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Examination of the Climate Factors That Reduced Wheat Yield in Northwest India during the 2000s

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Abstract: In India, a significant reduction of wheat yield would cause a widespread impact on food security for 1.35 billion people. The two highest wheat producing states, Punjab and Haryana in northern India, experienced a prolonged period of anomalously low wheat yield during 2002–2010. The extent of climate variability and change in influencing this prolonged reduction in wheat yield was examined. Daily air temperature (T_{max} and T_{ave}) was used to calculate the number of days above optimum temperature and growing degree days (GDD) anomaly. Two drought indices, the standard precipitation and evapotranspiration index and the radiation-based precipitation index, were used to describe the drought conditions. Groundwater variability was assessed via satellite-based approximation. The analysis results indicate that the wheat yield loss corresponds to the increase in the number of days with a temperature above 35 °C during the maturity stage (March). Reduction in monsoon rainfall led to a depletion of groundwater and reduced surface water for irrigation in the wheat growing season (November–March). Higher temperatures, coupled with water shortage and irregular irrigation, also appear to impact the yield reduction. In hindsight, improving the agronomic practices to minimize crop water usage could be an adaptation strategy to maintain the desired wheat yield in the face of climate-induced drought and precipitation anomaly.

Keywords: wheat yield; northwest India; precipitation; temperature; groundwater; irrigation

1. Introduction

Globally, India ranks third in wheat production, after the European Union (EU) and China, India's main wheat production lies in the northwest of the Indo-Gangetic Plain (IGP) [1,2]. The highest wheat-producing states in the IGP are Punjab and Haryana. There was a prolonged reduction in wheat yield during 2002–2010 in the states of Punjab and Haryana and this reduction significantly impacted the total Indian wheat yield [3]. In this study, an attempt was made to understand the wheat yield variability in northwest India with a focus on the prolonged reduction during the 2000s.

Wheat is a winter (rabi) crop sown in November–December and harvested in March–April and the crop fully relies on irrigation because of low precipitation during winter. Thunderstorms associated with the so-called Western Disturbances may occasionally occur. Increased rainfall during critical stages (crown root initiation, flowering, and physiological maturity) enhances the yield [4] more than dry years, while high temperature threatens the yield [5]. Variation of wheat yield in the IGP can also be caused by other factors such as sowing dates [6], soil moisture, and nitrogen application [7]. Among these factors, wheat is most sensitive to high temperatures, especially during the reproductive stage [8,9]. High temperatures increase levels of water stress in plant cells, crop water requirement, and respiration [10]. Heat stress also affects plant photosynthesis [11,12]. The optimum temperature range for the early growth stages of wheat is lower than the threshold for the later growth stages—a temperature range of 12–25 °C is ideal for seed germination, while the critical temperature for the grain-filling stage is 35.4 °C [13]. In the face of climate change, the projected increase in temperature, along with frequent hot and dry spells, heavy rainfall events, and droughts in semi-arid and tropical regions [14], can negatively impact wheat production. In India, a 1 °C increase in temperature can reduce wheat production by 4–5 mt [15,16].

The objective of this study is to determine the extent to which climate and related factors have played a role in the notable wheat yield reduction in India during 2002–2010 (shown later). The results are expected to be useful for informing management practices that can sustain normal wheat production with increased stress from a changing climate. Section 2 describes the method and data used; Section 3 shows the analysis results together with discussions. Finally, Section 4 provides some concluding remarks.

2. Materials and Methods

2.1. Study Area

The study was conducted for Punjab and Haryana (28–31° N and 74–79° E), located in the northwest part of the IGP (Figure 1). These two states accounted for 34% of total wheat production and 21% of the total cultivated area in India (Directorate of Wheat, India, 2014). The average annual rainfall in Punjab and Haryana is 649 mm and 617 mm (1948–2016), respectively, and 60–70% of annual rainfall is received during the monsoon season (June–September). The average standard deviation of the rainfall in Punjab and Haryana is 175.14 mm and 147.71 mm, respectively. This region receives a small amount of rainfall during December–January (vegetative and tillering stage). Therefore, irrigation is required for the overall growing season. The average winter temperature is 11–14 °C, which is good for spring wheat cultivation. Sowing dates vary from late October to the second week of December and harvesting dates vary from late March–April.

2.2. Data and Methods

2.2.1. Wheat Yield

The national average of wheat yield data for India during 1961–2014 was collected from the Food and Agricultural Organization [17] and the average-yield data at the state level for Punjab and Haryana during 1985–2015, compiled by the Indian Government, was obtained from a private source (this is because official channels of such data are not available). A linear trend was calculated for Indian wheat yield and differenced from the overall timeseries to minimize impacts from non-climate factors (Figure 1). Wheat yield anomaly and three-year running mean were constructed for Punjab and Haryana to identify the wheat yield break.

2.2.2. Climate Data Sources

(a) Drought:

A number of in-situ and satellite derived observations were used. The outgoing longwave radiation (OLR) Precipitation Index (OPI) and Standardized Precipitation and Evapotranspiration Index (SPEI) were used to investigate seasonal drought (November–March) during 2002–2010. The monthly mean OPI (2.5° × 2.5° resolution), as obtained from National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) [18], and the monthly mean SPEI dataset, based upon Climate Research Unit (CRU) (0.5° × 0.5° resolution), was used for analysis [19]. The area average for precipitation in Punjab and Haryana was calculated. The timeseries of OPI during 1979–2012 and SPEI during 1961–2012 were normalized and plotted against the three-year running mean (for smoothing and highlighting the decade-long drought).

(b) Growing Degree Days (GDD)

The daily maximum and minimum air temperature (Tmax and Tmin) during 1979–2012 were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) dataset (0.7° × 0.7° resolution), which assimilates station air temperature observations [20]. Average temperatures for the focus region were used to estimate the GDD following Equation (1) (given below), using 5 °C as the base temperature [21]. Sowing dates in the study area vary by farm location and time, so GDD was computed from 1 November to 31 March to provide total heat units from sowing to harvest.

Equation (1):

$$\mathrm{GDD} = \frac{(\mathrm{Tmax} + \mathrm{Tmin})}{2} - \text{Base Temperature } (5\ {}^{\circ}\mathrm{C}) \tag{1}$$

(c) Frequency of Extreme Temperature:

Daily maximum temperature data at 2.5° × 2.5° resolution was obtained from NCEP-NCAR to cover the regional perspective. ERA-Interim data were not considered due to unavailability. The maximum temperature of the focus region was used to calculate the number of days above the optimal temperature (35 °C). We calculated the areal average maximum temperature in March, because the grain filling and maturity stages (during March) are the most sensitive to high temperature. The number of days above 35 °C was calculated for the period 1979–2014.

(d) Precipitation:

Monthly averaged precipitation data, for the period 1961–2014 (54 years), was obtained from the PREC/L (Precipitation over Land) and Indian Institute of Tropical Meteorology (IITM) records [22] (available at http://www.tropmet.res.in). The dataset was area weighted and based on a total of 27 stations over the states of Punjab and Haryana. Both the monsoon and winter seasons were analyzed.

2.2.3. Hydrological Factors

(a) Water Balance Components:

We analyzed parameters in the water balance equation (without considering irrigation) to isolate the impact from natural causes. Monsoon precipitation is implied as a source of groundwater storage for the subsequent wheat growing season. Thus, we investigated the water balance parameters both in the monsoon and wheat growing season, based on:

$$\text{Precipitation} = \text{Runoff} + \text{Evapotranspiration} + \text{Changes in soil water} \tag{2}$$

Potential evaporation (PET) was used instead of evapotranspiration (ET) due to the unavailability of ET data. The increased evaporation can cause underestimation of the water demand due to the exclusion of plant transpiration, but given that ET is a function of crop-coefficient and PET [23], our result for PET is still valid in depicting the described relationship. Precipitation reconstruction over land, runoff from NCEP-NCAR reanalysis, PET, and soil water storage were obtained from the National Oceanic and Atmospheric Administration (NOAA) website (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). These data were acquired for computing the water balance equation. All of the relevant variables were area averaged for the Punjab and Haryana region from 1961–2014 (monsoon and wheat growing season).

(b) Groundwater Proxy:

Well data were sparse and difficult to obtain from northern India. Thus, changes in monsoon-season and winter groundwater were analyzed by using monthly data from NASA's Gravity Recovery and Climate Experiment (GRACE), to calculate a dataset of the liquid terrestrial water storage anomalies (TWSA) for 2002–2011 (https://grace.jpl.nasa.gov/data/). This is not the exact measurement of groundwater, but an approximation or accumulation of all forms of liquid water at and under the land surface assumed to exist above the bedrock. The aquifers in the area are mainly the unconfined type. That is why a lower precipitation rate played an important role in the vanishing groundwater of the region. This dataset measures changes on the local pull of gravity as water shifts around the Earth due to changing seasons, weather, and climate. Obviously, the satellite data/GRACE is not an accurate measurement to any local aquifer but is an indicator of the water storage in recent years. We had to use GRACE since local well data were not available.

All the climate parameters and the drought indices were area averaged (1985–2015) over the Punjab Haryana region.

2.2.4. Other Factors:

Non-hydrological factors such as cropping intensity change in areas net irrigated by canals and tube wells, and changes in the number of overexploited and safe blocks are the supportive factors that could contribute to the wheat yield variability. These datasets were obtained from http://www.punjabstat.com. Cropping intensity is defined as the number of crops in the same field during one agricultural year and is derived from Equation (3):

$$\text{Cropping Intensity} = \frac{\text{Gross cropped area}}{\text{Net sown area}} \times 100 \tag{3}$$

3. Results and Discussions

3.1. Wheat Yield Variation

Wheat yield across the entire Indian region has increased almost consecutively from 1961–2014, as show in Figure 1a, due to improvements in crop production technologies. However, there appears to be an inter-decadal variability embedded in this long-term increase. By removing the linear trend of wheat yield, the detrended pattern shows a marked decline followed by a prolonged pause during 2002–2011, as demonstrated by the black line in Figure 1a. This decline in wheat yield reflects a reduction of about 0.2–0.4 t/ha. Indian wheat is produced dominantly in the provinces of Punjab and Haryana, see Figure 1 map, and their respective wheat yields since 1985, as shown in Figure 1b,c, also show a corresponding reduction during the same time period. Since little to no drastic change in management practices or cultivation techniques could last for this long period (almost ten years), environmental factors such as climate variability could play a role in producing such a negative impact on wheat yield.

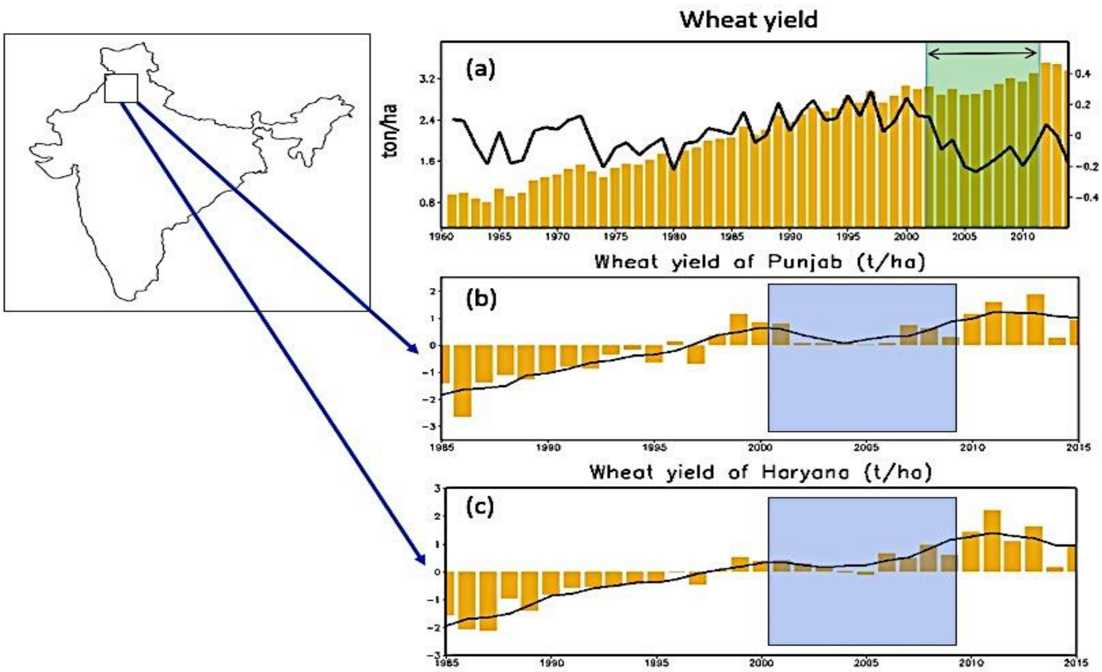

Figure 1. Study area (the box in India map): (**a**) total Indian wheat yield (tonnes/ha) (1961–2014), (**b**) normalized wheat yield of Punjab (1985–2015), (**c**) wheat yield of Haryana (1985–2015)—the black lines represent detrended wheat yield (**a**) and three-year running mean (**c**,**d**). The period of 2002–2010 is shaded.

3.2. Climate Impacts on Wheat Yield

3.2.1. Drought Indices

Two drought indices, OPI and SPEI (see Section 2.2.2), were used to examine the extent of possible water shortage conditions during 2002–2010. SPEI is a multi-temporal scale drought index based on the balance between precipitation and ET with respect to their climatology. Normalized seasonal OPI and SPEI during the wheat growing season (November–March) are shown in Figure 2a,b. Positive OPI values indicate surplus rainfall compared to regional climatology, whereas negative values indicate a deficit in rainfall compared to regional climatology. The OPI clearly shows a below normal condition during 2000–2012, corresponding to the wheat yield reduction. The seasonal SPEI also indicates strong drought with negative anomalies after 2004 (Figure 2b), which corresponds to the period of wheat yield reduction.

3.2.2. Temperature

Direct impacts of temperature on wheat yield can be depicted by GDD and the frequency of extreme temperatures above 35 °C during the growing season. Figure 2c shows normalized GDD timeseries and indicates a general high-GDD period during 2002–2010. A high-GDD environment can either shorten wheat maturity [24] or directly harm crop growth when the temperature exceeds the critical threshold. Additionally, a high GDD leads to early maturity which affects growth and yield. High temperature conditions also contribute to an overall negative effect on grain filling and physiological maturity.

Wheat crop exposed to temperatures above 34 °C after the anthesis stage has a significantly low yield due to accelerated senescence, decreased rate and duration of grain filling [25,26], and reduction in grain weight [27]. By quantifying the number of days with temperatures above 35 °C in March, which are critical for the grain filling and maturity, we found that the frequency of extreme temperature was relatively high during 2000–2010 (Figure 2d). Long periods (continuous days) of heat stress (above 35 °C) conditions during crown root initiation, flowering, and grain filling stages can cause significant yield reduction [28,29] and may lead to total crop damage. Additionally, continuous days with high temperatures can shorten wheat maturity. However, we noted a three-year "gap" in the anomalously high temperature years (2005–2007) and this could imply impacts from other factors (e.g., water resources) not related to heat in the atmosphere.

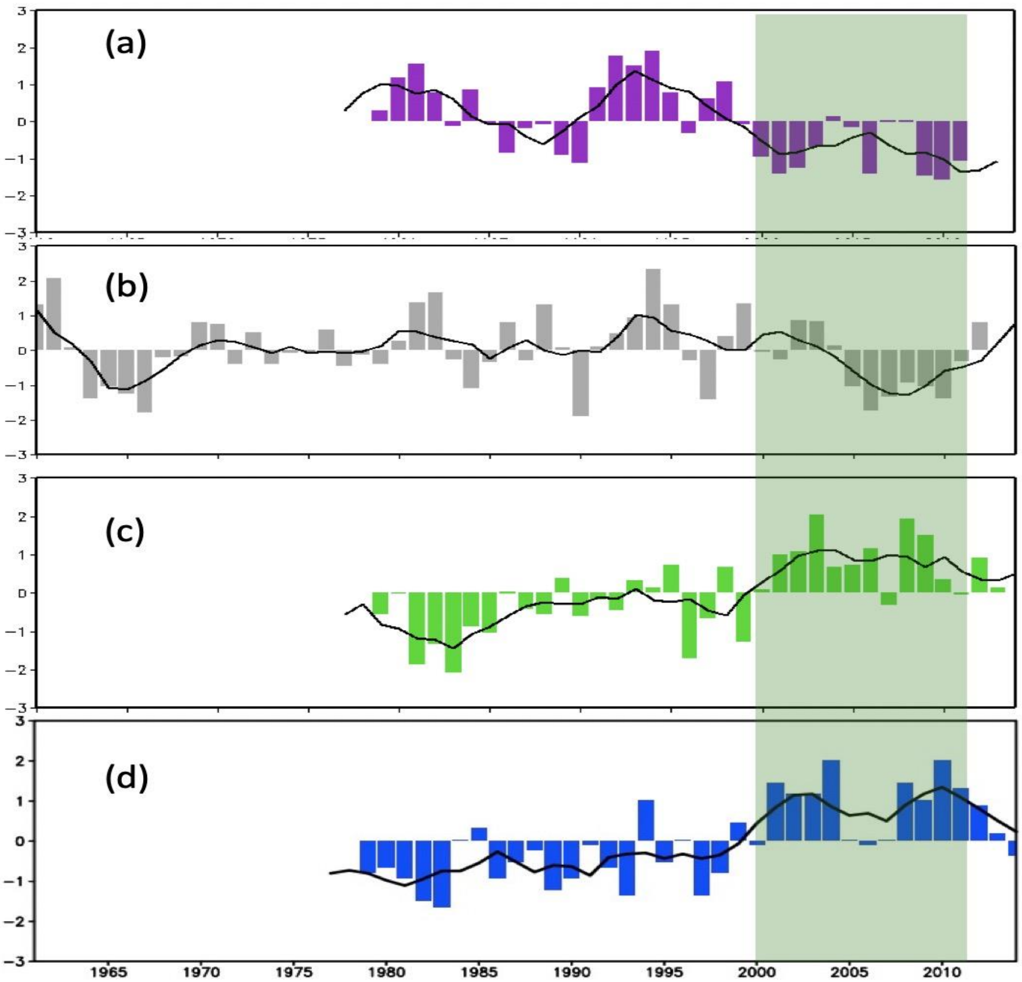

Figure 2. Normalized seasonal means (November–March) of (**a**) OLR Precipitation Index (OPI), (**b**) Standard Precipitation and Evapotranspiration Index (SPEI), (**c**) growing degree days (GDD), and (**d**) number of days above 35 °C (during maturity)—the black line in each figure indicates the three-year running mean, and the period of 2002–2011 is shaded.

3.2.3. Water Balance

Precipitation levels during the monsoon (June–September) and wheat growing season (November–March) are displayed in Figure 3 for (a) Punjab and (b) Haryana. Both the monsoon and winter precipitation fluctuated year-to-year, but they appeared to reach relatively low levels during the 2002–2010 period, particularly in Punjab, and the decline persisted through 2015. The decreases of monsoon and winter precipitation during this period, compared to their long-term (1948–2016) means, were 27.6% and 8% for Punjab and 16.5% and 33% for Haryana, respectively. The mean winter precipitation was less than 300 mm, which is not sufficient for wheat cultivation, so the monsoon precipitation plays a vital role in recharging the groundwater that is consequently used for wheat irrigation, mostly from tube wells. The PREC/L data shows similar precipitation variations, as shown in Figure 4a, as the IITM precipitation, characterized with a marked decadal-scale variability that was previously documented for both summer monsoon and winter seasons [29], suggesting natural variability in terms of the weather pattern change. However, the predominant reduction in precipitation during 2002–2010 suggests inadequate hydrologic input for recharging the groundwater supply.

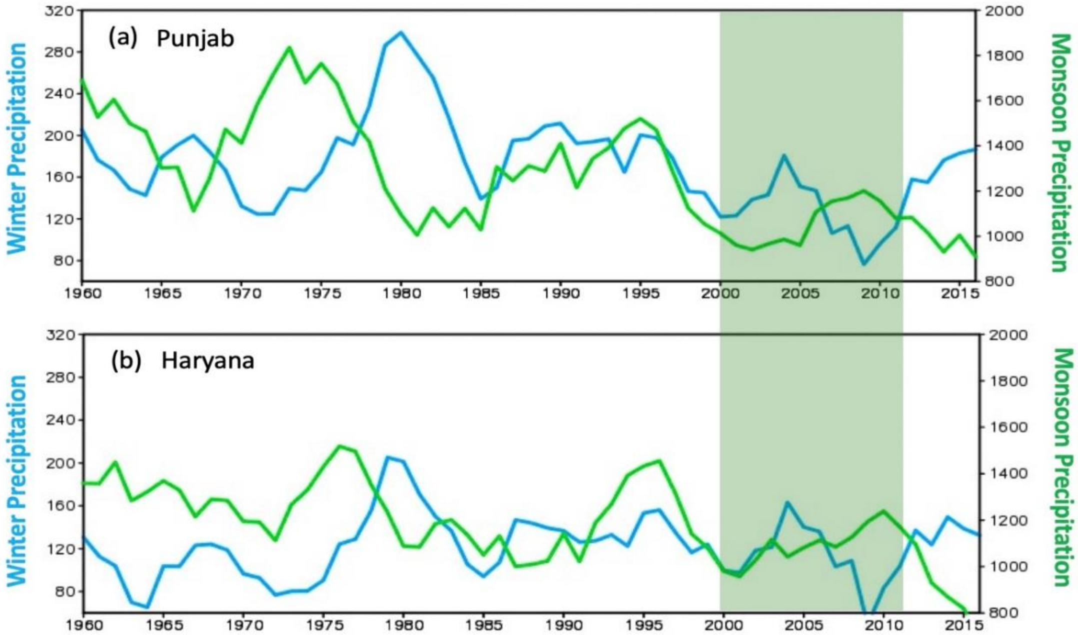

Figure 3. Timeseries of winter (indigo line) and monsoon precipitation (green line) (mm, 1961–2015) of (**a**) Punjab and (**b**) Haryana; the period of 2002–2011 is shaded.

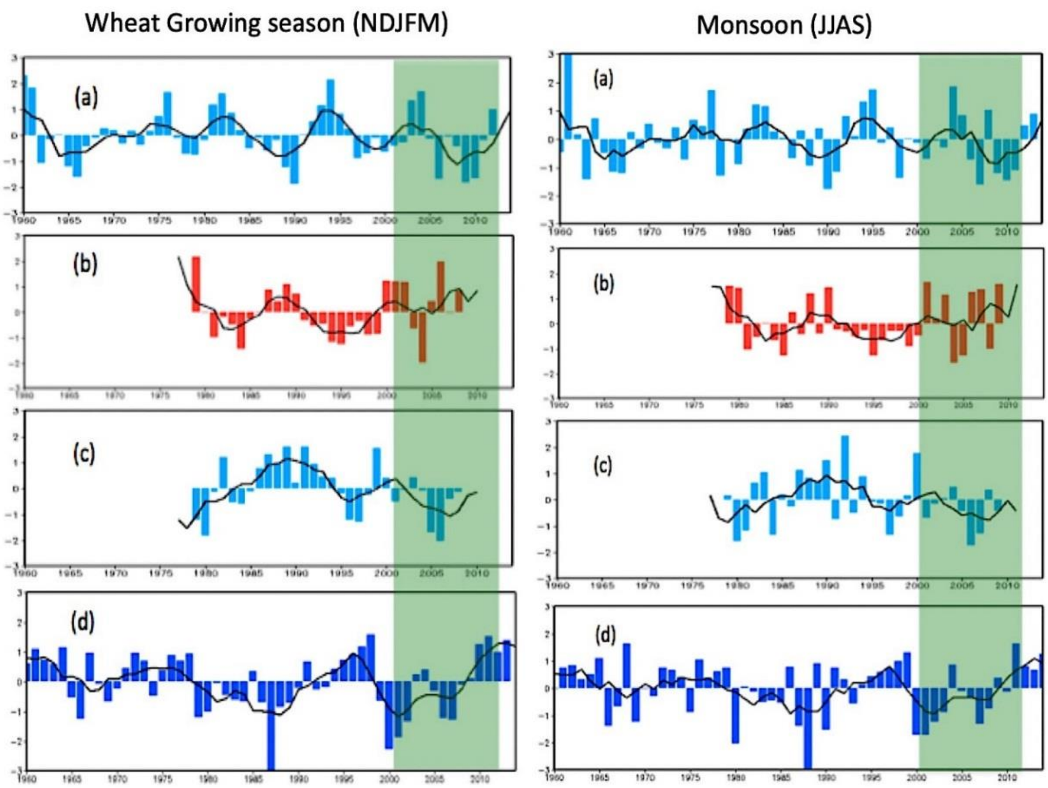

Figure 4. Seasonal (winter and monsoon) anomaly of (**a**) precipitation (1961–2012), (**b**) potential evaporation (1979–2010), (**c**) run-off (1979–2010), and (**d**) soil water storage (1961–2012)—the black line in each figure indicates the three-year running mean. The 2002–2011 period is shaded.

The increasing trend of potential evaporation during 2002–2010 in both seasons, as shown in Figure 4b, suggests a higher amount of water loss from the soil surface when precipitation started to decline. The seasonal run-offs in Figure 4c also show below-normal conditions, corresponding to the combined change in precipitation and PET. Soil water storage (Figure 4d) during the 2002–2010 period exhibited a clear reduction in both seasons, but the reduction was particularly pronounced during the wheat growing season. This reduction in soil water storage negatively impacted the critical stages of wheat growth, since low soil water storage can be harmful to crop growth through low water supply and unsuitable growth conditions. In the dry season, soil becomes hard to penetrate for the root system to absorb water and nutrients, especially during juvenile stages. Low soil water storage is a balance between a low amount of precipitation, high PET, and low run-off, which can impact groundwater and thereby irrigation.

Next, we present the changes in groundwater estimation during the monsoon and wheat growing seasons in Figure 5a,b in terms of the spatial distribution of the long-term trend in the GRACE TWSA. The northwestern part of India is characterized by a decade-long reduction in TWSA, suggesting groundwater depletion. By plotting the normalized timeseries of TWSA averaged over Punjab and Haryana (Figure 5c), the decline shows the reduction of the groundwater level (estimated) to be 2–3 cm during 2002–2011—this could mean a significant impact on crop irrigation. Similar results of the drastic depletion in groundwater level in northern India have been reported [30,31], for example, a groundwater decrease may be compounded by the overexploitation of groundwater for crop irrigation.

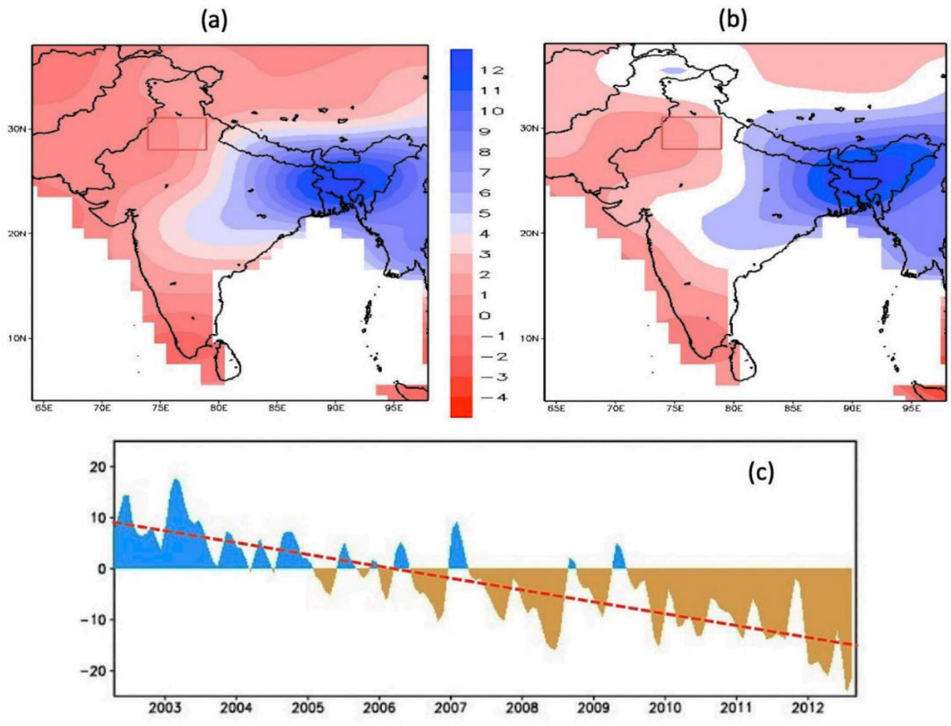

Figure 5. Changes in estimated ground water depth (mm) during 2002–2013 in (**a**) monsoon season (June–September) and (**b**) wheat growing season (November–March), (**c**) anomaly in estimated groundwater level (2002–2013)—the red-dotted line is the trendline.

3.2.4. Correlation between Climate Factors and Wheat Yield

Climate factors are always present when it comes to crop production, especially for wheat, which is very sensitive to heat and moisture stress. In Table 1, we list the major climate factors' correlation with the average wheat yields of Punjab and Haryana. Winter and monsoon precipitation did not a show significant correlation at the 95% significance level, which indicates an indirect relationship of precipitation with wheat yield in those two states. Air temperature had an inverse relationship, which indicates that higher temperatures during the growing season lead to a lower wheat yield. PET showed a non-significant linear relationship with wheat yield. Soil moisture storage can help the yield, though not significant at 95% significance level, which indicates that a higher soil moisture level can help to enhance the yield. From this correlation table, it can be concluded that not a single factor has a significant negative impact on the wheat yield; rather, there is a combined effect from all these climate factors. While the drought indices showed a significant correlation with the wheat yield, this analysis shows and supports the combined impact of climate factors on reduced wheat yield during the early 2000s.

Table 1. Correlation co-efficient table with different climate factors, drought indices, and wheat yield at the 95% significance level.

Climate Parameters		Correlation Co-Efficient
Winter Precipitation (November–March)	**Wheat Yield**	0.19
Air Temperature (November–March)		0.12
Monsoon Precipitation (November–September)		−0.33
Potential Evaporation (PET) (November–March)		0.29
Soil Moisture Storage (November–March)		0.31
Standard Precipitation and Evapotranspiration Index (SPEI) (November–March)		0.42
Outgoing Longwave Radiation Precipitation Index (OLR) (November–March)		0.47

3.3. Contribution from Other Factors

Cropping intensity and the irrigation situation were considered as well, since these variables are related to water availability and wheat yield reduction. As shown in Figure 6, the cropping intensity in Punjab and Haryana is 40–50% higher than that in all of India, suggesting a higher water demand for agricultural production in the two states. Because of the low rainfall during winter, overexploitation of groundwater and low water access can intensify. The decreasing monsoon rainfall [32] also reduces surface water and results in dry canals, which are the main sources of irrigation in these two states.

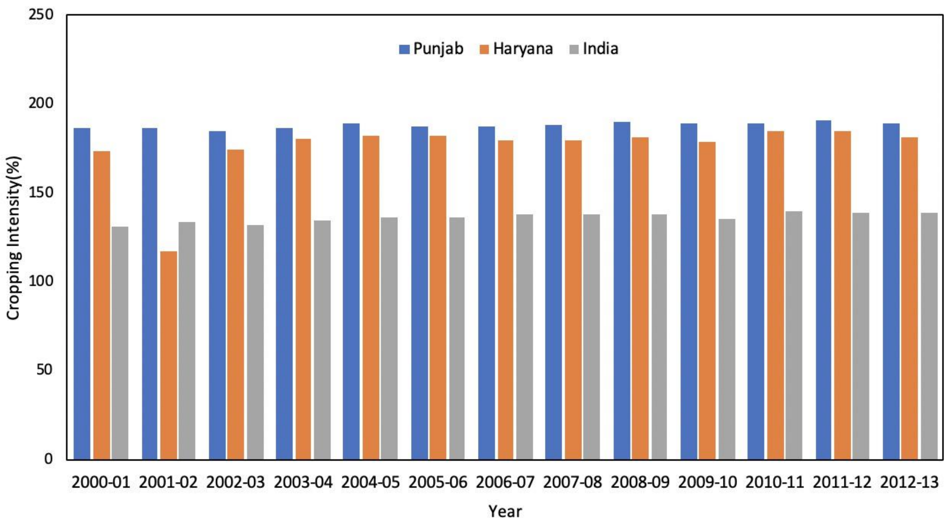

Figure 6. Cropping intensity (during one agricultural year, i.e., July–June) of Punjab, Haryana, and India (2001–2013).

As shown in Figure 7a, the area net irrigated by canals reduced after the 1990s in both Punjab and Haryana, whereas the area net irrigated by tube wells (Figure 7b) has increased over the years. Decreased surface water availability and increased cost of groundwater due to high demand may limit affordable irrigation for poor or middle-class farmers. The situation of groundwater consumption in Punjab is under consideration, but extensive in situ data will be needed. Meanwhile, the number of overexploited blocks is increasing, whereas the number of safe blocks is decreasing, as shown in Figure 8. This trend indicates the overexploited condition of groundwater, which has gone below a sustainable level. The opposite trend, a decreased number of overexploited blocks and an increased number of safe blocks, would have suggested a well-maintained groundwater level and limited usage of groundwater.

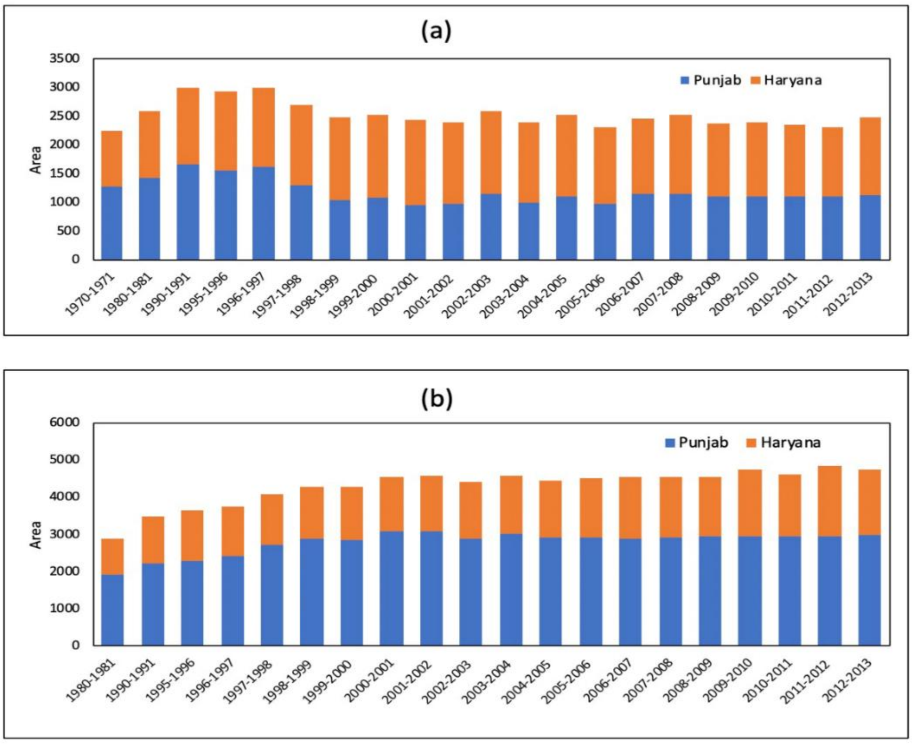

Figure 7. Net irrigated areas (thousand hectares) by (**a**) canals and (**b**) tube wells for Punjab and Haryana (1980–1981 to 2012–2013).

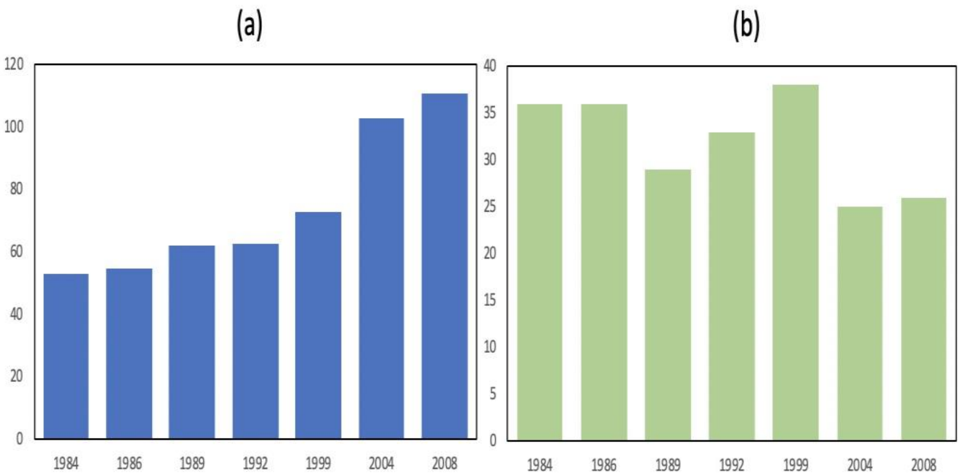

Figure 8. Number of blocks with (**a**) overexploited and (**b**) safe water resources in Punjab out of 143 total blocks.

For future research, we shall consider the other factors such as pests and diseases. We note that obtaining official reports of crop loss from pests and diseases during the 2002–2010 period has proven difficult. Moreover, economic and governmental policies regulating input support (e.g., variety, seeds, fertilizers, and pesticides) might be additional factors affecting wheat production. Exploration of these non-climatic elements on wheat yield is an important next step but is outside the scope of this study.

4. Conclusions

The climatological and hydrological factors associated with the pronounced wheat yield reduction during 2002–2010 over northwest India were examined in this study. By focusing on the two wheat growing states, Punjab and Haryana, our analysis indicates that the yield loss is linked to climate variability and change. Decreased trends of monsoon rainfall, winter rainfall, and the increment of average winter temperature were found during the 2002–2010 period, and these variations combined contributed to an adverse effect on wheat yield (both directly and indirectly). Multi-year drought conditions during this period related to the low rainfall, estimated groundwater level, and soil water storage, as observed from multiple sources of data, appeared to have contributed to the prolonged wheat yield reduction. Low water availability tends to limit irrigation requirements for wheat cultivation and can result in growth and yield decrease. Additionally, the increased frequency of days with extreme temperatures above 35 °C during the maturity stage is a significant factor affecting grain sterility and seed weight.

In the face of the projected increases in extreme temperatures in the IGP-wheat region, the decrease in wheat yield could become more dramatic. Alternative management practices may be adapted to maintain wheat yield under climate change in the IGP-wheat region, such as zero tillage (has a positive environmental aspect), water harvesting (a strategic tool for drought mitigation), Variable Rate Technology (VRT) to reduce excess water usage, precision farming, and the usage of drought-resistant varieties or high-yield varieties.

Author Contributions: Conceptualization: A.M., S.-Y.S.W., and P.P.; Methodology: A.M., S.-Y.S.W., and P.P.; Software: A.M. and P.P.; Data Curation: A.M.; Visualization: A.M.; Supervision: S.-Y.S.W.; Writing—Original Draft Preparation: A.M.; Writing—Review and Editing: A.M., S.-Y.S.W., and P.P.

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