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Estimating irrigation use and effects on maize yield during the 2003 heatwave in France☆

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ABSTRACT

The decline in maize yield and production during the 2003 heatwave and associated drought in France was only partly minimized by irrigation. National 2003 maize yield loss equalled ~1.5 t ha^{-1} compared to the 2000–2006 average. Spatially distributed maize irrigated area percentages were calculated earlier (Wriedt et al., 2009a) and correlate negatively to the 2003 yield anomaly between 44.5° and 48° latitude. The percentages are used to weigh irrigated and rainfed simulations with the EPIC crop growth model that runs on a 10 by 10 km grid with relevant land use, terrain, soil and management information. Maize was not irrigated in one simulation while other simulations allowed for daily, weekly and biweekly irrigation with a maximum application of 60 mm day^{-1}. The model reasonably reproduces regionally reported yields from 1999 to 2003. In regions with maize area irrigation percentages >20% yield loss in 2003 was reduced by ~53% relative to regions with maize irrigation percentages <20%. Similarly, simulated yield loss was compensated by irrigation by ~25% with biweekly and by ~42% with weekly irrigation in these regions. Even though yield loss was lower in regions with higher maize irrigation percentages; yield loss was still very considerable. Modelling suggests that regional drought mitigation increased with increasing maize irrigation percentages between 0 and 40%. At higher irrigation percentages the compensating effect of irrigation was small. Although the current irrigation infrastructure is sufficient under normal meteorological conditions, areas without irrigation infrastructure experienced high irrigation requirements during the extreme conditions in 2003. Since increasing the irrigation frequency from two weeks to one week had a significant impact on maize yield in 2003, but not in 2002, the most appropriate difference in irrigation rate is provided by the difference between the biweekly rate in 2002 (484 mm $year^{-1}$) and the weekly rate in 2003 (743 mm $year^{-1}$) which equals 259 mm $year^{-1}$. This corresponds to an increase in irrigation water use of ~1761 million m^3 compared to 2002 (~0.68 million ha of irrigated maize). Adapting to increased frequency of droughts under further climate change will require robust water allocation policies.

1. Introduction

Irrigation is an essential element of agricultural production in Southern Europe. In Northern and Central Europe irrigation is mainly used to improve production in dry summers (Wriedt et al., 2009b). In France these regions are located along a transitional N-S gradient. In France, 10–20% of total annual consumptive water use is used for irrigation, but this can go up to 80% regionally during dry conditions (UNESCO, 2006). Luterbacher et al. (2004) concluded that the summer of 2003 was probably the hottest summer in Europe since 1500 AD. France's agricultural production was strongly affected by the 2003 heatwave. The extremely dry and hot conditions also affected irrigated crops (COPACOGECA, 2003). France's maize output equalled 11.5 Mt, 30% down compared with 2002. It was estimated that 55% of the maize output lost at EU level (compared with 2002) was attributable to the drought in France (COPACOGECA, 2003). The financial loss caused by the drought was estimated at 265 million € for maize alone. An example of the development of weather conditions during the drought period in comparison to the previous years is given in Fig. 1 as daily and cumulative monthly rainfall and maximum temperature in France at 4.7° longitude and 46.8° latitude.

Heatwaves will accelerate crop development and advance ripening and maturity. Fischer et al. (2007a,b) showed that a rainfall deficit in the months preceding the 2003 heatwave combined with an excess in total net radiation in late winter 2002 and spring 2003, contributed to anomalous soil moisture

☆ The statements expressed here are purely those of the author and may not in any circumstance be regarded as stating an official position of the European Commission.

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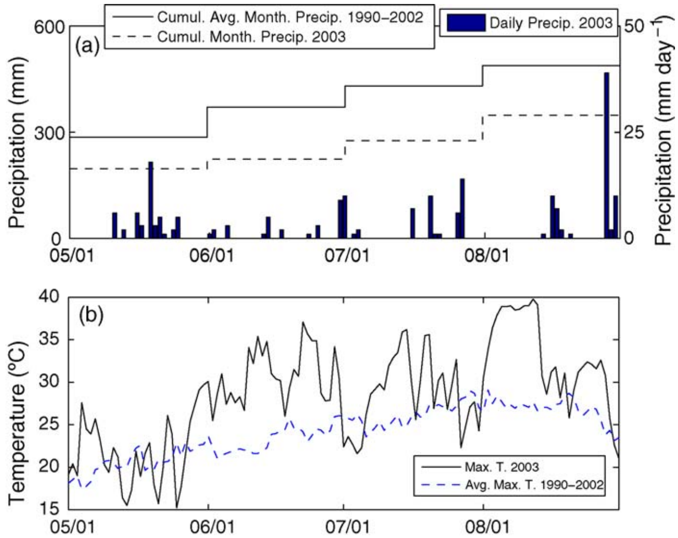

Fig. 1. Progression of precipitation and temperature over late spring and summer 2003 in France at 4.7° longitude and 46.8° latitude from the JRC's MARS 50 by 50 km climate database. Cumulative monthly precipitation averaged from 1990 to 2002 and cumulative monthly precipitation for 2003 (a, left axis) and daily precipitation in 2003 (a, right axis). Maximum daily temperature and maximum daily temperature averaged from 1990 to 2002 (b).

depletion and drought conditions in the summer of 2003. This resulted in reduced latent cooling which amplified the summer temperature extremes. Combined with droughts, cereal crops then risk entering into the grain filling stages under low soil moisture availability. Irrigation provides water to the plant's root zone and allows cooling of the plant's leaves through transpiration. Irrigation effectively alters local climate through the interaction of modified soil moisture conditions, transpiration, air temperature and vapour pressure deficit (Fowler and Helvey, 1974). Plant transpiration and soil water evaporation increase the latent heat flux and thus reduce soil and ambient air temperature. Resulting irrigation cooling is observable over large regions (e.g. California, see Kueppers et al. (2007)). Zaitchik et al. (2006) showed that during the 2003 heatwave the vegetation and surface temperature anomalies were greater for non-irrigated agricultural lands than for forests. This is consistent with the idea that shallow-rooted crops do not have access to deeper reservoirs of water leading to drying and a subsequent increase in sensible heat flux. Similarly, Teuling and Seneviratne (2008) found that cropland density related to the largest spectral albedo changes and total shortwave albedo anomalies.

The 2003 heatwave is used as a case-study to learn about the resilience of rainfed and irrigated maize cultivation to extreme heat and drought. Regional climate models predict that the late 21st century climate in France will increasingly be characterized by summertime drought (Raisanen et al., 2004). If the likelihood of heatwave and drought occurrence indeed increases in a warming climate, this will have important consequences for agricultural water management. The objectives of this paper are the quantification of the actual contribution of (supplemental) irrigation, irrigation interval, and irrigated area to the yield reported at regional level, to yield loss mitigation during the 2003 drought, and to quantify the additional volume of irrigation water used during the drought.

2. Materials and methods

Annual maize yield data were obtained at regional administrative level ('départements') for France from Agreste (2008). Reported yield in a region is a mix between irrigated and rainfed maize. To estimate the yields reported at regional level we performed simulations with a spatialized EPIC model (Williams, 1995; Bouraoui and Aloe, 2007; van der Velde et al., 2009) that runs on a 10 by 10 km grid with relevant meteorological, land use, terrain, soil and management information. Daily meteorological data were obtained from the Joint Research Centre's (JRC) MARS meteorological database given on a 50 by 50 km grid. Land use information was taken from a European land use map developed at JRC (Grizzetti et al., 2007), that combines land cover data of CORINE 2000 (ETC, 2000) with regional crop areas taken from the European farm structure survey (FSS) statistics, thus adding crop specific information to the CORINE agricultural land use classes respecting regional crop areas. Digital terrain information was derived from SRTM (Shuttle Radar Topographic Mission). Soil data were obtained from the European Soil Bureau Database (ESBD 2.0). Sowing dates were determined using the potential heat units program developed at the Texas agricultural experimental station at regional level. The program calculates the total number of heat units required to bring the crop to maturity using long term minimum and maximum temperatures, and optimum and minimum plant growing temperatures and the average number of days for the crop to reach maturity. The minimum temperature was set at 8 °C and the optimal temperature was set at 25 °C. The time to maturity for maize was different in the Atlantic, Alpine, and Continental and Mediterranean regions of France with respectively 180, 185 and 160 days (Bouraoui and Aloe, 2007).

The spatial data were linked to the 10 by 10 km modelling grid. Each 50 by 50 km grid cell of the meteorological database was linked to 25 10 by 10 km grid cells. Crop areas defined in the European land use map (Grizzetti et al., 2007) were tabulated with a class aggregation for each 10 by 10 km grid cell by crop category. Soil data originally at 1 by 1 km were aggregated to the modelling grid (for more details see Williams (1995) and Bouraoui and Aloe (2007)).

This approach allowed us to include relevant soil functions such as water storage capacity in evaluating yield responses and irrigation needs for years characterized by different climatic conditions. Given the high standard of agriculture in France and the generally high fertilizer inputs in French agriculture, we assume that plants do not suffer nutrient stress. Therefore we allowed the model to apply fertilizer automatically according to crop nutrient requirements.

Rainfed and irrigated maize yields are modelled separately and combined using the percentage of maize area that is irrigated (maize irrigation percentage) given by Wriedt et al. (2009a) at a resolution of 10 by 10 km based on EUROSTAT data (Fig. 2). This combined yield is then compared to the reported maize yield at regional level, since it is not specified how irrigated and rainfed maize yields contribute to the reported yield. One simulation was performed without irrigation of maize (rainfed) while other simulations allowed for biweekly, weekly and daily (no water stress) irrigation scheduling to evaluate the impact of different irrigation intervals on crop yields and water use. Irrigation was applied to satisfy plant water stress with a maximum application rate of 60 mm day^{-1} each irrigation interval. This can thus lead to variable irrigation rates from year to year. We consider the model run with a biweekly irrigation interval as our standard irrigation run. Irrigation was legally constrained during the 2003 heatwave and irrigation application therefore may not have been optimal.

Crop parameters were identical in the irrigated and rainfed model runs. Crop growth parameters were kept to the original EPIC crop parameters, except for the harvest index and the energy-biomass conversion that were set to 0.60 [−] and 45 kg ha^{-1} MJ^{-1} m^2 after calibrating to regionally reported yields. The results of these two simulations were combined by weighting