Wine, weather and climate

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The climatology and meteorology of viticulture is a vast and fascinating study. The fruit of the vine and indeed the style, quantity and quality of the resultant wine is immensely influenced by macro-, meso- and micro-climatic conditions of the vineyard and also the weather events occurring in each growing season. For instance, the dates of grape harvests have been famously used as phenological indicators of climatic fluctuations in northern Europe by Le Roy Ladurie (1971) and others. This paper provides a broad overview of the influence of climate and weather on wine and the interested reader is advised (and encouraged) to examine the other, more extensive, reviews in the texts listed (e.g. Robinson 1994 or the excellent text by Gladstones 1992).

Wine is an alcoholic drink made by fermenting the juice of fruit or berries. It is a potable chemical composed of ethyl alcohol, several other alcohols, sugars, carbohydrates, minerals, vitamins, polyphenols, aldehydes, ketones, enzymes, pigments, and at least 22 organic acids (Amerine 1964). The number of possible permutations and combinations of these ingredients is as immense as the varieties and qualities of wine. Distinctions between wines can arise from one season (or vintage) to the next but also feature on a variety of spatial scales – from differences between continents to those that could occur between adjacent vineyards.

The emergence of a 'fine' wine is fundamentally controlled by the variety of the grape, yet recent developments in viticultural practices have resulted in very drinkable wines from mediocre grapes. Having said this, the main spatial and temporal differences in wine are controlled by factors of physical geography, especially those related to weather and climate. These determine the limits of vine cultivation, the critical timing of cultivation practices, and the quality and quantity of the grapes.

In a comprehensive geographical account of viticulture, De Blij (1983) writes that climate, soil and slope are the key physiographic factors in wine growing, and of these factors climate is the crucial one. This environmental interplay is captured by the French word 'terroir', which, although often mistranslated to mean just 'soil', is actually the coming together of climate, soil and landscape. It is the interaction between slope, aspect, soils, geology, altitude, temperature, radiation, humidity, shelter, continentality and drainage.

Macroclimatic influences on viticulture

In the first instance, certain climatic means determine whether or not the vine will grow and produce a fruit. It is widely accepted that the best potential for viticulture lies somewhere between the 10 and 20 °C annual isotherms (see Fig. 1). Most wine-producing regions, therefore, are located between latitudes 30° and 50° in each hemisphere, although other wine is successfully produced at altitude in regions near the equator such as Bolivia, Kenya and Tanzania.

Temperature

Ideally, mean annual temperature should be about 15 °C, with a summer monthly maximum of 22 °C and a winter minimum of 3 °C. Moreover, grapes need sustained warmth to ensure a high sugar content in the fruit for conversion into alcohol. Warmer climates result in a more alcoholic, full-bodied wine, whereas a cool climate produces the more crisp, higher-acidity, fresher-flavoured product essential for dry table wine. Too cool a climate (less than 15 °C in the final month of ripening) and the grape does not ripen properly, leading to too much acidity, or it may not ripen at all.

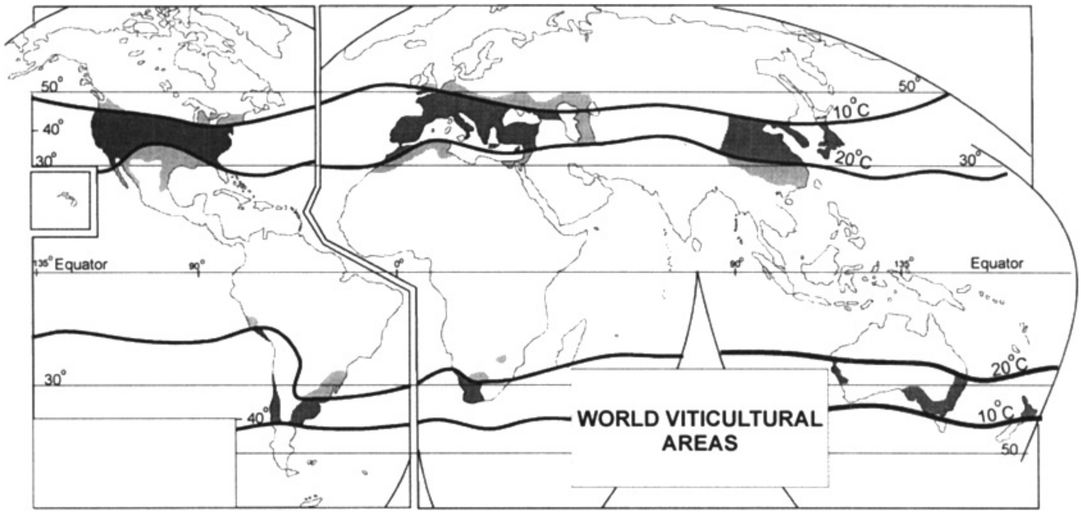


Fig. 1 World viticultural areas and 10 and 20 °C annual isotherms (from De Blij 1983). Dark (light) shading indicates areas of greater (lesser) importance.

A long growing season means that most of the British Isles lies to the north of the limits of production, and in other well known regions, such as southern Germany, lowland Switzerland and even the Champagne and Burgundy areas of France, colder years lead to low grape sugar and entail the addition of sugar to the wine at a later stage. In these regions the typical average mean temperature of the final month of ripening is about 15–16 °C. Warmer climates (21–24 °C), such as those of southern Spain, Sicily, Cyprus and southern California, lead to high grape sugar and low acidity which makes a very sweet product but one that lacks subtlety and colour. These regions often supply dessert wines. Ideal thermal conditions in Europe can be found in Bordeaux in France, in northern Spain, and in central and northern Italy (18–20 °C in the final month).

The variability of the summer climate is the main reason for the fluctuation in the quality of wines from year to year, and so there is an emphasis on certain 'vintage' years. The vine exhibits a marked annual cycle, making the annual distribution of temperature important. Vines are dormant throughout the winter months and this is a period during which the vine can rest (in the tropics, where vines are evergreen, the lack of a dormant period can lead to small crops of poor-quality grapes). When the mean daily temperature reaches 10 °C in the spring, rapid growth of shoots takes place. About eight weeks later, when mean daily temperature has risen to about 20 °C, flower clusters bloom, and after pollination and fertilisation small berries 'set' and grow.

Late frosts can be very damaging and, if they occur during budding or flowering, could mean that the crop never fully recovers. In winter, during dormancy, the vine is less susceptible on account of the accumulated sugar in the plant – a temperature as low as –18 °C can be tolerated for short periods – whilst in spring –4 °C will kill young leaves, and –2 °C will damage emerging flower clusters (Jackson and Schuster 1981). Cultivators routinely combat the effect of frost by warming the vineyard with heaters or large fans, or by spraying water on to the plants. The latter method leads to ice forming on the leaves and stem and prevents the temperature from falling much below 0 °C. Very cold spring weather results in what the French term 'coulure', which is the dropping of the flowers before satisfactory pollination, and 'millerandage', which is uneven flowering eventually leading to small hard berries featuring in the bunches. A particularly damaging frost in France occurred in 1991 (see later) but the most damaging cold weather in that country occurred in January and February 1709 and led to a huge restructuring of French viticulture. On 13 January 1709 the air temperature in Paris fell to –20 °C and remained there for ten days. This happened again in February, and the Channel port of Dunkerque was ice-bound until April. The freeze caused widespread destruction of vines, especially in low-lying valley areas, and created the need for extensive replanting. In fact, most northerly vineyards were not replaced but, somewhat paradoxically, the event stimulated a dramatic growth in wine production in France (Unwin 1991).

Although temperature is only one of many climatic controls, it is crucial. A good indicator of the temperature characteristics of regions suitable for viticulture is provided by a heat summation statistic, that is, the number of 'degree days'. Degree days can be used to assess the limits to viticulture, to evaluate what grape varieties are required and are best adapted to the conditions, and to ascertain whether irrigation is needed. Heat summation figures have proved valuable and have been extensively used to identify viticultural regions in California (Fig. 2) because here temperature has been found to be quite closely correlated to other climatic factors. The number of degree days is calculated by recording the mean temperature and counting the number of degrees by which each daily value exceeds 50 F (or 10 °C in places other than the USA). This

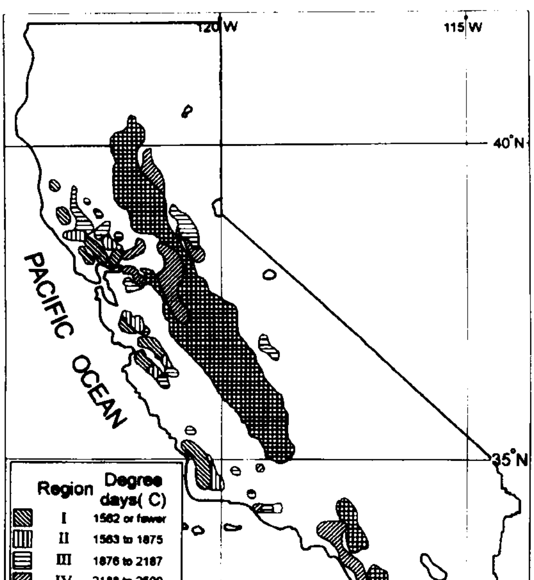


Fig. 2 Californian viticultural regions based on heat summation statistics (from De Blij 1983)

threshold value is regarded as the level of dormancy. Daily values can then be summed to provide an annual figure. This would mean that (based on Celsius) the Champagne region, which is on the northern limit of wine production, has about 1530 degree days per year, Bordeaux 1575, the Duoro valley in Portugal 1730, Jerez in southern Spain 2625 and Algiers 3250 (De Blij 1985). Unfortunately, in many locations (*e.g.* New Zealand, Australia and Italy) temperature is not correlated with other climatic factors and this approach is less useful.

Excessive daytime temperatures (greater than 40 °C) may lead to heat stress. In these conditions the vine literally 'shuts down' and stops photosynthesising. When combined with high sunshine amounts and high winds, there can also be water stress.

Sunshine

High sunshine amounts are essential for ripening the grape by providing the necessary energy source for photosynthesis. Warm, sunny climates ensure rapid ripening, higher sugar and lower acidity. On the other hand, in some regions there may be good reasons to attempt to reduce sunshine by artificial means, for instance by training. This is practised in north-west Portugal where vines are trained high up on arbours and trees, thus ensuring that berries are kept cool (there is plenty of shade and less reflection from the ground). The resultant wines (vinho verde) are typically sharp and fresh and high in acidity (Unwin 1991). Red wines generally require higher sunshine amounts, so cold and cloudy years, such as 1984 in France, result in some disappointing reds due to non-ripening of the grape. At the other extreme, overexposure to sun can lead to injured grape tissue in a condition known as 'sunburn'.

Moisture

An adequate moisture supply is required by all crops and is related to temperature with respect to the rate of evapotranspiration. Most wine-producing areas have annual rainfall amounts of between 400 and 800 mm; however, some regions (*e.g.* southern Spain) can prosper with adequate irrigation. Irrigation is a much maligned practice in viticulture and has been all but banned in France. Cultivators are less likely to pursue innovative means for dealing with the shortfall of water supply, and no irrigated vineyard has yet produced wines comparable to the best from unirrigated zones where there is natural growth. The reason for this is that a plentiful supply of water causes the vine to thrive, there are big berries and increases in yield (often by 300 per cent), but often poor-quality wine grapes.

In addition to total rainfall, the timing of rain events is critical. Rain is needed during winter and early in the season; however, high amounts in summer and early autumn around harvest time can be damaging – resulting in watery grapes or even causing them to split, ferment on the vine and be infected by fungus. In the wetter areas, drought years can often result in the best vintages, especially of red grapes. This is because the reduction in available moisture arrests excessive vegetation growth, leading to limited yields and small berries with a high ratio of colour and flavour-containing skin to juice. In dry years a small amount of rain near to harvest can be beneficial. In 1995 Bordeaux was said to have been 'saved by the rain' – towards the end of the hot dry summer the vines began to shut down which prevented the fruit from ripening; September rains resulted in rich ripe grapes and very concentrated wines (Fig. 3).

High atmospheric moisture can be a problem due to the tendency for mould, disease and insects to thrive, and this effectively rules out the south-east of the USA as a wine-producing area. In contrast, the welcome development of a fungus known as noble rot or 'pourriture noble' (*botrytis cinerea*) occurs in late-harvested grapes in certain vineyards in France and Germany. In September and October, days are warm and nights cool resulting in a heavy dew and an increased frequency of fog. The fungus gradually attacks the skin of the grape, piercing it and evaporating the water within. The result is a shrivelled and unsightly berry. However, as the grapes are ripe, far from spoiling the vintage this increases dramatically the concentrations of tartaric acid and sugar, giving the wine an immensely sweet flavour and stimulating the production of glycerol that results in its characteristic viscosity.

Perhaps the most famous botrytised wine is Sauternes. This is a product of a specific mesoclimate close to the Garonne in Bordeaux, where autumn mornings are very moist. The essential difference between a mediocre and a great Sauternes, therefore, is the willingness for growers to wait for noble rot to develop. Delay risks the chances of frost or rain which would ruin the harvest, whereas picking too soon gives an insipid sweet wine.

Other climatic factors

Many other climatic factors can be identified. Strong winds are hazardous and can be structurally damaging, requiring the erection of artificial windbreaks in particularly exposed areas (valleys, coasts and high land). In Morocco, winds from the Atlantic frequently subject vines to 65 km h^{-1} gusts. The mistral in the southern Rhone valley is another example of where natural or artificial barriers are needed. Even gentle breezes can pose problems to

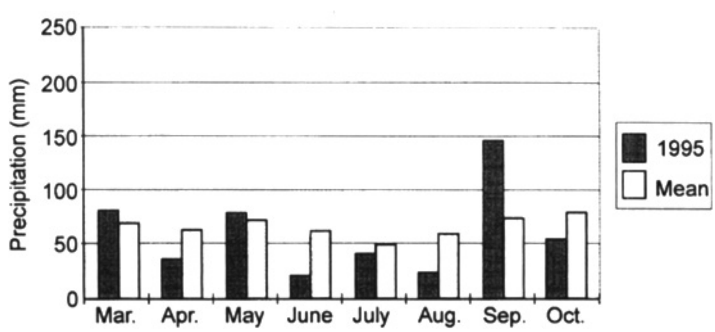


Fig. 3 Precipitation in Bordeaux in the 1995 growing season – a dry year 'saved' by September rains

coastal vineyards, as in California and South Africa, as salt-laden air can harm the leaves of the vine. In dry areas, increased wind speed enhances water stress by increasing rates of evapotranspiration. The sirocco from north Africa can afflict the vineyards of southern Europe in the same way as desert winds blowing out of central Australia can desiccate vines there. Nevertheless, some wind can be beneficial by bringing a moderating effect on days of very high temperature.

More recently it has been noticed that air pollution has an impact on vine health. This was first noticed in the 1950s in southern California. Photochemical pollutants such as ozone cause a dark stippling of vine leaves which inhibits photosynthesis, thus reducing growth, limiting grape size and reducing grape sugar.

Microclimatic factors

Small-scale variations in wine yield and quality are often due to microclimatic factors which are related to geographical location. Topographic factors determine microclimates; for instance, slope angle and aspect are crucial in determining vineyard location. River valleys often make desirable viticultural areas because of the moderating effect of water on night-time temperatures, reflection from the water surface and the fact that they permit the penetration of maritime influences some considerable distance inland (*e.g.* Bordeaux). Some of the best known wine regions reflect this fact; in France there is the Loire and the Rhone, in Portugal the Douro, and in California the Napa valley. Not all slopes are major river valleys; for instance, the Côte d'Or (Burgundy) is a major fault scarp with gentle south-east-facing slopes.

Vineyards are often positioned mid-slope in the so-called thermal belt. If they are located too high, they can be exposed to strong winds, yet on the other hand sites in valley bottoms should also be avoided due to the effects of katabatic winds (cold-air drainage) and potential waterlogging. Slopes that face the sun through much of the day (a southerly aspect in the Northern Hemisphere) are favoured as they are warmest, and this is most important at night when the soil radiates back the thermal energy. Warm soil temperatures stimulate the activity of the roots which is good for the vine's nutrition. Climatic contrasts between aspects are most noticeable at higher latitudes and early in the season (when the sun is furthest from the vertical), and when slopes are steeper. Easterly aspects are advantageous as they have their 'backs to the wind' and are less exposed to cold stormy winds, and because they warm up with the sunrise which is when the soil and air temperatures are lowest and most damage could occur. Examples of easterly aspects include the Côte d'Or in Burgundy and the Rhine valley of Alsace and Germany. Some isolated hills are the home to famous viticultural areas because the thermal zones are strongest as there is no large source of chilled air. Famous examples include the Hill of Corton at Aloxe-Corton in Burgundy and the Montagne de Reims in Champagne.

Rock and soil type influence the root temperature and that of the canopy by re-radiation. Chalk, for instance, takes warmth which is then reflected back to the vine. This can be useful in cooler regions.

Wine regions in France

France is universally accepted as the foremost producer of wines in the world (Fig. 4). It sets standards to which other countries aspire, and French grape varieties, for instance Cabernet Sauvignon, have been planted all over the world.

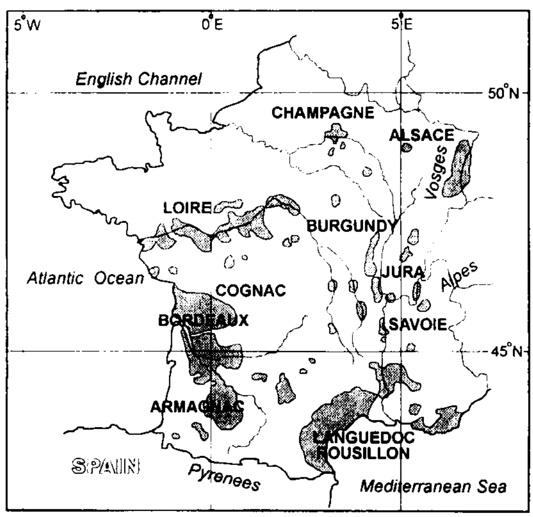


Fig. 4 Wine regions in France

Bordeaux

The chateaux of Bordeaux, collectively, provide by far the largest supply of high-quality wine in the world, yet there is still much year-to-year uncertainty about the vintage and this is related to weather. Usually, spring is mild and damp, giving ample supplies of moisture for early growth. Conditions at flowering in June are critical – cold rain and strong winds are most unwelcome. Summers are hot, yet often tempered by cool breezes from the Atlantic.

Burgundy

The vineyards of Burgundy extend across four departments to the south-east of Paris. The term 'Burgundy' encompasses a wide variety of wines such as Chablis and Beaujolais and the worst climatic hazards occur in the most northerly vineyard area in Chablis. Burgundy has a more continental climate than Bordeaux – colder and drier in the winter and with a shorter, more variable, summer. As a result, only early-ripening grapes are grown (such as the hardy Chardonnay). Reds often lack sufficient sun to ripen properly and so can be rather thin. Particularly heavy rain and hail often fall in May, June and October.

Champagne

The ancient province of Champagne produces wines of the same name in the most northerly vineyards in France. The region is very near to the limit beyond which grapes will not mature, and wine growing here is considered rather precarious. Champagne grapes do not ripen fully unless there has been a particularly hot summer, so this wine is traditionally blended. Blends of different villages and vintages are used. Certain vineyards are much better than others, depending on soil characteristics, and microclimate is less important in this region.

The weather is often bitter in winter although the hard frosts are less of a worry when vines are dormant. The enhanced continentality compared to Bordeaux leads to hot summers with thunderstorms, and even hailstorms, which can strip the vines of fruit and foliage. In general the area is flat with gentle slopes of about 100–150 m, most facing full south. The climate is cool, and with an average temperature of 10 °C over the year it is at the limit of vine survival; however, the thin chalky soil absorbs and reflects solar radiation giving extra warmth to the growing grapes.

Frost of April 1991 in western France

Many vine growers in the west of France awoke to a devastating frost on 21 April 1991. In places, temperatures fell as low as –12 °C. In the previous week a cold upper trough had established itself over central Europe and was feeding cold air in from the north (Fig. 5). At the surface the winds swung from westerly on the 17th (Fig. 6(a)) to northerly on the 18th (Fig. 6(b)) behind a depression which was moving slowly south-eastwards down the North Sea. A cold front in the rear of this system swept from north to south across France on the morning of 19 April, bringing light falls of snow and a drop in temperature. As the low moved into northern Italy, dry and cold surface flow was directed from Scandina-

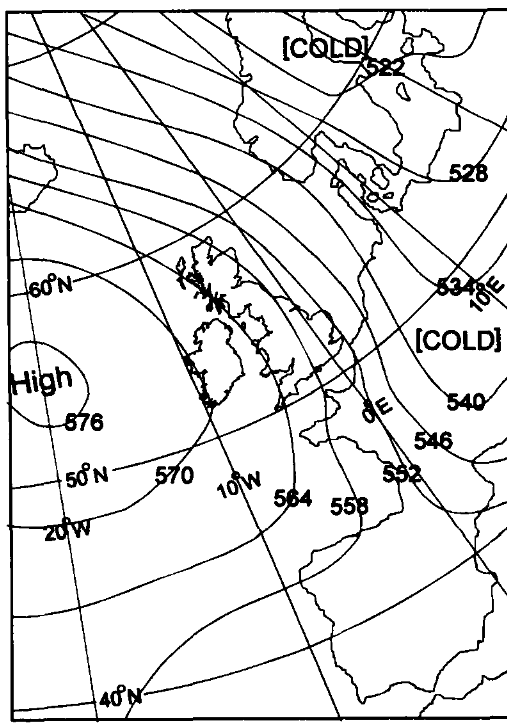
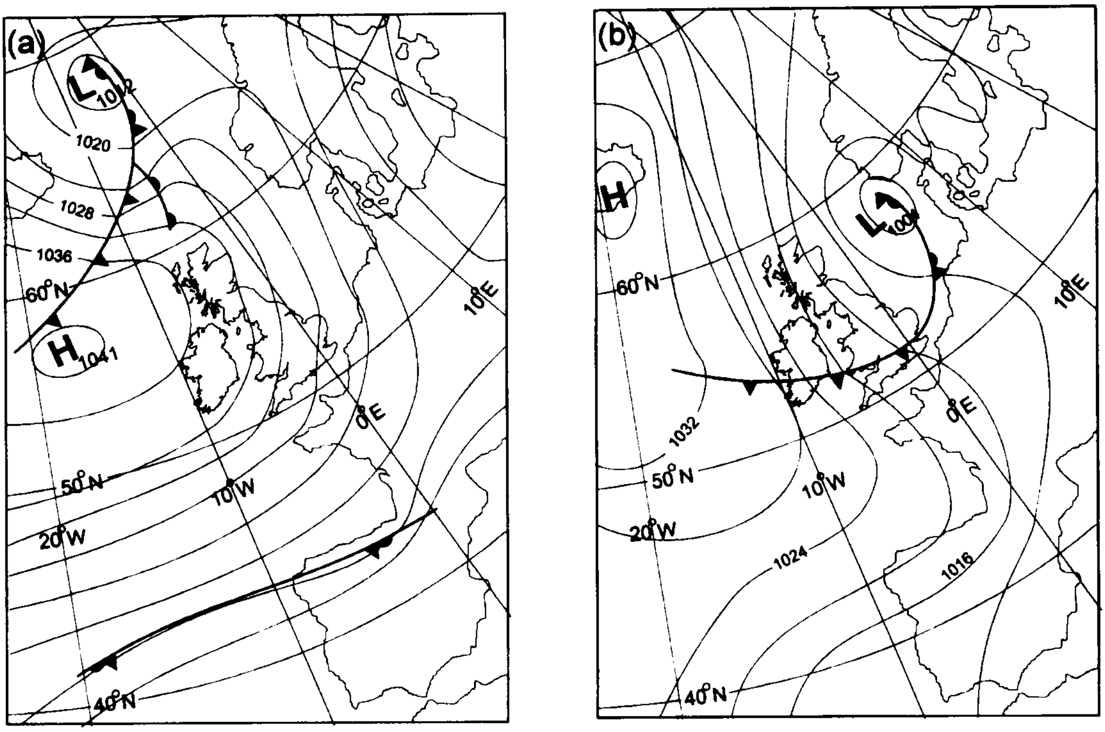


Fig. 5 500 mbar chart (dam) for 1200 GMT on 17 April 1991



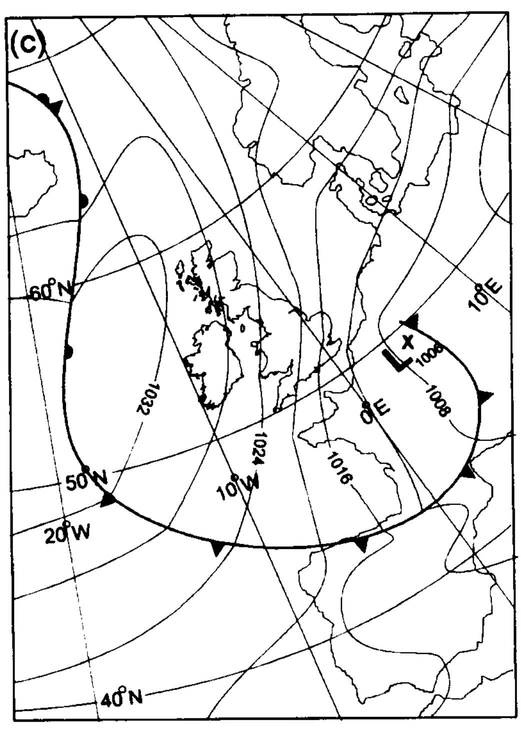


Fig. 6 Surface charts (mbar) for 1200 GMT on (a) 17 April 1991, (b) 18 April 1991 and (c) 19 April 1991

via (Fig. 6(c)). The result was a mass of cold air descending on the vines.

Attempts were made to control the damage. This included the use of helicopters to stir up the surface layers. However, the depth of cold air was considerable. Growers also burned tyres to heat the air but this has only a very localised effect. On the right bank of the Gironde, damage was calculated to exceed 80 per cent of the crop. Areas in the Bordeaux region nearer to the sea (such as the Medoc) were less affected due to the ameliorating effect of the Gironde estuary. Burgundy and regions in the east and south were much less affected by frost than Bordeaux; nevertheless, total French wine production in 1991 amounted to less than 43 million hl compared to the usual 65 million hl (Robinson 1994).

Recent vintages

Wine quality varies from year to year. The quality of a wine is assessed by tasting and the preparation of a vintage chart. The International Food and Wine Society's vintage chart is one of the best known and has been issued since 1935. Wines are given a rating from 7 (the best) to 0 (no good). Recent vintage ratings can be explained by particular meteorological factors in the growing season. For instance, 1990 was a good year for red Bordeaux (6) and red Burgundy (7). It was a hot dry summer across Europe with abundant sunshine. In 1991 the frost in spring and a generally wet growing season reduced wine quality (Bordeaux 3). On the other hand, the impact was not so great in eastern areas such as Burgundy (5). In 1992 rain at flowering and at harvest in Bordeaux (3) brought down the quality of the wine, yet again this was less of a problem for Burgundy (5). The impact of rainfall is well demonstrated in Fig. 7.

Conclusion

The question, therefore, is as follows: can one identify the best climate for wine, or growing-season conditions that are optimal? Lack of moisture can be addressed with irrigation, and windbreaks can be erected, but vineyard temperature and sunshine are beyond effective modification (De Blij 1985). Different grape varieties will require different conditions. Nevertheless, two climatic types have been identified as the best compromises for wine quality. First, there is the cool to mild growing season and uniform summer rainfall of regions such as western and central Europe. Vineyards in these areas are sheltered with east-facing slopes downwind of hills and mountains (*e.g.* Rhine, Burgundy). The second type is the warmer Mediterranean climate, particularly where the summer heat is moderated by afternoon sea-breezes or altitude. In this climate there is less risk from excessive rain and lower humidities (*e.g.* Languedoc Rousillon, Douro, South Australia).

In the past, most of the world's great table wines hailed from regions of the first climatic type due to the fact that only certain mesoclimates had the best conditions, yet in regions of the second climatic type wine was cultivated virtually anywhere. In recent years, with a better knowledge of climate and *terroir* requirements, improved irrigation (particularly in New World areas) and better canopy management, there has been an emergence of high-quality wines from Mediterranean climates.

The well known Koppen map of climatic regions (Fig. 8) can be used to illustrate these two climatic types. De Blij (1983) notes that, although the Köppen classification reveals little about available moisture for plant growth, it adequately indicates preferred environments. The crucial climatic type is C (humid temperate or humid mesothermal climates), although vines are cultivated in arid type B with irrigation. C climatic types divide into Cf, which includes northern Europe and is defined by moderate temperatures and rain falling in every month of the year, and type Cs which surrounds the Mediterranean Sea (and is also found in California, Chile and Australia). Cs is characterised by very limited rainfall (often drought) in the summer months. As the vine must have water, yet too much summer rain weakens the crop, 'ideal' conditions can be identified as the transition zone between Cf and Cs types. The summer drought of Cs climates is less pronounced at the northern margin in the Northern Hemisphere as it yields to the moister conditions of Cf. The transition zone, therefore, brings an extension of the winter rainfall period into early spring (the crucial time for budding and flowering), a summer with occasional rain and some cloudiness, and a warm sunny period of about a month to six weeks just before harvest in early autumn. Both Burgundy and Bordeaux are located in this Cf/Cs zone.

What of the future? With respect to climate change, proponents of the greenhouse effect suggest that there will be a profound impact on viticulture as a consequence of a 2 degC rise by the middle of next century (Kenny and Harrison 1992). Many wine growers in existing areas hope for a higher frequency of vintages of the quality of 1990 and 1995. Kenny and Harrison (1992) present detailed projections which include a poleward migration of successful wine-growing beyond the limits of the Middle Ages into very marginal areas such as England, northern France and the South Island of New Zealand. It is also likely that existing hot-climate viticulture will become less tenable.

Nowadays there is less sensitivity to environmental extremes due to cross-fertilisation and hybridisation. New cultivars are continually being developed to withstand late frosts, heat,

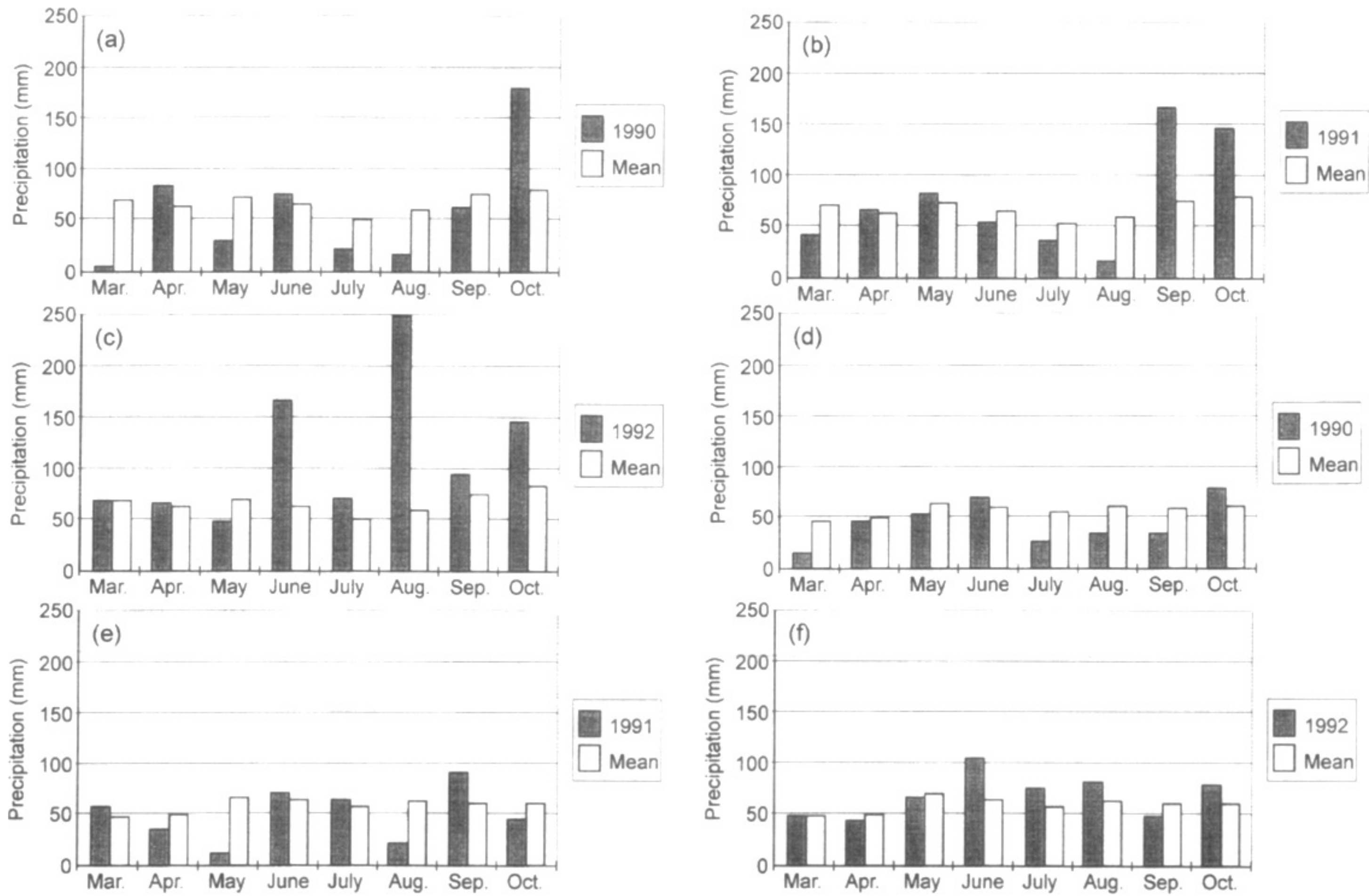


Fig. 7 Precipitation in Bordeaux and Burgundy, 1990–92. Statistics are derived from the global gridded precipitation dataset obtained from the University of East Anglia. The Bordeaux region is summarised by rainfall at 45.0 N, 0.0 W and Burgundy by rainfall at 47.5 N, 3.75 E. (a) Bordeaux 1990 – a magnificentvintage; a drought year with rain after harvest. (b) Bordeaux 1991 – The frost in April halved the crop and rain in September interrupted the vintage. (c) Bordeaux 1992 – rain at flowering in June, very heavy rain in August and at vintage; a huge yield but rather light. (d) Burgundy 1990 – a great vintage after the long drought. (e) Burgundy 1991 – small harvest; some rain at vintage. (f) Burgundy 1992 – good despite rain at flowering.

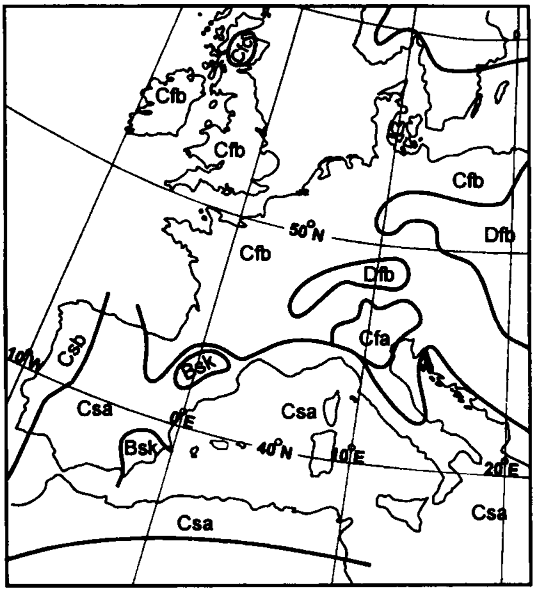


Fig. 8 Köppen climatic types for Europe. The two most important for wine growing are: Cf – average temperature of warmest month more than 10°C and coldest month between 18 and 0°C, precipitation at all times of the year; Cs – same temperature characteristics as Cf but precipitation in the driest month of the year is less than 40 mm, which is less than one third of the amount in the wettest month.

humidity, drought and winter cold. One would hope, however, that the climatic, meteorological, and indeed other, natural environmental factors that make wine so different and distinctive from place to place and year to year are not 'smoothed out' and wine continues to be an intriguing drink for many people.

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An unusual barograph

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Most readers will be aware that a barograph is a device which has the fascinating ability to record variations in atmospheric pressure on a paper chart. Some of these instruments operate on the principle of measuring the height of a column of mercury but the vast majority monitor the changes in dimension of an evacuated, thin metal box as it flexes under changing pressures. These 'boxes', known as aneroids (the word 'aneroid' simply means 'without liquid'), can take many forms. In every case, however, some means has to be found to prevent the aneroids from collapsing under the action of the large forces produced by the pressure of the atmosphere.

An interest in meteorological instruments extending over many years has led me to acquire over a dozen barographs, all of different patterns and arrangements. However, until 1998 I had never encountered one quite like the instrument shown in Fig. 1. In fact, in spite of reading widely on the subject, I have never seen one of these illustrated anywhere. On p. 431 of Middleton's classic *The history of the barometer* (Middleton 1964) there is a description of this instrument or of something similar but much larger:

> "... the largest aneroid barograph must surely be the one which stands in the