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Downscaling model in agriculture in Western Uzbekistan climatic trends and growth potential along field crops physiological tolerance to low and high temperatures

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ABSTRACT

The Global climate change is becoming an increasing challenge for agriculture. Beyond the increased local occurrence of extreme events high temperatures are becoming an increasingly present limiting factor in crop production. The agriculture in the West of Uzbekistan with very limited rainfalls is highly dependent on irrigation schemes using the Amu Darya water flow. With low Winter (freezing nights with minimum air temperatures of less than 0 °C) and high Summer temperatures (hot days and nights with temperatures above 35 °C during daylight, and minimum air temperatures of more than 20 °C during night time – tropical nights) the local continental arid climate temperatures are a main limiting factor faced by the local agriculture. The arid climate, with a crop production dependant on irrigation, allows putting the focus on temperatures influence on field crops, while rainfalls have barely any influence.

In temperate countries the focus has mainly been on low temperatures as a main limiting factor. Freeze is indeed influencing the sowing period and putting crops at early development stages at risk.

Even though, the West of Uzbekistan is facing low temperatures over the Winter period which is also challenging the local agriculture, high temperatures are becoming an increasing threat over the Summer period.

The present study is analysing day and night temperature trends over the period 1987–1990 and 2013–2017. The observed trends are further compared with data from the Intergovernmental Panel on Climate Change (IPCC) model available on the World Bank open portal. Regression lines have been calculated illustrating the trends over the period. The inter-annual temperature variations are important with a relative standard deviation which ranges between 16 and 50%. The trend is considered as not significant when the relative standard deviation exceeds the variation over the overall time-period.

The Day degrees are used to provide an insight into the climatic impact on crop growth along plants physiological tolerance. The day degree methodology has been especially adjusted in the present publication in order to take into account the tolerance of the studied crops to high temperatures.

While the hot period is progressively expending into the Spring period, Winters are not becoming much milder limiting the benefit for Winter crops. While the hot days and tropical night event will become predominant over the Summer period the yields in cotton and rice are expected to drop drastically over the second half of the XXIst century. The expected reduction of water inflow of the Amu Darya over the century will further strongly put into question the crop production model in the West of Uzbekistan.

The present publication aims at describing the ongoing trends, expectable changes in agricultural production and timelines. It is also illustrating how hot temperatures analysis could be integrated in downscaling models in agriculture in other regions of Uzbekistan and of the world.

1. Introduction

Temperature is an important factor influencing plants germination, growth, flowering and seeds production (Hatfield and Prueger, 2015). Plants are sensible to low and high temperatures with different tolerance levels according to the species and varieties. Wheat is more tolerant to lower temperatures but more sensible to high temperatures above 30 °C. Cotton can stand higher temperatures but has less tolerance to lower temperatures. Rice has a slightly better tolerance to high temperatures than cotton but requires much more water.

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Over the past decades in the North hemisphere (Europe, United States) agronomic research under temperate conditions has been mainly focusing on low temperatures as a main temperature limiting factor. This has influenced the research methodologies, among which the 'Day Degree' concept, allowing modelling the plants productivity.

Plants' productivity increases while temperature increase until an optimum maximum production level. If temperature raises beyond that point the plant productivity drops drastically until a zero-production point (Hatfield and Prueger, 2015). The yields of most crops decrease sharply when temperature rises above 35 °C (Meridja, 2011). Plants can compensate high temperatures to some extent by increasing evapotranspiration. However, over the zero-production level, the plants close its' stoma (opening in the cells through which gas exchanges with the outside occur) and thus stops the photosynthesis process.

The difference in temperature between the optimum maximum production level and the zero-production point can range between 2 and 10 °C. "Pollen viability and production of rice begins to decline as daytime maximum temperature exceeds 33 °C, and reaches zero at Tmax of 40 °C (Luo, 2011). The amplitude between day maximal and night minimal temperature and the stage of development of the plant are important factors in this regard. Night high temperatures also affect important plants physiological mechanisms linked to respiration, reducing sugar availability for other physiological mechanism and growth (Raja Reddy et al., 1996).

The optimum maximal temperature is around 32 °C at day and 26 °C at night for most varieties of cotton (Vara Prasad and Djanaguiraman, 2014).

The present analysis is focused on agronomic impact related to winter wheat, cotton and rice productions, as those are the main field crops cultivated in the studied area.

Most existing studies in Central Asia mainly rely on the assumption that water availability and extreme climatic event (droughts and heavy rain falls) are the main challenges faced in the background of climate change (Bobojnov and Aw-Hassan, 2014). Besides, the day degree concept has been applied to low temperatures as a main limiting factor for the region (Conrad et al., 2012). A world bank study published in 2013 has further estimated expected yield losses due to climate change in the three main agro-ecological areas of Uzbekistan (Sutton et al., 2013).

Cotton and wheat are from far the main cultivated crops in Uzbekistan (Sutton et al., 2013), as well as in the studied area. Rice is being cultivated in the Summer, but to a lesser extent. The rice cultivation was tolerated in a limited manner during the Soviet era and has increased over the past years, while farmers got some more liberty in choosing the crops (Couëtil, 2020). However, the rice requires substantially more water than cotton or wheat.

The sowing season for cotton production is taking place following two weeks without freeze (mid-April in average) and the harvest, most years, in September and lasting until November (J. Schlubach – field survey).

The sowing period for wheat is taking place two weeks after the cotton harvesting period. The wheat harvest, over the studied period, is in average taking place the first week of July (almost no growth happens in June while the wheat dries in the fields).

The rice sowing is taking place mid-April to June when temperatures are warm enough ensuring that no more freeze occurs; the harvest is taking place most years from September (Couëtil, 2020).

The region is semi-arid with very low rain falls and agriculture is only taking place under irrigated conditions. The frequent frosts between late September and April, hardly allow more than one crop a year. Double cropping with short growing vegetable is possible in favourable years (FAO, 2012), but at a limited scale in the vicinity of households.

The present study is focusing on the trend in daily low and high temperatures occurrence over the past thirty years according to meteorological data. Those trends are then compared to the trends produced by the climatic models until the end of the XXIst century. The Day Degree (DD) methodology is applied to assess the trend in crop productivity over the period 1986–2017. The theoretical impact on the crops development and yields is further discussed.

The scope of the study is not to calibrate the day degrees methodology which has been done in the frame of other studies (Constable and Shaw, 1988; Miller et al., 2018; Ranea and Nagarajanb, 2004; Raja Reddy et al., 1996; Robertson et al., 2007). The plant growth stages, including the effects of high temperatures at critical development stages have also been described in a range of publications (Constable and Shaw, 1988; Cottee, 2009; Hatfield and Prueger, 2015; Robertson et al., 2007; Cao and White, 2009; Lambers et al., 2005). It would nevertheless have been interesting to compare the seasonal meteorological data with field yields. However, such data are difficult to get in the case of Uzbekistan. Statistics exist at the regional level but those are also biased by the production targets set at a political level (Jozan, 2012). Thus, the aim of the present study is not to quantify the agricultural production as a whole, but rather to provide an insight into the shift in cropping seasons and how yields may evolve.

Regression lines are used to analyse the data. The relative standard deviation reflecting interannual variations presents a high error margin regarding the path of change. Trends can nevertheless be defined. The related findings are thereafter discussed in the present publication.

While the world is facing the consequences of climate change the present study may provide a reflection regarding areas where growing temperatures and water scarcity will be an increasing challenge. The proposed methodological approach may also be fine-tuned and completed with complementary field studies allowing developing downscaling models in Central Asia, as well as in other areas in the world.

1.1. Study area

The present study is focused on the semi-arid desertic area to the West of Uzbekistan.

Uzbekistan as a whole is facing a continental climate with hot Summers, cold Winters and marked by the scarcity of rain falls to the West.

The country agroecological areas range from mountainous areas to the East to desertic low lands (Kyzylkum and Karakum deserts) to the West with irrigated plains along the main rivers among which the Amu Darya constitutes the largest watershed in Uzbekistan. Those areas are considered as the three main agroecological areas in Uzbekistan (FAO, 2012). The agroecological areas can be further subdivided taking into account for example the specificity of Ferghana valley, to the East, vast irrigated plain in between mountain ranges, or the lower Amu Darya region located to the West in the vicinity of the former Aral Sea Basin.

The present study focuses on the region located to the East along the Amu Darya river in the vicinity of the former Aral Sea. The study region includes the Western part of Khorezm region as well as the Eastern part of the autonomous republic of Karakalpakstan bordering Khorezm region (see Figure 1).

The Lower Amu Darya, is located downstream of the water intake to Turkmenistan. It is characterized by an arid climate (Saharan upper) with rain falls which are below 100 mm a year (Gintzburger et al., 2003); 97 mm to the North (FAO, 2012) toward the border with Kazakhstan and less to the South. The rain scarcity is such that centuries old mud fortresses are still standing. The advantage of having an area with very low rain is that rain patterns do not require a specific analyse against the temperature patterns. The average climatic pattern of Uzbekistan is not representative of the prevailing arid conditions to the West of the country, but it nevertheless provides an insight into the overall climatic conditions (see Figure 2).

The meteorological stations selected for the purpose of the study are Khiva and Tuyumayun in Khorezm and Takhiatosh and Nukus in Karakalpakstan. Khiva station is located in the middle of an irrigated cultivated plain, Tuyumayun is located on the edge of the rock plateau of the Kyzylkum desert to the North next to the water reservoir serving the water intakes to Urgench and to Nukus, Takhiatosh and Nukus are respectively located to the South and the North of Nukus town.

The four studied meteorological station are located along a line going from the North West (North of Nukus town) to the South East

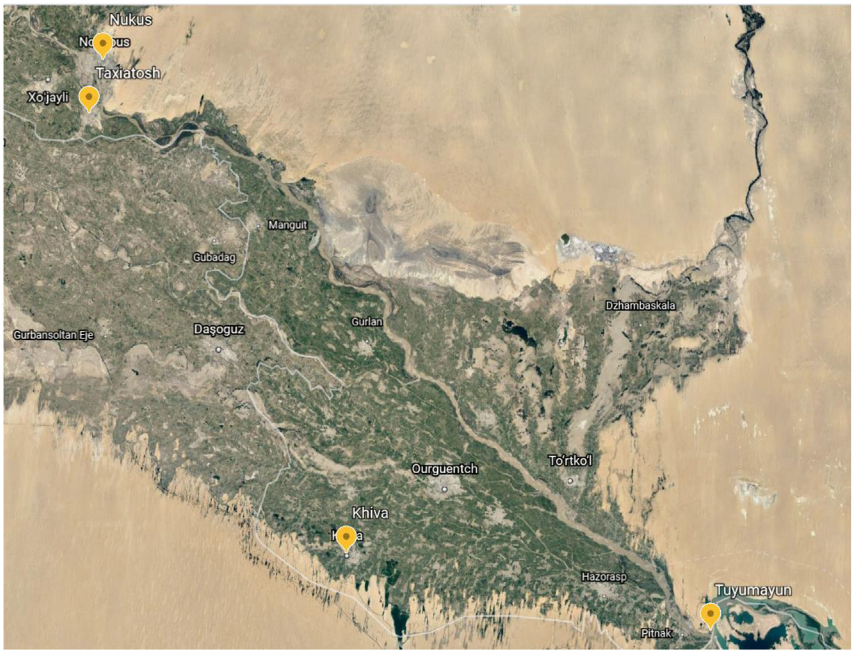

Figure 1. Map of the area and approximative location of the studied meteorological stations. Source Google earth, Landsat/Copernicus (41° 58′ 19° N, 60° 32′ 15° E) – Khorezm region (Karakalpakstan autonomous region to the North and the East, Turkmenistan to the South and West) – Localisation of the four studied meteorological stations – Scale: the distance in straight line between Nukus and Tuyumayun is of 200 km (1 cm = 11 km).

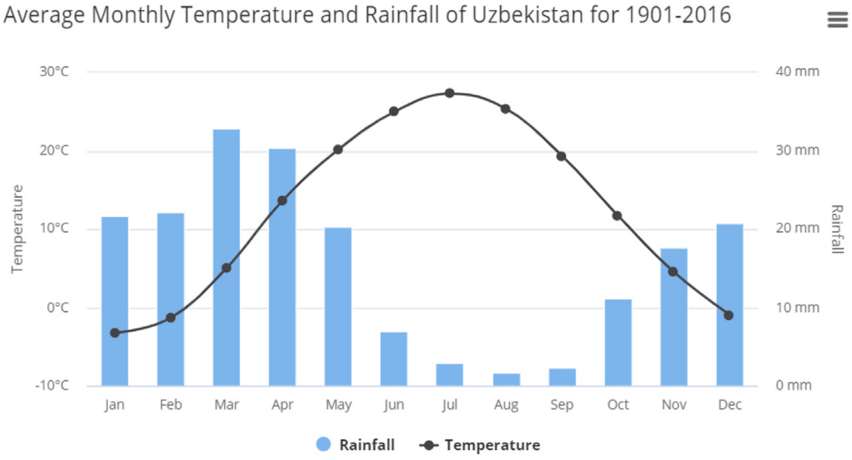

Figure 2. Average monthly temperature and rainfall at the country level between 1901 and 2016. (Source: World Bank - Climate change Knowledge Portal).

(Tuyumayun). The data show substantial discrepancies in the meteorological data and trends. Those discrepancies can at least partly be explained by the local eco-geographic location and conditions.

The meteorological station located north of Nukus and to some extend the station of Takhiatosh located to the South of the town are more exposed to the Northern air masses, as well as to the consequences of the withdrawal of the Aral Sea.

Khiva and Tuyumayun station are located about hundred fifty kilometres to the South. Khiva is surrounded by water masses and irrigated areas. Tuyumayun is next to the region main water retention basin and the largest along the Amu Darya river with a capacity of 7.8 square kilometre (FAO, 2012), as well as close to the irrigated plain. Water and vegetation may play there an important mitigating role reducing extreme temperatures. Data series from desertic ranges significantly differ from those reported by the stations located on irrigated land (Lioubimtseva and Henebry, 2009). Tuyumayun, is potentially more exposed to the cold air masses coming from Kyzylkum desert during the Winter.

Further studies could allow developing an insight into the mitigation provided in the fields by evapotranspiration, as well as in the increased water consumption while temperatures increase. The related soil salinization processes which are main challenges in the study area will also require further attention in the frame of separate studies.

1.2. Methodology applied to the analyses of temperature patterns on crops

1.2.1. Effect of low and high temperatures and applied analysis

In the present paper trends in meteorological maximal day temperature above 35 °C and of minimal night temperature above 20 °C (tropical nights) are being considered as limit temperatures allowing crop growth. Those are also limit temperatures used By the Intergovernmental Panel on Climate Change (IPCC) models. Besides, the assumption is that meteorological data taken in shadows at 1-m height are milder than field conditions. The trend in number of days above those thresholds provides an insight into the production potential. Those data can further be compared with the open portal data on climate change until the end of the century.

The study could be further fine tuned taking into account the plants development stages. Field temperatures at different crops growth stages compared with meteorological data would also allow fine tuning the analysis.

In order to reduce the volume of data to be processed the study is focusing on daily day and night temperatures over two periods of five years (1986–1990) and (2013–2017). The data provided by the Uzbek meteorological institute in Tashkent, is retrieved from four meteorological stations of Khorezm region (Khiva and Tuyumayun) and Karakalpakstan autonomous republic of Uzbekistan (Nukus and Takhiatosh).

It has been assumed that five-year periods would provide a sample with an acceptable statistical value of the range of temperature variations over the period. Comparing the two five years periods separated by 23 years provides thus a trend over a period of time of 33 years, which can further be compared with the trends, over the XXIst century, retrieved from the models accessible on the World Bank open portal.

For each meteorological station and each month a table has been established with the daily maximum temperature and the night lowest temperature.

The trend in low and high temperatures have been calculated applying the linear formula:

$$Y = a^{*}x + b;\ a = \mathrm{Sum}((X_i\text{-}mX_i)\ x\ (Y_i\text{-}mY_i))/\ \mathrm{Sum}\ (X_i\text{-}mX_i)^2;\ b = \mathrm{average}\ (Y_i)\ \text{-}\ a^{*}(\mathrm{average}(X_i))$$

X_i is the year, with 1986 being $X_1 = 1$ and 2017, $X_{32} = 32$

mX_i is the mean year value of the years over the studied period of time, 16.5 in the present case.

mY_i is the average value of the studied variable in a given year reflected in the graphs (number of very hot days, cumulated Day Degree value…).

For the purpose of the publication low Winter temperatures are illustrated by Freezing nights with temperatures below 0 °C at night and high Summer temperatures are illustrated by both Hot days with maximal temperatures above 35 °C at day and tropical nights with minimal temperatures above 20 °C at night.

1.2.2. Effect of high temperature and day degrees

The Day Degree (DD) value per crop, taking into account plants physiological productivity limits under low and high temperatures have been calculated based on Khiva and Tuyumayun meteorological stations.

Khiva in Khorezm region meteorological data are subject of more in-depth analysis related to the agricultural production potential.

The Day Degree are calculated based on the temperature (T°) under which a plant doesn't germinate or grow. This temperature is a main factor in the north hemisphere determining the sowing period.

For cotton the minimum temperature used in reference research papers in America is 12 °C (Raja Reddy et al., 1996).

In this case: DD = ((Tmax – 12) + (Tmin – 12))/2.

The day degrees per day are cumulated for the overall cropping period providing a total score reflecting the growing potential.

The maximum temperature reflects the highest temperature at day.

The minimum temperature reflects the minimum temperature at night.

The maximal reference day and night temperatures to be applied differ for each crop (see Table 1).

The cumulated daily DD over the cropping season provides the overall score. For cotton this score should reach 50 to 60 for germination/final emergence and 775 to 850 (in average 55 days with 28 °C at day and 20 °C at night) for flowering (Robertson et al., 2007).

With low temperatures the plant productivity increases while the temperature increase. This discrepancy to the maximum tolerable temperature allowing crop growth doesn't apply the same way. In the case of higher temperatures, the productivity increases until the maximum productivity level and beyond that point drops drastically to a zero-growth point. It is assumed that field conditions are more extreme then meteorological data and that the optimum production point reflected by a DD′ score equal to zero correspond to the zero-growth point.

Table 1. Crops temperature tolerances' (reference values are related to drought and temperature resistant varieties) – references (Ranea and Nagarajanb, 2004; Rahman et al., 2013; Vara Prasad and Djanaguiraman, 2014; Ahmad and Prasad, 2012; Shah et al., 2011).

Crop	Low Temperature tolerance °C	Max day Optimum T °C	Max Night T °C tolerance	Zero growth reference
Cotton	12	32	26	
Wheat	5	30	20*	
Rice		32	22*	
Maize		35	25*	
Sorghum		35	25*	40–43 °C

* By default maximal acceptable night temperature tolerance is considered as day maximal temperature minus 10 °C.

A formula taking into account the effect of high temperatures, based on the DD principle for cotton, is:

DD'= ((Optimum day max T° – day max T°) + (Max night T° tolerance – night minimal T°))/2

Applying the low temperature tolerance day degree (DD) and the high temperature day degree (DD') results in two graphs representing the production potential limits respectively in Winter and in Summer (see Figure 3).

The following assumptions have been made for the purpose of the data interpretation defining day degree crops production potential:

- A negative DD′ score is being considered as a zero-day degree potential growth;
- While the DD′ score remains positive the DD score applies reflecting the higher productivity while temperatures increase;
- The DD score while DD′ remains positive is adjusted by a factor reflecting the number of zero growth days during the week taking into account the days with maximum temperature above 35 °C within a given week for this purpose. In this case: DD'' = DD * (7 – x)/7; x represents the number of days in the week with day maximum temperature above 35 °C; the day degree are cumulated per week in this case – the aim is to thus take into account the stress cumulated by the plants while temperatures physiological tolerance limits are reached frequently over a limited period of time.
- A negative DD score is considered as zero productivity due to cold conditions;
- Cumulated DD′ score below 5 within a given week is considered as zero productivity;
- Cumulated DD score below 5 within a given week is considered as zero productivity;
- The sowing season for cotton production is considered starting after two productive weeks DD'>10 (reflecting practices mentioned by farmers in the field) – two weeks without freeze – mid-April (week 15);
- The sowing period for wheat is here considered taking place two weeks after the cotton harvesting period, thus mid-November (week 46) for the purpose of the study;
- For the purpose of the production Day Degree calculation, the wheat harvest, over the studied period, is assumed taking place the first week of July (almost no growth happens after mid-June while the wheat dries in the fields).
- For the purpose of the DD calculation the rice sowing is considered taking place in spring mid-April (week 15) ensuring no more frost occurs and the harvest counted as the first week of November (week 44) for the Day degrees calculation.

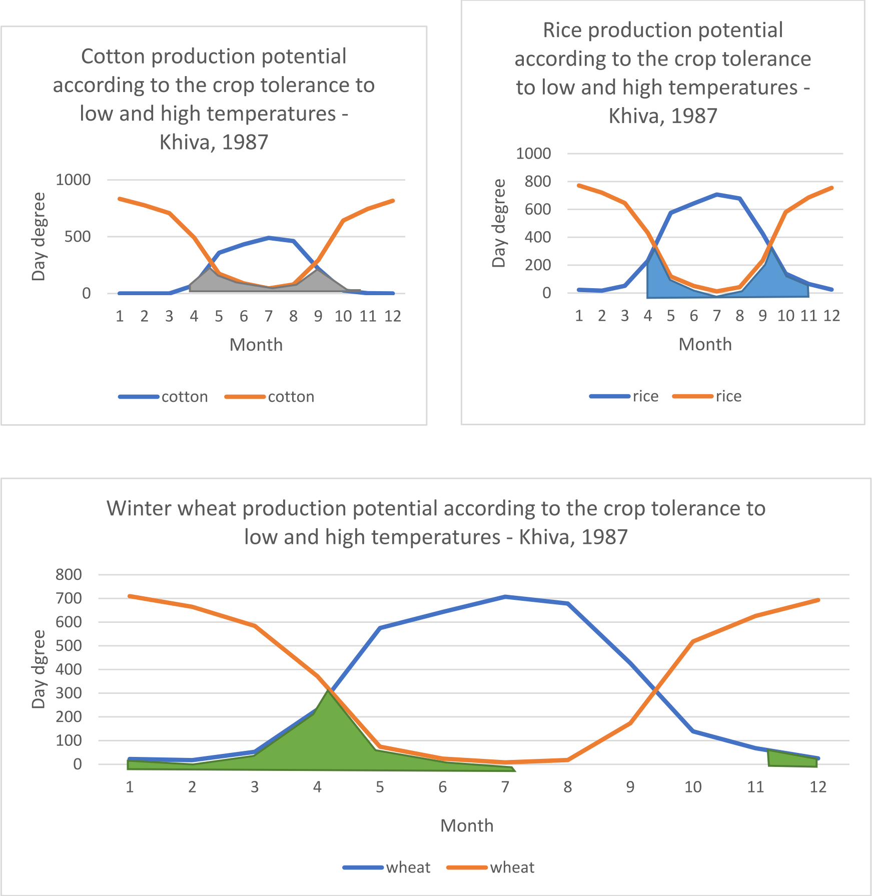

Figure 3. Day degrees according to low temperatures tolerance (DD) and to high temperature tolerance limits (DD′) and resulting ‘growth area’ corresponding to effective day degrees allowing crop development.

The day degrees calculation could be fine-tuned taking into account the temperatures hour per hour over the day and night. However, the temperature variations are mainly relevant in regard of low temperatures, while in the event of tropical nights the plant breathing biochemical mechanisms are threatened at all time of the night, also jeopardizing day plants productive capacity. The trend in the number of hot days and tropical nights events over the Summer don't present strong discrepancies (Figure 21). Besides, climate data present a global trend toward a higher increase in tropical nights than of hot days (Jones et al., 2012). It is thus considered, for the purpose of the present paper, that while minimum temperatures at night exceed the plants physiological tolerance, the growth at day is also dully affected, even though the maximal day temperature is only reached by midday.

The same linear regression line calculation, applied to temperature trends, has been applied to the day degrees analysis.

1.2.3. Hot and cold days trend in Uzbekistan according to the IPCC World bank open-source data

Climatic change models provide an insight on how average temperatures and rain patterns may evolve in average in the future at a global scale. A general warming up of 1–2 °C has been observed since the beginning of the XXth century across Central Asia (Lioubimtseva and Henebry, 2009).

The data available on the open data platform of the World Bank are average trend for Uzbekistan and Turkmenistan. They provide an insight into the overall trend but are not specific to the different regions within the countries. In the broader region, the altitude is an important factor explaining discrepancies, as well as the way mountain ranges influence air masses, stopping winter polar influences especially to the West (Tashkent) and tropical rains from the Indian Ocean to the South. The regression of the Aral Sea is an additional factor influencing the meteorology in the study area.

The data accessible on the open portal of the world bank are not specific to the different sub-regions of the five Central-Asian States, but provide nevertheless a trend which can be compared to the climatic trend observed over the 1986–2017 period at the level of the meteorological stations in the west of Uzbekistan. Temperature increase are projected to be particularly high in Summer and Fall, but lower in Winter (Lioubimtseva and Henebry, 2009).

The data retrieved from the World Bank open portal provides an insight into the regional trend over the XXIst century. For the purpose of the study the Representative Concentration Pathway (RCP) strongest scenario with a climatic forcing of +8.5 Wm-2 in the year 2100 compared to pre-industrial values (RCP8.5) data for Uzbekistan has been retained. The RCP scenarios having been elaborated in 2014, it is assumed that the assessment by then was rather optimist regarding the trend since then and most recent scientific analysis related to climatic prospective.

The study results show a comparable trend with the RCP8.5 scenario with an average temperature increase of 3.7 °C by the end of the century.

Downscaling models allow fine tuning the analysis at the regional or local level. However, further analysis grids are required analysing the impact of those changes on agriculture, energy consumption, health or other aspects of ecosystems and human life.

Modelling crops production under recurrent high temperatures conditions requires analysing daily maximum temperatures and night minimum temperatures, as well as possibly the daily water availability (correlations in this regard could be developed at a further stage). However, in the dependence of crops on irrigation in the study area allows focusing on temperature.

The daily temperatures' to be analysed should include, per month:

- Days with temperatures below the minimum production threshold (indicative 12 °C for cotton);
- Days with temperatures at the maximal optimum temperature (indicative 28 °C for cotton);
- Days with temperatures below the minimum production threshold (indicative 5 °C for wheat);
- Days with temperatures at the maximal optimum temperature (indicative 30 °C for wheat);

The number of days with temperatures below or above the threshold for wheat and cotton production allow drawing conclusions regarding possible shifts in crop seasonality, as well as regarding crops resilience and possible expected shifts in productions.

For the purpose of the trend comparison the number of days with minimal temperature below 0 °C at night (freezing nights) and the number of days per month with temperature above 35 °C at day (hot days) or with minimal temperatures above 20 °C at night (tropical nights) are being analysed. The assumption related to high temperature is that field temperature with direct exposure, as well as soil heating in the case of high temperatures are more extreme than meteorological data. It is therefore assumed that temperatures hot days and tropical nights are good indicators of zero growth conditions for the studied crops.

In the future further studies could be fine tuned analysing field data over the growing cycle of different crops and comparing them to meteorological data allowing introducing correction factors.

2. Analysis of temperature trends and impact on crop production

2.1. Temperature trends between end of 1980's and 2013–17 period

2.1.1. Overall trend in hot days, tropical nights and freezing nights events

The overall trend would be expected to be toward a reduction of the number of freezing nights in Winter and an increase of the number of hot days from April to September. However, while the number of hot days are increasing at a similar path at the level of the four meteorological stations, the trend is not clear toward a reduction of the freezing night events over the Winter (Figure 4). While Takhiatosh (Equation (Eq.) 2.1: y = -0.39 x + 120) and Nukus (Eq. 2.2: y = -0.42 x + 101) stations present a trend toward a decrease of the freezing nights events (Table 2) which results in average in 12 nights freezing events less in average by 2017 compared to 1986 (10–12%). There is no observed trend in the occurrence of freezing nights at the level of Khiva meteorological station (Eq. 2.3: y = 0.045 x + 88.6), while the occurrence is even increasing at the level of Tuyumayun station (Eq. 2.4: y = 0.55 x + 75).

The data of Nukus meteorological station show an increase of the number of hot days (Eq. 2.5: y = 0.39 x + 50) with temperatures above 35 °C (increase of 0.39 hot days per year). The number of freezing nights over the Winter period (Eq. 2.1) are decreasing at the same path as the increase of hot days (Eq. 2.5). Following the observed trend, the Summer will cumulate as many temperature limiting growth Temperature in Winter as in Summer by the second half of the XXIst century (2076 is an indicative value – Table 2). In the course of the XXIst century, the Summer period could become less favourable for crops than the Summer period.

The data of Takhiatosh meteorological station shows a steep increase of the number of days with high temperatures above 35 °C (increase of 1.19 hot days per year – Eq. 2.6: y = 1.19 x + 28). The number of freezing days over the Winter period (Eq. 2.2) are decreasing at a comparable path as the one observed at Nukus station. Following the observed trend, the Summer will cumulate as many temperature limiting growth Temperature as Winter before the middle of the century (2031 is an indicative value – Table 2).

The data of Khiva meteorological station shows that the number of hot days (Eq. 2.7: Y = 0.55 X + 47.2) are increasing in average by half a day per year. The number of freezing nights over the winter period (Eq. 2.3) remains quasi constant over the same period. The relative standard deviation applying to the trend in the number of hot days at Khiva meteorological station is of 27% which is a bit less than the expected increase in the number of hot days events over the period (35%). Thus, if a marked trend can be observed toward an increase in hot day events (Eq. 2.7), the observed data remain insufficient to draw strict conclusions related to the path of change. Following the observed trend, by the second half of the century (2068 is an indicative value – Table 2), the Summers and Winters are expected to present the same number of days with temperatures (whether too high por too low) not allowing crops growth.

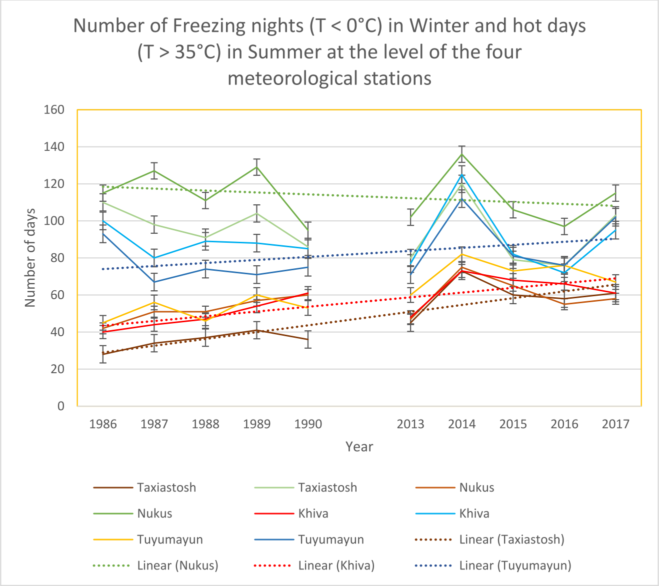

Figure 4. Number of cumulated Freezing nights in Winter and hot days in Summer over a year trend at the level of the four meteorological stations between 1986-1990 and 2013–2017 periods.

The data of Tuyumayun meteorological station show a quick increase of the number of hot days (Eq. 2.8: y = 0.97 x + 47) with temperatures above 35 °C (increase of 0.97 days per year). The number of freezing nights over the Winter period (Eq. 2.4) are also increasing even though at a slower path. Following the observed trend, by the middle of the XXIst century (2053 is an indicative value-Table 2), the number of hot days in Summer will be as numerous as the number of freezing nights over the Winter.

However, the Winters are not becoming warmer at the same path as the increase in hot days events over the Spring and Summer period. Until the end of the XXIst Century both seasons will face temperatures affecting crop growth.

The discrepancy between the results at the level of the four meteorological stations reflects the overall uncertainty due to yearly variations, as well as the differing conditions in the vicinity of the Aral Sea Basin and in Khiva flood plain. However, an overall trend can be distinguished. Even if it is not possible to state exactly in which year temperatures will reach a level barely allowing crop growth over the Spring and Summer period, trends remain significant. Besides, it is also possible to estimate in which time horizon specific crops potential growth might become too low to justify cultivation.

2.1.2. Trend in hot days and seasonal shift

There is no major discrepancy in the seasonal occurrence of hot days in between the four meteorological stations. The data of Khiva are used to illustrate the trend in number of hot days over the studied period.

There is no significant change in the number of hot days in June and July (Figure 5). However, the hot days event are increasing in May and

Table 2. Linear trend in hot days occurrence according to the meteorological station (X stands for the number of the year, X = 1 for 1986, X = 32 for 2017; Y stands for the number of freezing nights in column 2 and to the number of hot days expected a given year in column 3).

Station	Number of freezing nights (minimal T < 0 °C)	Number of hot days (T > 35 °C)	Year, Number of hot days equals number of freezing nights over the year	Year, Number of hot days exceeding 100 days in summer
Nukus	$Y (T < 0\ ^\circ C) = -0.39 X + 120$ (Equation (Eq.) 2.1)	$Y (T > 35\ ^\circ C) = 0.39 X + 50$ (Eq. 2.5)	2076	2114
Takhiatosh	$Y (T < 0\ ^\circ C) = -0.42 X + 101$ (Eq. 2.2)	$Y (T > 35\ ^\circ C) = 1.19 X + 28$ (Eq. 2.6)	2031	2046
Khiva	$Y (T < 0\ ^\circ C) = 0.045 x + 88.6$ (Eq. 2.3)	$Y (T > 35\ ^\circ C) = 0.55 X + 47.2$ (Eq. 2.7)	2068	2082
Tuyumayun	$Y (T < 0\ ^\circ C) = 0.55 X + 75$ (Eq. 2.4)	$Y (T > 35\ ^\circ C) = 0.97 X + 47$ (Eq. 2.8)	2053	2031

August, especially over the last decade, increasing the low growth Summer period. The relative standard deviation applying to the trend in the number of hot days is of 23% for June, of 16% for the observed values in July and of 35% for August. The relative standard deviation is increasing considerably for May and September with respectively 65% and 73%. Between 1986-1990 and 2013–2017 the number of hot days are increasing by 100% in average in May and by 50% in August. For those two months the increase in hot days events is substantially higher than the relative standard deviation to the average of the period 1986–2017. The observed data thus suggest that the hot period is progressively extending into May and August at the level of Khiva meteorological station, while there is no clear trend toward an increase for the months of June and July which cumulate already a high number of hot day events.

The interannual variations are thus much higher in the inter-seasons while the trend is much more stable in hearth of the Summer. Even though, a clear trend can be observed toward an increase of the number of hot day events, strong interannual variations may continue to be expected, especially in the Spring and in the Fall.

The relative standard deviation for the month of May reflects partly the increase in the number of hot day events compared to the average over the period; the hot days occurrence has doubled in average between 1986-1990 and 2013–2017.

The slight increase in the number of hot days in September is not of statistical significance in regard of the relative standard deviation.

The overall extension of the hot period can be observed at the level of the four studied stations.

At the level of Khiva meteorological station, the trend related to hot days event in May is increasing at the path of, in average, one additional hot day every five years. Following this trend, the number of hot days events increases in average by one every five years; in this case 100% of the days would be above plants cultivation tolerance in May by 2136. However, agriculture would be far too unfavourable in May before reaching this point.

An insight into the average temperature in May and September may provide a further indication of the trend related to the extension of the Summer period.

The trend in average temperature in May doesn't show a significant increase over the period 1986–2017 (Figure 6).

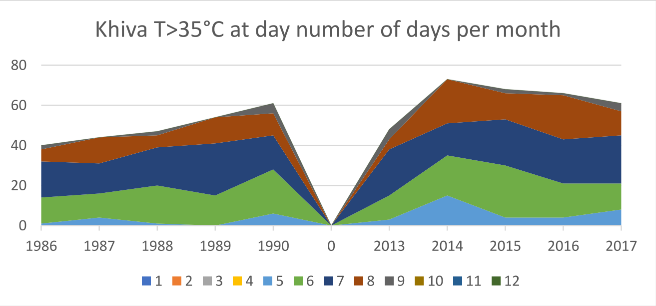

Figure 5. Trend in occurrence of hot days (>35 °C) at Khiva meteorological station.

The trend in average temperature in September doesn't show either a significant increase over the period 1986–2017 (Figure 7).

The mid-season average temperature in May and September show little change and few discrepancies between the four meteorological stations.

2.1.3. Trend in cold days and seasonal shift

There is no major discrepancy in the seasonal occurrence of freezing nights in between the four meteorological stations. The data of Khiva are used to illustrate the trend in number of freezing nights over the studied period.

The trend which could be expected toward milder winters is barely observed over the period.

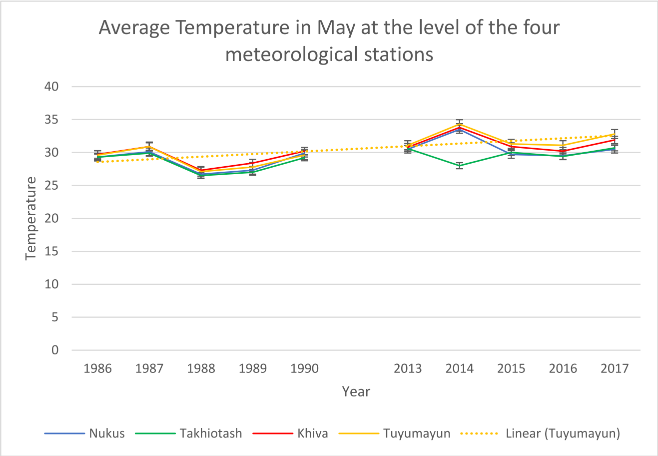

Figure 6. Trend in average temperature (°C) in May over the 1986–2017 period, at the level of the four meteorological stations.

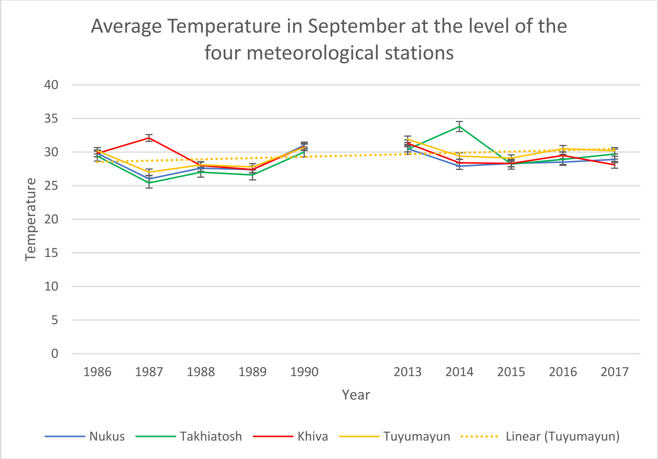

Figure 7. Trend in average temperature (°C) in September over the 1986–2017 period, at the level of the four meteorological stations.

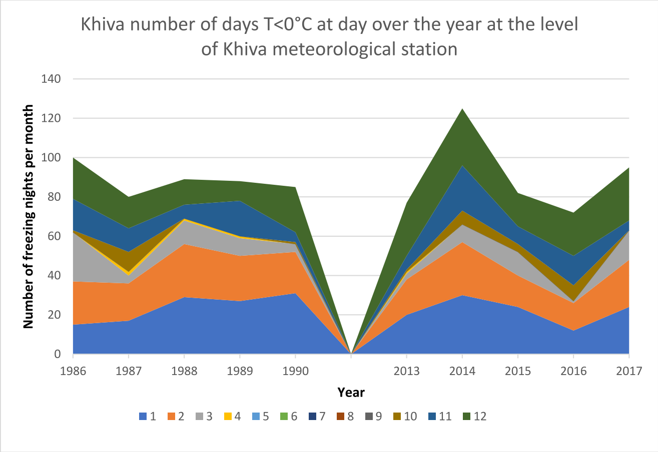

Figure 8. Trend in occurrence of cold days (T < 0 °C at day) per month over 1986–1990 and 2013–2017 periods at Khiva meteorological station (the numbered colours correspond to the months of the year).

The main cold months are December, January and February (in green, light blue and orange in the graph), with freezing nights occurring from October some years until March (Figure 8). There is no clear trend toward a reduction of the number of days below zero over the thirty past years. No clear reduction of the number of cold days can either be observed in March or in November (Figure 8). The main change would be related to the quasi disappearance of cold days in April (yellow line) which reduces the risk of late frost and allows progressively planning earlier sowing.

January in the middle of the Winter period is in the coldest period.

The average temperature in January provides a further insight into temperature trends in the Winter period.

The average temperatures trend in January, with a variation of less than 20% at the level of the four meteorological stations, doesn't show a significant increase over the period (Figure 9). The corresponding relative standard deviation to the average of the period 1986–2017 is of 50% for the average January temperatures. Thus, no trend can be drawn regarding a possible change in average temperatures for the month of January. Average temperatures fluctuate considerably from one year to another possibly depending on the influence of Siberian airmasses coming further South in some years. The slightly hotter climate observed in Khiva and Tuyumayun laying hundred kilometres Southward could benefit from the protection of Southern airmasses reducing the Siberian influence. However, the water masses and the vegetation more present around Tuyumayun and Khiva could also be an important mitigation factor. Both stations are also more far away from the influence of the disappearing Aral Sea to the North-West of Nukus. In this background the trend observed at the level of Khiva and Tuyumayun stations, more far away from the former Aral Sea Basin, may be more representative of the changes induced by the climate change, independently from other local climate influencing factors.

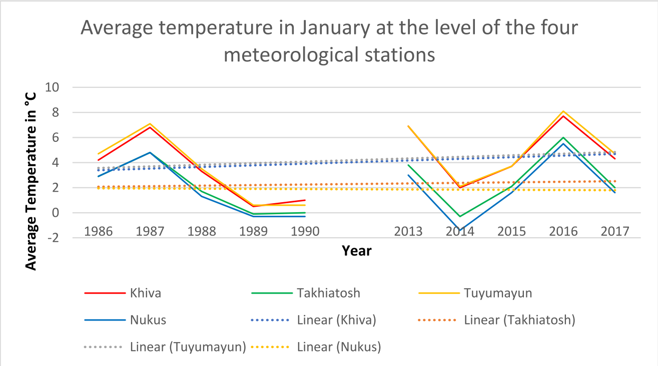

Figure 9. Average temperature in January at the level of the four meteorological stations over 1986–1990 and 2013–2017 periods.

The Winter period can be defined, as the period covering the months with a significant number of freezing nights. The Winter period thus runs from November to March. The trend in average temperature in those months allows to assess to what extent the cold period is becoming shorter.

The average temperature in March is increasing by 23% at the level of Tuyumayun meteorological station to 32% at the level of Takhiatosh meteorological station over the studied period 1986–2017 (Graph 9). The relative standard deviation is included in a range between 16% for Tuyumayun meteorological station and 22% for Nukus meteorological station. The trend in the increase in Temperature at the level of the four meteorological stations in March can thus be considered as significant, even though the path of change may be taken with caution.

The linear regression lines for Takhiatosh in the vicinity of Nukus and for Tuyumayun to the South show a parallel trend. The difference between the meteorological stations, within a 5% error margin, is not significant. The increase in average temperatures shows a trend toward warmer temperatures with a shift from 8-10 °C in years 1986–1990 to 12–15 °C in years 2013–2017.

The average temperature variation in March is significant, with a temperature increase of 3.3 °C in Khiva (28% increase over the period – Eq. 3.3: $y = 0.11\ x + 11.9$) for a relative standard deviation of 18% (Table 3, Figure 10).

The average temperature increase, over the period 1986–2017, in November is of less than 10% for Nukus, Takhiatosh and Tuyumayun meteorological stations (Figure 11 - Eq. 3.5 (Nukus): $y = 0.02\,x + 8.7$; Eq. 3.6 (Takhiatosh): $y = 0.03\ x + 8.9$); Eq. 3.7 (Khiva): $y =$ -0,08 x + 12,3; Eq. 3.8 (Tuyumayun): $y = 0.02\ x + 11.1$). A slight average temperature

Table 3. Average temperature in March and in November (X stands for the number of the year, X = 1 for 1986, X = 32 for 2017; Y stands for the average temperature expected for May or November a given year; the coefficient in front of X indicates the path of change).

	Calculated linear regression lines – the coefficient in front of 'x' provides a measure of the average annual variation in the longer term	
	March	November
Nukus	$y = 0.12\ x + 9.8$ (Eq. 3.1)	$y = 0.02\ x + 8.7$ (Eq. 3.5)
Takhiatosh	$y = 0.13\ x + 9.9$ (Eq. 3.2)	$y = 0.03\ x + 8.9$ (Eq. 3.6)
Khiva	$y = 0.11\ x + 11.9$ (Eq. 3.3)	$y = -\ 0.08\ x + 12.3$ (Eq. 3.7)
Tuyumayun	$y = 0.11\ x + 12.4$ (Eq. 3.4)	$y = 0.02\ x + 11.1$ (Eq. 3.8)

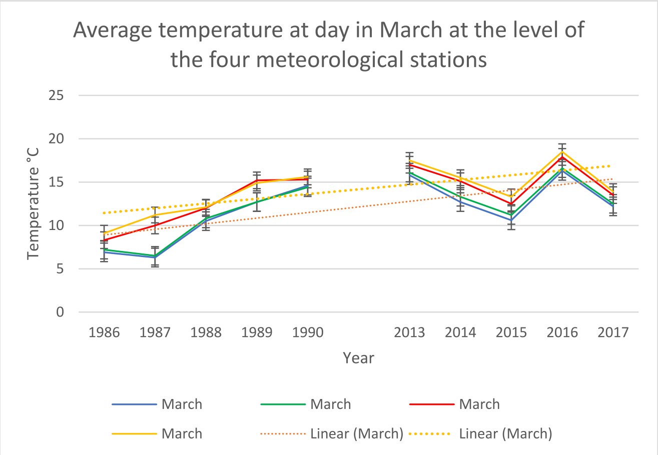

Figure 10. Average temperature in March at the level of the four meteorological stations over 1986–1990 and 2013–2017 periods.

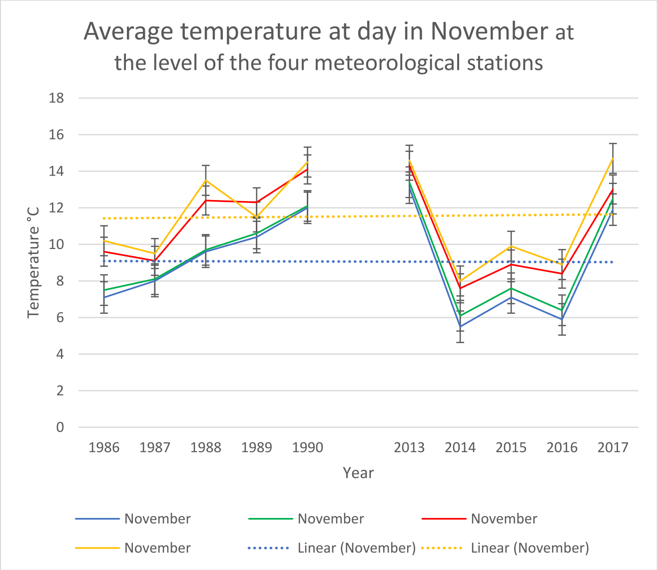

Figure 11. Average temperature in November at the level of the four meteorological stations over 1986–1990 and 2013–2017 periods.

decrease is even observed at the level of Khiva meteorological station (Table 3 – Eq. 3.7). The relative standard deviation to the period average is similar for the four meteorological stations ranging between 20 and 26%.

The average temperature in November thus present high inter annual fluctuations and a lower trend in temperature increase which doesn't allow drawing conclusion regarding a change in November average temperature over the period 1986–2017.

Thus, the month of March is becoming warmer over the past decades, while the month of November doesn't show a significant change over the period. A warmer month of March plays in favour or an early development of the winter wheat, decreasing the crop risk of exposure to early hot days events increasing occurrence in May.

The trend in freezing night decrease in the months of March and November may provide a further insight into changes which might be favourable for field crops early sowing and late development.

The number of cold days presents a trend toward a decrease in March (Figure 12; Table 4 - Eq. 4.1 (Nukus): $y = -0.28\ x + 20.7$; Eq. 4.2 (Takhiatosh): $y = -0.27\ x + 16$; Eq. 4.3 (Khiva): $y = -0.09\ x + 10.9$; Eq. 4.4 (Tuyumayun): $y = -0.05\ x + 8.8$). The trend is more marked for Nukus and Takhiatosh meteorological stations (Eq. 4.1 & 4.2) with a variation of 112% and 140% over the period 1986–2017. The trend is less marked at the level of Khiva and Tuyumayun meteorological stations with a variation of 58% and 38% respectively.

Table 4. Number of freezing night events (T < 0 °C) trend in March and November, at the level of the four meteorological stations (X stands for the number of the year, X = 1 for 1986, X = 32 for 2017; Y stands for the number of freezing nights expected a given year; the coefficient in front of X indicates the path of change).

	Calculated linear regression lines – the coefficient in front of ‘x’ provides a measure of the average annual variation in the longer term	
	March	November
Nukus	$y = -0.28\ x + 20.7$ (Eq. 4.1)	$y = -0.1\ x + 18.2$ (Eq. 4.5)
Takhiatosh	$y = -0.27\ x + 16$ (Eq. 4.2)	$y = -0.11\ x + 13.5$ (Eq. 4.6)
Khiva	$y = -0.09\ x + 10.9$ (Eq. 4.3)	$y = -0.08\ x + 13$ (Eq. 4.7)
Tuyumayun	$y = -0.05\ x + 8.8$ (Eq. 4.4)	$y = -0.05\ x + 11$ (Eq. 4.8)

The relative standard deviation to the period average is of 43 and 48% for Nukus and Takhiatosh. Both meteorological stations thus present a clear trend toward a decrease in the number of freezing nights over the period 1986–2017.

The relative standard deviations to the period average of 56 and 62% for Khiva and Tuyumayun are higher than the trend in decrease of the number of freezing nights in March. The relative importance of the interannual variation is more important in those cases, reducing the scope to conclude upon a clear trend.

The trend in the reduction of freezing nights in March might partly compensate the increase of hot days events in May (Figure 5), allowing an earlier development of the winter wheat crops. Following the same trend, the earlier sowing of cotton would allow partly mitigating the increasing number of hot days over the Summer period.

The cotton is sown following two consecutive weeks without freeze, in average mid- April, at least until the last decade of the XXth century. The period favourable for sowing cotton appears to be in average two weeks earlier in 2016 than it used to be in 1986 (Figure 13). This is also reflected by the impressions collected, by the author, through interviews with local farmers.

The rice is sown in June. It could possibly be sown earlier over the next decades.

A warming month of November is likely to have a limited impact on the Summer field crops development. It may nevertheless be favourable for late development stages in the case of cotton.

The average increase of temperature is not significant in November (Eq. 3.5 to 3.8) between the end of the eighties and 2017 (Graph 10). The number of freezing nights (Eq. 4.5 to 4.8) is also decreasing at a rather slow path with a variation over the period between 0% and 32% (Figure 14). The relative standard deviations to the period average are of

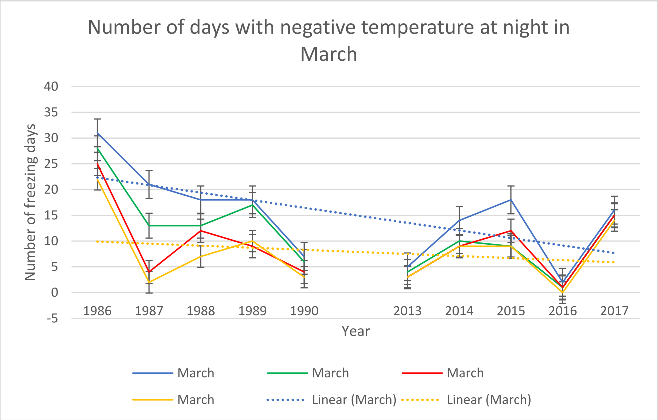

Figure 12. Trend in negative temperature occurrence in March at the level of the four meteorological stations over 1986–1990 and 2013–2017 periods.

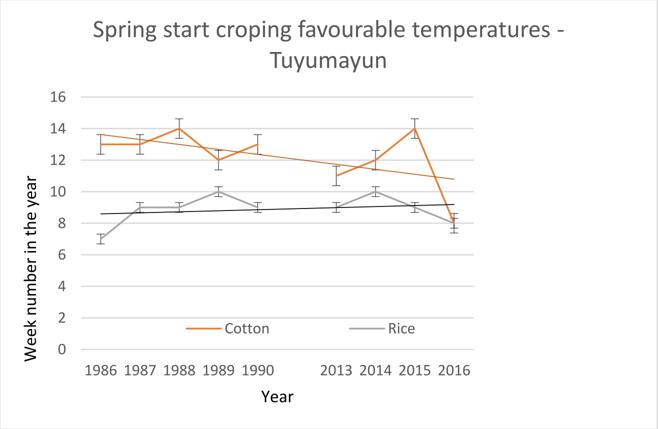

Figure 13. Trend in period favourable for sowing for cotton and rice at the level of Tuyumayun meteorological station over 1986–1990 and 2013–2017 periods.

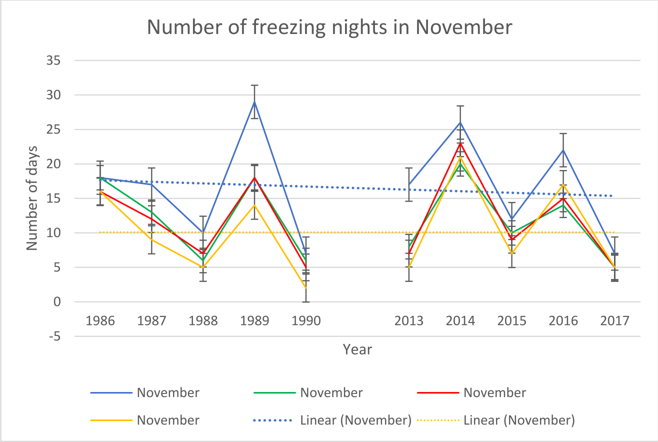

Figure 14. Trend in freezing nights occurrence in November, at the level of the four meteorological stations over 1986–1990 and 2013–2017 periods.

25% for Nukus and between 42 and 61% for the three other meteorological stations. The inter-annual variations are thus rather high while the trend over the period 1986–2017 doesn't allow drawing clear conclusions regarding a possible warming effect in November. The temperature conditions follow a similar trend in November, whether in average temperature (Eq. 3.5 to 3.8) or in number of freezing night events (Eq. 4.5 (Nukus): $y = -0.1\ x + 18.2$; Eq. 4.6 (Takhiatosh): $y = -0.11\ x + 13.5$; Eq. 4.7 (Khiva): $y = -0.08\ x + 13$; Eq. 4.8 (Tuyumayun): $y = -0.05\ x + 11$) at the level of the four meteorological stations.

Following the observed trends freeze at night in March would disappear at night between 2107 (Eq. 4.3) and 2162 (Eq. 4.4) in Khorezm flood plain and between 2045 (Eq. 4.2) and 2060 (Eq. 4.1) around Nukus.

There is no clear trend toward freeze disappearing in November. Following the observed trend freeze at night in November would not disappear around Nukus before the 22nd century (Eq. 4.5 & 4.6).

The difference in trend in March between Karakalpakstan and Khorezm flood plain (Figure 10) is partly explained by the mitigation effect of the water and the vegetation in Khorezm (Lioubimtseva and Henebry, 2009), while Nukus has been directly affected from the withdrawal of the Aral Sea and thus doesn't benefit anymore, or less, from a similar temperature mitigation effect, inducing a stronger inertia.

Thus, while no significant cultivation period gain is expected in November, the cropping season, especially for cotton, could progressively start earlier in March instead of April. However, the benefit of an earlier starting cropping season will be lost while the high temperature in Summer will become a predominant limiting factor. Besides, the water availability is likely to decrease over the next decades will the flow of the melting glaciers (Punkari et al., 2014) will reduce and the surface water evaporation increase.

A reduced water availability could in turn influence the local climate which could follow, in Khorezm flood plain, a trend similar to the one observed at the level of Nukus meteorological station.

2.2. Day degrees and crops production

Khiva meteorological station is located in a broad irrigated area and has been taken as such as reference station for the purpose of illustrating the agroclimatic trends in crop production.

Cotton and rice present a progressive decline in productivity over the 1986–2017 period. The trend is more marked for the cotton with a decline in productivity of about 25% (drop from 800 to 600 day degrees). The decrease in production potential of the rice is declining at about half that speed. remain competitive in the Summer period (Figure 15). The relative standard deviations to the period average are of 26% for the cotton and of 13% for the rice which is line with overall observed trend.

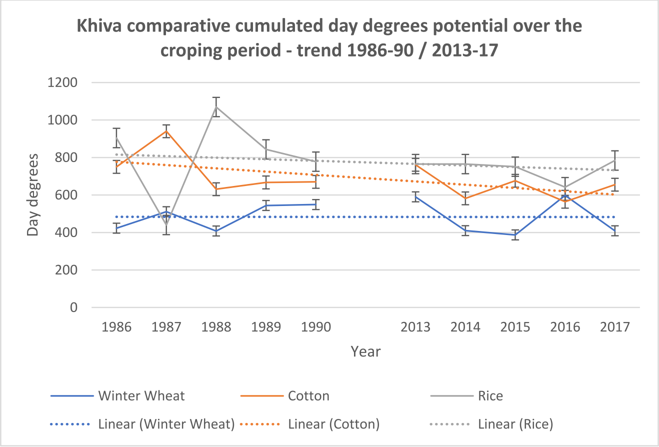

Figure 15. Trend in the Day degree production potential for the cropping season of winter wheat, cotton and rice in the vicinity of Khiva, over 1986–1990 and 2013–2017 periods.

The trend regarding Winter wheat is rather constant over the 1986–2017 (Figure 15), but could improve slightly if the winters should become milder over the coming decades. Whatsoever, the relative standard deviation to the period average is of 12% for the wheat which rather reflects inter-annual variations than a clear longer-term trend due to possible climatic changes in the Winter period.

The rice may stay competitive over the forthcoming period. However, the quantity of water required for rice cultivation is already much higher than for wheat or cotton and it is likely to increase following the temperature trend. Additionally, rice cultivation with a high volume of evaporated surface water may have an increasing impact on the local soil salinization processes.

There is no significant change in the number of zero growth weeks over the Winter period (Figure 16). The issue is mainly relevant for the Winter wheat. The day degrees applied to winter wheat in the vicinity of Khiva meteorological station, for the cropping season 2016/17, shows a clearly delimited growth period (Figure 17).

The wheat is sown at the wake of winter time but the growth mainly takes place starting the fourth week of March (week 13 of 2017) until the mid of May (week 19–20 in 2017) (Figure 17). The harvest takes place in July when the wheat has dried. The high temperature from mid-May and into the Summer don't allow the wheat growth. Ideally an optimal growth cycle would require 1600 cumulated day degrees *(P. Miller, W. Lanier, S. Brandt)*. The cumulated day degrees of the winter wheat production in the vicinity of Khiva meteorological station in 2016 have been below 650 (Figure 17).

The wheat is going through all plant development stages, allowing harvesting, even though the cumulated day degrees are sub-optimal. The

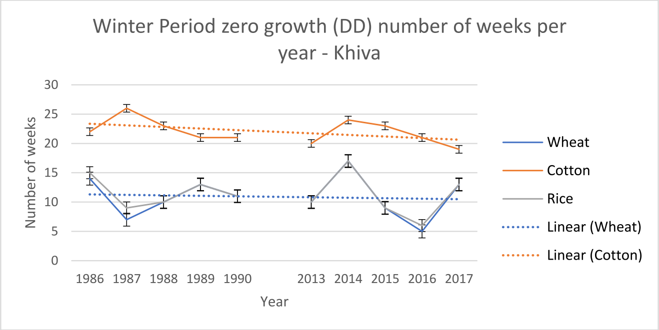

Figure 16. Trend in number of weeks too cold to allow vegetation development over the Winter period at the level of Khiva meteorological station over 1986–1990 and 2013–2017 periods.

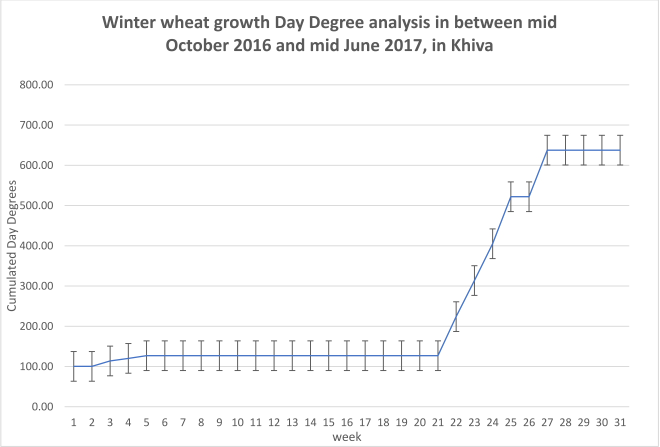

Figure 17. Cumulated day degrees growth potential for winter wheat in 2016/2017 winter season in the vicinity of Khiva (week 1 is week 46 in 2016; week 8 is week 1 in 2017; week 21 is the 13th week in 2017).

low day degrees potential implies that temperature is a main limiting factor for winter wheat along the flood plain in between the desert ranges of the lower Amu Darya. Wheat production conditions, over Summer, have much better growth conditions upstream closer to the Mountain ranges to the East of Uzbekistan.

High temperatures affect the crops over the Summer. The high temperatures barely affect the Winter wheat which is drying in the fields in June. However, it is a matter of concern for the Summer crops alike the cotton and rice.

The number of hot days events is increasing over the period 1986–2017 and so are the number of weeks where zero growth is happening (Figure 18). However, the growth potential remains relatively high for cotton and rice and doesn't jeopardize those crops in the short term. Nevertheless, the main risk in a near future is related to the shifts in hot day events and the growing risk that those may coincide with a critical development stage of the crops, alike flowering or the seeds development (Hatfield and Prueger, 2015).

The plants productivity varies from day to day according to the day and night temperatures. Besides, the vegetative growth, some stages are critical for the plant productivity including the fertility, the number of seeds developing, the size of those and their germination potential.

Over the Cotton cropping season in 2017 week 27, 30 to 32 and 35 have been especially hot stopping the cotton plants development (Figure 19). If such events coincide with critical crops development stages (Gintzburger et al., 2003; Rafiq Zahid et al., 2016), they can have a considerable effect on the yield to be expected, eventually annihilating any harvest perspective.

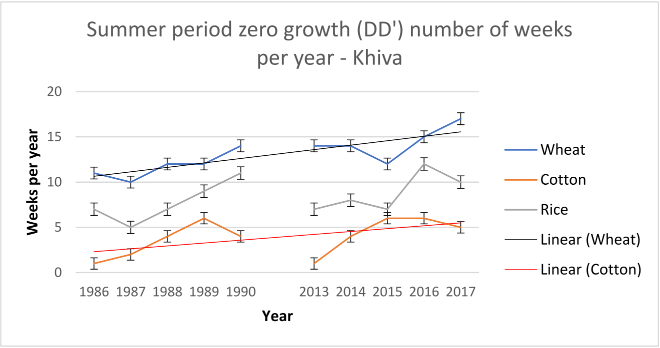

Figure 18. Trend in number of weeks too hot to allow vegetation development over the Summer in the 1986–2017 period at the level of Khiva meteorological station.

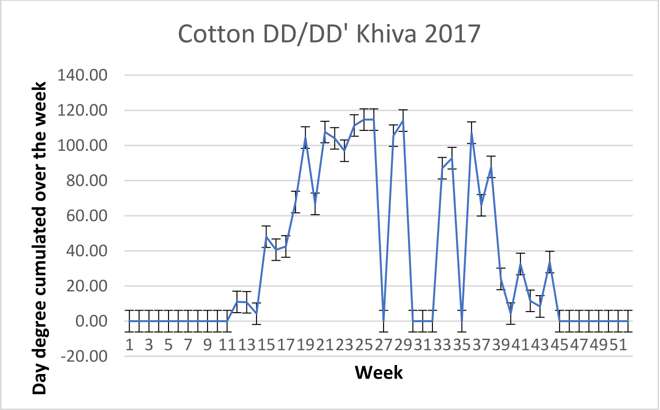

Figure 19. Day degrees (DD/DD′) cotton production potential per week over the year 2017 following Khiva meteorological data.

In 2017 conditions were still rather favourable. With conditions favourable for sowing in week 16 (mid-April – following two weeks without freeze at night) and the first week really impacted by hot days in week 27 (first week of July), the cotton crops had 12 weeks of optimal conditions to develop and pass critical flowering and seed development stages (Figure 19). The succession of hot days events in July and August may still affect the seeds production and therefore the yield. The germination potential may thus be expected to be strongly affected, which would exclude the region from seeds production.

Comparing climatic data over different years at different development stages, with the yields harvested in a sample of fields, would allow fine tuning the analysis.

2.3. Climatic change prospective modelling - hot days trend in Uzbekistan according to the IPCC World bank open-source data

Climatic change models provide an insight into how average temperatures and rain patterns may evolve in average in the future at a global scale. The number of hot days and tropical nights events foreseen by the model are an average at the country level including desertic lowlands of the West and high mountains of the East. Downscaling models allow fine tuning the analysis at the regional or local level.

Reflecting the national average, the number of hot days with temperatures above 35 °C for the years 2020–2040 (Figure 20) are substantially lower (about twice less) than the number of days observed for the period 1986–1990 and 2013–2017 at Khiva meteorological station (Figures 4 and 5). This reflects the difference between local conditions and a national average.

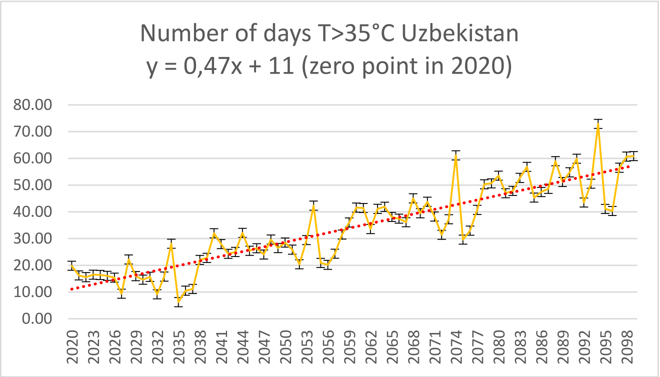

Figure 20. Trend in number of hot days events over the XX1st century in average in Uzbekistan, according to RCP 8.5 scenario.

Table 5. Trend in hot days events in 1986 and 2017 and over the century following the observed trend, at the level of the four meteorological stations (X stands for the number of the year, X = 1 for 1986, X = 32 for 2017; Y stands for the number of hot days expected a given year).

Station	Number of hot days (T > 35 °C)	Number of hot days observed in 1986	Number of hot days observed in 2017	Number of hot days expected in 2050 – observed trend	Number of hot days expected in 2100 - observed trend
Nukus	$Y (T > 35\ ^\circ C) = 0.39\ X + 50$ (Eq. 5.1)	42	58	75	94
Takhiatosh	$Y (T > 35\ ^\circ C) = 1.19\ X + 28$ (Eq. 5.2)	28	61	104	164
Khiva	$Y (T > 35\ ^\circ C) = 0.55\ X + 47$ (Eq. 5.3)	40	61	82	109
Tuyumayun	$Y (T > 35\ ^\circ C) = 0.97\ X + 47$ (Eq. 5.4)	45	67	109	157

The trend of the global model (Eq. 6: $y = 0.47\ x + 11$) is close to the trend observed at Khiva meteorological station over the 1986–2017 period (Eq. 5.3: $y = 0.55\ x + 47.2$). The average increase is of half a day hot event per year. The linear trend for Khiva meteorological station gives 70 days with temperatures above 35 °C in 2020. According to this trend the number of very hot days would average 84 in a given year by the mid of the XXIst century and 108 days by the end of the century (Table 5).

Over the 1986–2017 period, the trend in increase of the number of tropical nights follows about the same path as the increase in hot days, even though a delay can often be observed between hot days and tropical night events. At the level of Khiva meteorological station, hot days and tropical nights follow a similar trend in June over the period from 1986 to 2017. The tropical nights are rather predominant in July. Even though, the number of hot days has been substantially higher than the number of tropical nights in 2014 and 2016, the overall trend between hot days and tropical nights remains similar (Figure 21).

The night temperatures are of crucial importance to the plant physiology allowing them to carry out physiological processes for which lower temperatures are required. The high increase in tropical nights alike hot days will be an important element affecting plants productivity over the XXIst Century.

Following the observed trend over the period 1986–2017, between 50 and 72% of the days between the first of May and the 30th of September would be hot days by 2050 and up to 100% by 2100 (Table 5 – Eq. 5.1 to 5.4). Thus, even though the climate change didn't have a major impact on cotton and rice Summer productions until recent years, the conditions for the growth of those and other crops over the Summer period could be expected to deteriorate considerably over the coming decades.

With the main hot days until now concentrated in June, July and August the hot days will mainly expand into Spring and into Fall (Figure 22). However, the higher occurrence of hot days will also increase the risk for the yields, if the hot days events take place at a critical point of the plant or seeds development.

The global model shows a progressive increase in very hot days in May and September as well as in April increasing significantly over the century (Figure 22). This trend can be expected to be accentuated in the West of Uzbekistan (Aral Sea Basin). The continental location, the low altitude and the expected water shortages, increasingly reducing water bodies and irrigated plain area, are not leaving much scope for natural mitigation mechanism. The main hot day events increase is taking place over the Summer period, extending in May and September. By the second half of the century the number of hot days event is expected to become progressively also more significant in April and October.

The similar trend observed over the past decades in the West arid lowlands of Uzbekistan and from the global model forecast in average for Uzbekistan, possibly means that the observed trend at the local level will accelerate over the XXIst century. In such a scenario the trend described in the present publication might be an optimist scenario. The global

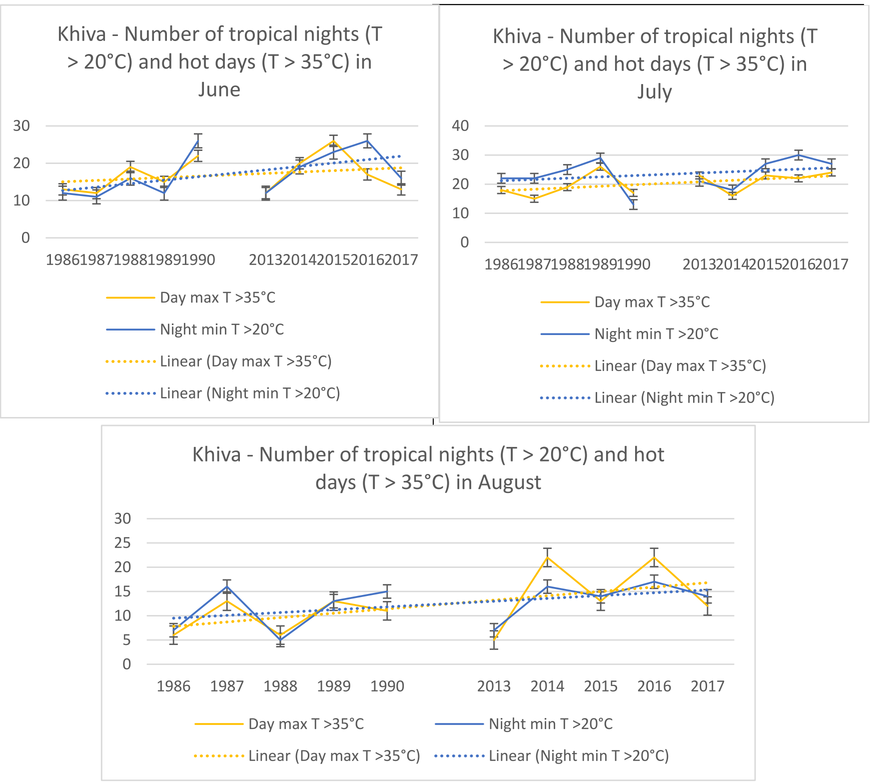

Figure 21. Trend in hot days and tropical nights occurrence in Summer between 1986 and 2017.

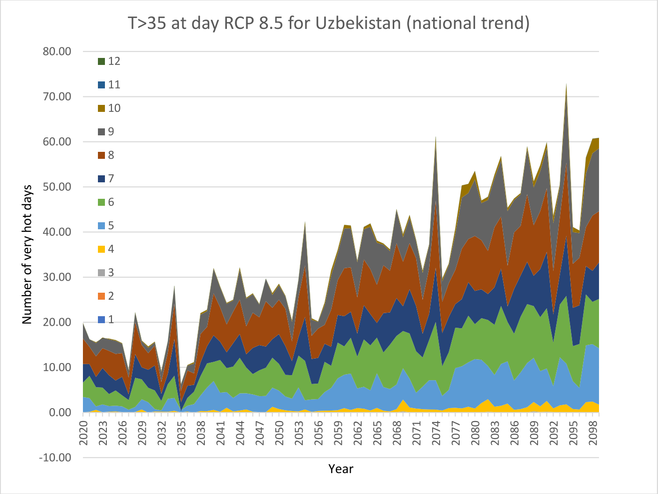

Figure 22. Model expected hot day events per month in average in Uzbekistan over the century following the RCP 8.5 scenario.

model also shows an extension of the hot days events into Spring and Fall (Figure 21) even though this has been the case only in a very limited manner over the studied period of time.

3. Discussion

The described trend applies to the lowland in the West of Uzbekistan and may not apply to other areas of the country alike higher altitude flood plain in the vicinity of the mountains to the East.

The close to absence of rain in the region making agriculture fully dependant on the water from the Amu Darya river, allows focusing the analysis on temperature patterns. The observed differences between the meteorological in the vicinity of Nukus affected by the withdrawal of the Aral Sea and stations located 100 km to the South allows distinguishing to some extent the local influences from the global warming process. Comparing trends between 1986 and 2017 with global warming models forecast until the end of the XXIst century allows further anticipating future changes. There is scope for fine tuning the analysis and extending it to new areas. In the present case some trends can be defined and conclusions drawn regarding how agriculture may evolve in the region over the next decades.

The number of days with temperatures below or above the threshold for wheat and cotton production allow drawing conclusions regarding possible shifts in crop seasonality, as well as regarding crops resilience and possible expected shifts in production. The day degrees methodology, adjusted to take into account the effect of high temperatures provides a useful insight regarding the trend in crop yields.

The increase in the number of days with temperatures above 35 °C follows a constant trend for the years over the period 1996–1990 and 2013–2017 (Table 2). The climate change level at the level of Uzbekistan over the century shows a similar trend (Figure 20). The same trend applies to tropical nights (Figure 21). Beyond the global climate change other factors influence the local climate alike the quick withdrawal of the Aral Sea since 1987. However, this factor doesn't result in a major discrepancy between the meteorological data observed in the vicinity of Nukus, to the North and hundred fifty kilometres to the South in the Khorezm region.

Even though no significant change has been observed in May and September over the past thirty years (Figures 6 and 7), by the end of the century the hot days and nights in those months may become predominant, following the trend observed over the 1986–2017 (Table 5). The same trend is observed analysing the data provided by the global model for Uzbekistan (Figure 20). In the course of the century Summers are likely to become progressively too hot for cotton and rice production (Table 2). Summer crops productivity is expected to diminish increasingly over time (Figure 15).

According to other studies, the foreseen yield reduction, by 2050, in the West-Uzbekistan steppe agro-ecological zone is expected to be in between 19 and 31% for cotton and 13 and 32% for winter wheat (Sutton et al., 2013).

Over the period 1986–2017 the hot days have been concentrated in June, July and August (Figure 5). The hot days events in May have started increasing over the last decades. Winters average temperatures in November and January didn't present significant changes over the same period (Figures 9 and 11). However, in March freezing nights decreased (Figure 12). Even though this trend didn't translate yet in more favourable winter wheat production, it could still be the case over the next decades. The World Bank study forecast of a winter wheat yield decrease by 2050 (Sutton et al., 2013) would be assessed along the expected reduced water availability. Summer crops will continue facing the risk of freezing nights in March in the meantime, thus limiting the scope for early sowing. Following the observed trend and in line with the global model, it would be expected that freezing nights occurrence will totally disappear in March by the beginning of the XXII century (Table 2).

Winter wheat could thus gain in productivity while Winter temperatures will rise, especially in early Spring (Figure 17). The trend regarding winter wheat barely shows any variation over the period 1986–2017 (Figure 15), but could improve slightly if the Winters should become milder over the coming decades.

In between 2031 and 2076 a turning point is expected to take place while hot days events in Summer will exceed freezing nights in Winter (Table 2). This would mean that the Summer period could progressively become an unfavourable cropping season to the same extent Winters can be.

The cotton and rice crops vegetation development potential is remaining high, up to 2017, over the Summer period (Figure 19). However, high temperatures at critical stages of the crop development may represent an increasing risk jeopardizing the expected yields (Hatfield and Prueger, 2015). This risk will increase at a quick path over the next decades, while increasing temperatures will also limit the plants vegetation production potential (biomass). Following the observed trend between 50 and 72% of days between May and September will be hot days events by 2050 and 100% by 2100 (Table 2).

Even though, rice production presents a less significant trend toward a production decrease than cotton (Figure 15), the production potential is expected to decline over the XXIst century. Besides, the quantity of water required for irrigation is likely to increase following the trend in temperature increase. Additionally, rice cultivation with a high volume of evaporated surface water has a strong impact on the soil salinization process. Due to water reuse in irrigation along the Amu Darya the water salinity has increased from 500 mg per litre in 1960 to 1,000 mg in 1990 (Pavlovskaya, 1995).

The water flowing into the regions downstream from Tuyumayun are mainly coming from the high mountains located to the East of Uzbekistan. Almost 40% of the inflow in upstream Amu Darya is generated by glacial melt. The inflow into the downstream area is expected to decrease by 26–35% by 2050 (Punkari et al., 2014). The situation is expected to further deteriorate with the increased temperatures and evapotranspiration, while the river discharge will radically reduce over time.

The increase in water demand by 2050 at the national level is expected to increase in between 9 and 14% for cotton and in between -1 and 5% for winter wheat (Sutton et al., 2013; Rakhmatullaev and Abdullaev, 2014; Lioubimtseva and Henebry, 2009). The decrease in water availability would further be expected to result in higher temperatures in Summer and to some extend in lower temperatures in Winter (Pielke et al., 2007).

Therefore, high temperatures can be expected to become an increasing challenge for the region, until the situation will become such that Summer crops won't be an option any more in the second half of the XXIst century (Table 5). Winter crops, on the other hand, may benefit from slightly better yields, in the course of the century. A shift in production in the Spring and Fall periods could be foreseen.

Winter crops have the advantage of requiring less water while temperatures remain low. In Uzbekistan in average cotton requires in between 10,000 and 12,000 cubic metre per cultivated hectare, while winter wheat requires in between 8,000 and 9,000 cubic metres (FAO, 2012). Winter wheat benefits also from the limited seasonal rainfalls occurring over the Winter period.

However, the cotton and wheat production are already assessed as having a negative cost/benefit balance in Uzbekistan (Sutton et al., 2013). The economic rationality of those crops in the arid areas west of Uzbekistan is expected to worsen.

Plants fixing carbon on four carbon molecules (C4) allows plants to reduce their stoma openings with a higher carbon gradient resulting in a higher photosynthesis with a reduced evapotranspiration (Yin and Struik, 2009). Maize, sorghum or millet thus present a higher temperature resistance. However, maize requires more water availability which may not be suitable to the area. Sorghum presents better characteristics and lower water demand but produces also lower yields. Millet presents a higher resilience but also with even lower yields. A shift toward high value crops, including fruit and vegetables resilient plants, alike pomegranate, on smaller surfaces might also be assessed as more rationale over the upcoming decades.

The defined trends based on regression lines present a relatively high error margin as illustrated by the relative standard deviation calculations. In some cases, the conclusion is that there is no significant change in temperature patterns for given months, alike November for the studied period 1986–2017. However, some trends are more marked, even though the speed and the extent of the subsequent expected change over the XXIst century may still be assessed with caution.

The methodology may be fine-tuned comparing field temperature collected at different heights and at different crops development stages, as well as air humidity parameters. The temperature pattern and how it evolves between day and night may be also further analysed and incorporated in a more complex model. The difference in temperature between the leaves and the air (Cottee, 2009) would require a special attention. However, the conclusions reached in the present paper regarding the West of Uzbekistan, would not change in substance regarding the effect of high temperatures. In the present case, temperatures at night, can be taken as the main limiting factor affecting plant physiology in Summer. The similar occurrence of tropical nights and hot days events (Figure 21) allows to draft a trend considering that plants production is drastically reduced when temperatures remain high at night. Tropical nights are likely to be a main limiting factor in the future in the study region. The methodology would require being further refined to take into account the broader water availability. If to be applied in other areas of the world, the methodology would require taking into account other factors, alike rain patterns and soil and air humidity. Finally comparing the day degree trend as presently defined with reliable crop yields data at the field level, for as far as those can be made available, would allow developing even more precise downscaling models.

4. Conclusion

In the course of the century crops productivity is expected to diminish increasingly until Summers will become too hot for cotton and rice production.

It is expected that freezing nights occurrence will totally disappear in March by the beginning of the XXII century, allowing possibly earlier sowing but with at the same time an increase in hot days and nights jeopardizing crops development. By the end of the XXIst century the period between May and September might not be suitable any more for most crop cultivation.

Winter crops, on the other hand, may benefit from slightly better yields, in the course of the century.

Besides, high temperatures at critical stages of the crop development are likely to become an increasing risk jeopardizing the expected yields. This risk will increase at a quick path over the next decades, while increasing temperatures will also limit the plants vegetative development.

While temperatures are increasing water demand for irrigation will increase. The increase in water demand by 2050 at the national level is expected to increase in between 9 and 14% for cotton and in between -1 and 5% for winter wheat.

At the same time, the inflow into the downstream area is expected to decrease by 26–35% by 2050. The situation will further deteriorate over the second half of the XXIst century, while the water demand will grow and the river discharge radically reduce.

A shift in agricultural production toward more resilient crops, already cultivated in the region, alike sorghum and millet, associated with high value crops, including fruit and vegetables resilient plants, alike pomegranate, on smaller surfaces, may take place over the next decades.

Declarations

Author contribution statement

Julian Schlubach: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

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