Climate and Climate Impact Scenarios for Europe in a Warmer World

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ABSTRACT

Scenarios for Europe in a warmer world, such as may result from increased atmospheric carbon dioxide levels, have been constructed using the early 20th century warming as an analogue. Mean temperature, precipitation and pressure patterns for the period 1934–53 were compared with those for 1901–20. These are the warmest and coolest twenty-year periods this century based on Northern Hemisphere annual mean surface air temperature data, differing by 0.4°C. The climate scenarios show marked subregional scale differences from season to season, and individual season scenarios often show little similarity to the annual scenario. Temperature scenarios show warming for the annual mean and for spring, summer and autumn. The largest positive changes are found in higher latitudes. Winters over a large part of Europe are actually cooler and show greater interannual variability during the warmer period. These changes appear to be associated with a greater frequency of blocking activity. Precipitation changes occur in both directions in all seasons. There is, however, an overall tendency for spring and summer to be drier and autumn and winter to be wetter.

The climate scenarios are used to construct scenarios of the impact of a global warming on energy consumption and agriculture. Cooler winters alone would imply greater energy demand for space heating, but this is largely offset by warmer temperatures in spring and autumn which reduce the length of the heating season. Increased temperature variability combined with a general cooling during winter over north and northwestern Europe suggests a greater frequency of severe winters, and thus larger fluctuations in the demand for heating energy. The impact on agriculture is difficult to assess because of the complexity of crop–climate relationships and because of the importance of nonclimatic factors associated with technological change and, perhaps, with enhanced photosynthesis due to increased carbon dioxide concentrations. In northern latitudes, the increase in the length of the growing season would appear to be favorable for agriculture, but warmer summers, drier springs and wetter autumns would be less favorable. A specific study was made of the effect of two different climate scenarios on crop yields in England and Wales with regression models constructed using a principal components regression technique. Most crops showed a decrease in yield for both warm-world scenarios, with largest decreases for hay yield and least effect on wheat yield. A similar regression analysis of French wine quality showed an improvement in the quality of Bordeaux and Champagne in a warmer world.

1. Introduction

Combustion of fossil fuels and, to a lesser extent, deforestation and changes in land use have lead to a substantial increase in the concentration of atmospheric carbon dioxide over pre-industrial levels. Historical data for the Northern Hemisphere compiled by Callendar (1958) suggest a pre-industrial concentration of 280–290 ppmv. Estimates based on ocean chemistry (Brewer, 1978; Chen and Millero, 1979) and ice core data (Neftal *et al.*, 1982) are slightly lower, around 260–270 ppmv, a level which is supported by some of the early measurements (Wigley, 1983). The present (1981) concentration of atmospheric carbon dioxide is about 340 ppmv. There can be little doubt that carbon dioxide production rates will increase in the future. Predicted values of atmospheric carbon dioxide for the year 2025 range from 440 to 600 ppmv, depending on the forecast growth rate of energy use (Wigley, 1982).

An increase in atmospheric carbon dioxide will tend to disturb the radiation balance of the earth—atmosphere system through enhancement of the greenhouse effect. Increased opacity of the atmosphere to infrared emissions will cause a rise not only in the level at which radiative equilibrium exists (at present ~5–6 km above the surface), but also in the temperatures of the Earth's surface and the atmosphere below the new equilibrium level. Mathematical models of the greenhouse effect are in general agreement that a doubling of the carbon dioxide content of the atmosphere would produce an increase in global mean temperatures of 2–3°C (Gates, 1980; Hansen *et al.*, 1981; Manabe and Wetherald, 1975,

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1980; N.A.S., 1982). However, the climatic impact of increasing CO_2 cannot be viewed purely in terms of a rise in global temperatures. The increase in energy availability resulting from the change in the radiation balance will perturb the whole atmospheric circulation system. Changes in pressure patterns, both geographical and seasonal, will in turn affect rainfall, temperatures, winds, indeed all of the meteorological variables that contribute to the overall climate at a given place.

Clearly then, as a result of a substantial increase in atmospheric carbon dioxide, the disturbance of the atmospheric circulation system will cause complex regional patterns of climatic change. Such changes may in turn lead to extensive disruption of man's climate-dependent economic activities. There are two such activities where the links with climate are critical, and where the climate of a place strongly influences the nature and scale of the enterprise at that place. First, energy consumption rates for space heating and air conditioning are intimately related to climatic conditions. Second, agriculture is strongly dependent for its success upon favorable climatic conditions. A prolonged and pronounced climatic change would force farmers to adapt their agricultural practices to the changed regimes of temperature and rainfall.

This paper seeks to determine the probable impact of carbon dioxide-induced warming on energy consumption and agriculture in Europe. Scenarios are constructed to show possible patterns of climate in a warm world. These scenarios are then interpreted in the light of the known relationships between climate and energy, and climate and agriculture, to demonstrate the resulting impact on these two economic activities. Climatic impact on agriculture is a composite of the impact on individual crops. Thus it is difficult to build from a series of scenarios of such variables as rainfall and growing-season length to an overall view of the impact of increased atmospheric CO_2 on agriculture. We have broken down this problem by examining a number of crops, individually, in spatially-restricted locations. By using principal component regression techniques, we have determined the optimal climatic conditions for each crop, and then interpreted the scenarios on the basis of these findings.

2. Construction of the scenarios

There are two possible approaches to the problem of deriving climate scenarios for a warmer world. The first is to construct numerical models of the general circulation's response to increased carbon dioxide concentrations. The second is to use past warm periods as analogues of a future, warm, high carbon dioxide world. For a comparison of different approaches to deriving warm-world analogues, see Pittock and Salinger (1982).

General circulation models contain various simplifications in order to make the problem numerically tractible with today's computers. Despite these simplifications, they are capable of producing reasonable simulations of present-day climates and some confidence can be placed in their predictions for a high-CO_2 world. However, the only model results which are appropriate for scenario construction are those which have a seasonal cycle and realistic geography. Seasonally specific regional results require either a specified, noninteractive sea surface temperature, or, more realistically, an interactive mixed-layer ocean. Gates *et al.* (1981; see also Schlesinger and Gates, 1981a,b) and Mitchell (1983) have modeled the effects of CO_2 with an ocean constrained to remain at present-day conditions. Such analyses are basically sensitivity studies and cannot be used for scenario development. Mitchell (1983) has modeled the effect of higher CO_2 with an ocean uniformly raised in temperature by 2°C. His results provide some useful insight into possible regional details of CO_2-induced climatic change, but the realism of a uniform 2°C sea-surface temperature warming must be subject to considerable doubt. The only GCM results which can reasonably be used for scenario development, then, are those of Manabe and Stouffer (1979, 1980; see also Manabe *et al.*, 1981). Even in this case the model used has admitted deficiencies and was certainly not meant to be applied to develop scenarios for such small regions as Europe. Furthermore, these models are strictly equilibrium response models, and, as Schneider and Thompson (1981) have demonstrated, it is likely that the regional details of equilibrium and (more realistic) transient response models will differ. Although ultimately model simulations provide the best avenue for scenario development, the models used to date require further work before they can be used in this way.

Fundamental to the analogue approach to scenario construction is the assumption that, given the same boundary conditions (as represented by the oceans and cryosphere), the general atmospheric circulation responds in a similar manner to different forcing mechanisms. Thus all warm periods are assumed to have the majority of near-surface meteorological characteristics in common, even though the underlying causes of the warmth may be quite different. Evidence to support this assumption has been provided by the numerical modeling work of Manabe and Wetherald (1980). They applied two different forcing mechanisms to their general circulation model: on the one hand increased levels of carbon dioxide, on the other increased values of the solar constant. In both cases, the near-surface response of the model climate was similar.

Episodes such as the Hypsithermal warm period and the medieval warm phase have been used as analogues (Flohn, 1977; Kellogg, 1977; Kellogg and Schware, 1981; Butzer, 1980). With such analogues, however, there is simply not enough regional and seasonal detail known in order to use them for scenario development over a region the size of Europe. Furthermore, boundary conditions during the Hypsithermal may have been substantially different from those of today. The approach adopted here is to use instrumental records of the past century to construct warm-world analogues. This method makes use of the natural variability of climate and allows regional and seasonal scenarios to be prepared.

There are a number of different ways in which one can choose years or periods from the instrumental record for the construction of the scenarios. Wigley *et al.* (1980), Williams (1980), Namias (1980) and Jäger and Kellogg (1983) all used composited data from individual years, either comparing warm years with the long-term mean, or contrasting warm and cold years or seasons. The choice of years can be based on a particular part of the globe and/or a particular season. For example, Wigley *et al.* used annual surface temperatures for high northern latitudes (65–85°N), justifying the choice of high latitudes on the grounds that the response to CO_2 is greatest in high latitudes. On similar grounds, winter temperature data might be more appropriate for defining warm (and cold) years. However, since the signal-to-noise ratio is highest in midlatitude summer or Northern Hemisphere annual temperatures (Wigley and Jones, 1981), neither high northern latitudes nor winter temperatures need be the best choice.

Furthermore, the use of single years (or, more particularly, composites of single years) has certain disadvantages. The climatic effects of increased atmospheric carbon dioxide will develop relatively slowly, and are likely to be associated with important changes of the oceans and cryosphere boundary conditions. If groups of consecutive years are used, the scenarios are likely to be more realistic than those relying on individual years, particularly in terms of the degree of equilibrium achieved between the atmosphere and the underlying boundary conditions. For a study of impact, this method has the added advantage that a comparison of the variability of meteorological parameters can be made, an often crucial factor in determining the effects of climate on man's activities. Clearly, the longer the two periods of consecutive years are, the more realistic the scenarios are likely to be. However, a limitation is imposed by the length of the instrumental record. As a compromise between these two considerations, we selected twenty years as the optimal length for each period of warm and cold conditions.

We chose warm and cold twenty-year periods using the gridded Northern Hemisphere temperature set produced by Jones *et al.* (1982). These data are presented as anomalies from a 1946–60 reference period, and extend back to 1881. Only the period 1901 to 1980 inclusive is employed here, as Jones *et al.* state that the earlier part of the series is less reliable due to the reduced area of data coverage. Twenty-year running means of the mean annual northern hemisphere surface temperature anomalies were calculated and inspected to determine the warmest and coldest periods. The warmest twenty-year period is from 1934 to 1953, and the coldest from 1901 to 1920 (Fig. 1). These two periods form the basis for the construction of the scenarios used in this paper. One of the attractive aspects of constructing scenarios by comparing the earlier cold period with the later warm period is that, if the pre-industrial CO_2 levels were as low as 260–270 ppmv, then a substantial part of this early 20th century warming may well be due to increasing CO_2 (see Wigley, 1983). Furthermore, some of the large-scale spatial characteristics of the early 20th century warming are remarkably similar to those predicted for a CO_2 increase by Manabe and Stouffer's (1979, 1980) GCM simulations (see Wigley and Jones, 1981).

The average Northern Hemisphere and Arctic (65–85°N) temperature differences between the warm (1934–53) and cold (1901–20) year-groups are presented in Table 1. The Arctic differences give some

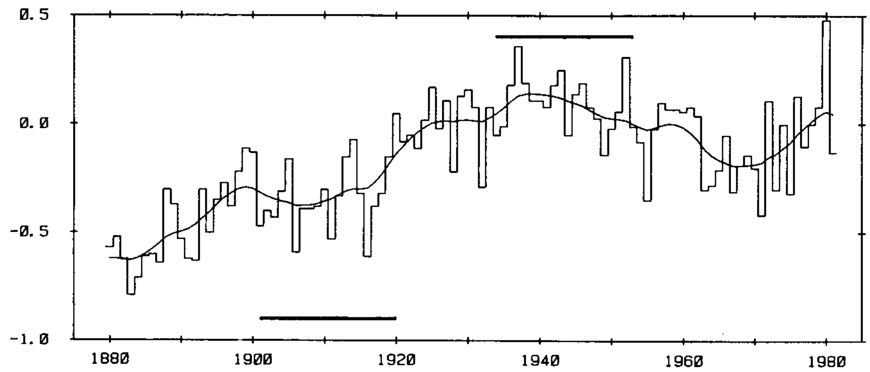

FIG. 1. Northern Hemisphere mean surface air temperature variations (°C) showing the chosen warm and cool 20-year periods. The curve shows 20-year filtered values using a 15-term Gaussian filter padded at each end with the mean of the first or last seven values.

indication of the scale of the high-latitude temperature contrasts. All of these temperature differences are statistically significant at the 1% level or better. This justifies the use of the warm and cold groups as analogues of separate populations, even though both are drawn from a single population.

To construct the scenarios of climatic impact in a warm world, as a first step three surface parameters were examined for regional patterns of change: sea level pressure, temperature and precipitation. Pressure and temperature scenarios were constructed using gridded data sets with a spacing of five degrees latitude by ten degrees longitude. These data sets were supplied by the U.K. Meteorological Office (sea level pressure) and by P. D. Jones of the Climatic Research Unit (temperature). Precipitation patterns generally show greater small-scale spatial variation than either temperature or sea level pressure. For this reason, the scenarios were derived from a dense network (118 sites) of European rainfall records compiled by Tabony (1980) and supplemented by data from World Weather Records. Scenarios were constructed for monthly, seasonal and annual data. These temperature, pressure and rainfall scenarios provide the basic information on the spatial patterns of climatic change associated with increased carbon dioxide.

The economic impact of climatic change will, of course, not only depend on these simple parameters, but also upon more sophisticated measures. We therefore constructed scenarios of variability change, and of the indirect temperature-dependent parameters heating degree-days, growing season degree-days and length of the growing season. Rainfall variability scenarios were constructed from the Tabony data set. Since the grid-point temperature values are expressed in the form of anomalies from the 1946–60 mean, scenarios of degree-days and growing-season length were derived using station data (largely from World Weather Records but subjected to quality testing and supplemented by other data). The network is shown in Fig. 3b.

3. Energy consumption in a warm world

Energy consumption and climate are related through the need to heat internal spaces in winter and cool them in summer. In Europe, air conditioning in summer is not customary, and the peak demand is in winter for heating purposes. A substantial proportion of the total energy consumption in the colder regions of Europe is accounted for by heating. To take the example of oil in the United Kingdom, it is estimated that during the heating season (the last three and first five months of the year), 40–70% of the total gas-oil consumption and 20–30% of the total fuel-oil consumption is accounted for by this purpose (Tellings, 1978). Thus a climatic change which produces a marked variation in consumption of energy for heating will also have a considerable impact on gross consumption figures.

Clearly, temperature is the chief climatic determinant of energy consumption for heating purposes. There are three aspects of this variable which must be examined to show whether an increase in atmospheric carbon dioxide may lead to changes in European energy consumption.

1) Heating energy consumption in Europe follows a seasonal cycle of peak demand in winter months and low demand in summer. Changes in both annual and seasonal temperatures may affect this consumption cycle.

2) Within the heating season, energy consumption is highly sensitive to changes in atmospheric temperature. A close linear relationship is known to exist between the number of degree–days in a month below a base temperature and the relative amount of energy used. The base temperature for Europe is normally taken to be 16°C (Tellings, 1978).

3) Any marked change in temperature variability will be accompanied by a parallel fluctuation in energy demand for heating.

The annual temperature scenario for Europe in a high-CO_2 world (Fig. 2) shows warming over the whole region, with warm–cold differences rising to over 1°C in the extreme north (cf. this 1°C with the corresponding Northern Hemisphere mean annual temperature change of 0.4°C). As also shown in Fig. 2, this homogeneity persists into the seasonal patterns of spring, summer and autumn. However, in winter there is a significant departure: a belt of negative values, centered on 50°N and extending for about 10° to the north and south, stretches across the whole of central Europe except the extreme west. To either side of this belt, positive differences are recorded. These patterns can be explained in the light of the MSL pressure scenarios. Fig. 3a shows the annual warm–cold year mean differences. Pressures are higher in a warm world for most of Europe, apart from the Arctic and Mediterranean Basin. The seasonal differences follow broadly the same pattern, although the exact location of the core of enhanced high pressure changes. The implication is that there is an increase in the number and/or intensity of European blocking anticyclones in warm periods, forcing traveling depressions to pass either to

TABLE 1. Warm minus cold temperature change for Arctic and Northern Hemisphere temperatures (°C) for the two 20-year periods, 1934–53 and 1901–20. (All values are significant at the 1% levels.)

Winter	Spring	Summer	Autumn	Annual
		Arctic		
2.1	1.1	0.5	1.3	1.3
		Northern Hemisphere		
0.5	0.4	0.4	0.5	0.4

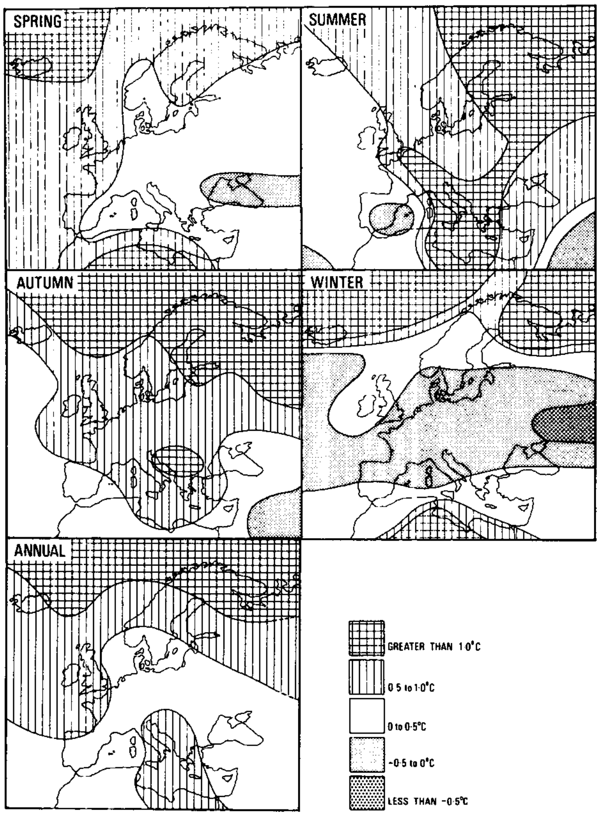

FIG. 2. Temperature differences, warm period minus cold period.

the north or south. This would naturally lead to warmer summers and cooler winters, as observed in the temperature scenarios.

With respect to the implications for energy consumption, two aspects of the scenarios must be examined: first, the direction and magnitude of temperature changes in the heating season, and, second, whether the length of the heating season will increase or decrease. Our scenarios point to an overall decrease in the length of the heating season in a warm world because of higher temperatures in spring and autumn. However, certain areas of Europe experience colder temperatures in winter, which may lead to greater energy consumption within the heating season itself. The balance between these two opposed tendencies determines whether or not annual energy consumption would increase or decrease. This balance is expressed, as already discussed, by the heating degree-day number. This was calculated by interpolating between successive monthly mean temperature values over the year and calculating the number of degree-days below a base temperature of 16°C. The difference between the values for the warm and cold years was standardized by expressing it as a percentage of the mean annual degree-day number for the period 1901–72. The choice of reference period is not critical, but some sort of standardization is required in order to be able to compare degree-day changes in different regions. The significance of any change in the mean is determined by the magnitude of this change relative to the long-term mean. The spatial distribution of the results is shown in Fig. 3b. Of the thirty-nine stations in the analysis, only six show an increase in the heating degree-day number in a warm world. These are located in northern Russia and Finland, in southern Poland and the Ukraine, and in the western Mediterranean Basin. Along the Atlantic coastline of Europe, the degree-day number drops by at least five percent. The conclusion must be, therefore, that the reduction in the length of the heating season more than offsets the effect of lower winter temperatures. Our scenarios indicate that total European consumption of energy for heating purposes in a warm world should be less than today, with the possibility of regional-scale opposing changes which would have implications for fuel distribution.

Changes in mean conditions are not the only, nor necessarily the most important, determinant of impact. Any change in the variability of temperature

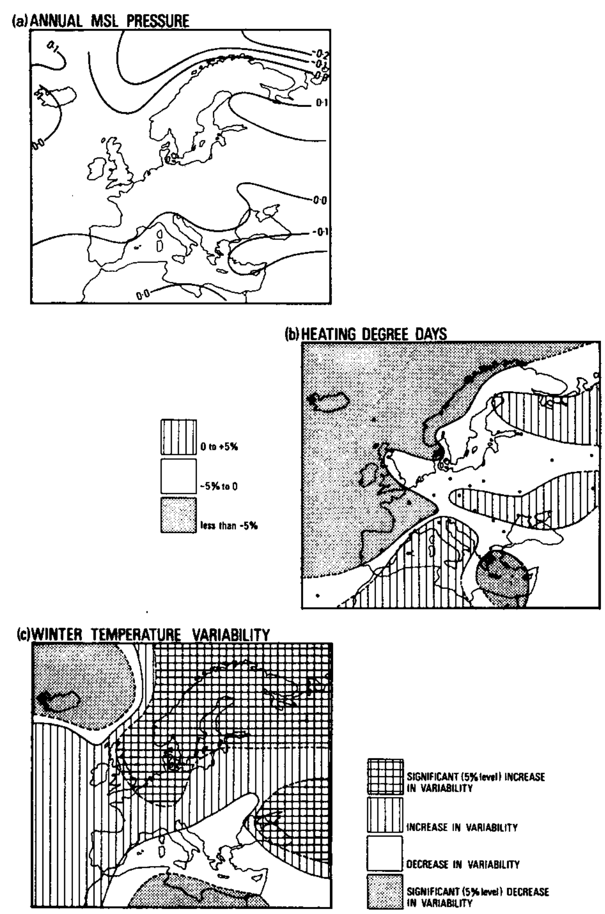

FIG. 3. Warm period minus cold period changes for various energy-related meteorological parameters: sea-level pressure (mb), heating degree days (percentage change) and winter temperature variability (standard deviations).

may lead to a more erratic demand for heating energy that may in turn cause short-term supply difficulties. The most obvious measure of variability is the variance. However, a direct calculation of variance over a twenty-year period will give a value which reflects variability on different time scales and which may be unduly influenced by, for example, a decadal time scale trend. We are concerned here with interannual variability. To isolate this short time scale, we first filtered the data with a 1:2:1 binomial filter and then calculated the standard deviation of the residuals from the filtered values for each of the two 20-year periods for each station used in the analysis. The difference between the two standard deviations (warm minus cold) is used as a measure of the change in interannual variability. Fig. 3c shows the results for winter. This is the season of maximum energy consumption and also the season when lower temperatures are a possibility over extensive areas of Europe in a high-CO_2 world. The whole of northern Europe shows increased variability, with an extensive area of statistically significant differences over eastern Britain, Germany and Scandinavia. The region of lower winter temperatures (Fig. 2) coincides over much of western Europe with the region of increased variability; both tendencies are consistent with an increase in blocking frequency. Our scenario points to a greater frequency of severe winters in these areas under warm world conditions.

To summarize, overall European energy consumption for heating purposes is likely to fall in a high-CO_2 world. However, for extensive areas of western Europe a higher frequency of severe winters is possible, and this could cause problems in matching supply to demand.

4. Agriculture in a warm world

The assessment of impact of a globally warmer climate on agricultural production is vastly more complex than it is for heating energy requirements. Heating energy consumption is largely dependent on one variable, temperature, whereas agriculture consists of a diversity of crops, all responding in different ways to changes in a range of climate parameters. Extensive research programs have been undertaken on the response of individual crops to climatic variables (see, e.g., Thompson, 1975; Haigh, 1977; Sakamoto, 1981). For North America, where reasonably well-defined crop zones exist, this research has been used to estimate the possible agricultural impact of increased carbon dioxide. Butzer (1980) has produced one of the most detailed analyses. He suggests that changes in the distributions of temperature and rainfall will cause shifts in the position of crop belts, leading to an overall decline in production in the United States which increased yields in Canada would fail to offset. In a warm world he predicts that the United States, now the world's greatest food exporter, will be barely self-sufficient.

Such scenarios of impact on agriculture do not exist for Europe. The problem is complicated by the lack of clearly-defined crop zones, and by the multiplicity of cultivation techniques. In seeking to produce meaningful scenarios, we isolated the following climatic variables, sensitive to increased atmospheric carbon dioxide, as the most critical determinants of crop yield: precipitation; precipitation variability; length of the growing season; and the degree–day number above a base temperature of 6°C. In addition, using principal components regression techniques (Briffa *et al.*, 1983), we determined the optimal climatic environment in limited locations for a number of economically-important agricultural products. The scenarios are further analyzed in the light of these results.

The effects of precipitation changes in a warm world may be intensified or lessened by changes in precipitation variability. We therefore derived scenarios for precipitation changes and for precipitation variability changes. Because of the station network used, based on the Tabony rainfall set, the spatial extent of these scenarios is more limited than those for temperature and pressure. The precipitation differences at each station were calculated as $(\bar{x}_w - \bar{x}_c)/s$, where $\bar{x}_w$ and $\bar{x}_c$ are mean precipitation in the warm and cold years, and s is the standard deviation of the rainfall series over the reference period 1901–72. Changes in precipitation variability were calculated using the same procedure as for temperature variability.

The scenario of annual precipitation changes in a warm world (Fig. 4) shows lower rainfall over all areas except highland Britain, northwest France, Norway, Sweden and parts of central and eastern Europe. In general the differences, both positive and negative, are less than half a standard deviation. However, in two areas the rainfall declines by between one-half and one standard deviation: northern Italy and south-central France. The patterns of change in precipitation variability (Fig. 5) are highly complex; spatial coherence of higher-order moments of meteorological variables tends to be less than for mean values. However, northern Italy and south-central France, where substantially less rainfall occurred in the warmer twenty-year period, both show an increase in variability.

For agriculture in western Europe, the seasonal distribution of rainfall is at least as important as the total amount available. Scenarios of the changes in seasonal precipitation and precipitation variability in a high-CO_2 world are shown in Figs. 4 and 5.

In spring, apart from small areas in the east of the study area, rainfall is generally lower in the warm period. The greatest differences are found over highland Britain and central France. Except along the Mediterranean fringes, these lower rainfall values are almost invariably associated with an increase in variability. Warm-minus-cold period differences are particularly severe in those parts of France where a rain-

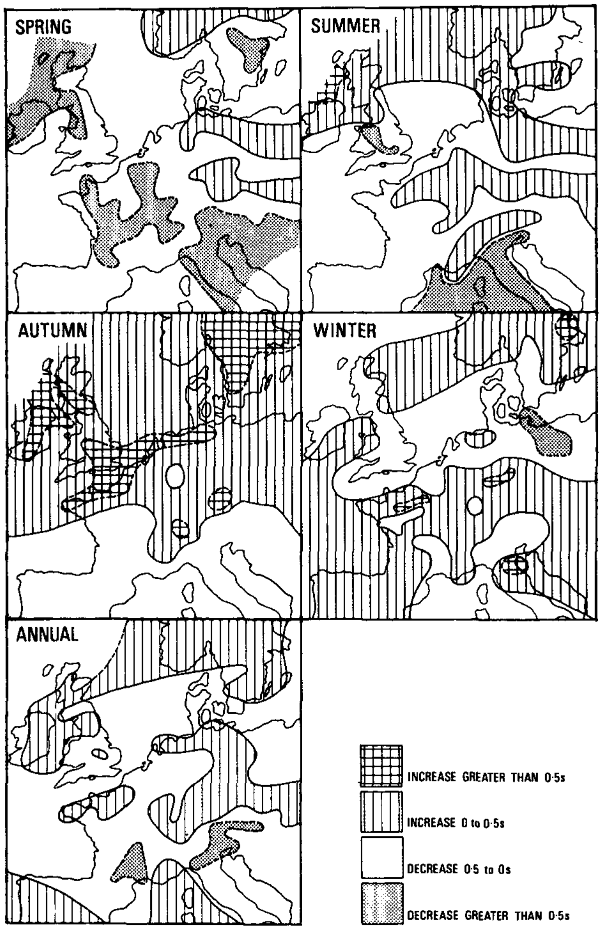

FIG. 4. Changes in precipitation (warm minus cold) as multiples of the standard deviation.

fall decrease of greater than half a standard deviation is associated with a substantial increase in variability. (The same combination in the English Lake District is unlikely to cause problems, given the extreme wetness of the present day.) Summer shows the same broad regional pattern as spring with less precipitation in a warmer world, although the areas of higher rainfall in the east are rather more extensive. The areas of increased variability are broadly coincident with those of increased rainfall. Overall, such summer rainfall patterns would remain favorable for agriculture in a high-CO_2 world. Autumn rainfall differences point to higher rainfall over most of northern Europe in a warmer world, in many places the increase exceeding one half standard deviation. Over southern Europe autumn rainfall is reduced. The distribution of change in variability is highly discontinuous. There is a large area of marked increase in variability over the central part of the study region north of the Alps which, apart from a small area of France and West Germany, is associated with higher rainfall. The winter months are characterized by a very variable distribution of wetter and drier conditions, but with a dry belt stretching westwards from Denmark and northern Germany to Britain. The eastern part of this belt is associated with a large increase in variability in the warm period. However, over most of the southern and western parts of the study region variability is less in the warm period.

To summarize, the spring season for most of Europe is drier in the warm period, whereas the maximum extent of wetter conditions is seen in the autumn and winter. Lower spring rainfall could have important agricultural implications in terms of soil moisture levels at the beginning of the growing season, particularly for the drier south. High soil moisture deficits may adversely affect young seedlings and so reduce final yields. Over western France, lowland Britain and the Low Countries reduced rainfall persists into the summer season. In autumn, our scenario indicates increased rainfall in a warmer world. Increased rainfall over northern Europe would be unfavorable for late-harvested crops, directly by hindering harvesting operations, and indirectly since the

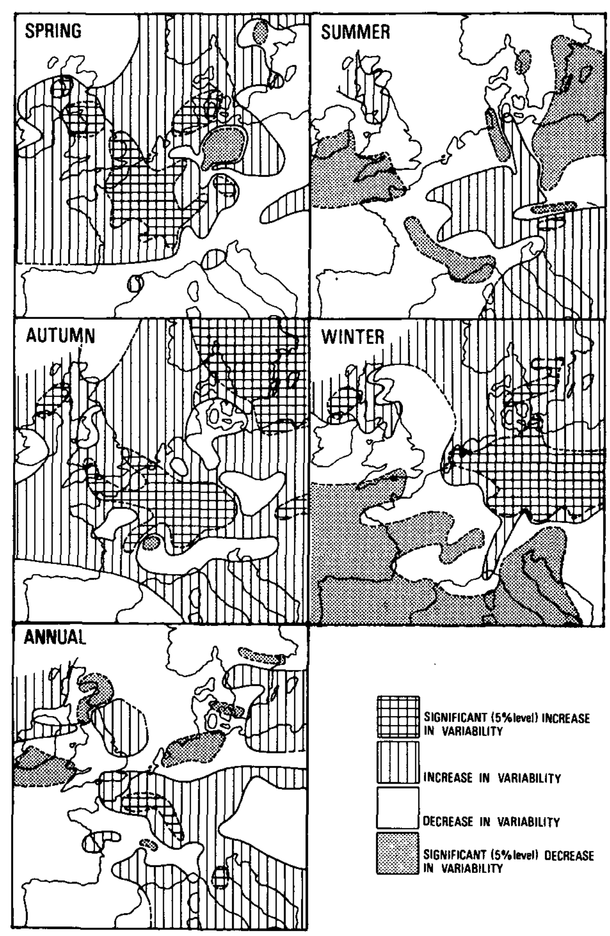

FIG. 5. Changes in the interannual variability of precipitation, cold period to warm period, based on high frequency filtered data (see text).

implied reduction in sunshine hours may delay ripening. The higher winter rainfall of our scenario would improve the antecedent soil moisture conditions.

Where a large change in rainfall (greater than 0.5 standard deviations) is associated with a large increase in variability (taken here to be an increase statistically significant at the 5% level) conditions may be particularly severe and substantial modification of the land-use systems may be required. For example, in eastern France in the spring season the indications are for a decrease in rainfall greater than 0.5 standard deviations, and a statistically significant increase in variability. Such a combination of circumstances must lead to a greater probability of drought.

Another general indicator of climate's impact on agriculture is the length of the growing season. In this study we took this to be the period of the year when the daily mean temperature lies above 6°C. The mean length was calculated for both warm and cold years by interpolating between successive values of the monthly mean temperatures and counting the number of days above the base line. The difference between the two values was then expressed as a percentage of the mean growing season length for the standardization period 1901–72. The results (not illustrated here) indicate that the growing season length would increase throughout Europe by up to 10%, the largest gains being experienced in the north.

The degree–day number, a related indicator, was calculated in the same way as for energy consumption, but using the temperature excess above a base of 6°C. Once again the values are invariably higher in a warm world, with a south–north trend in the increase from near zero in the south to +10% in the north.

Whether or not these general increases in the length and warmth of the growing season would be beneficial to agriculture is difficult to say; they would have to be evaluated crop-by-crop. For many crops (and for wheat in particular) *lower* growing season temperatures favor higher yields (see, e.g., Monteith, 1981). However, a longer growing season may favor higher yields so the two effects may tend to compensate. Increases in the length of the growing season in northern Europe may allow cultivation of crops which are currently marginal or impossible to grow in these areas.

a. Individual crop responses to a warm world

The scenarios presented here are difficult to interpret in terms of the impact upon agriculture because of the complex relationships which exist between climate and individual crops. In order to apply the results more meaningfully, it is first necessary to determine the optimal climatic conditions for a particular crop in a particular area. The scenarios can then be analyzed with reference to that area to determine whether the changes which might occur in a high-CO_2 world would affect the crop adversely or favorably. The method is demonstrated here with respect to a range of crops in England and Wales, and for the quality of wines from the Bordeaux and Champagne regions of France.

We developed statistical crop-climate models using the technique of principal components regression (Briffa *et al.*, 1983). The following crops were considered using total yield data for England and Wales: wheat (both winter- and spring-planted varieties), barley, oats, hay, and turnip and swede yields. Only the analysis for wheat is discussed in detail, although the results are presented for all crops. Crop–climate regression models have already been developed by other authors for some of these crops, and also for other parts of Europe (e.g., Hanus and Aimiller, 1978; Hanus, 1978), but in most such analyses insufficient information is given for one to judge the statistical reliability of the models.

For wheat, the dependent variable was wheat yield for England and Wales for the period 1885 to 1966 inclusive (we used MAFF, 1968, for all crop-yield data).

b. Procedure

To remove any long-term trend produced, for example, by technological progress, a 30-year Gaussian filter was fitted to the data, and then each yield figure was divided by the filter value for that year (cf., Mostek and Walsh, 1981). This procedure is somewhat different from the usual method of removing technology effects where a crop–climate model is developed using residuals from some long time scale trend. We are essentially assuming technology to have a multiplicative rather than an additive effect. We also examined additive-type models. Performance for these was similar, but invariably a little worse than for the models used here. As a final step before performing the regression analysis, the data were normalized.

The predictor variables in the regression were the twelve monthly values of gridded temperature from September to August (the harvest month) for grid point 50°N, 0° longitude, and twelve monthly values of England and Wales rainfall (Nicholas and Glasspoole, 1932; Wigley *et al.*, 1983) for the same months. Climate data were transformed to principal component (PC) variables, statistically insignificant PCs were eliminated and the remaining PCs used as candidate predictors in a multiple linear regression analysis. The final model used only those candidate predictors for which the *t*-value of the regression coefficient exceeded 1.0 (for further details of the method see Briffa *et al.*, 1983). The regression model for wheat explained 56% of the crop-yield variance [$F = 10.22$ with (9, 72) degrees of freedom; highly statistically significant], and the following conditions were found to contribute to good harvests: a dry winter and summer, warm conditions in winter and cool conditions in spring. The same procedure was followed for the other crops, with small differences in the analysis period. In all cases the climatic variables account for at least 50% of the interannual variation in yield.

As the next step, warm-world values for the climatic variables were fed into the regression models to predict the change in yield for each crop-type. Two sets of values were used. The first set was taken from the scenarios for the two groups of twenty consecutive years having the warmest and coldest mean hemispheric temperatures, as used throughout this paper. As a test of whether using an alternative method to select the warm and cold periods would give substantially different results, we derived a second set of scenarios. These were based on the method of Wigley *et al.* (1980), selecting the five warmest and five coldest years from the Arctic (65–85°N) temperature record for the period 1925–78 inclusive. The results are shown in Table 2, where Scenario A denotes the results based on the twenty-year warm and cold periods, and Scenario B the results based on the five warmest and five coldest years. Although the model calculations give quantitative results, Table 2 only shows the changes to be expected in a high-CO_2 world in qualitative terms. To do more would be to impart a false sense of precision.

In general, the results from the two sets of scenarios agree well. It is only in the case of wheat that no firm conclusions can be drawn, though the changes suggested in both scenarios are small. For the remaining crops, however, both scenarios agree on the sign of change in yield, which in all cases is for a reduction in warmer-world conditions. The most severe impact is upon hay yields. Further details of this crop-yield modeling work appear in Palutikof *et al.* (1983).

Information on wine quality from the Bordeaux and Champagne regions was extracted from Broadbent (1981) and used to rate each year's vintage on a scale from 0 (poor quality) to 5 (high quality). For the Bordeaux, the independent variables used were monthly rainfall at Bordeaux and mean temperature at Nantes (extracted from World Weather Records) for October to September (1890 to 1960 inclusive). The independent variables for the Champagne were the mean of monthly rainfall at Châlons and Laon, and the monthly mean temperature at Paris for October to September (1898 to 1973, inclusive). The proportion of the variance explained by the climatic variables was, for the Bordeaux, 58%, and for the Champagne, 63%. For both, the same conditions were conducive to good vintages: a warm spring and summer and dry summer weather. Our scenarios suggest that conditions in a warm world would lead to an improvement in wine quality, particularly of the Bordeaux. In both areas spring and summer temperatures are shown to be slightly higher (Fig. 2). Summers should be drier in the Bordeaux region, but wetter in the area which produces Champagne (Fig. 4). Increased temperature variability is indicated for both areas in the spring season and for the Bordeaux region in summer. Summer rainfall should be less variable for both areas.

5. Conclusions

We have constructed scenarios for Europe in a future, warmer, high-CO_2 world using the early 20th century warming as an analogue. Given the present state of development of GCM simulations of CO_2-induced warming, and given the criticisms which may be leveled at the use of paleoclimatic analogues and the use of composites of individual years, we believe that the method used here provides the most realistic climate scenario development approach available today. The fact that a part of the early 20th century warming may be associated with an increase in atmospheric CO_2 over this period strengthens the argument. Not all of our climate scenarios are described in this paper, only those most relevant to the impacts on energy demand and agriculture.

Our pressure, temperature and precipitation scenarios have the following general characteristics. First, subregional scale details differ noticeably from season to season, and individual season scenarios often show little relationship to the annual scenario. Precipitation changes occur in both directions. There is, however, an overall tendency for spring and summer to be drier with autumn and winter being wetter. Interestingly, the scenarios show some similarity with the climate of the Medieval warm period (c. 900–1300 A.D.). Lamb (1977 and earlier) suggested that late summers in this period were wetter than the pres-

TABLE 2. Estimated changes of crop yields in England and Wales for Scenarios A and B.

Crop	Scenario A	Scenario B	Percentage variance of yield accounted for by model (%)
Wheat	Small decrease	Small increase	56
Barley	Moderate decrease	Moderate decrease	49
Oats	Moderate to large decrease	Moderate decrease	52
Hay	Large decrease	Moderate to large decrease	59
Turnips and swedes	Moderate decrease	Moderate to large decrease	52

ent. Our own re-evaluation of the available, reliable, historical data shows that, in terms of the seasons JJA for summer and SON for autumn, this increased wetness was more confined to the autumn (spanning August, September and October), paralleling our precipitation scenario. Temperature scenarios show warming over the year as a whole and for spring, summer and autumn. The largest positive differences are found in higher latitudes. However, one somewhat unexpected result revealed by the past record is the possibility that winters over large parts of Europe may actually be colder (and more variable) in a warmer world. This latter result is associated with an increase in blocking frequency and, because of the importance of this synoptic feature, we believe that more effort should be directed towards improving GCM simulations in this regard. Very few present-day GCMs produce realistic blocking phenomena (W. Washington, NCAR, personal communication, 1982).

We have used our climate scenarios to construct scenarios of the impact of increased atmospheric carbon dioxide on energy consumption and agriculture in Europe.

The increase in frequency and/or intensity of high-pressure "blocking" situations in the winter is linked to lower mean winter temperatures. Although this will lead to increased energy consumption, warmer temperatures in both spring and autumn will reduce the length of the heating season. The net effect of these two opposed tendencies will, we believe, cut the consumption of energy for heating purposes. Increased temperature variability during winter over north and northwestern Europe suggests a greater frequency of severe winters, and thus larger fluctuations in the demands for heating energy than are experienced at present. It is often suggested that the main impact of climate and weather on man is through changes in variability, particularly in the frequency of extreme events, rather than through changes in the mean (see Palutikof, 1983, for an analysis of the economic impact of recent extreme seasons in England). The two items are, however, related. Since extremes are frequently defined in absolute terms (e.g., winter temperature below a given value, river levels above a certain limit, etc.) a change in the mean may cause a change in the frequency of extremes without any change in variability. This was a contributing factor to the perceived variability of the Little Ice Age in Europe (Ingram *et al.*, 1981, 13–14). Our variability scenarios did not specifically analyze extreme events, but where increases in winter temperature variability are associated with little change or a decrease in the mean this would necessarily imply an increase in the frequency of absolute extremes. We deliberately calculated variability about a medium-term filtered trend in order to decouple changes in variability from changes in the mean.

Changes in European temperature distributions in a warm world appear to be broadly beneficial for agriculture. Rainfall tendencies vary from season to season and are difficult to interpret. For Europe as a whole, spring is expected to be drier in the warm years, whereas autumn and winter are shown to be wetter. However, because of the complexity of crop–climate relationships, it is really only possible to interpret the scenarios on an individual crop-by-crop basis and for spatially-restricted localities. We did this for a selection of crops by developing specific crop–climate models using the technique of principal components regression. For two different warm-worldscenarios, the indications are that yields of staple crops in England and Wales will decrease. We have, however, taken no account of the possible influence of nonclimatic factors. The most important of these are the effects of technological change, the direct influence of increasing CO_2 on crop photosynthesis, and the indirect impacts through changes in the incidence of pests and disease (which may be a consequence of climatic change). Over the past 50 years or so, many crops have shown a steady upward trend in yield per unit area due to changes in farming technology—loosely referred to as the technological influence. Predicting the future influence of technology is a daunting task. In constructing crop–climate models, technology is invariably accounted for in an empirical way, either by fitting linear, piece-wise linear or quadratic trends to past data or by filtering (as in the present study). Extrapolation of past trends would be singularly inappropriate in many cases, and predicting future technological trends on the basis of assumed scientific/agronomic advances or assumed technological responses to stress would be equally fraught with uncertainty. Likewise, the direct influence of CO_2 on crop yield (CO_2 "fertilization") is difficult to estimate (Cooper, 1982; see also commentary by Wittwer, 1982, Rosenberg, 1982 and Oram, 1982); C-3 plants show enhanced photosynthetic activity and more efficient water use in controlled high-CO_2 environments. However, in the natural or large-scale field environment, where other factors tend to be limiting, this direct CO_2 effect may be less noticeable. In spite of a 25% increase in atmospheric CO_2 over the past century, no long-term CO_2 fertilization effect has been documented (although such an effect may well be obscured in the case of agricultural crops by the effect of changing farming technology). The possible importance of CO_2 fertilization in coming decades cannot be discounted, but predicting its magnitude and the more indirect effects through competition with weeds and changing water use efficiency is a formidable task. Finally, the effects of CO_2 on crop yield through changing pest and disease incidence may be large, although such factors are probably more amenable to technological "fixing". The influence of climate alone, itself subject to some uncertainty, is the most tractable aspect of producing a realistic high CO_2-world agriculture scenario.

Finally, we cannot at this stage place much confidence in these scenarios beyond the early decades of the 21st century. There must, for example, be some doubt about the realism of our climate scenarios for CO_2 levels of the order of double the preindustrial level (i.e., for the anticipated conditions which might prevail by the middle of the next century). The early 20th century Northern Hemisphere warming of around 0.4°C is substantially less than that expected to result from a CO_2 doubling, and extrapolations from past data into "no-analogue" regions, both in terms of the magnitude of the temperature change and in terms of future boundary conditions to the atmospheric circulation system, can only be made cautiously.

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