A Weather Watch for Semi-Arid Lands Within the Tropics [and Discussion]

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A weather watch for semi-arid lands within the tropics

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Meteorological measurements, at the Earth's surface and in the atmosphere, and satellite photographs are exchanged internationally. They can be used to follow the daily and monthly behaviour of the climatic variables that affect agriculture. The consequences of variation can be assessed to some extent by using heuristic models of crop growth and to a lesser extent from statistical correlations with yields.

The movement of air masses within the tropics has a systematic but irregular pattern, which is still not well understood. However, the statistical correlation of some weather variables, such as geopotentials, with the rainfall to come, can be used to indicate the character of the coming season in some parts of the tropics.

1. Introduction

Agricultural systems are determined, to a large degree, by climate and weather. Meteorological measurements are made throughout the world, and three main sorts of meteorological information are exchanged internationally. Measurements made several times daily, at the surface and in the atmosphere, are sent on a complex telecommunications network almost continuously to form the 'World Weather Watch' organized by the World Meteorological Organization. Copies of satellite photographs, taken both in the visible and infrared wavebands, from the National Oceanic and Atmospheric Administration of the United States of America are sent on a facsimile transmission system, usually daily. The monthly means of the measurements are sent out, early in the following month, on the 'Climat' system of the World Meteorological Organization.

This international exchange would be remarkably complete if it all worked all of the time. Even in the arid regions of the tropics there is a reasonable spread of meteorological stations which could report measurements at the surface (see figures 1 (west and northwest Africa) and 2 (Indian subcontinent)), though there are inevitably many fewer stations for atmospheric measurements. Unfortunately a number of countries almost continually fail to report, and others occasionally fail to report. More rarely, there are telecommunication failures.

The kinds of measurements which are transmitted are primarily determined by the needs of synoptic and dynamical meteorologists. Fortunately these include most of the measurements at the surface and in the atmosphere that are important in agricultural meteorology. Probably, means over periods of 5–10 days are the most useful starting data for agricultural meteorology because this is the length of period within which a crop changes measurably. However, it is far from easy to collect and derive 5-day means from measurements which are made daily, or even more frequently, for a very large number of places. We have therefore had to start, for lack of anything better, with the monthly means from the 'Climat' network. The use of periods as long as this may obscure important statistical and physiological relationships between weather and yield.

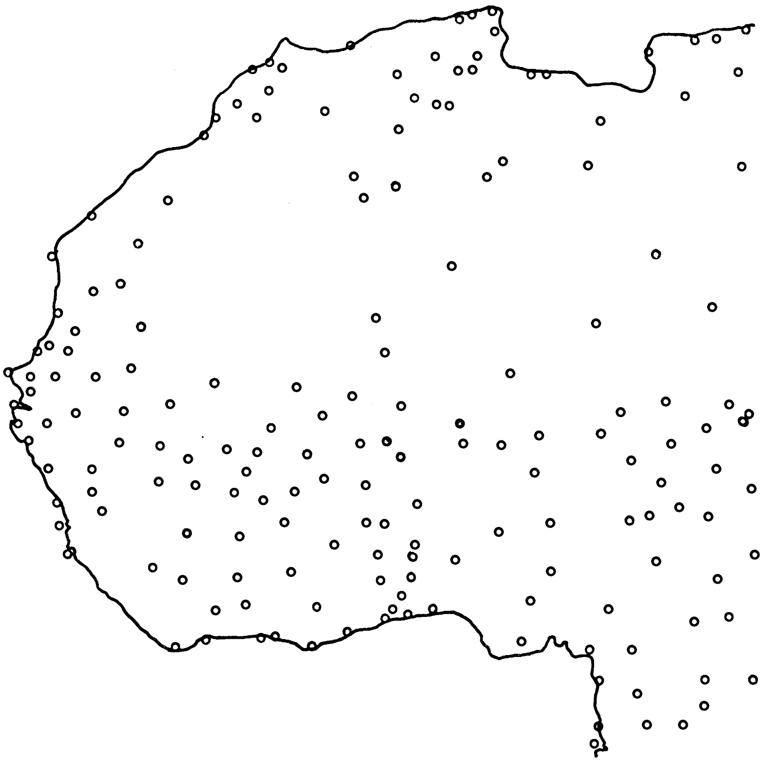

FIGURE 1. A map of West Africa showing the meteorological stations which could report surface measurements to the 'Climat' network.

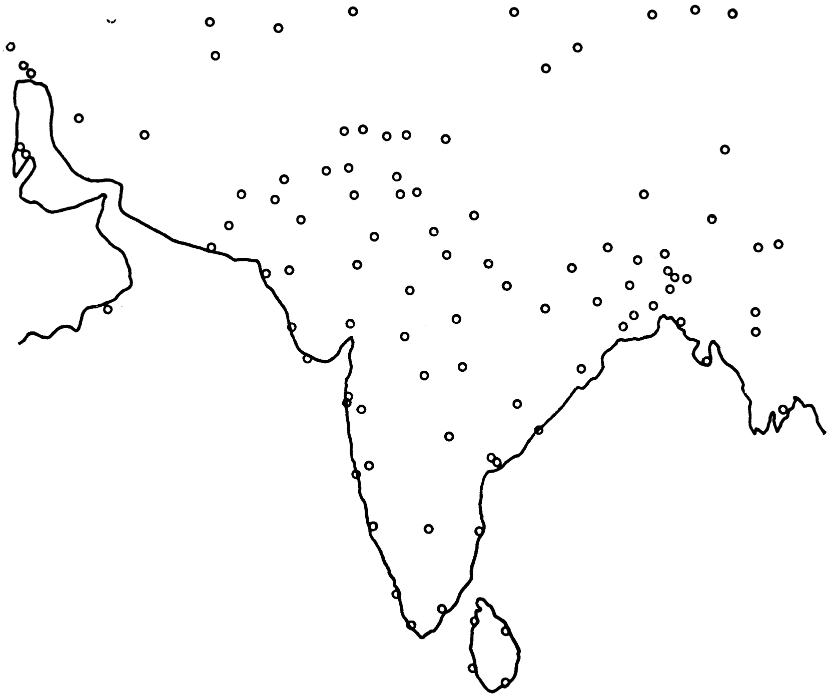

FIGURE 2. A map of the Indian subcontinent showing the meteorological stations which could report surface measurements to the 'Climat' network.

2. Models

The meteorological measurements must be organized within some conceptual frame before they can be used for most agricultural purposes. The development of such a frame is now one of the principal objectives of agricultural meteorologists throughout the world. Both statistical and heuristic models have been made to relate the yields of crops to weather variables. Such models are intrinsically more difficult to make for animals, partly because their behaviour is more difficult to quantify and analyse, but also because it enables animals to respond more flexibly to variations in the weather. Consequently, even though heuristic models relating animal production to weather would be very important for the arid tropics, no fully satisfactory ones yet exist (but see Gates & Schmerl 1975).

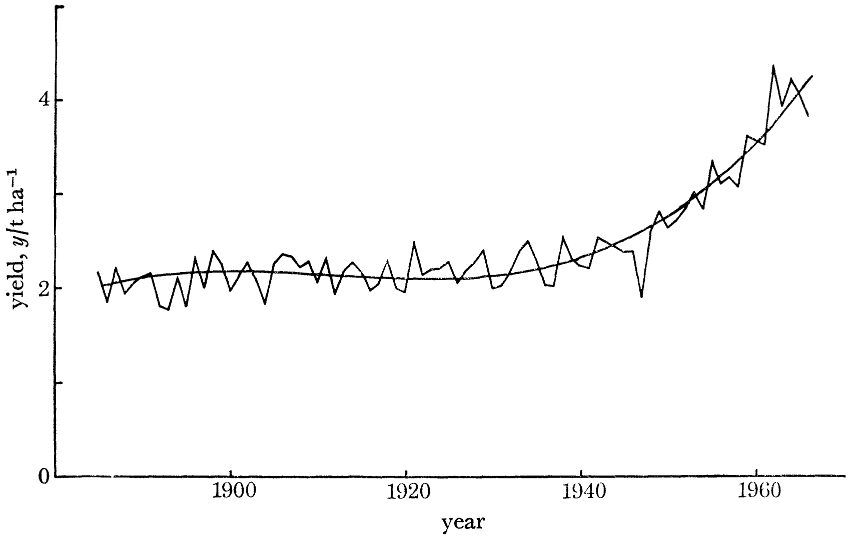

Figure 3. The yields of wheat in England and Wales from 1885 to 1966, with a fitted cubic regression ($r^2 = 0.89$).

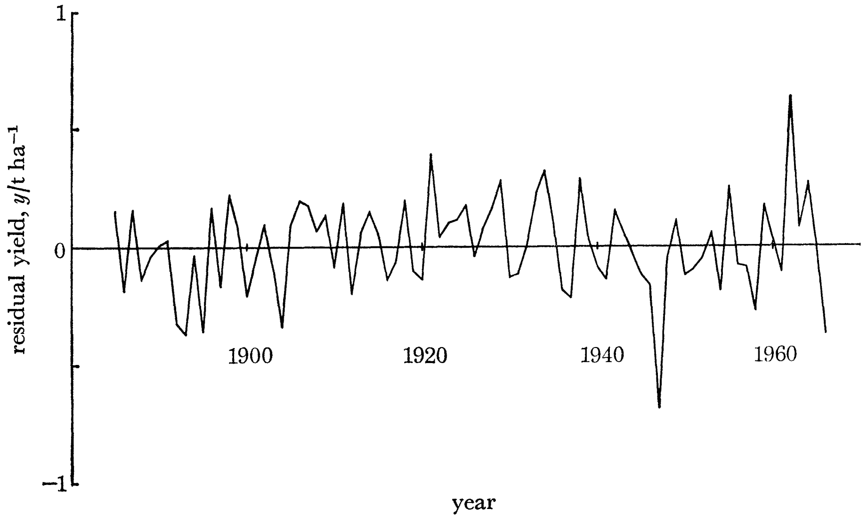

Figure 4. The residual variation of yield, after removing the trend, of wheat in England and Wales from 1885 to 1966.

A number of statistical models have been made to relate the yields of crops, often of cereals, to weather. Yields vary from year to year. They generally tend to increase with time; perhaps because agricultural technology improves and spreads. Polynomial regressions of yield on time can account for much of the variance in a long run, which might be more than 50 or more years of measurements. The fitted line can be taken to represent the effects of changes in farming practice and improved technology, though it is bound to include also the effects of any long-term variation in climate.

TABLE 1. THE MEAN YIELD, ITS STANDARD DEVIATION, AND THE STANDARD DEVIATION OF THE RESIDUALS OF YIELD, OF WHEAT IN ENGLAND AND WALES FOR 10-YEAR PERIODS FROM 1886

period	mean yield y /t ha^{-1}	standard deviation S_y/t ha^{-1}	coefficient of variation (%)	standard deviation of residual S_r/t ha^{-1}	standard deviation of residual as a % of mean yield
1886–1895	1.99	0.17	8.31	0.18	9.03
1896–1905	2.15	0.18	8.35	0.18	8.38
1906–1915	2.21	0.13	6.05	0.13	5.80
1916–1925	2.16	0.17	7.85	0.17	7.97
1926–1935	2.23	0.17	7.71	0.16	7.11
1936–1945	2.32	0.19	8.31	0.16	6.84
1946–1955	2.71	0.38	14.09	0.25	9.17
1956–1965	3.66	0.47	12.80	0.25	6.86

The average yields of wheat in England and Wales from 1885 to 1966 are given in figure 3, together with a fitted cubic regression. In this example yields have increased from about 2 to nearly 4 tonnes ha^{-1} during 80 years. The residuals from the regression line are set out in figure 4. They may be taken, at a first approximation, to represent the effects of weather or of the immediate consequences of variation in weather, such as fluctuation in the damage done by pests or pathogens. Statistical tests can then be used to correlate these residuals with variation in weather, especially solar irradiance and the water balance. The variance of the residuals itself varies with time; the standard deviation ranges from 0.13 to 0.25 t ha^{-1} (table 1); so that linear regressions are not always appropriate.

These models are statistical and not general. The equations relating weather variables to yield change from place to place. Even when the types of equation are similar, the constants vary. Furthermore, there are few long sets of reliable measurements of both weather factors and yield from which equations can be established, particularly in the tropics, though there are a few for industrial crops.

For example, records of sugar cane yield from Viti Levu, Fiji, have been collated by Dr P. C. Prasad (figure 5). The crop is grown on the seasonally arid western side of Viti Levu; not the most favourable environment for sugar cane. The yields have varied from 41.2 to 85.1 t ha^{-1}. The slope of the linear regression is small (0.3 % per year) and the yields are not generally correlated with either solar irradiance or water deficit (Prasad, Dennett & Elston 1975). The residuals are proportionately larger than for wheat, reaching 20 t ha^{-1} (figure 6).

The Food and Agriculture Organization of the United Nations has published measurements and estimates of yield for much of the world since 1948 in the Production Yearbooks. This is about the shortest period worth examining. However, the figures from the semi-arid tropics are sometimes inconsistent or unreliable.

A single weather factor of paramount importance may sometimes be statistically related to yield. Lomas (1972) found an asymptotic relation between rainfall and wheat yield in Iran. Kibukamusoke (1958) has shown that the yields of seed cotton in Uganda can be estimated from rainfall; but the form of the relation differs widely between different parts of Uganda.

Figure 5. The yield of sugar cane in Fiji from 1935 to 1965, with a fitted linear regression ($r^2 = 0.04$).

Figure 6. The residual variation of yield, after removing the trend, of sugar cane in Fiji from 1935 to 1965.

Heuristic models of growth and development, leading to general models of yield, are now being developed for crops (see Elston & Monteith 1975). The quantitative attributes of the crop at a particular time, such as the leaf area, the dry mass or the economic yield, depend upon the sum of the rates of many physiological processes. These processes have mechanisms, usually biochemical, whose rates are altered by meteorological variables. If the parameters that describe this dependence are known and if there are measurements of all the relevant meteorological factors then the states of the attributes can be predicted.

The rate of production of dry matter depends upon the solar irradiance intercepted by the crop. Monteith (1965, 1972) has shown how the physical structure of the canopy can be combined with the light response curve to predict the crop growth rate from the solar irradiance. This model, and variations on the same theme by other modellers, are accurate: figure 7 compares estimated and measured growth rates in four peanut crops at Samaru, Nigeria. The points fall close to the 1:1 line. We understand that part of the *place/weather/crop* system that describes photosynthesis reasonably well, and that relationship is general. The estimates of the crop growth rate can be integrated over time to give an estimate of the dry mass of the crop. In the two peanut crops which provided the data of figure 8 the estimate of the final dry weight exceeded the actual mass by less than 20 %.

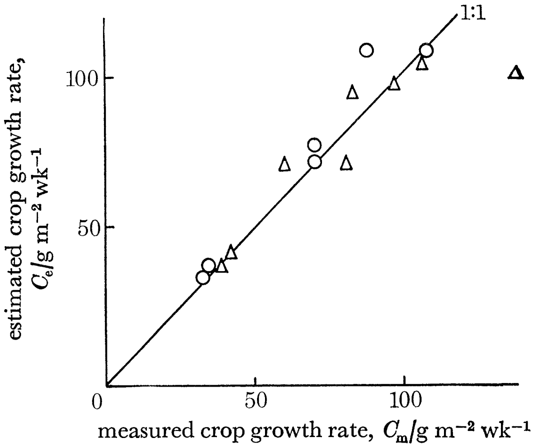

FIGURE 7. A comparison of estimated and measured growth rates for four groundnut crops from Samaru, Northern Nigeria. Taken from Monteith (1972).

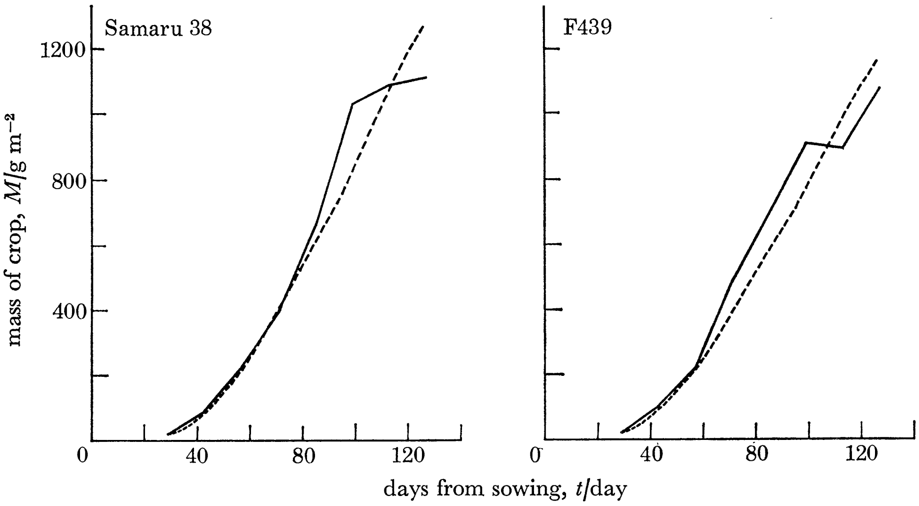

FIGURE 8. Prediction of the dry mass of an alternate (cv Samuru 38) and a sequential (cv F439) peanut crop based upon Monteith (1972) (dashed line) and the actual dry mass (continuous line) taken from Elston, Harkness & McDonald (1976).

Unfortunately we do not understand sufficiently well the relations between environmental factors and respiration, leaf growth and death, or the partition of dry matter. As a consequence a series of empirical relations have to be used to model these processes. For the peanut in a number of seasonally arid climates the partition of new dry matter between leaves and the rest of the plant (the leaf to total growth ratio) is a linear function of time (figure 9), falling from 0.6 at about 2 weeks to less than 0.2 at about 15 weeks from sowing. Increases in leaf area can then be simulated. A similar partition coefficient, the reproductive to total growth ratio, can be used to model yield. However, disease and age affect or kill peanut crops in very uneven ways, so the predictions of economic yield are generally less impressive than those of total dry matter.

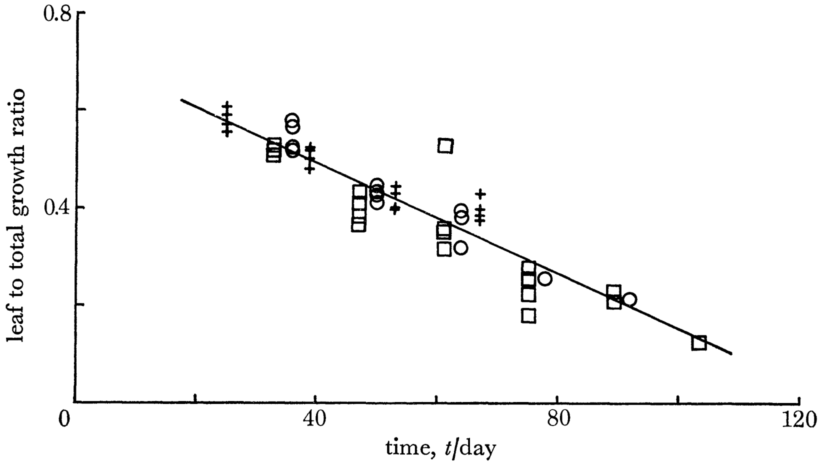

FIGURE 9. The leaf to total growth ratio against time for 13 crops of peanuts in three experiments at two places including six different cultivars with two different branching habits.

Similar empirical partition coefficients, though without the same simple dependence on time, can be made for other annual crops. The heuristic models do not at present describe development (as opposed to growth) satisfactorily. Indeed they remind us of all that is not known about weather and crop growth.

Many statistical and heuristic models, with weather variables as inputs, have been made. They are continually being used and some are being tested. They are still imprecise, but they do describe the limits of biological yield as a function of weather. The agricultural consequences of current weather will be more directly and reliably assessed as these models are improved.

3. The assessment of the current weather

A rising mass of warm damp air forms the meteorological equator. Surface winds from both hemispheres converge there to form the Inter-Tropical Convergence Zone. This moves in a regular fashion with time, bringing rain to the seasonally arid tropics. The basic physical system has long been understood (Hadley 1735). Both the mean position of the zone in any one month, and the mean pattern of rainfall, are known, but the movement varies from year to year. Moreover, a large part of the rainfall is convective, and is related to mesoscale disturbances within the convergence zone. Consequently the rainfall at one place can vary substantially from year to year. The dynamical explanations of these variations are not yet clear. We need to know much more about how the weather systems of the tropics work.

Solar irradiance, and so probably potential evaporation, is less variable from year to year than rainfall. Variations in yield are therefore more likely to be associated with variations in the water balance. Within the rainy months in the humid tropics water stress rarely limits the growth of crops, whose growth rate depends primarily upon intercepted radiation. In the arid tropics the system is less simple. A partial failure of the rains may lead to total failure of the crop, so that yield is not a continuous function of rainfall. Nor do we know enough to understand in detail the ways in which the variations in the water balance affect yield. There are no heuristic models and no satisfactory statistical models we can use to assess the consequences for yield of variation in rainfall. The agricultural assessment at the moment depends upon experience, intuition and belief. Within the semi-arid tropics smaller than average total rainfalls appear to decrease arable crop yields. In stable cropping patterns a seasonal total rainfall of about 80 % of the mean sometimes appears to be critical, though grasslands may behave rather differently. The distribution of rainfall is probably as important as the total quantity. Monthly rainfall figures obscure this source of variation in yield. Rainfall totals greater than average seem to be less important.

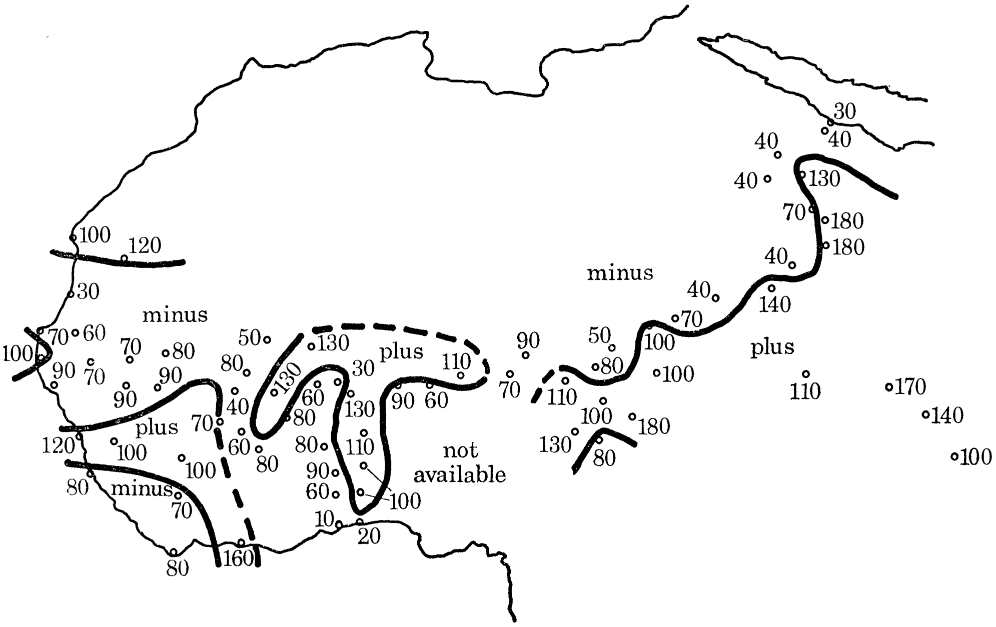

FIGURE 10. A map of West Africa showing the departures of the rainfall for August 1975 from the mean August rainfall, based upon 'Climat' reports.

The monthly rainfalls as reported on 'Climat' can be collected throughout the growing season for any country that reports regularly. The departures of the rainfall for a particular month from the mean for the month, the rainfall anomaly, can be plotted soon after the end of the month (figure 10) and the agricultural significance of the rainfall can be assessed, either qualitatively and intuitively, or statistically.

4. Predictors of seasonal rainfall

Part of the variation of rainfall from year to year is systematic. In the Sahel there has been a statistically unimportant oscillation with a period of more than 5 years (Bunting, Dennett, Elston & Milford 1976). An oscillation implies persistence in some characteristics of the atmosphere from year to year. An oscillation in rainfall, if it continues into the year to come, implies that some part of the rainfall of the season to come is predictable. However, Wright (1971) has listed two rules about such oscillations. The first rule states that some feature of the atmosphere can be found showing a period of the length required to justify a particular hypothesis, and the second states that such an oscillation generally dies shortly after discovery. The first rule is gratifying and both rules seem to be exact.

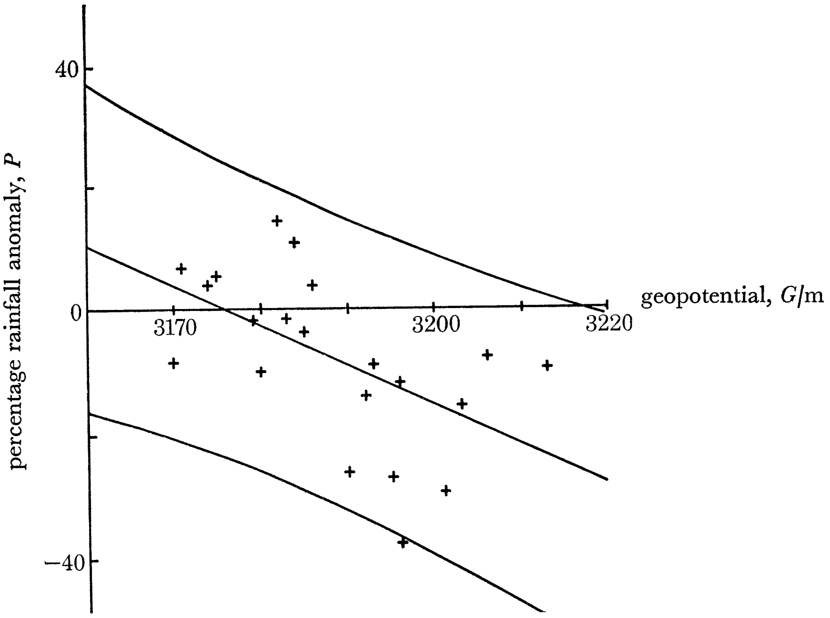

Figure 11. The percentage departure from the mean of the rainfall at 50 stations in the Sahel since 1955 plotted against the 700 mbar geopotential at Niamey. A linear regression ($r = -0.55$) and 95% confidence limits have been drawn.

Long range forecasts are now made for a number of countries. The British Meteorological Office releases a 30-day forecast every two weeks. The forecasters have relatively long runs of reliable weather measurements and use sophisticated statistical techniques, including eigenvector methods. Monthly forecast maps for rainfall and temperature are published for the United States of America. The assessment of the reliability of complex forecasts is difficult, but the general tenor of the British forecasts has been reasonable.

Delsi (1973), in a synoptic study of part of Africa, found that the anomaly of the mean monthly 700 mbar (70 kPa) geopotential persisted from June until August. (The geopotential may be taken as the height above sea level at which the barometric pressure reaches a particular value.) The rainfall in West Africa is also persistent from July until September (Bunting, Dennett, Elston & Milford 1975*a*). The 700 mbar geopotential at Niamey can be used to predict the July and August rainfall for the Sahel, provided the atmospheric relationships of the past continue to hold (figure 11). This predictor is statistical. However, the 700 mbar geopotential at Niamey in July depends upon the temperature and humidity of the air of the Inter-Tropical Convergence Zone, and the rainfall of the Sahel depends upon the northerly movement of this moist air. For confidence, the predictor for the July and August rainfall of the Sahel should be based upon the dynamics of the Convergence Zone.

The rainfall of the seasonally arid part of Viti Levu, Fiji, can be predicted from Wright's Southern Oscillation Index (Prasad *et al.* 1975) (figure 12). Rainfall increases with the Southern Oscillation Index. Perhaps the increased pressure gradient between the South Pacific and Australia that occurs when the values of the Index are large increases the advection of moister air and hence rainfall. Certainly the northerly wind component is increased, though there are also differences in the east–west circulation.

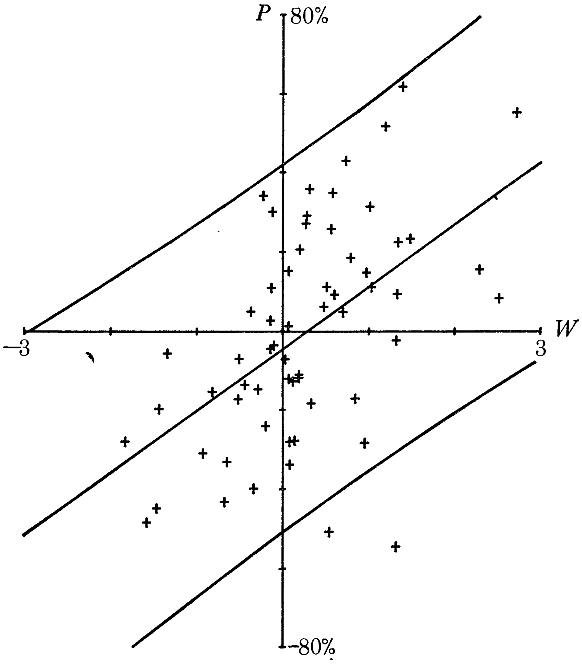

FIGURE 12. The percentage departure from the mean of the August to July rainfall (P) at 5 stations in the sugar cane area of Fiji from 1910 to 1970 plotted against Wright's Southern Oscillation Index (W) for the previous May to July. A linear regression ($r = 0.53$) and 95% confidence limits have been drawn.

The correlation coefficients of the seasonal predictors, though statistically significant, are relatively low. Typically, between 30 and 50% of the variation in rainfall is correlated with the predictor. As a consequence, the confidence limits are wide. We have therefore preferred to use contingency tables specifying the likelihood of wet, average or dry years rather than spuriously precise numerical predictions of the departure of the actual rainfall from the mean.

The chance accumulation of statistical predictors of rainfall would be both tedious and inefficient. Instead the climatological analysis of rainfall must include an analysis of the dynamical meteorology of the seasonally arid tropics. The temporal and spatial variations of rainfall can be analysed by using individual correlation coefficients between stations, correlation matrices and principal component analysis to identify patterns.

The principal component analysis produces a number of components, the eigenvectors, which are linear combinations of stations. The first eigenvector is that combination which accounts for as much variance as possible from the original observations. Successive eigenvectors are extracted from the remaining variance, with the provision that each component is uncorrelated with all previous ones. The analysis has at least two uses. Homogeneous areas can be defined from eigenvectors (see Dyer 1975), and the eigenvectors can be used to describe the large-scale variations of rainfall and to link rainfall with circulation patterns. Pittock (1975) has used these correlation techniques in an admirable study of Australian rainfall. In east and north Australia rainfall and Troup's Southern Oscillation Index are correlated. There are two principal patterns of rainfall anomaly. In the more important pattern, negatively correlated with Troup's Southern Oscillation Index, rainfall is below average in both east and north. In the second pattern, rainfall is above average in the centre of East Australia. These two patterns alone account for 54% of the rainfall variance. Pittock suggests that much of the observed variation in rainfall may be a more or less random fluctuation, possibly with persistence. It may be possible to predict the likely anomaly from the Southern Oscillation Index.

Table 2. The relation between Wright's Southern Oscillation Index for May to July and annual rainfall at Hyderabad, India, from 1893 to 1972

	rainfall		
	low	average	high
Southern Oscillation Index			
low	18	12	5
high	9	14	22

$\chi^2 = 12.8$; $P < 0.01$.

Extremes of rainfall are associated with Wright's Southern Oscillation Index in India (table 2). When the Index for May to July is small then the annual rainfall is likely to be average or less. The first eigenvector from a principal component analysis of annual rainfall from 1951 to 1974 for 26 stations accounts for 26% of the total variance of percentage rainfall anomalies. The coefficients are positive at all stations, showing a tendency for all the stations to behave in the same way in any one year. The percentage loadings of the eigenvector show the correlation between station and first eigenvector (figure 13). The relation between rainfall and the first eigenvector is greater in Western Peninsular India, where the loadings reach 82%. In the east and south the loadings fall to less than 20%, accounting for less than 4% of the variance.

The first four eigenvectors can be used to sort the stations into more nearly homogeneous areas (figure 14), which make it easier to establish predictors of rainfall. The first eigenvector is correlated with Wright's Southern Oscillation Index (figure 15) with a correlation coefficient of 0.57 ($P < 0.01$). This eigenvector is very closely related to the average of the Western Peninsular group of 13 stations ($r = 0.98$, $P < 0.001$), and the Southern Oscillation is related to the spatially averaged rainfall of this group of stations.

Clearly there is much work to be done before any predictor of rainfall for Peninsular India, save in the general terms of table 2, can be established. However, also clearly, there is a good chance of establishing such a predictor, using information freely available from 'Climat'.

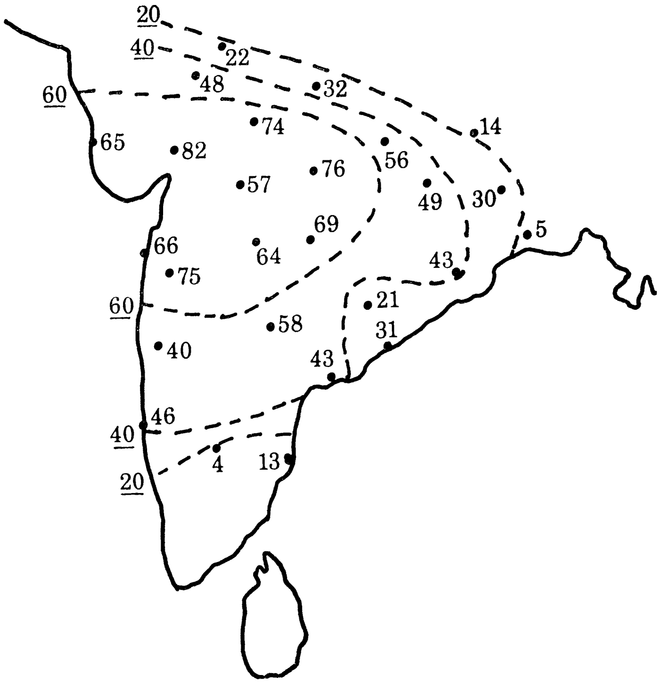

FIGURE 13. A map of Peninsular India showing the percentage loading of each station on the first eigenvector.

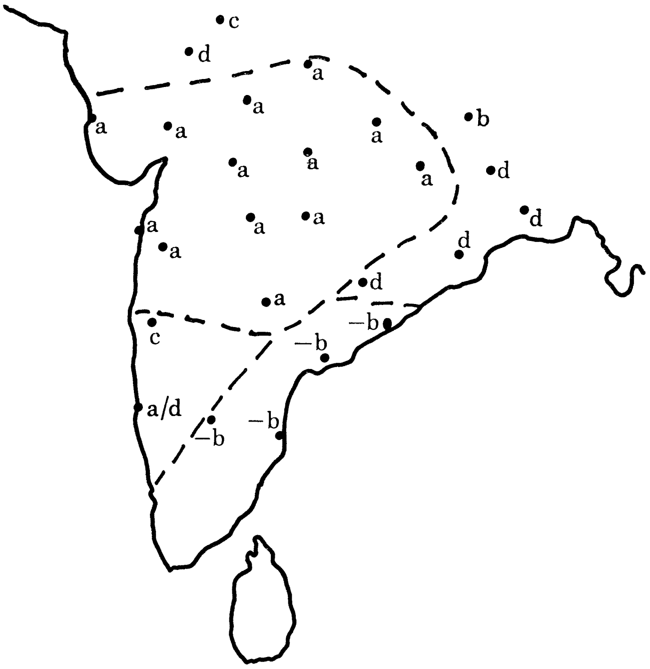

FIGURE 14. A map of Peninsular India showing the more nearly homogeneous areas of rainfall established from a principal component analysis.

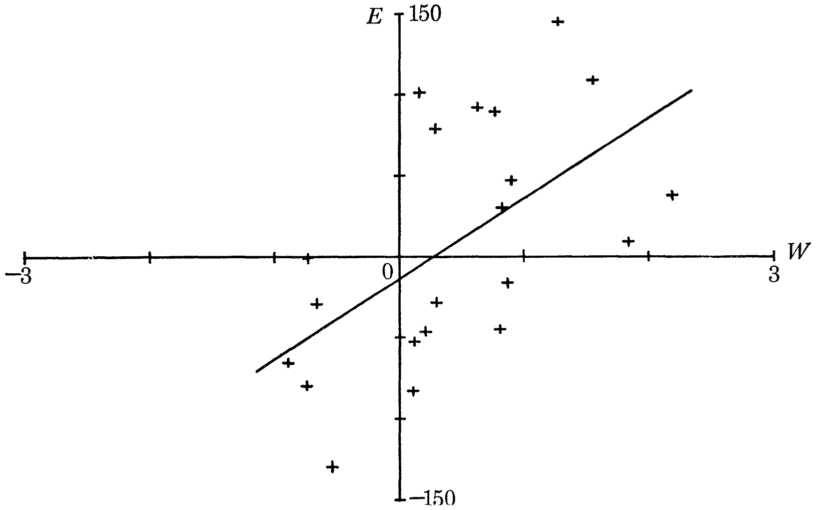

FIGURE 15. The first eigenvector (E) of the rainfall from 1951 to 1971 plotted against Wright's Southern Oscillation Index (W).

5. The use of forecasts

Subsistence farmers cannot respond directly to forecasts of the character of a season; their farming methods are not sufficiently flexible. The farm calendar is determined by climate and the pattern of crop growth, but the peak demands for human labour are fixed and are very restrictive. Little fertilizer is used; so that any saving from using less in dry seasons is likely to be unimportant in most semi-arid agricultural systems at the moment. It is seldom possible, at present, to substitute one species, or cultivar, for another; but this may change as agriculture becomes more commercial and seed industries develop. Spacing and crop combinations could be altered. Crops could be more widely spaced in dry seasons, though increased vegetative growth may compensate for wider spacing to some extent and so the expected saving of water may be limited. It is possible that some particular combinations of crops, in the multi-cropping systems that are almost universal in the seasonally-arid tropics, are less affected by drought than others. However, crop combinations have been largely neglected in agricultural research programmes and require very much more study.

Governments, on the other hand, can respond to forecasts of the character of a season. If an unduly dry (or wet) season is likely, they can store food and make preparation to distribute it. They can limit cattle numbers, perhaps by controlling access to wells. They can encourage and assist the migration of people away from the most marginal areas.

Perhaps most important of all they may achieve a degree of independence from the weather of one season by developing complementary economic and other exchanges with other climatic areas (Bunting, Dennett, Elston & Milford 1975 *b*). Rainfall changes quickly with distance in the tropics. Arid, seasonally arid and humid regions are relatively close to each other. The present national structure in West Africa has developed since the Congress of Berlin. Before that there was a well organized, reciprocal trading system running north–south, linking the drier and wetter regions. The scale of trade certainly depended in part upon the absence of wars and as a consequence varied greatly at different times. Nevertheless the humid south and dry north were linked together; and these arrangements continued and developed through the colonial period. The newer national structure of West Africa has placed administrative and political barriers across these north–south links, isolating the northern countries with their unreliable climates. These countries are politically independent, but they cannot now be economically self-sufficient through agriculture at any but the poorest level, because of their climate, nor are they able to handle the consequences of climatic fluctuation effectively within their own boundaries.

The work described here has been generously supported by the Ministry of Overseas Development. Professor A. H. Bunting and Professor J. L. Monteith, F.R.S., have made major, characteristic contributions to agricultural meteorology and have stimulated, encouraged and corrected us. We are extremely grateful to them. John Goodier of the Agricultural Research Council, Dr P. C. Prasad of the University of the South Pacific, R. A. S. Ratcliffe of the Meteorological Office and P. B. Wright of the University of East Anglia have helped us. We thank them all.

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Discussion

J. A. Adedokun (*Atmospheric Physics Group, Department of Physics, Imperial College, London S.W.*7). Elston's and Rainey's papers have mentioned the rôle played by the intertropical convergence zone (I.T.C.Z.) in influencing the Sahel rainfall.

Experience from our work here at Imperial College on West African precipitation shows that a station's position relative to the I.T.C.Z. determines, to a large extent, the amount and duration of its rainfall. The region of maximum convective instability occurs in a narrow band some 7–10° S of the I.T.C.Z. while the atmosphere is rather stable to the north and just south of the I.T.C.Z. Thus maximum convective instability and rain occurs in the Sahel in late July to early August, at which time the southern part (Lagos area) experiences its 'little dry season' (Ireland 1962).

Inter-station (cross) correlation of precipitation in the north–south direction indicates a maximum correlation between Lagos in the south and Sahel stations such as Niamey, Menaka and Kidal to the north, for a two-month lag. Over 20 years of monthly rainfall data (January 1951–December 1970) for Lagos and Niamey, the two-month lag correlation is 0.6. This suggests that the rainfall observed at Lagos can 'foreshadow' that of the Sahel region two months later. This two-month period might be usefully spent in making tactical agricultural plans to match the expected rainfall.

Consideration of a typical wet and a typical dry Sahel year shows that in the wet Sahel year the 'little dry season' extends further north. Moreover, the intensity of the 'little dry season' is related to the strength of the 'Zonal Walker Circulation' (Flohn 1971) and the Southern Oscillation (Walker & Bliss 1932).

May I know if the Southern Oscillation Index used in Elston's paper is the same as that derived by Sir Gilbert Walker in his 'World Weather Studies' or is it a modified form?

References

Flohn, H. 1971 The tropical circulation pattern, *Bonner Meteorologische Abhandlungen*, **15**, 49 pp.

Ireland, A. W. 1962 The little dry season of southern Nigeria. *Nigerian Met. Ser.*, *Tech. Note* No. 24.

Walker, G. T. & Bliss, E. W. 1932 World Weather V. *Mem. R. Met. Soc.* **4**, 53–84.

J. Elston. A simple form of the Southern Oscillation Index developed by P. B. Wright has been used. (This has since been published: Wright, P. B. 1975 An index of the Southern Oscillation, *Climatic Research Unit*, *University of East Anglia*, *Research Paper* **4**.)

S. Sandford (*Overseas Development Institute*, 10–11 *Percy Street*, *London W*1). Mr Sandford said that in discussing the utility of weather forecasts Dr Elston had concentrated on the use that *cultivators* could make of these. They could also be very useful for *pastoralists* in, for example, the following ways:

(*a*) Enabling them to plan and bring forward their sales of livestock in the face of drought; so that the sales were not delayed, as happens now, until the animals are in very poor condition and prices collapse because of the forced simultaneous sale of livestock in overloaded market and processing facilities.

(*b*) Preventing pastoralists being trapped in isolated grazing areas whence, because of drying up of water points on the route out, neither they nor their livestock could escape when rains are delayed.

(*c*) Enabling, where a system of grazing permits or stock licences are introduced, the quota to be adjusted *in advance* of drought instead of *after* it has started when some damage to the environment has already occurred.

G. Stanhill (*Volcani Centre of Agricultural Research*, *Israel*). I think it important to point out one serious limitation to the use of weather based statistical and modelling approaches to the study of yield variation. Once the technologically induced yield 'take-off' occurs, weather induced changes in yield become relatively less important even though their absolute size may still increase. Under such conditions the identification and interpretation of the causes of yield variation becomes extremely difficult and complex.

An admittedly non-arid example of this process can be seen in the changing pattern of inter-annual variability of the yield of wheat in England during this century. Since the end of the Second World War, secular causes of yield variation have for the first time become more important than the random variation, indicating that changes in technology are now a more important cause of yield variation than variation in weather.

J. **Elston.** I wonder if the limitations are as great in developed agricultures as Professor Stanhill believes. Whatever the technology, differences in yield must depend upon the physiology of the crop variety, upon the environment and upon the environment/genotype interactions. There have to be reasons for the differences in yield from year to year, and when these are understood they may be modelled heuristically. Certainly statistical models are intrinsically less good than heuristic ones. However, even now we can account for a good part of the variations in the departures from the regression by variation in weather variables. For example the correlation coefficient between the departures of the yield of wheat in Europe and July and August rainfall is about −0.7, for the period 1952–1971. Some correlation coefficients were even larger for the North American crop.

W. E. **Ormerod** (*Department of Medical Protozoology, London School of Hygiene and Tropical Medicine, Keppel Street, WC1E 7HT*). Several speakers in this conference have stated that enough scientific and technical information is available for the satisfactory management of the world's semi-arid regions and that the reasons why these regions in Africa, India and Latin America are not so managed are in the main social and economic.

Socio-economic problems are certainly formidable, yet I would like to express my doubt as to whether sufficient scientific information is available or that a satisfactory conceptual framework has been built up to allow us to grasp many of the problems. To illustrate this I would like to put forward two current theories which have not been discussed in this conference but which must nevertheless, if substantiated, be of fundamental importance to management of semi-arid regions. In stating my provenance, as a health worker, I emphasize my inability to assess the validity of these theories; I merely use them to illustrate my point.

The first theory states that the main damage caused by rainfall is, as opposed to that in temporate climates, a result of the high kinetic energy of individual drops (Ellison 1944 *Agric. Eng.* **33**, 491–496; Hudson 1971 *Soil conservation* London, Batsford).

If this theory is valid, at least some of the technology that has been described in the last two days could be dangerous to introduce because of the possible exposure of soils, even for short periods, to high energy rainfall without adequate vegetative cover.

The second theory (Charney *et al.* 1975 *Science, N.Y.* **187**, 434) states that the reflectivity of desert soils exposed by overgrazing can directly cause an inhibition of precipitation, which in the case of the Sahel may be as great as 70 %, thereby producing a 'feedback' relationship between the management of vegetation and climate.

It seems that the validity (or otherwise) of these theories is important to our concepts of management. There may be good reasons why these and other theories have not been taken into consideration, but their neglect and that of other seemingly important concepts leads me to question whether we have sufficient scientific information to enable us to transfer, with confidence, an empirical technology from one region to another in the face of great socio-economic difficulty.

J. Elston. Tropical agronomists are well aware of the damage that rainfall can cause to bare soils and that cropping systems are being designed to minimize it. Lawes has been testing such systems at Samaru in the early 1960s and they have since been developed further. Professor Charney's theory is nice and probably at least partly true. It is not possible to test it with a real experiment, but it can be assessed gradually as more measurements are made at the desert margins.

M. Mansell-Moullin (*Old Hatch, Lower Farm Road, Effingham, Surrey*). Previous speakers have mentioned the need for both more basic water resources data for development schemes in the semi-arid regions and also the greater transfer of knowledge between English and French-speaking scientists in this field. I strongly support both views.

In these regions the hydrological characteristics of the water resources fall into two groups – those which can be defined reasonably well from observations covering 2–3 years and those requiring much longer, say 10–50 years. Sufficient data on the former can be obtained during project investigations but the latter must depend mainly on existing records, usually transposed from elsewhere. Group 1 contains the more stable elements, e.g. the general climate, ground-water conditions, chemical water quality, etc. and group 2 mainly those related closely with precipitation, e.g. storm intensities, monthly and annual precipitation variations, runoff characteristics, sediment runoff, etc. Frequently the only information available on the items in group 2 is the knowledge of the local inhabitants, if any.

The limited, world-wide information on group 2 is seldom in a transposable form. I wish to recommend that an appropriate international organization should tackle this problem by (*a*) identifying those regions and countries where important water development schemes are having to be based on scarce data, (*b*) determining where there are reliable, long-term data from comparable areas and (*c*) reviewing and generalizing that data so that it can be transposed readily. The programme should be regarded as a pooling of present knowledge, rather than as research.