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ORIGINAL PAPER

Synoptic climatology of the long-distance dispersal of white pine blister rust. I. Development of an upper level synoptic classification

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Abstract This study developed a methodology to temporally classify large scale, upper level atmospheric conditions over North America, utilizing a newly-developed upper level synoptic classification (ULSC). Four meteorological variables: geopotential height, specific humidity, and u- and v-wind components, at the 500 hPa level over North America were obtained from the NCEP/NCAR Reanalysis Project dataset for the period 1965–1974. These data were subjected to principal components analysis to standardize and reduce the dataset, and then an average linkage clustering algorithm identified groups of observations with similar flow patterns. The procedure yielded 16 clusters. These flow patterns identified by the ULSC typify all patterns expected to be observed over the study area. Additionally, the resulting cluster calendar for the period 1965–1974 showed that the clusters are generally temporally continuous. Subsequent classification of additional observations through a z-score method produced acceptable results, indicating that additional observations may easily be incorporated into the ULSC calendar. The ULSC calendar of synoptic conditions can be used to identify situations that lead to periods of extreme weather, i.e., heat waves, flooding and droughts, and to explore long-distance dispersal of airborne particles and biota across North America.

Keywords Synoptic · Indexing · Classification · North America · Upper atmosphere

Introduction

Synoptic climatology presents a holistic view of the climate system rather than focusing on the individual elements or variables that combine to make up the system. This perspective is especially applicable to investigation of how biological systems interact with the climate system because organisms do not respond to changes in single weather variables; rather, they respond to the combination of variables working simultaneously to make up the overall climate condition (Kalkstein et al. 1996). Classification is often employed in synoptic climatological analyses because it provides a simple way to summarize the combinations of variables working together at a given time. Indexing emphasizes the differences between meteorological events that are useful to solve environmental problems and facilitates identification of periods of similar conditions. This study outlines the development of an upper level synoptic classification (ULSC), a system that categorizes upper level flow patterns across North America in order to investigate the dispersal of airborne pathogens and aerosols.

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Synoptic climate indices

A synoptic climate index classifies overall weather conditions into groups with minimal within group variance and maximal between group variance (Balling 1984). Consequently, a synoptic classification attempts to accentuate meteorological differences among categories. Indexing should also minimize the differences within each class. Yarnal (1993) identifies two major types of classification methods: manual and automated. In general, manual classification methods entail knowledge-based visual interpretation of individual weather maps. These classification schemes are subjective, time and labor intensive, and generally not repeatable (Sheridan 2002). Applications of manual classification schemes include forecasting (Elliott 1949), mesoscale modeling (Pielke and Segal 1986), environmental analysis, such as variation in pollution concentrations (Davies et al. 1986; Muller and Jackson 1985), and bioclimatological investigations (Muller 1985).

Automated classification schemes employ statistical algorithms, so they are generally fast to construct and easily replicated. Barry and Perry (2001) further identify two approaches for automated classification: correlation-based methods and component extraction methods combined with clustering algorithms. A major shortcoming of correlation-based methods, such as those of Lund (1963) and Kirchofer (1974), is that they frequently do not classify all observations analyzed. There is very little subjective analysis in correlation-based methods; that is, the judgement of the analyst is not considered necessary. Conversely, component extraction combined with clustering, employed in this study, introduces some subjectivity through the selection of variables. “Conceptually [the variables selected for analysis] should represent the radiatively, thermodynamically, and advectively determined components of local weather in a parsimonious manner” (Barry and Perry 2001: p. 560). Thus, the analyst should choose only those variables thought to be important for the intended application.

Historically, development of automated synoptic indices using cluster analytic techniques began in the mid-1970s as computing capacity enabled researchers to employ computationally intensive algorithms on larger and larger datasets. Ayoade (1977), for example, performed a climate regionalization for Nigeria by applying several clustering algorithms to a data matrix of 10 meteorological variables from 32 stations.

Kalkstein and Corrigan (1986) developed the Temporal Synoptic Index (TSI), a calendar identifying days with similar overall surface conditions at a single location. The TSI did not account for upper level conditions, but they may be induced by changing the input data matrix. A more fundamental limitation was that, as a point index, TSI did not recognize the spatial continuity of air masses. Therefore, when the same clustering procedure was applied to proximate stations, the resulting clusters were less similar than desired. Thus, TSI applications were generally limited to single locations, and not for comparing multiple, adjacent points.

The Spatial Synoptic Index (Davis and Kalkstein 1990) expanded the TSI into a spatial index that was able to identify homogeneous synoptic categories within a large area. Although the Spatial Synoptic Index is spatially continuous, it is temporally discontinuous; that is, air masses are similar at nearby locations but, over time, air masses arise from no apparent source. This index has gone through two further iterations (Kalkstein et al. 1996; Sheridan 2002), and is now produced daily for over 400 stations in North America.

To account for both spatial and temporal continuity of synoptic conditions, Vose (1993) developed the Regional Synoptic Index (RSI). This index considered a matrix of six variables at seven stations across a region and classified the observations following the method of the TSI. The result was a temporal index with the synoptic categories expressed as regional maps. The applications of this method were limited because it only included surface variables, but the RSI showed the potential for maintaining spatial and temporal continuity within a classification.

Integration of upper level data to cluster-based synoptic indexing began with Webber’s (1994) Upper Air Synoptic Classification (UASC). The UASC applied the techniques of the TSI to gridded upper level observations across North America. Because of the massive size of the study area, only two variables (geopotential height and air temperature, observed once daily at 459 points and three levels) were included in the development of the UASC. This index demonstrated that the technique was applicable to large-scale upper air circulation. The applicability of the UASC was limited, however, because it produced excessively inclusive clusters. For example, the UASC resulted in only one summer cluster. Representation of all days in a season within a single cluster seriously restricted its utility in many environmental studies. This problem may be alleviated by increasing the number of clusters allowed by the algorithm, but the inclusion of only two variables for analysis may continue to restrict the viability of this classification.

Schreiber (1996) incorporated both surface and upper level data in the development of the Surface/Upper Level Synoptic Index (SULSI). This index employed the techniques of the TSI and considered four-times-daily surface observations of six variables and twice-daily observations of five variables at three heights aloft. A small study area in the desert of the southwestern U.S. allowed the incorporation of many variables but restricted the geographic extent to which it could be employed.

Previously developed cluster-based indexes have had limited applicability as a result of their spatial extent or due to the fact that they produced excessively inclusive clusters, likely as a result of the inclusion of too few variables. The ULSC presented here expands upon previous indexes in that it identifies similar upper level synoptic situations across all of North America based on more observations of more variables on a finer spatial resolution. For example, the ULSC improves upon the UASC (which considers only temperature at the pressure surface height) by additionally considering both humidity and wind at the pressure surface. This suggests that the ULSC will be applicable to the investigation of many more circulation-related questions than previous indexes.

Materials and methods

The development of the ULSC begins with four-times-daily data for 4 meteorological variables at the 500 hPa level available from the NCEP/NCAR Reanalysis Project dataset (Kalnay et al. 1996; NOAA-CIRES 2002). This dataset is generated from the application of mathematical data assimilation and forecasting models to historical weather data from numerous sources (UCAR 2003). The result is a global, gridded, four-times-daily dataset with a period of record beginning January 1, 1948. This dataset is especially useful for application to upper level synoptic indexing; it provides a much finer spatial resolution (2.5°) than raw radiosonde sounding data and is standardized to account for changes in observational techniques and missing observations.

To accommodate potential applications, the ULSC is developed for a large region and long period of record. The study region extends from 20°N to 60°N and 60°W to 140°W and includes all of the conterminous United States and much of Mexico and Canada (Fig. 1). The initial period of record considered is from 1965 to 1974. This period is determined by the necessity of applying the classification to identifying a specific event during the period when white pine blister rust may have dispersed to a distant location in the southwestern United States.

The data matrix used to determine the ULSC includes four variables observed at the 500 hPa level four times a day on a regular spatial grid (Table 1). The 500 hPa level is selected for this analysis because it is generally midway between the levels of divergence and non-divergence; this level is commonly thought of as representative of the steering circulation for surface systems. The variables representing conditions at the 500 hPa level are height of the pressure surface (m), specific humidity (kg/kg), u-wind component (m/s), and v-wind component (m/s). Air temperature is excluded from this analysis because it is highly correlated with the height of the 500 hPa surface. The spatial resolution of the original grid of 2.5° latitude by 2.5° longitude is reduced to 3.54° resolution by eliminating every other point; results show that this data reduction does not affect the outcome of the classification in a negative manner while rendering the dataset much more manageable.

Introduction of raw weather data to a clustering algorithm gives each variable presented to the algorithm equal weight. This is problematic if the variables introduced have different units or if any of them are collinear, i.e., air temperature and dew point temperature. To avoid these

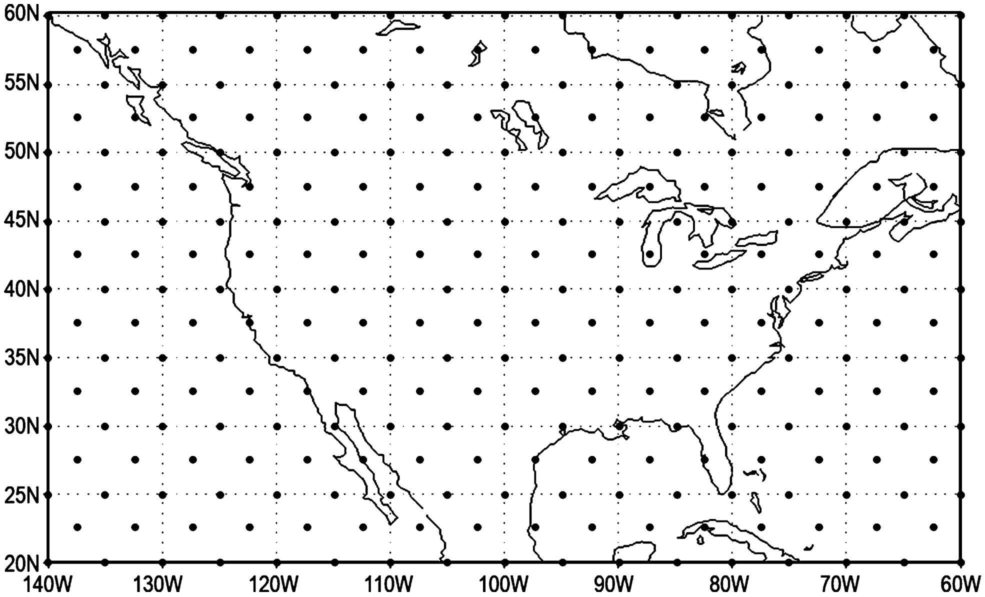


Fig. 1 The study area extends from 20°N to 60°N and 60°W to 140°W to include all of the conterminous United States and much of northern Mexico and southern Canada. Dots indicate points from which data were sampled for analysis

Table 1 Format of the 500 hPa data matrix input to the PCA and cluster algorithms to develop the upper level synoptic classification

	60°N, 140°W				→ 20°N, 60°W			
	0000Z z q u v	0600Z z q u v	1200Z z q u v	1800Z z q u v	0000Z z q u v	0600Z z q u v	1200Z z q u v	1800Z z q u v
1 Jan 1965								
2 Jan 1965		z = geopotential height						
3 Jan 1965		q = specific humidity						
↓		u = east-west wind component						
30 Dec 1974		v = north-south wind component						
31 Dec 1974								

problems, principal components analysis (PCA) with a varimax rotation, selected to maximize the variance of the loadings, is applied to the dataset before the clustering procedure begins. The 87 components with variance greater than 1.0 are retained for input to the clustering algorithm (Kaiser 1960). These components explain 96.6% of the variance within the original dataset. The first two components load most heavily on geopotential height in the northwest corner of the study area and explain over 32% of the variance in the dataset. The third and fourth components have heavier loadings on the wind and humidity variables and are more strongly associated with values from the central part of the study area. The first five components explain over half of the variance in the original data.

The components are then subjected to an average linkage clustering algorithm (Sokal and Michener 1958). Kalkstein et al. (1987) report this clustering method to be most appropriate for environmental analyses. Eleven main clusters resulted from the input of the components to the clustering algorithm. In an effort to identify potentially important within-cluster variations that could be present in clusters containing a large number of observations, any cluster that contained more than 20% of the total observations is then resubmitted to the procedure to yield a set of “nested” clusters. A total of 16 clusters are identified (Table 2). For illustrative purposes, a sum of squared z-scores method is used to identify the observation most similar to the cluster mean. The 500 hPa height contours for these observations were plotted using the Grid Analysis and Display System (GrADS) (IGES ND) by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov (Figs. 2, 4, and 5).

Results

As is expected for upper level flow patterns, examination of the resulting cluster calendar for the period 1965–1974 shows that the clusters are generally temporally continuous. Nearly 55% of all observations over the 10-year period are preceded by an observation in the same cluster. Only the three least frequently occurring clusters are not most often preceded by themselves (Table 3).

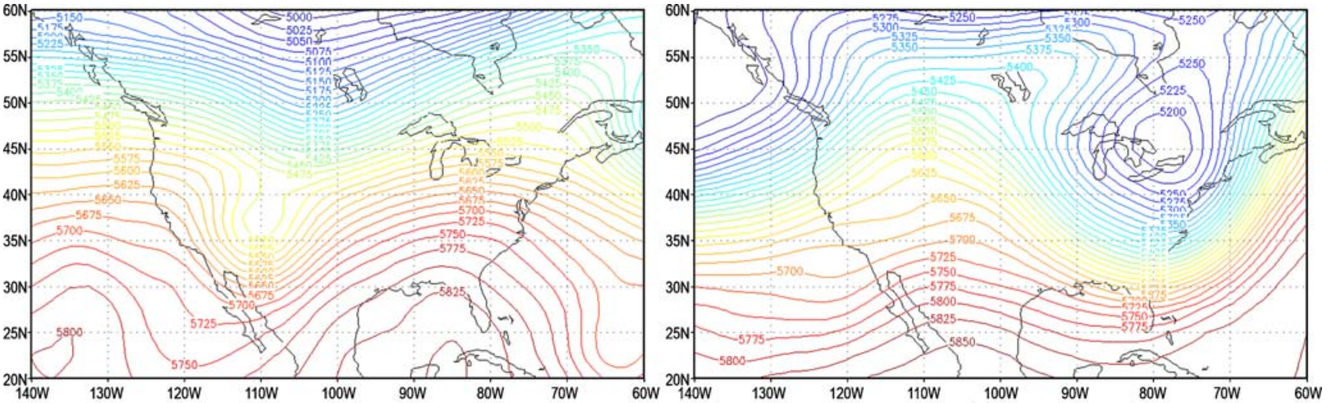
Winter clusters

Six clusters occur predominantly in the winter months (December, January, February) (Figs. 2, 3a). Winter clusters, as expected, are generally characterized by lower

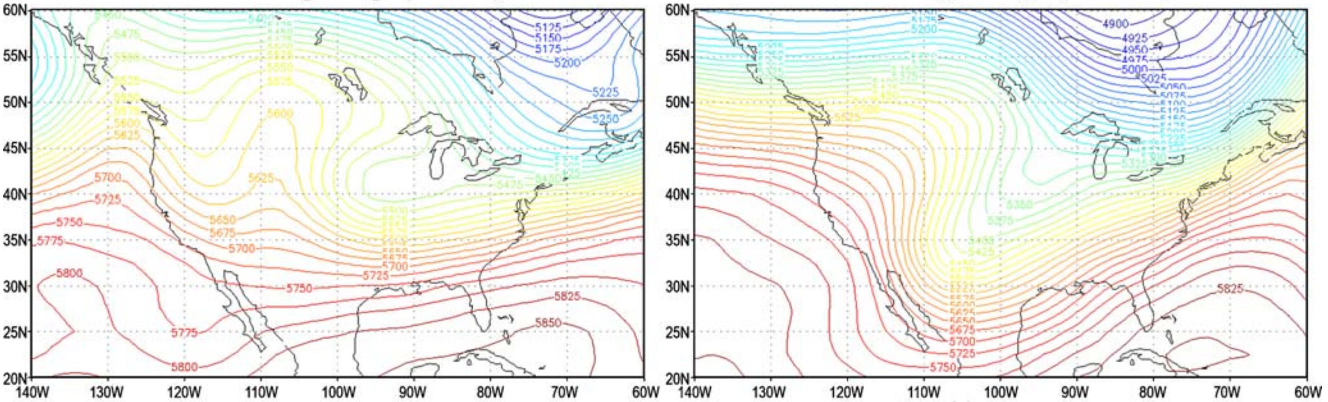
Table 2 Characteristics of the 16 clusters identified by the upper level synoptic classification

Cluster number	Description (west to east)	Season	Frequency (%)
1	Trough-Ridge	Winter	10.31
2[a]			33.58
2.1	Trough-Ridge	Summer	15.22
2.2	Trough	Summer	13.01
2.3	Trough-Ridge-Trough	Summer	4.69
2.4	Ridge-Trough	Transition	0.66
3[a]			21.25
3.1	Trough-Ridge	Transition	11.19
3.2	Ridge-Trough	Winter	4.57
3.3	Ridge-Trough (high amplitude)	Transition	5.49
4	Zonal-Warm	Winter	14.23
5	Zonal	Summer	11.28
6	Trough-Ridge-Trough (northerly displacement)	Summer	6.59
7	Inclined Trough	Winter	1.82
8	Zonal-Cool	Winter	0.53
9	Trough-Ridge-Trough (high amplitude)	Summer	0.31
10	Trough-Ridge-Trough (high amplitude)	Summer	0.05
11	Ridge-Trough (northerly displacement)	Winter	0.04

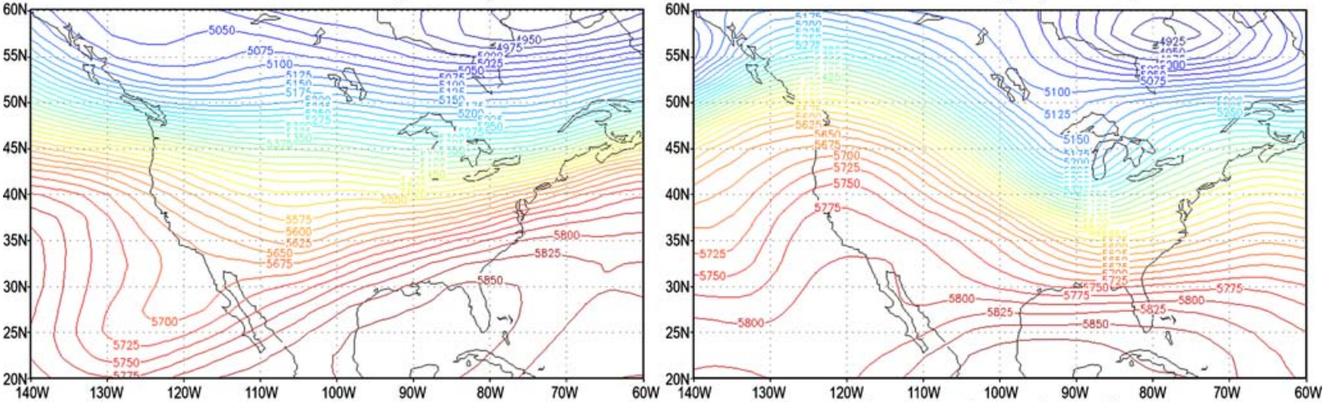
[a] Subclusters are denoted by the parent cluster number followed by an additional digit identifying the subcluster.



Winter-Trough-Ridge (cluster 1) Winter-Ridge-Trough (cluster 3.2)



Winter-Zonal-Warm (cluster 4) Inclined Trough (cluster 7)



Winter-Zonal-Cool (cluster 8) Winter-Ridge-Trough (northerly displacement) (cluster 11)

Fig. 2 Upper level flow patterns that occur predominantly in winter. (Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their web site at http://www.cdc.noaa.gov/)

500 hPa heights in the northern part of the study region with these low heights extending considerably south under some situations. The winter clusters generally exhibit more zonal flow than any other season, although meridional flow is represented by some clusters. Almost one-third of all observations fall in clusters with winter frequency maxima.

Observations falling in cluster 1 (Winter-Trough-Ridge) are associated with a trough in the western United States and a ridge in the eastern United States. Flow across the southern part of the study region is somewhat meridional, but more zonal conditions prevail in the north. This cluster is characterized by a trough in the western United States, a ridge over the eastern United States and a slight ridge off the west coast. It generally exhibits a fairly steep height gradient. This pattern occurs most frequently in December and January although it is observed in all months of the year.

Conversely, Cluster 3.2 (Winter-Ridge-Trough) observations denote a ridge in the west and a trough in the eastern United States. In this case, lower 500 hPa heights are

Table 3 Continuity for 16 upper level synoptic classification clusters

Cluster	1st most frequently preceding cluster (percent this cluster precedes)	2nd most frequently preceding cluster (percent this cluster precedes)
1	1 (61.3%)	4 (25.3%)
2.1	2.1 (48.3%)	5 (13.5%)
2.2	2.2 (52.9%)	2.1 (10.9%)
2.3	2.3 (45.4%)	2.1 (21.6%)
2.4	2.4 (43.8%)	2.2 (20.8%)
3.1	3.1 (39.6%)	4 (20.2%)
3.2	3.2 (39.2%)	4 (20.2%)
3.3	3.3 (38.5%)	4 (16.3%)
4	4 (47.6%)	1 (17.8%)
5	5 (42.6%)	2.2 (17.2%)
6	6 (57.4%)	5 (30.8%)
7	7 (45.9%)	1 (44.7%)
8	8 (59.0%)	7 (23.1%)
9	6 (64.4%)	9 (26.7%)
10	6/9 (37.5%)	10 (25.0%)
11	8 (83.3%)	11 (16.7%)

observed much farther south and the zone of steepest height gradient is much more pronounced and encompasses nearly the entire study area. This cluster exhibits the strongest height gradient of all clusters. Winter-Ridge-Trough patterns occur in all months but are most frequent in January, February and March.

Observations with Winter-Zonal-Warm flow are identified in cluster 4. Two low-amplitude features are present in the northern part of the study area—a ridge in the west and a trough in the east. The degree of slope of the 500 hPa level is less under this situation than in cluster 1 or 3.2 and heights are the highest of all winter maximum clusters indicating warmer temperatures. Cluster 4 occurs most frequently in December, but it is more frequent in the summer and transition months than any other cluster with a winter frequency maximum.

Cluster 7 (Inclined Trough) portrays a trough oriented northeast to southwest across the central United States. Cluster 7 shows the strongest meridional flow of the winter clusters (particularly in the West) with the trough axis along a line from the Great Lakes to Baja California. This cluster displays similar height gradients to other clusters with winter maxima. This condition occurs less than 2% of the time and is observed most often in January. Cluster 7 does not occur between May and September.

A particularly zonal upper level pattern is identified by cluster 8 (Winter-Zonal-Cool). These observations display lower 500 hPa heights farther south (indicating cooler conditions) and a stronger height gradient than those observations classed as Winter-Zonal-Warm (Cluster 4). Winter-Zonal-Cool conditions are most frequent in January and are not observed at all between April and September.

Cluster 11 is similar to cluster 3.2 in that it is a Winter-Ridge-Trough pattern. A particularly strong ridge is evident over the western United States, accompanied by a trough in the southeast. However, the ridge in cluster 11 is shifted north from that seen in cluster 3.2 and the gradient is considerably less steep. Winter-Ridge-Trough (northerly displacement) observations occur very infrequently, only 0.04% of the time. These conditions are present only in December, January and February and are most frequent in January.

Transition season clusters

Three clusters are observed primarily in the transition months (March–May and September–November) (Figs. 4, 3b). These clusters are characterized by a general meridional flow, especially in the southwestern United States. In addition, these three categories are similar in that they depict fairly strong height gradients. These clusters represent the strong latitudinal contrast between cold and warm air expected during the transition months. Less than 20% of all observations are placed in clusters with transition season maxima.

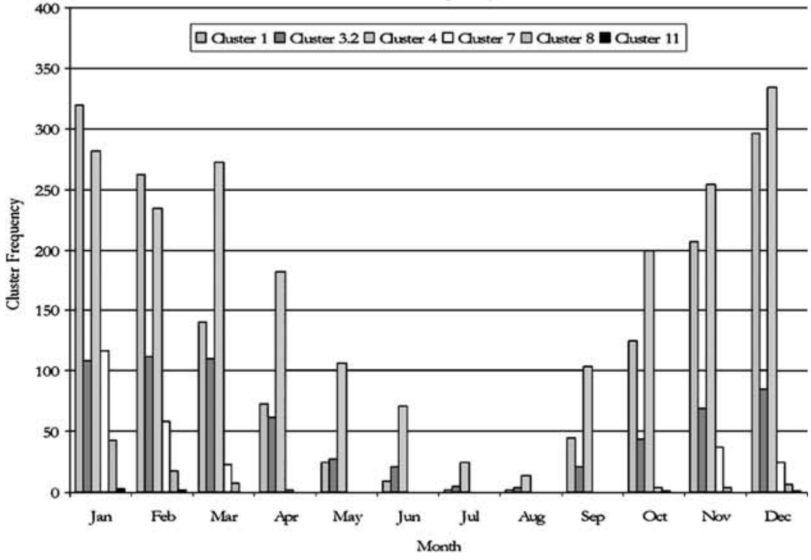
The most frequent transition season cluster is 3.1 (Transition-Trough-Ridge), which is characterized by a trough in the western United States, a ridge in the eastern part of the country and a cut-off low off the east coast. The height gradient is generally strong, especially in the western reaches of the region. This height gradient is stronger and shifted southward and westward from the pattern observed in Winter-Trough-Ridge (cluster 1), a category it resembles. Cluster 3.1 is most frequent in March and October but is observed in all months.

Observations with a high amplitude trough in the central and ridge in the western United States are grouped in cluster 3.3 (Transition-Ridge-Trough (high amplitude)). This cluster displays the greatest wave amplitude of all clusters, and the ridge over the West is particularly well pronounced. The wave axes are slightly inverted in cluster 3.3 but not as strongly as those in cluster 7 (Inclined Trough). Transition-Ridge-Trough (high amplitude) conditions occur most frequently in June and September but are present in all months.

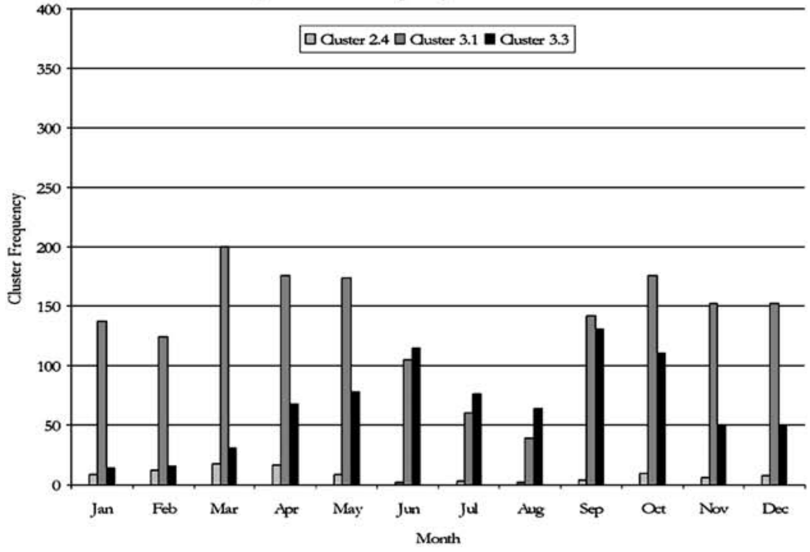
A second group of much lower amplitude Transition-Ridge-Trough observations comprises cluster 2.4. The strong height gradient is shifted north from that in cluster 3.3 and the degree of zonal flow in the southern reaches of the area is much higher. The wave features in Transition-Ridge-Trough have nearly the same amplitude as those of cluster 3.2 (Winter-Ridge-Trough) but are shifted slightly to the west. Transition-Ridge-Trough occurs in all months but

Fig. 3 Frequency of occurrence of clusters by month

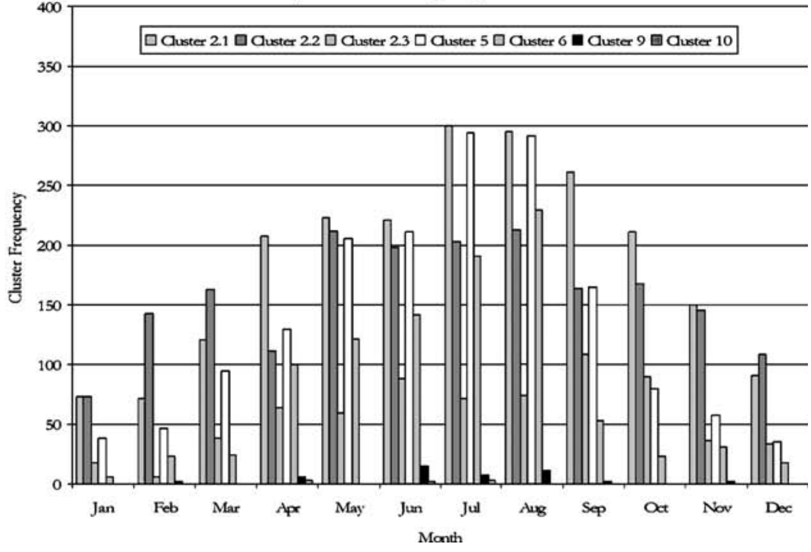
a) Maximum Frequency in Winter

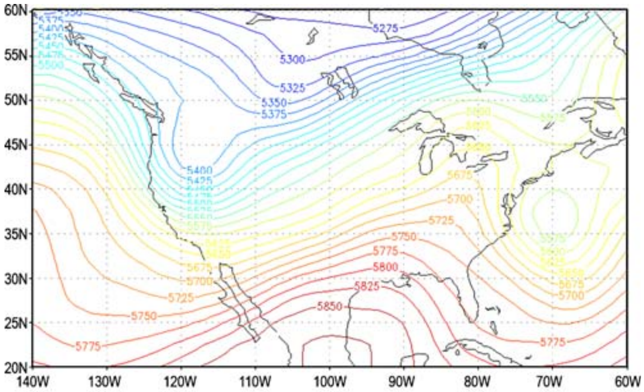


b) Maximum Frequency in Transition Months

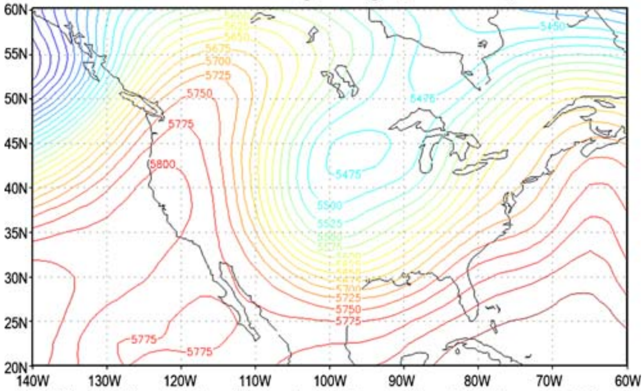


c) Maximum Frequency in Summer

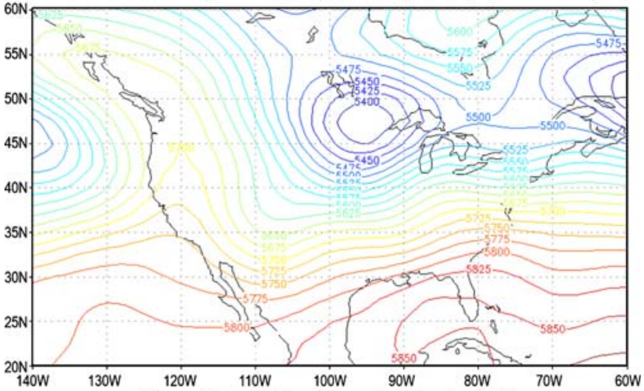




Transition-Trough-Ridge (cluster 3.1)



Transition-Ridge-Trough (high amplitude) (cluster 3.3)



Transition-Ridge-Trough (cluster 2.4)

Fig. 4 Upper level flow patterns that occur predominantly in the transition months. (Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their web site at http://www.cdc.noaa.gov/)

makes up less than one percent of the total observations. Cluster 2.4 occurs most frequently in the spring.

Summer clusters

Seven clusters occur most frequently in the summer months (June, July, August) (Figs. 5, 3c). Summer clusters have weaker height gradients than other seasons, as would be expected when warmer conditions shift farther north. Summer clusters are also characterized by higher 500 hPa heights that extend farther north into the study area, indicating the presence of warmer air. More than half of all observations were identified in clusters with summer maxima.

Cluster 2.1 (Summer-Trough-Ridge) is characterized by the same general flow pattern as cluster 1 (Winter-Trough-Ridge), but the height of the 500 hPa surface is much higher in the former. The amplitude of the waves is similar in the summer and winter Trough-Ridge clusters. The waves in Summer-Trough-Ridge are shifted slightly north from those in Winter-Trough-Ridge and are much farther north than Transition-Trough-Ridge. A warm-cored anticyclone is obviously present over the eastern United States, a common circulation feature in the summer “when the Bermuda high is well developed and extends westward” (American Meteorological Society, ND). Cluster 2.1 is the most frequently occurring cluster (15.22%) year-round and is found in all months. Summer-Trough-Ridge is most abundant in July and August.

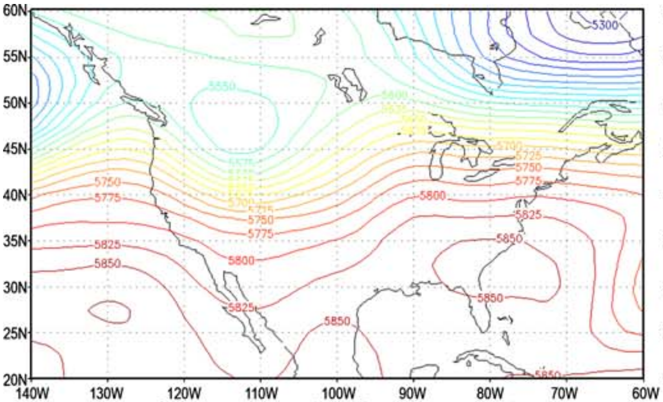
A trough in the western United States is also representative of cluster 2.2 (Summer-Trough), but the 500 hPa heights are much higher over the entire country and the area of steepest height gradient is almost entirely in Canada. No distinct ridge is present in the eastern United States as it is in the Trough-Ridge clusters. The amplitude of the trough in the west is greater than that of cluster 1 and cluster 2.1 and the height gradient is steeper around the trough and extends to higher 500 hPa heights. Cluster 2.2 is most frequent in the period May–August, but is present in all months.

A Trough-Ridge-Trough flow is present in cluster 2.3 although the eastern trough is much less well-defined than that in the west where the heights are much lower than those of either cluster 2.1 or cluster 2.2. A strong height gradient extends south to nearly 30°N and encompasses higher 500 hPa heights than cluster 2.1 or 2.2. The steep height gradient retreats to higher latitudes in the eastern part of the study region. Cluster 2.3 generally represents a shift north and west of the pattern observed in cluster 3.1. This pattern is present year-round but is most often observed in June and September.

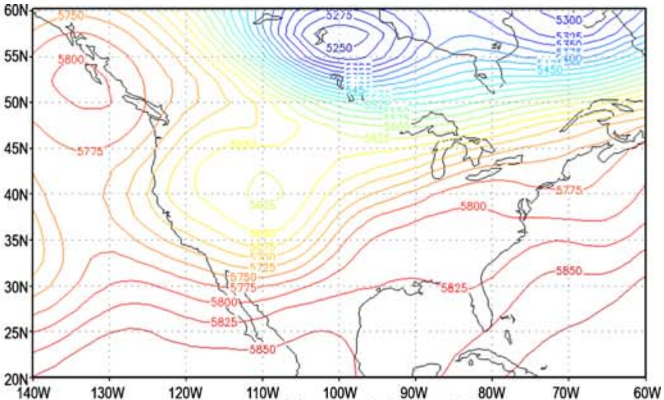
Observations with a zonal flow and a northerly displacement of the steep height gradient are grouped in cluster 5, Summer-Zonal. This most zonal of the summer clusters exhibits a higher degree of meridional flow and a steeper height gradient than the winter zonal clusters (clusters 4 and 8). Like many summer clusters, Summer-Zonal exhibits a warm-cored anticyclone in the southeast. This pattern occurs most frequently in July and August but is present year-round.

Cluster 6 is characterized by a trough-ridge-trough pattern but is distinguished from cluster 2.3 by the northerly displacement of the area of the steepest height gradient.

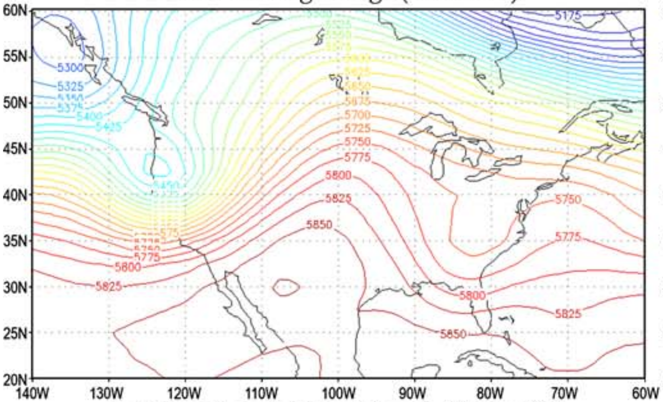
Fig. 5 Upper level flow patterns that occur predominantly in summer. (Images provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their web site at http://www.cdc.noaa.gov/) ▶



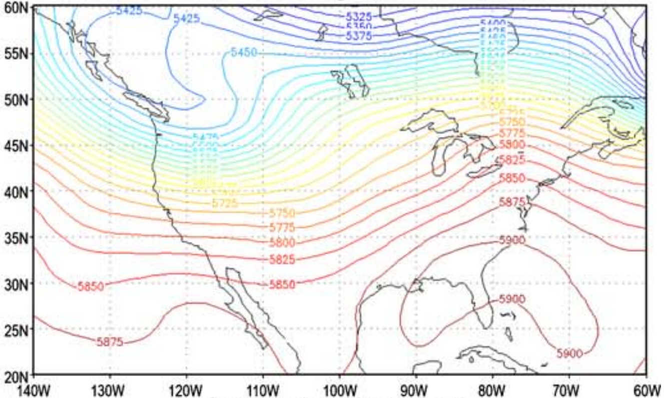
Summer-Trough-Ridge (cluster 2.1)



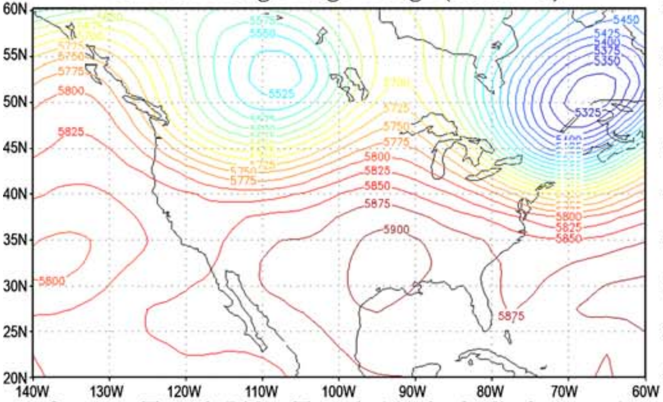
Summer-Trough (cluster 2.2)



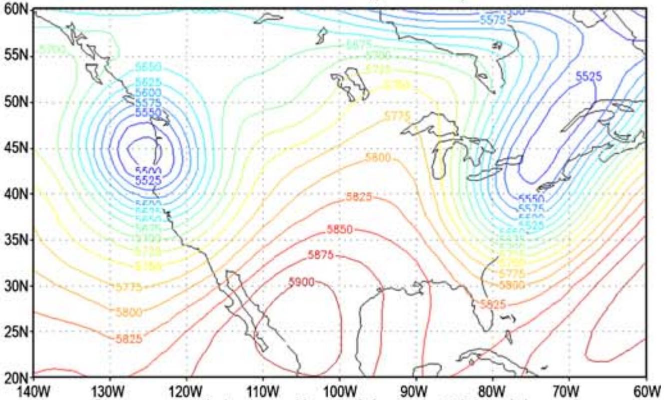
Summer-Trough-Ridge-Trough (cluster 2.3)



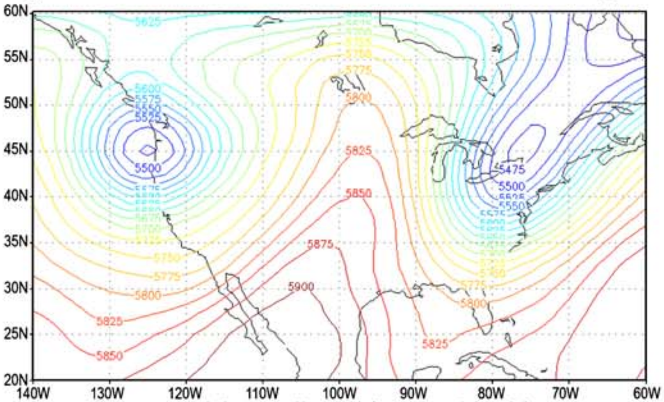
Summer-Zonal (cluster 5)



Summer-Trough-Ridge-Trough (northerly displacement) (cluster 6)



Summer High Amplitude Trough-Ridge-Trough (cluster 9)



Summer High Amplitude Trough-Ridge-Trough (cluster 10)

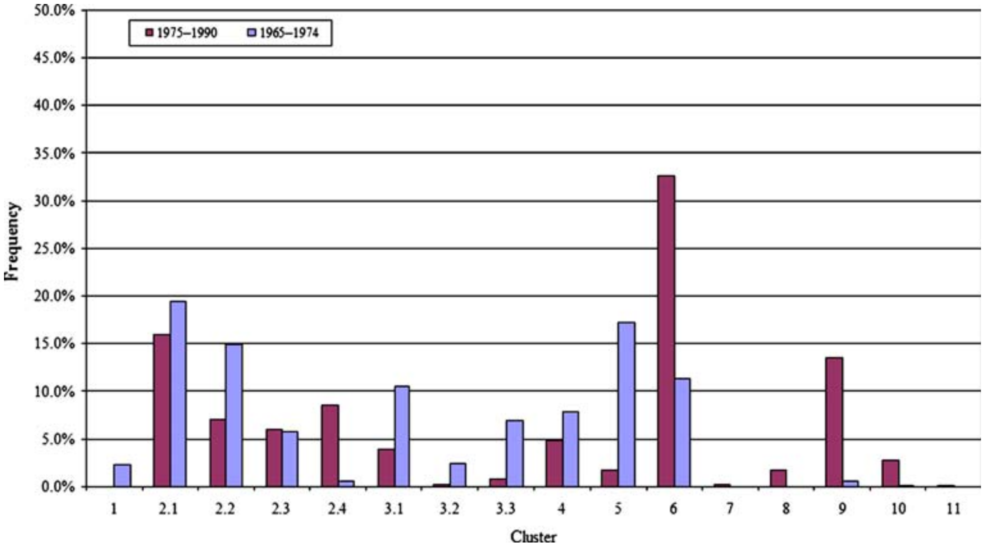


Fig. 6 April–July cluster frequency for the original 1965–1974 period and the 1975–1990 period, classified by the z-score method

This cluster shows the greatest northern displacement of the highest 500 hPa heights. The very high 500 hPa heights across much of the southern United States indicate very warm conditions across that part of the study region. These conditions occur most often in August but are present to some degree in all months.

Clusters 9 and 10 both exemplify a high amplitude trough-ridge-trough flow across North America. Both are characterized by high 500 hPa heights extending very far north in the Plains, surrounded by regions of low heights in the northwest and northeastern corners of the United States. These areas of lower heights are still higher than levels observed at the same latitudes in many of the winter clusters. Clusters 9 and 10 together comprise only 0.36% of all observations and are most often observed in June and July.

Classification of additional observations

Additional observations may be indexed by comparing their conditions to the mean conditions of each of the 16 clusters. Each observation is placed into the existing cluster to which the observation is most similar using an equally weighted sum of squared z-score (Sheridan 2002). This method is tested for the period April–July, 1975–1990. Figure 6 compares the April–July cluster frequency for the original 1965–1974 period with that of the newly-classified 1975–1990 period. While the frequency of some clusters change substantially, it is important to note that these changes are generally offset by a change in the frequency of another cluster with a maximum in the same season. For example, there is a large decrease in observations placed in cluster 5, Summer-Zonal. This decrease is accompanied by an increase in observations identified as cluster 6, also a cluster with a summer maximum. Overall, in April–July of the original 1965–1974 period the following seasonal cluster frequencies were observed: Winter maxima, 13%; Summer maxima, 69%; Transition maxima, 18%. In April–July of the newly-classified 1975–1990 period the observed cluster frequencies were, as would be expected, quite similar to that of the original study period: winter maxima, 7%; summer maxima, 80%; transition maxima, 13%; suggesting that the z-score method reasonably classifies new observations.

Discussion

The ULSC is a procedure applicable to analysis of numerous environmental questions. This methodology can help to spatially and temporally model the long-distance dispersal of airborne pathogens and aerosols. For example, in related work, Frank et al. (2008) use the ULSC to assess the relative frequency by which white pine blister rust may be transported from source populations in the Sierra and Cascade ranges to target populations in the interior southwest. The ULSC clusters provide a ranking of the spatial connection between sources and targets by representing potential pathways for the atmospheric transport of rust spores. The ULSC calendar identifies when a pathway of sufficient duration and co-incidence with epidemiological requirements occurred. Historic data are used to validate the model with specific events and to project the likelihood or frequency of dispersal. In a similar manner, ULSC clusters and calendars could help assess the potential transport of pollutants from sources to areas such as the Grand Canyon with specific local air quality standards.

The ULSC calendar is potentially effective for identifying synoptic conditions that lead to periods of flood or drought. Comparison of seasonal or annual ULSC calendars with precipitation records may identify combinations of upper level flow patterns that favor or disfavor precipitation in a region and thereby facilitate forecasting such conditions. In a similar manner but on a short temporal scale, the ULSC could help identify those flow patterns resulting in heat or cold waves. A temporal evaluation of the ULSC also improves understanding of climate change dynamics. For example, identical flow patterns could today lead to more severe or extended heat waves or longer lasting wet or dry periods than they did in the past. Finally, coupling of the ULSC with surface air mass calendars, like the SSC2 (Sheridan 2002), would allow investigation of the synoptic flows that precipitate surface conditions harmful to human and ecosystem health.

Conclusions

The ULSC successfully identifies observations with similar upper level flow patterns across North America and places these observations into clusters of acceptable size and character. The resulting clusters have high within-group similarity and high between-group dissimilarity. Examination of the resulting cluster calendar for the period 1965–1974 shows that the clusters are generally temporally continuous and the 16 flow patterns identified by the ULSC exemplify all patterns that are anticipated to be observed over the region. Compared to the previous synoptic typing of summer-time upper level flow in the Desert Southwest (Carleton 1987; Davis and Walker 1992), the summer ULSC clusters are similar. This suggests that the clusters identified by the ULSC are, indeed, representative of the types of upper level flow observed in the region. Additionally, the clusters presented here provide a basis for classification of additional observations that will occur during future years or that have occurred prior to the original ULSC dataset.

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