RESEARCH ARTICLE

Climate Change and Agriculture: Current and Future Trends, and Implications for India

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Abstract: Agriculture is vulnerable to the current state of climate variability as well as to projected changes in climate because of anthropogenic global warming. Models of crop production, considered together with global climate models, indicate that global warming will increase the exposure of major crops to temperature stress, leading ultimately to lower yields. Such decreases in yields vary significantly across the globe (and there remain significant uncertainties about their magnitude). Various studies also indicate that climate variability alone has the potential to decrease yields to an extent comparable to or greater than the decrease in yields expected due to rising mean temperatures.

Following a survey of these results at the global level, this paper explores some aspects of the impact of climate variability and projected changes in the mean values of temperature and precipitation at the regional level for India. There are significant uncertainties in predicting changes in rainfall patterns for India, particularly because of difficulties in understanding and predicting monsoon behaviour. More robust results are available regarding future rises in temperature expected in the Indian subcontinent. While the dependence of Indian agriculture on rainfall is well-known, the significance of increased temperature variability must also now be considered.

The paper emphasises the importance of distinguishing between current climate variability and future changes in climate with respect to the mean and the variance of climate variables, especially in understanding the socio-economic impact of climate change on Indian agriculture. Using village-level data on agricultural production, yield, and incomes from the Project on Agrarian Relations in India (PARI), it argues that conflating current climate variability and future climate change obscures the fact that inequality and oppression are the key to why poor and marginal farmers suffer the impact of climate variability today, even when climate change does not yet have a serious negative impact on Indian agriculture. At the same time, understanding the differentiated impact of climate variability across socio-economic categories of producers, agro-climatic zones, and crops in the current context can provide

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significant insights into climate adaptation in a future of global warming. A just and equitable policy for dealing with the impact of climate change on India's development must therefore pay as much attention to climate adaptation, especially with reference to agricultural production, as it does to climate change mitigation.

Keywords: Climate change, climate variability, regional climate model predictions for India, climate change and agriculture, socio-economic impact of climate change, climate variability and the peasantry, climate variability and Indian agriculture, impact of climate variability on agriculture, climate variability and disasters, extreme events.

Introduction

This paper covers three major aspects of the issue of climate change and agriculture. First, it draws attention to some significant recent advances in climate science that are of relevance to the impact of global warming on agriculture, particularly to crop production and its relation to climatic variables. Secondly, it briefly surveys the significance for agricultural production of climate variability and the occurrence of extreme climatic conditions in the context of increasing global warming both in the present and in the future. Thirdly, it considers some implications of these consequences for the study of the economic impact of climate change. In doing so, it also focuses on the need to understand the differential impact of climate change on agriculture across both spatial and temporal scales, and different socio-economic strata of producers. Identifying the people who suffer the consequences of climate change and the public action required to protect their well-being is a key normative issue in the making of climate policy, both nationally and globally. While not directly making any policy recommendations, the paper discusses issues relevant to policy with particular reference to India.

The main points that the paper makes are as follows. First, it is now fairly certain that the ongoing phenomenon of global warming has human origins. There is mounting evidence that global warming has a number of consequences that reflect its anthropogenic origin. This is clear from the publication of the first part of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), which deals with the physical science aspects of climate change (IPCC 2013).

Secondly, research in agricultural science as well as study of the effect of climate variability on actual crop production point to the importance of shifts in the intensity, duration, and frequency of climate extremes for agriculture. In fact, shifts in climate extremes are likely to be as important in this regard as the gradual shift of the mean values of climate variables due to global warming. The former should therefore perhaps be regarded as independent parameters alongside the latter. We also emphasise the importance of studying the impact of climate variability in the present in order to understand the consequences of climate change in the future.

Thirdly, in relation to India, we point to the importance of studying both current climate variability and future climate change at local levels, given the substantial climatic variations across time and space. While rainfall variability is a significant factor contributing to short-term fluctuations in agricultural production, we indicate the need to move away from this traditional emphasis by also taking into account temperature variability and extreme temperatures.

We draw on some results of the village surveys conducted as part of the Project on Agrarian Relations in India (PARI) by the Foundation for Agrarian Studies (FAS) and other existing literature in order to discuss the need to study the differential impact of environmental stresses and shocks across different socio-economic strata of the rural population. The paper concludes with a brief discussion of the need for India's climate policy to reflect a greater awareness of the efforts and costs required for climate change adaptation if global warming is allowed to proceed relatively unchecked.

Even while asserting the right to development, India's climate policy must also reflect the need for an early global climate agreement. Such an agreement is a fundamental aspect of protecting the vast number of India's rural poor from the additional burden of global warming.

New Results from the IPCC's Fifth Assessment Report

The first part of the Fifth Assessment Report by Working Group I of the IPCC provides the latest assessments from the field of climate science regarding our knowledge of the earth's climate system (IPCC 2013). It is clear that several trends associated with global warming of anthropogenic origin are intensifying, and that specific rates of their intensification can be quantitatively estimated with varying levels of confidence. While we have not recounted all the significant details of AR5 in this paper, some of the more relevant and striking results are listed below.

With reference to current trends in climate change, the following results are of interest. The atmospheric concentrations of the greenhouse gases carbon dioxide and nitrous oxide are now at levels that "substantially exceed" the highest levels of these concentrations known on earth for the last 800,000 years.

Global warming of land and sea continues to increase, and the levels of warming have been rising steadily every decade. Each of the last three decades has been warmer than any preceding decade since the year 1850. Global mean temperature rose by 0.85 degrees Celsius (°C) between 1850 and 2012. (This conclusion is based on analysis of multiple independent sources of data.) While global warming is not spatially uniform across the globe, there is almost no region in the world that has not experienced some rise in average temperature.

The data on rise in sea levels shows that the rate of rise of the global mean sea level has been increasing, with the rise in the most recent period of 1993–2011 being 3.2 mm per year, as compared to 1.7 mm per year between 1901 and 2011. These data also indicate with a high level of confidence that the rise in sea levels since 1901 marks a distinct transition from the rates of increase over the previous two millennia. Further, the observations on rise in sea levels now are increasingly in accordance with what is expected from theoretical calculations. According to these calculations, sea-level rise takes place due to different reasons, including thermal expansion of the oceans due to warming, melting of polar ice sheets and glaciers, and changes in land water storage.

Over the period 2002–11, annual carbon dioxide emissions from fossil fuel combustion and cement production averaged 8.3 GtC,[1] while emissions due to land-use change averaged 0.9 GtC. However, the uncertainties in estimating the latter are much larger. The annual range for the latter lies between 0.1 and 1.7 Gt, whereas for the former the range is between 7.6 and 9 Gt annually.

It is "extremely likely" (to use the IPCC's classification of the levels of confidence in various scientific statements in its report)[2] that human activity on the Earth since 1750 is the source of observed changes in global average temperatures. Other changes, such as in global mean sea levels, the melting of sea ice, and in the global hydrological cycle, are also attributable to greenhouse gas emissions of anthropogenic origin.

The ability of climate models to reproduce past climate change, an important test of their validity and reliability, has improved in different ways. Global mean temperatures are the best represented, especially at longer time scales, though they are subject to greater uncertainties at time scales of 15–20 years. Regional predictions using climate models show much improvement in representing temperature changes, but these predictions are poorer in quality than global predictions. Changes in precipitation in general are poorly represented as compared to changes in temperature, especially at regional levels.

Some of the AR5 results relating to extreme climate events and the current capabilities of modelling such phenomena are as listed below.

It is "very likely," to use the terminology of the IPCC again, that extremes of daily temperature, both in terms of frequency and intensity, occur due to anthropogenic global warming. In some regions, global warming appears to have more than doubled the probability of occurrence of heat waves. Cold days and nights have either decreased in number, or have become warmer, as a result of global warming.

[1] GtC refers to gigatonnes of carbon (referring only to the carbon content of carbon dioxide), where 1 gigatonnne = 1 billion tonnes.
[2] See IPCC (2013) for a ready reckoner of the terms used to characterise the degree of uncertainty or reliability of various conclusions in the report.

Global warming is also contributing to an increase in extreme rainfall events in terms of frequency of occurrence, intensity, and amount of precipitation, though the connection here is not as certain as in the case of temperature.

In contrast with the results mentioned above, the connection between the frequency and intensity of droughts, and global warming, is still ambiguous. Similarly, the connection between the frequency and intensity of tropical cyclones, and global warming, remains uncertain. There is, however, good evidence of a connection between the occurrence of unusually high sea levels and global warming.

With a further increase in temperature, it is clear that the frequency of some extreme climate events is likely to increase. The extent of increase that is expected corresponds to the extent to which such extreme events are connected currently to global warming. Thus, heat waves, very heavy rainfall, and abnormal surges in sea level are all likely in the future, while other extreme events listed above are not expected to occur with such increased frequency.

Overall, it appears that temperature increase and rise in sea levels (and indeed many other ocean-related effects) are fairly well connected to global warming of anthropogenic origin. However, uncertainty still surrounds many features of winds and precipitation. (It is worth noting here that issues of precipitation present greater difficulties with respect to the predictive abilities of climate models than, for example, temperature does.) We may therefore conclude that the connections between precipitation and global warming must await further scientific advance, and that the current absence of evidence regarding definitive connections relating to changes in precipitation (and related extreme events) may be modified in the future.

What will climate in the future look like with continued global warming? Such global warming may arise either due to unchecked greenhouse gas emissions, or even as a consequence of the limited emissions that may be permitted under a global climate agreement. The latter case would of course depend on the nature and extent of action under such an agreement. To predict the eventual nature of a global climate agreement is difficult, given the economic, political, and social dimensions of the problem, and thus the considerable uncertainties involved in making such a prediction.

The IPCC made an effort some years ago to develop 'scenarios' of the future which outlined different trajectories of global economic and technological development, and attempted to predict the broad range within which greenhouse gas emissions would lie (IPCC 2000). These scenarios could also incorporate the effects of a global climate agreement. Typically, future climates and their impact were studied by the IPCC under these different scenarios, as were the trajectories of the resulting greenhouse gas emissions they predicted. Other studies adopted a more obvious and simpler strategy by defining a trajectory of growth and a subsequent decline of emissions in purely physical terms, without any explicit reference to a socio-economic basis for such a trajectory.

The IPCC's predictions of future climate change and its effects are based on emission trajectories which describe how emissions rise and then possibly decline, such that, by the end of the twenty-first century, they result in a specific level of global warming. The emission trajectories are called Representative Concentration Pathways (RCPs), and they are labelled by a number that refers to the global warming expected (in terms of energy in watts per square metre, not in terms of temperature) for each pathway by the year 2100. All the results in the IPCC's AR5 are based on four such reference trajectories: RCP 2.6,[3] RCP 4.5, RCP 6.0, and RCP 8.5.

Two significant conclusions in AR5 regarding the consequences of each of these RCPs need to be emphasised. First, the report predicts the range of temperature increase expected from each of the RCPs by the year 2100. Secondly, the report estimates the cumulative carbon dioxide emissions associated with each RCP from the reference year 2012 until 2100. In effect, then, the IPCC has set down a global carbon budget, that is, the total cumulative carbon dioxide emissions the world may be allowed if temperature increase is to be kept within a specified range. We summarise this information from AR5 in Table 1 below.

Equivalently, for different amounts of cumulative emissions of carbon dioxide between 2012 and 2100, we can estimate the probability that the corresponding maximum temperature increase will stay below 2°C. Following the international climate negotiations at Copenhagen in 2009, and subsequently at Cancun in 2010, all nations have agreed that 2°C is the ceiling for temperature increase.

The presentation of these results in this form in AR5 amounts to acceptance by the IPCC of the notion of a global carbon budget. This budget sets the quantum of greenhouse gases that the world as a whole can emit in the future and yet keep maximum temperature increase below a certain limit. This is a very significant development for global climate negotiations. This global carbon budget (based on figures from IPCC's AR5) will be the global allowance for greenhouse gas emissions from now on, an allowance that must be shared among all countries from the present into the indefinite future. Agreement on how the allocation and sharing are to be carried out in practice will be the real challenge for climate negotiations in the years to come.

To sum up, there is little doubt that global warming of anthropogenic origin is causing global and regional mean temperatures to rise, resulting in the melting of glaciers

[3] Thus RCP 2.6 refers to a Representative Concentration Pathway that leads to global warming of 2.6 watts per square metre in the year 2100.

Table 1 *Increase in global mean temperature and probability of temperature rise exceeding 2°C by 2100 for specified cumulative emissions corresponding to different Representative Concentration Pathways (RCPs)*

Representative Concentration Pathway (RCP)	Cumulative emissions in the period 2012–2100 (GtC)	Range of increase of global mean surface temperatures for the period 1850–2100 (°C)	Probability of exceeding 2°C	
RCP 2.6	270	0.9–2.3	Unlikely to exceed 2°C (medium confidence)	<33% probability of exceeding 2°C
RCP 4.5	780	1.7–3.2	More likely than not to exceed 2°C (high confidence)	>50% probability of exceeding 2°C
RCP 6.0	1060	2–3.7	Likely to exceed 2°C (high confidence)	>66% probability of exceeding 2°C
RCP 8.5	1685	3.2–5.4	Likely to exceed 2°C (high confidence)	>66% probability of exceeding 2°C

Notes: (i) Representative Concentration Pathways (RCPs) are emission trajectories that describe how emissions rise or decline.
(ii) The range in column 3 is obtained by taking the mean ± 1.64σ of the predictions from all the models included in the Coupled Model Intercomparison Project version 5 (CMIP5).
(iii) For RCP 6.0 and RCP 8.5 the probability in column 5 cannot be 100 per cent as there are models whose predictions fall outside the range given in column 3.
Source: IPCC (2013).

and polar ice caps, a rise in sea-levels, and other effects that point unmistakeably to the role of greenhouse gas emissions in global warming.

The Impact of Global Warming on Agriculture

As the IPCC's AR5 of Working Group II is yet to be released, it is difficult to provide a global overview of the current and future impact of climate change on agriculture, and of the developments in various methods and techniques used to measure and analyse such impact. Nevertheless, there are three important developments that are very likely to feature in any such global review (these have been noted in HLPE 2012, and Schellnhuber *et al.* 2013).

Reducing Subjective Uncertainties in Quantifying Climate Change Impact on Crop Production

Predictions of the impact of climate change on crop production are made using simulation models of crop growth. These are complex mathematical models that take into account a number of factors in determining how changes in climatic conditions affect crop growth. In addition to climate variables, other variables considered in these models typically include soil conditions, the effects of pests and weeds, crop management, and so on. There are many such crop growth models. When these models are used to predict the impact on agriculture of climate change, they are integrated with climate models that also forecast the values of climate variables in the future. Thus integrated results can be obtained from climate models and crop growth models, though of course at the price of a combination of uncertainties from both.

A major international collaborative effort, the Agricultural Model Inter-Comparison and Improvement Project (AGMIP),[4] is now under way, to compare and integrate the results across a variety of models for different aspects of the impact of climate change on agriculture. Data from this collaboration help us to evaluate robust results – particularly common trends from different models – as well as uncertainties in the present state of knowledge.

The AGMIP is patterned on a prior collaboration, the Coupled Model Inter-comparison Project (CMIP). CMIP provides integrated, comparable data from a variety of climate models for predicting climate effects. Specifically, future climate variables, such as temperature and precipitation, are given in terms of the average of the values predicted by different models, together with the corresponding variations. This average is referred to as the CMIP5 model mean (CMIP5 is the current version of CMIP) for the corresponding climate variable.

[4] Available at http://www.agmip.org.

One significant set of results from AGMIP is an extension of the findings of Working Group II of the Fourth Assessment Report (AR4) of the IPCC with respect to the impact of climate change on the production of some major crops (Rosenzweig *et al.* 2013). These results take into account the differential rise in mean temperatures that will occur at high and low latitudes. These results, which include the effect of decreased nitrogen availability, are summarised in Figure 1.

The figure shows that more recent calculations from various climate and crop growth models differ significantly from the predictions of the IPCC's AR4 when nitrogen stress is not included. However, the results from AR4 are closer to more recent calculations when the latter take into account the effect of nitrogen stress. In general, the extent of grey areas in the figure indicates the considerable uncertainties in these calculations, uncertainties that have in fact increased in comparison to the results reported in AR4. Rosenzweig *et al.* (2013) attribute this to wider coverage of crop-growing areas and the greater number of models that have been taken into account.

The Role of Climate Variability in Determining the Impact of Climate Change on Agriculture

One of the important consequences of global warming, as already noted, is increased variability of temperature and precipitation. The increased variability of key climate parameters could be a consequence of a shift in the mean, or a consequence of a change in the distribution of values of such parameters without a shift in the mean, or a combination of both. The three possible situations are illustrated using temperature as an example in Figure 2.

There is now increasing evidence that climate variability matters as much to crop production as the mean values of climate variables during the crop season. The evidence comes from agricultural science research as well as analysis of crop production data.

A striking result from agricultural science research is that climate variability alone, without change in mean temperature, can cause a decrease in crop yield that is comparable to or greater than the decrease due to an increase in mean temperature. This result, which is familiar to some crop modelling experts, is not commonly cited in the literature on climate and agriculture. Semenov and Porter (1995), using a crop model calibrated for wheat in the United Kingdom, showed that a doubling of the standard deviation with the same mean temperature would give the same decrease in yield (7 per cent) as a 2°C rise in mean temperature. Such connections appear to vary by region. French wheat showed a 9 per cent decline in yield for a doubling of the standard deviation, while a 4°C rise in mean temperature showed a yield decline of only 3 per cent. For wheat in the United Kingdom, the combination of a 2°C rise in mean temperature together with a doubling of the standard deviation in temperature caused yields to decline by 19 per cent.

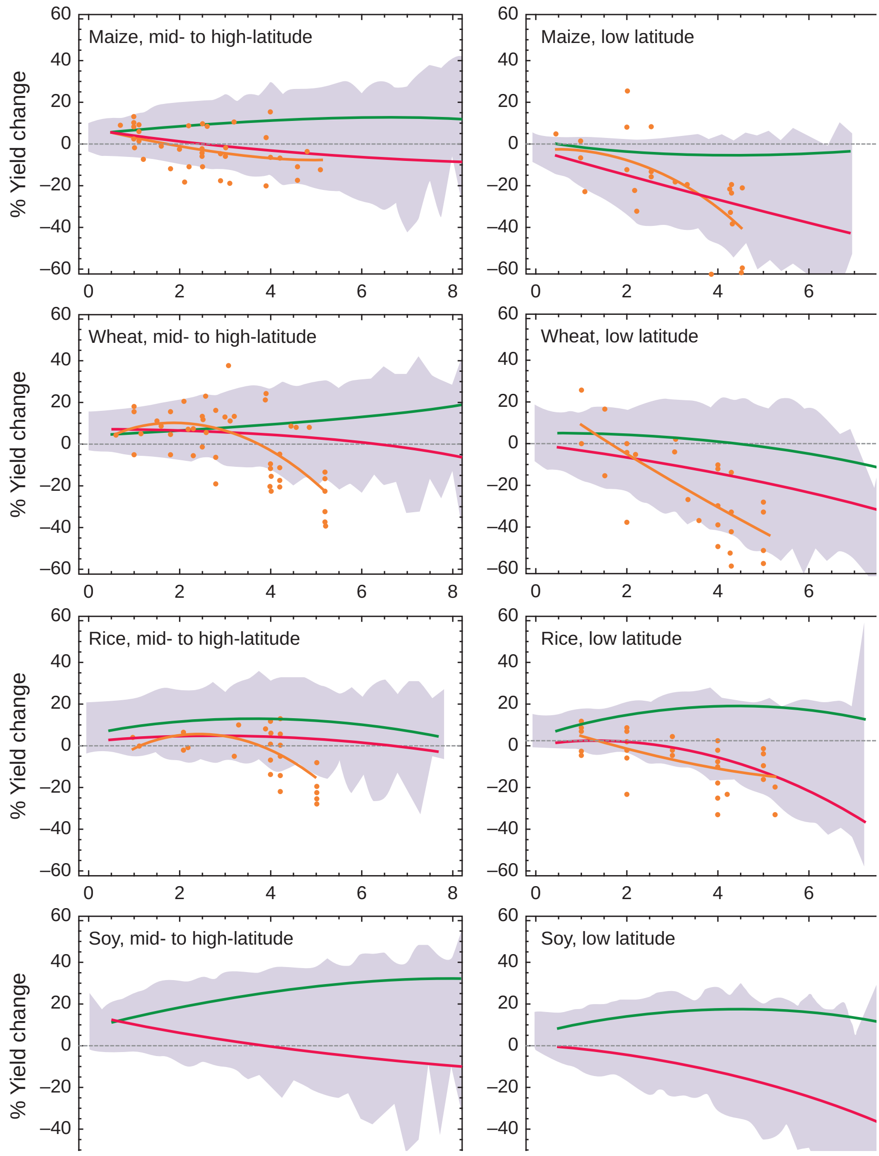

Figure 1 *Sensitivity of crop yield to temperature change, maize, wheat, rice, and soybean, 1980–2010*

Notes: (i) The figures show mean relative change in yield corresponding to local mean temperature change in 20 major food-producing regions for each crop and latitudinal band.
(ii) The green and red lines are best fits to data derived from combined crop and climate models. The green line is the best fit to data from models that include fertilizer application, and the red line is the best fit to data that does not include fertilizer application.
(iii) These results are for the future emission scenario corresponding to RCP 8.5.
(iv) The orange data points indicate mean values from the IPCC's AR4 (Easterling *et al.* 2007), and the orange lines are their quadratic best fits. These are provided for comparison.
(v) The best fit lines are not used as a predictive tool but to summarise results across studies. The grey shaded area indicates the uncertainty in the 15–85 per cent confidence level range of all the models considered together.
Source: Rosenzweig *et al.* (2013).

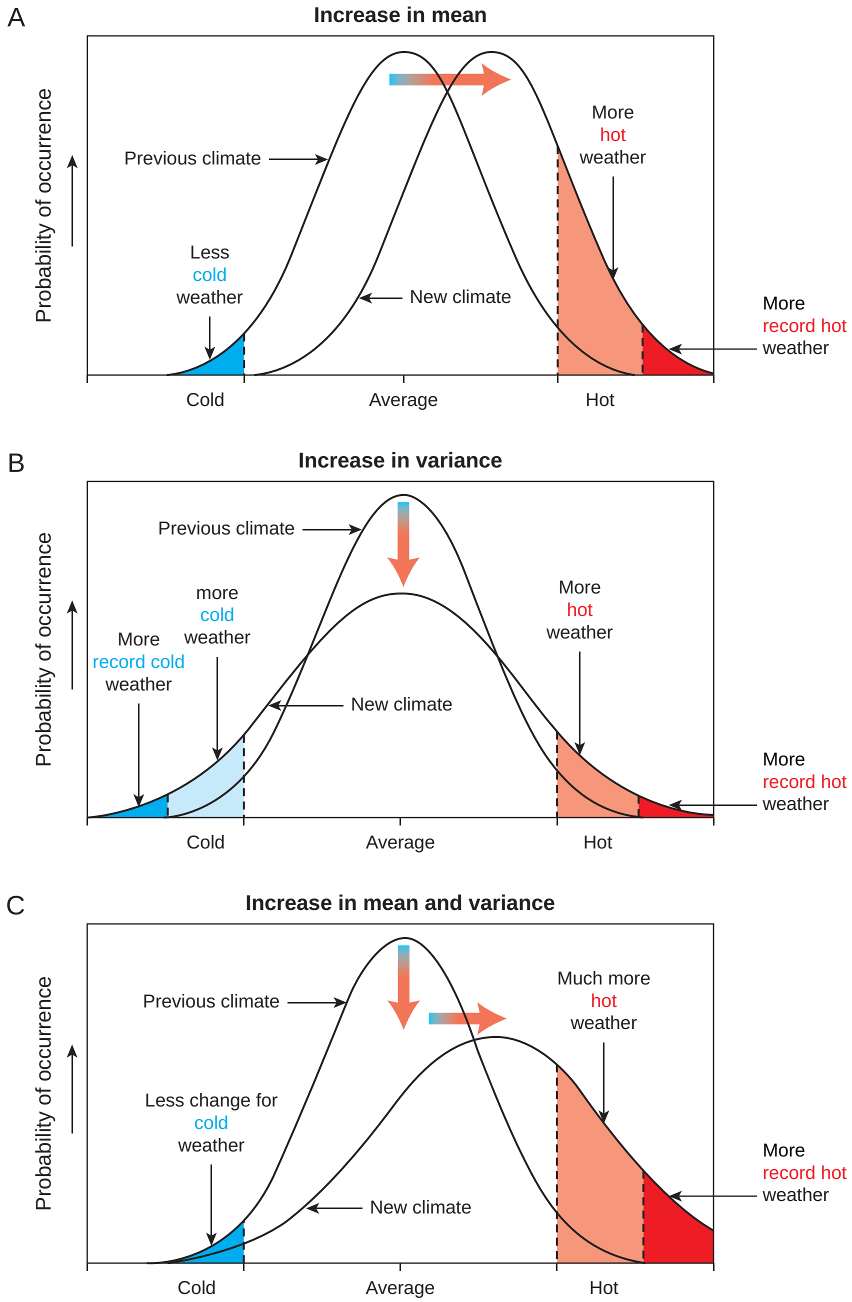

Figure 2 *Possible changes in mean and variance of climate variables (using temperature as the example) because of global warming, and their implications for weather*
Source: IPCC (2001).

A useful review of the impact of temperature and precipitation variability, and their impact on yield, relevant to Indian conditions, is provided in Singh and Singh (1995).

The significance of climate variability for agriculture goes beyond the purely technical aspect of its impact. It is well known that small and marginal farmers are particularly vulnerable to weather-related stresses and shocks. The impact of climate variability on smallholder agriculture in the present can therefore provide important insights into its vulnerability to future climate change.

More frequent occurrence of extreme climate events, such as drought, floods, cyclones, and so on, is also expected to be a feature of future climate change. As in the case of climate variability, the vulnerability of agricultural production to loss and damage due to such extreme events – both in terms of loss of production in general, and loss of production and incomes for small, marginal, and medium farmers in particular – is a subject of particular concern. In such cases too, dealing with the impact of climate shock in the present can provide important insights into the future.

Globally, for several crops and in many regions, there is increasing exposure to heat stress, in terms of the number of days of the growing season in which the crop is exposed to temperatures beyond a critical threshold. We show the results from one such study, Gourdji *et al.* (2013), in Tables 2 and 3. Table 2 shows the trend in increased exposure to heat stress, and Table 3 shows the heat stress to be expected in the future based on extrapolation from current trends.

Another study (Teixeira *et al.* 2013) shows the extent of land across the world that will be exposed to heat stress in the future for one of the IPCC scenarios (the A1B scenario[5]) with high levels of global warming (see Figure 3).

Taken together, these results indicate that heat stress is not yet an immediate problem for all crops. Nevertheless heat stress is increasing both in intensity and duration, and in a future of pronounced global warming it is likely to increase for all crops.

Current Impact of Mean Temperature and Precipitation Changes on Crop Production

There is more evidence now of the impact of climate change on current agricultural production. However, there is as yet no detailed update on the work done by Hafner (2003), cited in AR4, on overall trends in the growth of yields of major crops across

[5] The A1B scenario refers to a future climate where the total concentration of all greenhouse gases in the atmosphere increases to 720 parts per million by 2100. In this scenario, by the 2090s, global temperatures are expected to rise by 2.8˚C above the 1980–99 average. For further details, see IPCC (2001), available at http://www.ipcc.ch/ipccreports/tar/wg1/029htm#storya1.

Table 2 *Global rate of change in mean temperature during the growing season and percentage of global harvested area exposed locally to such change, and global rate of change in number of days of exposure during growing season when temperatures are above a specified critical temperature (T_{crit}), and the share of global harvested area exposed locally to such rise in exposure, wheat, maize, rice, and soy, 1980–2011*

Crop	Mean temperature in growing season			Number of days of exposure above T_{crit} in growing season		
	Trend from 1980 to 2011 (°C/decade)	% area with trend ≥0.1 (°C/decade)	% area with trend ≤−0.1 (°C/decade)	Trend from 1980 to 2011 (days/decade)	% area with trend ≥0.1 (days/decade)	% area with trend ≤−0.1 (days/decade)
Wheat	0.33	83	5	0.12	27	10
Maize	0.21	68	3	0.14	32	25
Rice	0.23	86	2	0.04	15	7
Soy	0.16	68	1	0.01	6	5

Note: The rate of change in mean temperature and reproductive days above critical temperature in the growing season is estimated using daily temperatures for all crop-growing locations, obtained by interpolation of daily maximum and minimum temperature data from about 40,000 weather stations. The global trend is given by a weighted average of the trends at all these stations. The area associated with such changes is estimated by considering the harvested area for each crop within 100 km of each station. The critical temperatures for selected crops are 34°C for wheat, 35°C for maize, 36°C for rice, and 39°C for soybean.
Source: Gourdji *et al.* (2013)

Table 3 *Percentage of global harvested area likely to be exposed to temperatures above the associated critical temperatures for varying durations of exposure, specified crops, 2000s, 2030s, and 2050s*

Crop	1 day			5 days			10 days		
	2000s	2030s	2050s	2000s	2030s	2050s	2000s	2030s	2050s
Wheat	19	32	41	5	11	18	2	4	8
Maize	32	52	63	15	31	44	8	18	29
Rice	14	28	44	8	16	27	5	10	18
Soy	4	11	20	0	3	8	0	1	3

Note: 2000s, 2030s, and 2050s refer to the twenty-year period centred around each of these years, and the areas exposed to temperatures higher than T_{crit} are the annual averages for these periods. These predictions are the average of the predictions from all the models included in the Coupled Model Inter-comparison Project version 5 (CMIP5).
Source: Gourdji *et al.* (2013).

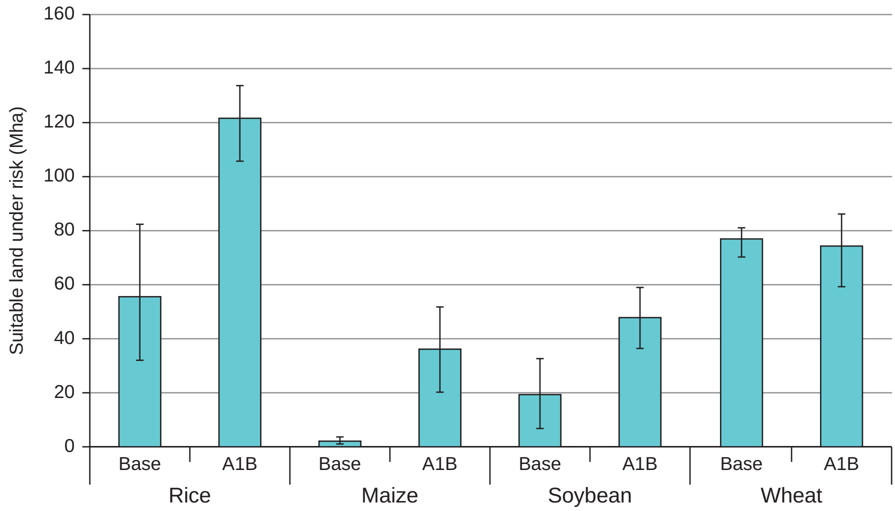

Figure 3 *Extent of global land area exposed to risk of heat stress for specified crops: rice, maize, soybean, and wheat*

Notes: (i) Risk of heat stress occurs when a crop is exposed to daytime temperatures above its critical temperature for one or more days during its reproductive phase. The relevant critical temperatures for rice, maize, soybean, and wheat are 35°C, 35°C, 35°C, and 27°C, respectively.
(ii) The figure shows the global acreage for specified crops that was exposed to heat stress risk in the period 1971–2000 (referred to as Base), and compares it to the expected heat stress risk for the period 2071–2100 in the A1B scenario. The A1B scenario refers to a future climate where the total concentration of all greenhouse gases in the atmosphere increases to 720 parts per million by 2100, and where global temperatures in the 2090s are expected to be 2.8°C above 1980–99 levels.
(iii) The results for the A1B scenario are from a global-level analysis using daily minimum and maximum temperatures obtained from General Circulation Models (GCMs).
(iv) The height of the column indicates the median value, and the line at the top of the column shows the variation from the 25th to 75th percentile for the 30-year analysis period.
Source: Teixeira *et al.* (2013).

the world. In this paper, we have made rough estimates[6] (to be confirmed by more detailed analysis) which confirm the trends indicated by Hafner (2003).

These estimates show that the global rate of growth of yield exceeds 33 kg/hectare/year, the figure required to maintain current global per capita availability of food for a population of 9 billion in the year 2050. There is also evidence that there is continuing scope for increasing yields, as borne out by the detailed study of maize by Gustafson *et al.* (2013). One of the questions raised in Jayaraman (2011), written after the publication of AR4, was whether the necessary increase in yields would be sustainable if it is achieved by intensified use of existing methods of cultivation. While there is as yet no direct answer to this question, Gustafson *et al.* (2013) suggest that more technically advanced agriculture in the developed countries has greater eco-efficiency than low-productivity agriculture in the developing countries. They argue that for low levels of

[6] Based on simple analysis of data up to 2012, available from FAOSTAT.

agricultural intensification (measured in terms of use of land, water, and energy), the environmental impact of agriculture is low. This impact then rises significantly for medium levels of intensification, and decreases again for highly intensified agriculture. The eco-efficiency metric, however, does not use indicators that relate to other aspects of sustainability, such as the active nitrogen that is released into the environment (and water bodies in particular) or the impact of intensification on soil health.

These results do not exclude the possibility that climate change is indeed having a negative effect, which is however being offset by other factors such as better management or improved technology. On balance, the latter would ensure that both production and yield keep rising. That this currently is indeed the case is evident from the work of Lobell *et al.* (2011), which analyses the impact of temperature and precipitation changes on the production of four major crops across the world. The study indicates a mixed picture (though mostly negative) of the impact of climate change on crop production. Significantly, it is temperature, overall, that appears to have a more significant impact on crop production, whether positive or negative, compared to precipitation. The study also usefully compares the relative negative effects of temperature increase to the positive effects of yield growth due to other factors. Figure 4 below shows the impact of temperature and precipitation on yields for four major crops, both globally and in five countries located in different regions.

Climate Change and Agriculture: The Indian Context

Temperature and Precipitation: Current and Future Trends

We now turn to considerations specific to India with regard to climate change and agriculture. We begin with a brief review of the trends in climate variables for India, including changes in temperature, and the current and future state of rainfall, especially with reference to the monsoon.

Our calculations from Indian Meteorological Department (IMD) data show an overall rise of about 0.6°C to 0.8°C in mean annual temperatures for India over the period 1850–2010. There is clear evidence of a rise in the rate of increase in the most recent period. Figure 5 shows the deviation of mean annual temperature from the 30-year average for the same variable over the period 1960–99.

Temperature trends also show a definite increase, as reported by India in its Second National Communication to the United Nations Framework Convention on Climate Change (Natcom II, 2012). According to this communication, annual mean temperatures across India rose by 0.56°C over the 100-year period ending 2007. Mean winter temperatures increased by 0.7°C over the same period. However, the rate of increase was more rapid in more recent years – 0.2°C every 10 years from 1971 to 2007 – with a sharper increase in minimum temperatures than in maximum temperatures. The all-India maximum temperature increased by 1.02°C over the last

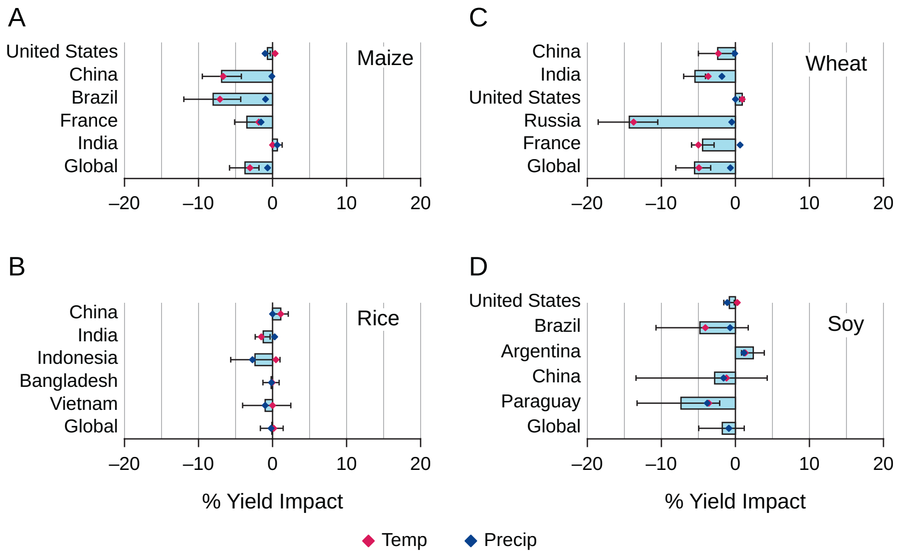

Figure 4 *Effects of changing temperature and precipitation because of global warming on crop yields for four major crops, global and by country, 1980–2008*

Notes: (i) The grey bars show the median net impact on crop yield due to the combined effect of changing temperatures and precipitation over the period 1980–2008, expressed as a percentage of the average yield for the same period. The error bars show the 5 per cent and 95 per cent confidence interval for the median estimate from a bootstrap resampling of the historical data. The red dots and blue dots denote the median decrease in yield (as a percentage of average yield) for the effect of temperature and precipitation alone. (ii) It must be emphasised that the yield impact refers only to the effect of changes in temperature and precipitation, and not to any changes in actual yields.

Source: Lobell *et al.* (2011).

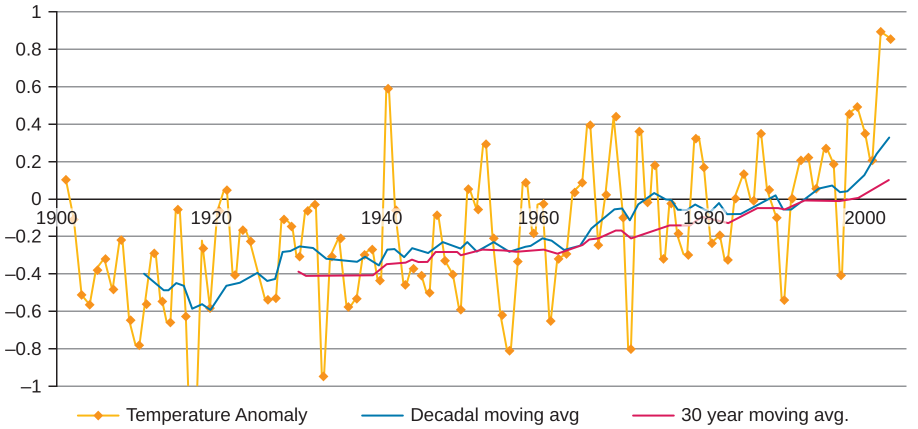

Figure 5 *Change in mean temperatures, India, 1900–2009*

Notes: (i) Temperature variations are expressed in terms of the anomaly given by the difference between the yearly mean annual temperature and the long-term average of mean annual temperature for the period 1960–99. The moving averages are also plotted in terms of a similar anomaly with respect to the same period. (ii) The rise in both decadal and 30-year moving averages indicates the increase in mean annual temperatures between 1900 to 2009.

Source: http://www.tropmet.res.in/

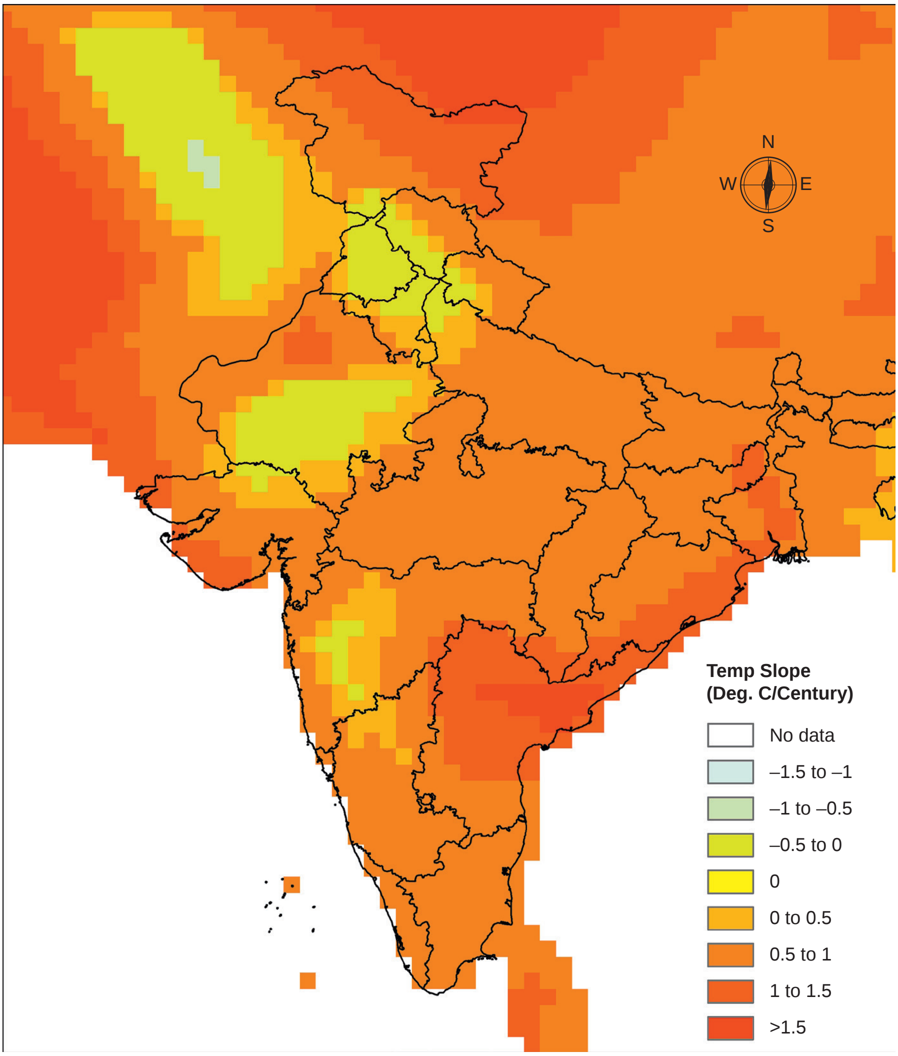

Figure 6 *Spatial variability of rates of change of mean annual temperatures, India*
Notes: (i) The rate of change in mean annual temperature is expressed in °C per century. The trends are calculated using the 0.5° (denoting spatial grid size in both latitude and longitude) monthly mean CRU (Climate Research Unit, University of East Anglia) temperature dataset, covering the period 1901 to 2012.
(ii) All trend values are at 95 per cent significance level. Trend values for locations that do not show a trend at 95 per cent significance level are set to zero.
Source: http://www.cru.uea.ac.uk/cru/data/hrg/

100 years, while the minimum temperature increased by only 0.12℃ over the same period. During 1971–2007, however, the minimum temperature rose by 0.2℃ every 10 years, faster than the maximum temperature.

Changes in temperature also varied across different regions of India. Figure 6 shows the regional variation of temperature trends.

Table 4 *Expected increase in annual mean temperatures and annual precipitation for emission scenarios corresponding to different Representative Concentration Pathways (RCPs), India, 1961–90 to 2071–2100*

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Temperature (°C)	1.5	2.4	2.8	4.3
Precipitation (%)	6	10	9	14

Note: These predictions are obtained by averaging the corresponding values taken from all the models included in the Coupled Model Intercomparison Project version 5 (CMIP5). The variations between models are fairly low in the case of temperature predictions and they also reproduce past observations with reasonable fidelity (Chaturvedi *et al.* 2012).
Source: Chaturvedi *et al.* (2012).

What will be the future trends in temperature over the Indian subcontinent? The answer to this question derives from two kinds of models. The first are global climate models, which deal with the Earth's atmosphere, oceans, and land as a whole. These models provide climate information for particular regions, but the information is coarse and may miss significant local features. The second kind of model, referred to as "dynamically downscaled models," are tailored to provide information on climate at the regional scale, using inputs from global models. These models are expected to provide finer details than the first type. Scientific research groups from all over the world have constructed both kinds of models. As we have pointed out earlier, the results from these are compared and shared in international collaboration initiatives. For global climate models, the current version of the collaboration initiative is CMIP5. For "dynamically downscaled models" which provide regional climate predictions, the current collaboration initiative is the Coordinated Regional Downscaling Experiment (CORDEX).

Temperature trends for the future are available from both CMIP5 and CORDEX. From the global climate models (Chaturvedi *et al.* 2012), the predicted rise in mean average temperature by the 2080s across the Indian subcontinent for different RCPs is as given above, in Table 4. Note that these increases are relative to the average for 1961–90.

These increases are not uniform but vary regionally. Between different scenarios (given by different RCPs), in the short term – that is, up to the 2030s – there is not much variation. But from the 2060s, the variation increases for increased RCPs. This indicates that regional variations in temperature rise increase with rising global temperatures.[7] However, the expectation that results from CORDEX would provide robust regional-scale projections of temperature rise in the future has yet to be realised in practice. Here we illustrate the problem using temperature projections for the Mahanadi river basin using two such models. In Figure 7 below, we plot the expected increase in temperatures as projected by both these models for two

[7] The choice of this region is due to convenience, based on prior work by one of the authors (Kamal Murari) on this region.

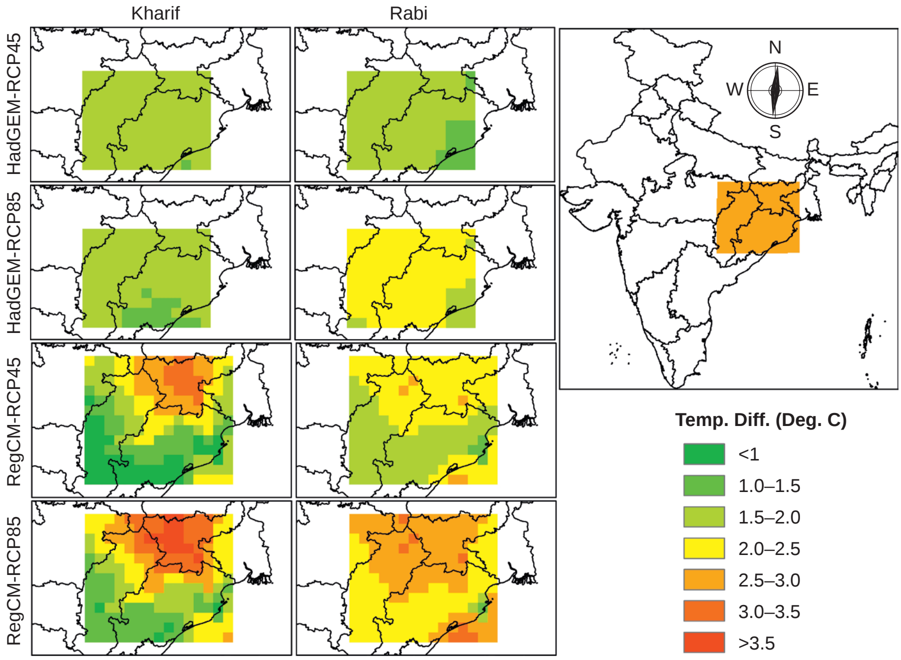

Figure 7 *Projections of increase in seasonal mean temperatures from two regional climate models for the kharif and rabi seasons, Mahanadi river basin, India, 1981–2000 to 2031–2050*
Notes: (i) The figures show the difference in the averages of seasonal mean temperature for the period 2031–50 and the period 2031–50 for two RCP emission scenarios: RCP 4.5 and RCP 8.5.
(ii) RegCM and HadGEM are the two regional climate models used here, and the results for the two RCPs for each model are distinguished by the associated RCP label.
Source: CORDEX (Coordinated Regional Climate Downscaling Experiment) data, available at https://cordex-ea.climate.go.kr/main/searchPageCdx.do

distinct RCPs. The figure shows considerable variation in the projections of regional-scale temperature increase. The high variation in the results indicates that "dynamic downscaled models" for regional-scale temperature projections are in need of considerable improvement.

There are considerable uncertainties in the results of climate science for precipitation, in terms of both the current and the future impact of climate change on the monsoon. As is well known, the monsoon is a complex phenomenon with considerable variations across space and time (from intra-seasonal variability to inter-annual variability, and stretching to variability across several decades). Since it is not possible to encompass all of this in the space of a brief review, we highlight only very few features in this paper; for a comprehensive review of some basic features of the monsoon, we refer the reader to Gadgil (2003).

Modelling secular monsoon behaviour is a challenging task even if we do not take climate change into account. All the causal factors involved in determining the characteristics of the monsoon are not fully understood, and the subject remains a field for ongoing research. There are two basic methods for modelling monsoon behaviour. One method is to work with models that predict monsoon behaviour starting from the first principles of atmospheric behaviour. This class of models, while much needed, requires much further development before they are fully usable (Gadgil and Srinivasan 2012). The second method is to use models that extrapolate past monsoon behaviour to the future. Such models, by contrast, have registered much improvement.

Has current global warming led to any major shifts in the behaviour of the monsoon? The answer to even this basic question is not entirely clear. The monsoon has a well-marked 70-year cycle, and includes periods of annual rainfall above the long-term mean as well as periods of annual rainfall below the long-term mean. Interestingly, monsoon variability is lower in the former phase. This is clear from Figure 8 below (from Gadgil and Kumar 2006). The figure shows the difference between a 31-year moving average and the long-term average for mean annual monsoon rainfall for the period 1871–2004. It also shows the difference between the standard deviation associated with the 31-year moving average and the standard deviation of the long-term average. An implication of this finding is that any analysis of shifts in monsoon behaviour due to global warming must take this cycle into consideration.

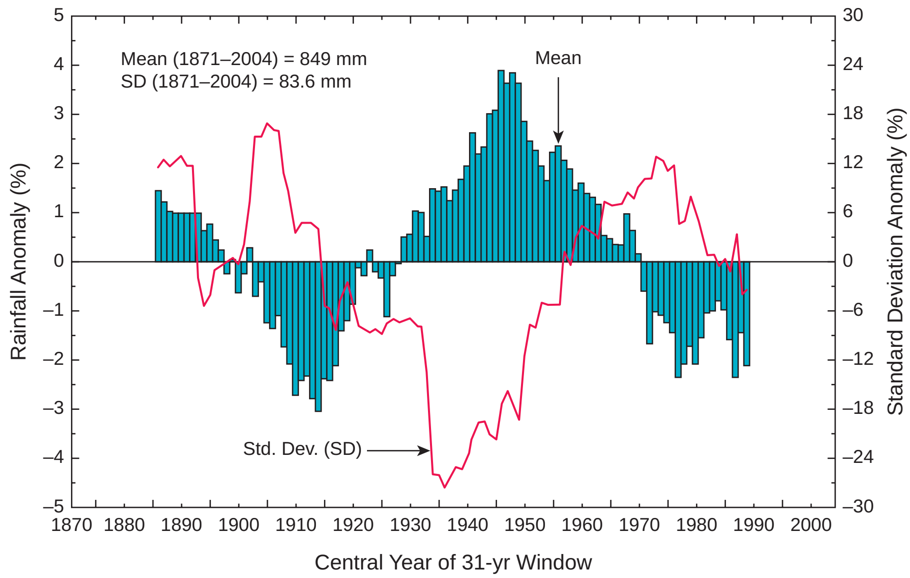

Figure 8 *Anomalies in mean and standard deviations of annual summer monsoon rainfall, India, 1870–2004*

Notes: (i) The 31-year window refers to a 31-year moving average. The anomaly refers to the difference between the 31-year moving average for the annual summer monsoon rainfall and the long-term mean for the same, for the period 1871–2004.

(ii) A similar anomaly is plotted for the standard deviation of the 31-year moving average for annual summer monsoon rainfall with respect to the standard deviation associated with rainfall for the period 1871–2004.

Source: Gadgil and Kumar (2006).

One way to test whether monsoon behaviour has changed over the long term is to compare the probability distribution of different amounts of annual rainfall from a 50- year period around 150 years ago, with a similar probability distribution for the most recent 50-year period. Such tests can be done for monsoon behaviour in particular regions as well. This is illustrated by Figure 9 below, based on IMD data for the period 1871–2012. The figure shows that the variation in all-India rainfall is not statistically significant. But the variation in rainfall pattern in the two regions – Chhattisgarh, and Konkan and Goa – is significant. The data indicate that the decrease in monsoon-time precipitation in Chattisgarh, and the increase in precipitation in the Konkan and Goa sub-divisions, are statistically significant. (The detailed statistical analysis required to obtain these results is not reported in this paper.)

Table 5 shows that among all the meteorological sub-divisions in the country, very few report any statistically significant (at 95 per cent confidence level) change in rainfall over the period 1871–2012. Of course, one needs further analysis to be sure that even the reported changes are attributable to global warming.

The review by Turner and Annamalai (2012) provides an overview of the problems of evaluating changes in monsoon behaviour because of current climate conditions as well as the uncertainties associated with predicting future monsoon behaviour. With respect to the former, they conclude that there is no unambiguous evidence that global warming has had a discernible impact on monsoon behaviour.

Global climate models do not perform very well when they are put to the test of reproducing past observations from precipitation estimates (Menon *et al.* 2013). From Figure 10 it is clear that when tested against past observations, most of the individual model predictions of average values of monsoon mean rainfall differ significantly from observed mean values. However, it can be shown that the "ensemble average" value of monsoon-time precipitation, obtained by averaging the mean values of all individual models, is closer to the observed value. But there are still significant divergences between the ensemble average and the observations that make it difficult to use the former for quantitatively definite predictions for the future (Chaturvedi *et al.* 2012).

Broad trends, however, are discernible. In general, the simulations indicate a likelihood of increased rainfall across different future scenarios of climate change. All the models also generally predict greater variability in rainfall in the future.

Murari *et al.* (2013) have suggested that it may be better to take a weighted average (referred to as a "super ensemble average") rather than a simple average (ensemble average) of the results of different climate models for rainfall predictions. In this weighted average, individual models that simulate mean values of monsoon-time precipitation closer to observed values (for past years) are given correspondingly

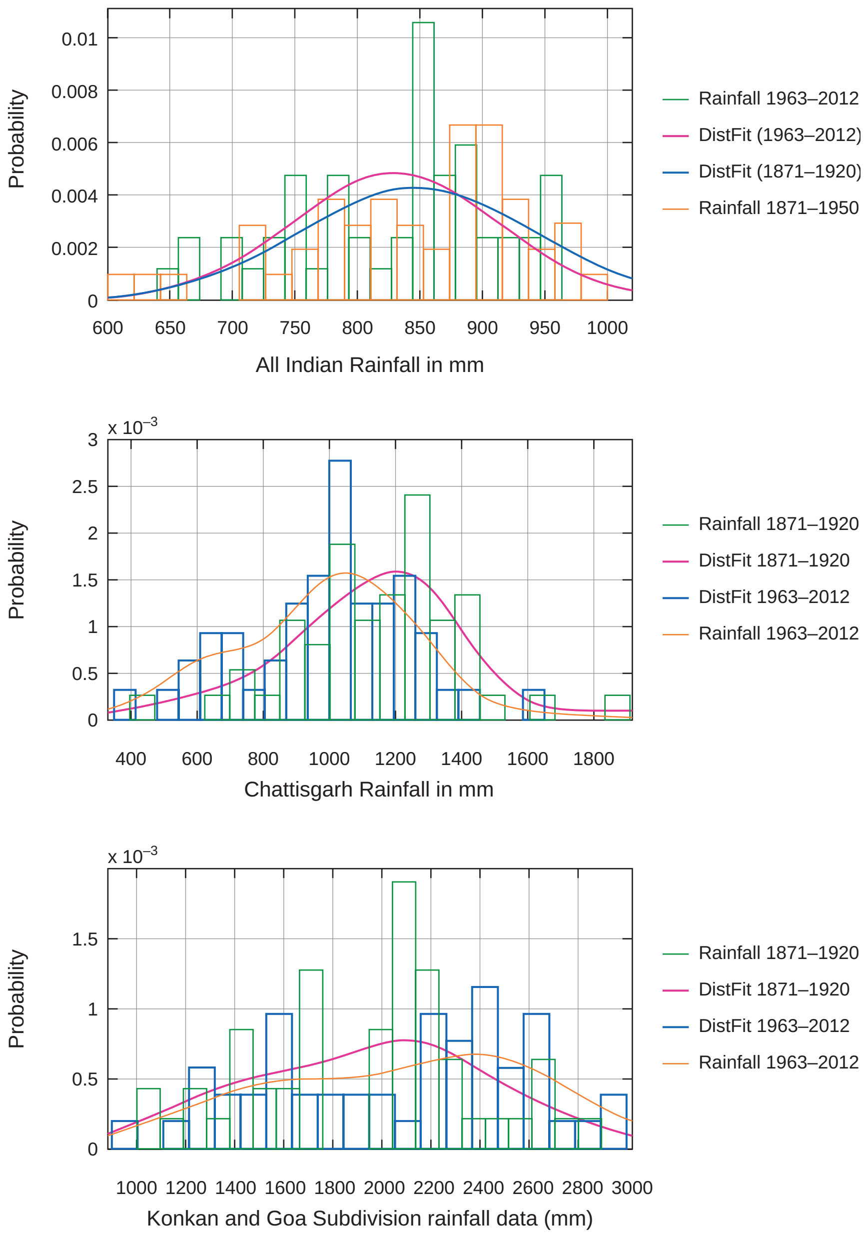

Figure 9 *Shifts in monsoon rainfall behaviour using rainfall distribution patterns for India and two Indian Meteorological Department (IMD) sub-divisions, 1871–1920 and 1963–2012*

Notes: (i) Rainfall distribution is shown for two 50-year periods: 1871–1920 and 1963–2012.
(ii) The rainfall histogram for the period 1871–1920 is marked in blue and the rainfall histogram for the period 1963–2012 in red. The blue and red lines are distribution fits of the rainfall histograms for the two periods.
(iii) All-India rainfall shows no significant shift in rainfall distribution. The rainfall distribution for Chattisgarh, and Konkan and Goa sub-divisions, show a significant shift between the two periods. Significance is inferred using the two-sided Kolmogorov–Smirnov test.
Source: IMD data, available at http://www.tropmet.res.in/static_page.php?page_id=53

Table 5 *Rate of change in total summer monsoon rainfall (June–September) for all Indian Meteorological Department (IMD) sub-divisions, 1871–2012*

Sub-divisions	Trend (mm/decade)	Statistical Significance
All-India	−1.984	Not Significant
Assam and Meghalaya	−9.446	Significant
Nagaland and Mizoram	−13.258	Significant
Sub-Himalayan West Bengal	−3.006	Not Significant
Gangetic West Bengal	5.793	Not Significant
Orissa	−1.309	Not Significant
Jharkhand	−2.254	Not Significant
Bihar	−4.471	Not Significant
Eastern Uttar Pradesh	−2.986	Not Significant
Western Uttar Pradesh Plains	−2.955	Not Significant
Haryana	2.481	Not Significant
Punjab	5.016	Not Significant
Western Rajasthan	1.015	Not Significant
Eastern Rajasthan	−3.044	Not Significant
Western Madhya Pradesh	−3.264	Not Significant
Eastern Madhya Pradesh	−9.710	Significant
Gujarat	−1.975	Not Significant
Saurashtra and Kutch	3.244	Not Significant
Konkan and Goa	14.642	Significant
Madhya Maharashtra	0.382	Not Significant
Marathwada	−2.403	Not Significant
Vidarbha	−5.127	Not Significant
Chhattisgarh	−13.916	Significant
Coastal Andhra	3.253	Not Significant
Telangana	1.560	Not Significant
Rayalseema	2.634	Not Significant
Tamil Nadu	0.146	Not Significant
Coastal Karnataka	17.804	Significant
North Karnataka	2.727	Not Significant
South Interior Karnataka	2.405	Not Significant
Kerala	−1.999	Not Significant

Note: Statistical significance is determined by the student t-test associated with the trend estimate for each sub-division.
Source: IMD data, available at http://www.tropmet.res.in/static_page.php?page_id=53

greater weight. Murari *et al.* found the weighted average method to be a better approach to represent the observed behaviour of the Indian summer monsoon, not only in reproducing the mean and variance, but also the seasonality pattern seen in the data. In Figure 12, in the graph on top, the ensemble average and the super ensemble average estimates for observed probability distribution of annual all-India summer monsoon rainfall are compared to the observations. In the graph below, the

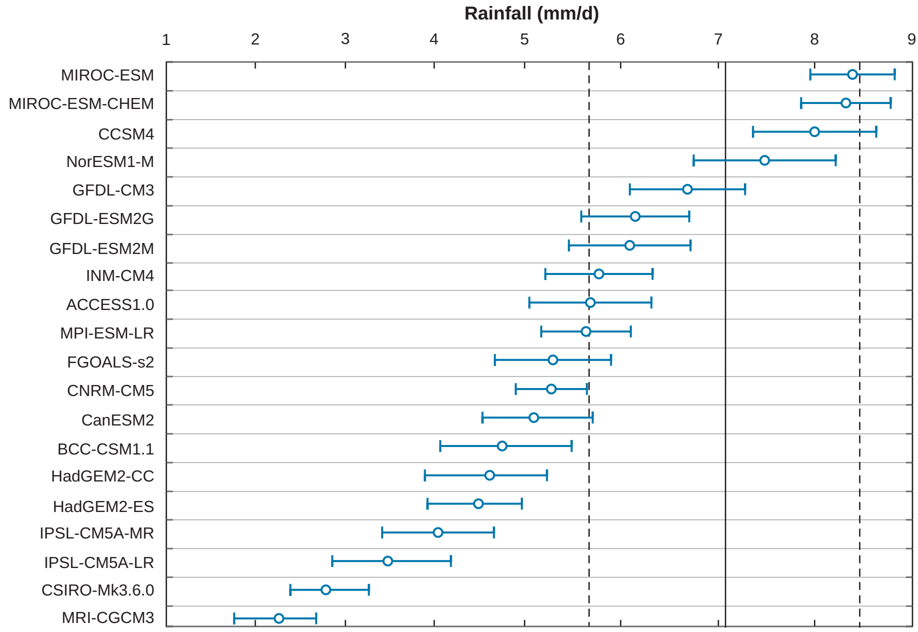

Figure 10 *Comparison of predictions of CMIP5 models with observed values for summer monsoon mean daily rainfall, India, 1871–2004*

Notes: (i) The left vertical axis shows abbreviated names of climate models used in the study. Menon *et al.* (2013) provides further details of these models. The black vertical line is the observed mean monsoon rainfall for the reference period, and the vertical dashed lines denote plus or minus two standard deviations from this mean. For each model, the circle is the calculated mean monsoon rainfall for the same period, and the error bar denotes plus or minus one standard deviation for each model.

(ii) CMIP5 = Coupled Model Inter-comparison version 5.

Source: Menon *et al.* (2013).

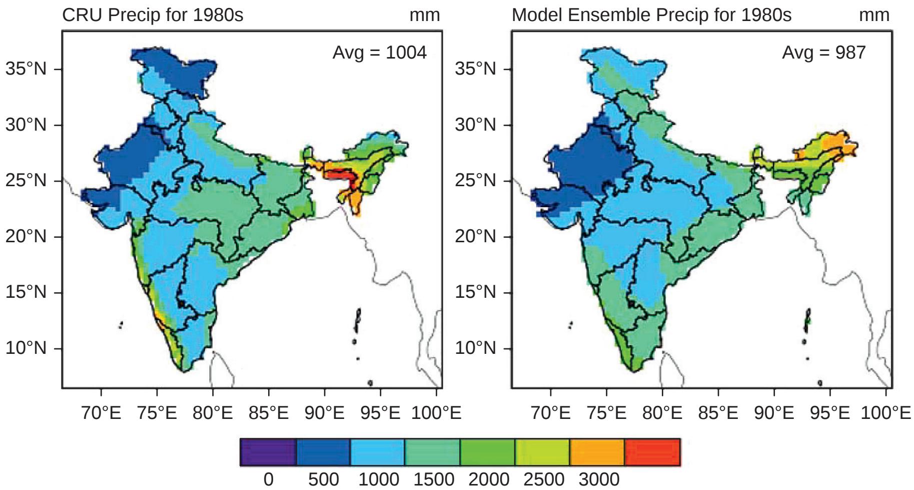

Figure 11 *Comparison of observational data with average of predictions from all CMIP5 models for mean annual precipitation, India*

Note: CMIP5 = Coupled Model Inter-comparison version 5.

Source: Chaturvedi *et al.* (2012).

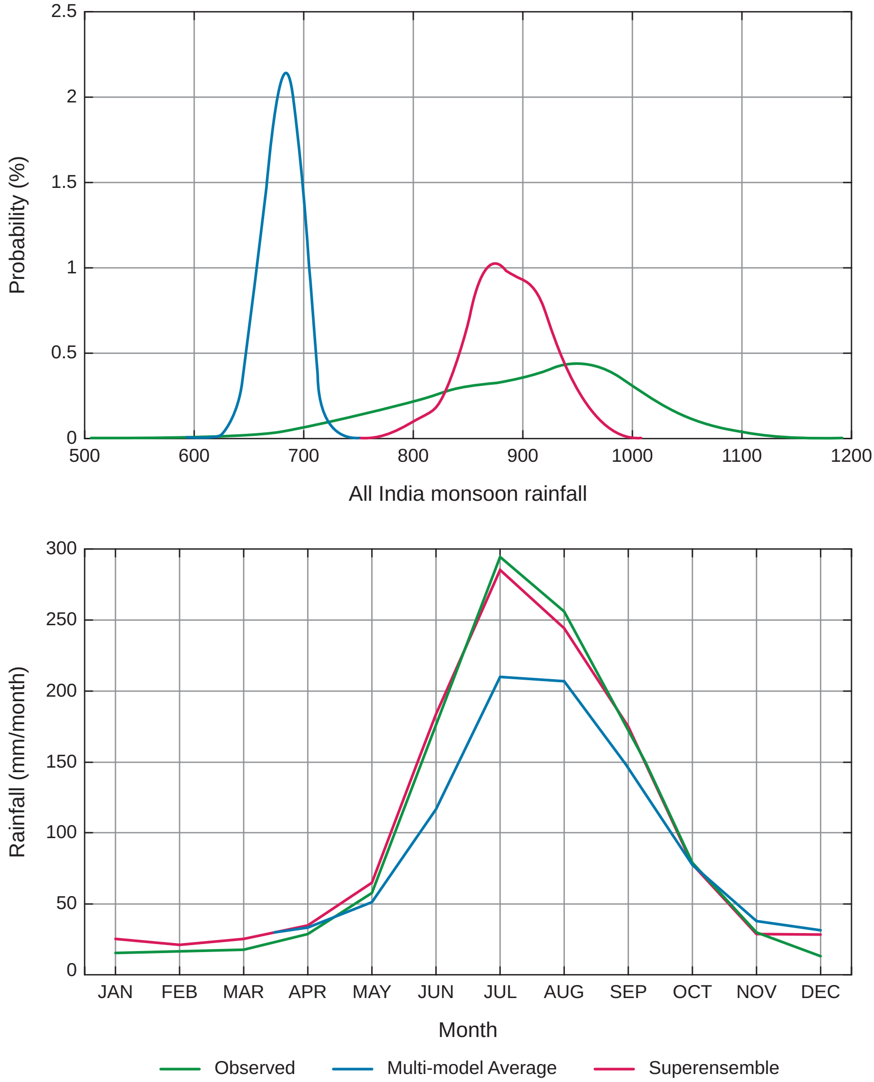

Figure 12 *Comparison of CMIP5 multi-model ensemble (normal average) and super-ensemble (weighted average) predictions with observed data for summer monsoon rainfall distribution, India*

Notes: (i) The graph on top shows the distribution of annual summer monsoon precipitation for the period 1871–2005 as observed and as predicted by the two methods. The graph below compares the predictions of the two methods for inter-seasonal distribution of rainfall (averaged over the entire period) to the observed values.

(ii) Average here refers to the average of predictions from 10 models included in CMIP5, and weighted average is defined on the basis of the predictions of the same set of 10 models, where higher weights are assigned to values from models whose predictions match past observations more closely.

(iii) The graphs indicate that the weighted average method is a better approach of combining climate model results to reduce uncertainty in projections.

(iv) CMIP5 = Coupled Model Inter-Comparison version 5.

Source: Murari *et al.* (2013).

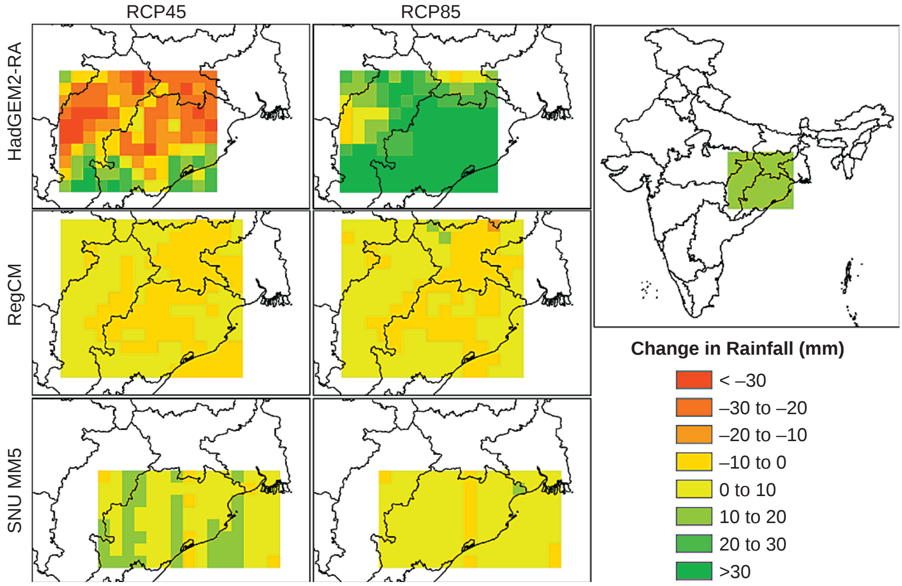

Figure 13 *Predictions of change in annual summer monsoon rainfall (June–September), Mahanadi river basin, India, 1981–2000 to 2031–50*
Notes: (i) Predictions of change in mean monsoon rainfall are shown as indicated by three regional climate models from the CORDEX (Coordinated Regional Climate Downscaling Experiment) suite of regional climate models, namely, the HadGEM, RegCM, and SNU MM5 models.
(ii) Predicted changes in mean annual summer monsoon rainfall between 1981–2000 and 2031–50 are shown for two Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5.
Source: CORDEX data, available at https://cordex-ea.climate.go.kr/main/searchPageCdx.do

ensemble and super ensemble average estimates for seasonal distribution of rainfall are compared to the observations. In both instances the super ensemble results are found to be closer to the observations.

Models that are designed for regional-level predictions are also characterised by considerable uncertainty, with widely varying results between the models. We give an example in this regard from a model that covers the Mahanadi river basin region (the model we used in our discussion of temperature predictions: see Figure 13).

What is the overall picture for India? Broad trends suggest an increase in temperatures, including in the mean temperature, and the mean day and night temperatures. With respect to the impact of global warming on the monsoon, both in the present and in the future, there is still much uncertainty. Table 5 shows that there are only six regions in India that exhibited statistically significant (at 95 per cent significance level) changes in rainfall over the last 140 years, four of them showing a decreasing trend and two of them an increasing trend.

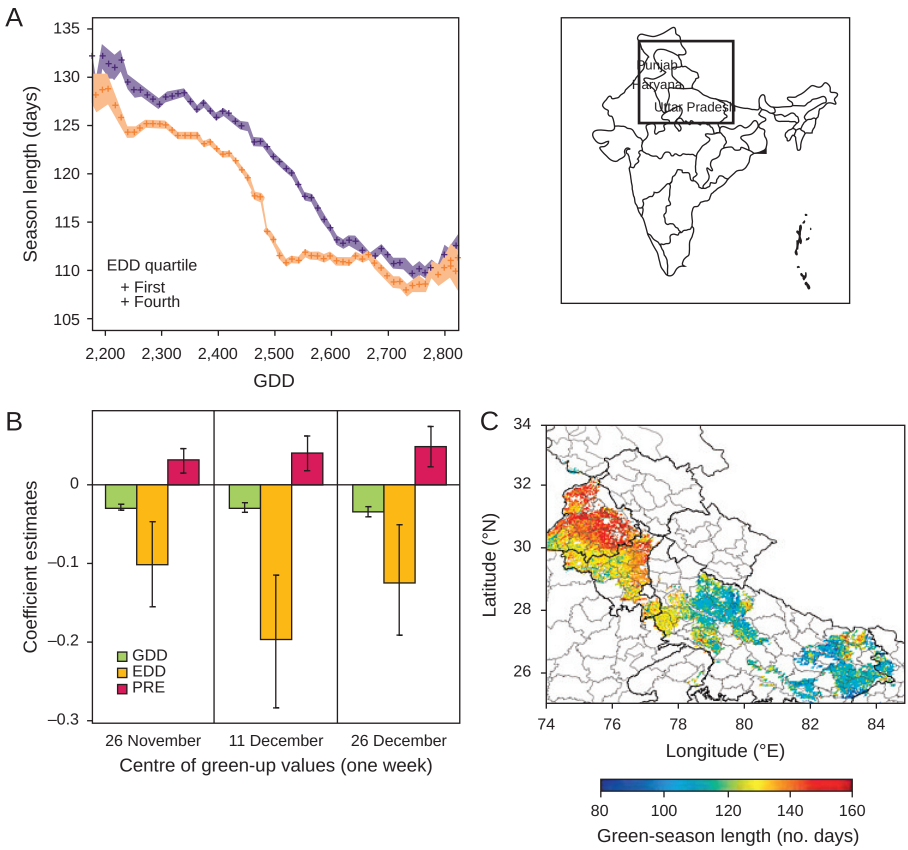

Figure 14 *Dependence of growing season length on number of growing degree days (GDD)*[8] *and extreme degree days (EDD)*[9] *for rabi wheat in Northern India*

Notes: Plot (a) shows growing season length at different locations with respect to the number of GDD and number of EDD for that location, with the start of the growing season lying in a 14-day window centred around 11 December. Only the locations with the number of EDD lying in the first (red) and fourth (blue) quartile of the distribution of EDD are included for each value of GDD. The red and blue shading indicate the two standard deviations range of the quartile estimation. Plot (b) shows the estimated coefficients of regression[10] of GDD, EDD, and growing season precipitation for three different choices of the start of the growing season, lying, respectively, in 14-day-intervals, centred around 26 November, 11 December and 26 December. Error bars indicate the 95 per cent confidence interval of the estimated regression coefficient. Plot (c) shows the growing season length of the selected regions, where the white regions are those with less than 40 per cent of area under wheat production. The wheat-growing regions of Punjab, Haryana, and Uttar Pradesh included in the study are as indicated in the map.

[8] GDD is given by the total exposure to different temperatures. This is determined by multiplying the value of the excess temperature (above a base temperature) times the number of days of exposure to this value of temperature, summed over the entire growing period.

[9] EDD is a measure similar to GDD but only measures the exposure to temperatures above the critical threshold of 34˚C.

[10] The coefficient of regression is obtained by taking the length of growing season as an independent variable, and GDD, EDD, and growing season precipitation as dependent variables. Plot (b) in the figure shows the regression coefficient of independent variables.

Sensitivity of Indian Agriculture to Temperature and Rainfall

The sensitivity of Indian agriculture to rainfall is both well known and well established (see, for instance, Gadgil and Kumar 2006, particularly the conclusions with regard to the dependence of paddy cultivation on the quantum of monsoon rainfall in India). With respect to the sensitivity of Indian agricultural production to temperature variability, a subject that so far had not been well studied, there are some new and interesting observations.

Lobell *et al.* (2012) have analysed the impact of temperature variability on wheat production in India, using data from the States of Punjab, Haryana, and Uttar Pradesh over the period 2000–09. They show that the number of days that the crop is exposed to temperatures higher than 34°C has a significant effect on the length of the growing season of the crop (see Figure 14). In particular, the number of days the crop is exposed to temperatures above the critical temperature (expressed in units of extreme degree days – EDD – above this temperature) is as significant as the number of days of its growth at temperatures lower than the critical temperature (expressed in units of growing degree days – GDD – below this temperature). EDD thus appears to be an independent variable. Since the length of the growing season is a determining factor in wheat productivity, it is evident that wheat yields are significantly dependent on climate variability. This result is of course in line with the expectations from agriculture science, which we had noted in the previous section.

The work of Lobell *et al.* (2012) is heavily dependent on analysis and interpretation of remote sensing data, using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data for measuring the Normalised Vegetation Difference Index (NDVI)[11] which is used as the basis for the analysis. It would be useful and necessary to confirm their results by other means.

Along with temperature variability, variability of precipitation is also a factor in this regard. The rough correlation between variations in total annual monsoon rainfall and variations in kharif food-grain production has already been reviewed in Jayaraman (2011). In the rest of this sub-section, we consider the variability of precipitation across different regions and at different scales. A more detailed analysis to establish the correlation, if any, between these fluctuations in regional precipitation and corresponding fluctuations in regional agricultural production awaits detailed study, and is not currently available in the literature.

[11] The NDVI measurement gives a number (an index) that measures the difference in the reflection from ground features such as vegetation, rock, etc., in the red and infra-red parts of the electromagnetic spectrum. The NDVI differs significantly between vegetation and other features. In this way, NDVI provides a measure of the extent of greenness due to vegetation on the ground. To distinguish crops in particular, further evidence such as land-use data, etc., is required. In this paper, regions known to have less than 40 per cent area under wheat are excluded.

Under conditions of climate change, it is expected that periods of extreme rainfall will be more frequent. Even if total rainfall were to remain the same, there could still be significant changes in the frequency and intensity of precipitation. In an analysis of IMD data, Goswami *et al.* (2006) point out that the number of rainfall events per year with precipitation greater than 100 mm had shown an increasing trend over the Central India region between 1950 and 2000. In the same period, the number of moderate rainfall events per year had shown a decreasing trend. Such behaviour can be expected to extend and become more significant in the future. Extreme rainfall events or more frequent intense rainfall events could lead to negative effects such as greater water run-off from the fields and increased soil erosion. Dramatic extreme rainfall events, such as the Mumbai floods of 2005 or the Uttarakhand disaster of 2013, could have even more damaging effects.

Precipitation variability can also take the form of a significant decline in rainfall in specific years. As has already been noted, the Indian monsoon's annual variability over the long term (150 years) is of the order of 10 per cent, which is equivalent roughly to one standard deviation of the long-term mean annual rainfall. This implies that roughly once in three years, total monsoon rainfall is 10 per cent or more below the mean. The frequency of deficient rainfall is predicted to rise in periods of the monsoon cycle when rainfall is consistently below the long-term mean, and to fall in periods when rainfall is above the mean (Gadgil and Kumar 2006).

The regional variability of rainfall is also noteworthy. Regions that receive relatively low rainfall display greater year-to-year variability. The coefficient of variation for each meteorological sub-division is roughly inversely proportional to the mean annual rainfall in the sub-division (Figure 15). The value of R^2 reported in the figure below is statistically significant at a 95 per cent confidence level. If the three outliers of very high annual rainfall are excluded, the value of R^2 rises to approximately 0.5.

Figure 16 shows the regional variations in mean annual rainfall across India, as well as the frequency of occurrence of deficient annual rainfall for deficiency of the order of 20 per cent or more. This may be termed the return period for 20 per cent deficient rainfall, or, in other words, the number of years in which such deficient rainfall will occur at least once. Interestingly, the figure shows that regions of low annual rainfall (below 600 mm) are more likely to have a 20 per cent deficient rainfall year than regions of high annual rainfall. The coefficient of variation of annual rainfall is significantly higher in areas of low rainfall than in areas of high rainfall.

Table 6 shows the return periods and deviations from regional means for each of two levels of administration. At the top is Marathwada sub-division in Maharashtra, disaggregated into its constituent districts; below is Osmanabad district disaggregated into its constituent taluks. The data show that mean rainfall varies significantly in both cases.

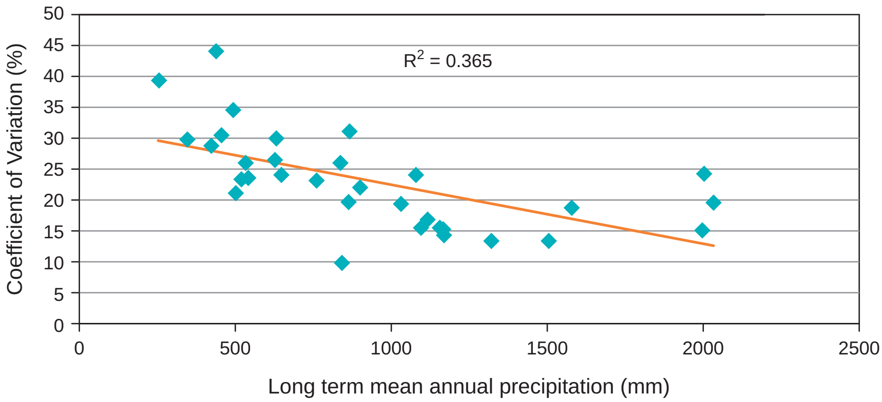

Figure 15 *Relationship between inter-annual variability and long-term mean of annual summer monsoon rainfall for all India Meteorological Department (IMD) sub-divisions*
Note: The analysis is carried out for data covering the period 1871–2012. The graph shows that sub-divisions with lower means have higher variability. The coefficent of variation here refers to the ratio of the standard deviation to the mean for the long-term data, and is calculated independently for each IMD sub-division.
Source: IMD data, available at http://tropmet.res.in

At present, there are no conclusive analyses that bring together analyses of temperature and precipitation variability, and relate them to fluctuations in agricultural production. This is clearly an important area for future research. Lobell *et al.* (2011) presents some preliminary results in this regard.

Before we conclude this section, we briefly summarise the main points that have been made here. There is clear evidence of rising temperatures across India. Mean annual temperatures over the period 1850–2010 have risen between 0.6°C and 0.8°C. Warming has been faster in the most recent decades. Regional trends indicate that mean annual temperature increase could be higher than even 1°C for some areas, like parts of the eastern coast and western Rajasthan (Figure 6). Global climate models provide reasonably good predictions at the all-India level. In the case of more extreme scenarios of global warming, temperatures could rise by as much as 4°C by the end of this century, as compared to the average temperature in the 1961–90 period. However, regional-level predictions of temperature increase due to global warming are still subject to many uncertainties, which are reflected in wide variations between the predictions of different models.

The determination of current trends in precipitation itself is still subject to many uncertainties. This is primarily because the climatic factors that determine the major characteristics of the Indian monsoon are still not well understood. There is unambiguous evidence of changes in rainfall over the period 1871–2012 only in very few regions in the country. However, a striking feature of both monsoon and annual precipitation in India is its variability at all spatial scales. Climate models still cannot reproduce monsoon precipitation with any degree of skill, even in terms of predicting mean annual precipitation. The simulation of precipitation variability is even more

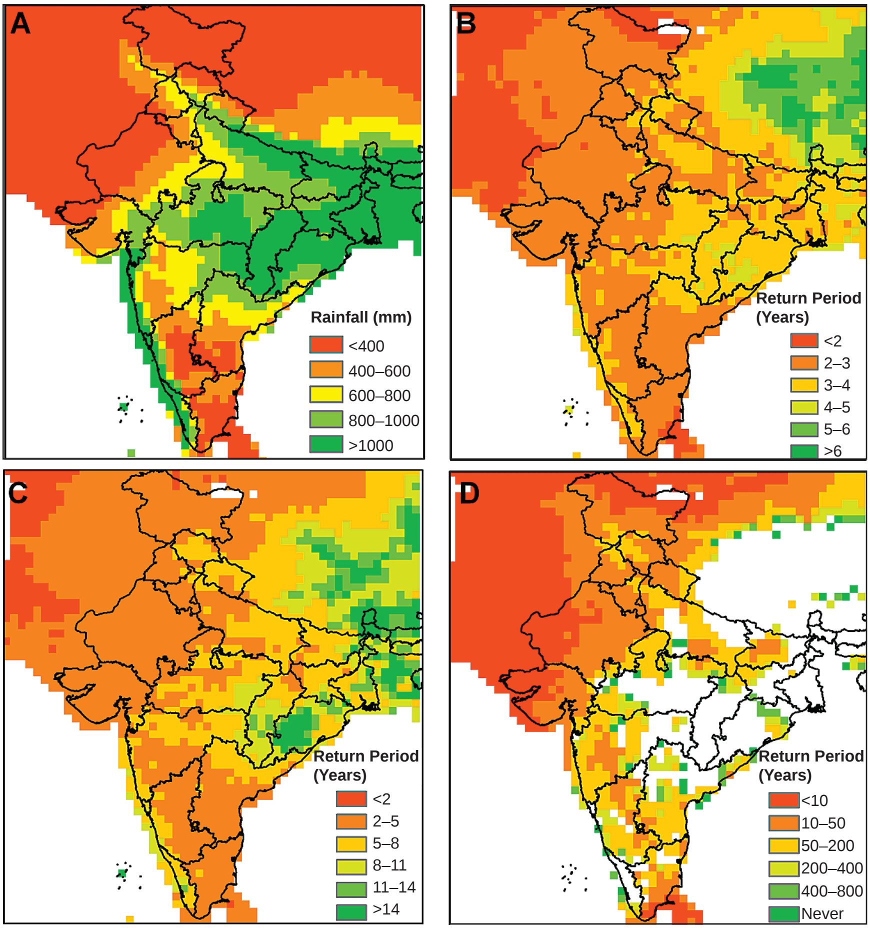

Figure 16 *Regional variations in mean annual summer monsoon rainfall and the return period of departure from their long-term mean*

Note: We have used CRU (Climatic Research Unit) monthly precipitation data covering the period 1901–2012 to estimate mean and return period values for each grid in the dataset. Return period value refers to the number of years in which the associated deficiency (or increase) in the quantum of rainfall occurs at least once during this period. Plot (A) shows the regional variation of the long-term mean, while plot (B), plot (C), and plot (D) show the regional variations of the return period for 10 per cent, 20 per cent, and 50 per cent departure from their respective long-term mean at that spatial location.

Source: CRU data, available at http://www.cru.uea.ac.uk/cru/data/hrg/

unclear from climate models. Understanding the regional variation of precipitation is important, particularly in light of the fact that historical data show that regions with low mean rainfall have high inter-annual variability as compared to regions with high mean rainfall. Regional climate models for India that can reproduce all these features are still in a very nascent state.

Indian agriculture is particularly sensitive to climate variability. Studies suggest a strong dependence of fluctuations in paddy production on fluctuations in summer

Table 6 *Spatial variability of mean annual summer monsoon (June–September) rainfall and spatial variation of inter-annual variability for Marathwada sub-division of the India Meteorological Department*

District	District mean (mm)	Difference between district mean and sub-division mean (mm)	RP 10 (year)	RP 20 (year)	RP 50 (year)
Aurangabad	596.83	−94.17	2.23	4.29	Never
Beed	650.61	−40.39	2.40	4.21	118.25
Latur	742.65	51.65	2.32	4.92	96.68
Nanded	870.39	179.39	2.29	4.89	Never
Osmanabad	660.42	−60.06	2.24	5.37	71.46
Parbhani	767.01	76.01	2.08	6.83	Never
Hingoli	824.01	133.01	2.74	3.83	Never
Jalna	679.55	−11.45	2.16	5.23	Never
Taluks of Osmanabad district	**Taluk mean (mm)**	**Difference between district mean and taluk mean (mm)**	**RP 10 (year)**	**RP 20 (year)**	**RP 50 (year)**
Osmanabad	729.9	38.90	1.96	2.81	593.40
Tuljapur	723.72	32.72	2.55	3.31	Never
Paranda	528.24	−162.76	2.13	4.06	Never
Bhum	674.02	−16.98	3.23	3.59	Never
Kalamb	718.35	27.35	2.23	3.14	Never
Umarga	640.94	−50.06	2.14	5.60	256.49
Lohara	589.86	−101.14	2.38	8.97	Never
Vashi	678.36	−12.64	3.17	3.71	Never

Note: RP refers to the return period in years, and the number alongside refers to the extent of deficiency in rainfall, expressed as a percentage departure from the mean, for which the return period is given.
Source: District-wise data are obtained from http://www.nicra-icar.in, available for the period 1971–2004, and taluk-wise data are obtained from Maharashtra State Agriculture Department (www.mahaagri.gov.in) data, available from 1998–2012.

monsoon rainfall. An interesting study of wheat production (Lobell *et al.* 2012) concluded that wheat yields in India are sensitive to the number of days of exposure to extreme temperatures (above 34°C). Moreover, the study also suggests that exposure to extreme temperature could have a greater impact on yield (through decrease in the growing season length, expressed in terms of growing degree days and extreme degree days) than precipitation in the growing season. This suggests that with future climate change, rabi wheat production would be particularly sensitive to increasing temperatures.

The Economic Impact of Climate Change

What are the economic implications of present and future climate change for agricultural production in India, in terms of the well-being of those whose livelihoods and incomes are dependent on agriculture?

Climate Variability as an Indicator of Future Climate Change

Currently, agricultural production in India is not directly affected by climate change, as the secular trend of the past several decades continues in both production and yield. This is partly because production levels began from a low base and there is much scope for increase before any kind of limit to growth is approached. Globally, too, there are many regions where, although current yields are close to potential yield with respect to different crops, there is little or no evidence of agricultural production being seriously compromised or reduced as a consequence of climate change.

Climate scientists are making an effort to analyse the extent to which specific extreme climate events or climate variability can be attributed to climate change. However, the shifts and changes in the pattern of agricultural production that can definitively be attributed to climate change remain few in number. Some of these are referred to in Jayaraman (2011).

Gadgil and Kumar (2006) have studied fluctuations in total seasonal rainfall and the onset dates of the monsoon, and their relationship to fluctuations in rice production. They report a strong correlation between these variables.[12] Similar studies for other crops and regions are still to be undertaken.

The importance of further study of climate variability for predicting the future effects of climate change has been emphasised by Iizumi *et al.* (2013). A study of groundnut production in Gujarat, where crop models were tested by their ability to predict past production, showed that the crop model predictions were most affected by errors in

[12] However, their discussion of the fluctuations in GDP of the agricultural sector and climate variability appears uncertain and inconclusive.

the data on inter-annual variability of temperature and precipitation, and errors in crop yield data.

Who is Affected by the Sensitivity of Agriculture to Climate?

Jayaraman (2011) has reviewed the different mathematical techniques and models that have been used to measure the impact of environmental stresses and shocks on aggregate agricultural production, and the consequent impact on commodity supplies and prices. His critique of such models remains broadly valid; the main change is that the techniques used in the earlier models are being extended to more countries and crops.

We are concerned that with the data, resources, and expertise that are being brought into large-scale research collaborations in this area, the methodologies that are being used will begin to dominate the field in a one-sided way. In particular, we are concerned that impact studies of environmental stress and shock on agricultural production do not take sufficient account of differential impact on different classes of producers.

A succinct criticism of contemporary mainstream models has been made by the report of the High Level Panel of Experts (HLPE) on Food Security and Climate Change of the Food and Agriculture Organisation (FAO): "None of these global scenario efforts attempts to address distributional issues within countries and the possibility that climate change affects the vulnerable disproportionately" (HLPE 2012, p. 47).[13] The report also notes, in relation to food security and the World Trade Organisation (WTO), that governments need to build a transparent, rules-based, and accountable multilateral trading system. More specifically, it states that

> these rules need to give a larger place to public policy concerns regarding food security, better account for the heterogeneity of World Trade Organisation (WTO) member states and take into account the special needs of poor and vulnerable countries or social groups. (*Ibid.*)

It is generally acknowledged that globally, the poor and sections of the population that are most vulnerable to climate change are categories with a substantial overlap. As a consequence, when agricultural production and food supply are affected by environmental shocks, they are the most likely to suffer the consequences. Overall social and economic development that guarantees an adequate supply of food, nutrition and health, education, and access to basic amenities to the broad masses of the population constitutes the first line of defence against climate change.

In a pioneering econometric study, Guiteras (2009) attempted to quantify the impact of future climate change on yields (in terms of value of output per hectare) under

[13] For a brief review of this report and other reports of the HLPE, see Sridhar (2012) and Sridhar (2013).

various scenarios, by regressing observed yields against current temperature and precipitation trends (taking careful account of variability in both), and then utilising these results for future predictions. A limited number of economic variables were also included in the analysis to ensure that the relationship between yields, and temperature and precipitation, was accurately estimated. This study predicts that climate change will affect Indian agriculture significantly, and that the reduction in yield in the long term (that is, by 2070–99) would be of the order of 20 to 30 per cent and in the medium term (that is, by 2040), of the order of 10 per cent. It is possible, Guiteras suggests, to estimate the distributional outcomes of such reductions in the value of agricultural output using various methods, including those based on the social accounting matrix (SAM). This study, and a few other similar studies of agriculture in the United States and Europe, have not received adequate appreciation in the literature; nevertheless, it appears to be a fruitful methodology and worth exploring further.

The HLPE of the FAO has pointed out both the crucial role played by small farmers in food production and food security, and their particular responsibility in adaptation. At the same time, the Panel recognises that we perhaps know too little yet about variations in agricultural production and livestock-rearing methods across different scales of production and economic activity.

> We know too little about how crops and livestock (are) grown and management practices change with scale to identify global patterns consistently, but it is commonly assumed that small-scale farms are more likely to engage in diversified crop and livestock agriculture, which might be more resilient to climate change. On the other hand, small-scale operations are less likely to have access to extension services, markets for new inputs and seeds, and loans to finance operations. Gaining a better understanding of the differences in farm activities, and vulnerabilities to climate change is critical, both to finding ways to improve food security and to deal with the challenges which climate change poses to agricultural productivity and stability (HLPE 2012).

What is clear is that when households are classified by some criterion of *economic size* – that is, by size-class of landholding, or size-class of assetholding, or size-class of annual total (or crop) income earned, or by other methods of socio-economic classification – the overwhelming reality is of very sharp economic *inequality*.

It is also clear that small farmers – that is, farmers at the lower end of the scale with regard to household holdings of land, other assets, and incomes – as well as poor and middle peasants are the most vulnerable to different kinds of environmental and economic shocks, and to fluctuations in livelihoods and incomes. They are worse off in respect of crop output (in value and physical terms), the scientific equalisation of inputs, other aspects of technology, and land-tenure arrangements.

Table 7 shows the drastic divergence of the mean of income from crop production between the worst-off 20 households and the best-off 20 households in eight selected

Table 7 *Average annual net income from crop production per acre from operational holding of poorest 20 households and richest 20 households in eight PARI survey villages, surveyed between 2006 and 2010*

State	District	Village	Bottom 20 households	Mean	Top 20 households
Andhra Pradesh	Anantapur	Bukkacherla*	−5027	1049	6648
	Karimnagar	Kothapalle*	−1801	3091	8015
Uttar Pradesh	Bijnor	Harevli	−4965	6343	16350
	Ballia	Mahatwar	−3016	2665	9017
Maharashtra	Buldhana	Warwat Khanderao	−782	6301	15893
	Kolhapur	Nimshirgaon*	−72	10598	26253
Rajasthan	Sri Ganganagar	25F Gulabewala	3553	7737	12024
Madhya Pradesh	Gwalior	Gharsondi	−5172	5338	20081

Notes: Incomes are estimated at 2008–09 prices using state-level CPIAL (Consumer Price Index for Agricultural Labour). * Bottom and top 20 households of the villages marked with an asterisk are averages of sample households.
Source: PARI (Project on Agrarian Relations in India) survey data, as reported in Ramachandran (2011).

Table 8 *Average income from crop production of households operating land by decile of agricultural income, pooled data from PARI survey villages, at 2008–09 prices*

Decile of household ranked by income from crop production	All villages
1	−19161
2	−2397
3	859
4	3296
5	6419
6	11788
7	19427
8	33338
9	60661
10	323049
D10/D9	5.32

Note: This table is based on data from nine survey villages: three in Andhra Pradesh, Ananthavaram, Bukkacherla, and Kothapalle; two in Uttar Pradesh, Harevli and Mahatwar; two villages in Maharashtra, Warwat Khanderao and Nimshirgaon; one village in Rajasthan, 25F Gulabewala; and one village in Madhya Pradesh, Gharsondi. For the purpose of comparison, incomes of all households were converted to 2008–09 prices using state-level CPIAL (Consumer Price Index for Agricultural Labour).
Source: PARI (Project on Agrarian Relations in India) survey data, as reported in Ramachandran (2011).

villages surveyed as part of the Project on Agrarian Relations in India (PARI). As can be seen, the earnings of the top 20 households are a multiple of the mean, while the earnings of the bottom 20 households are a fraction of the mean. In seven out of eight cases, the figure is *negative* for the bottom 20 households; that is to say, on average, they ran at a loss from crop production in the survey year.

Table 8, which pools data from the same eight villages, further illustrates inequalities of income.

The households in the lowest deciles or among the bottom 20 households need not, of course, refer solely to small holders. Households may belong to these categories because of the instability of agricultural production under current conditions, particularly the higher exposure to risk in some crops and the instability of dryland agriculture in some villages. Table 9, based on pooled data from the same villages reported in Tables 7 and 8, reports on median net incomes per acre among different socio-economic classes.

The inability of small farmer households to keep production costs down, to use inputs efficiently, and to obtain a higher income per unit of production is a reflection of the socio-economic inequalities of rural society, particularly inequalities in the ownership of land and other productive assets, the payment of rents for land and machinery that small farmers have to make, the higher costs at which they gain access to inputs, and their lack of access to markets. The conditions of labour and

Table 9 *Median net income from crop production per acre of operational holding by class, pooled data from PARI survey villages, at 2005–06 prices*

State	District	Village	Landlord	Peasant 1 (Rich)	Peasant 2 (Middle)	Peasant 3 (Poor)	Hired manual worker
Andhra Pradesh	Guntur	Ananthavaram	7534	15022	3238	485	993
	Anantapur	Bukkacherla	−274	1134	894	207	2159
	Karimnagar	Kothapalle	4839	2210	3188	3523	2039
Uttar Pradesh	Bijnor	Harevli	6636	8627	6640	2134	1634
	Ballia	Mahatwar	3458	6957	2656	952	1745
Maharashtra	Buldhana	Warwat Khanderao	9576	7594	5515	5660	1358
	Kolhapur	Nimshirgaon	16231	13001	9449	5888	−58
Rajasthan	Sri Ganganagar	25F Gulabewala	7077	6004	5890	nil	nil
	Sikar	Rewasi	3304	3299	469	517	−572
Madhya Pradesh	Gwalior	Gharsondi	7031	5634	3924	3035	1258

Note: PARI = Project on Agrarian Relations in India.
Source: Rawal (2014).

livelihood for manual workers, and small and medium farmers also translate into serious human development deficits for a significant proportion of rural households.

Similar results, which speak to the issue of scale raised by HLPE (2012), are reported from another study commissioned by the Planning Commission, Government of India, on agriculture in eastern India (Haque *et al.* 2010). This study uses a sample drawn from several districts across the States of Uttar Pradesh, Bihar, Jharkhand, Odisha, and West Bengal. It shows that crop yields from ownership holdings of marginal and small farmers are significantly lower than corresponding yields from operational holdings of large farmers. The study also reports lower input–output ratios as well as income–input ratios on marginal and small landholdings, than on large holdings.

The considerable differentials in output and incomes suggest that small and marginal farmers are more susceptible to climate variability and climate change than are others. Climate change is effectively an immediate threat to small and marginal farmers, though this is not to forget that their susceptibility to environmental stresses and shocks is a consequence of socio-economic conditions rather than any form of "environmental poverty."

With reference to the impact of climate change on agriculture, the Central Research Institute for Dryland Agriculture (CRIDA) has produced a number of publications[14] dealing with drought, drought management, and various strategies and coping plans for drought and its impact on different sub-sectors. These publications are undoubtedly of scientific value from the point of view of agricultural science. But they make little or no reference to issues of scale, and the potential and actual implementation of their recommendations by farmers of different socio-economic categories.

Climate Variability, Climate Change, and Disasters

As in the case of climate variability, natural disasters also offer a window on some of the more dramatic potential consequences of climate change. While climate variability or climate extremes may be thought of as hazards or threats, the term natural disaster implies something more. It typically refers to a moment when the normal processes of coping with natural hazards are overwhelmed. These normal processes then prove dramatically insufficient in the face of the scale of the particular event. Typically, the nature of human activity itself can amplify the impact of a natural hazard on social and individual well-being (or indeed even provoke the event on some occasions).

[14] Some of these publications can be accessed on the web at www.crida.in

Natural disasters continue to be an ever-present feature of life in rural India. While the threat of famine is a thing of the past, the rural population continues to suffer the impact of drought, floods, cyclones, and other such natural hazards. Low levels of development expose the rural population, particularly the poor among them, to hazards on a daily and continuing basis. Women and children disproportionately suffer the burden of an enormous range of such daily hazards: for example, we know even from the daily press of the young who lose their lives as they make their way by country boats to school; of the toll on women's lives from the smoke of the traditional stove; and of floods that occur due to causes such as the release of water from an overflowing dam into downstream channels that are not adequate to receive such sudden flows.

Poverty can drive rural households to livelihoods that place them in the path of such natural disasters. Poor farmers cultivating on river beds or in low-lying areas close to flood channels are susceptible to sudden flooding. People of the villages in Uttarakhand who work in the tourist and pilgrimage industry, for instance, are very exposed to the threat of disaster and death from sudden flooding. Unregulated, unmonitored construction projects continue to expose large sections of the population to natural hazards in different parts of the country, both rural and urban.

Climate change is expected to increase the occurrence of natural disasters such as very heavy rainfall events, increased river flows and intensified floods, and intensified and perhaps more frequent cyclones. Other such possible phenomena include the bursting of the banks of natural lakes created by landslides in the path of melting glaciers, or even a general increased tendency to flooding in low-lying areas. In many ways, implementing disaster risk reduction through reducing the occurrence of natural disasters, mitigating their consequences when they do occur, and designing appropriate means to ensure recovery are the first line of defence against the challenge of climate change. An authoritative and fairly exhaustive survey of the relationship between disasters and climate change is provided in the IPCC's Special Report on Extreme Events (IPCC 2012).

With regard to new directions for study, the report of the FAO's High Level Panel of Experts on Food Security and Climate Change acknowledges that far more work is required to understand the impact of climate change on conditions of production in agriculture. There is little information currently available on the differential impact of climate, climate variability, and climate change across different scales of production and differing socio-economic strata of producers. A beginning could be made by studies that follow the impact of disasters on agricultural production, that assess the loss and damage to agricultural production, and continue to study production and producers right through the process of recovery. Such studies must also take into account the differential impact of disasters as well as the differential process of recovery across different strata of rural households. Panel data on rural populations, with a special focus on the relation between climatic variables, crop production, and the incomes of different socio-economic strata of farmers, would also provide valuable information.

In this paper, we have sought to underline the importance of understanding the climatic conditions of agricultural production in the present and its economic consequences. This is especially necessary in view of the large section of India's rural population that is dependent on agriculture for livelihoods and incomes. By any yardstick of reckoning, the very fact of the size of the population that depends on agriculture makes the issue of their vulnerability to climate variability and climate change a subject of relevance and importance in its own right.

We need to understand the relative importance of secular temperature and precipitation trends, and their relation to fluctuations in crop production, disaggregated by crops and agro-ecological zones. Studies are needed on the extent to which irrigation mitigates such fluctuations. Such relationships do not necessarily reflect environmental conditions alone. They may also reflect to some extent crop choices made by farmers, based on their judgement of potential precipitation (Gadgil and Kumar 2006) and potential returns.

A significant issue that we have not elaborated upon in this paper is the course of action that is required by way of climate adaptation in the agricultural sector. Despite the omission, some broad features of what is required follow from our discussion in the previous sections. Development of India's agricultural sector, and especially ensuring the stability and productivity of the bulk of its manual worker households, and marginal, small, and medium farmer households, appears to be the first necessary condition for agricultural production that will be resilient to climate change. In stating this, one of course must note that current state policy has been particularly problematic for these same sections of the rural population (Ramachandran 2011). Given the current state of affairs, climate change and its accompanying effects will constitute a further onerous challenge for these sections of rural India.

We have also discussed the considerable uncertainties regarding the future impact of climate change. An important consequence of such uncertainties is that climate adaptation cannot be a one-shot strategy that purports to determine how we move from the current situation to a predetermined final state of affairs. Clearly, climate adaptation has to evolve, and decision-making would require constant monitoring and re-alignment as the future unfolds.

However, the uncertainties do not in any way take away from the need to learn to deal with climate variability. While such learning is essential for the rural population in the present, it will also be valuable when more serious impacts of ongoing global warming are likely to present themselves. This argument also does not imply that the issue of climate change and agriculture lacks urgency. If anything, it makes the issue of overall rural development even more urgent. Given the experience of other developing countries, we may make a fair estimate of the time-scale required for large-scale poverty eradication and the advance in well-being of the bulk of the rural population. Such time-scales now coincide with the time-scale when global warming impacts will be much more manifest. Thus development in general and development of climate resilience need to go together. India's global climate policy unfortunately does not reflect any serious understanding of this except as rhetoric. It is in India's interest to push for an early climate agreement which could ensure that the burden of adaptation does not become onerous.

Conclusions

There is now widespread agreement (other than among a die-hard, climate-sceptic minority) that global warming is a scientific fact, and that it is ongoing. However, there are differences, and indeed confusion, regarding the current action that is needed to deal with the future consequences of climate change. Of particular relevance in this regard is the relationship between the intrinsic variability of climate, and the impact of changes in the levels and variability of climate indicators as a result of global warming.

Some climate science and policy researchers and activists suggest that global warming has already led to widespread negative consequences for agricultural production. The hallmark of such arguments is the juxtaposition of scientific conclusions regarding *future* climate change with examples drawn from the impact of *current* climate variability without clarifying the relationship between the two. The problem in this regard is enhanced by the fact that such examples are typically drawn from case studies of small and marginal farmers among whom agricultural production is vulnerable to different kinds of variation, including climate variation, even in the absence of climate change.

Another line of argument, though more circumspect about asserting that the negative consequences of climate change are already apparent, nevertheless regards climate change as *the* issue of over-riding concern for agriculture. In this view, issues related to agricultural production have to be examined in the context of global warming. This line of argument often pays little attention to the complexity of the interplay of socio-economic factors affecting agricultural production, and the environmental and climatic conditions in which such production occurs.

The first line of argument has been popular especially with non-governmental and social work organisations, international and national.[15] The second line of argument

[15] A good illustration is provided by a report due to the Working Group on Climate Change and Development, a consortium of 23 non-governmental organisations (Working Group on Climate and Development 2007).

has been put forth by multilateral institutions of various kinds, agencies from the United Nations system, and aid agencies of individual developed nations.[16]

A crucial problem with such arguments is that they do not adequately study data on agricultural production over time, and across regions, crops, and socio-economic strata of producers, in order to understand the environmental and socio-economic dimensions of the climate-sensitivity of agriculture. Further, many studies routinely conflate problems of current climate vulnerability with problems of adaptation to climate change in the future.

Climate policy today runs two kinds of risk. First, it runs the risk of underestimating the burden of adaptation in dealing with climate change in the future. Secondly, it runs the risk of overemphasising the environmental and climatic constraints on agricultural production in the present, while ignoring the role of socio-economic factors as significant barriers to agricultural growth.

This paper, which is based on a review of the literature, seeks to distinguish the issue of current climate variability and its consequences from the issue of the impact of climate change in the future. It also discusses the uncertainties in predicting the future impact of climate change, uncertainties that constitute a barrier to determining adaptation requirements. At the same time, the paper also attempts to draw lessons relevant to dealing with a future of climate change.

The first section of the paper presents highlights of the scientific findings of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. The findings relating to temperature increase and temperature variability are the most robust on the global scale, while the findings relating to precipitation are subject to greater uncertainty. Sea level rise is another area in the field of global warming studies where significant and robust results are available.

Global temperatures are rising, as also the occurrence of extreme temperature events when temperatures rise above the mean. Such events are "very likely" to be attributable to anthropogenic global warming. Global warming is also contributing to the increase in extreme rainfall events in terms of frequency of occurrence, intensity, and amount of precipitation, though in this case the connection to anthropogenic global warming is not as certain as in the case of temperature.

[16] There are many reports that follow this second line of argument. Among some recent ones are World Bank (2012) and World Bank (2013). The latter reference has specific discussions of the impact of climate change on agriculture in South East Asia, South Asia, and Sub-Saharan Africa. However, it does not refer to yield gaps. There is little discussion in this report of how and why current agricultural production is sub-optimal in many regions, and how dealing with production deficits can help cope with climate change in the future. The report also tends to overemphasise the negative effects of climate change in a one-sided way without a careful discussion of the uncertainties involved.

The second section of the paper reviews some recent results on the impact of climate change on agriculture, with a focus on the impact of climate variability on crop production. In general, there are more studies now available on the impact of higher average temperatures on crop production than at the time of the Fourth Assessment Report of the IPCC. It now appears that, in the absence of nitrogen stress, the impact of climate change on crop production is not as severe as estimated earlier.

With regard to the role of climate variability, we noted that simulation models provide evidence that greater climate variation alone can lower yields to an extent comparable to (or greater than) the impact of increased mean temperatures. There is empirical evidence in this regard: more days of exposure to extreme temperatures of wheat in Northern India resulted in correspondingly lower yields.

Ongoing climate change through rising temperatures has had a negative impact on crop production in different parts of the world, though this impact has been more than offset in practice by improved management and other technological factors. Predictions from climate models of temperature trends in the future indicate that a greater proportion of global crop production will be exposed to heat stress, potentially leading to lowered yields and decreased production.

The third section of the paper examines some of the results for India with respect to current and future trends in temperature and precipitation, the two most critical climate variables for agriculture. Data from the Indian Meteorological Department show that the mean annual temperature across the subcontinent has risen by 0.6 to 0.8°C across the subcontinent over the period 1850–2010. Regionally, this increase varied between 0.5°C and 1°C. In the case of temperature predictions for the future, despite the many uncertainties in climate model predictions at the regional scale, the general trend is clearly one of rising temperatures. The magnitude of the predicted increase, however, varies across climate models, especially with regard to predictions for smaller spatial units.

Precipitation trends are a more complex issue, especially because of difficulties in modelling monsoon behaviour. The Indian monsoon shows substantial variability over the last 150 years. The value of the 30-year moving average for total annual summer monsoon precipitation shows a distinct cyclical pattern over a period of approximately 70 years. The data show that periods of high total annual summer monsoon rainfall are strongly correlated to periods of low inter-annual variability of total monsoon rainfall, and vice versa. A similar trend is also evident spatially, at regional scales (up to the sub-district level). Regions of high average long-term annual summer monsoon precipitation are characterised by low inter-annual variability of annual summer monsoon precipitation, and vice versa.

A comparison of the probability distribution of total annual summer monsoon rainfall in the first 50 years of the period 1871–2012 and the last 50 years of the same period did not show any statistically significant changes. At regional levels, only three out of 32 meteorological sub-divisions (by the classification of the IMD) showed any significant statistical variation for similar comparisons. For all other regions there is no statistically significant trend of variation in monsoon behaviour by this measure.

Over the period 1950–2000, the number of extreme rainfall events – with precipitation over 100 mm – increased, while the number of moderate rainfall events decreased. The number of extreme rainfall events is expected to increase with global warming.

Predictions relating to precipitation at the subcontinental and regional levels are, however, subject to significant uncertainties. The only robust prediction appears to be that total rainfall over the subcontinent may be expected to increase, although the magnitude of that increase is very uncertain. Climate modelling for future rainfall in the Indian subcontinent needs to advance much further for more robust conclusions to become available.

There is little evidence at present that climate change has had any widespread impact on yields or on total agricultural production in India. However, our discussion of the significance of climate variability for agricultural production indicates that the impact of variations in temperature and precipitation on Indian agriculture is an important source of information for coping with the impact of climate change on agriculture in the future. In particular, apart from variations in rainfall, which have traditionally been the primary concern with regard to the relation between climate and agriculture in India, the impact of temperature variations also needs seriously to be considered. The literature on this subject is limited, and this is an area of research that merits concerted effort.

In less developed countries, one of the critical issues is the impact of climate variability and climate change on the most vulnerable sections of the rural population, particularly landless workers, and small and marginal farmers. Much of the current scientific effort at modelling the economic impact of climate change on agriculture pays little attention to its differentiated nature with respect to various socio-economic strata.

Current empirical analyses clearly indicate that small farmers are among the most vulnerable to all manner of environmental and economic shocks. This vulnerability is clearly related to the existing socio-economic inequalities of rural society. These inequalities also result in serious human development deficits for a significant proportion of all rural households. For these disadvantaged sections of rural society, climate change is an immediate threat.

The outstanding issue today in climate change and agriculture is not, in essence, the technical issues of climate change, precision in estimating its impact, or the nature of climate resilience and adaptation strategies – although all of these are, in themselves, important issues indeed. The issue that has not yet made it to centrestage, despite its importance, is that the ultimate cause of the persistence of poverty and deprivation among a large section of those engaged in agriculture is not to be found, in the final analysis, in environmental conditions. It lies squarely in the social and economic relations of rural society. A radical transformation of these conditions will be crucial in determining the manner in which the people of rural India ultimately cope with the global environmental challenge.

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