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Climatic changes in yield index and soil water deficit trends in China

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Abstract

Long-term trends of the combined effects of evapotranspiration and precipitation effect surface hydrology and soil water and consequently natural and agricultural ecosystems. This paper analyses yield index and soil water deficit time series derived from water balance calculations for multiple cropping systems with FAO methodology. The analysis shows that yield index values have increased and soil water deficits have consequently decreased over much of China during 1954–1993. The likely parameters contributing to this trend are precipitation changes north of 35°N and maximum evapotranspiration as well as available soil water trends south of this line. Increasing the assumed maximum soil water storage did not result in substantially different results. While this analysis indicates that regional climatic change appears to have had a beneficial effect for several regions in China, predictions from combined global climate model climate change experiments anticipate decreasing yields due to decreased water availability by 2050 in the same regions.

Keywords: Climate change; Yield index; Potential evapotranspiration; Soil water; Water balance; China

1. Introduction

The warming of the earth's atmosphere by between about 0.3 and 0.6°C since the late 19th century (IPCC, 1997) has been established with a fair degree of confidence. Other climatological parameters, such as precipitation, cloudiness and evaporation have been investigated which show strongly varying trends on both global and regional scales. Important as the understanding of the changes of these single parameters may be, the response of terrestrial ecosystems to changing climatic conditions will ultimately depend not on a single but on the combined effects of several climatic variables. In this respect, soil water content, which is mainly determined by precipitation, evapotranspiration and soil characteristics, is one of the most crucial factors in both natural and man-made (agricultural) ecosystems. Climate change is very likely to have a major impact on the hydrological cycle and consequently on the available water resources, flood and drought potentials, and agricultural productivity (Evans, 1996).

In agro-ecosystems, the soil water content directly determines the amount of water available to field crops and in turn yields and irrigation requirements. Declining soil water contents and consequently declining yields can put agricultural based societies at risk if countermeasures are not put forward in time. Asian countries relying traditionally on the highly water consuming rice crop are especially vulnerable in this respect. China, with the world's largest population, plays a crucial role in any possible emerging world food crisis (Harris, 1996). Studies on changes in agricultural production due to changing climatic conditions over China, based on recorded climate data, have remained inconclusive (Zheng, 1994) or

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have used the inappropriate Thornthwaite approach (Thornthwaite, 1948) to calculate evapotranspiration rates (e.g. Chen et al., 1992). Hulme et al. (1992) combined the results of several GCM simulations and predicted a negative net balance of precipitation and evapotranspiration throughout China by the year 2050.

Several studies have been made of precipitation changes in China (Chen et al., 1992; Hulme et al., 1994; Yatagai and Yasunari, 1994; Zhai et al., 1997; Domrös and Schäfer, in press). Work on evapotranspiration trends is relatively scarce (Kayane, 1971; Chen et al., 1992) and has relied on the Thornthwaite formula that is inaccurate in tropical areas (Thornthwaite, 1951). During the last decades (1951–1990), summer precipitation has been mostly decreasing in Southeast, Southwest and East China. Most precipitation trends, however, seem to reflect decadal-scale variations rather than long-term trends (Hulme et al., 1994). Penman–Monteith evapotranspiration estimate trends (1954–1993) have shown to be declining in almost all seasons with some regional exceptions (Thomas, in press). The strongest seasonal changes have been found in summer with mainly negative trends in Northwest and Central China and slightly positive trends in Southwest and Northeast China. These observed changes would indicate that agricultural production particularly in parts of South and Southwest China would have to cope with decreasing water availability in the growing season.

This paper presents the results of a study assessing the combined influence of precipitation and evapotranspiration changes on crop production over China in recent decades. It uses water balance estimations as a tool to determine soil water variations and water availability for crops. It presents trend data, identifies the main contributors to observed changes and discusses their significance for agricultural production in China.

2. Data and analysis procedure

Water balance calculations were made for 65 stations (Fig. 1) contained in the Carbon Dioxide Information Analysis Center (CDIAC) numeric data package NDP039/R1 which is an updated and enlarged version of the original NDP039 data package (Tao et al., 1991). Station altitudes vary between 1 and 4273 m a.s.l. with all stations above 1500 m altitude located in south-west China and East Tibet. While western China and Tibet are only sparsely represented both longitudinal and meridional coverage of the agriculturally important eastern provinces of China east of 100°E is good. In addition long-term means (1951–1980) of temperature for 279 stations

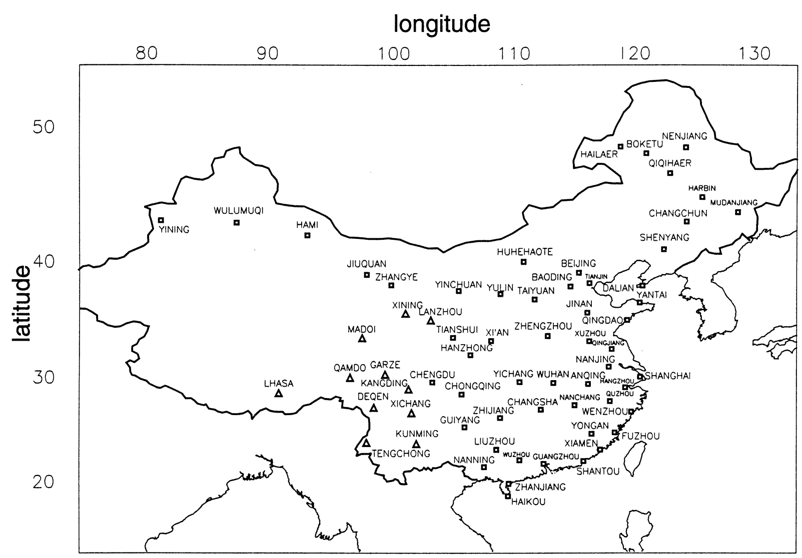

Fig. 1. Stations in the 65 station CDIAC data set. (△) Denote stations above 1500 m a.s.l.

were taken from Domrös and Peng (1988) in order to evaluate the beginning and length of the growing season in more detail.

Of the available data only years of the 40-year period from 1954–1993 have been used as observation methods in China were not standardized until 1951 with the set up of the meteorological observation network of the People's Republic of China. Penman–Monteith evapotranspiration (E_P) estimates were calculated for all months with complete records using ET1.0 software distributed by Cranfield University (Hess and Stephens, 1993). The Penman–Monteith method appears to be the most reliable method to estimate evapotranspiration under various climates (Jensen et al., 1990) and is recommended by FAO (Smith, 1992a). Aerodynamic resistance was estimated according to Smith (1992a) as

$$r_a = 208\,U^{-1} \quad (1)$$

where U is the windspeed measurement at 2 m height.

Although the Penman–Monteith approach would eliminate the use of crop coefficients, there is insufficient consolidated information on individual crop resistances presently available (Smith, 1992a). A fixed canopy resistance of $70\,\mathrm{s\,m^{-1}}$ was used throughout and maximum crop evapotranspiration (E_M) was consequently defined as

$$E_M = E_P k_C \quad (2)$$

with k_C as the crop coefficient of the respective phenological stage of the crop (Smith, 1992b). Monthly k_C values were obtained by first interpolating a smooth crop coefficient curve for each crop from lengths of individual growing stages (Doorenbos and Kassam, 1979) and corresponding k_C values (Smith, 1992b) using a cubic spline interpolation. After scaling the duration of the crop coefficient curve linearly in relation to the calculated growing season of each station (see below), monthly k_C values were resampled from the interpolated values. Crop coefficients for fallow periods were set to 0.2 and for winter wheat during winter dormancy to 0.4.

Estimations of the water balance follow the FAO approach (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Smith, 1992b) of a simple water budget calculation. This methodology has been used in many country-level studies under various climates around the world (FAO, 1994, 1996). Monthly soil water values were determined on a running basis beginning with January of the first year of complete data at each station and initial soil water content set to zero. Low soil water contents in January correspond closely to January estimates of the following years as the annual soil water minimum is reached during the winter dry season. This calculation procedure allows to monitor interannual variations and to calculate trends and is thought to be more meaningful than estimating climatic variability with the help of probabilities of exceedance as recommended by FAO (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Smith, 1992b).

Monthly soil water values were calculated in the general form of

$$S_W = P_E - E_A + S_{W\text{-}1} \quad (3)$$

with S_W as the soil water content over the considered soil depth, E_A as the actual monthly crop evapotranspiration and P_E as effective monthly precipitation of the current month. $S_{W\text{-}1}$ is the soil water left over from the preceding month. P_E was set to 90% of measured precipitation for all months as most agricultural land in China is level or terraced with little surface run-off.

If water available to the crop in a given month did not meet the demand of the plant ($E_M > P_E + S_{W\text{-}1}$), E_A was calculated as

$$E_A = P_E + S_{W\text{-}1} \quad (4)$$

otherwise, $E_A = E_M$. No effort was made to include the effects of soil water depletion into estimates of E_A. Henderson-Sellers (1996) argues that on monthly time scales without proper information on the temporal structure of precipitation it is neither necessary nor possible to assess vertical water movement in the soil with detail. Monthly soil water amounts surpassing the water holding capacity of the soil were assumed to be lost by run-off. Seepage and percolation were not accounted for. An undifferentiated soil profile with a water holding capacity of 200 mm/m was assumed for all locations in China as most of the arable land in East China is on heavily textured lowland soils (FAO, 1991) for which a total available soil water content of 200 mm/m soil depth is typical (Doorenbos and Kassam, 1979). Values for the crop specific development of rooting depth defining the actual soil depth available as soil moisture reservoir have been taken from

Smith (1992b) and interpolated to monthly values as described for k_C values. Maximum rooting depth for all crops except rice was set to 1.0 m.

Independent of crop development, rooting depth values of rice have been fixed at 0.3 m, the average depth of the impermeable plough sole in rice soils (Frère and Popov, 1979). In order to assess the effects of a larger soil moisture reservoir, a second run with maximum rooting depths of 0.60 m was conducted.

Crop performance and soil water variation are estimated with the agricultural water balance (AWB). AWB is based on site specific thermal conditions and calculates soil water variations for a crop or combination of crops chosen to represent the typical cropping pattern of that climatic zone with k_C values set to the interpolated values of the respective months. To calculate AWB, the beginning and length of the (thermal) growing season (BGS and LGS, respectively) were determined with the help of accumulated temperatures. Accumulated temperatures (mainly with daily temperatures >10°C) are widely used by Chinese scientists to characterize thermal growing conditions in China (Zhang, 1959; Zhang and Lin, 1992; Zheng, 1994) and have been correlated to climate zones and cropping systems. According to Ren (1985), seven thermal zones and their respective cropping systems can be delineated for China (Table 1, Columns 1 and 2).

Accumulated temperatures for each station were determined by interpolating mean monthly temperatures to mean daily values using a cubic spline interpolation and summing all interpolated mean daily temperatures >10°C (Fig. 2). BGS was obtained by determining the first day with temperatures >10°C, LGS by rounding degree–day sums to monthly values. BGS values belonging to the second half of a month were assigned to the following month in order not to overestimate the actual starting date. LGS values were treated similarly.

Scatter of LGS values occurs due to the combination of long, warm growing seasons in subtropical climates and short, but hot growing seasons in continental climates. Even within thermal zones LGS values determined from the 279 station data set vary considerably by 30–80 days. An additional complication is introduced through mountain stations above 1500 m a.s.l. These stations, with one exception located in West or Southwest China and Tibet, show different correlations between accumulated temperatures and BGS/LGS than lowland stations due to progressively lower temperatures at increasing altitudes (Fig. 3). For a given accumulated temperature, BGS occurs up to 40 days later at southern subtropical mountain stations in Southwest China compared to lowland stations while LGS increases by up to 50 days. The highest station (Madoi, 4273 m a.s.l.) was excluded from AWB calculations as no growing season was recorded.

Representative cropping patterns for lowland stations were chosen for each thermal zone based on information by Ren (1985). Cropping patterns at altitudes above 1500 m a.s.l. are different (Table 1) with rice being supplanted by maize in cooler environments (Thomas, 1992). LGS values of rice in mountain cropping systems were corrected for delayed crop development at higher altitudes (Li and Liu, 1988) and

Table 1
Selection of cropping systems according to thermal zones and altitude for water balance calculations[a]

Thermal zone	Accumulated temperature >10°C	<1500 m a.s.l.		≥1500 m a.s.l.	
		Harvests per year (t)	Typical cropping system	Harvests per year (t)	Typical cropping system
Frigid temperate	<1700	–	–		
Temperate	1700–≤3200	1	Wheat	1	Maize
Warm temperate	3200–≤4500	1.5	Rice/wheat	1.5	Maize/wheat
North subtropical	4500–≤5000	2	Rice/rice or rice/wheat	1.5	Rice/wheat
South subtropical	5000–≤7000	2.5	Rice/rice/wheat	1.5	Rice/wheat
Quasi-tropical	7000–≤8000	3	Rice/rice/sweet potatoes	–	–
Tropical	>8000	3	Rice/rice/rice	–	–

[a] Harvests of 1.5 and 2.5 per year indicate that the harvest takes place in the next calendar year after sowing; source: (Ren, 1985, Thomas, 1992).

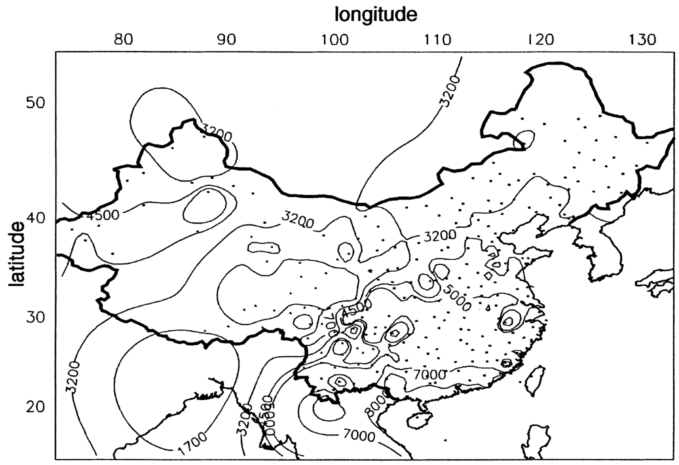

Fig. 2. Accumulated daily temperatures above 10°C based on the 279 station data set. Stations above 1500 m a.s.l. are marked by (△). Boundaries shown correspond to thermal zones listed in Table 1.

for the prolonged nursery period (He, 1981). During the establishment period of rice with plants growing in the nursery, 90% of the cropping area was assumed to lie fallow and 10% planted with rice seedlings.

Results are expressed as the yield index (Y_I) and the cumulative soil water deficit. In contrast to Doorenbos and Kassam (1979), Y_I is defined as the percentage to which the cumulative water demand of the crop over the growing season has been met:

$$Y_I = \frac{E_A}{E_M} \times 100 \quad (5)$$

where Y_I is the cumulative yield index (%) over the growing season. Y_I gives a relative estimate of the obtainable yield in relation to the maximum obtainable yield under the given agronomic conditions. While crops vary in their growth and yield response to water deficit, about 80–85% of the yield variation due

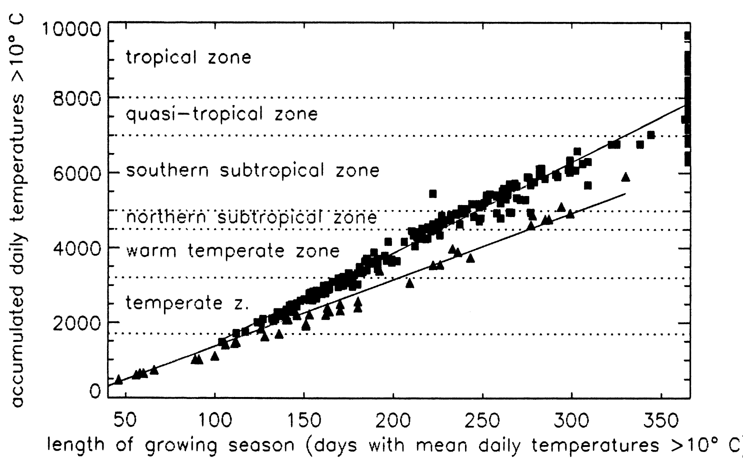

Fig. 3. Variation of length of growing season (determined from interpolated daily temperatures above 10°C from the 279 station data set) vs. station altitude. Solid lines are regression lines for stations below (■) and above (▲) 1500 m a.s.l. Definitions for thermal zones are as given in Table 1.

to different water availability can be explained by Y_I (Doorenbos and Kassam, 1979).

The cumulative soil water deficit (D_{SW}) over the growing season has been defined as:

$$D_{SW} = E_A - E_M \quad (6)$$

A major part of China's agricultural areas is irrigated so that, in practice, D_{SW} is controlled and kept to a minimum. In this study, additional water input by irrigation has not been taken into account so that Y_I is an estimate of cropping performance under rainfed conditions and D_{SW} closely resembles the seasonal irrigation demand for the given cropping system. For cropping systems with more than one crop per growing season Y_I and D_{SW} represent estimates of the cumulative performance and irrigation requirements of all crops during that growing season.

Linear regression was performed on annual Y_I and D_{SW} values of all stations for the period 1954–1993. For China as a whole (All-China series) mean linear trends were calculated from the unweighted results of all stations. For the interpretation of the significance of linear trends the trend-to-noise ratio (Birongg and Schönwiese, 1988) and for non-linear trend signals Mann's Q (Hartung, 1993) were applied. If not, otherwise, noted significant' trends are significant at the 95% level and are given for the 40-year period 1954–1993.

3. Results: observed trends 1954–1993 and contributing variables

3.1. All-China series

The mean linear trend for the country as a whole shows that Y_I rates have been increasing by 3.0% (Fig. 4) over the last 40 years. Correspondingly, D_{SW} rates have been decreasing by 36.4 mm (Fig. 5). Also apparent in the time series are large fluctuations with a frequency of about 10 years. Y_I trend values show a highly significant ($\geq$99%) non-linear trend. Over the observation period, Y_Is have increased by 4.5% relative to the long-term mean while D_{SW}s decreased by 13.9%.

3.2. Yield index and soil water deficit trends

Y_I rates have increased over much of China. Maximum significant positive trends of up 23.5% are found in East China (Fig. 6) with lesser increases of about 10–15% along the South Chinese coast. In Southwest,

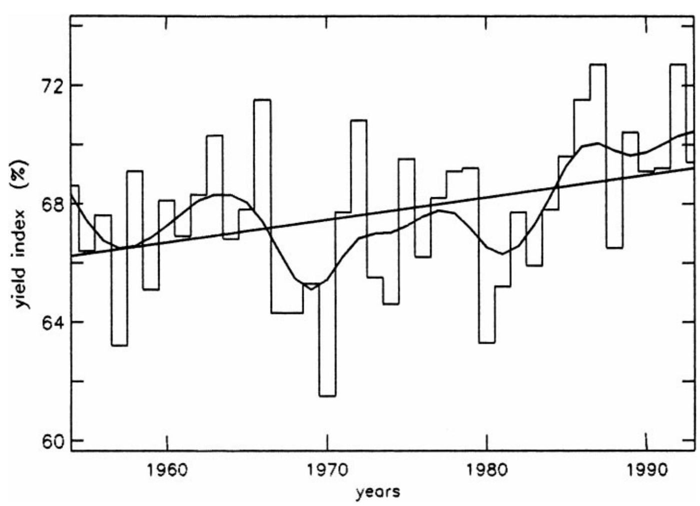

Fig. 4. Regionally averaged yield index (%) from 1954–1993 for 65 stations over China. Straight line shows the linear trend from 1954–1993. The smooth line results from a Gaussian binomial low-pass filter (10 years) that was applied to suppress high-frequency variations in the data.

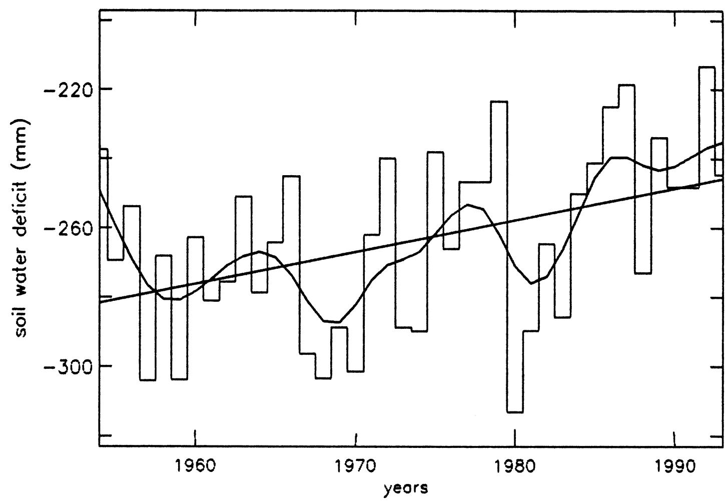

Fig. 5. Regionally averaged soil water deficit (mm/growing season) from 1954–1993 for 65 stations over China. Straight line shows the linear trend from 1954–1993. The smooth line results from a Gaussian binomial low-pass filter (10 years) that was applied to suppress high-frequency variations in the data.

Northwest and Northeast China increases have been slight with insignificant trends of around 5%. Consequently, over large areas of South and East China, D_{SW}s have been decreasing to a considerable extent (Fig. 7). Both along the South Chinese coast and in East China D_{SW} positive trends surpass 200 mm, in the major part of East China south of 40°N stations record a D_{SW} decrease of at least 40 mm. The highest increase occurred in the Northwest Chinese desert region with 305 mm which however does not show up significantly in Y_I trends as this amounts to <20% of the annual evapotranspiration total.

Insignificant negative Y_I trends ($\leq -18\%$) are restricted to the Yellow Sea region and to North, Northeast and South Central China in general not surpassing D_{SW} increases of 50 mm. Only along the Yellow Sea

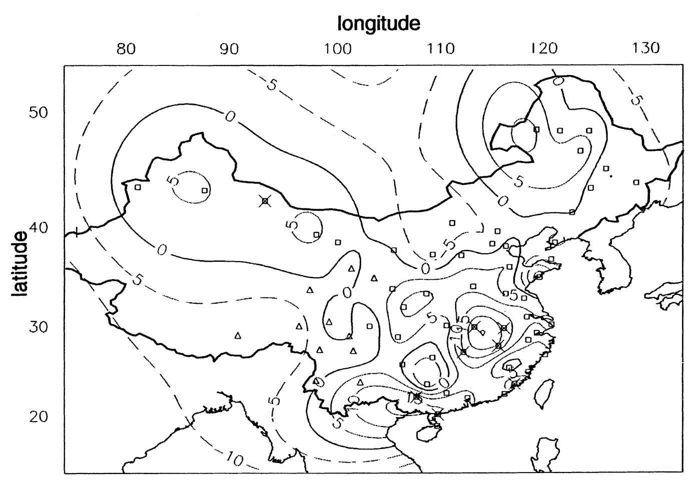

Fig. 6. Yield index trends (%) over China from 1954–1993. Solid lines depict positive trends, broken lines show negative trends. Open symbols mark station locations, station symbols with a cross mark significant non-linear trends.

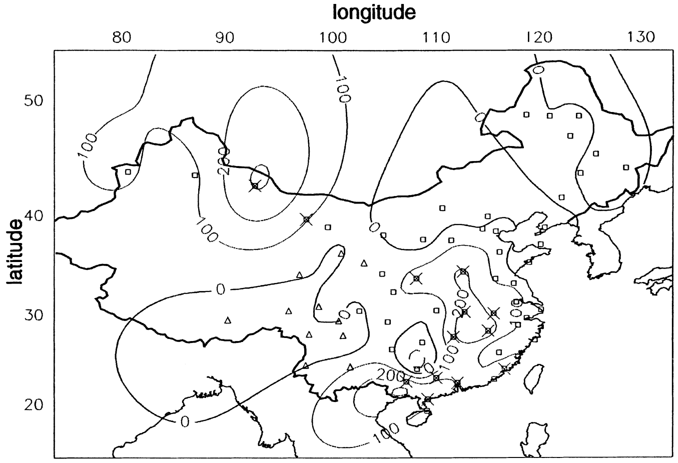

Fig. 7. Soil water deficit trends (mm) over China from 1954–1993. Solid lines depict positive trends, broken lines show negative trends. Open symbols mark station locations, station symbols with a cross mark significant non-linear trends.

coast D_{SW} values have increased by 152 mm (significant at the 90% level) over the last four decades.

Setting the maximum rooting depth to 60 cm in rice-based cropping systems did not result in any particular changes. Maximum Y_I differences amounted to 3% with the majority of trend changes remaining below 0.5% (not shown).

3.3. *Influence of meteorological variables and soil water on yield index changes*

While Y_I trends have been increasing in most parts of China both positive and negative trends of precipitation and evapotranspiration have been identified. Regional anomalies persist most notably in South

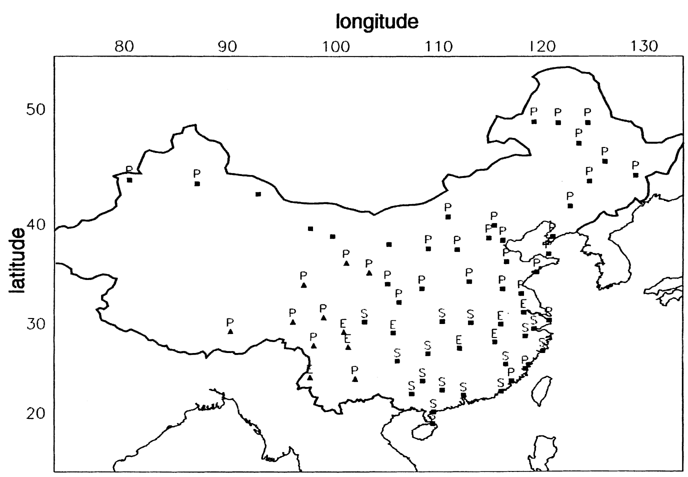

Fig. 8. Contribution of precipitation, maximum evapotranspiration and available soil water over the growing season to yield index rates over China (1954–1993). The first regression coefficient for each station is shown. *P*, *E*, and *S* indicate, respectively, precipitation, maximum evapotranspiration and available soil water. For four stations either no regression coefficients could be determined or the correlation was statistically not significant. (▲) Denote stations above 1500 m a.s.l.

and East China where E_P rates have decreased while precipitation has increased. In order to identify those variables that contribute most to the observed changes in Y_I a linear stepwise multi variate regression was performed for Y_I rates with P_E, E_M and available soil water summed over the growing season as independent variables. Only for one station could no correlations be determined.

All multiple correlation coefficients accounted for more than 90% of the explained variance; 49% of the correlation coefficients of the first regression coefficient were significant at the 99% level; 3% of all cases were not significant at the 95% level.

As expected, P_E and soil water are positively correlated with Y_I while E_M is negatively correlated. Fig. 8 shows a clear zonal arrangement of the most important variables contributing to Y_I changes. In general, precipitation appears to be most important north of ≈32°N, followed by evapotranspiration in a small band centered on 30°N and soil water south of 25°N and along the southeastern Chinese coast. A doubling of the rooting depth to 60 cm for rice based cropping systems resulted in changes at 8 stations (13%) located mainly in South and East China (not shown). In five cases, precipitation or evapotranspiration replaced soil water as the most important variable, in two cases, soil water became the most important variable.

4. Discussion

Based on water balance calculations with monthly precipitation data and Penman–Monteith evapotranspiration estimates yield index rates (1954–1993) were found to have increased by up to 23.5% over a large part of China with statistically insignificant decreases of 18% restricted to the Yellow Sea region. In the major part of West China (east of 105°E), no significant changes in yield index rates have occurred. In terms of actual soil water changes water deficits over the growing season have decreased by up to 300 mm over the major part of South, East and West China with only few localized upward trends of about 100 mm in South and East China.

For China as a whole, no single factor can be pointed out as leading to changed yield index estimates during the recent decades. Instead regional differences can be traced chiefly to seasonal courses of precipitation and evapotranspiration in different climates of China combined with the spatial pattern of precipitation and evapotranspiration trends.

In northern China, the beginning and length of the single crop growing season and the rainy season are well correlated. With high evapotranspiration rates precipitation is always the limiting factor and the most important variable regulating yield index changes.

South of 35°N precipitation and cloudiness increase rapidly due to the influence of summer monsoon frontal systems over East China (Domrös and Peng, 1988). Thermal conditions begin, however, to allow double cropping systems south of this climatic dividing line. With the length of the double cropping growing season extending beyond the rainy season pre and post rainy season evapotranspiration becomes the most important factor determining yield index rates. Evapotranspiration trends in this region are obviously linked to changes in sunshine duration (Thomas, in press) thought to be caused by variations of the strength of the summer monsoon and the associated cloudiness (Kaiser and Vose, 1997). The diminishing influence of precipitation with decreasing latitude is also reflected in the growing importance of stored soil water, that increasingly contributes to the water supply outside the rainy season. As surface hydrology and soil moisture feedback are thought to have important impact on the northward progression of the Indian monsoon (Webster, 1983), a similar process might influence Chinese summer monsoon dynamics.

South of ≈25°N triple cropping becomes feasible in East China. During the rainy season the contribution of stored soil water in relation to monthly precipitation is small. Despite the large precipitation surpluses during the rainy season soil water storage, as assumed here, is however, not fully capable of supporting crop evapotranspiration during the winter months with mean 1954–1993 yield index rates in this zone reaching only 70%. This emphasizes the importance of the contribution of stored soil water to the water balance in the quasi-tropical and tropical zone when the growing season extends considerably beyond the rainy season.

Despite this fact the relative importance of contributing variables for yield index rates did change only at 8 stations (13% of all stations) when maximum rooting depth and therefore maximum available soil water were doubled for rice-based cropping systems. In five cases, the response matched the expected change towards a diminished importance of soil water. Different results were obtained in a case study in Bangladesh (Frère and Popov, 1979) where the yield index calculated for paddy with a rooting depth of 60 cm did not show any water stress while restricting the rooting depth values to 30 cm reduced yield index by up to 20%. Even under generally similar climatic conditions increased soil water storage capacity does obviously not lead in any case to an increased yield index; but has to be assessed individually based on the local precipitation, evapotranspiration and soil data.

Results of several combined GCM simulations (Hulme et al., 1992) predicted a larger area for rice based cropping systems in East China by the year 2050, but with mean yields decreasing due to decreased water availability. Wheat based double cropping systems should be even more affected. The general ability of current GCM simulations to predict regional climatic change for resource assessment studies has, however, been seriously challenged (Grotch, 1989, 1992) while Evans (1996) noted that precipitation outputs from GCMs particularly will remain speculative and should not be used in detailed water resources planning. Kim et al. (1998) did, however, report good agreement of observed precipitation records with short term simulations of precipitation and soil moisture over East Asia with the Regional Climate System Model.

5. Conclusions

Results presented here indicate that water supply situation has generally improved over the last 40 years, particularly in the important agricultural centers of East and South China. Yield index rates, on average at about 70–80%, have increased by 5–10%. Irrigation demand (as determined by the soil water deficit) has decreased by more than 100–200 mm in this region. In Northeast China, the situation should have worsened to some extent as the assumed irrigation demand has increased by up to 100 mm to about 150–350 mm. Yield index decreases have however remained slight at about 5%. The largest decrease in water demand of more than 300 mm recorded in Northwest China is actually small in relation to the actual water demand and is based on the results of only one station.

Regional climatic change appears to have had a beneficial effect for several regions in China that have to cope with an increased demand on water resources by a growing population and industry as well as an intensified agriculture. Whether this trend will continue is an open question as simple trend analysis results should not be extrapolated without additional analysis into the stability of the trends.

Results of climate model simulations have failed so far to capture the magnitude and distribution of climatic variables necessary for water resources planning. Further analysis of observed water balance trends with an increased station density and detailed soil parameters should be useful for providing detailed results against which Regional Climate Models can be calibrated.

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