# Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble

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## ARTICLE INFO

## ABSTRACT

Currently, the analysis of heat waves and the representation of such events in a comprehensible and accessible way is a crucial challenge for climate services, in particular for delivering scientific support to policy makers. In order to fulfil this need, a new method for analysing the heat waves in France has been defined. Heat wave detection is based on the high quantiles of daily temperature distributions, and can be applied on any series of temperature. The heat waves are characterised by their duration, maximal temperature and global intensity. Their characteristics are calculated for historical and future climate based on the EURO-CORDEX regional multi-model ensemble, under two different Representative Concentration Pathway scenarios: RCP4.5 and RCP8.5. The historical simulations are evaluated against the SAFRAN reanalysis data. The EURO-CORDEX ensemble simulates heat waves which characteristics are consistent with the events detected from the SAFRAN thermal indicator between 1971 and 2005. Models are able to simulate waves as intense as the 2003 outstanding event. Under future climate conditions, whatever the considered scenario, the heat waves become more frequent and have higher mean duration and intensity. Moreover, heat waves could occur during a larger part of summer. The 2003 event corresponds to a typical event at the end of the century, and its duration and intensity are much lower than the strongest waves that could occur over the last 30 years of the 21st century. However, the intensity of the evolution during the end of the century will strongly depend on climate policies.

**Practical implications**     Heat waves are one of the most worrying climatic extremes due to the vulnerability of our society and the expected increase in their frequency and severity in the 21st century (IPCC, 2013). France was particularly impacted by the 2003 summer heat wave which caused an excess of about 15,000 deaths from 4th to 18th August directly attributable to the heat (PoumadÉre et al., 2005). By combining peaks of extreme temperature and severe soil and hydrological droughts, this event affected numerous economical sectors at the same time (Bador et al., 2016): crop yield in agriculture, forest fires, energy production (cooling process of thermal power plants), buildings (cracks caused by shrink-swell of clay). These last years, numerous regions of the world experienced severe heat waves with comparable effects: Russia in 2010, Texas in 2011, Australia in 2012, India and Southern Pakistan in 2015. Therefore, the ability of our society for adapting to the changes of heat wave characteristics in the future is one of the biggest stakes for climate policies. At the EU level, the ''climate-adapt'' portal has identified heat waves as one of the four main climate threats for urban adaptation (http://climate-adapt.eea.europa.eu/tools/urban-adaptation/climatic-threats/heat-waves). In France, a national plan to better cope with heat waves has been decided after the 2003 event. More generally, a national Plan for climate adaptation (http://www.developpement-durable.gouv.fr/-Plan-national-d-adaptation-2011-.html) was defined in 2011 and took into account heat wave impacts for six sectors: fishery, urbanism, health, natural risks, energy industry and agriculture. The basic climate change scenarios for this plan, communicated through regular reports (Ouzeau et al., 2014) and through the DRIAS national web portal (www.drias-climat.fr), include a state-of-the-art of the projection of heat wave occurrence and intensity over the 21st century in France.

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According to this plan, learning from past experience of extreme events cases is crucial to compare with upcoming future events.

However, the ability of detailed analysis and past-present-future comparison of these events is today hindered by the lack of a universal definition for heat waves. They are usually identified as periods with warm temperatures above the normal observed during several consecutive days, but the parameters allowing their detection and qualification vary a lot (duration, threshold etc).

This leads in France to several climate change indices on the different national portals for climate change, without direct correlation with real heat wave events:

– the National Observatory On Effects of Climate Warming (ONERC in French) presents an index of the observed evolution of the yearly number of summer days (max temperature higher than 25 °C).
– the DRIAS portal, a French referential climate service for climate projections data dissemination, uses the Stardex definition for heat waves: 5 consecutive days with 5 degrees anomaly with respect to mean temperature in summer.

The French ministry of ecology therefore asked to define clear indices as part of the national adaptation plan (Extremoscope project).

The method presented here is an event-based approach synthesizing all aspects of heat waves, without targeting a specific sector. A sufficiently universal index as proposed here is necessary to cover several impacted sectors, allowing comparative studies needed for a lot of policy makers and climate services such as those mentioned below. This method accounts for duration (start and end), maximum temperature and global severity. It contains an innovative multi-dimensional representation of events, based on ''bubble'' plots, synthesizing these characteristics, in a comprehensible and accessible manner for both research studies and policy makers. It is diverted from the operational method used by Météo-France for climate monitoring (http://www.meteofrance.fr/climat-passe-et-futur/bilans-climatiques/bilan-2015/bilan-climatique-de-l-ete). Its application has been recently extended for climate services into the French application Climat[HD] (http://www.meteofrance.fr/climat-passe-et-futur/climathd), in order to represent both present-day and future heat waves. This representation has been adopted in a report about cities climate change adaptation for the Paris Urban Area (www.apc-paris.com).

Here the method is improved by using quantiles of the events or model distributions. We propose original graphical representations of both multi-dimensional and multi-model information, adapted to climate services.

This development will be used soon in an operational context for different climate services:

– For local authorities, it will be used to update the Cities Climate plans, aiming to take into account heat wave and urban heat island monitoring.
– At the national level, it will be used in on-line services as DRIAS and Climat[HD]. An update of heat wave indices will be done shortly.

The method will be adapted in sectoral applications such as for Energy in the frame of Copernicus Climate Change Service to represent cold wave events associated to high energy demand.

Since prolonged periods of heat or cold affect the demand and generation of electricity, anticipating the energy consumption associated to these climate events is important. Furthermore, the evaluation of such events in present-day climate is crucial to adapt existing power installations. Moreover, providing expertise about the evolution of occurrence of heat and cold waves is necessary to integrate future climate conditions into the design of new installations.

The method suggested here can be applied on any series of temperature, for the needs of any country. For example in United Kingdom, the power sector works on infrastructure resilience and long-term adaptation planning. It was agreed with the government that a coordinated response to both these work streams, by the electricity sector as a whole, was an appropriate way to assess climate change risks.

## 1. Introduction

Instrumental observations and reconstructions of temperature evolution reveal a pronounced global warming during the past 150 years (IPCC, 2013). Several studies show that this warming is associated with changes in temperature extremes at various locations around the globe. Implications of global warming for changes in extreme weather and climate events are of major concern for society, in particular in relation to impacts on economy, ecosystems and health. One implication of global warming is the increase in the number of heat waves, which continued at a sustained rythm over the past decades (Seneviratne et al., 2014). Previous studies suggest that the change of the heat wave characteristics in future climate are linked to the changes of the extremes of the daily temperature distribution in summer (Schoetter et al. 2014) due to an increase of the interannual temperature variability in some regions (Schär et al., 2004; Cattiaux et al., 2015). A period of extremely high temperatures is generally considered as a heat wave but there is no unique definition. Many indices are constructed with a certain impact group or sector in mind, which may be impacted in a different way than another group by extremely high temperatures. Indices defined in one region or group may not be relevant in different conditions. They may not be rep-

resenting all aspects of heat waves appropriately (Perkins and Alexander, 2013). However, most definitions rely on a characterization of the events by their duration, intensity or severity. Russo et al. (2014) focused on the magnitude of extreme heat waves in present and future climate that occurred worldwide, using global outputs from the Coupled Model Intercomparison Project phase 5. In particular, they proposed a Heat Wave Magnitude Index that can be compared over space and time.

France experiences a very variable summer climate, as many countries in South/Central Europe. This is essentially due to the possible influence of dry enough soils to trigger positive feedbacks between temperature and soil moisture (Zampieri et al., 2009; Seneviratne et al., 2010). However such dry conditions are only present in some summers, such as the 2003 and 2015 summers, but not in others, enhancing interannual temperature variability.

Gibelin et al. (2014) showed via a new dataset of monthly homogeneous series of temperature, that from 1959 to 2009 the mean warming over France (+0,3 °C per decade) is mainly explained by spring and summer temperature increase. Several studies have examined heat wave characteristics and their evolution in future climate in Europe (Schär et al., 2004; Beniston et al. 2007; Barriopedro et al. 2011; Lau and Nath 2014; Jacob et al., 2014). Fischer and Schär (2010) focused on summer heat

waves indices over Europe, simulated by the ENSEMBLES project RCMs (Hewitt and Griggs, 2004) and found increases in the heat wave frequencies and durations over France. Lemonsu et al. (2014) drew the same conclusion at the scale of the Paris basin using the same ensemble of simulations.

In a recent study, an assessment report of climate conditions in France over the 21st century has been conducted (Ouzeau et al. 2014), and provides climate indices and analysis of changes in climate extremes for the development of measures for adapting to climate change. This assessment is crucial for the many players concerned with the problem of adaptation. This study also revealed the large change in heat waves in the future climate, using the new EURO-CORDEX simulations (Vautard et al., 2013; Jacob et al., 2014).

Due to the many aspects of heat waves, the need of new indices covering several characteristics of heat waves was identified. This paper aims at providing a new method of heat wave detection based on the upper quantiles of temperature distributions that fulfil this need. This method can be applied on any series of temperature, and enables the study of heat waves across different time periods and regions which have different thermal characteristics and temperature variability. For this paper, the method is applied on every day of the year, allowing the detection of events that could occur outside of the summer season, in particular in the context of a warming climate.

Evolution of summer temperature over France during the 21st century is investigated in Section 3, using the EURO-CORDEX simulations. Details about the method of detection can be found in Section 4.1. Then we propose a detailed analysis of heat wave events detected over France in terms of occurrence, duration and intensity, for present-day climate in Sections 4.2 and 4.3. Section 4.4 provides analysis of changes in heat waves characteristics in the climate change framework, under two Representative Concentration Pathway (RCP) scenarios used in the fifth IPCC report (IPCC 2013), using regional simulations computed for the EURO-CORDEX project. The conclusions and outlook are given in Section 5.

## 2. Data

### 2.1. The SAFRAN atmospheric reanalysis

SAFRAN is an atmospheric reanalysis system that computes vertical profiles of the atmosphere for climatic homogeneous zones over France, by combining large-scale fields and ground observations through Optimal Interpolation (Durand et al., 1993). The algorithm, its validation and its application over France are detailed by Quintana-Seguí et al. (2008). SAFRAN hourly outputs of liquid and solid precipitation, near surface air temperature,

specific humidity, wind speed, surface visible and infrared radiations are interpolated from 605 climatic homogenous zones over France onto a 8-km regular grid (8602 cells) to provide atmospheric forcings for land surface schemes. Vidal et al. (2010) demonstrated the overall robustness of the SAFRAN reanalysis for the assessment of regional climate change. It is also used for operational needs at Météo-France (Besson et al., 2015) and has been extended to 2015.

### 2.2. The EURO-CORDEX ensemble

The EURO-CORDEX initiative is a part of the global Coordinated Regional Downscaling Experiment (CORDEX, http://wcrp-cordex. ipsl.jussieu.fr/; Giorgi et al. 2009) which aims to organize and coordinate an international framework to improve regional climate scenarios for the land-regions worldwide. It provides regional climate projections for Europe at 50 km and 12.5 km resolution, which downscale the CMIP5 global climate projections (Taylor et al., 2012) and the new RCP scenarios (Moss et al., 2010). Details about the grid configuration and differences in the parametrisation schemes for the different participating models can be found in Jacob et al. (2014), Vautard et al. (2013) and Kotlarski et al. (2014).

Models and scenarios used for this study are detailed in the Table 1. Six different RCMs and four different GCMs have been used. This ensemble can be splitted into two categories. The first one is the historical set covering the 1971–2005 period, which consists of ten different model simulations. The second type includes the 21st century projections driven by two RCP scenarios, RCP4.5 and RCP8.5. The RCP8.5 is the highest emission scenario and its $CO_2$ concentration reaches 936 ppm by 2100, while RCP4.5 reaches 538 ppm by 2100. Eight simulations have been used for both ensembles driven by RCP4.5 and RCP8.5 scenarios, and provide daily data from 2006 to 2100.

### 2.3. The CDFt correction

Simulations have been bias adjusted using the Cumulative Distribution Function transform (CDFt) method (Vrac et al., 2012), recently revised in order to account for the singular distribution of precipitation (Vrac et al., 2016). The methodology is a variant of the quantile-mapping technique, where the evolution (e.g., from one time period to another) of the model historical simulation CDF is taken into account and adapted to the CDF of the observations (Vrac et al., 2012).

Before correction, all simulations of the EURO-CORDEX ensemble have been interpolated on the France domain and SAFRAN reanalysis have been used as "observations" for bias corrections.

**Table 1**
The EURO-CORDEX simulations used in this study.

| Short name | Simulation | Institution | GCM | RCM | Hist | RCP4.5 | RCP8.5 |
|---|---|---|---|---|---|---|---|
| m1 | CNRM-CERFACS-CNRM-CM5_RCA4 | Swedish Meteorological and Hydrological Institute | CNRM-CM5 | RCA4 | X | X | X |
| m2 | CNRM-CM5_CCLM4-8-17 | CLM Community | CNRM-CM5 | CCLM4-8-17 | X | X | |
| m3 | EC-EARTH_RCA4 | Swedish Meteorological and Hydrological Institute | EC-EARTH | RCA4 | X | X | X |
| m4 | IPSL-CM5A-MR_WRF331F | Institut Pierre Simon Laplace | IPSL-CM5A-MR | WRF331F | X | X | |
| m5 | EC-EARTH_RACMO22E | Royal Netherlands Meteorological Institute | EC-EARTH | RACMO22E | X | X | X |
| m6 | MPI-ESM-LR_CCLM4-8-17 | CLM Community | MPI-ESM-LR | CCLM4-8-17 | X | X | X |
| m7 | MPI-ESM-LR_REMO019 | Climate Service Centre | MPI-ESM-LR | REMO019 | X | X | X |
| m8 | IPSL-CM5A-MR_RCA4 | Swedish Meteorological and Hydrological Institute | IPSL-CM5A-MR | RCA4 | X | | X |
| m9 | MPI-M-MPI-ESM-LR_RCA4 | Swedish Meteorological and Hydrological Institute | MPI-M-MPI-ESM-LR | RCA4 | X | | X |
| m10 | CNRM-CM5-ALADIN53 | Centre National de Recherches Meteorologiques | CNRM-CM5 | ALADIN53 | X | X | X |

## 3. Simulated evolution of summer temperature and associated heat waves over France

First, we analyse the simulated evolution of the mean summer (from June to August) temperature anomalies (relative to the reference 1976–2005 climatology) over France from 1971 to the end of the 21st century, under the two different scenarios. Fig. 1 provides time series smoothed with a polynomial regression of the median values and the [25–75%] model range for each scenario. Results show that the simulated change slowly increases until the mid-21st century, for both RCP4.5 and RCP8.5. The EURO-CORDEX ensemble simulates a median France warming of about 1.3 °C and 1.5 °C for the near future (2021–2050), under the RCP4.5 and RCP8.5 scenarios, respectively. The range of projected change is [0.5–2.1 °C] under the RCP4.5 scenario, and [0.8–2.5 °C] under the RCP8.5 scenario. It is almost the same change as experienced from 1900 until today (the increase of the observed summer temperatures in France from 1900 until 2015 reaches +1.4 °C, see http://www.meteofrance.fr/climat-passe-et-futur/climathd). The projected summer changes for the end of the 21st century are stronger, on the order of 1.9 °C (median value) under the RCP4.5 scenario and 4.5 °C for the RCP8.5 scenario, with ranges extending to [1.1–3.0 °C] and [3.6–5.7 °C].

The increase in the average temperature in France is particularly strong in summer at the end of the 21st century under the RCP8.5 scenario. How can this change affect the evolution of extreme temperatures? Schär et al. (2004) suggested that a recent increase of the variability of the summer average temperature has reduced the return-period of a 2003-like heat wave. A recent study by Christidis et al. (2015) confirmed this. Moreover, climate change could have an impact on the shift and spread of the temperature distribution, which are consistent with the increase in probability of extremely warm temperatures (Weisheimer and Palmer, 2005).

Fig. 2 shows maps of changes in number of heat wave days relative to the 1976–2005 reference period, under the RCP8.5 scenario. This diagnostic, available on the French portal of climate services DRIAS (http://drias-climat.fr), relies on the STARDEX heat wave duration index (http://www.cru.uea.ac.uk/projects/stardex). For this index, a heat wave is defined as a period during which the daily maximum temperature exceeds the climatology by more than 5 °C for at least 5 consecutive days in summer. The number of days simulated by the EURO-CORDEX ensemble at the end of the 21st century is consistent with the mean temperature increase. For the 75th percentile of the multi-model ensemble, the number of heat wave days varies from 10 to 60 more days than the 1976–2005 reference period, from the north to the southeastern part of the country.

This index is useful for estimating the total number of days considered in a heat wave for each grid point of the territory, allowing the analysis of spatial patterns of local extreme temperature changes. The STARDEX definition emphasizes temperature anomalies rather than heat wave events. Considering a fixed temperature exceedance of 5 °C over the climatology to define a heat wave is dependent on the local climate and can not necessarily be applied to regions with different thermal characteristics and variability.

Although the scientific community agrees on the increase in extreme events related to the global climate change, there is actually no consensus about the definition of a heat wave event. The meteorological variables used to define a heat wave can be daily maximum, minimum or mean temperatures. They are usually defined by the exceedance of the temperature over a given threshold for several consecutive days. This threshold can be a climatological reference value (like the STARDEX indicator), or a fixed value tailored to the extreme temperatures of the studied geographical area. Based on this definition, heat waves can be both summertime and annual events.

The problem with these definitions based on a single threshold, is that they don't allow comparative studies using different models without appropriate bias corrections, nor covering several geographical areas having different temperature variability. In the following section, we propose a new heat wave diagnostic-adapted from the operational method of heat wave detection in
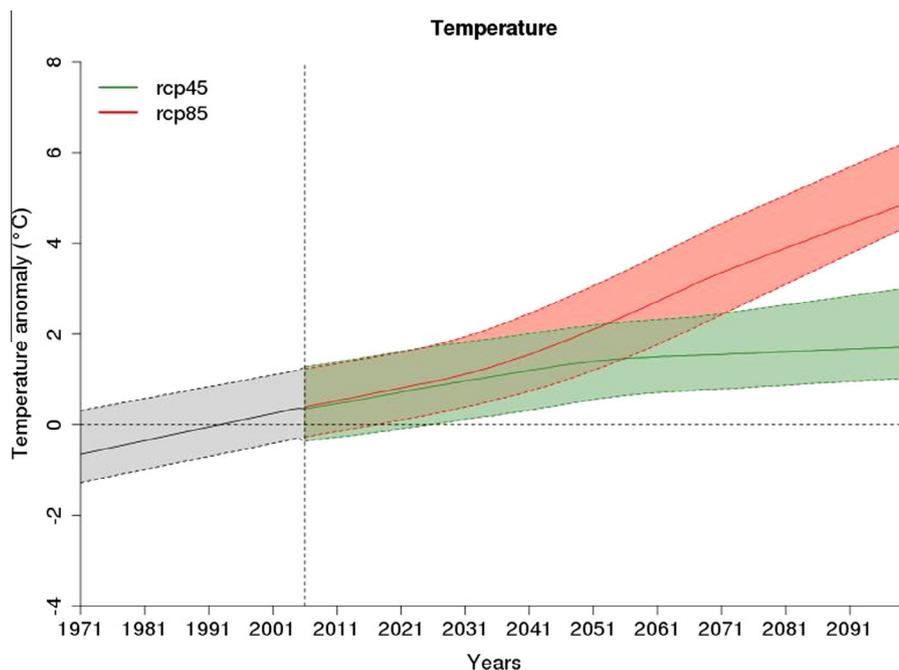


**Fig. 1.** Time evolution of France mean temperature anomalies in summer relative to the 1976–2005 climatology simulated by the EURO-CORDEX models (historical simulations: grey, RCP4.5: green, RCP8.5: red). Solid lines give the median, shading and dashed lines give the envelope defined by the [25–75%] model range for each scenario. Time series are smoothed with a polynomial regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 2.** Summer Heat Waves STARDEX index for the 2021–2050 (left) and 2071–2100 (right) periods, for RCP8.5 scenario. Anomalies relative to the 1976–2005 climatology. Maps on the top give the 25th centile of the multi-models ensemble, maps at the bottom give the 75th percentile. Source: http://drias-climat.fr.
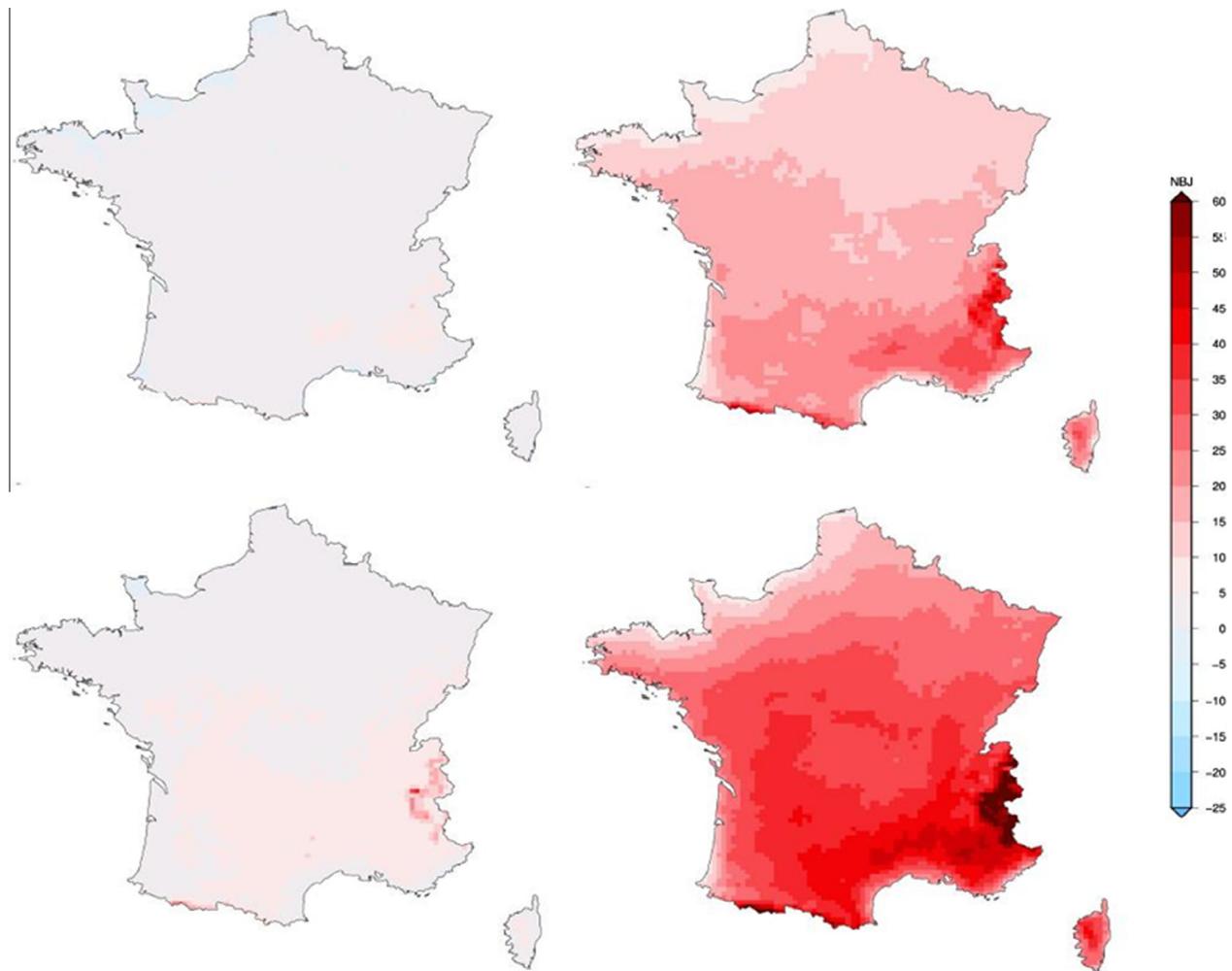
France- which can be applied to any observed or simulated temperature time series, at different spatial scales. The diagnostic proposed here is universal enough to cover several impacted sectors and allow comparative studies. Moreover, it can be easily transposed to the detection of cold waves, in particular for the needs of the energy sector. This method consists of an event-based approach synthesizing the main aspects of heat waves (duration, maximal temperature and global intensity), and proposes an innovative representation of these events using bubble plots.

## 4. A new analysis of heat waves in France

### 4.1. Method

The operational method of heat wave detection used in France since 2006 (http://www.meteofrance.fr/prevoir-le-temps/meteo-et-sante/canicules#) needs as input the daily national mean temperature. It is based upon three settings: the temperature threshold beyond which an event is detected (Spic = 26 °C), the threshold that defines the beginning and the end of the heat wave (Sdeb = 23 °C), and the interruption threshold (Sint = 20 °C) which allows merging two consecutive episodes without a significant drop in temperature (Fig. 3). This last threshold was adjusted in order to detect clearly identified heat wave events in France (1947, 1976, 1983, 1994 (Besancenot, 2002) and 2003). The detection is carried out in the following manner: If the temperature

reaches the Spic threshold, a heat wave is detected. The start of the event is defined by the first day for which the temperature is above the Sdeb threshold. The heat wave is interrupted if the temperature is below the Sdeb threshold for at least three consecutive days, or if the temperature falls back (even occasionally) to values below the Sint threshold. Once a heat wave is identified, it can be characterized by three values: duration, maximal mean temperature reached during the event, and global intensity which is defined by the cumulative difference between the temperature and the Sdeb threshold during the event, divided by the difference between Spic and Sdeb (bright red area of the Fig. 3). The global intensity represents the severity of an event and should be proportional to its effects on a specific sector.

This method, developed for climate monitoring, allows to obtain a complete inventory of past heat waves in France and was also adapted for cold spells (Schneider and Dandin, 2012). Its success comes also from the associated 3D graphic representation, in terms of bubbles (see below). However, the use of absolute thresholds (defined only at French national level) limits the benefits of the method. The chosen thresholds have been indeed adapted to the detection of known past heat waves at the scale of the whole French territory. This doesn't allow the distinction of specific events at the sub-regional scale with climate characteristics diverging from the average French climate characteristics (like in coastal or mountainous areas). This is not also adapted for the detection of well identified heat waves in other countries
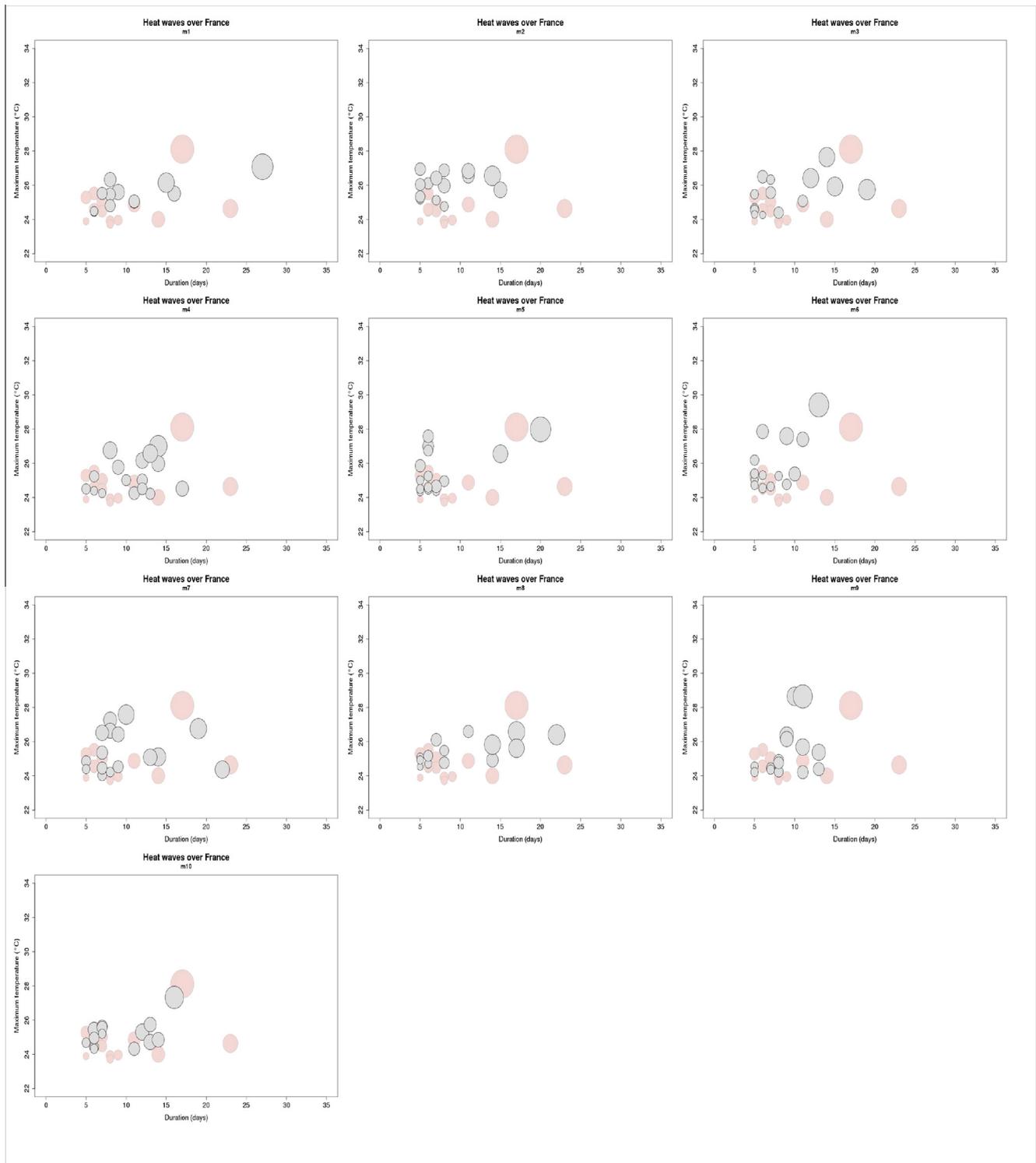
**Fig. 3.** Characterization of a heat wave from a daily mean temperature indicator over France (example of a time series from June 30 to August 5, 1983): Duration (start and end), maximal temperature and global intensity (red area of the plot). Temperatures above (below) climatological line (1981–2010 reference period) are represented by pink (blue) area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Percentiles and corresponding thresholds for SAFRAN and the EURO-CORDEX ensemble median [ensemble standard deviation].

|                                  | Spic        | Sdeb        | Sint        |
|----------------------------------|-------------|-------------|-------------|
| Percentile                       | 99,5        | 97,5        | 95          |
| SAFRAN thresholds (°C)           | 23.66       | 21.68       | 20.52       |
| Ensemble thresholds median (°C)  | 24.27 [0.20]| 22.03 [0.16]| 20.67 [0.10]|

experiencing a very different climate from the French one. In addition, the chosen absolute thresholds are also attached to one specific past period (1947–2006) forbidding all flexibility in the choice of the reference period. The choice of absolute thresholds rather than relative ones might however be more suitable in the context of specific climate impact studies. To illustrate this we can mention studies of climate change that make reference to thresholds of temperature adapted to severe impacts on health (e.g. Willett

and Sherwood, 2012) or on crop yields (e.g. Brisson et al., 2010). But we here want to define a more universal index not too strongly related to one specific impact sector and, for this purpose, the relative thresholds are more adapted.

In order to adapt it to the characteristics of any set, the operational method has thus been modified based on percentiles of annual distributions over the reference period 1976–2005. Percentiles have been selected after a detailed preliminary analysis which led to heat wave identifications (frequencies, duration, maximal and global intensities) close to the application of the operational method.

A post-processing filter is applied in order to retain only heat waves that last at least five days. Table 2 gives the percentiles and thresholds used for our analysis, computed from the daily temperature distributions over the 1976–2005 period for the two datasets. Thresholds associated with the EURO-CORDEX ensemble are higher than those of the SAFRAN indicator, due to a shift and



**Fig. 4.** Heat waves detected during the 1959–2015 period with the SAFRAN indicator. Each bubble gives the duration (x axis), maximum temperature (y axis) and global intensity (bubble size).

**Fig. 5.** Heat waves during the 1971–2005 period for the ten EURO-CORDEX models (grey bubbles) and the SAFRAN reanalysis (pink bubbles). Each bubble gives the duration (x axis), maximum temperature (y axis) and global intensity (bubble size). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

broadening of the distribution in the models, compared to the SAFRAN reanalysis (not shown).

For our study, heat wave analysis has been done first for present-day climate from a daily indicator based on the SAFRAN reanalysis. It is calculated as the half-sum of the analysed daily minimum and maximum temperatures, an estimate of the daily mean temperature, averaged over the France domain from the 1959 to 2015 period. It is used in the following to analyse the characteristics of observed heat waves in France. Heat waves detected from this indicator are also compared to those simulated by the multi-model ensemble EURO-CORDEX to assess the ability of regional models to simulate such events. Then the analysis of heat

waves evolution in future climate is made for the EURO-CORDEX ensemble over the period 2006–2100, under the scenarios RCP4.5 and RCP8.5.

### 4.2. Heat wave characteristics in present-day climate

In this section, the characteristics of simulated and observed heat waves over the 1959–2015 period are analysed. Fig. 4 shows a "bubble" representation of the heat waves events detected from the SAFRAN indicator over France, where each bubble gives the three main characteristics of an event. This innovative multi-dimensional representation synthesizes these characteristics in a comprehensible and accessible way, and is usable for both research studies and policy makers.

A total of 25 heat waves has been detected with the SAFRAN indicator, with durations varying from 5 to 23 days (July 1983), and maximum temperatures between 23.7 °C (June 2010) and 28.1 °C (August 2003). Some heat waves have been experienced during the same summer. For example, two different events respectively of 8 and 9 days duration are identified for the warm 2015 summer.

The strongest heat wave in terms of global intensity occurred in August 2003 (from August 1 to 17), for which the maximum temperature during the event was 28.1 °C, with a global intensity of about 32. The second most important wave occurred from July 10 to July 30 in 2006. Its global intensity was about 20.7 and the temperature reached 25.9 °C. Finally, the third strongest heat wave occurred in 1983 (July 9 to July 31), with a global intensity of about 13.5 and for which the mean temperature reached 24.6 °C. It is the longest event detected over the period. We can also note that the first heat wave that occurred during the 2015 summer appears in third place in terms of maximum temperature.

### 4.3. Simulation of heat wave events in the EURO-CORDEX ensemble

Fig. 5 shows the bubble plots for heat waves simulated during the 1971–2005 period by each model of the ensemble EURO-CORDEX. It allows to estimate the ability of models to reproduce the events correctly. We note some differences in the distribution of the heat wave characteristics but the number of events is very similar across simulations: 12–16 heat waves are detected according to the models, therefore the simulated range of events is consistent with the number of waves detected from the SAFRAN indicator (14). Most of them simulate durations and global intensities comparable with SAFRAN.

Fig. 6 shows the mean heat wave characteristics (duration, maximum intensity, global intensity) for SAFRAN and each model of the ensemble. The mean durations of these waves lie between
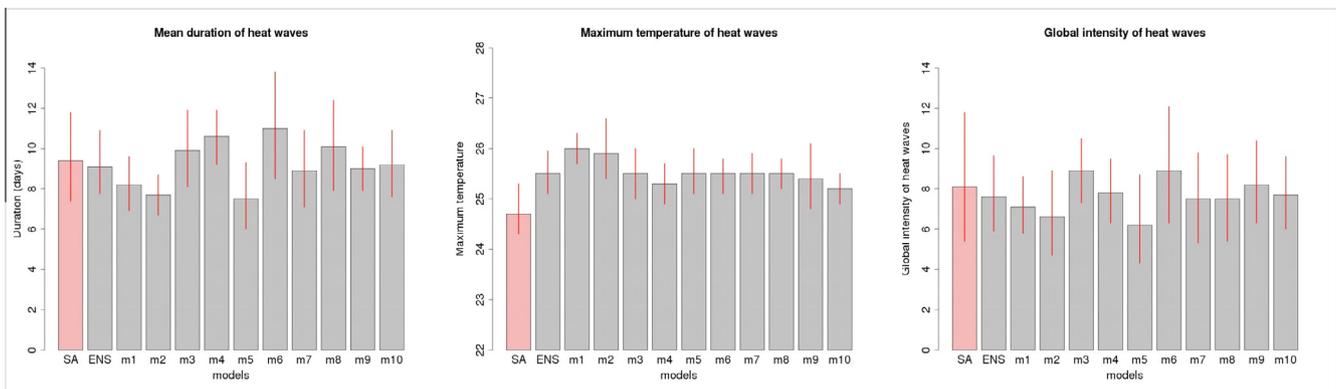


**Fig. 6.** Mean characteristics over the 1971–2005 period for the SAFRAN reanalysis (pink) and 10 EURO-CORDEX models (grey): duration (left), maximum intensity (middle), global intensity (right). Histograms named "ENS" represent the ensemble medians. The 90% confidence intervals of the mean characteristics calculated by bootstrap for each model and for the reanalysis are given by the red segments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
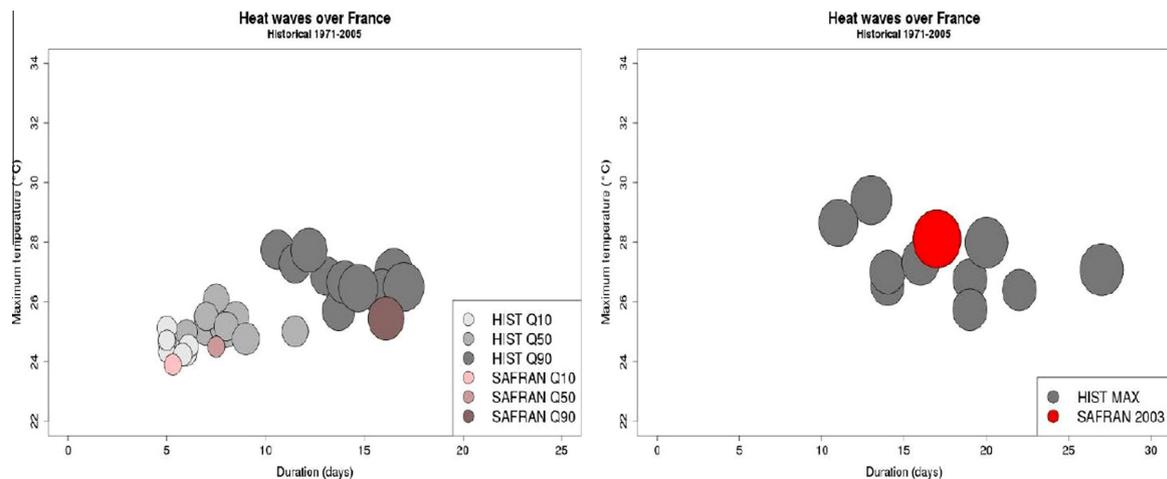


**Fig. 7.** Statistics on heat waves characteristics during the 1971–2005 period for the EURO-CORDEX models (grey bubbles) and the SAFRAN reanalysis (pink bubbles). Left: Percentiles [10%–50%–90%] calculated for each model from its heat waves ensemble. Right: Maximum global intensity heat waves simulated by models compared to the 2003 SAFRAN event. Bubbles description as in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7 and 11 days. These values are within the confidence interval (estimated by bootstrap method) of the waves detected from the SAFRAN indicator. The ensemble median of the mean heat wave duration (9.3) is very close to the value obtained for SAFRAN (9.4). The mean maximum temperatures lie between 25.2 °C and 26 °C. Some simulations produce maximum temperature beyond the confidence interval of SAFRAN. Global intensities lie between 6.2 and 8.9, which is consistent with the SAFRAN value (8.1).

In summary, the EURO-CORDEX ensemble simulates heat waves for which mean characteristics are consistent with the events detected from the SAFRAN indicator during the 1971–2005 period. Although not surprising because model outputs were bias adjusted using a method based on percentiles, this result was not straightforward in particular in terms of event duration. This also corroborates the evaluation of the RCMs made in Vautard et al. (2013) where models were found to reasonably simulate heat wave events during 1989–2008 using ERA-Interim boundary forcing.

In order to study more specifically the statistics associated with heat waves simulated by the models, Fig. 7 provides a bubble representation of the 10th, median and 90th percentiles of the 3 characteristics of heat waves. Median duration (Q50) lies between 6 and 11.5 days according to the models, and the median global intensities range from 4.4 to 9.1. The 90th percentiles of duration lie between 10.6 and 17 days. The 90th percentiles of global intensities vary between 9.9 and 15.9. The percentiles of heat waves characteristics simulated by models are close to the percentiles associated with the SAFRAN indicator, although the mean maximal temperature reached during the events is generally higher. This means that the ensemble generally succeeds in simulating heat waves which characteristics are consistent with heat waves detected from the SAFRAN indicator.

As a comparison, the 2003 heat wave detected from the SAFRAN indicator lasted 17 days with a global intensity of about 32. Duration and maximal temperatures associated with stronger heat waves-in terms of global intensity-are close to or stronger than the observed characteristics of the 2003 event. This implies that models occasionally simulate waves as intense as the 2003 heat wave, which remains an exceptional event compared to observed waves over the 1971–2005 period.

The following section focuses on the evolution of heat waves simulated by the EURO-CORDEX models in future climate. Diagnoses are based on the RCP4.5 and RCP8.5 scenarios, and focus on two 30-year periods: 2021–2050 and 2071–2100.

### 4.4. Evolution of heat wave characteristics in future climate

Over the 2021–2050 period, 28–48 (median value: 34) heat waves are simulated under the RCP4.5 scenario, and between 21 and 40 events (median value: 34) under the RCP8.5 scenario (Fig. 8). The number of simulated events from the multi-model ensembles is similar under the RCP4.5 and RCP8.5 scenarios, and corresponds to an increase of 19 events compared to the median number of heat waves simulated over the 1976–2005 period. At the end of the century, the number of heat waves slightly increases under the scenario RCP4.5, with 29–60 events simulated over the 2071–2100 period depending on the models. The number of simulated waves increases considerably under the scenario RCP8.5 with a median number of 87 (61–99 depending on the models), i.e. 72 more than in the 1971–2005 period.

Fig. 9 provides a bubble representation, for each RCP scenario and model, of the 10th, median and 90th percentiles of the 3 characteristics of heat waves simulated by the models, splitted into the 2021–2050 and 2071–2100 periods.

Under the RCP4.5 scenario, median duration (Q50) lies between 7 and 10 days at the middle of the century according to the models, and between 8 and 13 days at the end of the century. The median global intensities range from 5.8 to 10.6 at the middle century and from 6 to 13.4 at the end of the century. The 90th percentiles of duration lie between 14 and 23 days at the middle of the century according to the models, and between 15 and 30 days during the 2071–2100 period. The 90th percentiles of global intensities vary between 13 and 33 over the 2021–2050 period and between 15.9 and 35.3 in the 2071–2100 period. In comparison, the 2003 heat wave characteristics detected from the SAFRAN indicator are similar to the strongest heat waves that could occur at the end of the century. We can note that the 90th percentile values of maximal temperatures reached during the events do not change a lot between 2021 and 2050 and 2071–2100. This suggests a physical constraint on this maximum temperature.

Under the RCP8.5 scenario, median duration varies between 7 and 11 days on 2021–2050, and between 11 and 17 days at the end of the century. The median global intensities range from 5.8 to 9.8 over the 2021–2050 period and from 11.2 to 16.2 over the 2071–2100 period. The 90th percentiles of duration lie between 12 and 27 days at the middle of the century, and between 23 and 76 days at the end of the century. The 90th percentiles of global intensities vary between 9.8 and 39.5 over the years 2021–2050 and between 40.9 and 136.1 for the 2071–2100 period. The charac-
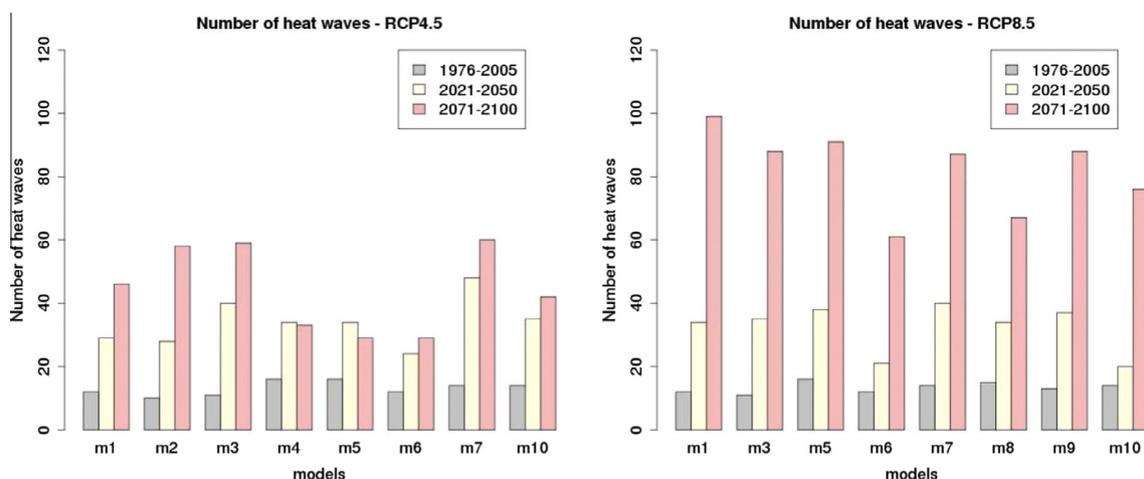


**Fig. 8.** Number of heat wave events during the 1976–2005 (grey), 2021–2050 (yellow) and 2071–2100 (pink) periods, for 8 EURO-CORDEX models. Left: RCP4.5 scenario, right: RCP8.5 scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
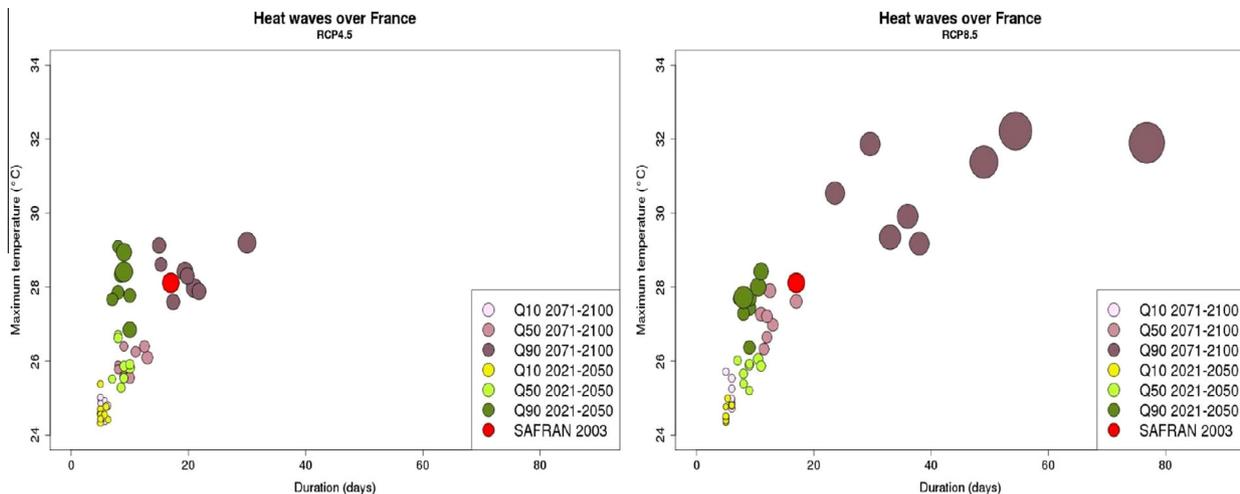
**Fig. 9.** Statistics on heat waves characteristics during the 2021–2050 and 2071–2100 periods for the EURO-CORDEX models. Left: RCP4.5 scenario. Right: RCP8.5 scenario. Percentiles [10%–50%–90%] are calculated for each model from its heat waves ensemble over the two periods. The 2003 event detected with SAFRAN indicator is displayed in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
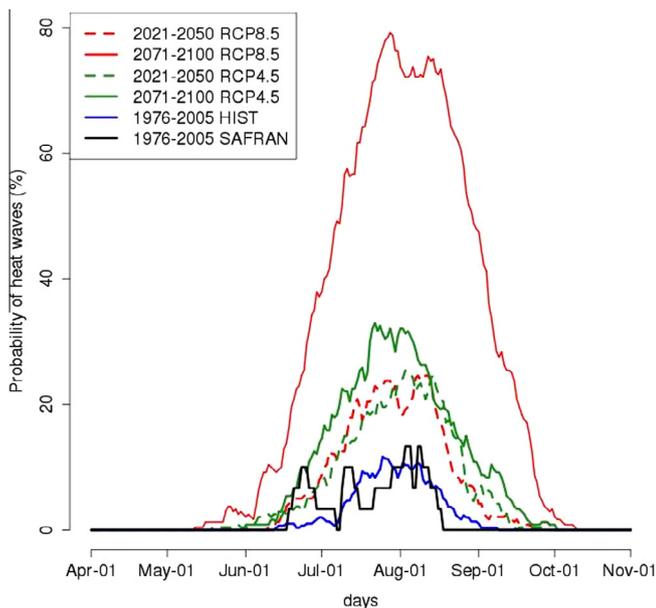


**Fig. 10.** Climatological annual cycle of the heat wave frequency from the 1st of April to the 31th of October.

teristics related to the 2003 exceptional event remain above the median heat waves that could occur between 2021 and 2050, both in terms of duration and global intensity. If such an event happened again, it would correspond to a typical event at the end of the century, and its characteristics would be much lower than the strongest waves that could occur over the last 30 years of the 21st century. Under this scenario, there are strong changes in the 90th percentile values from the 2021–2050 to 2071–2100 periods in terms of maximum temperature and duration. We can also note a larger multi-model spread during the 2071–2100 period for the 90th percentile bubbles.

Besides the evolution of the number, duration and intensity of heat waves, climate change could have an impact on the climatological annual cycle of the occurrence of heat waves. For this purpose we calculate the frequency of heat wave occurrence for each day of the year, for different periods and scenarios (Fig. 10).

Between 1976 and 2005, heat waves occurred between the 18th of June and the 17th of August. The highest frequency of occurrence is around the first half of August. Concerning the model simulations, we consider the whole ensemble of EURO-CORDEX models. For the 1976–2005 period, the simulated heat waves occur between the 13th of June and the 8th of September. The highest frequency of heat wave occurrence is dated around the 25th of July.

During the 2021–2050 period, the climatological annual cycle are similar for the two RCP scenarios, with higher frequencies and heat waves occurring during a larger part of the summer. The maximum frequency increases from 12% in the historical simulation mean to 25% under both RCP4.5 and RCP8.5 scenarios (respectively around the 1st and 10th of August). The frequencies similar or higher than the maximum frequency of the simulated heat waves over the 1976–2005 period cover the period from the 8th of July to the 25th of August under the RCP4.5 scenario, and the period from the 4th of July to the 20th of August under the RCP8.5 scenario.

For the end of the century (2071–2100), the frequencies similar or higher than the maximum occurrence frequency of the simulated heat waves over the 1976–2005 period cover the period from the 27th of June to the 29th of August under the RCP4.5 scenario, and from the 16th of June to the 27th of September under the RCP8.5 scenario. The heat wave frequencies reach 33% around the 22nd of July for the RCP4.5 and 79% around the 28th of July for the RCP8.5 scenario.

In summary, the frequency of occurrence increases in future climate for both RCP4.5 and RCP8.5 scenarios, with heat waves occurring during a larger part of the summer season (or even near autumn for the RCP8.5 scenario at the end of the century). This confirms the need to apply the method to the whole year and not only to the summer days. Compared to the SAFRAN atmospheric reanalysis, the maximum frequency of the simulated heat waves over the 1976–2005 period is reached earlier in the year. Furthermore, the simulated climate change has no significant impact on the date of the maximum frequency, regardless of the scenario and the projection period.

## 5. Conclusion

The aim of this paper was to study heat wave characteristics over France in present and future climate using a new method of detection based on an event approach, convenient for both climate

monitoring and climate change analysis, using upper quantiles of the temperature distributions. It proposes an innovative representation of multi-dimensional events, with a multi-model approach, necessary to take into account the uncertainty relative to the regional simulations. Results show that the EURO-CORDEX ensemble simulates heat waves of which mean characteristics are consistent with the events detected from the observation-derived SAFRAN indicator during the 1971–2005 period. Bias-corrected models are able to simulate waves as intense as the 2003 event, which remains an exceptional event beyond the highest observed heat waves.

The main characteristics related to the heat waves simulated by the EURO-CORDEX ensemble slightly increase for the 2021–2050 period under both RCP4.5 and RCP8.5 scenarios. These characteristics differ in the second half of the century according to the scenario, with changes becoming more pronounced under the RCP8.5 scenario. The number of simulated waves increases considerably, as do their duration and global intensities. The exceptional (compared to the present-day climate) 2003 event corresponds to a typical event of the end of the century, and has lower duration and intensity than the strongest waves that could occur over the last 30 years of the 21st century.

Moreover, the frequency of occurrence increases in future climate, with heat waves occurring during a larger part of summer. The maximum frequency calculated from the ensemble of simulations is reached earlier in the year than in the observations. Finally, climate change does not seem to have a great impact on this date for both RCP4.5 and RCP8.5 scenarios.

The adaptability of this new method of heat wave detection enables analysis of an event relative to the climate of any period and geographical area. In the current context of global warming, the chosen reference period has an impact on the heat wave detection. For instance, and as expected due to the warming trend, fewer events are detected during the 1971–2005 period when using a 1981–2010 reference than with an earlier reference, due to higher detection thresholds. Beyond these considerations which have to be taken into account for heat wave detection, this method offers a wide range of opportunities, among which the use of a running reference period centred on one year, which could allow the consideration of climate change adaptation.

Another interest of this new method is the possibility of a spatial event approach as done for heat waves experienced in France during the 2015 summer (Soubeyroux et al., 2016). Since a mean indicator for France based on national mean temperature could mask some regional disparities, the detection has been applied to French districts for this case study. This spatial approach allowed the production of maps of heat wave durations and intensities, which showed a strong spatial variability of the 2015 heat wave intensity. This confirms the importance to take into account the spatial dimension of the heat waves. Furthermore, the method can be applied to any time series, but it is all the same sensitive to the quality of the series used. For example, its application to a meteorological station can lead to some unrealistic heatwaves if the measured time series presents temporal breaks, so it requires the use of homogenized temperature time series.

This method establishes a useful tool to provide an accessible analysis which can be used not only for research studies, but also for several impacted sectors such as human health, electricity supply or urban sector. It remains however sufficiently general for not being attached to a specific impacted domain. For example, it has been recently applied for climate services in the French portal Climat[HD], in order to represent present-day and future heat waves. Moreover, the "bubble" representation has also been adopted in a report about cities adaptation to climate change for Paris Urban Area.

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