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CLIMATE IMPACTS ON INDIAN AGRICULTURE

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ABSTRACT

Agriculture (arguably the backbone of India's economy) is highly dependent on the spatial and temporal distribution of monsoon rainfall. This paper presents an analysis of crop–climate relationships for India, using historic production statistics for major crops (rice, wheat, sorghum, groundnut and sugarcane) and for aggregate food grain, cereal, pulses and oilseed production. Correlation analysis provides an indication of the influence of monsoon rainfall and some of its potential predictors (Pacific and Indian Ocean sea-surface temperatures, Darwin sea-level pressure) on crop production. All-India annual total production (except sorghum and sugarcane), and production in the monsoon (except sorghum) and post-monsoon seasons (except rice and sorghum) were significantly correlated to all-India summer monsoon rainfall. Monsoon season crops (except sorghum) were strongly associated with the three potential monsoon predictors. Results using state-level crop production statistics and subdivisional monsoon rainfall were generally consistent with the all-India results, but demonstrated some surprising spatial variations. Whereas the impact of subdivisional monsoon rainfall is strong in most of the country, the influence of concurrent predictors related to El Niño–southern oscillation and the Indian Ocean sea-surface temperatures at a long lead time seem greatest in the western to central peninsula.

KEY WORDS: climate–agriculture; ENSO; Indian monsoon rainfall; seasonal forecasts; climate-applications

1. INTRODUCTION

Agriculture is the backbone of India's economy. Its contribution to gross domestic product (GDP) has declined from 57% in 1950–51 to around 28% (1998–99) due primarily to growth in other sectors of the economy. The declining share of the agricultural sector, however, has not affected the importance of the sector in the Indian economy. Owing to both the direct value of agricultural products and agriculture's indirect impact on employment, rural livelihoods and other sectors that use agricultural products, the growth of India's GDP has largely been determined by the trend in agricultural production. Its impact on the welfare of the country is much greater than the macroeconomic indicators suggest: as nearly 70% of the working population depends on agricultural activities for their livelihood. The majority of India's population depends on cereal and pulse production for sustenance. Agriculture is also a major supplier of raw materials for industry. Examples include cotton and jute for textiles, sugar and vegetable oil. Some 50% of all the income generated in the manufacturing sector in India can be attributed directly or indirectly to agricultural production. Agricultural commodities, and products that depend on agriculture, account for nearly 70% of the value of exports. Tea, sugar, oilseeds, tobacco and spices are major export commodities.

Cereals dominate India's agricultural output, accounting for more than 90% of the food grains; pulses account for the rest. Rice (44% of production) and wheat (37%) are the main cereals, with coarse cereals (e.g. maize, sorghum, millet) accounting for about 18% (Central Statistical Organization, 1998). Table I gives the areas under the principal crops considered in this study and their changes over the years (Figure 1).

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Table I. Area under various crops in India. (Source: Central Statistical Organization, 1998)

Year	Area (10^6 ha)					
	Food grains	Rice	Wheat	Pulses	Oilseed	Sugarcane
1970–71	124.3	37.6	18.2	22.5	16.6	2.6
1980–81	126.7	40.2	22.3	22.5	17.6	2.7
1990–91	127.8	42.7	24.2	24.7	24.1	3.7
1994–95	123.5	42.2	25.6	23.2	25.3	3.8
1996–97	124.5	43.3	25.9	23.2	26.8	4.2

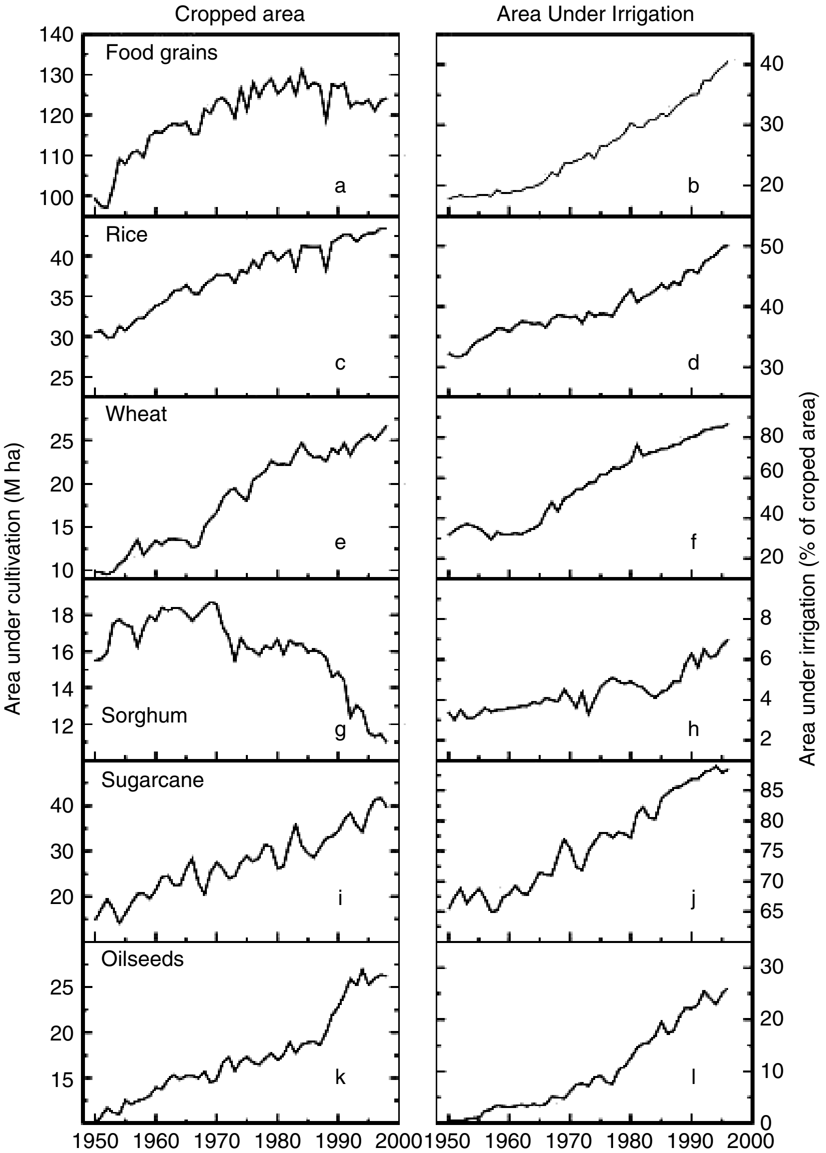


Figure 1. Area under various crops and percentage of cropped area irrigated in India during 1949–50 to 1997–98

Agricultural production is the product of cultivated area and average yield per unit area. The introduction of economic planning and special emphasis on agriculture in 1950–51 gave rise to an increase in production due to increases in both area under cultivation and average yields per hectare. The early 1960s saw rapid growth in yields associated with improvements in production technology. The annual rate of growth in cultivated area was greater during the pre-Green Revolution period (1950–65) than during the post-Green Revolution period (after 1965) (Table II). However, the annual growth rate in average yields increased after the Green Revolution, particularly for wheat and oilseeds. Much of the increase is likely due to (a) development of crop varieties that respond to fertilizers, (b) expanded use of these high-yielding varieties, and (c) changing cropping patterns and agricultural practices. Production trends also reflect changes in cultivated area.

Although there has been substantial growth in production, there is also substantial variability about the trend. Year-to-year weather variability is regarded as the primary cause of year-to-year fluctuations in yields. Fluctuations of climate (the statistics of weather integrated over time and space) are more relevant when considering crop production at an aggregate spatial scale. Extreme weather conditions, such as floods, droughts, heat and cold waves, flash floods, cyclones and hail storms, are direct hazards to crops. More subtle fluctuations in weather during critical phases of crop development can also have a substantial impact on yields. Cultivated areas are subject to a broader range of influences, including changes in commodity prices, costs of inputs and availability of irrigation water. Climate may have indirect and possibly lagged influences on harvested areas. For example, shortfalls in rainfall can reduce irrigation water supplies, leading to reduced areas under irrigated crops and potentially increased areas under rain-fed crops in the subsequent season. By influencing international commodity prices, large-scale climate anomalies in major competitors' regions can exert an indirect influence on areas planted to different crops.

More than 60% of the cropped area in India still depends solely on monsoon rainfall (Central Statistical Organization, 1998). In India, the onset of the southwest monsoon is expected in June or July, depending on location. The highest concentration of rain-fed agriculture occurs in western and southern areas under oilseed, grain, and cotton cultivation and in the east, where much of the rice is rain fed. The irrigated area increased from 22% of the sown area in 1970–71 to 38.6% in 1996–97 (Figure 1). Punjab, Haryana, Uttar Pradesh, Bihar and Tamil Nadu (refer to Figure 2 for states) have an irrigated area that are more than 50% of the net sown area in the state. The irrigated area in Punjab is almost 95% of cropped area. In more recent years, Gujarat, Madhya Pradesh and Rajasthan have had a significant expansion in arable area under irrigation. In Gujarat, the gross irrigated area has gone up by more than 25%, as the ratio moved up from 27% of gross sown area in 1989–90 to 33% in 1996–97. Likewise, the gains in irrigation in Madhya Pradesh and Rajasthan are 75% and 51% respectively. However, these states are still rain dependent, with just 25–30% of the gross sown area being irrigated. Maharashtra, on the other hand, has reported insignificant success in bringing more land under irrigation in the 8 years between 1989–90 and 1996–97. The gross irrigated area has declined from 15.8% in 1989–90 to 14.5% in 1996–97 as a percentage of sown area. Wheat, sugarcane and banana are among the major crops in the country that are grown on mostly irrigated area. Comparatively less irrigated area is sown under cotton, groundnut, coarse cereals and pulses (Figure 1). These crops would suffer most from a late or weak start to the rainy season, and are susceptible to extended breaks in monsoon rains. If the southwest monsoon withdraws from the region earlier than expected, then late-planted crops may be damaged from lack of moisture during grain filling. Conversely, a late withdrawal resulting in late-season rains can be

Table II. Annual rate of agricultural growth in India

Crops	Cultivated area (%)		Mean yield (%)	
	1950–65	1995–97	1950–65	1995–97
Food crops	1.4	1.2	1.4	2.4
Non-food crops	2.5	0.7	0.9	1.6
All crops	1.6	0.3		

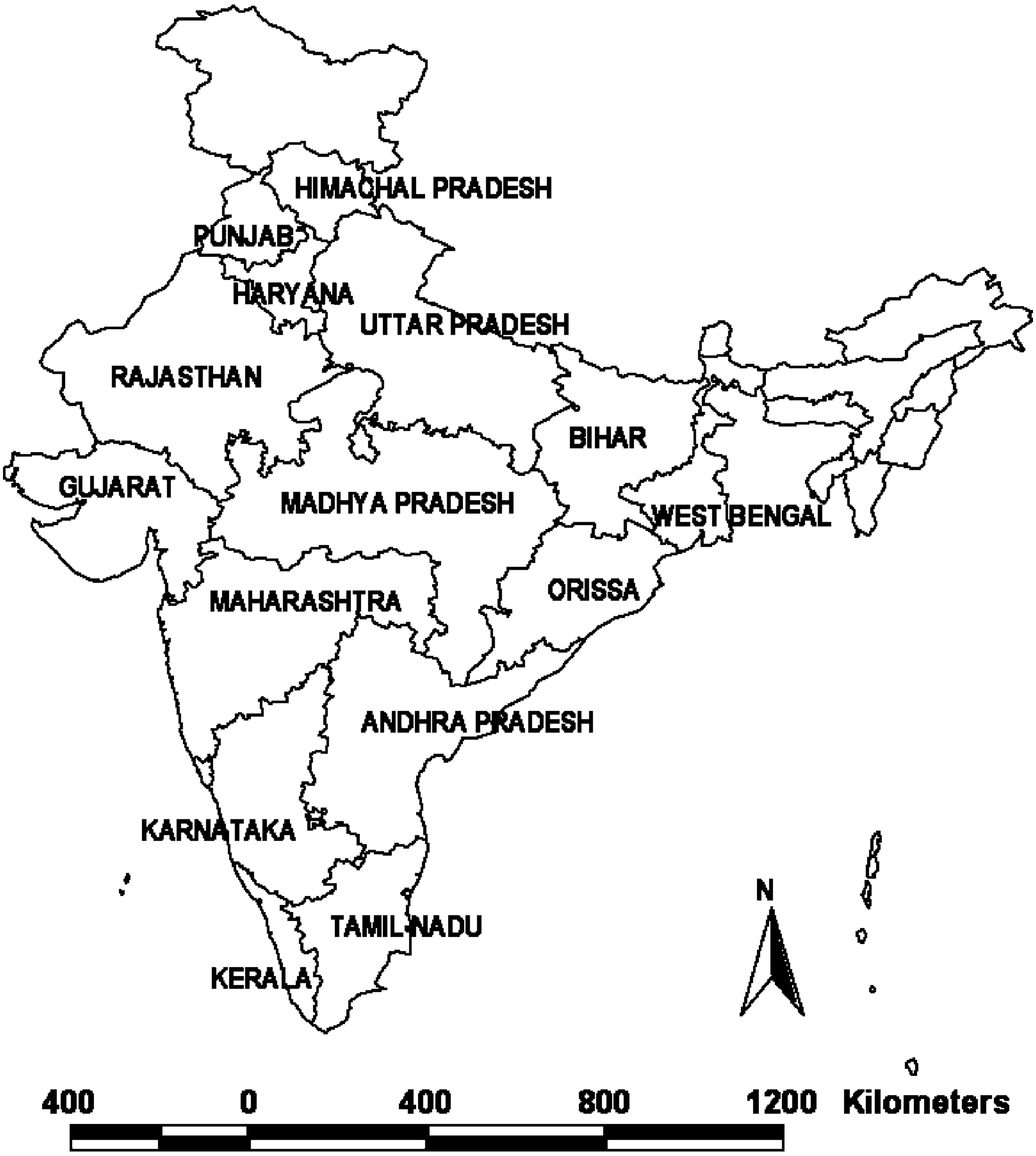


Figure 2. Location of states within India

detrimental to maturing crops, especially cotton. Strong monsoon circulation can bring flooding, especially along the Ganges and Indus Rivers.

The summer, or '*kharif*', growing season (June–September) coincides with the southwest monsoon. Depending on crop duration, *kharif* crops can be harvested during the autumn (October–November) or winter (December–February) months. The southwest monsoon is critical to the *kharif* crop, which accounts for more than 50% of the food-grain production and more than 65% of the oilseeds production in the country. Year-to-year fluctuations in summer monsoon rainfall over India have a strong impact on the variability of aggregate *kharif* food-grain production (Parthasarathy *et al*., 1988, 1992; Gadgil, 1996; Webster *et al*., 1998).

The '*rabi*' growing season starts after the summer monsoon, and continues through to the following spring or early summer. Rainfall occurring at the end of the monsoon season provides stored soil moisture and sometimes irrigation water for the *rabi* crop, which is sown in the post-monsoon season (October–November). The summer monsoon, therefore, is responsible for both *kharif* and *rabi* crop production over India. The northeast (winter) monsoon contributes substantial rainfall in much of Tamil Nadu and eastern Andhra Pradesh, permitting rain-fed crop production during the *rabi* season.

The 1987 Asian drought was one of the worst of the 20th century. Below-normal rainfall and record heat levels damaged crops and stressed livestock throughout South Asia. In India, the main-season grain and oilseed production were reduced to below expected levels, and winter crops that depend on residual summer moisture for germination were planted well beyond the normal time (USDA, 1994). During the drought of 1987, *kharif* crop production was down as temperatures and rainfall were respectively among the highest and lowest on record in central and northern rain-fed grain, oilseed, and cotton areas (USDA, 1994). All-India *kharif* food-grain production corresponding to 1987–88 was found to be 74.5×10^6 tonnes as against 80.2×10^6 tonnes during 1986–87 (Directorate of Economics and Statistics, 2002). *Rabi* crops, planted primarily in southern India and areas with adequate irrigation reserves, partially compensated for the shortfall but also suffered some losses. In winter wheat areas, planting was delayed for months due to insufficient moisture availability for germination. Although most of the crop is irrigated, low reservoir levels and fuel shortages hampered irrigation efforts. Although the impact of the drought did not approach the severity of the famine years of the 1970s, agricultural imports rose, reserves and exportable supplies were reduced, and growth in other sectors was limited (Dutt and Sundharam, 1999).

The impact of El Niño–southern oscillation (ENSO) on the Indian monsoon rainfall is quite well known (refer to Krishna Kumar *et al.* (1995) and Pant and Rupa Kumaar (1999) for details on monsoon rainfall–ENSO linkages). Sadhuram (1997) and Clark *et al.* (2000) have shown a statististically significant positive correlation between the Indian monsoon rainfall and sea-surface temperatures (SSTs) over most parts of the north Indian Ocean at lead times of 6–12 months. Hence, the potential (associated with ENSO and other large-scale climate teleconnections) to anticipate fluctuations in both monsoon rainfall and resulting agricultural production prior to the start of the growing season (Selvaraju, 2003) has important implications for agricultural decision making at farm and policy levels. It offers the potential to reduce uncertainty, and to tailor agricultural planning (e.g. relief) and management decisions to expected climatic variations in order to reduce adverse impacts or take advantage of favourable conditions. India was the birthplace of scientific seasonal climate forecasting well over a century ago (Blanford, 1884; Walker, 1918), yet the potential to integrate seasonal climate prediction into agricultural development in a coordinated manner across India has only recently begun receiving widespread attention. A consortium of state- and national-level climate and agricultural institutions is exploring how to advance the use of seasonal forecasts for the benefit of the rural populations who depend on agriculture for livelihood and sustenance.

As a step toward better management of the present and future impacts of climate variability on agriculture, we present an analysis of past climatic impacts on agricultural production. Detailed analyses of the association of agricultural output with monsoon rainfall, two indicators of ENSO, and Indian Ocean SSTs are presented. The study considers aggregate food grains, cereals, pulses and oilseeds, rice, wheat, sorghum, groundnut and sugarcane, by season, at the national level and for particular regions within India.

2. APPROACH

2.1. *Crop data*

We used historical agricultural statistics to explore the association between agricultural production and short-term rainfall variations over India. The study uses all-India and state-level agricultural statistics (area, production and yield) available from 1949–50 to 1997–98 for individual crops (rice, wheat, sorghum, groundnut, oilseeds and sugarcane) and for combined cereals, pulses and food grains. The agricultural statistics have been obtained from two periodicals: *Area and Production of Principal Crops in India, (1949–50 to 1997–98)*, published by the Directorate of Economics and Statistics, Department of Agricultural and Cooperation, Ministry of Agriculture; and *An Overview of Agriculture — August 1997*, published by the Centre for Monitoring Indian Economy (CMIE). These documents present state-by-state time series data for more than 60 major agricultural crops. They also present time series on land and water, seeds and fertilizers, farm mechanization and other agricultural statistics. These documents provide information on shifts in cropping patterns, gains in productivity and regional diversity.

The analysis was carried out for annual totals, and separately for the *kharif* and *rabi* growing seasons. Statistics for individual seasons, depending on the crop, are available for shorter periods than for the annual totals (Table III). State-level crop statistics were obtained for periods of more than 30 years for *kharif* and *rabi* rice, wheat, sorghum, groundnut and sugarcane (Table III). We focused on production because it has greater economic relevance than yield, and aggregates possible climate impacts on both yields and harvested areas. Yields may miss climate impacts that are severe enough to lead to abandonment of planted areas prior to harvest.

The Directorate of Economics and Statistics publishes production estimates for 51 principal crops that, together, account for nearly 87% of the nation's agricultural output. The final estimates of crop production are based on enumeration of area harvested, and yields estimated through crop cutting experiments conducted within General Crop Estimation Surveys (GCESs). More than 500 000 such experiments are conducted annually throughout the country. With the existing sampling system and the number of crop cutting experiments, the all-India production estimates are expected to have a sampling error of less than 2%.

2.2. *Climate data*

The spatial means of rainfall over India have been obtained by area-weighted averaging of the rainfall at 306 stations (Parthasarathy *et al.*, 1994). The rainfall series (1871–1999) for each of 29 meteorological subdivisions have been prepared by assigning area weights to each rain gauge station within a subdivision. An all-India series (http://www.tropmet.res.in/data.html) was prepared similarly as the area-weighted average of all of the subdivisions.

This work uses global SST anomalies to study the impact of large-scale climate anomalies (Kaplan *et al.*, 1997). Since the tropical interannual variability is dominated by ENSO, we used ENSO indices: (a) NINO3 (SST averaged over 5 °S–5 °N and 90–150 °W); (b) NINO4 (SST averaged over 5 °S–5 °N and 160 °E–150 °W) anomaly series; (c) Darwin, Australia, sea-level pressure (SLP) anomaly series. All are obtained from CPC, NOAA, Washington DC, USA (http://www.cpc.noaa.gov/products/). The Indian Ocean SST index used is the averaged SST over the region 8–22 °N and 55–72 °E.

2.3. *Analyses*

For reasons we discussed earlier, the crop production and yield time series feature strong trends that mask the short-term fluctuations which are most likely associated with year-to-year climate variations. Researchers have attempted to isolate these short-term fluctuations by fitting and removing trends with polynomial and other parametric functions, and several forms of smoothing filters. Parthasarathy *et al.* (1988, 1992) used an exponential function to filter the all-India food production statistics for use in a regression-based food

Table III. State-level agricultural statistics used in the study

Crop	Data period	State
Kharif and *rabi* rice	1950–51 to 1994–95	Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Orissa, West Bengal, Uttar Pradesh
Wheat	1950–51 to 1992–93	Punjab, Uttar Pradesh, Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Karnataka
Sorghum	1950–51 to 1992–93	Karnataka, Andhra Pradesh, Maharashtra, Gujarat, Madhya Pradesh, Rajasthan, Bihar, Uttar Pradesh
Groundnut	1950–51 to 1997–98	Karnataka, Andhra Pradesh, Maharashtra, Madhya Pradesh, Gujarat, Rajasthan, Uttar Pradesh, Bihar, Haryana
Sugarcane	1950–51 to 1997–98	Uttar Pradesh, Maharashtra, Gujarat, Andhra Pradesh, Karnataka, Tamil Nadu

grain production-forecasting model. We detrended each time series by taking the difference, $\Delta z_i = z_i - z_{i-1}$ between the value z in each year i, and the value in the previous year $i - 1$ (Box and Jenkins, 1976). These values are then expressed as the percentage change from the previous year's value. This method reduces any piecewise linear trends to small constant terms, and functions as a high-pass filter, attenuating the amplitudes of low-frequency signals by a factor of $\sin(f, t)$, where f is the frequency and t is the time interval (i.e. 1 year) between samples (Stephenson *et al.*, 2000). Therefore, the biennial signals with periods of 2 years suffer no attenuation, whereas signals with periods of 4 years have their amplitudes attenuated by a factor of $\sqrt{2}$. Decadal and lower frequency variations are attenuated to less than 30% of their original amplitudes. Using a spectral smoothing filter (Press *et al.*, 1989) to detrend selected crop production series gave similar results (results not shown).

Inferences about the degree and significance of association are based on pairwise Pearson's correlation between detrended crop and detrended climate time series. This is an exploratory analysis. Any attempt to predict crop production based on climate indices would need to be based on more conservative statistical hypothesis tests that guard against the risk of spurious correlations that can arise from repeated application of pairwise correlation.

3. RESULTS AND DISCUSSION

3.1. *Aggregate food-grain production*

Aggregate food-grain production is strongly correlated (at 1% significance level) with monsoon rainfall (Figure 3, Table IV). Most of the food crops are grown during the *kharif* season, when correlation with monsoon rainfall is particularly strong (Figure 3(d)). Both cereal and pulse production (year totals and each season) show high, significant correlations with monsoon rainfall (Table IV). Year-to-year variations in cereal and pulse production are comparable to those of total food-grain production. Production of food grains, cereals and pulses show strong association with NINO3 and Indian Ocean SST anomalies during the *kharif*, but not during the *rabi* season (Table IV).

3.2. *Rice*

Kharif rice is grown in most parts of India. Orissa, West Bengal and Assam in the east, coastal Andhra Pradesh and coastal Tamil Nadu in the southern peninsula, Madhya Pradesh in the central region, and parts of Uttar Pradesh and Punjab in the northwest form the major rice-growing areas. Minor rice-growing areas include Kerala and Karnataka in the south. *Kharif* rice is sown in July–August and harvested between October and January. The major rice-growing states account for 85% of the total area under *kharif* rice. The rice grown during the *rabi* season is mainly confined to the region affected by the northeast monsoon. Andhra Pradesh, West Bengal, Tamil Nadu, Karnataka and Orissa account for more than 90% of the area under *rabi* rice. It is planted in November–December and harvested in March–May.

All-India total rice production from 1949–50 to 1997–98 shows both a strong trend and high year-to-year variability (Figure 4(a)). The strong increasing trend is the result of both an increase in cultivated area and the influence of improved production technology. The strong correlations with rainfall suggest that year-to-year fluctuations in production are largely due to fluctuations in the climate. Series of all-India rice production and monsoon rainfall, both detrended by the backward difference filter (Figure 4(b)), show a strong ($r = 0.77$, Figure 4(c)), significant (at 1% significance level) relationship. The correlations with rainfall during individual months (Figure 4(d)) are also significant throughout the June–October period.

Kharif rice production is significantly correlated with June–August SSTs through a substantial portion of the Pacific basin (Figure 5(a)). Correlations with NINO3 SST anomalies and Darwin SLP anomalies (Table IV) suggest a strong influence of ENSO on rice production in India. Indian Ocean SSTs show a long-lead association with total and *kharif* rice production (Figure 5(b)), but not with the *rabi* rice crop (Table IV). Both total and *kharif* rice production show strong correlations with the ENSO indices and Indian Ocean SSTs.

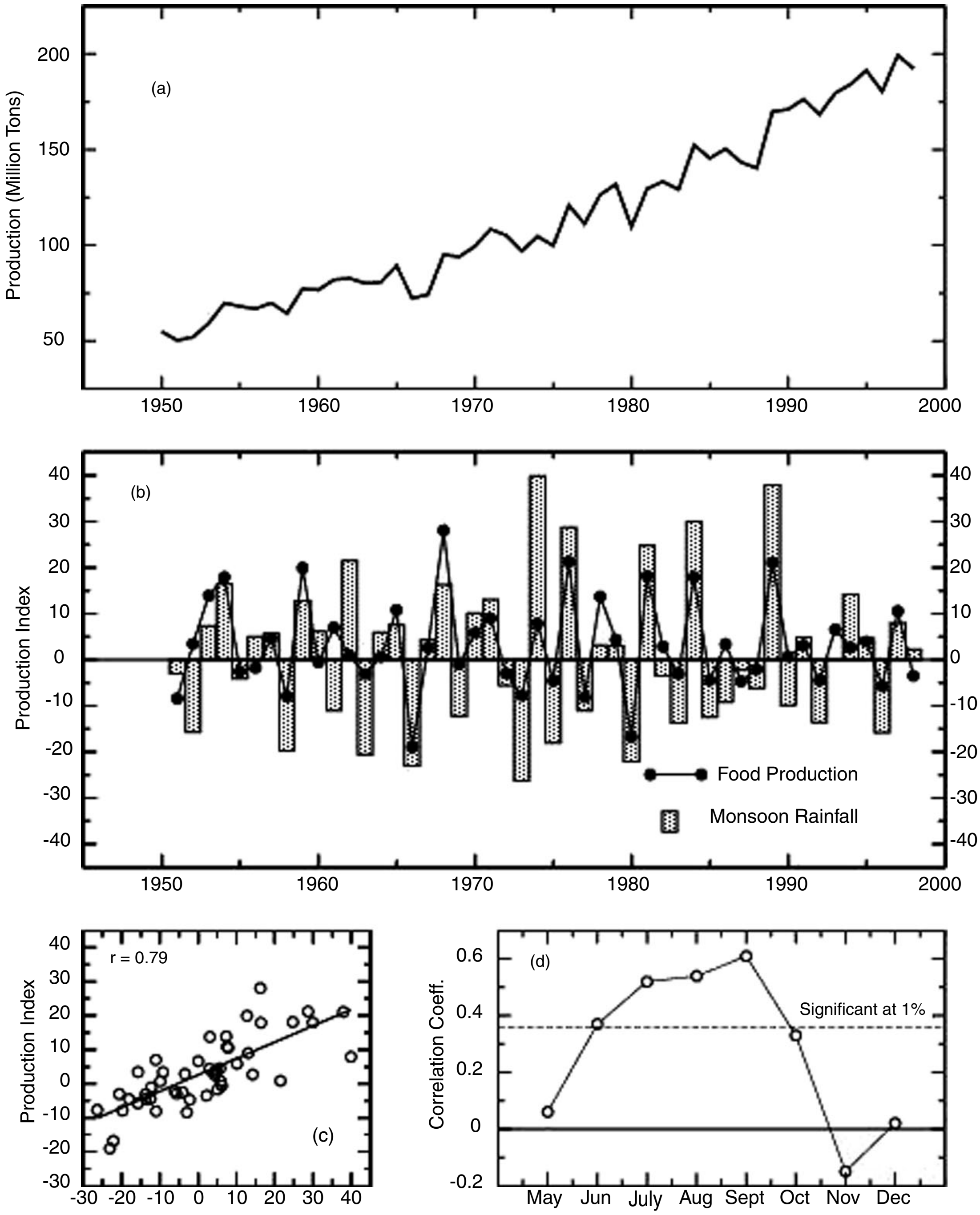


Figure 3. All-India total food-grain production and its association with rainfall over India. (a) Growth in food-grain production. (b) Year-to-year variations in food-grain production and monsoon rainfall. Correlation between food grain production and (c) monsoon seasonal rainfall and (d) individual monthly rainfall during May to December. Correlations are based on data during the period 1949–50 to 1997–98. The values shown in (b) are backward-differenced crop production and monsoon rainfall indices expressed as percentage change from their respective previous year's values

Table IV. Correlation between crop production and climatic indices. Correlation coefficients significant at 1% level are indicated in bold

Crop	Period	SST-NINO3		SST-Indian Ocean		Darwin SLP		Indian rainfall JJAS
		JJA	MAM–DJF	JJA-1	SON-1	JJA	MAM–DJF	
Total								
Rice	1950–98	**−0.40**	−0.32	**0.42**	**0.37**	−0.35	−0.26	**0.77**
Wheat	1950–98	−0.32	−0.16	0.33	0.27	−0.11	−0.21	**0.47**
Sorghum	1950–98	−0.01	0.00	0.02	0.02	−0.16	−0.15	0.00
Groundnut	1950–98	**−0.61**	**−0.44**	**0.59**	**0.53**	**−0.54**	**−0.46**	**0.64**
Oilseeds	1950–98	**−0.62**	**−0.53**	**0.61**	**0.54**	**−0.47**	**−0.55**	**0.69**
Sugarcane	1950–98	0.04	−0.19	−0.07	0.04	0.11	**0.40**	−0.04
Food grains	1950–98	**−0.50**	**−0.39**	**0.50**	**0.45**	**−0.39**	**−0.38**	**0.79**
Cereals	1951–95	−0.18	−0.04	**0.49**	**0.43**	−0.35	**−0.43**	**0.81**
Pulses	1951–95	**−0.43**	−0.35	0.33	0.16	−0.36	−0.29	**0.62**
Kharif								
Rice	1963–95	**−0.49**	**−0.42**	**0.52**	**0.52**	**−0.40**	−0.32	**0.8**
Sorghum	1963–95	−0.03	−0.08	0.35	0.25	−0.10	−0.12	0.07
Groundnut	1972–95	**−0.67**	**−0.50**	**0.59**	**0.59**	**−0.57**	−0.48	**0.67**
Oilseeds	1971–95	**−0.68**	**−0.46**	**0.66**	**0.65**	**−0.53**	**−0.57**	**0.72**
Food grains	1967–98	**−0.50**	**−0.43**	**0.60**	**0.60**	**−0.41**	−0.41	**0.83**
Cereals	1963–95	**−0.55**	**−0.49**	**0.60**	**0.58**	**−0.47**	−0.43	**0.85**
Pulses	1967–95	**−0.42**	**−0.38**	**0.56**	**0.44**	−0.27	**−0.47**	**0.69**
Rabi								
Rice	1963–95	0.16	−0.01	0.16	0.32	−0.17	0.14	0.15
Sorghum	1963–94	−0.14	−0.11	0.33	**0.46**	−0.19	−0.19	0.01
Groundnut	1972–95	−0.34	−0.44	**0.55**	**0.69**	−0.25	−0.30	**0.54**
Oilseeds	1971–95	−0.12	−0.21	**0.57**	**0.60**	−0.04	−0.16	**0.43**
Food grains	1967–98	−0.27	−0.08	0.30	0.21	−0.10	−0.19	**0.67**
Cereals	1963–95	−0.28	−0.27	0.24	0.21	−0.12	−0.18	**0.55**
Pulses	1967–95	−0.33	−0.17	0.13	0.07	−0.18	−0.19	**0.60**

3.3. *Wheat*

Unlike rice, the annual total wheat production comes from a single growing season. It is planted during October–December and harvested during March–May. The chief wheat-producing states lie along the Indo-Gangetic Plain (Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Bihar and Assam) and in the far west (Rajasthan), and account for 95% of the total area under wheat in India. More than 80% of the area under wheat is irrigated.

The time series of all-India wheat production (Figure 6(a)) shows a sudden increase after the mid-1960s that can be attributed to the Green Revolution. The year-to-year variability of wheat production is weaker than that of rice, and lacks a strong association with monsoon rainfall (Figure 6(b) and (c)). Although wheat is grown during non-monsoon months, its production shows a rather weak but significant correlation with monsoon rainfall in the months of July and September (Figure 6(d)), and is correlated with monsoon rainfall ($r = 0.47$; Table IV). The total wheat production does show some association with summer SST anomalies over the Pacific (Table IV), although the association is not as strong as in the case of rice.

3.4. *Sorghum*

Sorghum is grown in both the *kharif* and *rabi* seasons, although *kharif* sorghum contributes more than 70% of the total production. *Kharif* sorghum is planted during June–July and harvested in December–February. *Rabi* sorghum is planted after the monsoon season (October–November) and harvested in March–April.

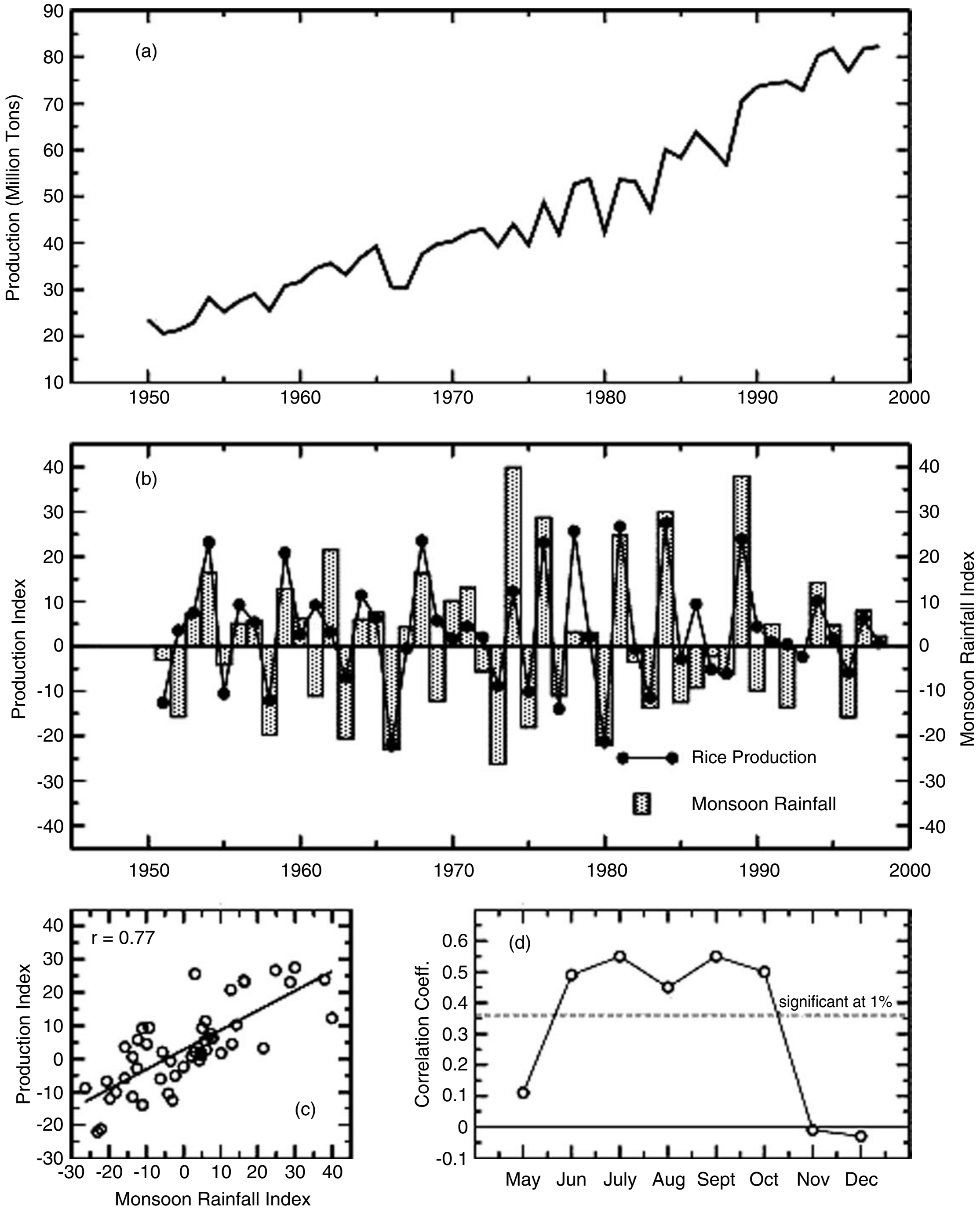


Figure 4. Same as Figure 3, but for total rice production

Sorghum is grown mainly in the semi-arid belt spanning from the southern peninsula to western India, and is seldom irrigated. About half of the sorghum production in India comes from Maharashtra in the western part of the peninsula, while Karnataka (13%) and Madhya Pradesh (12%) also make significant contributions, and Andhra Pradesh, Uttar Pradesh, Tamil Nadu, Rajasthan and Gujarat produce smaller amounts. Sorghum

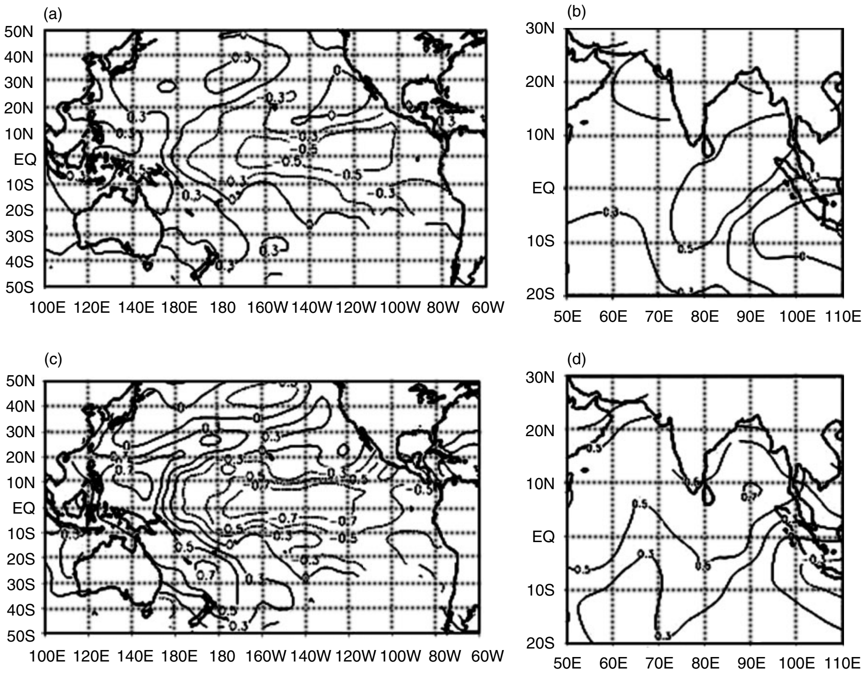


Figure 5. Correlation between SSTs and the production of *kharif* rice and groundnut. (a) *Kharif* rice production and June–August SSTs in the Pacific Ocean. (b) *Kharif* rice production and SON-1 SSTs in the Indian Ocean. (c) *Kharif* groundnut production and June–August SSTs in the Pacific Ocean. (d) *Kharif* groundnut production and SON-1 SSTs in the Indian Ocean

is grown mainly in the semi-arid regions, and is seldom irrigated. In the early 1990s, less than 8% of the cultivated area was irrigated. All-India sorghum production shows an increasing trend (Figure 7(a)) due primarily to increase in the area irrigated. The total area under sorghum is decreasing (Figure 1(g)). Year-to-year variability is high, but is not associated with monsoon rainfall ($r = 0.02$, Table IV). The monthly rainfall during the monsoon months also seems to show no significant association with the all-India sorghum production. However, the rainfall during November is positively correlated with sorghum production.

Analysis of correlation with the summer SSTs over the Pacific (not shown) indicates a lack of ENSO influence on Indian sorghum production. This is also evident from the weak correlation with NINO3 SST and Darwin SLP anomalies (Table IV). The Indian Ocean SSTs (not shown) also seem to have no influence on sorghum production. This may suggest that the determinants of variability in sorghum production are strongly local in character. A detailed analysis of regional agricultural statistics would possibly clarify the influence of climate.

3.5. *Oilseeds*

Groundnut is an important commercial crop grown throughout the semi-arid regions of peninsular India. Andhra Pradesh (28%), Karnataka (15%) and Tamil Nadu (12%) in the south, and Gujarat (22%) in the west, account for the majority of the cultivated area. It is also grown in Maharashtra, Madhya Pradesh, Rajasthan and Orissa. Although it is grown in both the *kharif* and *rabi* seasons, more than 70% of production comes from the *kharif* harvest. The *kharif* crop is planted during June–July and harvested in the post-monsoon season. All-India total groundnut production has a strong association with monsoon rainfall ($r = 0.64$), with significant correlations with monthly rainfall during July–September (Figure 8(b)–(d)). Total oilseed production also shows a strong association with the monsoon rainfall (not shown). Groundnuts constitute a major share of the country's oilseed production. All-India total groundnut and oilseed production show high correlations with monsoon rainfall ($r = 0.64$ and 0.69 respectively) and with the ENSO indices and the Indian Ocean SSTs

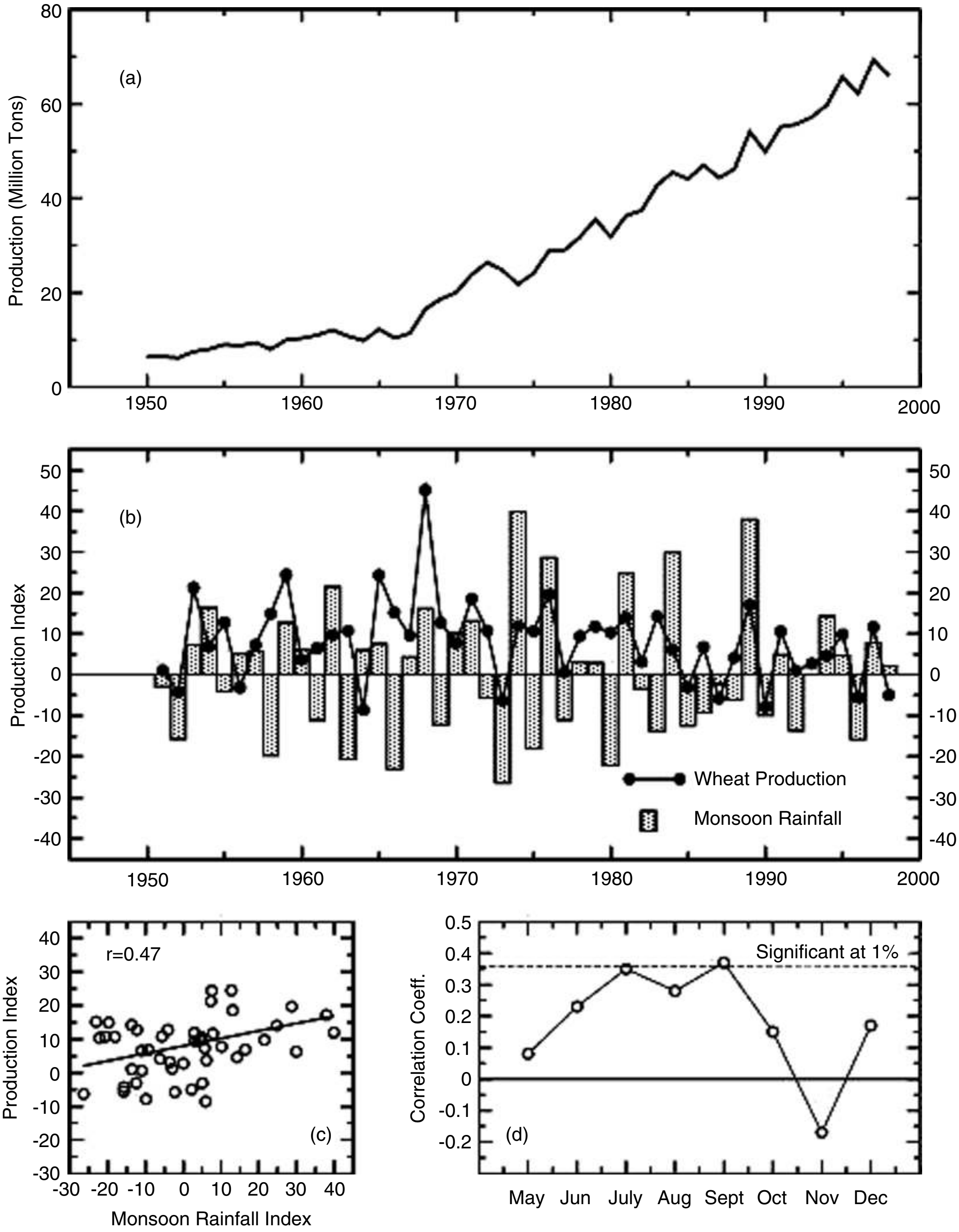


Figure 6. Same as Figure 3, but for total wheat production

(Table IV); the same holds for production in the *kharif* season. Groundnut and total oilseed production show strong correlations with summer (June–August) SST anomalies over the Pacific (Figure 5(c)) in the *kharif* season, but not the *rabi* season (not shown). Long-lead correlations with the SST anomalies in the Indian Ocean are high and significant in both seasons (Figure 5(d) for the *kharif* groundnut).

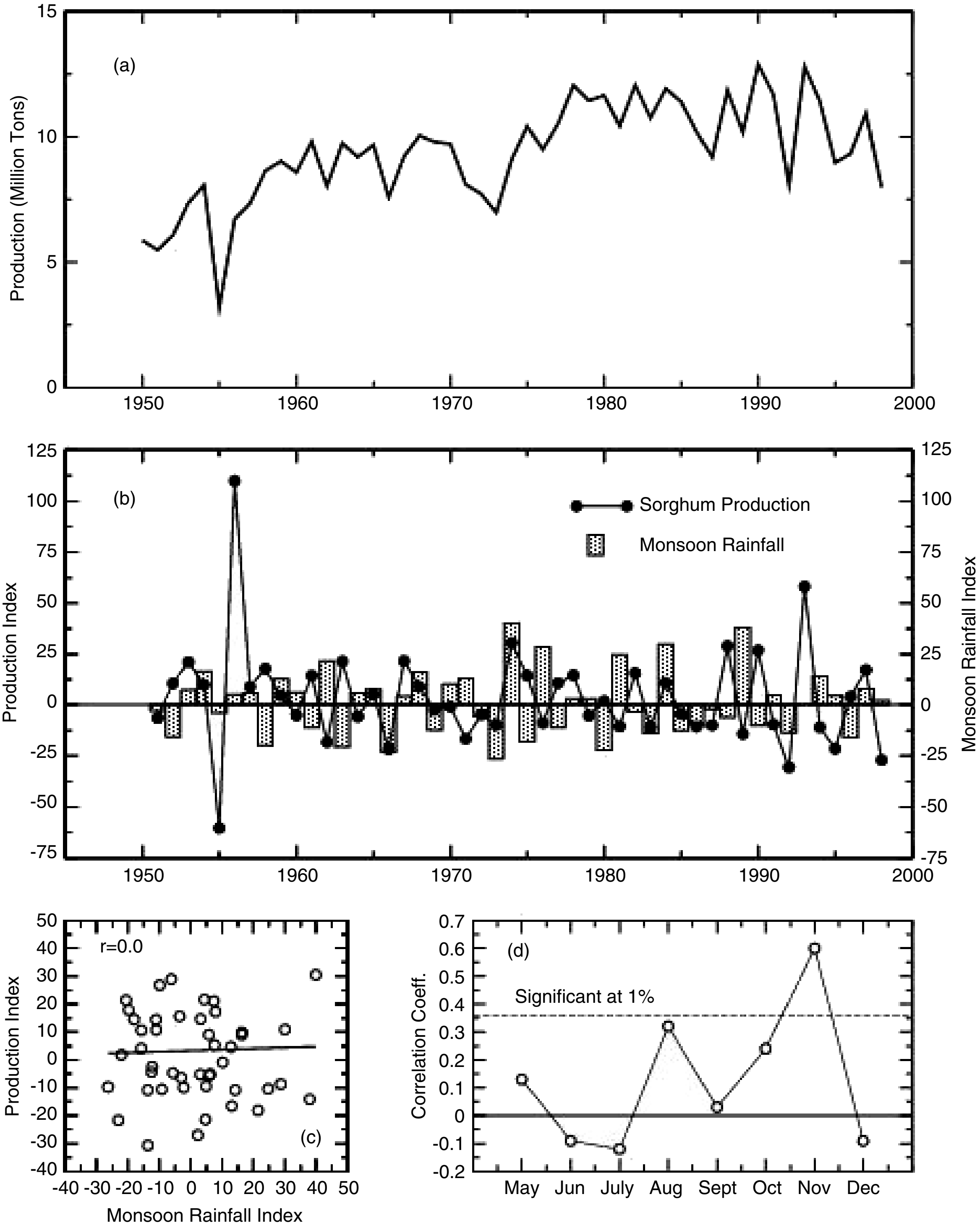


Figure 7. Same as Figure 3, but for total sorghum production

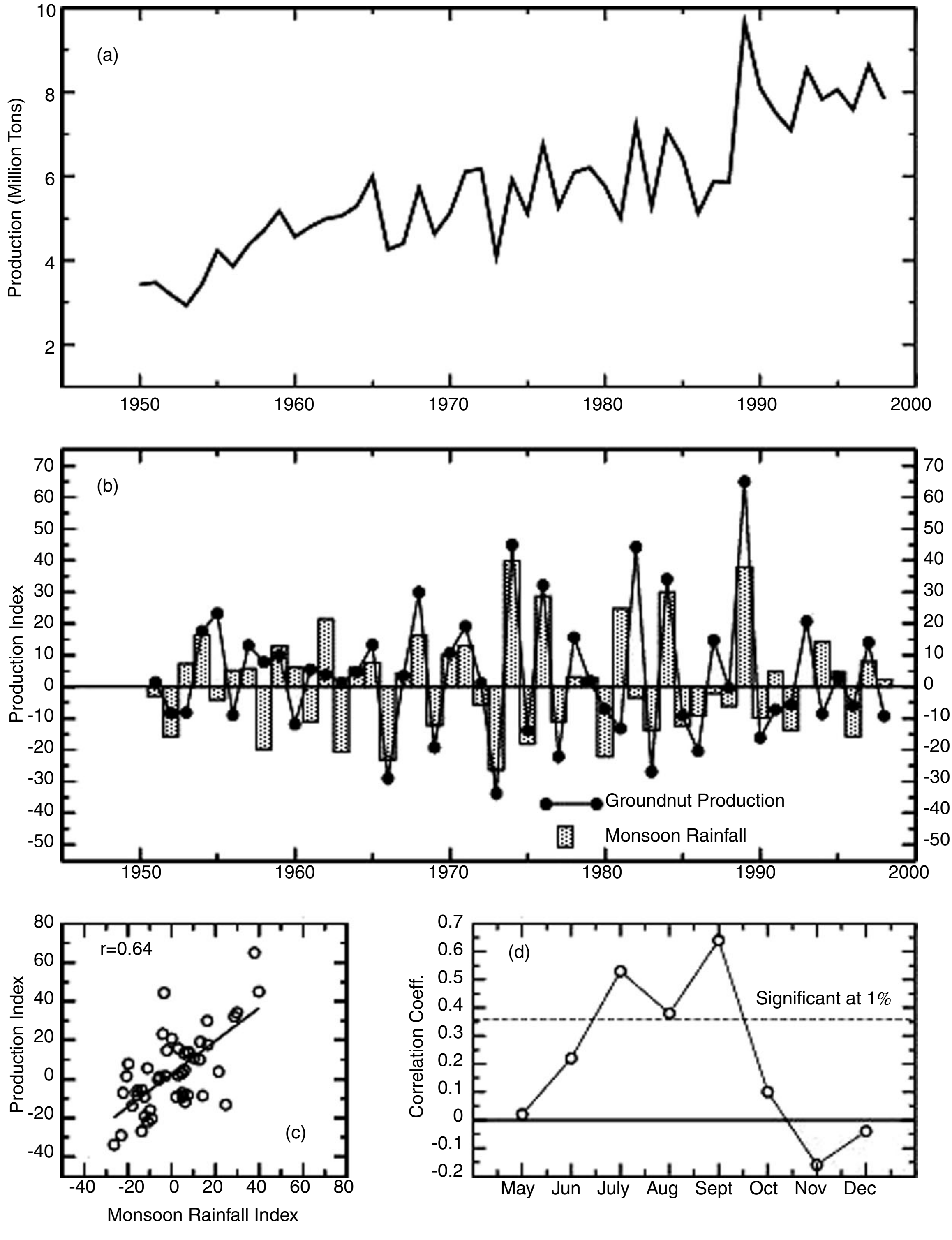


Figure 8. Same as Figure 3 but for total groundnut production

3.6. *Sugarcane*

Sugarcane is grown as a commercial crop throughout India except for western Rajasthan, western Gujarat and some northeastern states. Uttar Pradesh, in the north, produces 44% of the total. Other major sugarcane-producing states are Maharashtra, Tamil Nadu, Karnataka and Andhra Pradesh, all in the peninsula. The crop calendar for sugarcane spans the entire year in most of the country. It is planted during November–February, and is harvested after 1 year. The lack of significant association with monsoon rainfall or ENSO indices (Table IV) seems to reflect the fact that more than 85% of the area under sugarcane is fully irrigated.

3.7. *Crop–climate associations on a regional scale*

Despite the large spatial variability in the agricultural production and the diversity of agricultural practices, the all-India indices seem to be strongly associated with large-scale (all-India monsoon rainfall), regional (Indian Ocean SST anomalies) and global (ENSO) climate variations. Since production varies from one region to another within India, we used monsoon rainfall data from meteorological subdivisions to study local-scale climate influences on crop production — *kharif* food grains, *kharif* and *rabi* rice, total wheat, *kharif* sorghum, and *kharif* groundnut production — in individual states (Figure 9(a)–(f)). Each state contains one or more rainfall subdivisions. We also consider state-level crop response to large-scale teleconnections with June–August NINO3 (Figure 10) and Indian Ocean SST index corresponding to the previous year's June–August season (Figure 11).

Kharif food grain production in most states (Figure 9(a)) shows the strong influence of regional monsoon rainfall. However, weak correlations in the states of Kerala and West Bengal demonstrate the spatial variability of crop–climate associations. It is also interesting to note that, within Bihar, *kharif* food-grain production is strongly correlated with monsoon rainfall in the northern Bihar Plateau, but only weakly correlated with

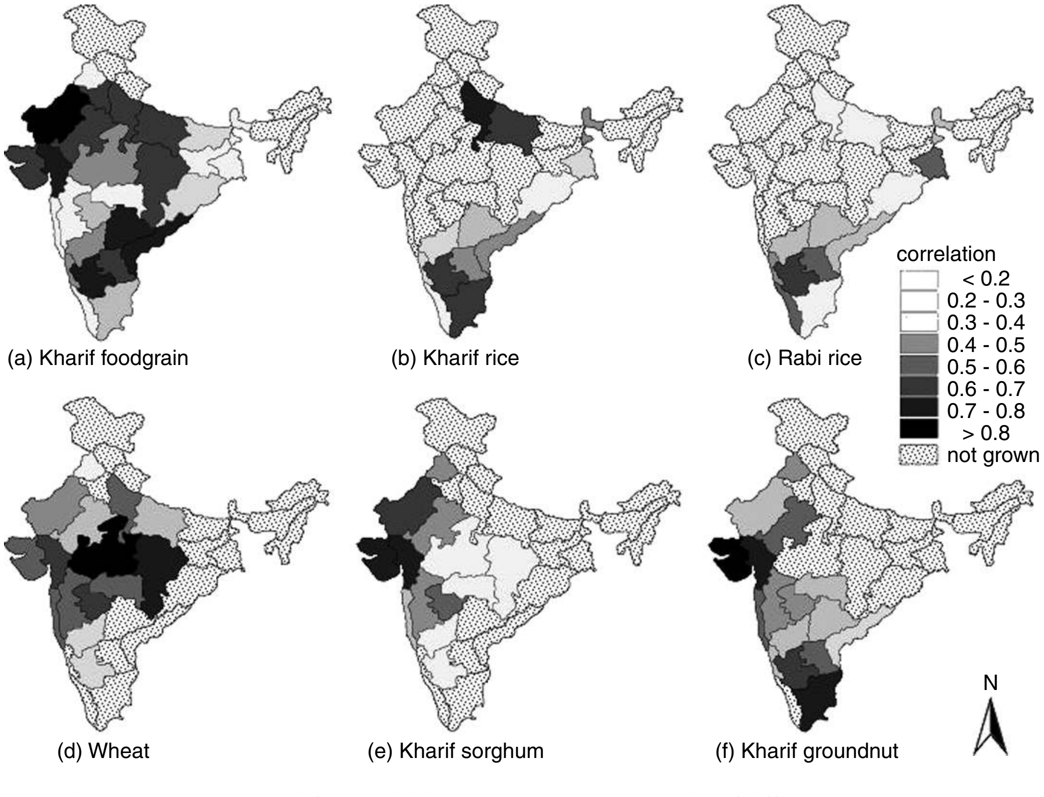
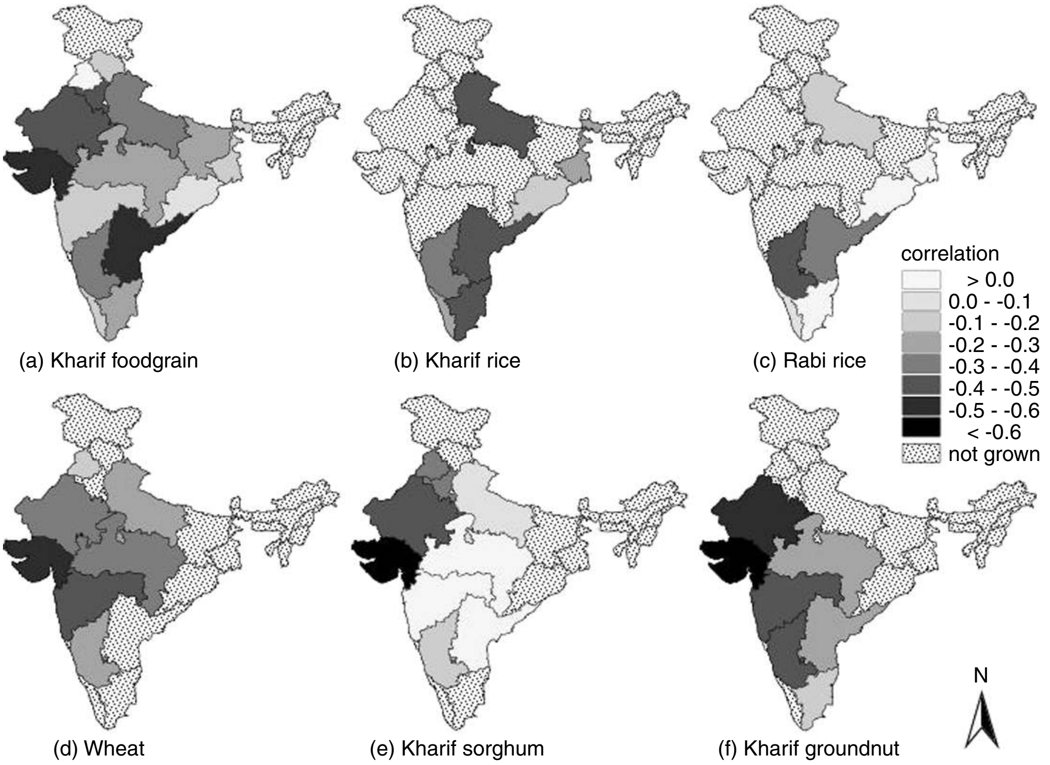


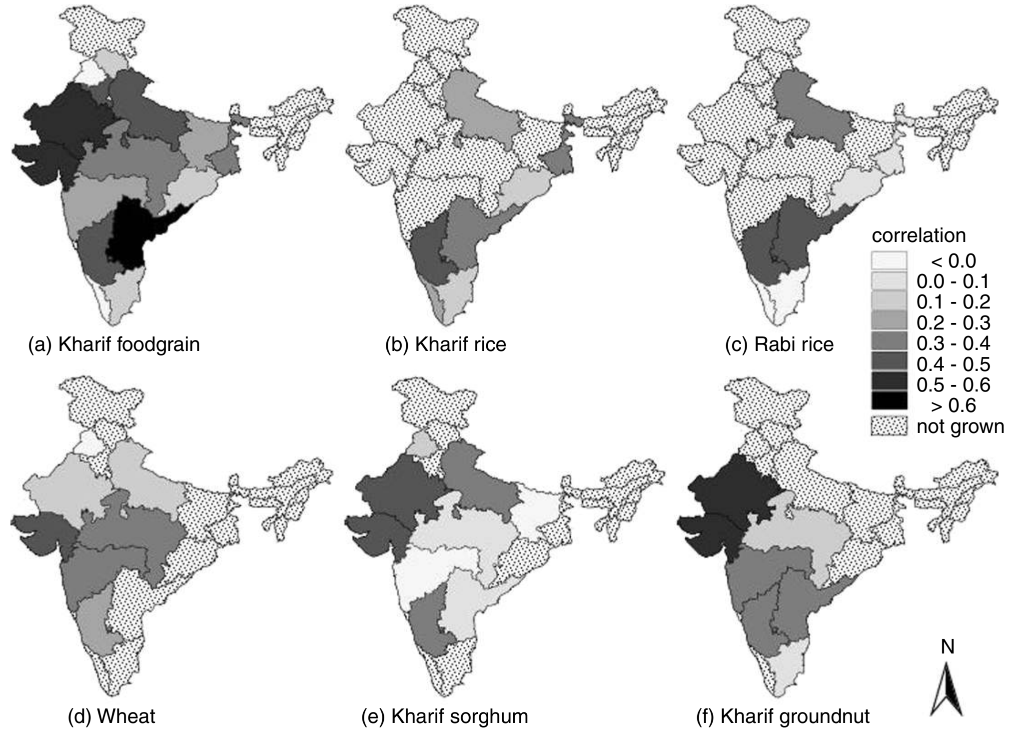
Figure 9. Correlation between monsoon rainfall (subdivisional) and state-level production of different crops. The correlation coefficients shown in (e) for Maharashtra are with the post-monsoon (October–November) rainfall of the subdivisions in that state



(a) Kharif foodgrain (b) Kharif rice (c) Rabi rice

(d) Wheat (e) Kharif sorghum (f) Kharif groundnut

Figure 10. Correlation between summer (June–August) NINO3 SST anomalies and state-level production of different crops



(a) Kharif foodgrain (b) Kharif rice (c) Rabi rice

(d) Wheat (e) Kharif sorghum (f) Kharif groundnut

Figure 11. Correlation between the Indian Ocean SST (JJA-1) and state-level production of different crops

monsoon rainfall in the plains. Similar spatial variability is also apparent in Maharashtra (*kharif* food grains and *kharif* sorghum) and Karnataka (*kharif* rice, wheat and *kharif* groundnut). Although wheat shows a strong response to local rainfall in Madhya Pradesh, Uttar Pradesh, Gujarat, Maharashtra and Rajasthan, wheat shows a poor correlation with local rainfall in Punjab, a major wheat-producing state. The strong influence of monsoon rainfall on sorghum observed in Gujarat, Rajasthan and Punjab is not seen in the major sorghum-producing state of Maharashtra. However, Maharashtra sorghum production shows strong, significant correlation with local rainfall during the months of October–November (Figure 9(e)). This is an interesting contrast with all-India sorghum production, which shows significant correlation with all-India rainfall only in November. *Kharif* groundnut production is strongly related to subdivisional monsoon rainfall in all of the groundnut-producing states (Figure 9(f)).

The *kharif* food grains in Gujarat, Rajasthan, Haryana and Andhra Pradesh show high and significant correlations with NINO3 SST anomalies (Figure 10(a)), consistent with the relationship observed with all-India food-grain production. Uttar Pradesh, Karnataka and Tamil Nadu also show strong associations with NINO3 SSTs. *Kharif* (Uttar Pradesh, Andhra Pradesh, Tamil Nadu and Karnataka; Figure 10(b)) and *rabi* rice (Karnataka and Andhra Pradesh; Figure 10(c)) are significantly correlated with NINO3 SSTs. *Rabi* rice production in Tamil Nadu is positively associated with NINO3 SST anomalies. This is not surprising, as the post-monsoon rainfall over Tamil Nadu is known to be positively correlated with ENSO-related SST indices (Ropelewski and Halpert, 1987). Total wheat (Gujarat, Maharashtra, Rajasthan and Madhya Pradesh; Figure 10(d)), *kharif* sorghum (Gujarat, Rajasthan, Haryana and Punjab; Figure 10(e)) and *kharif* groundnut (Gujarat, Rajasthan, Maharashtra and Karnataka; Figure 10(f)) also indicate a strong influence of summer NINO3 SST anomalies.

We noted earlier (Table IV) that all-India production of several crops is associated with SST anomalies in the Indian Ocean at a long lead time. *Kharif* food-grain production (Figure 11(a)) in all the individual states (except Punjab and Kerala) is positively related to Indian Ocean SST index anomalies corresponding to the previous year's June–August season. *Kharif* and *rabi* rice (Karnataka and Andhra Pradesh; Figure 11(b) and (c)), total wheat (Gujarat, Maharashtra and Madhya Pradesh; Figure 11(d)), *kharif* sorghum (Gujarat, Rajasthan, Uttar Pradesh and Karnataka; Figure 11(e)) and *kharif* groundnut (in the entire region of groundnut cultivation; Figure 11(f)) similarly show a strong long-lead influence of Indian Ocean SST anomalies.

4. SUMMARY

With the exceptions of sorghum and sugarcane, annual total all-India production of the crops we considered show a strong relationship with all-India summer monsoon rainfall. Crops grown in both the (*kharif*) monsoon (except sorghum) and the (*rabi*) post-monsoon seasons (except rice and sorghum) respond significantly to the summer monsoon. The results using state-level crop production statistics and subdivision monsoon rainfall are generally consistent with the all-India results, but they reveal some surprising spatial variations. Understanding the mechanisms for the observed spatial variability of crop–rainfall association will require further study. We speculate that the spatial distribution of irrigation, soil hydrological and fertility characteristics, and phenology (as a function of cultivars and planting dates) can account for this spatial variability, but it cannot resolve these effects with the state-level data used in this study.

All the *kharif* crops except sorghum are strongly associated with ENSO conditions (i.e. NINO3 SST and Darwin SLP anomalies). However, none of the *rabi* crop indices showed this relationship. When examining annual statistics, the influence of ENSO is apparent only for rice, groundnut, oilseeds and food grains. At a higher spatial resolution, the influence of NINO3 SST anomalies on *kharif* food-grain production is strongest in the western and central peninsula (Gujarat, Rajasthan, Uttar Pradesh, Punjab, Andhra Pradesh), and to a lesser extent in Karnataka and Tamil Nadu. When examining the correlations for the recent two decades between different crop indices and NINO3, it was found that the magnitude of correlations shows some reduction but is still statistically significant, unlike the recent weakening of correlation between all-India monsoon rainfall and NINO3 (Krishna Kumar *et al*., 1999). This appears primarily because the correlations between NINO3 and the monsoon rainfall in some of the major rice- and groundnut-growing states are still statistically significant, though they show some weakening. Also, crop production and yield depend not only on the rainfall, but also on other climate factors (e.g. surface temperature, humidity, cloud cover) that may be associated with large-scale ENSO-related climate anomalies in the region.

The significant correlations with the Indian Ocean SST anomalies suggest that *kharif* crop production indices (except sorghum) have some predictability at a long lead time. Although *rabi* groundnut, oilseed and sorghum production indices are related to the Indian Ocean SST anomalies, such a relationship for annual total production is evident only for rice, groundnut, oilseeds and food grains.

Although the impact of subdivision monsoon rainfall is strong in most parts of the country, the influence of (a) global climatic teleconnections studied using the NINO3 SST anomalies and (b) the long-lead Indian Ocean SST anomalies broadly seem to favour the western part of India covering Rajasthan, Gujarat and Maharashtra.

The results of this study provide evidence that crop response to monsoon rainfall has some predictability, even before the start of the growing season. This is a necessary, but not a sufficient, condition for farm and policy applications of long-lead climate forecasts (Hansen, 2002). Exploiting this predictability will require further work with refined predictors and prediction systems, higher resolution crop and rainfall data, and perhaps process-level models of crop response. The results also indicate, at the very coarse state scale, what major crops and regions show the greatest sensitivity to the predictable components of monsoon rainfall. This type of analysis, at a finer spatial scale, could provide useful information for targeting interventions.

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