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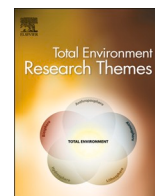
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How abrupt changes in surface temperature impacts water cycle over France? The case study of winter bread wheat area.

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ABSTRACT

Since 1980s over western Europe, warming trend intensifies strongly, consistent with climate simulations including anthropogenic forcing. As a result of this warming tendency, a shift is detected in France in maximum and minimum air temperature, delimiting two different climatic periods: 1959–1987 and 1988–2021. Along with this abrupt warming, a trend towards stagnation of crop yields is observed since the 1990s. Bread wheat yields are particularly affected. The impact of climate hazard and agro-climatic risk on the evolution of bread wheat yields is a major issue for agricultural sector, including insurance companies. This work aims at analyzing how surface warming shift impacted water balance over main French bread wheat production basins. The SIM (Safran-Isba-Modcou) dataset with an 8km spatial resolution grid of reanalyzed surface meteorological observations at daily time step from 1959 to 2021 offers the opportunity to address the complexity of processes leading to changes in local water cycle. Water balance is computed on main bread wheat production basins using a two-reservoirs model, SIM climate data and crop agronomic parameters as inputs. Our results suggest that the abrupt shift in air temperature in France in 1987/1988 had a strong influence on the water cycle variables evolution. Along with the increase of water demand and soil drying, water balance is modified on the post-shift period, with various spatial patterns between main production basins. Harsher hydric stress events alter the crop growth cycle. The evolution of climate hazard linked to water balance leads to changes in agro-climatic risk, identified as one of the main factor affecting the evolution of bread wheat yields. Such conclusions suggest that, with both mean and variability changes in water balance state, probability to overcome risk threshold increases. This is of major concern for our partners and may lead to adaptation process from managers.

Introduction

Over the recent years, France has experienced severe yield losses due to adverse weather events (Beillouin et al., 2020; Ciaïa et al., 2005). Farmers, states and insurance companies were highly impacted by the resulting economic losses (Douvillé, 2019; Gambarini, 2022). Along with the increase in frequency of extremes weather events, yields stagnation of several crops has been observed over western Europe since 1990s (Brisson et al., 2010; Finger, 2010; Schaubberger et al., 2018). The turning point is often identified in the beginning of the 1990s (Peltonen-Sainio et al., 2009). Several driving factors are identified such as lack of genetic improvement, changes in crop management, legislative limitations on fertilizer use, and climate hazard (Hawkins et al., 2013; Lin & Huybers, 2012; Michel et al., 2013).

Bread wheat is particularly impacted by yields stagnation in France

(Grassini et al., 2013), the year of inflection being observed in the middle of the 1990s (Brisson et al., 2010). This leveling-off of bread wheat harvest questions food security, as the country is the first producer of the European Union (EU) in 2020, exporting half of its production to the other countries of the EU and the rest of the world (Agreste. Graphagri, 2021). Confronted to the increasing world food requirements and limited potential new farmland, this statement represents a major societal issue (Spiertz & Ewert, 2009).

Among all the causes identified, climate constitutes a non negligible factor of variation of wheat yield trends (Wheeler et al., 2000). The impact of climate variability on yields trends and variability has been widely studied, and differs according to the region and the crop studied (Lobell et al., 2008; Lobell et al., 2012; Osborne & Wheeler, 2013). In some parts of Europe, the increase in temperature may have benefic impacts, allowing for example an extension in the arable area in

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northern latitudes (Holmer, 2008). In more temperate parts of Europe, such as France, climate change is unfavorable to cereals yields, warming intensifying heat stress and drought (Brisson et al., 2010).

Western Europe experienced a rapid increase in air temperature over the last few decades, exceeding the evolution simulated by models (van Oldenborgh et al., 2009). Both minimal and maximal temperature showed an abrupt increase around 1987/1988 over France (Brulebois et al., 2015) and Europe (de Laat & Crok, 2013; Reid et al., 2016). Spring and summer seasons are particularly impacted, mean air temperature of the 1988–2013 period being 1.55 °C higher than the mean of the 1961–1987 period (Brulebois et al., 2015). Substantial warming of North Atlantic ocean through North Atlantic Oscillation (NAO) variations and decrease in the use of aerosols coupled with global warming are the main identified factors leading to this regional abrupt warming (Sutton & Dong, 2012; Robson et al., 2012; Terray, 2012; Evan et al., 2009). After this 1987/1988 warming shift, temperatures show a little positive trend up to 2000, followed by a so-called 10 years hiatus period linked to La Nina conditions (Meehl et al., 2011). This offers on both sides of 1987/1988 shift roughly two stationary periods that mainly differ from their average surface temperature. Note that since 2012/2014, a strong surface temperature increase is observed, suggesting a new step in climate warming process over France.

After 1987/1988, Brulebois et al. (2015) show modifications of the hydrological cycle, significant decrease in runoff from January to July occurred in 1987/1988 for 40 French watershed, while no changes in the annual amount of rainfall was detected. Such findings highlight the role of evapotranspiration as a major cause of the modification of the hydrological cycle (Boé & Habets, 2014).

The increase in potential evapotranspiration (PET) – or climatic water demand (Doorenbos & Pruitt, 1977) – after the rise in air temperature also impacts the agronomic water cycle. During spring and summer season for example, the increase in evapotranspiration reduces soil water availability, leading to drought situations (Teuling et al., 2013). Actual evapotranspiration (AET), directly linked to vegetation cover type, phenological development stage and soil water content (Allen et al., 1998), is impacted in various ways regarding the seasons and the territories. Those modifications of local water cycle under temperature increase highlight changes in soil water balance, directly impacting crop development and growth by increase frequency or intensity of water stress events (Li et al., 2009). Evolution of agro-climatic risks linked to drought highly depends on crop vulnerability and water stress threshold (Parkash & Singh, 2020). Some studies tried to understand the impact of climate change on water balance of wheat fields under different future emissions scenarios over the world (He et al., 2018; Wang et al., 2009).

The rapid increase in air temperature in France in 1987/1988 had specific effects on the hydrological cycle and evapotranspiration evolution. This offers a new opportunity to focus on water balance response to warming, especially for winter wheat crop, as the latter constitutes one of the most important production in the country (Food and Agriculture Organization of the United Nations (FAO), 2022). The 1987/1988 abrupt change in observed minimum and maximum temperatures delimits along 1959–2021 two periods of 29 and 34 years respectively. This partition is first statistical, based on Bayesian breakpoints and differences tests (Brulebois et al., 2015). But it is also physical, as the abrupt warming might be a result of the combination between dynamic atmospheric processes (positive NAO phase persistence) and radiative processes (aerosols-cloud microphysical effects) (Sutton & Dong, 2012; Booth et al., 2012). The temporal depth of the two delimited periods offers the opportunity to assess robustly how climate change signal trend i.e. structural change affected winter wheat water balance.

This innovative work aims at depicting the trend evolution of water balance on winter bread wheat fields in metropolitan France both sides of the abrupt warming of 1987/1988. Spatial and temporal modifications of the agro-climatic risk linked to water stress are analyzed for the main production basins of the country. Water balance results of hydric

interactions between soil, vegetation cover and atmosphere. Day-to-day variability of the different components – precipitation, evapotranspiration, runoff – is jointly soil, land-use/land-cover and climate dependent. To study its evolution, we used a simplified two-reservoirs water balance model forced with a daily re-analysis of surface climate data covering the entire French territory with an 8 km-resolution and winter bread wheat characteristics. Starting in the end of the 1950s, the climatic dataset offers two periods of similar and relevant time depth both side of 1987/1988.

Material and methods

Study area and datasets

The initial dataset used for this study comes from the Safran-Isba-Modcou (SIM) model developed by Meteo France (Habets et al., 2008; Soubeyroux et al., 2008). This 8km-resolution reanalysis chain combines the Safran meteorological analysis system (Durand et al., 2009), the Isba land surface model (Noilhan & Planton, 1989) and the Modcou hydrogeological model (Ledoux et al., 1989).

The analysis system of the atmospheric forcing, Safran, is based on a robust vertical interpolation method for the main meteorological parameters (Durand et al., 1993). The French territory is divided in more than 600 climatically homogeneous zones, taking explicitly into account the elevation parameter. The model relies on both the observation network and the analysis of the atmospheric models (Arpège or ECMWF), and solar radiation terms (visible and infrared) are estimated using a radiative transfer model. A total of 8 meteorological parameters are analysed at a hourly time scale on more than 9000 grid points (Soubeyroux et al., 2008), including liquid precipitation needed to compute water balance. This allows to have a continuous and uniform spatial information covering the entire French territory, in real time and in delayed time. A validation of Safran module confirmed the relevance of the meteorological analysis, especially for the precipitation fields and the air temperature (Quintana-Seguí et al., 2008; Vidal et al., 2010). Safran also computes Potential EvapoTranspiration (PET) using Penman-Monteith equation (Allen et al., 1998).

The SIM chain dataset starts from the 1st of august 1958 and is updated periodically until present time. In this work, 1959–2021 period is selected. This offers a 60-years time depth, allowing us to distinguish two climates based on 1987/1988 shift in surface temperature warming. Water balance is modeled for each grid point on the metropolitan territory using winter bread wheat characteristics.

Along with climatic variables, capacity of surface and deep soil water reservoirs are required for water balance modeling. Each class of useful water reserve from GISSol database is weighted by its surface for each SIM grid point and averaged with the other classes of the grid point (GIS Sol, 2011; Le Bas, 2018).

The evolution of water balance indicators is assessed for each winter bread wheat main production basins (Fig. 1). Each SIM grid point containing at least 10% of their surface covered by winter bread wheat fields using the 2019 Registre Parcellaire Graphique from the National French Geographical survey is selected. Main production basins are designed and approved by field insurance experts. The impact of the abrupt warming is assessed for Nord-Pas-de-Calais, Parisian Basin, Poitou-Charentes, Centre, Bourgogne/Rhône-Alpes and Aquitaine Basin regions.

Phenological modeling and maximal evapotranspiration

Along with climatic variables and soil water content characteristics, daily maximal evapotranspiration (MET) must be computed to model water balance. The latter corresponds to the amount of water in mm that a given crop can evapotranspire under optimal soil water content and actual climatic conditions (Allen et al., 1998). It corresponds to potential evapotranspiration (PET) crossed with a daily crop coefficient (Kc)

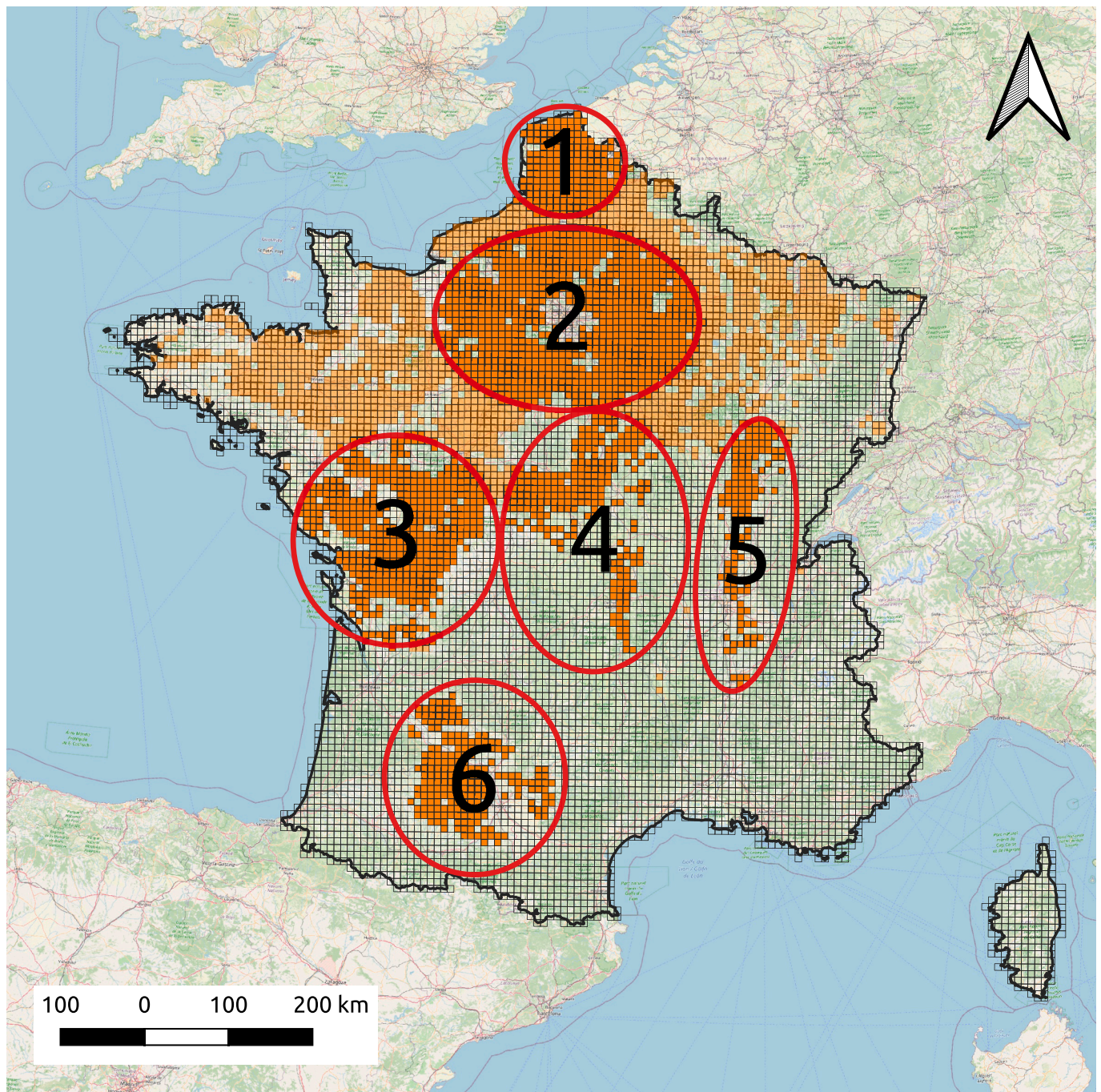


Fig. 1. Map of the main winter bread wheat production basins in metropolitan France. Transparent grid is the Safran-Isba-Modcou climate data grid (Météo France), orange points are the points on which at least 10% of the surface is covered by winter bread wheat fields according to the 2019 Registre Parcellaire Graphique (Institut National de l'Information Géographique et Forestière, 2019). Red contours represent main winter bread wheat production basins: 1. Nord-Pas-de-Calais, 2. Parisian Basin, 3. Poitou-Charentes, 4. Centre, 5. Bourgogne/Rhône-Alpes, 6. Aquitain Basin. The background map comes from OpenStreet Map database.

depending on the phenological stage of the crop (Fig. 2).

To determine the start date of each phenological stage, growth and development of crop of interest must be modeled. A simple growing degree-days (GDD) model is developed on R, using growing degree-days needs to reach one phenological stage from Gate (1995) (Fig. 2). This GDD model compute, for each year, growing degree-days on a 0°C basis, starting at a sowing date on the 1st of November. Each time a growing degree-days need is achieved, the crop reaches the following phenological stage. Once maturity is reached, the crop is harvested and we consider soils remain bare up to the next sowing date.

Dates of phenological stages for each crop cycle are modeled from

1959 to 2021, then the corresponding crop coefficient is assessed to each day. Kc series crossed with PET values for each grid point provide maximal evapotranspiration series, needed as input for water balance modeling.

Water balance modeling

Jacquet & Choisnel (1995) developed a simplified two-reservoirs water balance model, computing daily water balance on a given crop cover using liquid precipitation, maximal evapotranspiration (MET) and size of soil surface and deep water reservoirs as inputs. Simplified water

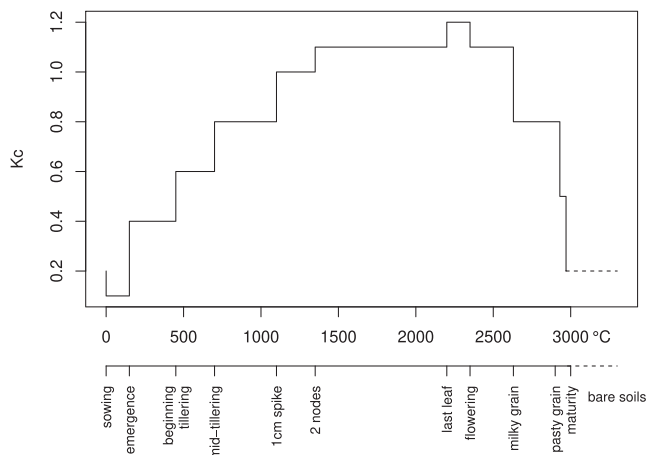


Fig. 2. Crop coefficient (K_c) function of cumulative degree-days needs for winter bread wheat.

balance model does not involve an explicit resolution of surface energy balance equation, and thus accepts maximal evapotranspiration computed from potential evapotranspiration as input. This model displays good performance when compared to the coupled model Earth, a surface energy balance and water balance model (Choisnel, 1985). It gives an accurate estimation of the regulation of the actual evapotranspiration (AET), especially during an alternation of dry and wet sequences.

The model computes a possible water storage by the soil water reservoir on a homogeneous soil texture, called $R(t)$ and varying with time. The inferior limit of $R(t)$ is 0, the superior limit is the useful water reserve (RU). The latter is constant and depends on soil characteristics: in this work one RU value is computed for each grid point (see *Study area and dataset*).

$R(t)$ water storage is managed by decomposing soil water content in two reservoirs: the surface reservoir supplied by liquid precipitation and emptying in case of excess in the deep reservoir. This allows to separate two different regulation of actual evapotranspiration (AET):

- AET = MET when the water is coming from the surface reservoir;
- AET < MET and is regulated when the water is coming partly or totally from the deep reservoir.

The use of two separate reservoirs gives an accurate representation of the dependence of evaporation on soil water content near surface (Mahr and Pan, 1984), and allows to better account for dry and wet sequences succession and their impact on water availability in particular during the spring and summer seasons. In a simplified water balance model, surface reservoir dimension is fixed as a constant fraction of the total useful water reserve. The previous and more complex water balance model Earth, developed by Choisnel (1985) and using a variable dimension for the surface reservoir, was used as a reference to validate the simplified two-reservoirs water balance model. In the Earth model, the AET/MET ratio drops significantly when the $R(t)/RU$ ratio is going under 60% (Choisnel, 1985). Through those findings, in the Jacquart & Choisnel (1995) water balance model, the partition of the top (RU1) and deep water reservoirs (RU2) corresponds respectively to 40% and 60% of the total useful water reserve (RU).

Daily soil water content in both reservoirs are computed iteratively in function of actual evapotranspiration, liquid precipitation amount and soil water content at the end of the last day. Contributions to actual evapotranspiration (AET) from surface and deep reservoirs are computed separately as function of maximal evapotranspiration (MET) (see Jacquart & Choisnel, 1995 for more details).

The version of the model used in this study to compute daily water balance needs as inputs for each SIM grid point:

- daily liquid precipitation (PRELIQ);
- daily maximal evapotranspiration (MET);
- surface useful water reserve (RU1);
- deep useful water reserve (RU2).

Daily water balance is modeled from 1959 to 2021, the first year is considered as a spin-up of the model and is removed from statistical analysis.

Water balance results analysis

Water balance is defined as the proportion of the capacity of soil water reserve filled with water. Jacquart & Choisnel (1995) model outputs are used to compute daily water balance as follow:

$$REW_j = R1_j + R2_j / RU.$$

with REW the Relative Extractable Water (REW in %), $R1_j$ and $R2_j$ respectively the j day amount of water in the surface and deep reservoirs and RU the total capacity of soil water reserve.

The daily REW mean cycle is then computed for each period before and after the abrupt increase in air temperature (1960–1987 and 1988–2021), for each grid point. Spatial aggregation for each winter bread wheat main production basins (Fig. 1) reveals the evolution of mean REW daily mean cycle with climate.

When REW is decreasing under a threshold, vegetation cover is considered being under hydric constraint. The REW threshold for which the rate of leaf expansion and gas exchanges starts to diverge from a reference value varies according to several factors, such as evaporative demand, root distribution, soil texture and soil bulk density (Sadras & Milroy, 1996). Meyer and Green (1980) for example estimated that when 52 to 57% of the REW is used, the winter wheat leaf growth starts to decrease. The rate of evapotranspiration is also declining when 20 or 30% of the total REW remains in the soil profile of the experiment in Meyer & Green (1981), and the extension growth of winter wheat is decreasing when REW is 33 to 34%. An other experiment on a substrate-based nutrient delivery system designed for spaceflight applications estimated that the limit of extractable water for wheat is 39.7% (Norikane et al., 2003). According to those findings, we consider in this work a fixed hydric stress threshold at 40% of the total REW, under which winter wheat growth is affected by hydric stress (Jacquart & Choisnel, 1995).

Crossing daily water balance evolution with the hydric stress threshold highlights the evolution of water stress. For each SIM grid points, we computed the mean annual number of days for which water balance goes under 40%, for both 1960–1987 and 1988–2021 periods. The difference between the mean number of days under hydric stress after 1987/1988 compared to before 1987/1988 is represented on France map for each grid point on which at least 10% of the area is covered by winter bread wheat fields. This allows to study spatial evolution of hydric stress with warming.

Results

Water balance daily mean cycle modification

The pattern of REW shows as expected values close to 1 (i.e. field capacity) for the fall and winter seasons, while in spring and summer values are decreasing. Note that a REW equal to 0 indicates a soil water content at permanent wilting point.

The analysis of REW daily mean cycle points out spatial disparities in the pattern of evolution after the abrupt warming (Fig. 3).

North of France production basins (zones 1 and 2) are strongly impacted by a decrease in REW during the 1988–2021 period compared to the 1960–1987 period, especially between March and August. In the Nord-Pas-de-Calais production basin for example, minimum water filling of soils reservoirs occurs in August (40%) in the 1960–1987 period. After the abrupt increase in air temperature, the rise in

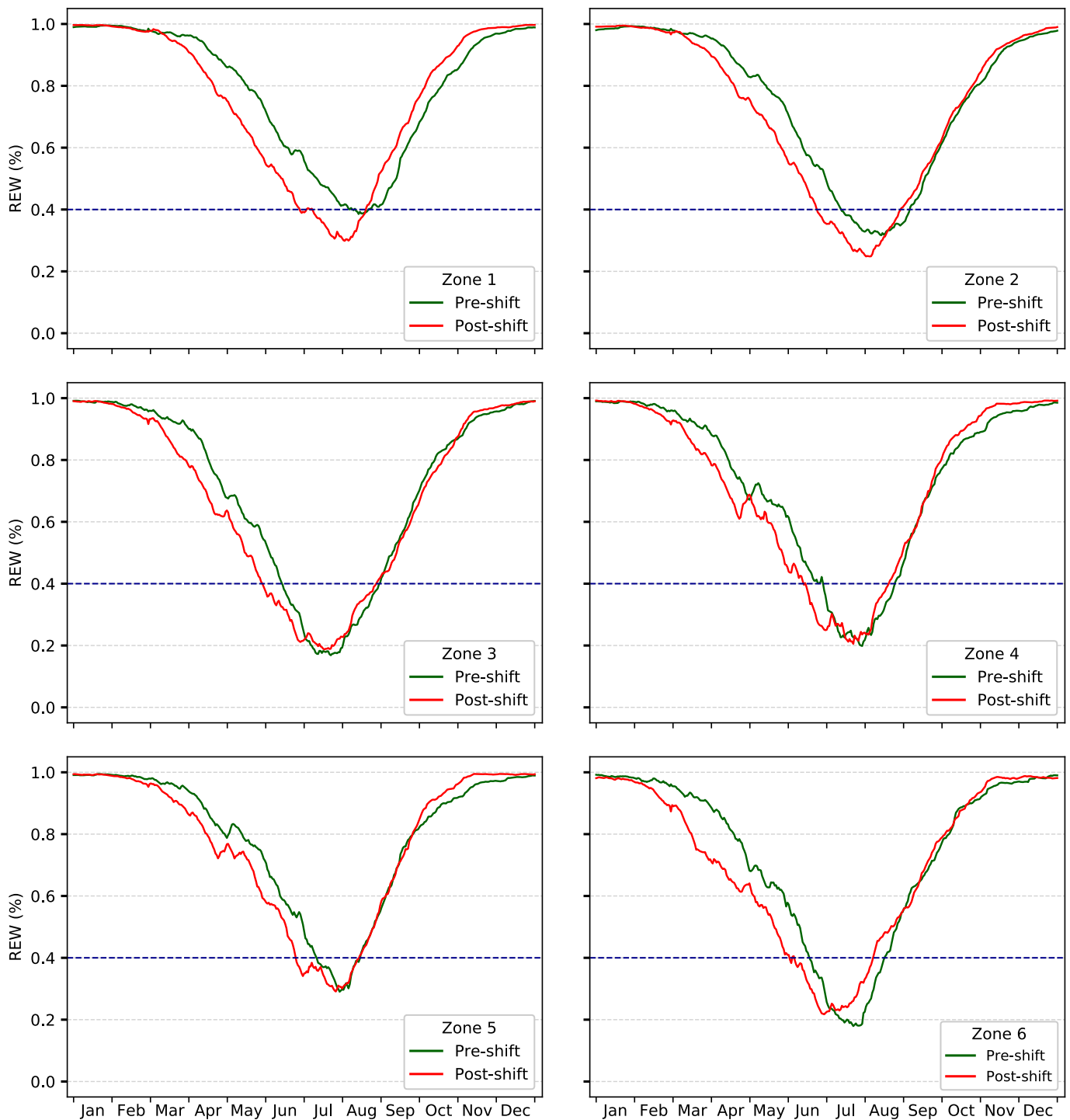


Fig. 3. Water balance daily mean cycle for each winter bread wheat main production zone. Green: daily mean for 1960–1987 period; red: daily mean for 1988–2021 period. Blue line: stress threshold.

evapotranspiration results in an important decrease in water balance, minimum water filling of soils reservoirs occurring in the end of July with approximately 30%. After 1987/1988, REW daily mean cycle crosses stress threshold, revealing the apparition of water stress in July and August. In Nord-Pas-de-Calais region and Parisian Basin, water stress events are thus longer and more intense on winter bread wheat fields after 1987/1988 abrupt warming.

Poitou-Charentes, Centre and Bourgogne/Rhône-Alpes regions (respectively zones 3, 4 and 5) display same pattern of water balance evolution. During the 1960–1987 period, REW daily mean cycle already

crosses stress threshold from June to August up to 20%, 20% and 30% of soil water reservoir filled at the minimum for respectively zone 3, zone 4 and zone 5. This intensity of water stress remains the same on the second period for all the production basins. But for those three regions, REW daily mean cycle goes under stress threshold earlier during the 1988–2021 period compared to the 1960–1987 period. Water stress events start around 15 days earlier on the three regions. For Poitou-Charentes, Centre and Bourgogne/Rhône-Alpes regions, water stress events do not intensify after 1987/1988, but get longer, especially start earlier.

Aquitain Basin (zone 6) shows another pattern of REW daily mean cycle evolution. 1988–2021 cycle is offset compared to 1960–1987 period cycle, water balance going under and then upper stress threshold earlier during the year on the 1988–2021 period. Mean hydric stress event on this production basin keeps its length and intensity during the 1988–2021 period (minimum REW at 20%), but is shifting by about 15 days compared to the 1960–1987 period. Such changes in the evolution of REW can be due to modifications of the phenological cycle of winter bread wheat crop. Degree-days needs are reached faster in this zone with the increase in air temperature. Water requirements increase more quickly, leading to water stress events starting earlier in the 1988–2021 period. Crop maturity is also reached earlier, inducing earlier harvests and leading to water stress events ending earlier after 1987/1988.

The rapid increase in air temperature in 1987/1988 over France impacted winter bread wheat water balance cycle through the increase in evapotranspiration combined with quite stable liquid precipitation. Spatial disparities are highlighted in the evolution of hydric stress events. Further investigations are needed to understand how the 1987/1988 abrupt warming modified hydric constraint on winter bread wheat fields over metropolitan French territory. Spatial analysis offers the opportunity to study on a finer scale the evolution of water stress.

Spatial disparities in the evolution of hydric stress

At the annual scale, almost the entire French territory is impacted by an increase in the number of days under hydric stress threshold (Fig. 4a). North and Northeast of France experience the most important increase in number of days during which wheat water balance is going under stress threshold after the 1987/1988 abrupt warming, with between 20 and 40 more days under hydric stress per year. This confirms that Nord-Pas-de-Calais and Parisian Basin regions display more hydric stress events on the 1988–2021 period that were very few along the 1960–1987 period.

Seasonal scale analysis details this trend. In spring, southern production basins reveal the most important increase in number of days under hydric stress. As previously pointed out, Poitou-Charentes, Centre and Aquitaine Basin regions experience a shift in water stress events after 1987/1988, first day of hydric constraint occurring earlier in the year. This leads to a rise in the number of days under hydric stress during spring season, between 10 and 20 days more under stress threshold.

In summer, considerable increase in number of days under hydric stress occurs in North and Northeast parts of France. Nord-Pas-de-Calais and Parisian Basin production basins encounter hydric stress events on the 1988–2021 period that they did not have to deal with on the 1960–1987 period or only slightly. Poitou-Charentes and Aquitaine Basin regions show a slight decrease in the number of days under hydric stress in summer, which confirms the advancement of crop maturity and the earlier harvest, lowering vegetation cover water requirements and hydric constraint earlier in the year.

Main winter bread wheat production basins are differently impacted by the abrupt warming in air temperature, temporally and spatially. Number of days under hydric stress increase on almost the entire French territory at the annual scale, revealing the increase in intensity and/or length of hydric stress on the 1988–2021 period compared to the 1960–1987 period.

Evolution of climatic variables linked to water cycle

To better understand the evolution of water cycle over France between the two studied periods, it is interesting to study the evolution of climatic variables linked to water cycle after 1987/1988. Tables 1 and 2 depicts the differences between the mean of 1988–2019 period compared to the mean of 1959–1987 period on each main production basin for liquid precipitation and potential evapotranspiration.

Potential evapotranspiration is increasing significantly on all zones and at every time scale studied after 1987/1988. Spring and summer, as

expected, experience the most important difference between the two studied periods, following the evolution of temperature. In spring, most important increases in water demand are observed in Nord-Pas-de-Calais, Aquitaine Basin and Bourgogne/Rhône-Alpes production basins. Potential evapotranspiration summer increase is also very important in Parisian Basin, Aquitaine Basin and Bourgogne/Rhône-Alpes. North and Southwest of France endure the most important rise in water balance outputs with the abrupt 1987/1988 warming, explaining the intensification and/or precocity of water stress events on those zones.

Cumulative liquid precipitation displays more contrasted changes spatially and seasonally. In spring, only Poitou-Charentes and Bourgogne/Rhône-Alpes regions show significant changes, respectively downward and upward. Relative stability of water balance inputs, especially on northern production basins, exacerbates water stress events precocity in spring. Summer changes are significantly positive on every production basin except in Aquitaine Basin, but less important than the changes in evapotranspiration. The rise in water balance inputs can not counteract the increase in water balance outputs during this season. In autumn, cumulative liquid precipitation significantly increases in Centre and Bourgogne/Rhône-Alpes regions, on a more important way than evapotranspiration, contributing to the soil water reservoirs filling. On northern production basins (zones 1 and 2), cumulative liquid precipitation changes can not counteract the rise in evapotranspiration, lengthening water stress events in autumn.

Discussion

In this innovative study, we try to assess robustly the impact of temperature warming driven by climate change (long term signal) over France on winter wheat water balance and hydric stress. The abrupt warming in 1987/1988 provides two mean climatic states subperiods of sufficient temporal depth to statistically determine the structural modifications of hydric stress and drought.

The abrupt increase in minimal and maximal air temperature over France in 1987/1988 caused significant increase in evapotranspiration. Along with stable annual liquid precipitation amount, this led to soil water content decrease. These regional impacts of warming on climatic water balance evolution are consistent with studies at other scales (Chaouche et al., 2010). As the evolution of evapotranspiration depends on the vegetation cover water requirements, it is necessary to address specifically the evolution of our crop of interest water balance. In this study, we show that after the abrupt warming of 1987/1988, winter bread wheat crop experience a drying of soil water content on almost all the main production basins. This induce an increase of the frequency and/or the intensity of days where soil reservoirs water content goes under stress threshold of 40%. Thus, the abrupt warming modify hydric stress events distributions, in various ways depending on the season and the geographical zone. Over almost all production basins studied, hydric stress events after 1987/1988 are starting earlier in the year, lengthening up to mid-August. From June to August, the winter wheat grain filling stage is highly sensitive to drought (Hlaváčová et al., 2018). Thus, the drought risk exposure is increasing on those production basins. South West of France (zone 6) is the only production basin experiencing an offset of hydric stress event, starting and finishing earlier in the year after 1987/1988. This is probably due to anticipated phenological stages and harvest. As spring temperatures show the most important increase after the abrupt warming (Brulebois et al., 2015), the anticipated phenological stages could face similar evapotranspiration requirements as before 1987/1988. Risk exposure might then be similar on both subperiods on this production basin. The offset in the crop cycle also induce crop management constraints and vulnerability to other climatic hazards such as late cold spell or late frost.

Precipitation and evapotranspiration – i.e. inputs and outputs of water balance – evolutions are identified as drivers of water cycle modifications. We reveal that seasonal and spatial disparities in differences between 1988 and 2019 and 1959–1987 period partly explain the

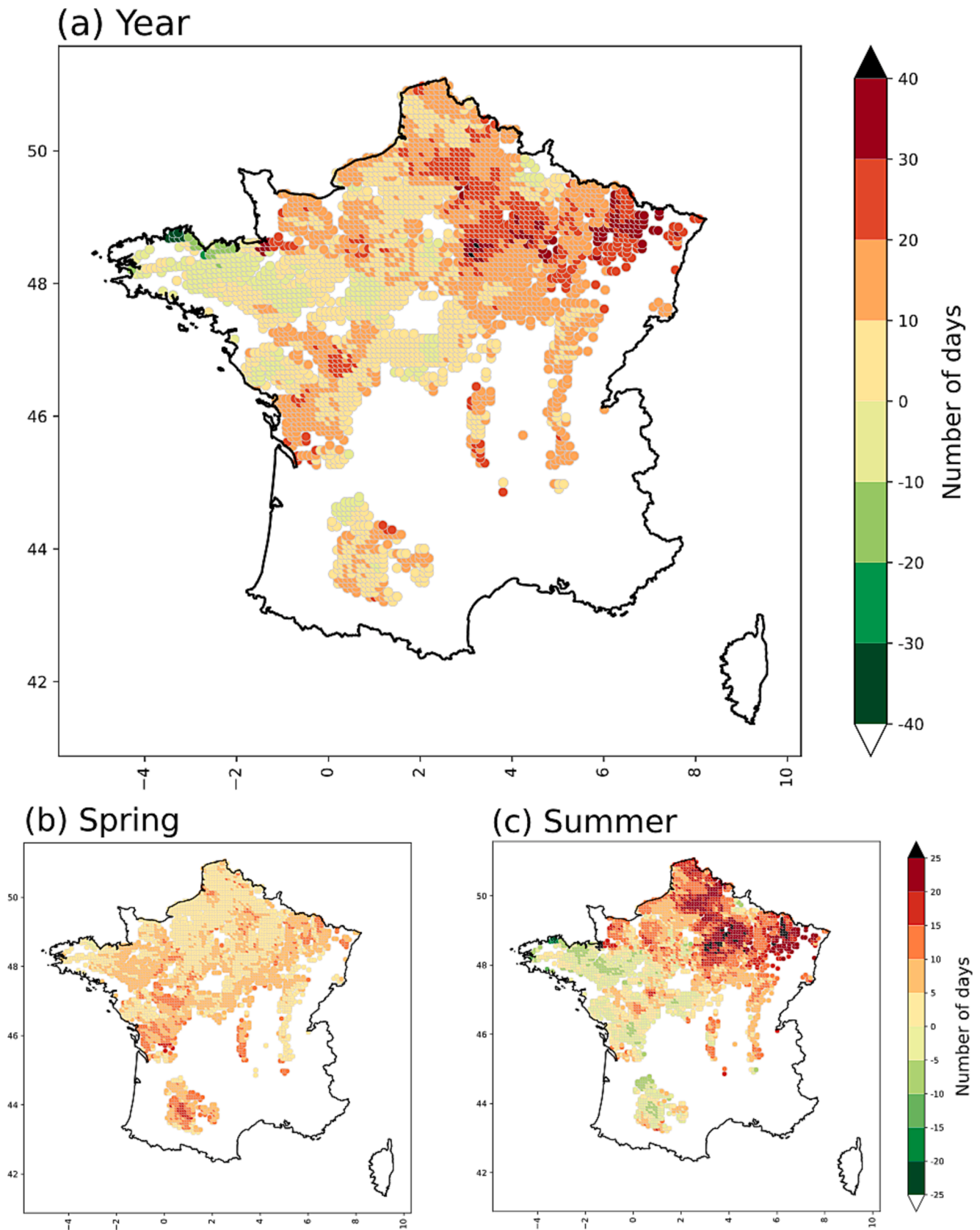


Fig. 4. Difference in the number of days under hydric stress threshold (40%) (1988–2021 period – 1960–1987 period) for each SIM grid point containing at least 10% of its area covered with winter bread wheat fields. (a) Annual scale, (b) spring March-April-May (MAM), (c) summer June-July-August (JJA).

Table 1

Difference of 1988–2019 period compared to 1959–1987 period for potential evapotranspiration (PET) at the annual and seasonal scale. * indicates that the difference is significant according to Bayesian differences test (95% HDI).

| Production basin | Year | Winter (DJF) | Spring (MAM) | Summer (JJA) | Autumn (SON) |
|------------------|--------|--------------|--------------|--------------|--------------|
| Zone 1 | 92.5* | 5.7* | 33.3* | 40.4* | 12.5* |
| Zone 2 | 93.7* | 3.0* | 29.8* | 44.4* | 14.9* |
| Zone 3 | 97.0* | 4.1* | 33.0* | 39.0* | 20.6* |
| Zone 4 | 87.1* | 3.2* | 30.5* | 42.1* | 10.3* |
| Zone 5 | 101.0* | 7.4* | 36.8* | 46.8* | 11.7* |
| Zone 6 | 138.2* | 13.2* | 42.3* | 53.9* | 28.7* |

Table 2

Same as Table 1 but for liquid precipitation (PRELIQ).

| Production basin | Year | Winter (DJF) | Spring (MAM) | Summer (JJA) | Autumn (SON) |
|------------------|--------|--------------|--------------|--------------|--------------|
| Zone 1 | 80.4* | 42.8* | 1.5 | 18.6* | 3.8* |
| Zone 2 | 29.1* | 17.2* | -0.3 | 9.1* | -4.4* |
| Zone 3 | 2.8 | -8.7* | -7.3* | 6.6* | -2.1 |
| Zone 4 | 33.9* | -0.1 | 2.0 | 9.1* | 14.5* |
| Zone 5 | 49.9* | -2.3 | 11.0* | 7.0* | 29.0* |
| Zone 6 | -25.7* | -33.1* | -1.1 | -4.4* | -0.4 |

evolution of REW and water stress events. Raymond & Ullmann (2021) also investigate intra-seasonal precipitation evolution on the 1950–2019 period through dry spells episodes. Northeast, center and Southwest of France experience an increase in the number of dry days (liquid precipitation < 1 mm). Precipitation distributions evolve since 1950 in North and Northeast of France, long and very long dry spells being more frequent from spring to September. Summer atmospheric drought extends into beginning of autumn. Those findings are key factors to clarify precocity and worsening of water stress on Nord-Pas-de-Calais and Parisian Basin zones. Winter season is less subject to dry spells, the number of dry days mainly remains constant or decreases on the French territory. The more important amount of precipitation counteract losses due to spring, summer and autumn water stress events.

Drought events and heat-waves are linked by land–atmosphere feedback processes, intensifying and propagating each other (Miralles et al., 2019; Hartick et al., 2022; Zhou et al. 2019). The aggravation of drought conditions on the 1988–2021 period may have participated to the increase in frequency of heat-waves over Europe (Poumadère et al., 2005; Schär et al., 2004; Teuling, 2018). Heat-waves and drought events have various effects on wheat yields anomalies in France depending on the region (Zampieri et al., 2017). Higher temperatures lead to an increase in the atmospheric demand for water and reduce crop water-use efficiency. Extreme high temperatures, i.e. heat stress, induce direct plant damages by provoking perturbations in cellular structures and metabolic processes (Nakamoto & Hiyama, 1999). In this original work, we demonstrate that the structural changes in water cycle following the abrupt warming over France in 1987/1988 affect drought over winter wheat production basins. This would be interesting to study how extreme heat-waves, through negative land–atmosphere feedbacks, participated to those changes.

As hydric stress events are longer or more intense after 1987/1988, new phenological stages of the crop could be affected. On northern production basins, hydric stress appears in summer on the 1988–2021 period, altering grain forming and ripening, development stages that were rarely impacted on the 1960–1987 period (Arvalis Institut du Végétal, 2022). Production basins of the southern half of the country already encounter hydric stress events on the 1960–1987 period, but these last start earlier in the year on the 1988–2021 period. On those production basins, the number of days under hydric stress increase in spring after 1987/1988, and may affect bolting development stages (Arvalis Institut du Végétal, 2022).

Many studies showed the impact of water deficit on crop growth and development (Chaves & Oliveira, 2004; Verslues et al, 2006). Drought is the main abiotic constraint on cereal crops, ultimately affecting crop productivity (Boyer, 1982; Araus et al., 2002). This work reveal the impact of 1987/1988 abrupt warming on the increase in drought risk over winter bread wheat fields in France, which is identified as one of the cause of crop stagnation observed in the 1990s. This is confirmed in Le Gouis et al. (2020), pointing out drought during stem elongation and grain filling phenological stages as drivers of wheat yields stagnation. As wheat is the main cultivated crop in France, covering almost 50% of surfaces cultivated in cereals in 2020, those findings raise concerns about the country's food security (Agreste. Graphagri', 2021).

The mean temperature is expected to rise by 2100, between 4 and 5°C at the global scale and more than 5°C in France under the most pessimistic scenario (IPCC, 2021). This warming is likely to result in further increases in evaporation and an intensification of the hydrological cycle (Huntington, 2006). Douville et al. (2013) demonstrated that anthropogenic radiative forcings impact latitudinal and decadal differentiation of recent evapotranspiration variations. At the European continental scale, climate changes could lead to the amplification of seasonal soil water index, even if precipitation simulations are still uncertain (Planton et al., 2005). Over France, evapotranspiration is expected to decrease in summer due to an important increase in meteorological and agricultural drought (Dayon et al., 2018). By 2100, intensity and spatial coverage of drought events are foreseen to increase dramatically, with stronger changes for agricultural droughts (Vidal et al., 2012).

Observed modifications of drought risk due to the abrupt warming in 1987/1988 in France and their impacts on crop growth and development combined with future expected evolution of drought risk are of major concern for the agricultural sector. Economic losses due to drought episodes are increasingly important and accelerate the need for better knowledge to limit damages and adapt strategies (Charpentier et al., 2022; Hagenlocher et al., 2019). Agricultural insurance industry, particularly vulnerable to adverse climatic events, is strongly affected by this crucial issue. Many studies tried to investigate the link between agro-climatic risk evolution and the agricultural insurance loss ratio (Fusco et al., 2018). Assessment of agro-climatic risk for food production is complex and depends on the geographical region studied, the crop characteristics and its growth and development modeling (Ewert et al., 2015). In France, the link between agro-climatic risk evolution and agricultural insurance loss ratio is already studied by insurance companies, but needs to be detailed by crop of interest and production basin.

Conclusion

This work aim at exploring the impact of the abrupt increase in air temperature in 1987/1988 in France on the evolution of water balance of winter bread wheat fields. On the 1988–2021 period, winter bread wheat main production basins all experience a decrease in water balance daily mean cycle compared to 1960–1987 period. The latter exceeds stress threshold in various ways depending on the season and the geographical area. Nord-Pas-de-Calais and Parisian production basins experience more longer and more intense hydric stress events after 1987/1988, particularly in summer. On Poitou-Charentes, Centre, Bourgogne/Rhône-Alpes and Aquitaine production basin, the number of days under hydric stress increase substantially in spring, lengthening hydric stress episodes. Modifications in hydric stress events distributions after 1987/1988 abrupt warming are expected to impact winter bread wheat growth and development, and affect yields. The evolution of climatic hazard after 1987/1988 abrupt warming and associated agro-climatic risk link to drought highlighted in this study is of major concern for the agricultural sector, including insurance industry. Drought risk modifications regarding 1987/1988 climatic shift are multifactorial, driven by both potential evapotranspiration and precipitation evolution. The magnitude of changes in these elements may be

exacerbate by natural climate variability. Along with the mechanical increase in potential evapotranspiration, dry spells evolution could have foster drought conditions over the country. Further investigations are needed to support this. Since the 2014/2015 years a new abrupt warming seems to appear over France. As a consequence four of the five last years have experienced severe drought conditions. Such rapid warming may happen again in the future, accelerating the need for disentangling the effects of radiative forcing and natural variability to better understand their causes and impacts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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