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WATER RESOURCE FORECASTING

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SUMMARY

A major element in the provision of water resources is the forecasting of climatic change with its implications both directly for precipitation and indirectly for agriculture and economy. A deterministic climate model is presented here which allows such forecasting. Its output is successfully tested in hindcast by comparison with observed climatic variations over both recent and historical timescales with particular emphasis on the developing world. By application on any timescale and incorporating climatic calibration on a regional basis this provides a very flexible new means of water resource forecasting.

INTRODUCTION

Water is Man's precious ally and yet sometimes his most fearsome foe. Without it his very existence is numbered in days; with too much he can be swept away by floods. Little wonder then that major efforts are made, as they have been throughout history, to secure the right balance between too little and too much. Consider adding another factor in passing, quality - for Man requires not just the liquid but water free of certain contaminants. The requirement for a dependable water supply is becoming ever more obvious and will continue to do so as the World population increases relentlessly towards the 10 billion mark expected early next century.

What problems do we face in seeking to provide water supplies. They are both physical and human.

Physical problems stem from the vagaries of the climate and its variation, the very source of the resource. They also include geological elements especially connected with the structure of aquifers and their geochemical assessment along with the topographical constraints of the ground surface from the point of view of run-off, collection, storage and transport. The former is often seen as an unpredictable and uncontrollable natural phenomenon whereas the latter lend themselves to circumvention by the ingenuity of Man who introduces engineering works and alters the constituents of the valuable resource to achieve a suitable product despite the ever increasing pressures from pollution.

Human problems, if such they may be termed, are manifold and yet would be largely unnecessary in a properly structured, orderly and humane society. Perhaps the most pressing is the demographic factor already broached - global population. This has risen approximately exponentially since at least the industrial revolution. However, the increase is not uniformly distributed. The greater numbers are arising in those regions least able to provide them with that precious and essential resource, water. Before accepting this population explosion as a natural phenomenon beyond human intervention we should recognise the current progress of the People's Republic of China in its experiment to contain its population growth by imposing restraints based on both fiscal and moral pressure. Whether a population is metred or not it is in any case the human lot to resolve water supply problems by engineering means. As much of this activity is on a large scale and costly it has immediate economic implications which in turn result in both social and political reverberations in both undeveloped and developed coutries alike.

What are the solutions? Again they are both physical and human. Of course, we cannot control a major physical phenomenon such as the climate but we can go further towards understanding it and thereby being less at its mercy. In the meantime we also have at our disposal engineering, economic and socio-political management systems.

In reverse order, the time-honoured solution to water supply is to undertake engineering works to convert what is often an erratic resource, both temporally and geographically, into a steady supply where it is most needed. For millenia, Man has built dams to hold back reservoirs which are then distributed by canals, tunnels and pipes for irrigation, industry and social use. This is essential and will continue to be so. Industries both central and peripheral to this are legion, embracing civil, mechanical and electrical engineering and their many associated disciplines.

Whereas engineering solutions are the physical expression of Man's initiative to secure a steady water supply, economic and socio-political manoeuvres are never far behind the scene. Economic issues arise prior to the engineering intervention in order to define its requirement and provide its impetus; they also follow on from the commissioning of a completed structure in seeking to derive the maximum benefit from its installation. The economic factors which generate the demand for an engineering enterprise are often accompanied by socio-political factors and may even be triggered by them. Similarly these parameters are often equally closely interdependent when the benefits of an engineering solution are distributed. Thus we see that the solutions to problems of water supply touch the heart of society.

But what of the climatic issues? Both strategic economic and socio-political planning and detailed engineering planning are currently undertaken on the basis that climate is relatively stable over the longterm and will continue to vary only between limits which can be assessed by statistical means applied to past records. As such this physical factor is considered to be no more nor less predictable than the major human factor, demography, which joins with it to constitute the central imponderables in forecasting water resource requirements. There are immediate problems in this approach to climate forecasting. Perhaps the main question concerns the reliability of forecasts based on statistical extrapolation to a period in the future beyond the timespan for which past data is available; that and the uncertainty whether or not climatic variation is random - for, if it is not, then a statistical approach to forecasting is in error and should give way to a deterministic model.

This in essence is the subject of this paper which aims to present such a model for forecasting precipitation over many timescales and in various regions of the world. It concludes by suggesting that the model is sufficiently well substantiated for incorporation in strategic planning of water resources and other related factors around the world.

CLIMATE

The study of climate has been approached from many directions. Typical of the regional studies is the descriptive work of Austin Miller (1976) who investigated lateral variations of climatic types. Secular variations of climate in the form of its many direct parameters or proxy data relating to and dependent on climate have been recorded by many workers for a long time. Typical among those recording parameters of direct relevance to climate are Jones and Wigley (1980), who described the temperature of the northern hemisphere during the last 100 years or so and the UK Meteorological Office (1977) who examined rainfall records of England and Wales since 1727.

Recently general circulation models (GCMs) have evolved to try to explain the circulation of the atmosphere and the consequent impact of seasonal variations and other variable factors around the world. Among these, examples are to be found in the studies of Manabe et al (1979) and Iribarne and Cho (1980) with their analyses of the dynamics of atmospheric masses.

The consideration of longer term variations of climate and their explanation forms the basis of modern climatology which stemmed from the early work of Milankovitch (1938) with its own roots in the concepts of Croll (1875). Their theme was that variations in astronomical patterns, the orbit and orientation of the Earth in relation to the Sun, cause changes in the Earth's climate owing to the consequent variation of the distance of different parts of its surface from the Sun. They paid particular attention to the periodic recurrence of ice ages which have exercised geological intellects at least since the days of Agassiz(1840). The references to longterm climatic time series, both direct and proxy records, are legion among the more prominent of which are the many valuable time series involving the analysis of isotope ratios by N.J. Shackleton and his co-workers, e.g. Shackleton and Cita (1979).

Longterm climatic time series normally enter the literature in the form of the variation of raw data. To use such data for forecasting future trends two distinctly separate approaches are pursued. For instance, statistical analyses are implemented to explore the probability of the return of a particular climatological phenomenon, such as drought, on the basis of extrapolating into the future from a record of the past. This method is very commonly used in water resource forecasting. However, it is philosophically at odds with the very roots of modern climatology based as it is on a correlation with the known non-random variations of astronomical parameters.

The astronomical theory, which recognises longterm cycles occupying periods of thousands of years, allows deterministic forecasting of longterm climatic variation. Until recently this has been too vague and outside practical timescales for applied forecasting. However, Denness (1981) briefly introduced a more complete deterministic climate model which incorporated approximations of known astronomical cycles and extended that cyclic series both to longer geological variations and also to the higher frequency climatic cycles which impact on the timescales of engineering activity. This model was substantiated by Denness (1983; in press, a) by comparative hindcasting. It was also used by Denness (in press, b) to describe a comprehensive analysis of the Greenhouse Effect, the global warming thought to result from increasing atmospheric carbon dioxide, and again (Denness, 1984) to provide comment on cycles of prosperity in overall global economy and its primary and national components - in both cases with a sensitivity of interpretation of the order of a few years and decades, similar timescales to those of interest to the water resource forecaster.

This new method arising from Denness essentially describes the variation of global temperature on all timescales by application of the sine series contained in the expression:

$$G(t) = \sum_{n = N(T)}^{\infty} A(T)\ a^{n} \sin b^{1-n} \frac{\pi t}{T}$$

zero registered at time T_o.

in which $G(t)$ is a time-based climate index, say global temperature,

$A(T)$ is the amplitude of a reference periodicity T,

$N(T)$ is the reference integer for periodicity T,

a, b are absolute constants, here taken as 0.84 and 0.50 respectively

n is an integer, i.e. the reference number of a particular sine component.

and t is time in years

For water resource forecasting this equation must be calibrated in terms of its implications for precipitation in the region under study. Fortunately such a calibration is available for the northern hemisphere through the regional and secular climate mapping of Wigley et al (1980) and for the whole Earth in more general terms by Klein (1982). Figure 1 shows the regional precipitation change found by the former to occur in response to global warming. Coupled with the above equation, which can forecast the variation of global temperature, it thus allows the forecasting of regional water resource variation.

REGIONAL EXAMPLES

It must suffice here to show but a few examples of the matching of hindcasts from the above model to the trend of observed climatic time series relating in their various direct and indirect ways to water resources over periods ranging from about 400 to 700 years and across three continents before culminating in a global assessment for the last century or so. The developing world naturally features prominently in these examples, with special attention drawn to the climatically sensitive Sahel.

Northern Africa

Figure 2 shows the output from the climate model of global temperature variation (thin continuous line) superimposed on the trends of observed climate-related data compiled by Sharon Nicholson and published by Lamb (1977), with emphasis on general maxima and minima of the model drawn by the solid arrows. For Algeria the recurrence of famine caused by drought (thick continuous line) is seen to have marched generally in step with the global temperature model as expected by reference to Figure 1. As Algeria remains relatively warm even in periods of global cooling but then receives more rainfall according to Figure 1, it is to be expected that the occurrence of plague there will follow the reverse pattern shown by the thick-thin continuous line because the additional precipitation encourages the prosperity of disease organisms.

Turning now to the Sahelian countries of Senegal and Gambia (thick dashed line) and Mali (thin dashed line) it is seen that drought has increased in both during periods of relative global warmth hindcast from the model. This is to be expected from Figure 1.

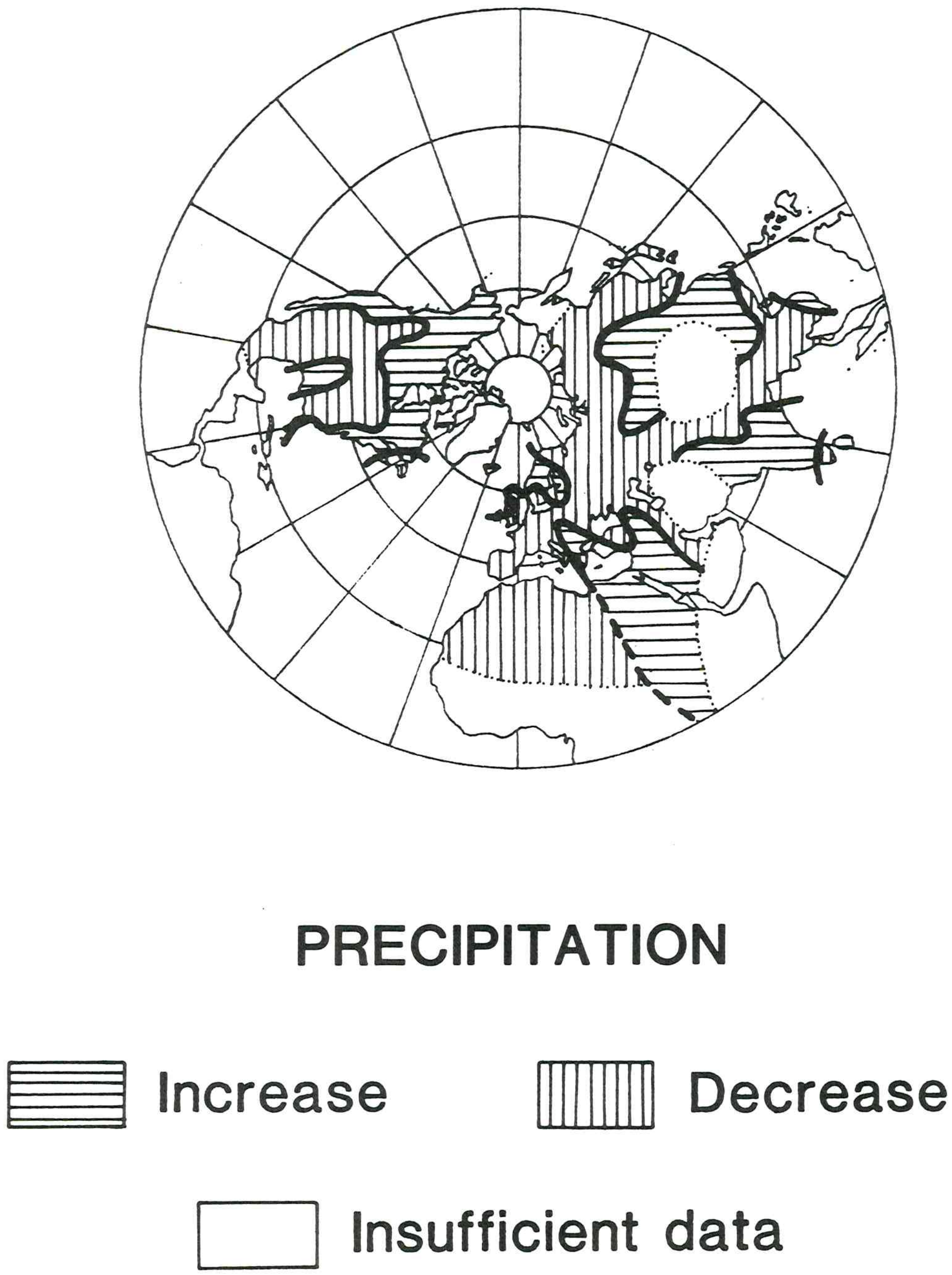

FIGURE 1: Regional precipitation response to increased global temperature

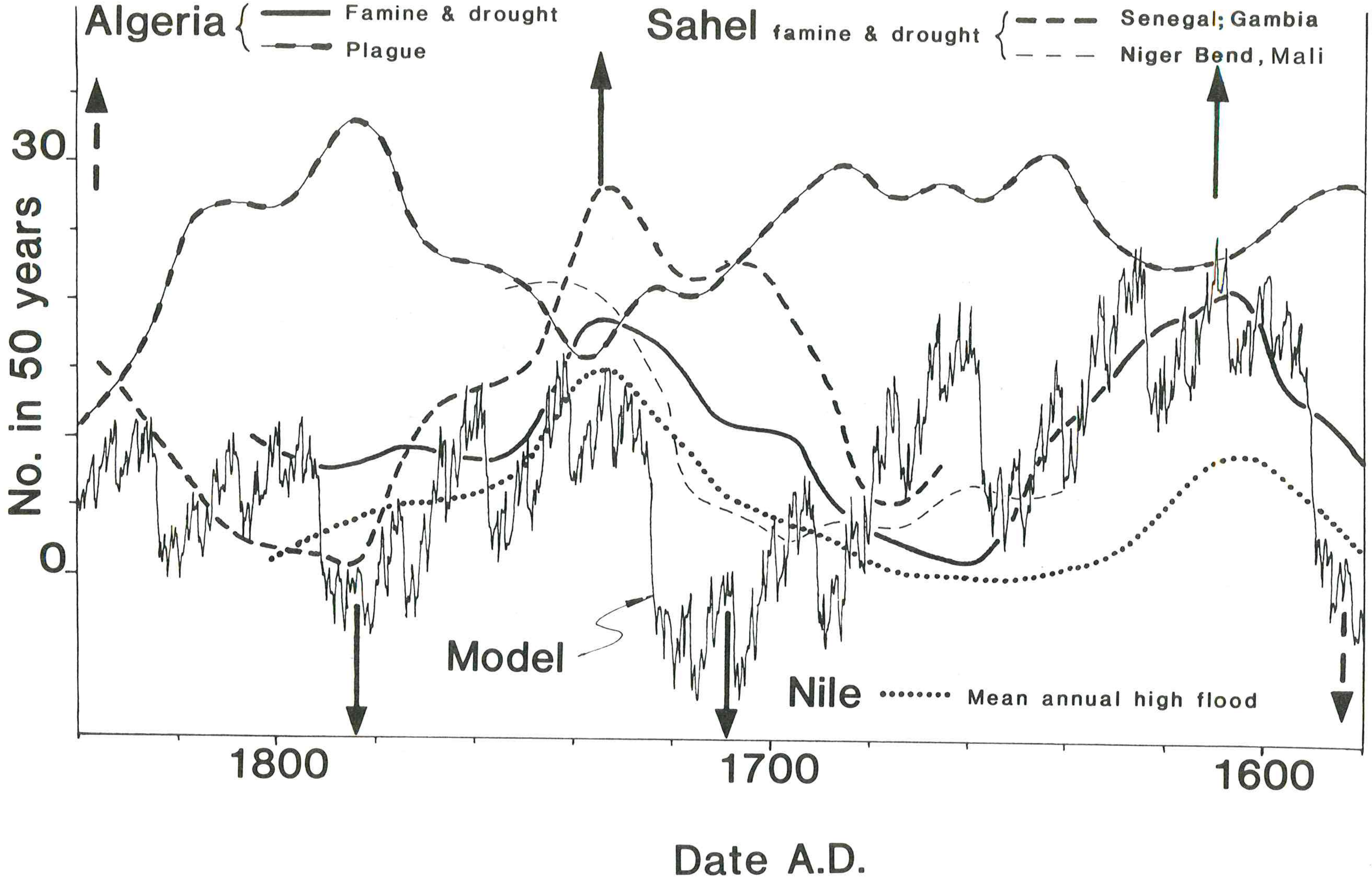

Figure 2: Comparison of climate model with climate-related records in N.W. Africa 1580-1840 AD.

Before leaving this regional study it is perhaps appropriate to consider the trend of the occurrence of flooding of the River Nile also shown on Figure 2. Here it is seen that the flooding increases with increased global temperature. This is again to be expected from Figure 1 which shows that northeast Africa, through which the Nile flows, becomes wetter with increasing temperature. One possible significance of this would be to promote the consideration of securing west African water resources from the eastern quarter, as the one appears (from both observation and theory) to become drier as the other becomes wetter. The reader will be able to extend this logic for application to his own area of interest.

China (PRC)

Figure 3 shows the variation of global temperature hindcast from the model, this time smoothed by the moving average process detailed by Denness (1983) portrayed by a thick continuous line as it is in all the remaining figures. Superimposed on the model is proxy data for the variation of rainfall observed over the past 600 years as described by two separate estimates, the raininess index from Yao (1944) and cloudiness determined by Link (1958). As expected from Figure 1 the trends of observations and model are similar with the wetter periods generally coinciding with times of global warming as shown both by the major solid arrows at primary temperature maxima and minima and also the intermediate maximum and minimum indicated here by lesser arrows but disguised by the smoothing technique.

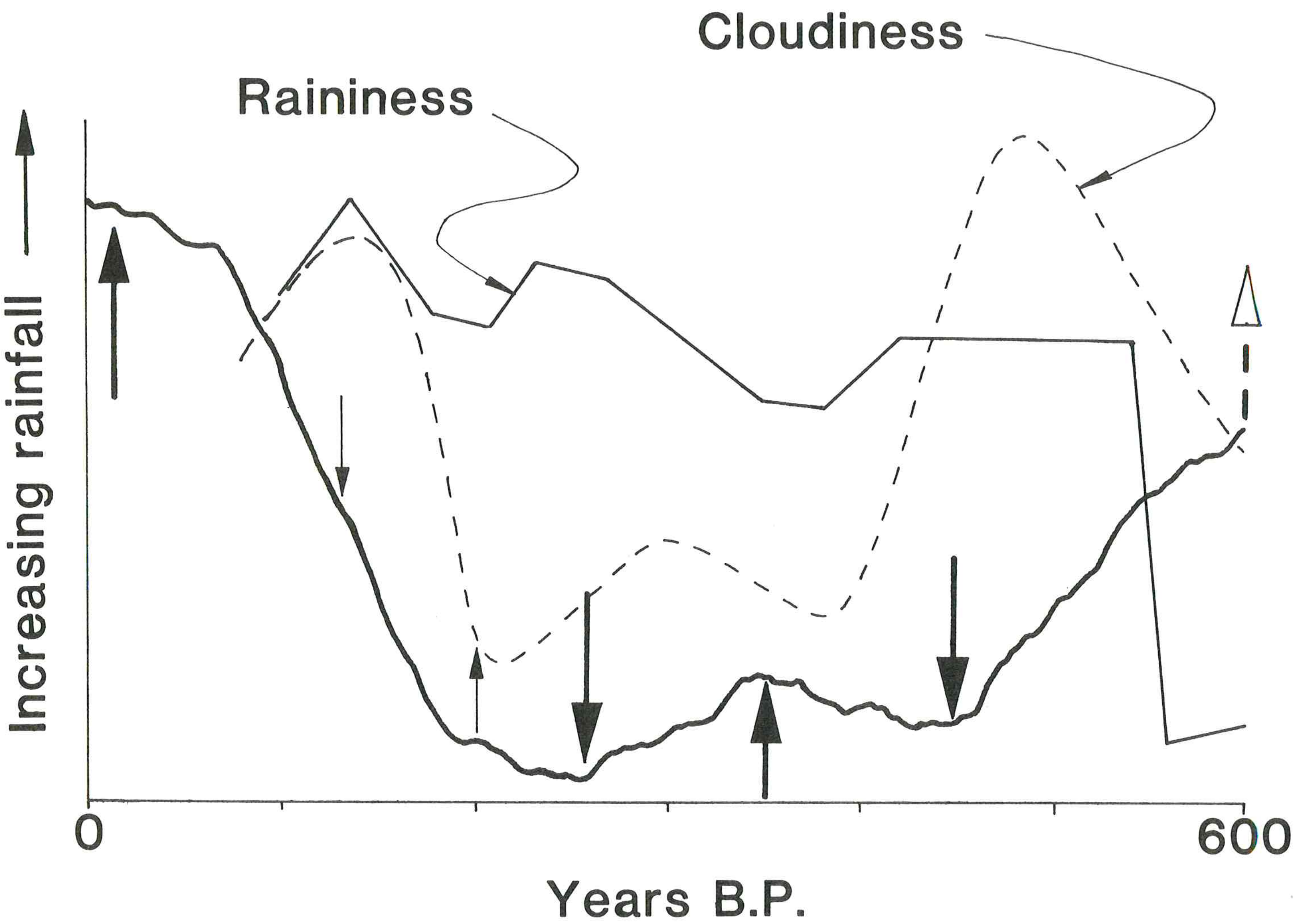

FIGURE 3: Comparison of climate model with precipitation records in China since 1380 AD.

Europe

Figure 4 shows the reduced model superimposed on the trends in the price of bread in England and France since 1270 AD as reported by Lamb (1977) based on data from L.M. Libby. A general correspondence of the timing, if not the amplitude, of price increases with global temperature hindcast is seen. It is suggested that Figure 1 again holds the key to this connection: it shows that western Europe becomes generally drier with increasing global temperature so that, as the agriculturalist is aware, crops then generally become less productive with the consequence that grain becomes scarce and market forces drive up the price of the resulting bread product in those warmer periods.

A historical note is in order. During the substantial global warming of the eighteenth century France experienced price increases which stabilised at a high level while the initial very high rise in England was succeeded by a dramatic fall to below pre-rise prices; yet both countries become drier as global temperature rises so why the anomaly? It is suggested that while France was at the mercy of climatic vagaries at that time, England was able to take advantage of rapidly growing supplies from its colonies in more productive parts of the world, such as Canada and Australia, to reduce prices on the home front.

The World

Now that it has been shown that there is a connection between global temperature and not only the primary variable, water supply but also an economic factor dependent upon it, the price of bread, it is appropriate to extrapolate from the regional to the global scale. Figure 5 permits this to be done by comparing the model hindcast since 1850 AD with an economic analysis derived from an assessment by Cleary and Hobbs (1983). It is seen that global prosperity has occurred only in relatively cool times with recession following relentlessly in its wake as the globe warmed again in a series of economic cycles as observed in more detail by Denness (1984).

It is again suggested that the agricultural connection is at the root of the relationship as postulated above. The main food producing parts of the developed northern hemisphere are the mid-west of the USA, northwest Europe and Kasakhstan in the USSR. Figure 1 shows that all of these become drier at the same time in response to global warming. Therefore, it seems reasonable to suppose that the consequentially threatened food deficit has periodically been circumvented through engineering (irrigation) and chemical (fertilizer) means by diverting resources from other sectors of the economy at a cost to industry and energy development which has reflected itself in depression during global warming.

CONCLUSION

It has been shown that a new deterministic climate forecasting model has successfully entered the literature. The model has been seen to match well in hindcast a range of observed climatic time series around the world over different timescales of interest to the strategic resource planner. It is now available for application to the forecasting of future water resources on a regional basis.

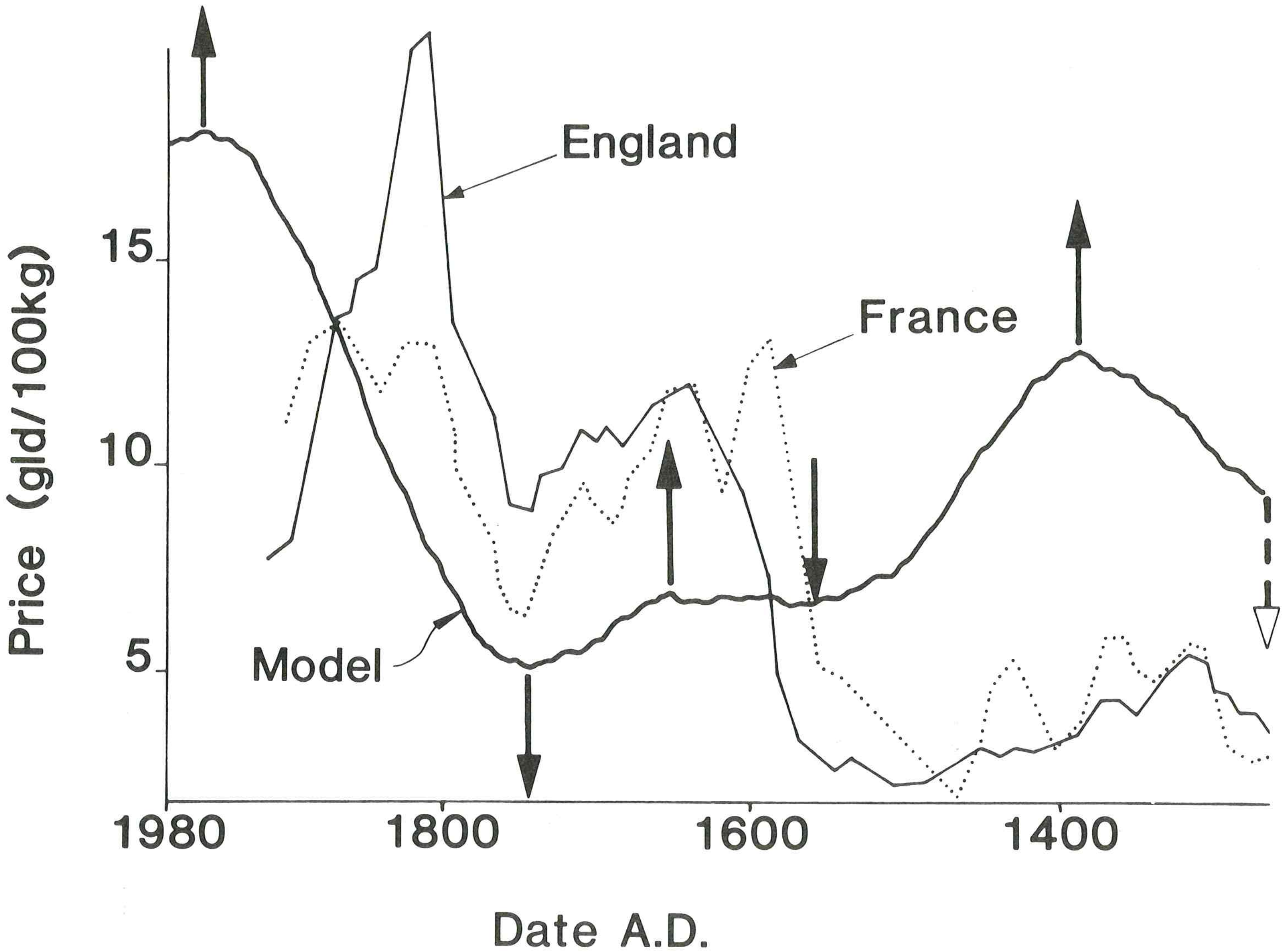

FIGURE 4: Comparison of climate model with cost of bread in N.W. Europe since 1270 AD.

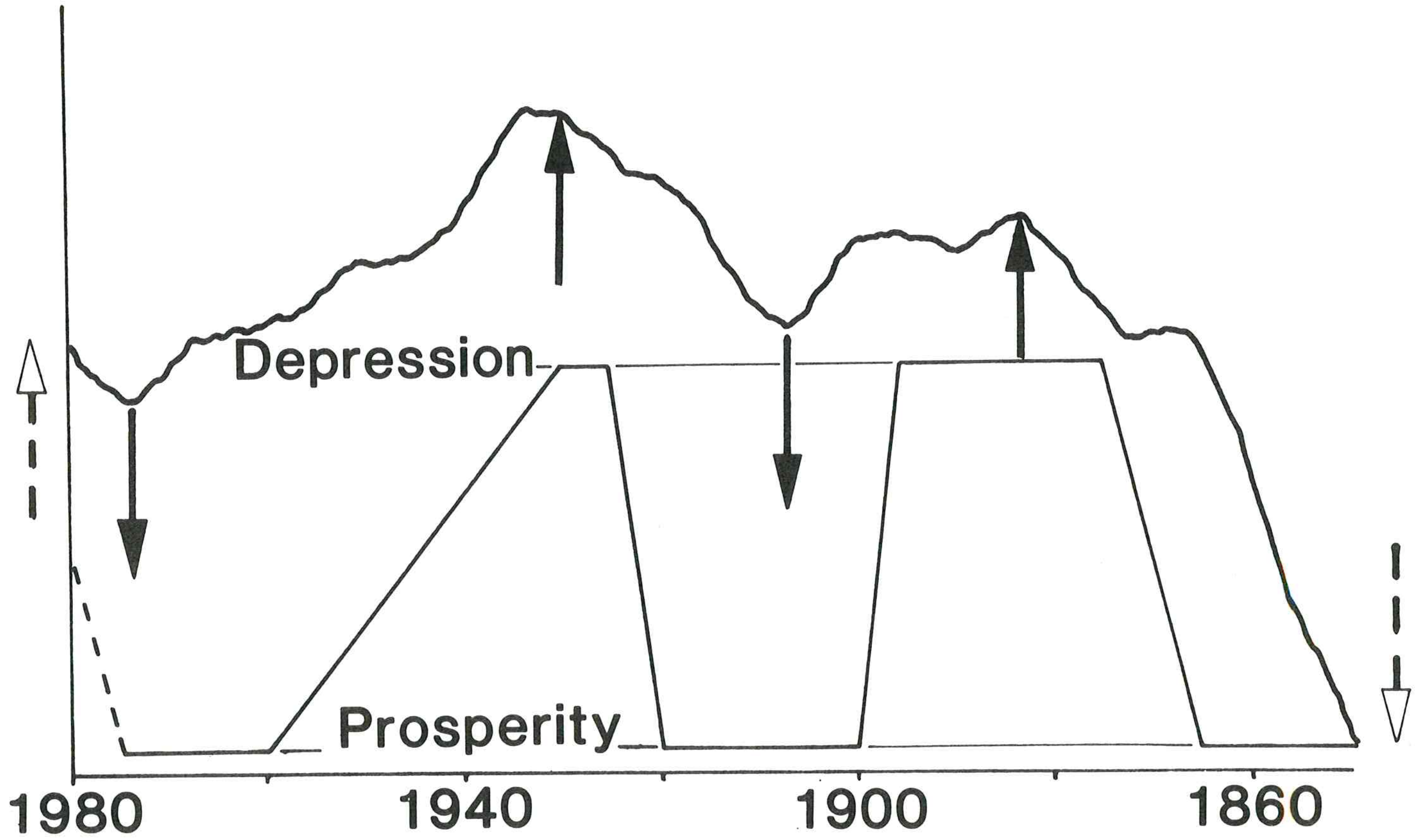

FIGURE 5: Comparison of climate model with global economy since 1850 AD

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