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Workshop on
Land-Atmosphere Interactions in Climate Models
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Agricultural Impacts of Climate

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Agricultural impacts of climate I — Observations

1 Global agricultural production

The following classification is intended as a guideline only. The scientific definitions outlined do not necessarily follow those used by the general public.

Fruits	—	Edible reproductive structure, e.g. tomatoes
Vegetables	3%	Edible stems and leaves
Cereals	60%	Grass crop, producing dry fruit (grain)
Tuber	5% (with roots)	Swollen underground storage organ
Legumes	22% (with oilseed)	Pod fruit (seed) e.g. pulses, groundnut, sunflower

Agroecological zones:
Climate determines what is grown where (figure 1)
Rice — warm and humid conditions
Cereals — more temperate regions

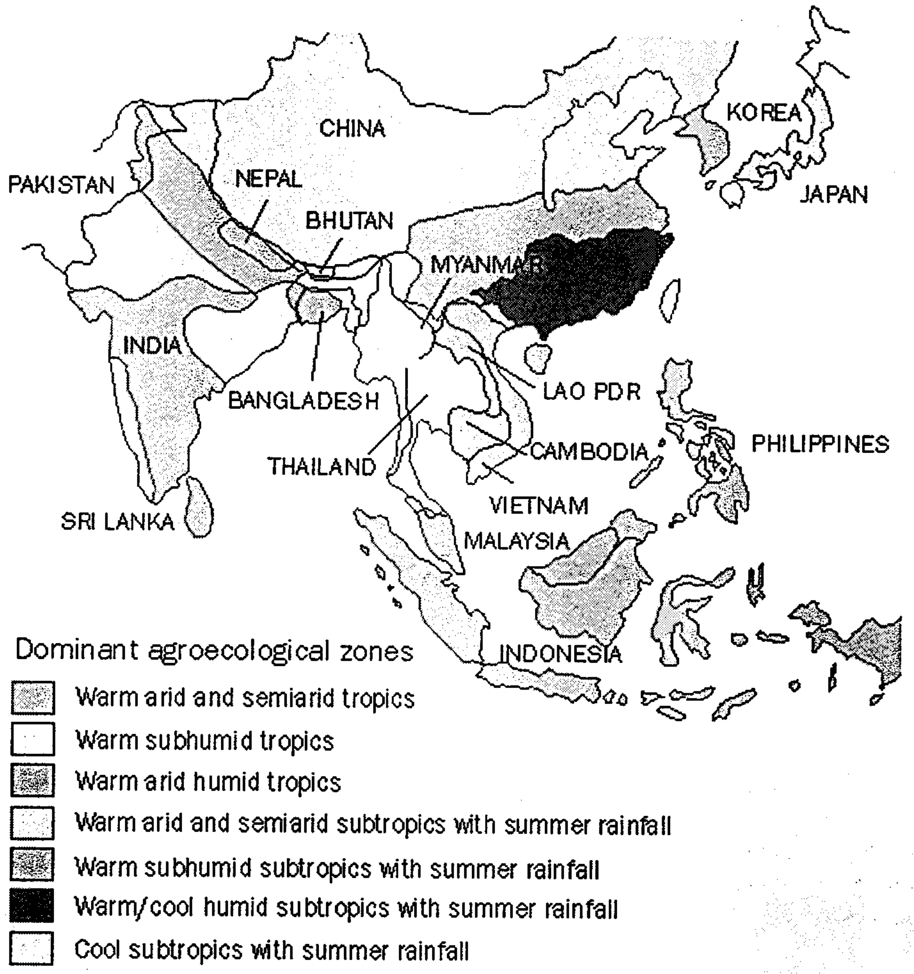
Soil types:
Soil type is usually the second most important determinant of crop yield. It affects the hydrological balance, the ability of roots to expand and the nutrition available to the plant. The simplest way to classify soils is by the size of the inorganic particles:
Sand — large particles $\sim 10^{-5}$–10^{-4}m
Silt — medium particles $\sim 10^{-6}$–10^{-5}m
Clay — finest particles $\lesssim 10^{-6}$m
Loam — blend of the above three types

Other classifications exist - e.g. by geographical region; "–sol" (alfisol, vetisol etc). Important soil characteristics include composition, density, texture, water-holding capacity, and horizon (or profile) information.

A *soil horizon* is distinct layer of soil, arising from a particular formation process. Hence top-soil (cm–m) includes decomposing organic matter from above ground, so that temperate regions often produce thicker top-soils. Sub-soil and rock (parent material) layers lie below this upper layer.

Risk management
Growers must balance Vulnerability to climate with maximisation of production. Risk can be minimised by crop management strategies. Subsistence farmers tend to be more risk-averse, whereas larger-scale growers can invest more in technology and information which can minimise risk.

FIGURE 1



AEZs, population pressure, and food grain production

Population pressure on arable land is highest in the humid and subhumid subtropics and humid tropics but these AEZs also have favorable growing conditions for food grain crops. The production of food grain per ha of arable land is about 5.7 times higher in the subhumid subtropics (southern and southwestern China and Taiwan) than in the semiarid tropics (southern and western India). The arid and semiarid tropics have the lowest production potential of the AEZs. The higher production potential in favorable AEZs, however, is offset by higher population pressure on land. So the difference between AEZs in food grain production per capita is small. In 1990, food grain production per capita was highest in the subhumid subtropics (377 kg per person), and almost 50% higher than in the semiarid tropics, which produced the lowest.

Analysis of land use patterns in the AEZs of Asia indicates that rice is the dominant food crop in the humid subtropics (76% of the area under food grains), humid tropics (75%), and subhumid tropics (51%). It is an important crop in the subhumid subtropics (36%) and semiarid tropics (19%), but is insignificant in the semiarid and cool subtropics. Riceland ecosystems may be defined in various ways. In the other topics in

www.riceweb.org

2 Response of crops to environment

2.1 Basic definitions and processes

Cultivar (cv.) — A highly bred variety of crop.

Genotype — Genetic constitution (narrower definition than cv.)

Phenology — This is crop development studied in relation to the seasons. i.e. it is the plant's response to the environment.

Thermal time — Crop development is controlled by temperature accumulated above a base temperature (temperature * time). Hence a crop will have a defined thermal time between key stages of its development (e.g. flowering, pod-filling, maturity).

Leaf Area Index — Area of leaf per unit area of ground. The leaf area index of a crop follows a seasonal pattern of growth up to a maximum value near the middle of the season, followed by senescence (for some crops). The timing of the maximum value is dependent on the phenology of the crop.

Photosynthesis — Light is intercepted by the leaves (this is a function of LAI, canopy architecture and solar radiation). Photosynthesis uses this electromagnetic energy to convert CO_2 into sugars, which in turn are converted to dry matter.

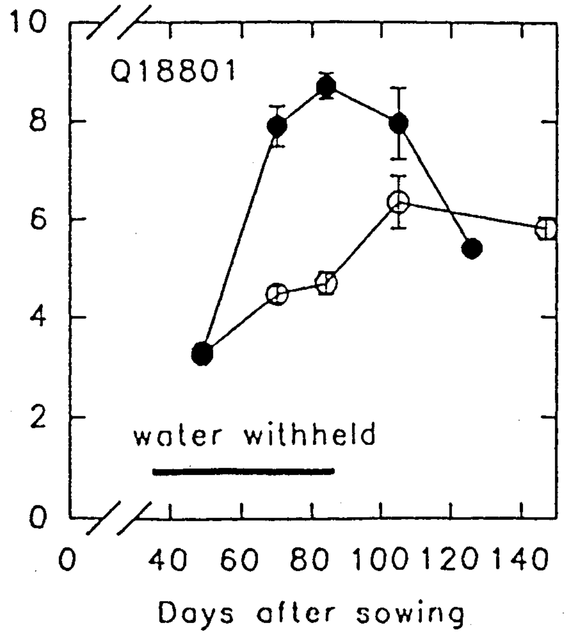
Nitrogen fertiliser — This increases the leaf size and longevity, thus increasing light interception. Note that there is an optimum LAI, above which no LAI increase can increase light interception.

Transpiration — As the stomata open up to allow CO_2 in, water vapour is allowed out, thus cooling the plant. Stomata close in response to water-stress.

Dry matter partitioning — In the early stages of development, dry matter is partitioned to the leaves (to improve light interception) and to the roots (to improve water uptake). Later in the season the reproductive organs are formed.

Potential yield — Yield attained under conditions where neither water nor nutrient availability limit the crop's growth

LAI
(groundnut)



● WELL-WATERED
○ WATER WITHHELD

Chapman et al (1993)

2.2 Crop field experiments

Usually performed on small plots or in pots or greenhouses, these experiments seek to discover causal relationships between crop variables. e.g. population density/LAI, rooting depth/water uptake etc. Isolating these relationships is non-trivial since the soil–crop–atmosphere system is non-linear. Where the fundamental processes are understood (soil physics, for example) the system remains complex and hard to measure and predict. The crop adds a biological aspect which is less well understood, and in which the action of cause and effect are less easily discerned.

Efficiencies and ratios are often calculated in order to compare different crops and cultivars; e.g.

Transpiration efficiency — Mass of dry matter produced per unit mass of water transpired.

Water use efficiency — Mass of dry matter produced per unit mass of evapotranspiration.

Radiation use efficiency — Mass of dry matter produced per unit radiation intercepted.

MAHESWARA RAO ET AL (1989)

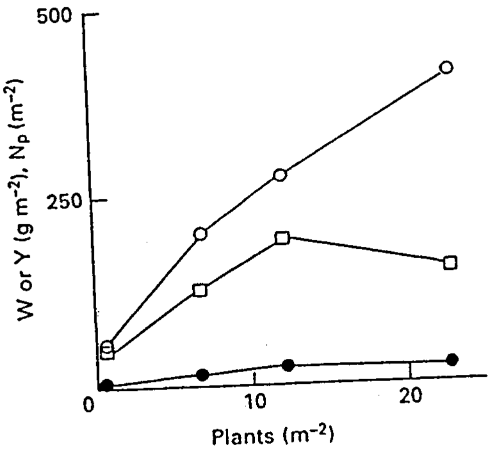


Fig. 4. The influence of population on total dry matter (W, o), pod yield (Y, •) and pod number (Np, □) per unit land area at 90 days after sowing.

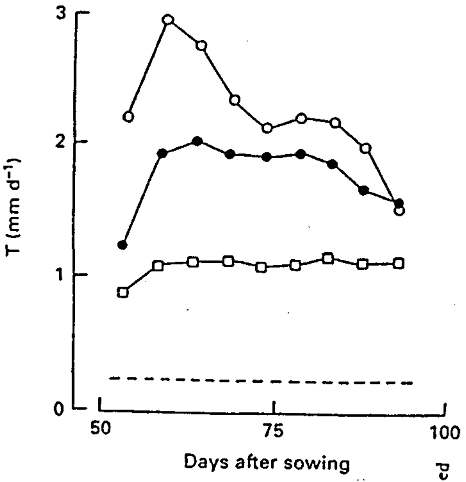
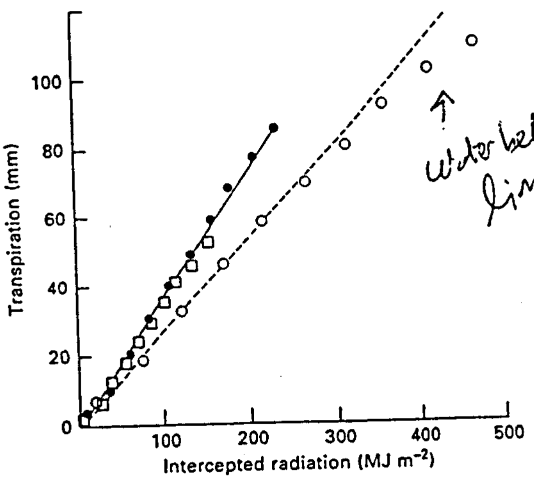


Fig. 9. The change in transpiration rate (T) with time in the A (o), B (•) and C (□) spacings. The dashed line indicates the average rate of transpiration in the D spacing between 50 and 95 days after sowing.

SIMMONS AND WILLIAMS (1989)

S.N.AZAM-ALI *et al.* (1989)



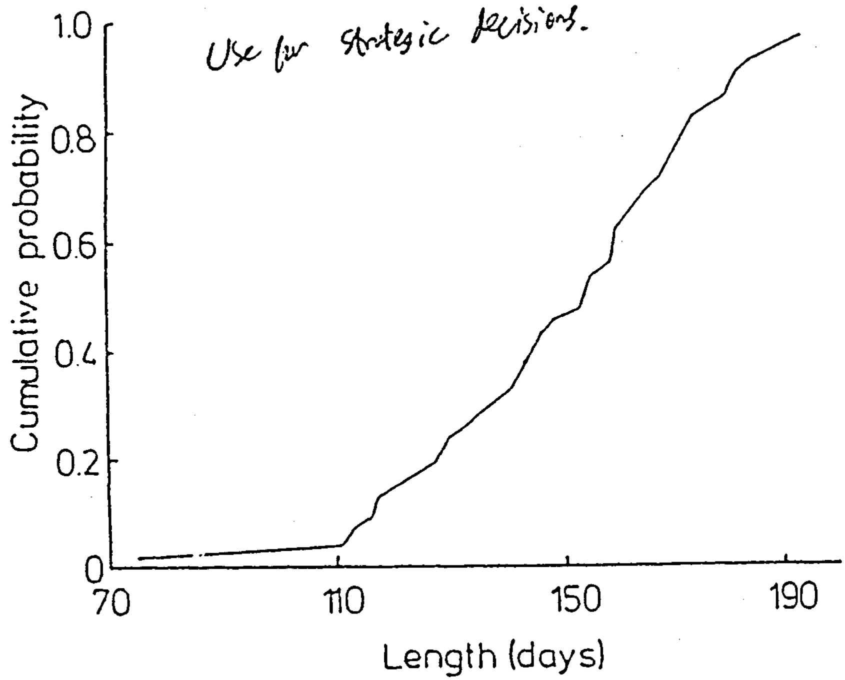
water balance limiting.

Fig. 5. The relation between cumulative transpiration and cumulative radiation interception; slope for B and C spacings = 0.37 (±0.01) kg MJ^{-1} ($r^2 = 0.98$); initial slope for A spacing (fitted through first five points) = 0.28 (±0.01) kg MJ^{-1} ($r^2 = 0.98$). (o, A spacing; •, B spacing; □, C spacing.)

3 Crop management (response of grower to weather)

3.1 Strategic management

This refers to long–term agricultural planning which enables farmers to cope with year–to–year variability in both the weather over the growing season and the economy. Strategic decisions may include the purchase of machinery and the choice of crop to plant (based on seasonal forecasts, cost of seed, price of crop etc).



Use for strategic decisions.

Fig 5 *The cumulative probability distribution of the length of the growing season at Kano. The probability is that of having a season shorter than or equal to the value on the length axis*

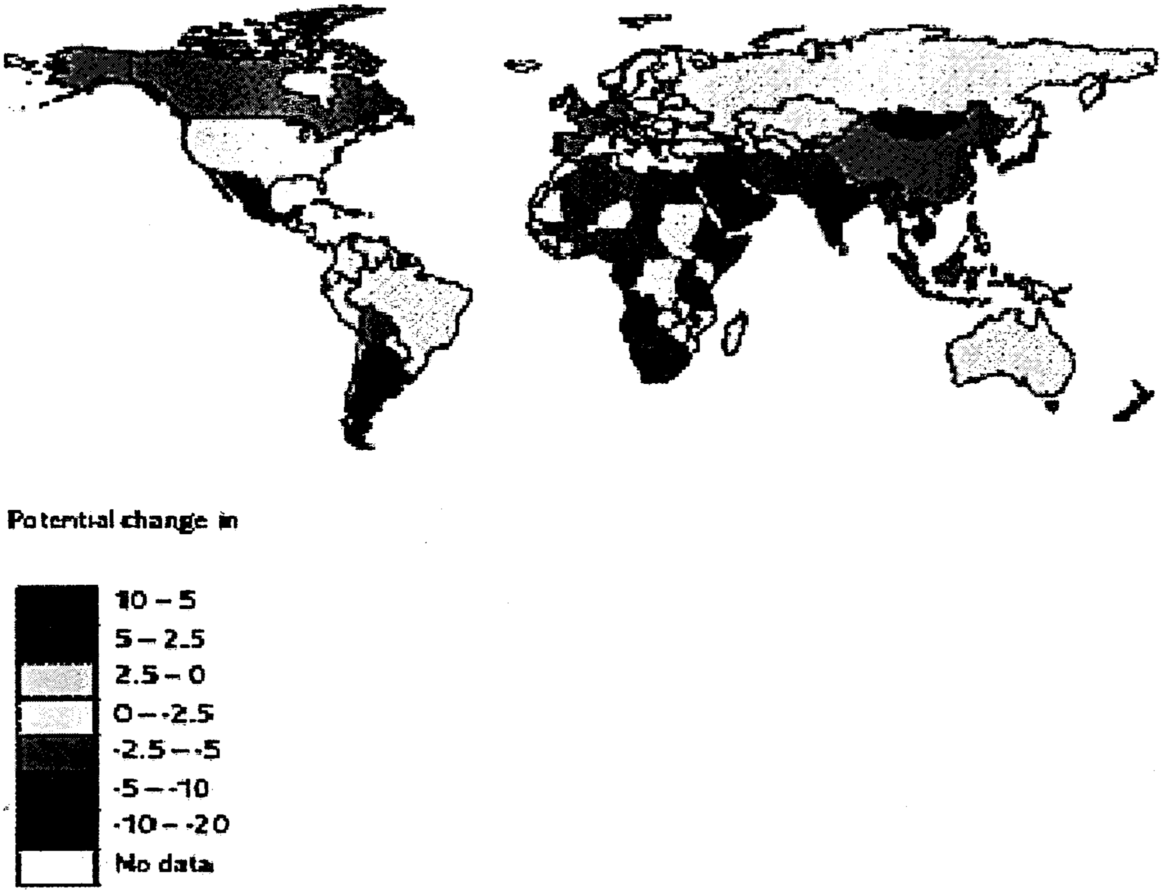
3.2 Tactical management

This refers to shorter time-scales, and would typically be in response to weather forecasts with a lead time of days to a week. Examples of this type of decision include choice of planting date, pesticide spraying, irrigation.

4 Climate change

If mean temperatures and CO_2 levels continue to increase then crop production patterns will change (due to increased photosynthesis and faster accumulation of thermal-time). Precipitation patterns may also be modified over the coming decades. These changes have a potentially huge impact on crop production. A word of caution — the science of climate change is not understood well enough for definite statements to be made about future climates.

Crop models can be used to estimate what yields would be under future climate scenarios e.g. the following, from the Hadley Centre;
http://www.metoffice.com/research/hadleycentre/pubs/brochures/B1999/
which is for cereal yields in the 2080's, in the case of stabilisation of CO_2 at 750 ppm.



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http://www.riceweb.org/envi_zones.htm

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http://www.smithandhawken.com/html/resource/gooddirt/basic.jhtml

Chapman et al (1993) *Effect of drought during early reproductive development on growth of cultivars of groundnut I. Utilization of radiation and water during drought* (Field crops research 32 pp 193–210)

Nageswara Rao et al (1989) *Population, water use and growth of groundnut maintained on stored water. I. Root and shoot growth*

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(These last three can be found in *Experimental Agriculture* vol 25)

http://www.co2science.org/edit/v3_edit/v3n35edit.htm

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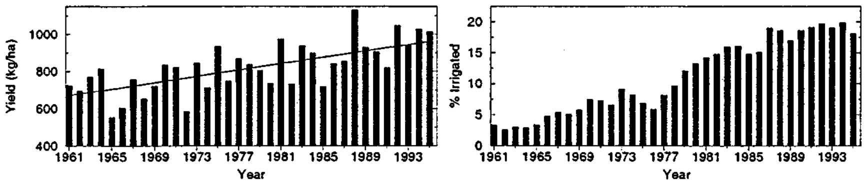
Agricultural impacts of climate II — Modelling

1 Empirical approach

1.1 Direct weather–yield correlations

Measure weather parameters (typically rainfall) and perform a statistical regression of yield (or production) based on weather and a technology trend. The time trend in yield exists because of improvement is crop management, such as increased and better-timed irrigation and fertilisation. In the case of All-India groundnut yield:

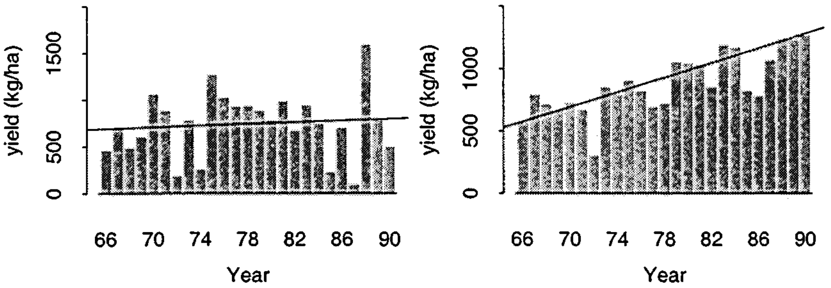


(a) Yield (line shows linear trend, $r^2 = 0.49$)

(b) Irrigated fraction

Figure 1: All-India groundnut yield time trends.

However, note that this relationship is not necessarily spatially homogeneous:

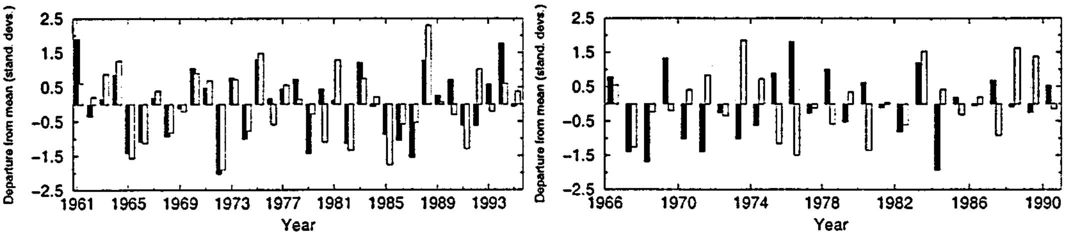


(a) Saurashtra and Kutch

(b) Madhya Maharashtra

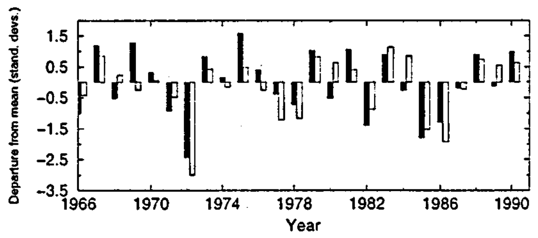
Figure 2: Yield time series for two Indian subdivisions, with least-squares fit shown

and that, similarly, the resulting correlations between yield and rainfall are not necessarily spatially homogeneous:
There are many reasons for this inhomogeneity. There will be errors in the measurements of the yield, and also with the measurement of weather parameters. For example, in this case, the rainfall estimates are for areas of 10^5 km^2, and there will be variability within this region. Pests and diseases can also have a significant local



(a) All-India; $r^2 = 0.52, p < 10^{-4}$

(b) Coastal Andhra Pradesh; $r^2 = 0.10$ (negative correlation), $p = 0.13$



Challinor et al (2000)

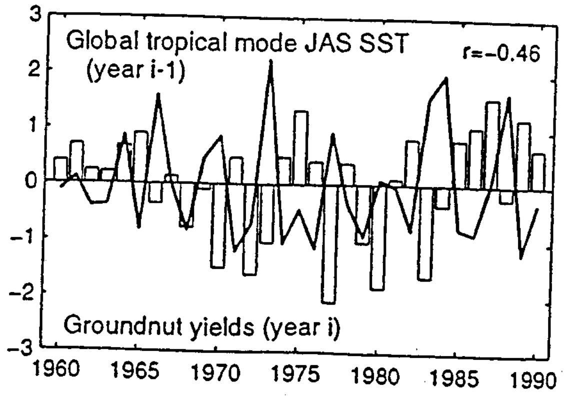
(c) Madhya Maharashtra; $r^2 = 0.62, p < 10^{-4}$

Figure 3: Detrended groundnut yield (outline) and seasonal total (Jun–Dec) rainfall (filled)

impact upon yield, as can positive management practices such as irrigation. Note however that for very large areas (e.g. all-India) inhomogeneities can average out so that a strong signal remains.

1.2 Teleconnections

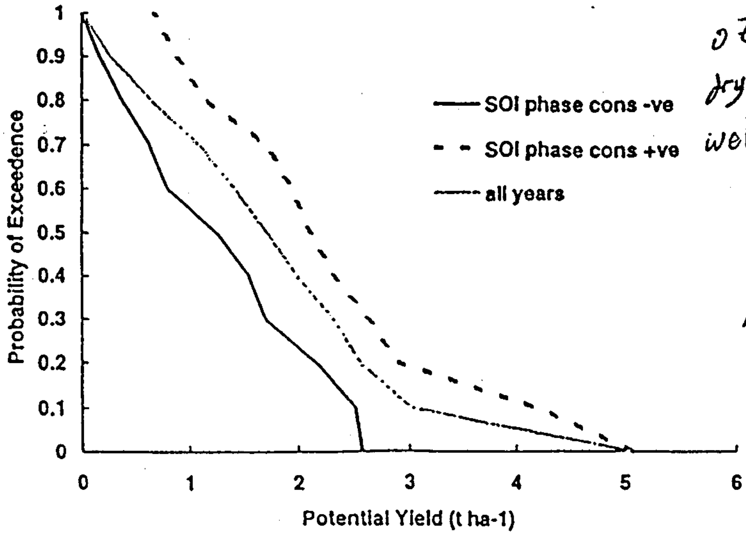
Take some index of the state of the atmosphere and correlate this with yield. e.g. SST (as related to ENSO)



Camberlin and Diop (1999)

Fig. 10. Time-series of groundnut yield in Senegal (bars) and PC1 JAS sea-surface temperature anomalies for the previous year (ENSO, line), Both series are standardised

or SOI



oz
dry
wet

Meinke et al
(1996)

Figure 2. Probability of exceeding a certain potential yield level by SOI phases 'cons +ve', 'cons − ve' and the 'all years' case.

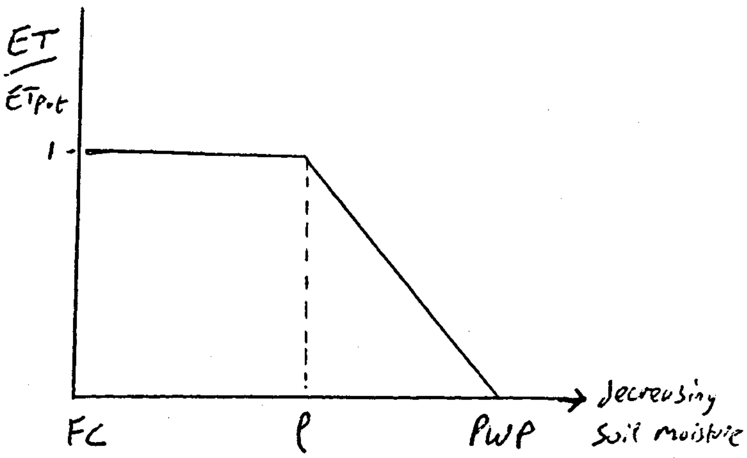
Again, this can work well for large areas, but will not pick up on regionality. Note also that changes in climate may change the nature of any of these teleconnections.

* * *

2 Semi-empirical approach — FAO method

This is essentially a crop water use approach. Some reference evapotranspiration is calculated, and a crop coefficient k_c calculated, such that $ET_{pot} = k_c * ET_{ref}$.

k_c is an empirically determined function of time and planting density (i.e. crop cover), and crop type. Actual ET can then be calculated by estimating the soil moisture stress (i.e. below a threshold soil water content, $ET < ET_{pot}$).



FC = FIELD CAPACITY
p = Frac. of water extracted at potential rate
PWP = PERMINANT WILTING POINT

ET_{ref} can be calculated using the Penman–Monteith combination equation, which combines the equation for surface energy balance ($R_n = G + H + L * ET$) with equations for the surface fluxes H and $L * ET$;

$H \propto \frac{\Delta T}{r_a}$ and $ET \propto \frac{\Delta e}{r_a + r_c}$

Note that the Penman–Monteith equation could be used to calculate actual ET directly if the resistances were known. When used to calculate ET_{ref}, assumptions are made regarding these quantities. The Priestly–Taylor equation is a further simplification of the Penman–Monteith equation, which can be employed when the supply of energy is the controlling factor (i.e. in humid climates where aerodynamic exchange isn't a major determinant of ET).

Once ET has been calculated, a measure of soil moisture stress needs to be determined, and this means solving the surface moisture budget: $P + I = R + D + ET$. Precipitation and irrigation are known, whilst runoff and drainage depend on the the soil profile, and need to be calculated using a soil moisture balance model (unless water is assumed to be non-limiting). This can be a complex multi-layered model or a simple assumption such as $R \propto P$.

3 Process-based approach

This seeks to apply fundamental physical and physiological principles to the system. The full modelling approach uses General Circulation Models (GCMs) together with (mechanistic) crop models. Crop models can in principle be used with weather inputs from any source.
In practice, even the most theoretical approach has empirically determined constants and parameterisations. It does, however, include as much *a-priori* reasoning as possible.

3.1 Crop models

The focus here will be on mechanistic crop models which are used for predictive purposes. Note that mechanistic crop models are also used for research purposes. In this latter case, the model will tend to include many processes and parameterisations, so that the interaction between these processes can be studied. However, the existence of numerous parameters can mean that a great deal of tuning is required in order for such models to be used in prediction.

Inputs
Weather — T_{max}, T_{min}, solar radiation, rainfall, [wind speed, humidity]
Initial conditions — Soil water [and N], plot layout
Genetic coefficients — Thermal time to flowering etc
Soil properties — Hydrological, [nutritional]
[Management practices] — fertiliser, irrigation efficiency, tillage

Model components (a very brief overview of some approaches)

Development — controlled by thermal time requirement (and photoperiod response)

Dry matter production — (i) resource capture method; use water use efficiency, transpiration use efficiency or radiation use efficiency. There must be confidence in the prediction of the relevant driving variable! (ii) Direct modelling of photosynthesis via a CO_2 exchange rate

Partitioning to harvested part of crop — the Harvest Index determines the proportion of dry matter allocated to the harvested part of the crop. This is a function of time, though its rate of change can be constant.

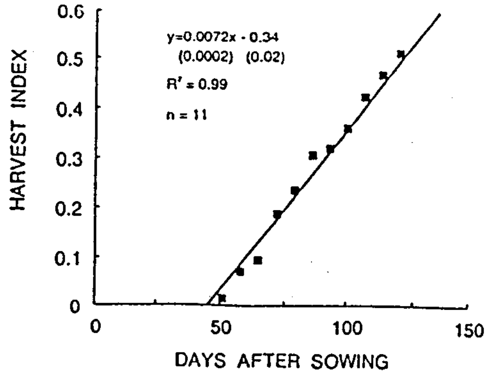


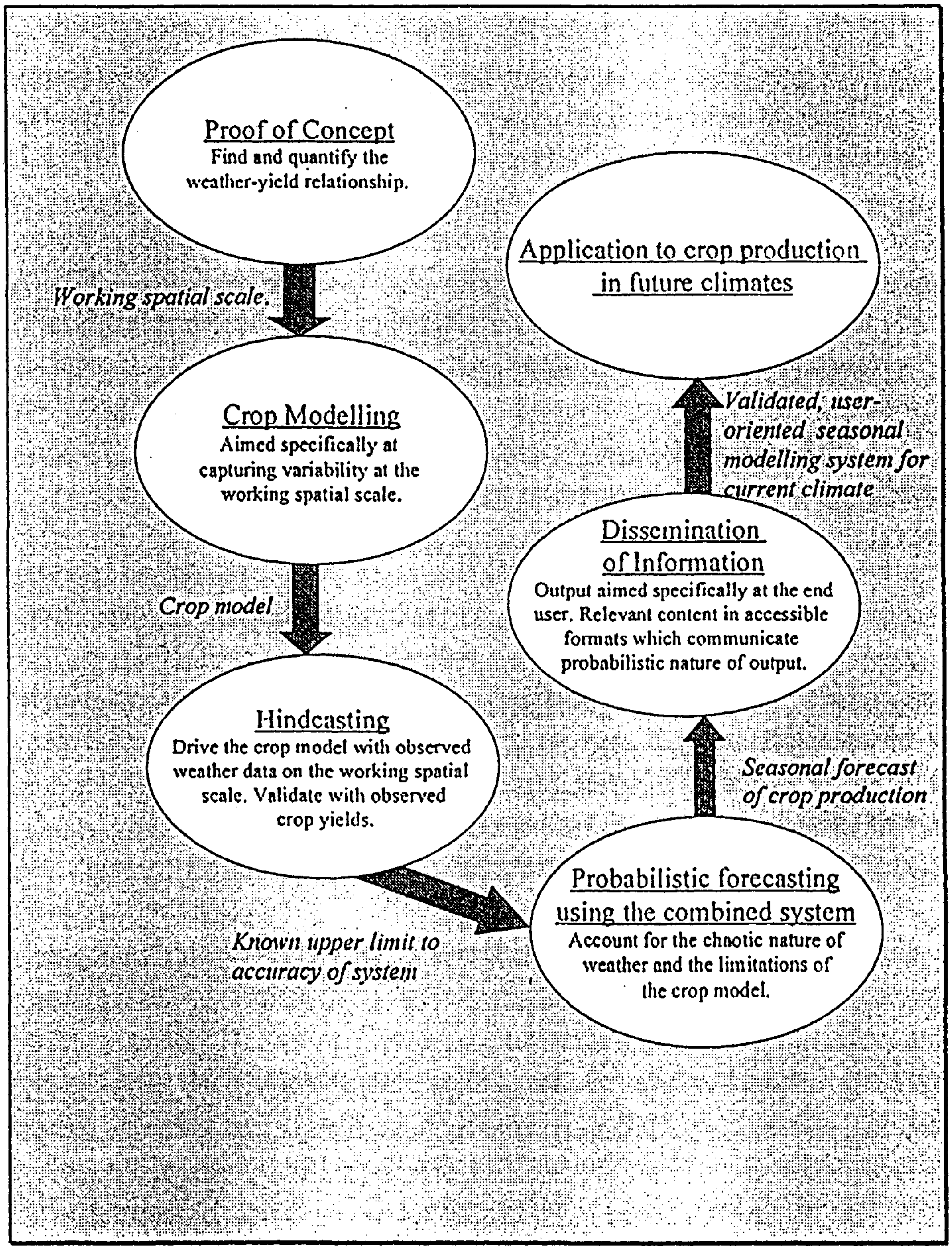
Fig. 3. Harvest index of pods (ratio of pod biomass to total crop biomass) vs. days after sowing for Early Bunch peanut grown at Gainesville, FL (after Bennett et al., 1993).

Hammer et al (1995)

LAI — (i) a partitioning sub-model can be used to determine the proportion of dry matter allocated to leaves, or (ii) a maximum rate of change of LAI can be used, reduced by water stress and possibly a plant density factor (for low densities).

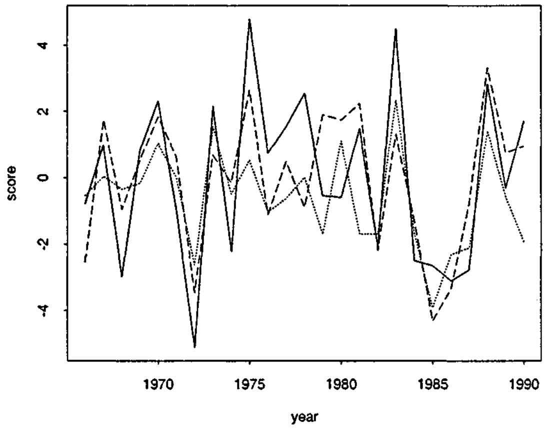
3.2 Combining CMs and GCMs

3.2.1 A methodology



EOF analysis

One way of finding a working spatial scale to use for modelling is to use Empirical Orthogonal Functions (EOFs). Note that this method is also known as Principal Component Analysis. This analysis takes a time series of a spatial pattern (such as rainfall or yield) and extracts the dominant spatial pattern. This dominant mode is the mode that explains the largest percentage of variability over the time series. The spatial pattern (EOF) has an accompanying time series (Principal Component time series). Time series from different EOF analysis can be correlated, and the EOFs compared.



Challinor et al (2000)

Figure 4: First PC of rainfall (unbroken line) and yield (dashed line), $r^2 = 0.53$, $p < 10^{-4}$. Also shown is the the seasonal mean of the subseasonal 850hPa circulation PC3 (dotted line), taken from Sperber et al. (2000)

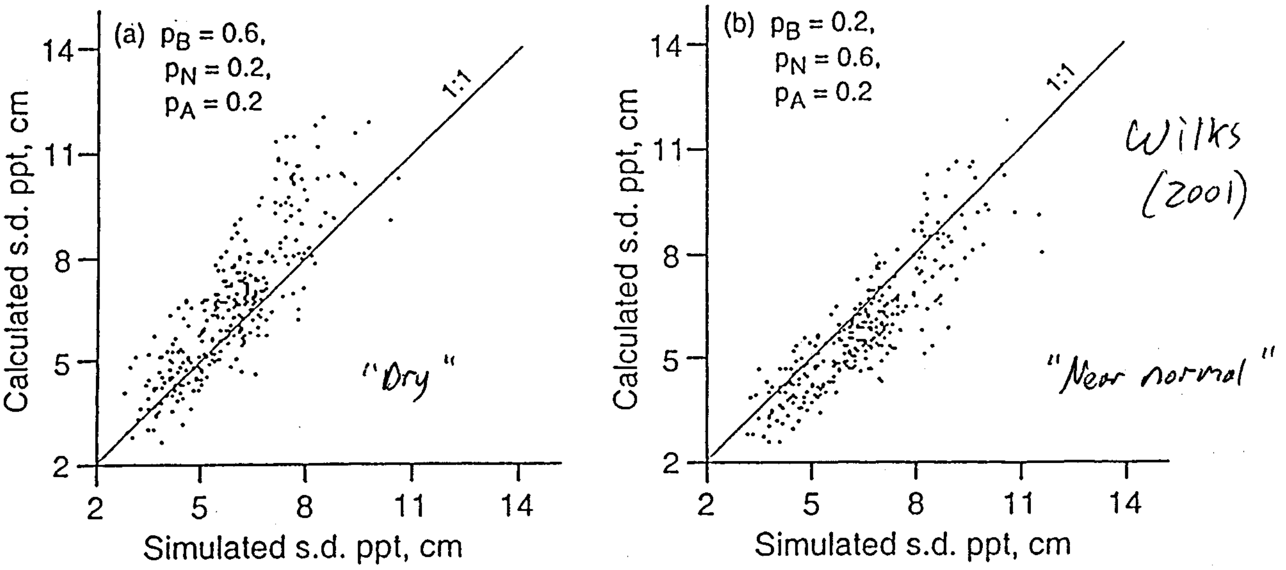
3.2.2 Downscaling of GCM output

Process-based crop models are typically point-models, and cannot make large-scale predictions. If they are to use the output of GCMs, the gap in scale needs to be bridged. Here are some of the key methods used in downscaling. Note that more than one of these concepts can be used in any one downscaling model.

Linear and non-linear regression — Use predictor variable(s) (geopotential height, pressure, RH, cloud cover etc) to perform regression. The ideal variable is strongly correlated, physically sensible, preserves covariance between local variables, well predicted by climate model (this favours circulation-based predictors, usually). The statistical model (form of regression) used will vary with location, and may also vary with time. Seasonality must be removed before doing this. This may be done by defining fixed seasons or by letting the time evolution of variables determine the seasons (floating seasons). This method is low-tech, efficient and pragmatic, but not very portable. Also, since precipitation can be highly localised, this is the hardest variable to predict.

Weather classification and re-sampling — Define weather types and assign these (statistically) to particular circulation patterns. This captures non-linear effects. However ,it only allows the generation of previously recorded weather.

Stochastic weather generators — Avoids repetition of previous weather patterns. Can use seasonal mean values from records (deterministic) or from forecasts (probabilistic) and/or local climate records to condition the output.
Clustering of seasonal forecasts into representative groups (possibly using re-analysis data also) produces analogue ensembles. These account for the probabilistic nature of the forecasts in a more rigorous way.



Wilks (2001)

Nested models — Put a Regional Climate Model within the domain of interest of the CGM. The GCM provides the time series of boundary conditions for the RCM.

3.2.3 Upscaling of the crop model

Another way around the gap in scale is to up-scale the crop model. This can be done by creating a meta-model which runs on monthly data. This can produce similar results to the daily-time-step model. The meta-model can be used on larger scales than the more complex model (eg. 50km). However, it won't capture non-linear processes on time scales of less than one month. This method has the advantage of not being site-specific.

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FAO method; e.g. Doorenbos, Kassam et al (1979) *Yield response to water* (FAO Irrigation and Drainage paper 33)

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