HOW ABRUPT CHANGE IN SURFACE TEMPERATURE IMPACT WATER CYCLE OVER FRANCE ?

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Abstract: Along with the rapid warming tendency of the last decades over France, a shift in air temperature has been detected in 1987/88, delimiting two main climate periods from 1959 to 2019. Evidence of pre- and post-shift runoff seasonal differences suggest an impact of this abrupt warming on water cycle evolution. As yearly precipitation slightly evolve during the studied period, evapotranspiration appears to be one of the main drivers of the hydrological cycle evolution. Spring is marked by a strong increase in evaporative demand, followed in summer by a rise in water stress and a drying of soil water content. Besides temporal disparities, this local water cycle evolution depicts different spatial responses over France. Modifications of climate hazard linked to water cycle is expected to impact agro-climatic risks and crop yields.

Keywords: climate hazard, water balance, abrupt shift, warming

Résumé: La tendance rapide au réchauffement des dernières décennies en France montre une rupture dans les températures en 1987/88, délimitant deux périodes climatiques de 1959 à 2019. Les différences saisonnières dans les débits pré- et post-rupture suggèrent un impact de ce réchauffement abrupt sur l'évolution du cycle de l'eau. Les précipitations évoluent peu sur la période étudiée, l'évapotranspiration apparaît alors comme le moteur principal de l'évolution du cycle hydrologique. Le printemps est marqué par une hausse importante de la demande évaporative, suivie en été par une augmentation du stress hydrique et un assèchement du contenu en eau du sol. Outre cette diversité temporelle, cette évolution du cycle de l'eau local montre des réponses spatiales différentes sur le territoire français. Les modifications de l'aléa climatique lié au cycle de l'eau est susceptible d'impacter les risques agro-climatiques et les rendements.

Mots-clés: aléa climatique, bilan hydrique, rupture abrupte, réchauffement

Introduction

Since 1980s in France, the warming trend intensifies strongly, consistent with climate simulations including the anthropogenic forcing (Terray & Boé, 2013). As a result of this warming tendency, an abrupt shift is detected (Brulebois et al., 2015, Reid et al., 2016) in maximum and minimum surface air temperature around 1987/1988, delimiting two main climate periods: 1959-1987 and 1988-2009. Comparison of runoff pre- and post-shift shows significant decrease between January and July. Variations in runoff response suggest local water cycle changes with a "soil memory effect" : negative soil moisture anomalies in spring lead to drier soils in summer, inducing lower runoff at the end of summer (Boé & Habets, 2014). Which climatic variables, i.e. precipitation and/or evapotranspiration, are responsible for this local water cycle evolution? Beyond that, what are the spatial and the temporal pattern changes of water balance? As there is no necessary correlation between temperature changes and long term water cycle and water balance variations (Senevitrane, 2012), it is necessary to highlight this subtle balance.

1. Material and methods

1.1. Study area and data

The initial dataset used for this study comes from the Safran-Isba-Modcou model (SIM2) developed by Météo France (Soubeyroux et al., 2008). This 8-km-resolution reanalysis chain combines a meteorological analysis system, a land surface scheme and a hydrogeological model. A validation of the whole SIM chain show that the model is quite robust both in space and time, and gives a good estimation of the water fluxes (Habets et al., 2008). The quality of the SIM chain for the representation of the actual climate at a fine resolution is a major asset for climate change impact studies (Soubeyroux et al., 2011, Vidal et al., 2010b). With an 8km spatial resolution at daily time step, SIM interpolated precipitation and computed PET (Potential EvapoTranspiration) and AET (Actual EvapoTranspiration) from 1959 to 2019 data are relevant to address the complexity of processes leading to changes in local water cycle (Soubeyroux et al., 2008). Based on the surface warming abrupt shift, these data allow us to quantify the evolution of climate hazard linked to local water cycle on a continuous time-scale and over the entire French territory.

1.2. Agro-climatic indices

Four variables among all SIM outputs are considered here: maximal 2m-temperature (Tmax), liquid precipitation (PRELIQ), potential and actual evapotranspiration (PET and AET). These daily variables are aggregated to monthly, seasonal and annual scale and are used to compute several types of indices providing informations on the evolution of water balance and hydrological cycle components.

Potential evapotranspiration (PET) (Doorenbos & Pruitt, 1977), considered as a climatic measurement, is introduced to study the evaporative demand of the atmosphere only affected by climatic parameters (Allen et al., 1998). When cultivating crops in fields, the agronomic management and environmental conditions can differ from standard conditions, leading to an actual evapotranspiration (AET) that may vary from PET. In the SIM chain, PET and AET are computed in Isba land surface scheme using methods and equations described in Noilhan & Planton (1989) and in Noilhan & Mahfouf (1996). Isba model as it is used in the SIM chain is driven by incoming radiation, precipitation, atmospheric pressure, air temperature and humidity, and wind speed at a reference level. Along with PET and AET, two indices depicting the evolution of the water balance are computed: the difference PET - AET informs on the soil water deficiency, the ratio AET/PET depicts the efficiency of the evapotranspiration process. The study of the evolution of those two indices allows to assess the impact of temperature increase on the evolution of water balance and crops hydric stress.

1.3. Statistical analysis

The four daily series of the variables of interest are aggregated to monthly, seasonal (winter: December-January-February (DJF); spring: March-April-May (MAM); summer: June-July-August (JJA); autumn: September-October-November (SON)) and annual time scale. Robust statistical tests such as change point detection and distribution comparison techniques are used to assess the characteristics of the evolution in precipitation, PET and AET due to temperature evolution.

As change-points detection techniques were used in Brulebois et al. (2015), they are used here to identify shifts in climate data series. Among all techniques available to study climatic shifts, Bayesian approaches appear to be adapted to the characterization of abrupt changes (Barry et Hartigan, 1993), especially in climatic records (Ruggieri, 2013). The method assesses posterior mean and change-point probability, and quantifies the level of confidence when change-points are identified as significant.

Significant differences in mean values for liquid precipitation and PET and AET before and after 1987/1988 temperature shift are detected with a robust Bayesian test (Kruschke, 2013). This estimation is based on the Bayesian posterior probability distribution, evaluating whether the probability of a difference is high enough to matter. By using the values of the 95% Highest Density Interval (HDI) to define the confidence interval, the Bayesian method provides information about the magnitude and significance of the difference between two distributions.

2. Results

2.1. Detection of shift in temporal evolution of variables linked to the hydrological cycle

Temporal analysis of variables linked to the hydrological cycle depicts important shifts in PET and PET – AET at the end of the 1980s, following the evolution pattern of maximal temperature (Figure 1). Yearly, the mean of the 1988-2019 period for PET is around 100mm higher than the mean of the 1959-1987 period (720mm) (Figure 1a). AET increases to a lesser extent than PET (+50mm in average between the two periods), resulting to an abrupt increase in PET – AET from 200mm before the 1987 shift up to 250mm after. As a result of a sharp increase in maximum air 2m-temperature in 1987/1988 over France, evaporative demand (PET) increases. Vegetation cover and soils are not able to respond to this rise at the annual scale (AET), revealing the large deficit of soil water content in the second period, implying an increase in hydric constraints (PET – AET). Yearly precipitation remain quite stable during the whole period, confirming the major influence of temperature on the evolution of water demand and soil water content.

Contrasted seasonal changes highlight a strong increase in evaporative demand in spring after 1987/1988 (Figure 1b), followed by a rise in hydric constraints. Our results show that water constraints strongly increase in summer (Figure 1c), along with the drying of soil water content. In autumn (Figure 1d) and winter (Figure 1e), water demand and hydric constraints increase more slightly or even decrease after the shift, which could be explain by the refill of soil water reservoirs with precipitation.

Since 2010 however, a new step of water constraints seems to be reach as shown with the increase of the PET – AET index values. Summer and even autumn depict the same pattern, pointing out the extension of the drying period of soils during the year.

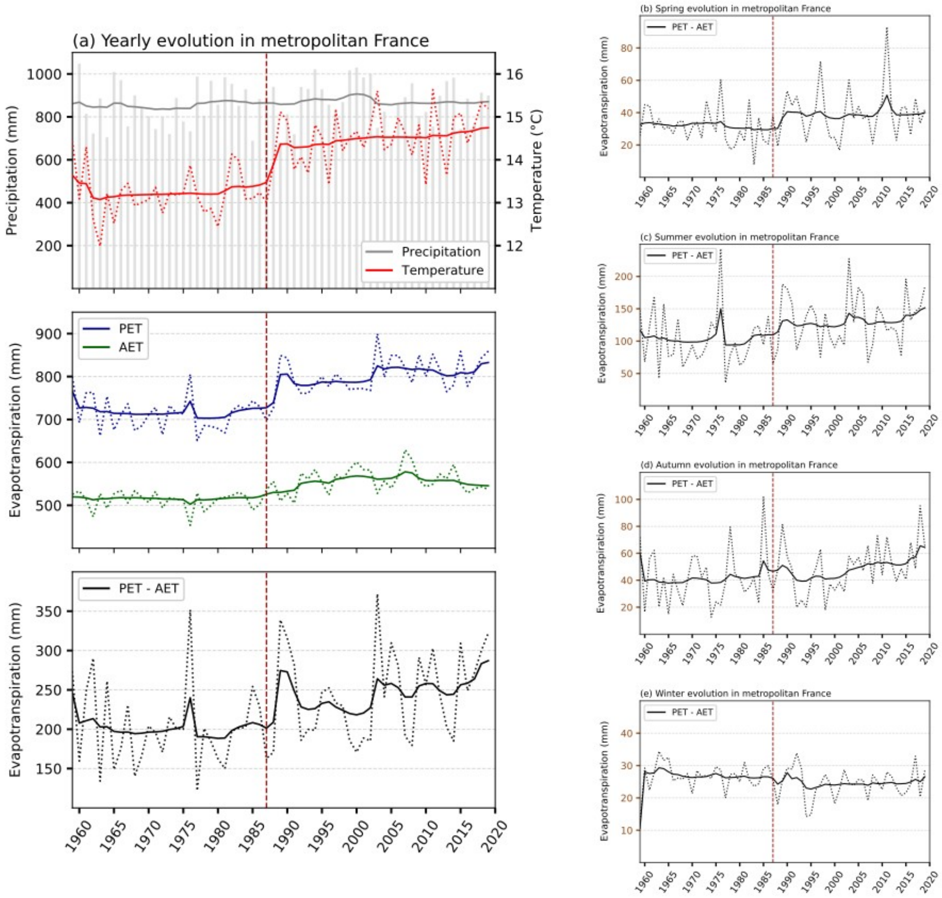

figure 1. (a) Yearly and (b, c, d, e) seasonal evolution of variables linked to hydrological cycle between 1959 and 2019. PET: Potential EvapoTranspiration; AET: Actual EvapoTranspiration. Gray bars: SIM chains values; gray solid curves: Bayesian posterior mean values. Solid coloured curves: Bayesian posterior mean values; dashed coloured curves: SIM chains values. Vertical dashed line indicate 1987.

2.2. 1987/1988 shift: a turning point

The evolution of the means of the hydrological cycle variables before and after the 1987/1988 shift depicts annual and seasonal temporal disparities (Tables 1, 2 and 3). PET and AET means both increased significantly on the 1988-2019 period compared to the 1959-1987 period at the annual scale. This evolution is larger and more widespread for PET (+90mm, 45 % of SIM grid points) than for AET (+45mm, 9 % of stations), highlighting the rise in evaporative demand and in water stress after 1987/1988.

Spring experiences the highest percentage of stations recording a shift in 1986/1987/1988 for PET and AET (Tables 1 and 2), directly impacted by the brutal increase in air 2m-temperature in this season (Brulebois et al., 2015). Summer display the larger gap between PET and AET anomalies, rising from respectively 39mm and 8mm. Precipitation slightly increases yearly and in summer and autumn in the second period, but always to a lesser extent than PET (Table 3). These results point out an important increase in evaporative demand in spring, draining soil water content after 1987/1988 shift. Evaporative demand still rises in summer, resulting in an aggravation of water constraints between June and August, even extending into autumn. Autumn and winter are characterised by a refill of the reservoirs, although a rise in water constraints is depicted in the recent decade during autumn season.

Table 1. Percentage of SIM grid points recording a shift in 1986/1987/1988, anomalies (ΔPET) and 95% confidence interval of the difference in the mean (95% HDI) at annual and seasonal scales, for potential evapotranspiration (PET).

Period	Potential evapotransiration (PET)		
	% of stations	ΔPET (mm)	95 % HDI
year	45	+90.3*	89.8 – 90.9
DJF	31	+5.73*	5.64 – 5.81
MAM	69	+32.5*	32.4 – 32.7
JJA	16	+38.5*	38.2 – 38.8
SON	9	+13.6*	13.5 – 13.8

Table 2. Same as in Table 1 but for actual evapotranspiration (AET).

Period	Actual evapotranspiration (AET)		
	% of stations	ΔAET (mm)	95 % HDI
year	9	+45.7*	45.4 – 46.1
DJF	37	+8.29*	8.19 – 8.40
MAM	54	+23.2*	23.0 – 23.3
JJA	4	+7.69*	7.43 – 7.96
SON	4	+5.35*	5.25 – 5.46

Table 3. Same as in Table 1 but for liquid precipitation (PRELIQ).

Period	Liquid precipitation (PRELIQ)		
	% of stations	ΔPRELIQ (mm)	95 % HDI
year	0	+23.2*	22.0 – 24.3
DJF	1	-3.07*	-3.60 – -2.56
MAM	3	+0.28	-0.12 – 0.69
JJA	1	+3.53*	3.08 – 3.99
SON	0	+10.4*	9.90 – 10.9

As for precipitation, the evolution of the variables linked to the hydrological cycle outlined in these results may hide geographical disparities.

2.3. Geographical response of water balance to temperature shift

Anomalies of the variables and indices linked to the hydrological cycle depict spatial diversity in their evolutions (Figure 2). PET is rising almost everywhere after the 1987/1988 air 2m-temperature shift, confirming the strong influence of the abrupt warming on the evolution of water demand. Vosges, Jura and Morvan massif, centre of France, Ardèche, Cévennes and Haut-Languedoc regional natural reserves and southwest of France experience the strongest increase in evaporative demand, the mean of the 1988-2019 period being around 30% higher than the mean of 1959-1987 period. AET is also almost increasing everywhere, with a 30% rise after the 1987/1988 shift in the Vosges, Jura and Massif Central. Even if some contrasted evolution are show at local scale, the south of France shows roughly a decrease of liquid precipitation whilst north part (above 45N°) shows a clear increase.

Consequently, means of the AET/PET index present contrasted territorial evolutions. On the extreme northeast, in Picardie, along the Rhône valley, on the mediterranean coast and southwest of France, PET increases more than AET, leading to a decrease of AET/PET indice of about 10 to 20% on the 1988-2019 period compared to the 1959-1987 period. On those regions, evaporative demand increases considerably after the abrupt rise in air temperature and soil dries up, intensifying hydric constraints on vegetation. Only on mountainous regions (Ardennes, Vosges, Jura, Alps and Massif Central), AET/PET ratio decreases slightly at the annual scale. On those areas, at the annual scale, hydric constraints are less impacted than previous regions by the 1987/1988 warming.

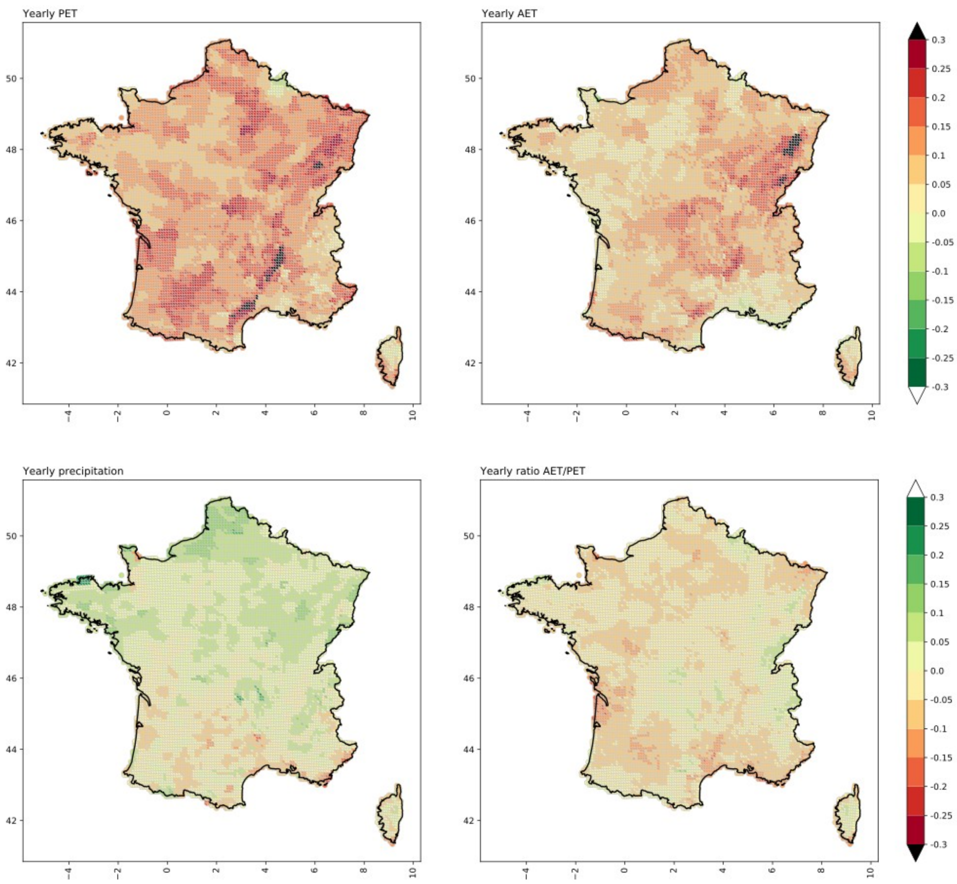

figure 2. Yearly relative anomalies of period 1988-2019 compared to period 1959-1987 for all variables linked to the hydrological cycle.

Seasonal evolutions of PET and AET depict various geographical changes (not shown), affecting the evolution of local hydric constraints in different ways throughout the seasons. In spring, AET/PET ratio decrease up to 20% over the entire France except mountainous regions, highlighting the beginning of the water stress increase. These hydric constraints extend on almost all the French territory in summer, AET/PET ratio decreasing up to more than 30% on some areas.

Most of the regions experiencing an important increase in hydric constraints after the 1987/1988 shift in air 2m-temperature at the annual and seasonal scales are large agricultural production areas.

Conclusion

As expected, our results clearly point significant changes in the elements of the local water cycle. One interesting result shows that, at yearly scale, a large part of the territory has been able to follow the large increase in PET. However, subtle evolutions are shown seasonally and at local scale. Summer is particularly impacted by an increase in hydric stress, PET – AET being around 30mm higher after the 1987/1988 shift. Extreme northeast of France, Picardie, Rhône valley, Mediterranean coast and southwest of France are the most exposed territories, AET/PET ratio rising between 10 to 20% on the post-shift period at the annual scale. Furthermore, it appears that the last decade seems to experiment a new acceleration stage of the hydrological cycle that may affect water balance. This latter is of primary importance for the productivity of grass, crop and forest covers (Creed et al., 2015, Sergent et al., 2014). Since the 1990s in France, a trend towards stagnation of crop yields is observed, bread wheat being particularly affected (Schauberger et al., 2018). The evolution of climate hazard linked to the water cycle depicted in this study is thus expected to be one of the main causes of crop yields evolution. Hence, consecutive agro-climatic risks evolution is of major concern for decision-makers, and may lead to adaptation process from managers.

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