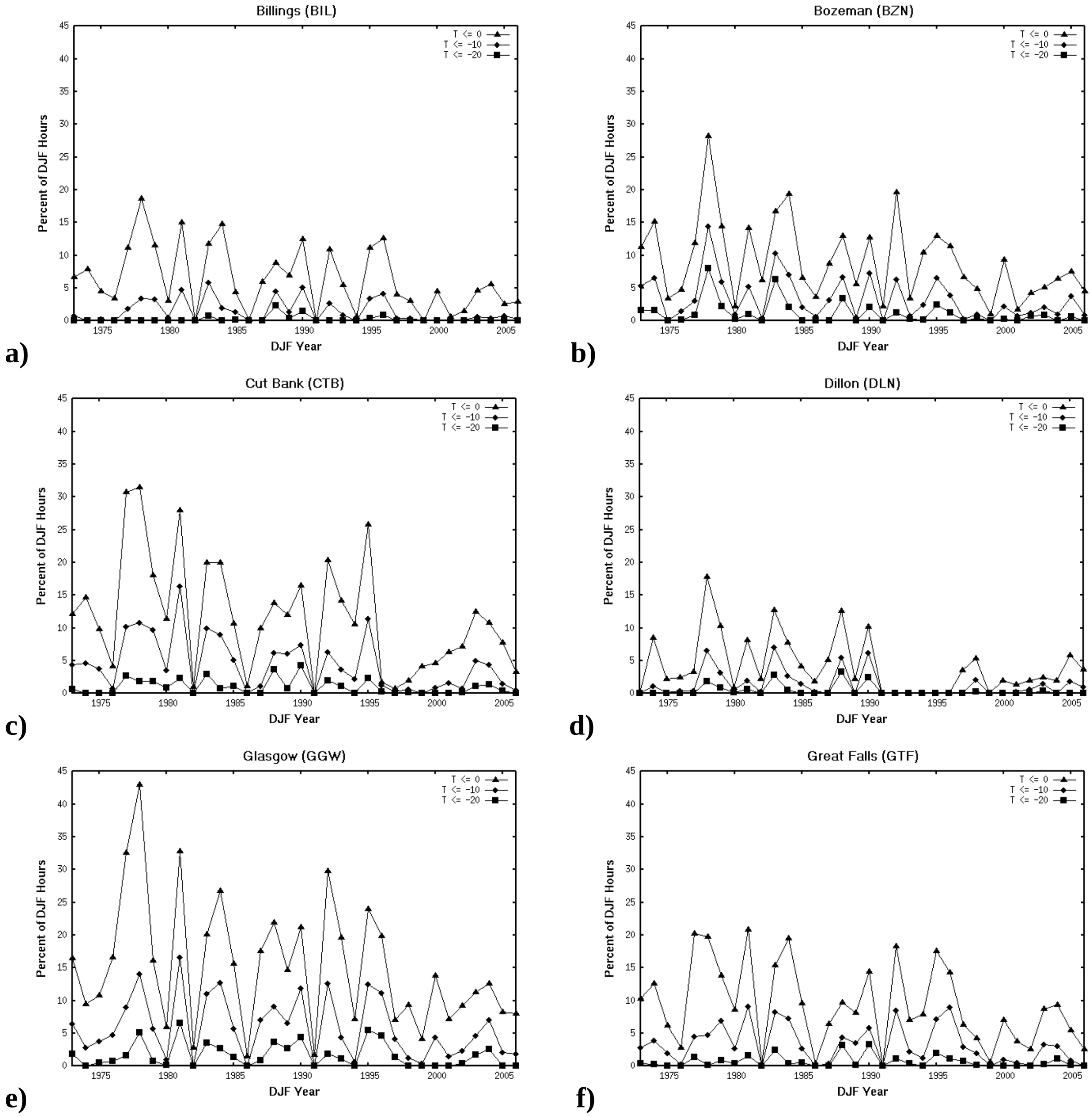
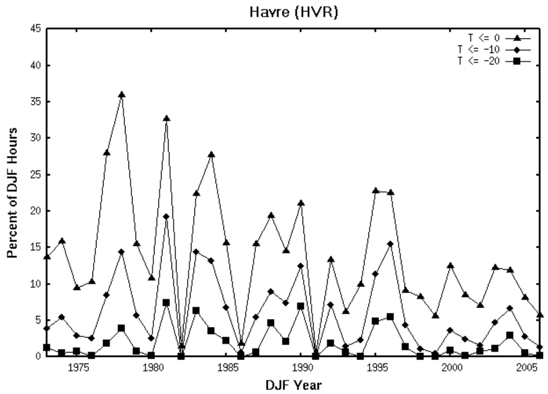


Figure 3. Same as Fig. 2 except for percent of winter hours at (a) Billings, (b) Bozeman, (c) Cut Bank, (d) Dillon, (e) Glasgow, (f) Great Falls, (g) Havre, (h) Helena, (i) Kalispell, (j) Lewistown, (k) Livingston, (l) Miles City, and (m) Missoula ASOS sites.



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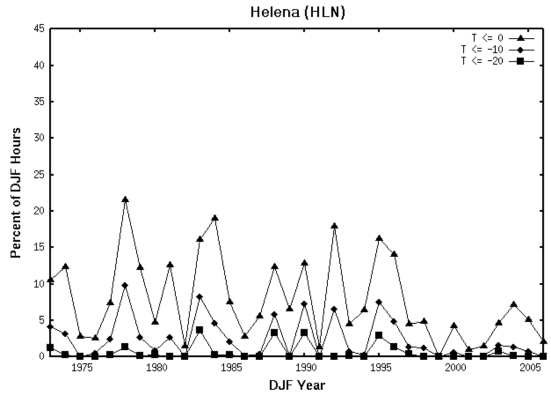

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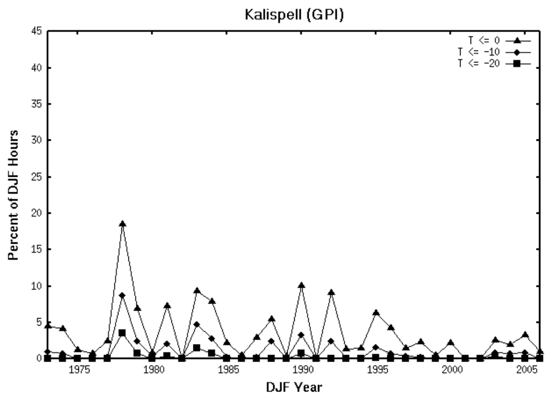

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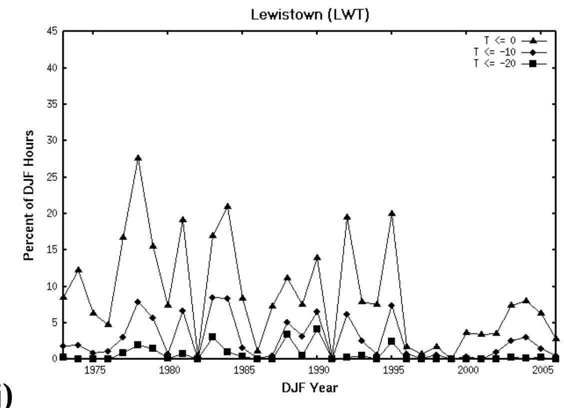

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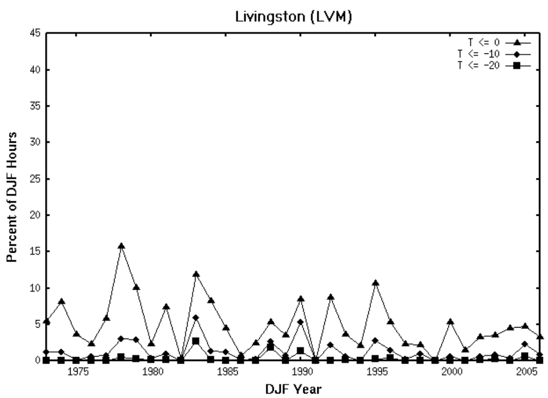

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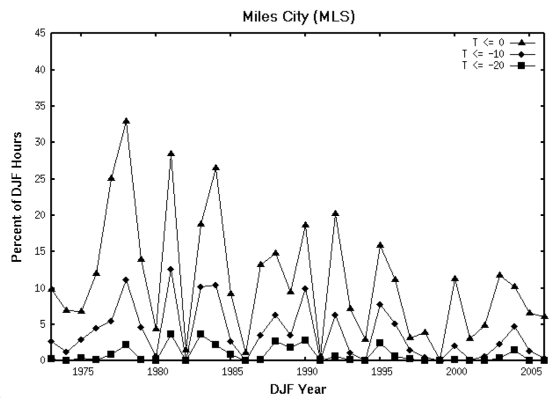

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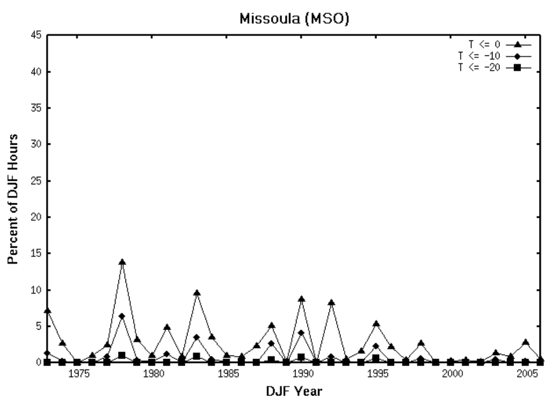

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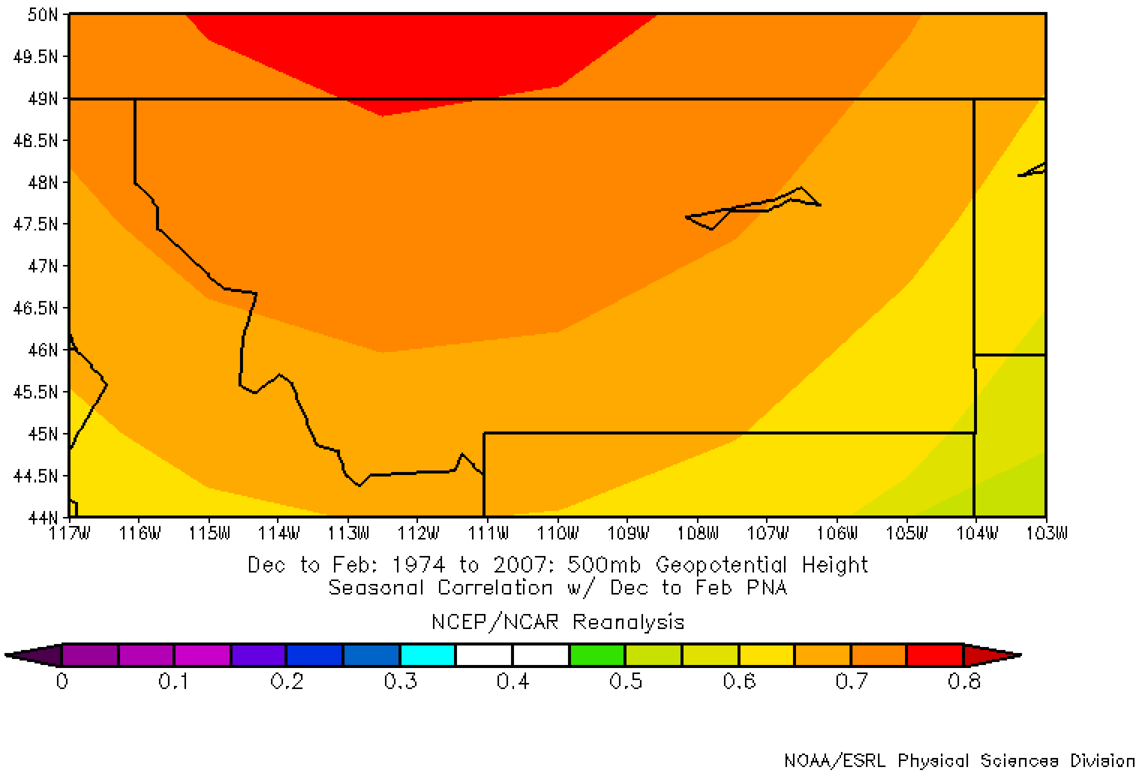

Figure 4. Correlation of 500 hPa geopotential height to the PNA index for all winters 1973-2006 (courtesy NOAA/ESRL/PSD).

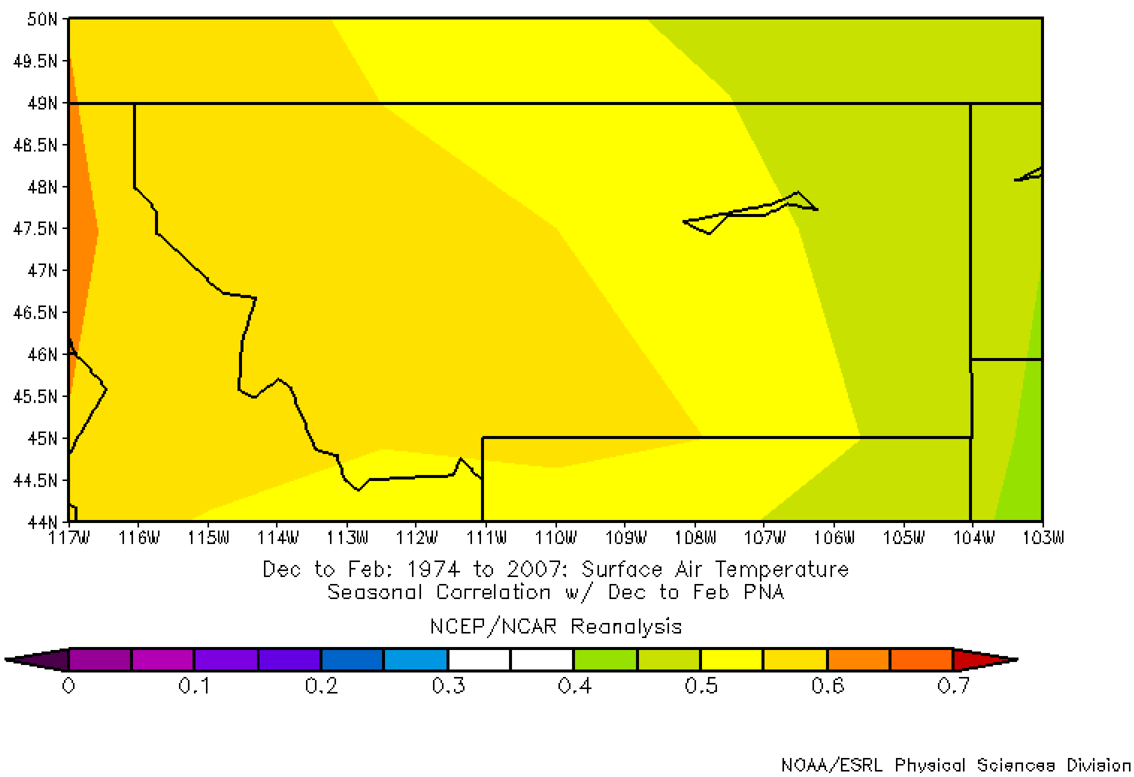

Figure 5. Correlation of surface air temperature to the PNA index for all winters 1973-2006 (courtesy NOAA/ESRL/PSD).

There is a low correlation between the monthly number of winter days when 0 degree, -10 degree, and -20 degree CAOs were present at the 14 ASOS sites and the monthly PNA index (Table 1). Correlation coefficients here are negative, ranging from -0.10 at BTM for days when 0 degree CAOs were present to -0.40 at CTB for days when either -10 or -20 degree CAOs were present.

At some ASOS sites, the strength of negative correlations between the monthly number of winter 0 degree, -10 degree, and -20 degree CAO days and the monthly PNA index vary greatly. At BTM, for example, the monthly PNA index is more negatively correlated to the monthly number of winter -20 degree CAO days (-0.31) than to the monthly number of winter 0 degree CAO days (-0.10). Based on Table 1, the average negative correlation of the monthly PNA index to the monthly number of days when CAOs are present, when considering all ASOS sites, is strongest for -10 degree CAOs. However, even the highest correlation coefficient between -10 degree CAOs and the PNA index is relatively low and may not be considered skillful if applied to forecasting the number of winter CAOs based on forecast PNA phase.

ASOS site	0 deg CAO (r)	-10 deg CAO (r)	-20 deg CAO (r)
BIL	-0.35	-0.36	-0.20
BZN	-0.17	-0.29	-0.34
BTM	-0.10	-0.24	-0.31
CTB	-0.38	-0.40	-0.40
DLN	-0.24	-0.29	-0.26
GGW	-0.34	-0.27	-0.27
GTF	-0.35	-0.37	-0.34
HVR	-0.35	-0.36	-0.33
HLN	-0.30	-0.34	-0.29
GPI	-0.36	-0.35	-0.30
LWT	-0.34	-0.36	-0.31
LVM	-0.31	-0.32	-0.22
MLS	-0.30	-0.24	-0.23
MSO	-0.27	-0.31	-0.26

Table 1. Correlation coefficients for all Montana ASOS sites when comparing the monthly number of 0, -10, and -20 degree CAO days to the monthly PNA index for all winters 1973-2006.

5. CONCLUSIONS

This study of winter CAOs in Montana was motivated by the forecast challenges and related weather hazards that are associated with CAO occurrences. While the objective method used here for identifying winter CAOs at the surface over monthly and seasonal timescales is limited by contamination from local effects at some ASOS sites (e.g., basin cold pool buildup), the historical frequency of temperatures at or below the CAO criterion used is valuable for characterizing the winter-to-winter temperature variability in Montana.

Basin cold pool development at some ASOS sites (e.g., BZN) appears to inflate the number of days and percent of hours when 0 degree, -10 degree, and -20 degree CAOs were present during winter. However, MSO and GPI, both located in valleys west of the Continental Divide, had much fewer CAOs throughout the study period than all other valley locations on either side of the Continental Divide. A weak positive correlation (0.35) was found between the annual number of winter days with 0 degree CAOs at CTB and GPI (not shown). Hence, the frequency of winter CAOs occurring west of the Continental Divide was not necessarily sensitive to the frequency of winter CAOs occurring east of the Continental Divide.

It is evident that the timescales at which CAOs occur, including the number of days that CAOs are present, are much less than what can be characterized using monthly intervals. A cursory investigation of monthly winter 500 hPa geopotential height anomalies during the study period revealed that negative (positive) height anomalies were present during years with the highest (lowest) number of days with CAOs. However, previous case studies have shown that CAOs can occur even in the absence of a negative upper level geopotential height anomaly (e.g., Hartjenstein and Bleck 1991). Despite being well-correlated with 500 hPa geopotential height and surface temperatures throughout an entire winter, the PNA index appears to be of little use when applied to forecasting winter CAO occurrence in Montana.

6. ACKNOWLEDGEMENTS

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