USING A SYNOPTIC CLIMATOLOGICAL APPROACH TO UNDERSTAND CLIMATE–VITICULTURE RELATIONSHIPS

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ABSTRACT

Regional circulation and local air mass synoptic climatologies are developed for Bordeaux, France, to examine the relationship between climate and viticulture. Using a variation of the temporal synoptic index, days with similar weather (both throughout Western Europe and at Bordeaux) are grouped together. The annual relative frequencies of these groups are used as independent variables to investigate climate–viticulture relationships for the region. The viticulture data are divided annually into stages based on the region-wide mean phenology of the grapevines. Synoptic climate–phenology models are then developed using multiple linear regression analysis.

A high degree of spatial and temporal cohesiveness is found between the regional and the local synoptic climatologies. Circulation patterns identified in the regional circulation analyses are linked in a consistent fashion with corresponding thermal, moisture, wind and cloud cover conditions at the Bordeaux site.

A small number of synoptic clusters greatly affect viticultural potential throughout the year. In general, vintage quality and production are reduced by (i) increased frequencies of cold- and moisture-producing events that delay the plant's physiology, and (ii) increases in frontal incursions and the associated winds and rain that affect flowering and the setting of berries. Conversely, the relative occurrence of warm, stable events during maturation lead to full ripeness and higher vintage quality. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: synoptic climatology; air masses; circulation; phenology; grapes; Bordeaux

1. INTRODUCTION

In regions with strong seasonal contrasts in climate (i.e. the midlatitudes), the phenology of plants is driven by daily changes in both the hydrosphere and the atmosphere. The atmospheric conditions in these regions regulate the phenological responses of plants that ultimately determine the final output (yield and quality) of most crops. The large seasonal and daily changes in the midlatitude's weather are related to changes in air mass dominance from Arctic, polar and subtropical source regions. Given the coupling of air masses and circulation, a study of the daily frequencies of air masses and the various circulation regimes that control their movements could prove useful in understanding yearly variations in any plant system's phenology and output.

In most agroclimatic resource assessment studies, crop–weather models are employed to estimate both the yields and the timing of important growth stages of the crop and to examine the agricultural impacts of climate change scenarios (Santer, 1985; Carter *et al.*, 1991; Adams *et al.*, 1995; Maytin *et al.*, 1995). But most of these models utilize mean climatological parameters that often mask important (in some cases, critical) day-to-day weather events that have a significant impact on the quantity and quality of the year's harvest. In actuality, crops respond to the daily changes of a large suite of weather parameters; thus, mean-based models provide only modest insight into the impact of weather variations on the crop studied.

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For example, a crop model that uses average temperature and/or precipitation as independent variables fails to directly account for the effects of varying levels of insolation, cloud cover and wind on the physiology of the plant and the thermal and moisture structure of the canopy. It is proposed that it may be advantageous to evaluate the whole suite of weather elements as they are instantaneously grouped through the use of synoptic climatological techniques. These groups or categories of weather elements provide better representations of true meteorological situations at a moment in time (Kalkstein *et al.*, 1987).

The value of synoptic climatological approaches has been demonstrated by linking the atmosphere with surface processes in studies of pollution levels, plant phenology, human mortality, visibility and temperature variability (Kalkstein and Corrigan, 1986; Schwartz and Marotz, 1988; Kalkstein *et al.*, 1990; Davis, 1991; Kalkstein, 1991; Davis and Gay, 1993). Although synoptic climatological applications to agriculture have been limited, both Dilley (1992) and Michaels (1982) have shown that map–pattern circulation studies can be used to successfully predict corn yields in various regions of the US. Others have examined the impacts of varying atmospheric thermal and moisture regimes in relation to peaches (Winkler *et al.*, 1990), corn (Meyer *et al.*, 1991), lentils (Keatinge *et al.*, 1995) and alpine forbs (Walker *et al.*, 1995).

Some of the most interesting results have been obtained by Schwartz and Marotz (1986, 1988), Schwartz and Karl (1990) and Schwartz (1990, 1992, 1995, 1996, 1997) using phenological records of lilacs (*syringa chinensis*) in the midwest and northeastern US. The classifications have been able to detect a spring 'green wave' or boundary layer effect from the greening of the vegetation. This effect initiates a rapid increase in transpiration by the new foliage of the plants, which in turn alters the energy budget and thermal regime of the surface layer.

1.1. Phenology and viticulture

Phenology is the study of individual physiological events or growth stages of plants or animals that recur seasonally in response to the climate. Most phenological studies aim to describe and correlate the timing of these events, and their variability, with the prevailing climate and other phenotypic events for that species (i.e. the dates of flowering and harvest). Understanding the phenology of a given plant system is important for determining the ability of a region to produce a crop within the confines of its climatic regime. From a husbandry viewpoint, knowledge of a plant's growth stages is advantageous as both cultural and chemical practices can be applied at optimum times in a plant's annual growth cycle. In addition, information regarding growth stages can be useful in estimating crop yields, forecasting human health alerts (e.g. pollen warnings for allergy sufferers) and predicting tourism variations (e.g. the best time to photograph flowers or peak leaf colour).

Vitis vinifera grapevines ('wine-bearing vines') are a phenologically distinct crop with the most important developmental stages being débourrement (bud break), floraison (flowering), nouaison (fruit set), véraison (colour change and maturation nascent), harvest (grape maturity) and leaf fall. The time between these phenological stages varies greatly with grapevine variety, climate and geographic location. In regions with cool climates and short growing seasons, early-ripening varieties are necessary whereas in hot climates, late-ripening varieties have enough time to achieve full maturation. The timing of these developmental stages is also related to the ability of the vine to yield fruit, with early and fully expressed phenological events usually resulting in larger yields (Mullins *et al.*, 1992). In addition, the phenological timing has been related to vintage quality, with early harvests generally resulting in higher quality vintages (Ribereau-Gayon and Guimberteau, 1996).

The economics of a viticulture region are driven by the quality rating given to each year's vintage (de Blij, 1983). This is particularly evident in the Bordeaux region of southwest France—a region with a long history of producing some of the finest wines in the world (Figure 1). The quality of each vintage is highly dependent upon the interplay of numerous edaphic and climatic factors such as insolation, precipitation, humidity and temperature extremes (Amerine and Winkler, 1944; Prescott, 1965; Winkler *et al.*, 1974; Amerine *et al.*, 1980). While numerous climate studies have been conducted for viticultural regions of the world (e.g. Winkler *et al.*, 1974), a regional examination of the influences that circulation variations and
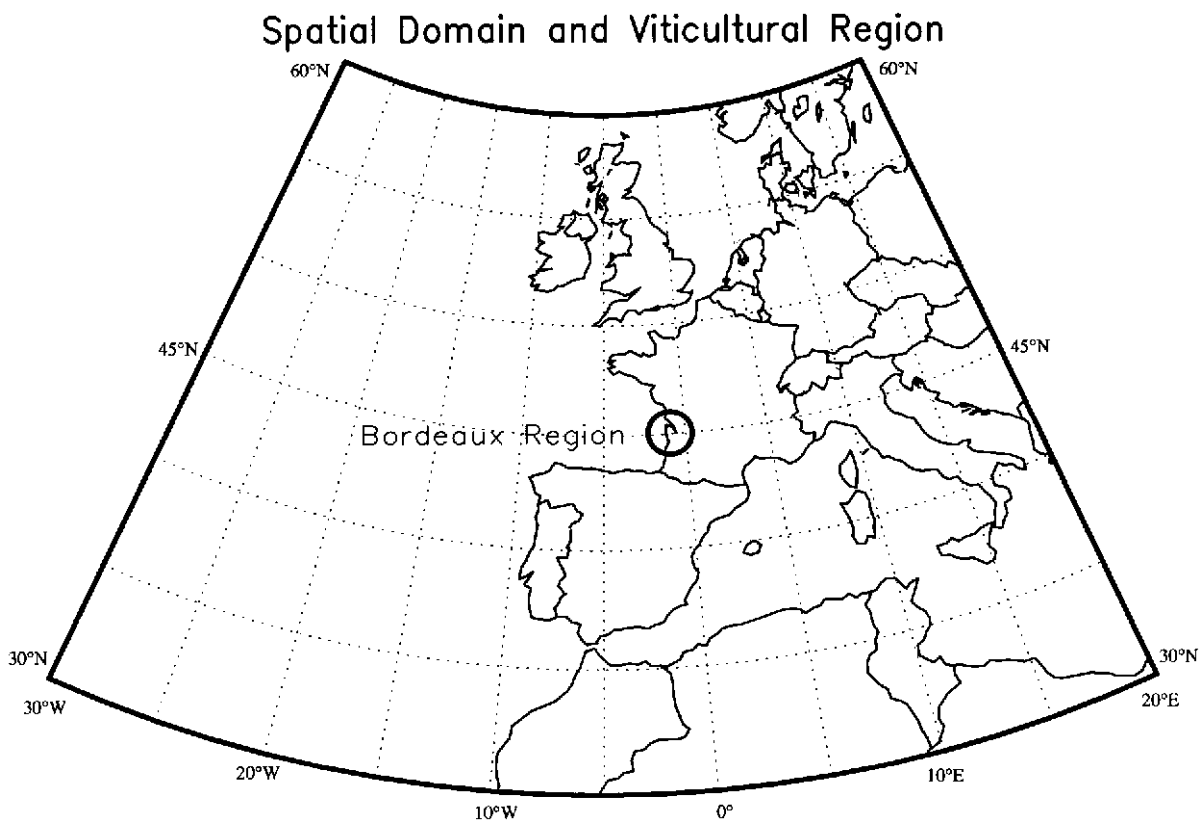
Spatial Domain and Viticultural Region

Figure 1. Map depicting the location of the Bordeaux viticultural region and the spatial domain used in the circulation analysis

air mass frequencies (i.e. synoptic climate) have on the phenology of the grapevines and on the quantity and quality of the wine produced from them has not been attempted.

This paper aims to examine the relationships between both regional synoptic circulation regimes and daily air mass frequencies during the critical growth stages of grapevines in addition to examining the quantity and quality of vintages from the Bordeaux region. The long grapevine phenological record for Bordeaux (1952–1995) and the observation of multiple phenological events (floraison, véraison and harvest) permits a more comprehensive viticulture phenological study than has been conducted previously. From this research will be developed methods to allow for mid-season and yearly assessments of the regional responses of grapevines to the prevailing synoptic climate conditions.

2. DATA AND METHODS

2.1. Climate data

Two distinct synoptic climatological analyses are employed: a spatial, region-wide analysis of the surface pressure fields and a temporal examination of the air masses at Bordeaux, France.

To examine the influences that the prevailing circulation have on the viticulture of the Bordeaux region, a spatial domain consisting of 77 5° latitude × 5° longitude grid nodes is used in a map–pattern analysis. This region covers the North Atlantic Ocean, Western Europe and the Mediterranean from 30°N to 60°N and from 30°W to 20°E (Figure 1). Sea level pressure (SLP) data for the study domain are obtained from the National Center for Atmospheric Research (NCAR) gridded SLP data set. The data set includes daily values of SLP from 1900 to 1995 for the Northern Hemisphere that have been interpolated to a 5°

latitude × 5° longitude grid network. This spatial domain incorporates all of the major air mass source regions and circulation features that influence the region. Each year, the data are divided into four seasons or stages as dictated by the region-wide mean phenology of the grapevines. For this research, if any grid node has a missing observation, that day is deleted from the data set. This restriction resulted in the elimination of 723 of a possible 35 064 days. This SLP data set has been utilized frequently in other atmospheric studies and has been analysed for its reliability and biases (Williams and van Loon, 1976; Trenberth and Paolino, 1980). Davis *et al.* (1997) found that, over the Atlantic region, potential errors in the early part of the record do not confound climatological analyses. All of the above studies note that the Atlantic Ocean and Western European regions have the most consistent records and contain minimal spatial and temporal errors or biases.

Local air mass influence on viticulture is examined using hourly meteorological data for the city of Bordeaux meteorological station obtained from METEO-France (1996). The weather station is located at 44°49′N and 00°41′W at an elevation of 47 m and has not been relocated over the period of record. The hourly data set was sampled to include observations four times per day (00:00, 06:00, 12:00 and 18:00 h local standard time (LST)) of cloud cover, temperature, dewpoint temperature, SLP, wind speed and wind direction. The wind direction and wind speed variables are converted to u and v components resulting in six meteorological variables recorded four times per day for a total of 24 variables. The period of record for the station data is 1949–1995 and is virtually free of missing observations (0.35% missing). If more than two consecutive hourly observations are missing for any of the six variables, that day is removed from the analysis; if one hourly observation for one variable is missing, then the data point is replaced through linear interpolation.

The SLP data (in which grid nodes are the variables) and Bordeaux meteorological data (using 24 daily weather variables) are processed independently using a variation of the Temporal Synoptic Index (TSI) developed by Kalkstein and Corrigan (1986) and modified by Davis and Kalkstein (1990). The procedure employs a three-step routine in which days with similar meteorological conditions are clustered into distinct climatologically homogeneous groups. The first step of the procedure involves principal components analysis (PCA), which is used to eliminate the inherent collinearity in the data and to reduce the total number of variables. Various tests are employed to determine the number of principal components (PCs) to retain, including the 'scree test' (Cattell, 1966), the averaged root test (Jolliffe, 1972), the eigenvalue separation test (North *et al.*, 1982) and 'Rule N' (Preisendorfer, 1988). The resulting PC scores are then clustered using a two-stage cluster analysis (CA) technique. Because the component scores are weighted by each PC and are thus dependent upon the original weather observations and the component loadings, days with similar scores have similar circulation and meteorological conditions.

CA attempts to combine and categorize a set of observations by maximizing external isolation and internal cohesion (Anderberg, 1973; Balling, 1984). In this paper, average linkage CA (Sokal and Michener, 1958) is used to develop an initial partition. Although there is no clear consensus as to which of the many CA approaches to use, Kalkstein *et al.* (1987) and Bunkers *et al.* (1996) found that *average linkage* produced the best results. As in the PCA, the number of clusters to retain is determined based on a suite of measures, including the pseudo-F and pseudo-T^2 statistics (SAS Institute, 1988) and several other diagnostics developed by Davis and Kalkstein (1990).

The final step in the classification procedure is the application of a non-hierarchical k-means CA (Davis and Kalkstein, 1990). This method allows for the free movement of cluster members (in this case, individual days) after they have been classified into a given group at each step of the CA, thereby acting to optimize the final cluster groupings. Milligan (1980) suggests that application of this second stage achieves smaller within-group variation than using average linkage alone. Mean component scores from the average linkage procedure are used as initial seeds in the k-means analysis. However, one characteristic of the average linkage method is that it tends to produce outliers or isolated clusters containing few members. If these anomalous clusters are used as seeds in the k-means routine, their values would serve as the basis from which new clusters would be developed. Given that the goal of any synoptic classification is to reveal climatic events that commonly recur, average linkage clusters with frequencies less than 3% are not used as seeds in the k-means CA (Davis and Walker, 1992). Although these outlier

clusters are removed from the creation of seeds, the days that produced these outlier clusters are still used in the analysis. After the removal of the anomalous average linkage clusters, seeds are calculated and each observation is assigned to the nearest cluster based upon its distance from the seeds. New seeds are computed and the process is repeated until a stable partition is achieved. Details of these procedures can be found in Kalkstein and Corrigan (1986), Davis and Kalkstein (1990), Davis (1991), Davis and Walker (1992), Davis and Gay (1993) and Jones (1997).

For the SLP/map–pattern analysis, the maps for all days in each cluster are averaged to produce mean SLP maps. For the station air mass analysis, mean values of the 24 meteorological variables are calculated for all days within each particular cluster. Calendars of the resultant k-means clusters for both the circulation and air mass climatologies are produced for each stage of grape development for the time period, with each day being represented by a given cluster. Frequencies of each stage's clusters are calculated for each year and standardized by subtracting the long-term mean. The annual frequency deviations of each cluster for each respective season are then used as the independent variables in all subsequent analyses.

2.2. Viticulture data

Data on the occurrence of floraison, véraison and harvest dates for red wine grapes (Cabernet Sauvignon and Merlot) and the associated vintage quality are obtained from the University of Bordeaux II's Department of Œnology (Ribereau-Gayon and Guimberteau, personal communication). The data consist of the mean date of occurrence of the phenological event and an assessment of the average quality of the vintage based on samples from 10 to 15 of the most renowned châteaux throughout Bordeaux. The phenological observations consist of the number of days until the event (starting from 1 January) and are compiled in Julian days (1–365 or 366 for leap years). The floraison and véraison events are considered to occur when, for a given varietal, 50% of the plants exhibit the physiological response. Harvest date is recorded as the point at which, owing to the optimum sugar levels, the first day of grape harvest commences for a given varietal. These data, from 1952 to 1995, are used to divide the synoptic climatologies into distinct phenological seasons on a year-by-year basis.

This series of annual phenological dates does not contain observations on bud break. To include this important phenological stage, a simple model was employed to derive a bud break date. Amerine *et al.* (1980) and Mullins *et al.* (1992) stated that for most viticultural regions, on average, grapevines start to produce buds when the mean daily temperature is above 10°C for 5 consecutive days. Therefore, for each year (1949–1995) the mean daily temperature is compiled and analysed. The first occurrence of 5 consecutive days of mean daily temperatures greater than 10°C that is not followed by a series of 5 or more days with mean temperatures lower than 10°C, or by any notable period of variable but prolonged cold, was counted in the procedure. Bud break was then considered to occur on the sixth day. While estimation of the bud break date from temperature data may not exactly coincide with the region-wide mean occurrence of bud break, the method does produce values consistent with 25 years of observed Merlot bud break in Bordeaux (Pouget, 1988; mean bud break given as 21 March) and with site-specific observations of bud break for an individual château ($r = 0.72$, $n = 33$, Château Latour). In the absence of region-wide bud break observations, the estimation provides a reasonable method by which to divide the early growing season climate.

Vintage ratings have been compiled over various time periods by a wide variety of sources (e.g. Broadbent, 1981; Parker, 1985; Penning-Roswell, 1989). While any qualitative assessment of a vintage is a generalization (wines from different properties and regions will vary) and a guess (no one can be sure how wines will develop in the bottle), ratings commonly serve as the industry-wide benchmark by which vintages are compared. Ratings are usually based upon a collection of estimates from one to five or seven classes (from exceptional to bad) and quality scores or ratings (i.e. Broadbent, 1981; Parker, 1985; Riou, 1994; Ribereau-Gayon and Guimberteau, personal communication). The rating of a given vintage is usually conducted in a single blind tasting of the individual varietals by a panel of experts. This procedure allows the taster to know the grape variety and the region of origin but not the appellation (France's

viticultural equivalent of a crop district) within the region nor the property within the appellation. In addition to the phenological data described above, a quality value is assigned to the overall vintage for the Bordeaux region from 1940 to 1995 (Desclee, 1991; Ribereau-Gayon and Guimberteau, personal communication). While this rating does not consider variations in quality among the individual châteaux, it is the most comprehensive overall rating compiled for the Bordeaux region. Quality is scaled from one to seven, with one being a terrible year and seven being an exceptional year.

Production data for the Bordeaux region is obtained from the Conseil Interprofessionnal du Vin de Bordeaux (1995), which is an agency that acts as a liaison between the growers of the region and the consumer. The Conseil Interprofessionnal du Vin de Bordeaux (CIVB) maintains the most reliable and comprehensive data on region-wide production, acreage planted and yield for the region. The data analysed in this paper consist of the production of AOC (Wines from the Appellation d'Originie Contrôlée) red wines for 1938–1995. These data most closely match those regions and châteaux from which the phenological observations are made.

In most agricultural systems, there is a noted increase in the yield of the crop over time owing to technological advances in husbandry and mechanization (Thompson, 1969). Many researchers have noted that viticulture experiences trends in production and yield similar to other crops (Amerine *et al.*, 1980; Johnson, 1985; Loubere, 1990; Mullins *et al.*, 1992). Gladstones (1992) found that, after accounting for technology, climate is the main control on the grapevine's output. To determine the relationship between the quantity of the harvest and climate, the production data are detrended using the most appropriate estimator (linear, quadratic, etc.) (Michaels, 1982). Any technological increasing or decreasing production trend is, therefore, accounted for and the remaining deviations can be related to climatic variations.

2.3. Regression procedures

Multiple regression procedures are used to relate the viticulture (dependent) variables (production, phenological dates and vintage ratings) to the climate (independent) variables (cluster frequencies by phenological stage) for both the regional and the station climatologies. To achieve the optimum set of models, an 'all possible combinations' regression method is employed. The first stage uses a procedure that determines the combination of independent variables that produces models with the highest coefficient of determination (adjusted R^2). This procedure finds the best one- through n-variable models for the cluster–phenology, cluster–wine quality and cluster–production relationships. The 'adjusted R^2' statistic is used because it minimizes the inflated R^2 values that frequently occur in models with low df (Draper and Smith, 1981). The second stage determines which of the suite of n-variable models best describes the relationship for each dependent variable (Kalkstein and Davis, 1989).

For the all possible combinations method, variance inflation factors (VIFs) are used to determine if severe collinearity exists between the variables (Draper and Smith, 1981; SAS Institute, 1988). High VIFs indicate that two or more collinear variables are in the model. Then, the procedure removes the variable from the model that explains less of the variance in the dependent variable. The criteria for the final model selected include a significance level of 0.01 and VIFs of less than 2.00 (SAS Institute, 1988). Regression diagnostics and residual plots are examined to ensure quality control in the modelling.

3. RESULTS

3.1. Regional circulation analysis

The original regional circulation data set consists of 35 064 possible days from 1900 to 1995. Over the period of record, 451 days were missing during the period 1944–1945 and an additional 272 days were deleted in other time periods. The resulting 34 341 day × 77 grid node data set is divided into four seasons based on the annual observations of the region-wide phenology of the grapevines in the Bordeaux region. This division results in a series of four data sets whose nascent is defined by the physiological event that initiates it (e.g. the floraison stage starts when 50% of the vines are undergoing flowering and proceeds

until the next phenological stage, véraison). In order to adequately model the climatic effects on the annual cycle of the grapevine, the data are organized into 'vintages'—the period from the end of one growth year (as defined by the harvest date), through dormancy, the vegetative growth cycle, the maturation of the crop and harvest of the following year. Results of the TSI procedure vary across phenological seasons, with as few as eight spatial clusters identified during the véraison stage and as many as 13 during the bud break stage (Table I(a)). To verify the results, the daily calendar is examined by comparing a large subsample of days with published daily weather maps (German Meteorological Service, 1995).

Mean and S.D. SLP maps are plotted for each phenological stage. The seasonal variation reveals the relative movement and strength of two primary synoptic controls—the Azores high and the Icelandic low—which define the wet–dry Mediterranean climate of the southern part of the study region and the cool, moist maritime climate of the northern part of the area (Figure 2). The mean SLP field for the dormant stage displays the lowest pressures and the most southerly advance of the Icelandic low along with a southerly position of a weakened Azores high and the presence of the Genoa low feature over the Mediterranean (Figure 2(a)). The bud break stage mean field depicts a weakening of the pressure gradient between the two centres of action, a strengthening of the Azores high, and the continued presence of the Genoa low over Italy (Figure 2(b)). During the floraison stage, the mean SLP field shows an eastward expansion and strengthening of the Azores high into Europe along with a decrease in the strength of the Icelandic low and the absence of the Genoa low over the Mediterranean (Figure 2(c)). In late summer and early autumn, the véraison stage mean SLP field displays the continued domination of the Azores high into Europe but an increase in zonal flow across the British Isles along with a re-emergence of the Genoa low over the Mediterranean (Figure 2(d)). The S.D. fields of the SLP data for each stage show maximum deviations in regions frequented by transient low pressure systems along the northerly latitudes where the Icelandic low dominates and decreasing deviations southward toward the more stationary Azores high (Figure 2(a–d)). Furthermore, the S.D.s decrease from the dormant stage into the bud break and floraison stages before increasing in strength again in the véraison stage in conjunction with the seasonal pulse of the strength of the Icelandic low.

Table I. Analysis summary for each of the four phenological stages for (a) the map-pattern or circulation analysis and (b) the station air mass analysis

	Total no. of days	Final no. of days	PCs retained	% variance explained	No. of average linkage clusters	No. of k-means clusters
(a) Map–pattern analysis						
Dormant stage	16 336	15 993	3	70	29	11
Bud break stage	7673	7566	3	64	39	13
Floraison stage	6319	6219	3	57	26	9
Véraison stage	4285	4188	3	60	19	8
(b) Station air mass analysis						
Dormant stage	8078	8071	3	65	22	10
Bud break stage	3816	3810	3	64	13	8
Floraison stage	3130	3130	3	63	19	8
Véraison stage	2142	2142	3	62	20	8

Final number of days represents those days left after removing all days with missing grid nodes or hourly observations. Percentage variance explained is related to the number of PCs retained for each stage analysis. The number of average linkage clusters indicates the optimum number chosen from the procedure. All average linkage clusters occurring greater than 3% are used as seeds from which the number of k-means clusters are calculated. The number of k-means clusters represent the final solution for each stage.
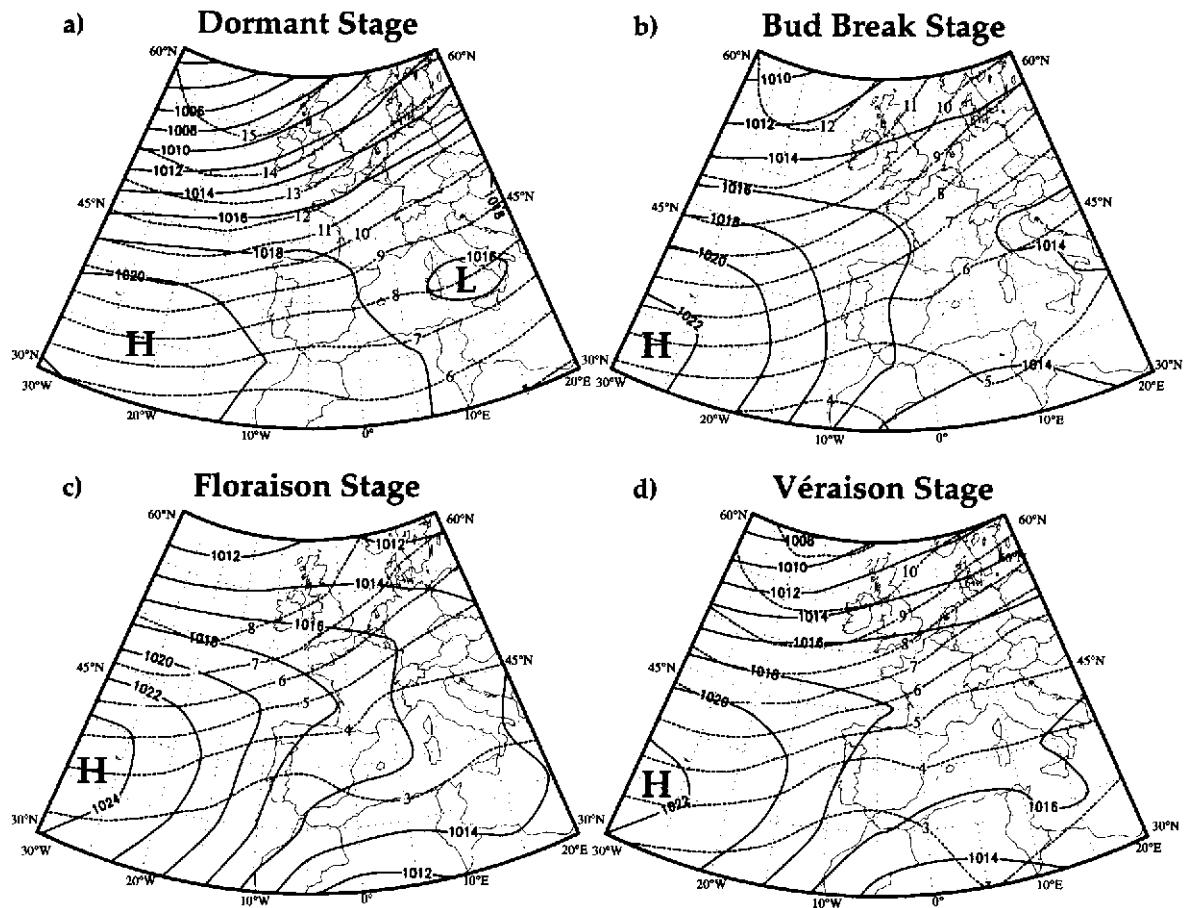
Figure 2. Mean (solid line) and S.D. (dashed line) sea level pressure (SLP) fields derived from data for 1900–1995 for the (a) dormant stage, (b) bud break stage, (c) floraison stage and (d) véraison stage

3.2. Bordeaux air mass analysis

The second data set—hourly data from the weather station at Bordeaux—consists of 17 153 days (from 1949 to 1995) after accounting for missing observations. The TSI procedure ultimately generated from eight to ten clusters depending on the phenological season (Table I(b)). Mean values for each of the 24 variables are calculated for each cluster and the results verified by comparison with daily synoptic charts. Each cluster is described relative to the thermal and moisture properties of the air masses that influence the region.

For Western Europe, the relative frequency of air masses for each phenological stage are identified according to the following categories: maritime polar (mP), continental polar (cP), warm overrunning (wO), continental tropical (cT), maritime tropical (cT) and cyclonic (C). These are displayed for each phenological stage (Figure 3). Each air mass cluster was grouped into the categories mentioned above by examining their thermal and moisture characteristics (Kalkstein et al., 1993) and by comparing them with published weather maps (German Meteorological Service, 1995). Examination of these frequencies both within and across phenological seasons provides insight into the mean synoptic character of each stage. For the study region used in this research, the main difference in the generalized description of air masses given by Kalkstein et al. (1993) is that associated with cold overrunning events. While warm fronts are common over land and western ocean margins, over eastern ocean margins the ocean modifies warm fronts making them more difficult to identify (Pédélaborde, 1957). This is obvious in the comparison of
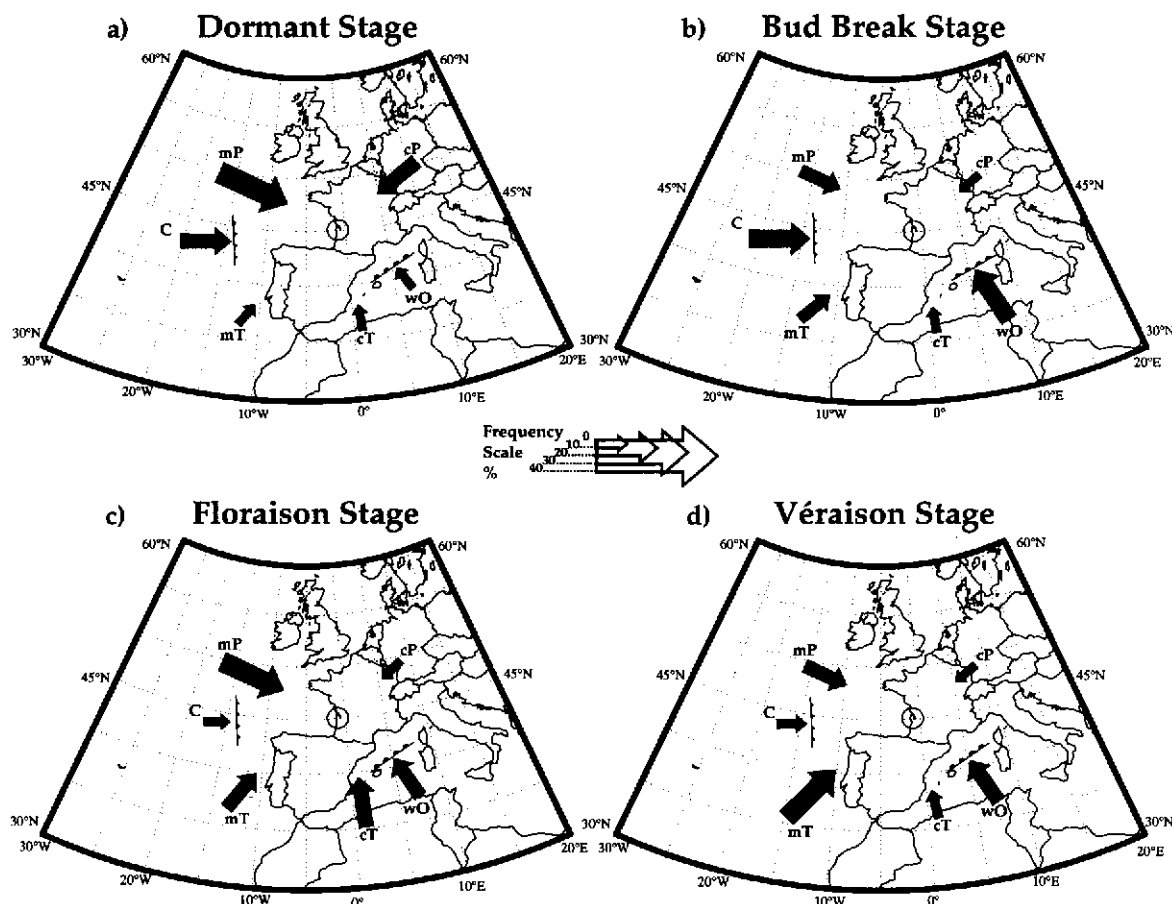
Figure 3. Average air mass frequencies during the (a) dormant stage, (b) bud break stage, (c) floraison stage and (d) véraison stage as defined for the Bordeaux region. Air masses with similar characteristics are grouped into their respective types: cP, cT, mP, mT, wO and C, as described in the text

daily weather maps (German Meteorological Service, 1995) and the derived clusters. While the thermal and moisture characteristics associated with events similar to those defined as cold overrunning are found, they are concurrent with cyclones that typically lack a warm front. Because the conditions associated with these events appear preceding cyclones and along the associated cold fronts, they are termed cyclonic (Jones, 1997). Aside from this modification, the derived air masses are in general agreement with those given by Belasco (1952), Pédélaborde (1957), the Meteorological Office (1962, 1964) and Kalkstein *et al.* (1993).

3.3. Presentation format

Space limitations do not allow for a complete depiction of the synoptic climatology for all seasons (41 SLP clusters and 34 station air masses). (Interested readers may refer to Jones (1997) or should contact the lead author.) Instead, only those clusters deemed statistically significant in the regression analyses are shown. For each figure, the mean SLP field is plotted. Also included on each map are the mean daily meteorological conditions at 12:00 h (LST) for the Bordeaux station based on all of the days in that cluster. Below each map is a four-panel station model for the Bordeaux cluster that most closely corresponds to that SLP cluster. Each four-panel figure shows the mean meteorological conditions for that station air mass at 00:00, 06:00, 12:00 and 18:00 h LST at Bordeaux (see Appendix A for the station model key).

For example, Figure 4(a) depicts the mean spatial SLP field associated with bud break cluster two (SLP-B2) (the nomenclature used to describe the different clusters is as follows: SLP indicates circulation clusters; BDX indicates station air mass clusters; D, B, F and V indicate the respective season of the cluster—dormant, bud break, floraison and véraison), developed from the 632 days in this cluster (8.4% of all bud break stage days). The SLP field depicts a strong cyclone to the west of Ireland and an anticyclone over Scandinavia—a situation typically associated with warm conditions in Bordeaux. For these 632 days at 12:00 h LST at the Bordeaux weather station, the skies are 50% overcast with weak easterly winds and temperatures and dewpoints of 19.7°C and 10.3°C, respectively. After comparison with the results from the separate Bordeaux station air mass climatology, it is found that the cluster most
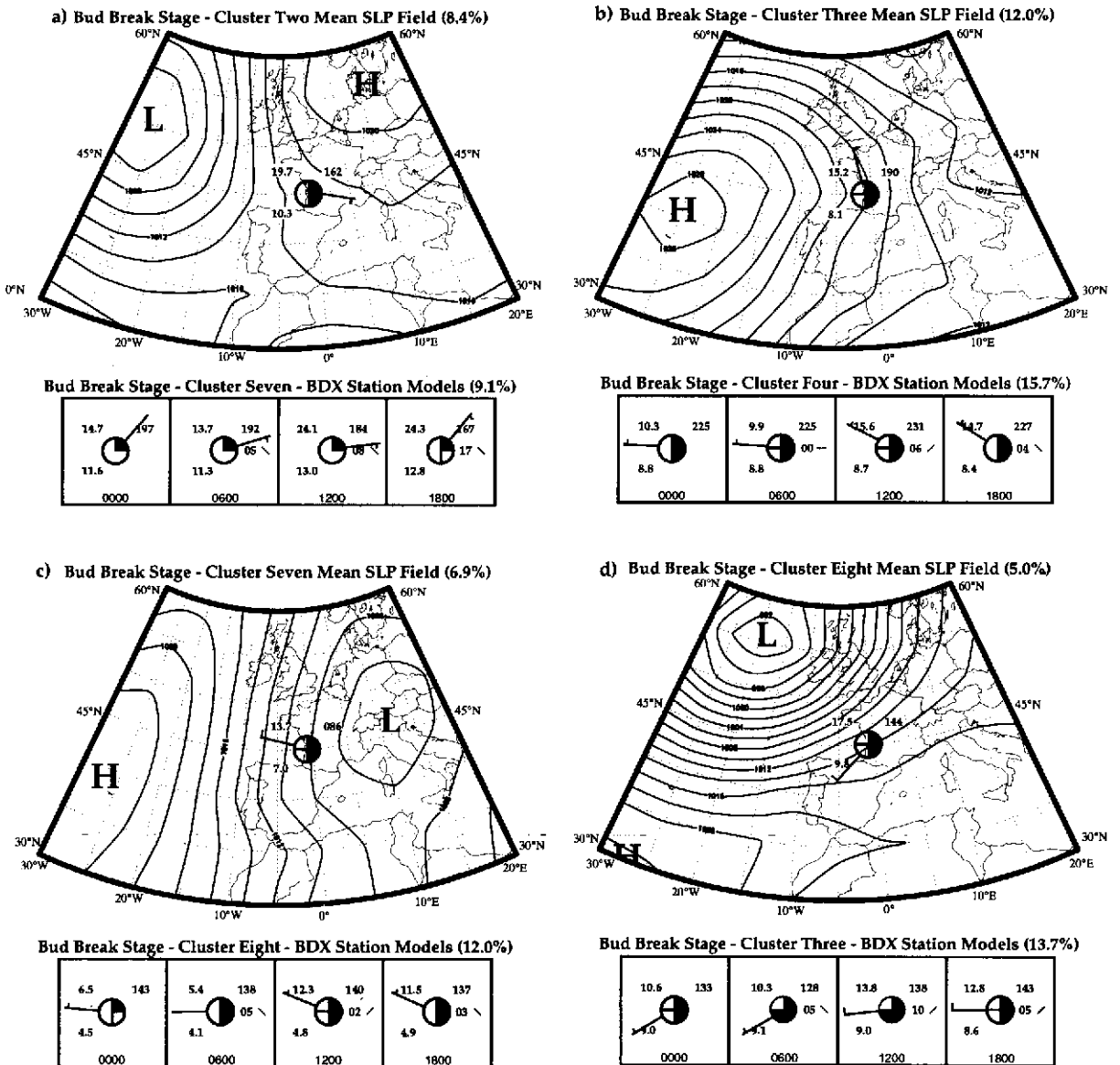

Figure 4. Examples of bud break clusters for the sea level pressure (SLP) and Bordeaux station (BDX) synoptic climatologies. The mean SLP fields are shown for each cluster along with the weather conditions at 12:00 h LST at Bordeaux for all days in that cluster. Below each map are the mean observations (at four times per day) at Bordeaux for the BDX cluster that has the highest correspondence with this SLP cluster. The relative frequency of each cluster is given in parentheses. Refer to Appendix A for the station model key

commonly associated with bud break SLP cluster two is bud break BDX cluster seven (BDX-B7), described as a warm, continental tropical air mass (the warmest bud break cluster). BDX-B7 occurs 9.1% of the days during the bud break stage and the mean weather conditions for the 337 days in this cluster are shown for the four observations times. For this SLP–BDX pairing, over comparable time periods, 38.8% of SLP-B2 days are associated with BDX-B7.

3.3.1. Dormant stage. During the winter season of vine dormancy, the region is influenced by 11 regional circulation clusters with annual frequencies between 5.1 and 13.8% and ten air mass clusters ranging in frequency from 7.2 to 14.3% and consisting of the four main air masses (cP, mP, cT and mT) and two mixed frontal conditions (Figure 3(a)). Because of the wintertime southward expansion of the circumpolar vortex, the related southward migration of the polar front and the weakening of the Azores high (Davis *et al.*, 1997), this season is characterized by a wider variety of synoptic situations. However, the regression analysis presented later does not demonstrate any relationships between dormant clusters and the region-wide phenology, production or ratings; thus, the dormant season results are not presented here (see Jones, 1997, for details).

3.3.2. Bud break stage. The bud break and early vegetative stage, which occurs from March through June, is a transitional period during which frontal incursions and cP air become less common and the Azores high begins building into the region from the west. Example clusters include:

 (i) SLP-B2 and BDX-B7: the warmest spring days in Bordeaux with average afternoon highs approaching 25°C (Figure 4(a)). With a surface cyclone to the northwest and an anticyclone to the northeast, tropical air is easily advected into France, sometimes in association with transient cyclones crossing the Mediterranean Sea.
 (ii) SLP-B3 and BDX-B4: a strong anticyclone to the east and the resulting strong northwesterly winds bring cool, maritime air into the region (Figure 4(b)). This is among the most common situations during the bud break stage.
(iii) SLP-B7 and BDX-B8: strong meridional flow associated with a cyclone to the east results in cold conditions after a frontal passage (Figure 4(c)). This cluster has the lowest temperatures at noon and is among the coolest at night despite the relatively high cloud cover (highlighting the magnitude of the cold air advection).
(iv) SLP-B8 and BDX-B3: a deep low pressure system and cold front northwest of the British Isles produces windy, overcast conditions in Bordeaux and strong, southwesterly flow (Figure 4(d)).

The bud break stage is represented by a nearly even distribution of cold versus warm events (Figure 3(b)). Cyclonic and warm overrunning clusters are the most frequent air masses (25.8 and 26.9%, respectively) and cT air masses are the least common (8.8%). This is consistent with the occurrence of more transient cyclone families over the region during spring (Pédélaborde, 1957).

3.3.3. Floraison stage. During the floraison stage (June–August), the Azores high has reached its maximum intensity and the circumpolar vortex is in its most contracted configuration. During this period, little rainfall occurs over Bordeaux and there is little synoptic variability. Example air masses include:

 (i) SLP-F1 and BDX-F4: a fairly common situation at this time of year, with a dominant Azores high, a cyclone north of the British Isles and prevailing surface westerlies (Figure 5(a)). Morning fog is frequent in this maritime air mass.
 (ii) SLP-F5 and BDX-F5: with the Icelandic low stronger and the Azores high weaker than mean conditions for the period, continental air is prevalent (Figure 5(b)). This is one of the rare cases when there is not a strong correspondence between the station and circulation-based climatologies. While the circulation-based analysis shows this to have among the warmest conditions at noon, the Bordeaux station climatology shows noon temperatures almost 9°C lower. Weak circulation during this time of year can make the correspondence between circulation and station air masses more difficult.
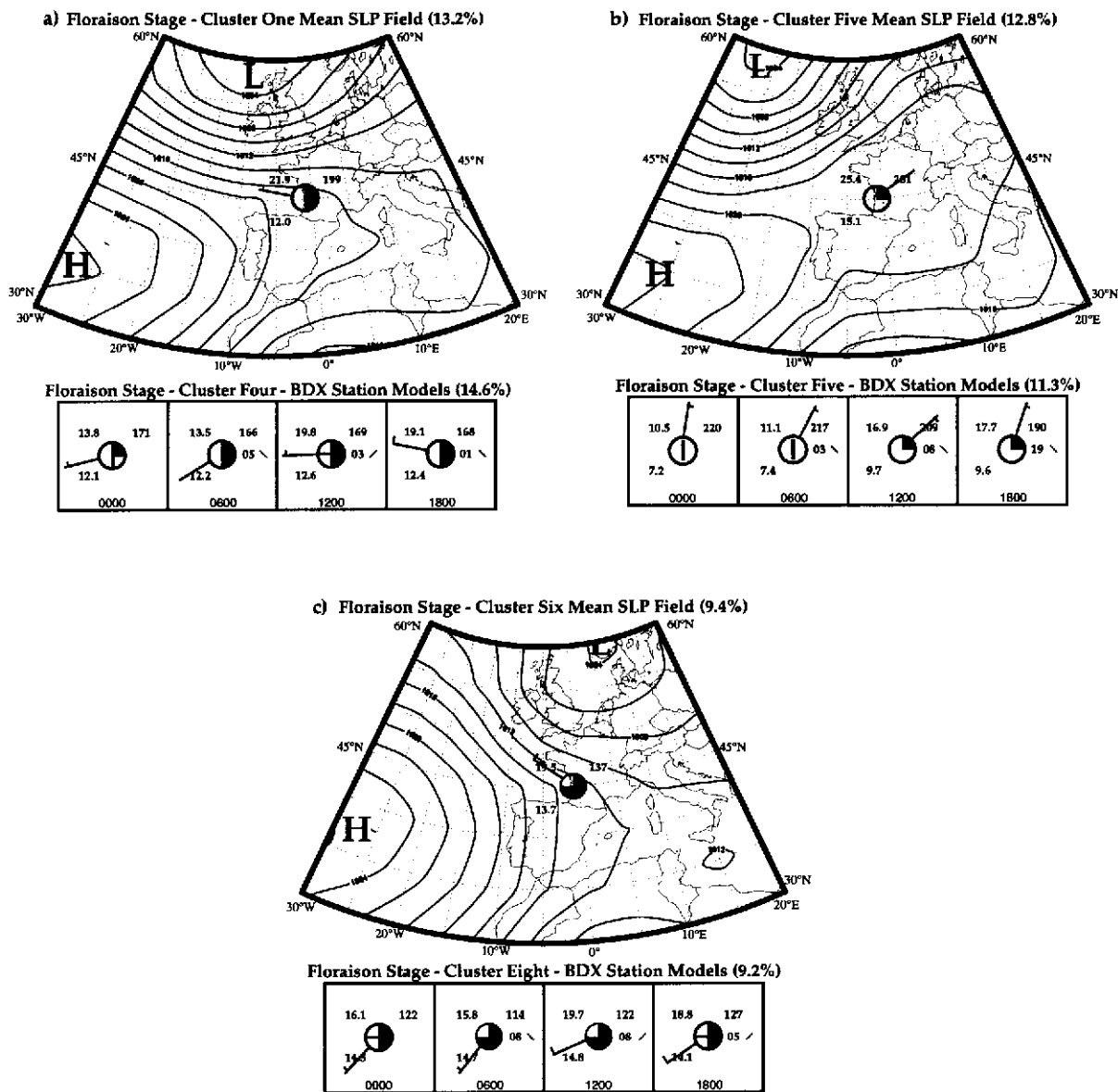
a) Floraison Stage - Cluster One Mean SLP Field (13.2%)

b) Floraison Stage - Cluster Five Mean SLP Field (12.8%)

Floraison Stage - Cluster Four - BDX Station Models (14.6%)

Floraison Stage - Cluster Five - BDX Station Models (11.3%)

c) Floraison Stage - Cluster Six Mean SLP Field (9.4%)

Floraison Stage - Cluster Eight - BDX Station Models (9.2%)

Figure 5. As for Figure 3, but for the floraison stage clusters: (a) cluster one; (b) cluster five; and (c) cluster six

(iii) SLP-F6 and BDX-F8: a low pressure system to the north and a frontal passage brings modified cP air into France (Figure 5(c)). This cluster has the lowest mean temperatures and highest mean winds and cloud cover at 12:00 h LST of any cluster, and the station analysis shows similar unusually windy and cloudy conditions.

Maritime polar air masses are the most frequent (27.3%) during the flowering stage and cyclonic conditions decline in frequency (9.3%) from the previous stage (Figure 3(c)). Overall, there is a shift to a higher frequency of warm air mass clusters and moderation or warming of the mP and cyclonic conditions.

3.3.4. Véraison stage. During the véraison stage of August and September, when the berries are ripening, the region experiences generally stable weather conditions. Even though the Azores high is beginning to weaken from its late July intensity maximum (Davis *et al.*, 1997), the polar front has not yet begun to strengthen much.

(i) SLP-V3 and BDX-V2: anticyclonic blocking over most of Northern and Central Europe and the British Isles generates continental easterly flow and very warm conditions (Figure 6(a)). This cluster has the highest 00:00 and 12:00 h LST temperatures of any véraison cluster.

(ii) SLP-V4 and BDX-V7: the least frequent cluster during this stage depicts a high pressure region over most of Europe with zonal flow over the British Isles (Figure 6(b)). Conditions are relatively cool and dry, especially in the early morning when single digit temperatures and dewpoints are common.
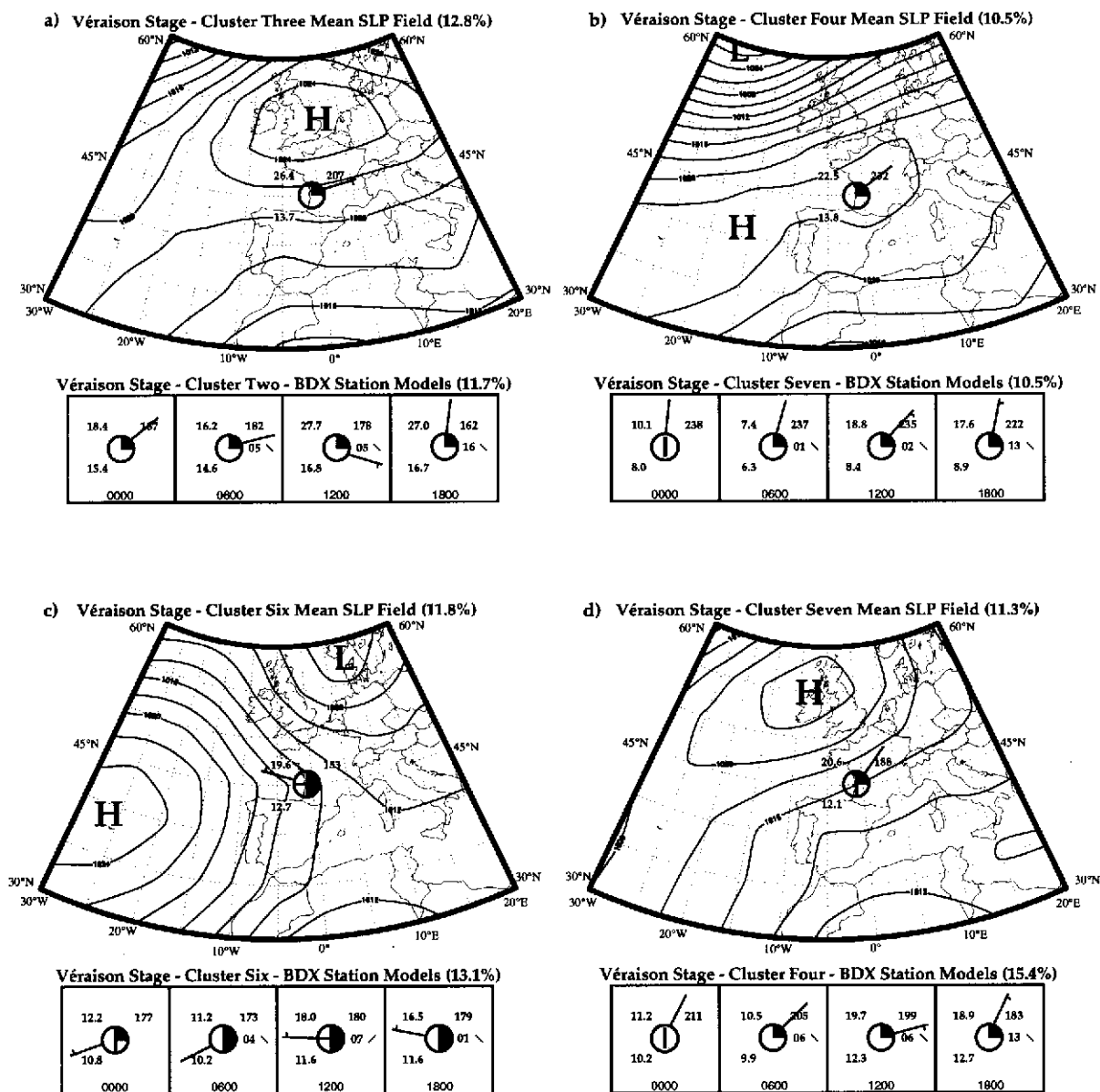

Figure 6. As for Figure 3, but for the véraison stage clusters: (a) cluster three; (b) cluster four; (c) cluster six; and (d) cluster seven

(iii) SLP-V6 and BDX-V6: low pressure over Scandinavia and an unusually strong anticyclone off the coast bring cool, maritime air into the region (Figure 6(c)). Temperatures are comparable with those of BDX-V7 but the dewpoints are higher and skies are more overcast.

(iv) SLP-V7 and BDX-V4: another blocking situation with an anticyclone positioned over the British Isles and weak pressure gradients across Western Europe (Figure 6(d)). Low dewpoint temperatures characterize this dry, relatively cloud-free situation.

The overall air mass frequency reveals a summertime shift to generally warmer and drier air masses for the Bordeaux region (Figure 3(d)). Maritime tropical air masses are the most frequent (28.3%) and cP conditions are the least frequent (10.4%) occurrences during this stage.

In summary, over the course of a year, variations in the cluster mean spatial fields reveal the seasonal changes in circulation over the study region. During the dormant and bud break stages, a higher degree of variability is found in the surface pressure fields as transient systems spawned from the Icelandic low increase in frequency. The 11 SLP clusters during the dormant stage and the 13 clusters during the bud break stage consist of numerous fields dominated by low pressure systems. In addition, the dormant and bud break stages also exhibit a relatively large number of clusters that depict variations in anticyclonic blocking and meridional flow. During the floraison and the véraison stages, the reduced strength of the Icelandic low and the intensification of Azores are accounted for by the cluster frequencies. In addition, a general reduction in the strength of the circulation is observed as the overall gradients in the mean cluster spatial fields decrease during floraison and véraison.

3.4. Comparison of the climatologies

A comparison of the synoptic climatologies described above is necessary to examine the degree to which the two procedures represent similar climatic regimes. Because the general circulation drives the air mass structure of the region, temporal frequencies of the local air mass clusters, as related to the regional circulation clusters, are examined.

Frequencies of occurrence of the local air mass clusters are compiled for each regional circulation cluster. We are interested in whether the station air mass clusters are independent of the occurrence of the circulation clusters. In other words, is the frequency with which one air mass cluster occurs significantly related to the occurrence of a certain circulation cluster? To answer this question, the data are cast into a $p \times q$ contingency table and Pearson's chi-square statistic is used. The analysis utilizes frequencies that would be expected if the null hypothesis of independence was true.

For each stage comparison, the null hypothesis is rejected, indicating that the individual station air mass cluster frequencies are not independent of the circulation cluster frequencies (see Jones, 1997, for details). Furthermore, each air mass cluster that has the highest temporal correspondence with a given circulation cluster contributes the largest cell dissimilarity to the overall statistical summation, indicating that the relationships found are statistically significant and non-random.

For example, during the véraison stage, the eight circulation clusters are primarily coupled with eight different air mass clusters (Table II). The level of correspondence for individual matches varies from 32 to 51% and from 51 to 74% for the two most frequent coupled clusters. For example, the temporal correlation between circulation cluster three and air mass cluster two is 39.4%. The conditions found during these events are a strong high pressure system over the British Isles and Northern Europe with the general flow off the continent bringing warm days with relatively low winds and cloud cover at Bordeaux (Figure 6(a)).

3.5. Viticulture

For the Bordeaux region, the mean derived bud break date is 21 March and the S.D. is 18 days (Table III). The time series shows an earlier occurrence of bud break in the later part of the record that is consistent with the trends in the observed phenological dates (Figure 7). It may be noteworthy that this derived variable has a much larger S.D. (18 days) than the other measured phenological variables (8 days

Table II. Véraison stage cluster comparisons

SLP cluster	BDX cluster	Correspondence (%)	Correspondence sum (%)
1	1	37.6	54.3
	6	16.7	
2	5	38.1	63.0
	2	24.9	
3	2	39.4	63.1
	1	23.7	
4	7	35.5	56.6
	4	21.1	
5	3	51.4	74.0
	5	22.6	
6	6	32.0	58.4
	8	26.4	
7	4	34.6	52.9
	5	18.3	
8	8	35.7	51.2
	6	15.5	

Example of the temporal correspondence between circulation and air mass clusters. Véraison stage circulation (SLP) clusters listed along with the two station air mass clusters (BDX) occurring in the same stage that display the greatest temporal correspondence (or percent of the time one occurs in conjunction with the other).

for each). The mean date of floraison is 12 June but it has occurred as early as 27 May and as late as 27 June (Table III). The annual progression of flowering is shown to have a parabolic time series (Figure 7), with advanced flowering in both the early and later periods in the record and relatively delayed flowering during the mid 1960s through the early 1980s. Véraison has occurred as early as 4 July and as late as 3 September and on average occurs on 18 August (Table III). The time series of the date of véraison displays a large degree of annual variation, with generally later dates in the late 1970s and earlier dates
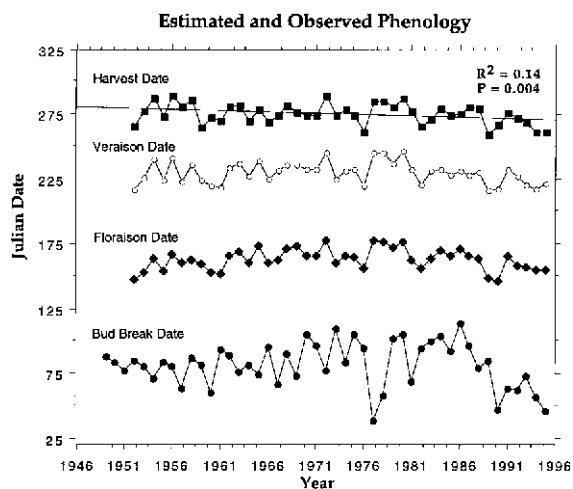

Figure 7. Time series of the major region-wide phenological events for the Bordeaux region: estimated start of bud break for the Bordeaux region, 1949–1995; mean date of floraison, or the flowering of the grapevines; mean date of véraison, or the start of maturation of the berries; mean date of the start of harvest, 1952–1995 (data are derived from 10 to 15 châteaux sampled from within the region; source: Ribereau-Gayon and Guimberteau, 1996)

Table III. Summary statistics for the independent viticulture parameters examined in the analysis

Variable	n	Mean	S.D.	Maximum	Minimum	Range
Estimated bud break	47	March 22/81	17.5	114	39	75
Floraison	44	June 12/163	8.1	178	147	31
Véraison	44	August 18/230	8.3	290	259	31
Harvest	43	October 2/275	7.8			31
Quality (scale one to seven)	55	4.8	1.9	7	1	6
AOC red wine production (hl)	58	1 953 296	1 382 742	5 044 680	370 978	4 673 702

Variables include region-wide mean phenological dates (means given as Julian days and calendar days) of estimated bud break, floraison, véraison and harvest, the vintage quality rating (rated from one to seven) and the AOC red wine production (hectoliters) (data sources: Conseil Interprofessionnal du Vin de Bordeaux, 1995 and Ribereau-Gayon and Guimberteau, 1996).

in the last two decades (Figure 7). The average harvest date for the region is 2 October, although it has commenced as late as 10 October and as early as 16 September (Table III). For the period of record, there is a statistically significant downward trend such that the harvest is now 10 days earlier than it was in the 1950s (Figure 7, $R^2 = 0.14$). This trend is thought to be mostly the result of warmer growing season conditions but could be in part because of a recent tendency for vintners to harvest earlier (J.-P. Valette, personal communication, 1996).

There has been considerable variability in vintage quality from year to year (Figure 8(a)) with many more years given exceptional ratings ($n = 12$) than poor ratings ($n = 2$) (Table III). The volume of production plays a small, positive role in vintage quality, although many years with high production have both high and low vintage ratings ($r = 0.31$, Table IV, Figure 8(b)). Region-wide phenological dates are highly correlated—the date of an individual event is highly correlated with the date of the one immediately preceding it (e.g. floraison and véraison, $r = 0.91$) (Table IV). This is logical because an early bud break will typically lead to advanced physiological growth and earlier flowering. The vintage quality rating is negatively correlated with each phenological measure. This means that the overall quality of the vintage decreases as phenological events are delayed (e.g. harvest date and quality, $r = -0.61$).
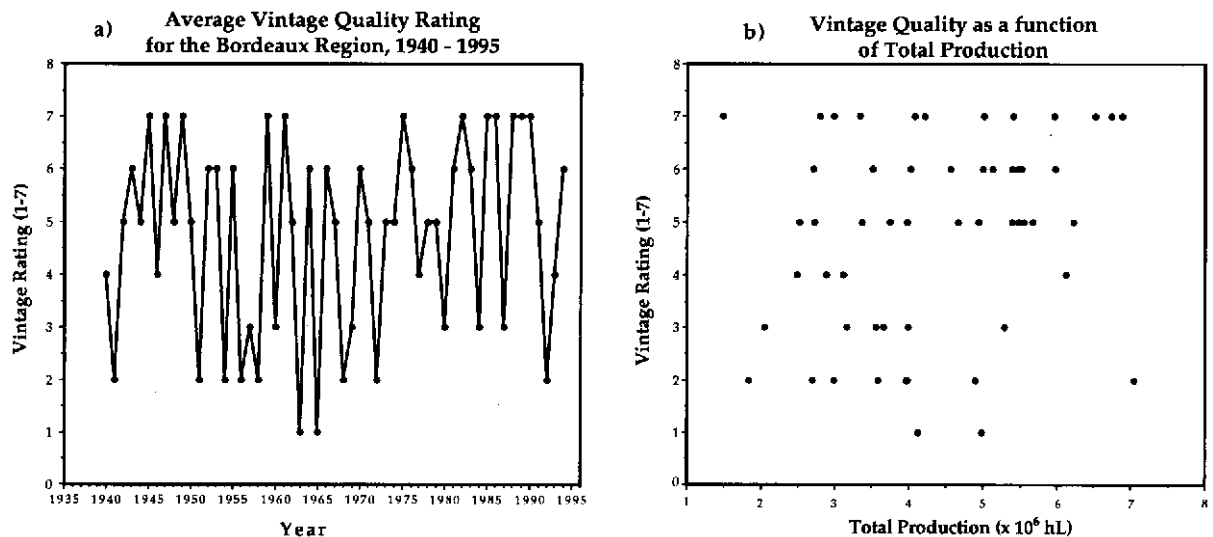

Figure 8. (a) Region-wide average vintage quality ratings for 1940–1995 for Bordeaux on a scale of one to seven, with one being termed bad and seven being termed excellent. (b) Region-wide average vintage quality rating (scale one to seven) compared with total production (hectoliters) in the Gironde Department, 1940–1995 (data sources: Conseil Interprofessionnal du Vin de Bordeaux, 1995 and Ribereau-Gayon and Guimberteau, 1996)

Table IV. Correlations between the region-wide mean phenological dates, the vintage quality ratings, and AOC red wine production for the Bordeaux region

	Floraison date	Véraison date	Harvest date	Vintage quality	AOC red production
Floraison date	1.00				
Véraison date	0.91	1.00			
Harvest date	0.75	0.86	1.00		
Vintage quality	−0.46	−0.55	−0.61	1.00	
AOC red production	−0.37	−0.37	−0.35	0.31	1.00

All correlations are significant at the $\alpha = 0.05$ level.

AOC red wine production in the Bordeaux region has exhibited a non-linear increase since 1938 (Figure 9) that can be mostly attributed to improvements in technology and increases in acreage planted (Penning-Roswell, 1989). Timing of each of the phenological events displays negative correlations with AOC red wine production and reveals that production, like quality, decreases with delayed events (Table IV).

AOC red wine production has clearly experienced a technological trend over time and is detrended with a second order polynomial function (Figure 9). Phenological dates of events and individual vintage ratings have not been found to be influenced by technological trends in viticulture (Johnson, 1985; Parker, 1985). While there has been some genetic improvement in the cloning of varietals, this is usually accomplished in order to make an individual variety hardier or more disease resistant. Therefore, phenological dates of bud break, floraison, véraison and harvest have experienced little technological influence over time (Le Roy Ladurie, 1971). It is interesting to note that while viniculture (wine making) has been modernized with improved cellaring techniques, new materials and chemicals, and the education of new generations
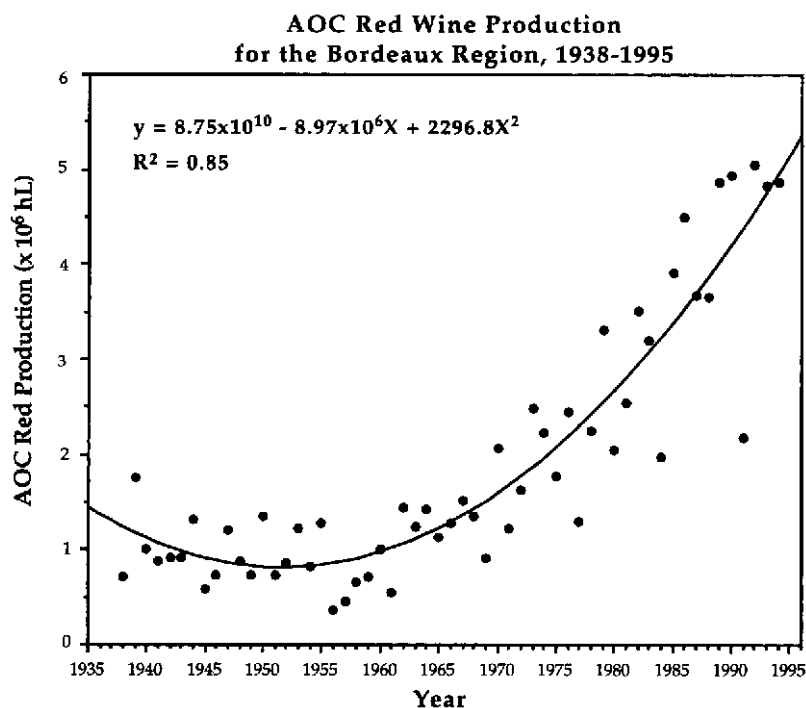
AOC Red Wine Production for the Bordeaux Region, 1938–1995

$$y = 8.75 \times 10^{10} - 8.97 \times 10^{6} X + 2296.8 X^2$$
$$R^2 = 0.85$$

Figure 9. Appellation d'Originie Contrôlée (AOC) red wine production (hectoliters) for Bordeaux. The trend line indicates the statistically significant function used to detrend the time series and is given by the equation inset in the figure (data source: Conseil Interprofessionnal du Vin de Bordeaux, 1995)

of enologists, the quality of wine has not improved in a similar manner. Is it that the taste buds of wine aficionados have improved or that we have just become less tolerant of bad products? Whatever the reason, results show that the individual vintage ratings are relatively free of technological advances, with no trend evident over the period of record (Figure 8(a)). Historically, these individual vintage ratings have been attributed primarily to variations in both climatic and edaphic conditions (Unwin, 1991). Given that the literature does not suggest technological trends in either phenological events or vintage quality, their variations are assumed to be mostly a function of climate and are not detrended.

3.6. Regression analysis

A calendar of k-means clusters for the circulation and air mass analyses is produced for each stage of grape development for 1949–1995. Annual cluster frequencies are calculated for each phenological stage (based on the phenological dates for each year) and standardized by subtracting their long-term mean. These deviations are then used as independent variables in the examination of the viticulture–climate relationships for the region. The phenological date models are developed using all of the circulation and air mass cluster frequencies that occur during the phenological stages prior to a given event during the vintage (1949–1995). For example, the model for floraison is run using all of the map–pattern and air mass clusters that occur during the dormant and the bud break stages prior to flowering.

Analysis for the date of floraison in the Bordeaux region results in a two variable model that accounts for 31% of the annual variation in that event (Table V(a)). Circulation cluster SLP-B7 (Figure 4(c)) and air mass cluster BDX-B4 (Figure 4(b)) have positive coefficients indicating that as they increase in frequency the date of floraison occurs later in the year. Both clusters depict cool to cold and moist conditions that could play a role in delaying the onset of floraison.

A model of the annual variation in the date of véraison is derived from the circulation and air mass clusters occurring in the dormant, bud break and floraison stages and includes the clusters SLP-B7, SLP-F6, BDX-B4 and BDX-F5 (Table V(b)). This model describes 47% of the variation in the date of véraison with each cluster variable having a positive coefficient and magnitudes ranging from 0.43 to 0.93. Each of the variables in the model is associated with days in which there are cool to cold conditions and fog or rain events that delay the onset of véraison (Figures 4(c), 5(c), 4(b) and 5(b), respectively).

For the annual observations of harvest dates in Bordeaux, three clusters appear in a model that describes 65% of the variation (Table V(c)). The model contains three clusters that occur during the véraison stage—SLP-V4 and BDX-V7 (Figure 6(b)) and BDX-V6 (Figure 6(c))—with each variable having a positive coefficient. The combined climatic effect of the three clusters is that increases in the frequency of cP air masses and cyclonic events during véraison are associated with later harvests.

For vintage quality, a model containing three clusters that combine to describe 54% of the variation in the region-wide vintage rating is produced (Table V(d)). The influence of the cluster variables in the model—BDX-F8, BDX-V2 and BDX-V4—on vintage quality suggests that the occurrence of windy and rainy conditions during floraison may adversely affect the ability of the flowers to set completely, whereas mild air masses during véraison provide ample opportunity for the berries to mature (Figures 5(c), 6(a) and 6(d), respectively). The magnitudes of the respective coefficients indicate that the conditions during véraison are slightly more influential in determining a given vintage's quality.

The AOC red wine production model contains two circulation clusters (SLP-B7 and SLP-F1) and one air mass cluster (BDX-B7) (Table V(e)). Two of these clusters do not occur in any of the phenology or vintage rating models, indicating that different climatic influences could be attributed to grapevine production. In addition, the lack of véraison clusters indicates that production is largely controlled by early season climatic influences. The model describes 49% of the variation in AOC red wine production (Table V(e)). Variable SLP-B7, with a negative coefficient, represents low pressure and frontal situations over the region, suggesting that windy conditions and precipitation generating events adversely affect the setting of the inflorescence and thereby reduce the yield (Figure 4(c)). The clusters with positive coefficients—SLP-F1 and BDX-B7—each represent generally mild conditions with anticyclonic events dominant during bud break and floraison, confirming that stable conditions early in the season may be critical to the setting of the inflorescence (Figures 5(a) and 4(a), respectively).

Table V. Viticulture regression models

Model	Adjusted R^2	p value	RMSE Model	RMSE Null	Coefficients of variables in model SLPB7	SLPF1	SLPF6	SLPV4	BDXB4	BDXB7	BDXF5	BDXF8	BDXV2	BDXV4	BDXV6	BDXV7
(a) Floraison	0.31	<0.0001	5.7	8.6	0.90				0.48							
(b) Véraison	0.47	<0.0001	4.9	8.3	0.93		0.70		0.43		0.50					
(c) Harvest	0.65	<0.0001	3.8	7.8				0.99							0.81	0.67
(d) Rating	0.54	<0.0001	0.9	1.9								-0.17	0.19	0.26		
(e) AOC red production	0.49	<0.0001	310 000	522 000	-47 035	31 526				57 643						
Corresponding figure					5(a)	5(c)	6(b)	6(b)	4(b)	4(a) 5(b)	5(c)	5(c)	6(a)	6(d)	6(c)	6(b)

Viticulture regression models described for: (a) floraison dates, (b) véraison dates, (c) harvest dates, (d) vintage quality rating (scale one to seven), and (e) AOC red wine production (hectoliters) using the derived circulation (41 variables) and air mass (34 variables) cluster's annual departures from their mean frequency. Adjusted R^2, model significance, and root mean square error (RMSE) between the regression model and a null model using the mean values of each dependent variable are reported along with the sign and magnitudes of the coefficients for each independent variable (SLP = circulation clusters, BDX = station air mass clusters, D = dormant stage, B = bud break stage, F = floraison stage, V = véraison stage). Below each variable in the model is a reference to the corresponding figure, which depicts that cluster's characteristics.

In addition to adjusted R^2, the root mean square error (RMSE) is used to compare the dependent variables, calculated using our regression models, with null models that use the average values of phenological dates, quality and production (Table V(a–e)). For each parameter, our regression model is an improvement over the null model (e.g. predicted harvest date has a RSME of 3.8 days versus the null model's 7.8 days). In addition, each regression model has a much lower unsystematic component of the RMSE and a greater index of agreement with the observed data, indicating better model performance (Willmott *et al.*, 1985).

3.7. Temporal trends

Nine of the station air mass clusters exhibit statistically significant trends over the period of record. Within-stage correlation analyses (Pearson's product-moment correlation, $\alpha = 0.01$) indicate a general shift to milder and less stormy conditions during each stage.

During the bud break stage, BDX-B7 and the warm cT conditions associated with it exhibit an increasing trend (Figure 10(a)). This cluster has a significant negative correlation with BDX-B2, which
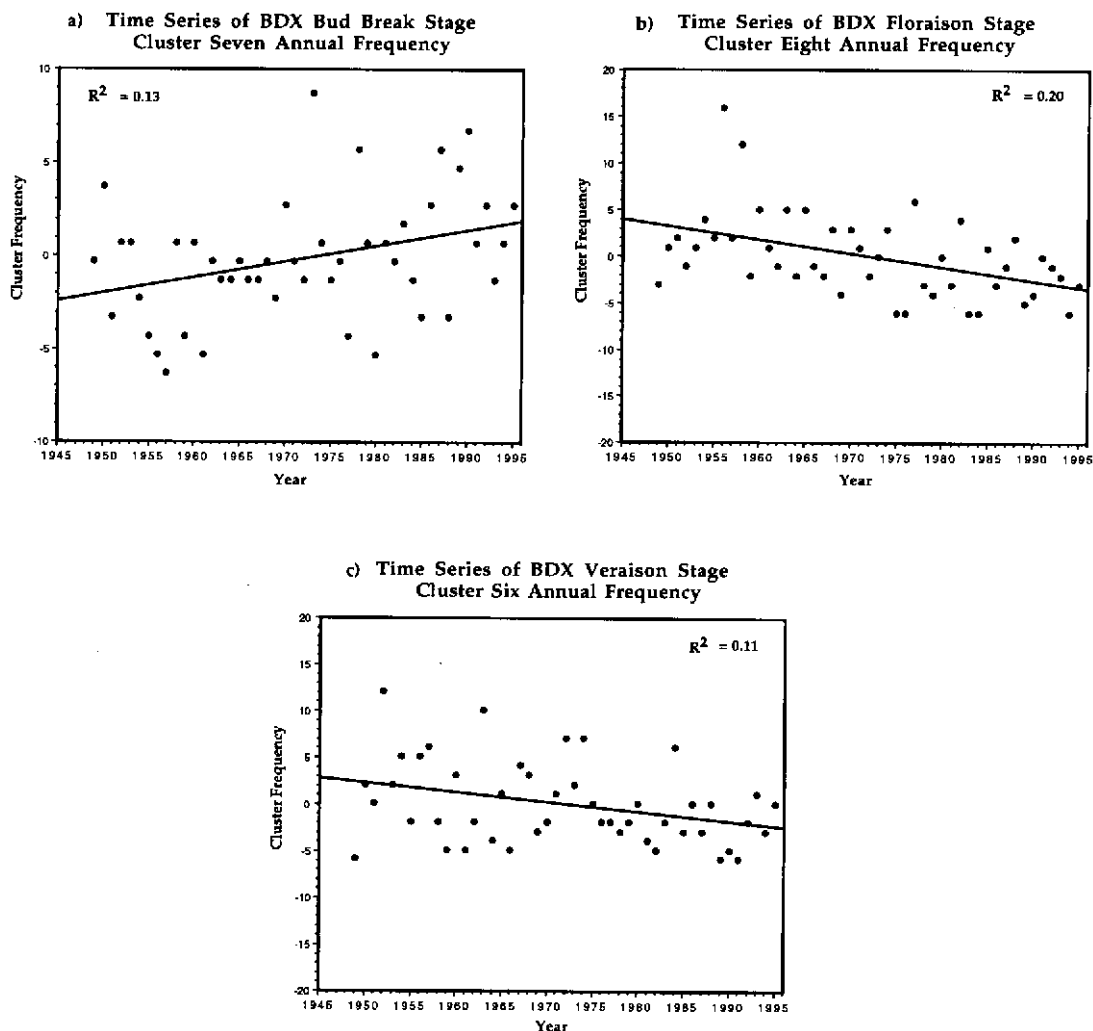

Figure 10. Statistically significant time series trends for three of the nine station air mass clusters (only those clusters that appear in the viticulture models displayed): (a) bud break stage cluster seven—cT air mass; (b) floraison stage cluster eight—cyclonic events; and (c) véraison stage cluster six—cyclonic events

indicates that the increase in cT frequencies is occurring at the expense of cooler and moister mT air (not shown).

During the floraison stage, BDX-F8 has a statistically significant negative trend (Figure 10(b)). This represents a decrease in the number of cyclonic events (Figure 3(c)) and is accompanied by an increase in the milder, warm overrunning associated with BDX-F6.

During the véraison stage, BDX-V6 and the cyclonic conditions found during days in which it occurs has decreased (Figure 10(c)). Correlations with other véraison clusters reveal that this decline corresponds with warmer conditions associated with higher frequencies of mT, cT and mP air masses (Figure 3(d)).

4. CONCLUSIONS

For most crop–climate studies, an arbitrary division of the year by calendar dates is used to conduct within-season analyses. While this can lend some insight into the crop–climate relationship, the lack of a physiological basis may produce results that are inconsistent with the phenological response of the plant. One advantage of the present study is that each vintage for the Bordeaux region is divided according to the major phenological events of bud break, floraison, véraison and harvest, thereby creating four stages based upon the grapevine's annual response to the prevailing climate. This allows for a comprehensive analysis of not only the climatic influences on the timing and duration of the phenological stages, but also for identification of the air masses that are most influential in determining both yield and quality.

Another advantage of this research is the use of air mass-based synoptic climatological approaches that address the integrated effects of climate on viticulture parameters. In air massed-based approaches, there are no *a priori* decisions about which of the variables, or combinations of variables, influence grape growth, production and quality. This 'holistic' approach to crop–climate studies describes how plants respond to the evolving atmospheric environment rather than to the levels of specific discrete climate variables (i.e. temperature, precipitation, etc.). Furthermore, the daily time step used in this paper provides a more detailed analysis than has any previous climate–viticulture research for Bordeaux.

The two synoptic analyses—a regional map–pattern analysis and a local air mass analysis—produce 75 clusters that define the regional circulation (41 clusters) and the air masses (34 clusters) at Bordeaux over the course of a year. A high degree of both spatial and temporal cohesiveness is evident between the two sets of derived synoptic climatological clusters. A comparison reveals that some of the air mass clusters occur in more than one circulation cluster, indicating that different spatial fields can result in similar local air masses. In addition, air mass clusters that occur most frequently with a given circulation cluster are consistent with the spatial surface pressure fields. For example, spatial fields that depict anticyclonic conditions over Western Europe are associated with Bordeaux air mass clusters that have high station pressure, low temperatures and dewpoint temperatures, winds from the north to northeast and little cloud cover.

Viticulture and viniculture are intimately linked to climate. Despite the vast amount of research previously conducted on this topic, there have been few long-term systematic studies of how day-to-day changes in weather affect grapevine phenology, the quantity of the wine produced and the quality derived from it. This research demonstrates that daily variations in regional circulation and air masses that affect the Bordeaux region are closely tied to all of these parameters.

On a region-wide basis, a large amount of the annual variation in phenology, production and quality is accounted for by a few synoptic situations. For the phenology of the grapevines, from 31 to 65% of the annual variation in the timing of the events are explained. In general, events that bring about cooler and moister conditions (associated with cP or mP air masses and circulations) during the preceding stage control to a large degree when the phenological event occurs.

Over half of the annual variation in vintage ratings is described by the relative frequency by which three local air mass clusters occur. Cyclonic events and precipitation generating situations during floraison are shown to have a negative effect on quality, presumably through their adverse affect on flowering and berry set. Generally warm and stable air masses occurring during véraison, on the other hand, exhibit a

positive influence and thus increase the likelihood that full berry maturation will occur. Overall, while some of the variability in vintage quality can be described by events that occur during flowering, it is evident that a larger degree of wine quality variability is derived during the véraison stage of grape maturation.

Detrended AOC red wine production is described by a collection of events that occur early in the vegetative stages. Increased occurrences of stable and warm anticyclonic spatial fields and mild air mass clusters promote inflorescence formation during the bud break stage, the completeness of flowering, and the setting of the berries during floraison. Conversely, increased frequencies of low pressure fields and frontal air mass conditions are found to adversely affect the inflorescence initiation, flowering and berry set and, therefore, to reduce production.

Nine air mass clusters display temporal trends that are indicative of a general shift to warmer, less stormy conditions during each stage. This trend toward more mild days could be responsible for the excellent vintages (in terms of both production and quality) observed over the last 20 years. Of the nine air mass clusters that display trends over the period of record, three appear in several of the viticulture models as significant variables. Cluster BDX-B7 (warm continental air) has increased in frequency and, because it has a large positive influence on production, might be responsible for some of the high production levels in the last decade. Cluster BDX-F8 (cyclonic events) produces strong winds and rain and has a negative effect on vintage quality by affecting flowering and berry setting. This cluster has declined in frequency over the time period. Cluster BDX-V6 (cyclonic events associated with frontal incursions during véraison) contributes to later harvest dates and its decreased frequency could account for the earlier maturation and ripening of crops.

While this research has focused on historical climatic influences on grape growth, quality and productivity, future trends for the wine industry in Bordeaux are promising. Over the last two decades, the major phenological events for grapevines occurred earlier than the first part of the record. These observations are in agreement with an observed lengthening of the growing season in Europe of nearly 11 days over the last 30 years for many species in the International Phenological Garden (IPG) network (Menzel and Fabian, 1999). The IPG phenological modelling indicates that temperature effects, as related to regional warming, are driving the changes. Furthermore, Bindi *et al*. (1996), comparing different models of future climate change for Italy, found indications of a composite 23-day reduction in the interval from bud break to harvest and possibly an increased yield variability for Cabernet Sauvignon and Sangiovese grapes as a result of increased carbon dioxide levels and temperatures. While it is clear that climate change adaptation in phenology and yield between varieties and viticultural regions will occur (Kenny and Harrison, 1992), a longer and warmer growing season will bring greater ripening potential and, therefore, greater wine quality to Bordeaux.

In conclusion, it is clear that unique combinations of weather elements act to influence the phenology, the quantity and the quality of the vintage in Bordeaux. Variations in the regional circulation and the local air masses are shown to affect variations in each viticulture variable. Using the major observed phenological events for the Bordeaux region—bud break, floraison, véraison and harvest—has allowed for a realistic physiological division of the seasons from which a better representation of the climatic influences on viticulture are established and evaluated. The development of the day-to-day synoptic climatologies has provided a detailed description of the integrated effects of climate on viticulture for the region and provides much more detailed information than do traditional climatological methods.

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APPENDIX A. STATION MODEL KEY

Symbolic meteorological station model descriptions, as used in Figures 4–6. Pressure is reported on the station models in standard meteorological form in tens and tenths of millibars. The initial 9 or 10 and the decimal point are omitted (e.g. 158 = 1015.8 mb or 978 = 997.8 mb).

Station Model Key
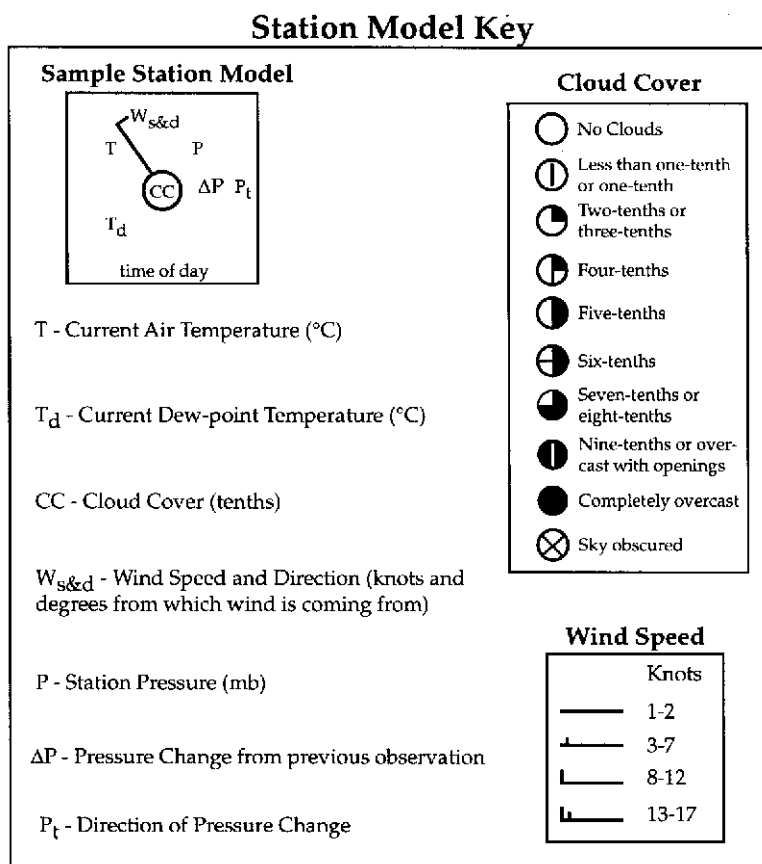
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