



**HAL**  
open science

# Instrumental agreement and retrospective analysis of trends in precipitation extremes in the French Mediterranean Region

Juliette Blanchet, Jean-Dominique Creutin

► **To cite this version:**

Juliette Blanchet, Jean-Dominique Creutin. Instrumental agreement and retrospective analysis of trends in precipitation extremes in the French Mediterranean Region. *Environmental Research Letters*, 2022, 17 (7), pp.074011. 10.1088/1748-9326/ac7734 . hal-03752002

**HAL Id: hal-03752002**

**<https://hal.science/hal-03752002>**

Submitted on 16 Aug 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

LETTER • OPEN ACCESS

## Instrumental agreement and retrospective analysis of trends in precipitation extremes in the French Mediterranean Region

To cite this article: Juliette Blanchet and Jean-Dominique Creutin 2022 *Environ. Res. Lett.* **17** 074011

View the [article online](#) for updates and enhancements.

You may also like

- [Regionalization of anthropogenically forced changes in 3 hourly extreme precipitation over Europe](#)  
Parisa Hosseinzadehtalaei, Hossein Tabari and Patrick Willems
- [Internal variability in European summer temperatures at 1.5 °C and 2 °C of global warming](#)  
Laura Suarez-Gutierrez, Chao Li, Wolfgang A Müller et al.
- [Long-term precipitation in Southwestern Europe reveals no clear trend attributable to anthropogenic forcing](#)  
D Peña-Angulo, S M Vicente-Serrano, F Domínguez-Castro et al.

ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## Instrumental agreement and retrospective analysis of trends in precipitation extremes in the French Mediterranean Region

## OPEN ACCESS

RECEIVED  
9 March 2022REVISED  
24 May 2022ACCEPTED FOR PUBLICATION  
9 June 2022PUBLISHED  
21 June 2022Juliette Blanchet\*  and Jean-Dominique Creutin 

Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, F-38000 Grenoble, France

\* Author to whom any correspondence should be addressed.

E-mail: [juliette.blanchet@univ-grenoble-alpes.fr](mailto:juliette.blanchet@univ-grenoble-alpes.fr)

Keywords: extreme precipitation, trend, French Mediterranean Region, rain-gauge

Original Content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



## Abstract

In this letter we show the emergence of an agreement between the instruments of a rain-gauge network to point toward a positive trend in daily precipitation extremes since 1960 in the French Mediterranean Region. We identify for each gauge the time varying parameters of the generalized extreme value distribution of annual maximum precipitation over incremental time-windows. These distributions provide for each station of the network a trend assessment over a chosen period that can be interpreted for instance as a trend of the mean or as the trend of a chosen quantile. The incremental window, i.e. a window containing the series of data available at a given date, mimics the annual assessment of the trends that could have been made through time. Each year we thus have one trend per gauge that we can look in distribution through the network in order to assess the level of consensus among instruments. We show how the increasing size of the datasets used over a period of possible climate non-stationarity progressively leads from a dissensus anarchically pointing to no trend (before the 2000s) to a consensus where a majority of gauges points toward a positive trend (after the 2000s). The detected trend in this Mediterranean Region is quite substantial. For instance the 20 year return period precipitation in 1960 turns out to become a 8 year return period precipitation in 2020. Using a simulation basis we try to characterize the effect of decadal variability that is quite readable in the consensus evolution. The proposed metrics is thought to be a good candidate for the assessment of the local time and rate of emergence of climate change that has important implications in regards to adaptation of human and natural systems.

## 1. Introduction

Over recent years, some studies relying on ground observation data started to show positive trends in rainfall extremes at regional scale over the French Mediterranean (Tramblay *et al* 2013, Blanchet *et al* 2018, Ribes *et al* 2019), while in previous comparable studies over the same region trends were apparently undetectable (see for instance Soubeyroux *et al* 2015). In this letter we conduct a retrospective study to show the emergence of consistent trends in rainfall extremes over this region prone to heavy precipitation events (HPEs) generating devastating flash-floods during the fall season. The area is studied for its quite intensive rainfall regime (Molinié *et al* 2012) as well as for the related socio-environmental issues at stake (Lutoff and Durand 2018, 2020). In this context detecting the emergence of a change regards impacts

and adaptation because human and natural systems start to be vulnerable and have to adapt when unprecedented climate conditions appear, whether they are related to the ‘anthropogenic’ global warming effects or not (IPCC 2021, chapter 12.5.2).

Obtaining climate change information from observed data is important for at least two reasons. First, a change revealed by observation means obviously that new conditions already emerged, which is informative in regard to adaptation decisions, or absence of decision. Second, the use of observations looks quite necessary when modeling outputs are hardly conclusive in regard to the complex atmospheric conditions generating HPEs. The complexity of rainfall formation in this mid-latitude area with a quite marked topography neighboring a warm sea basin (Delrieu *et al* 2005, Ducrocq *et al* 2008, Nuissier *et al* 2008, Drobinski *et al* 2014) makes available

regional climate modeling outputs difficult to use in regard to significant biases at high-order quantiles (Colmet-Daage *et al* 2018). This difficulty stems more from model physics, in particular convection parameterization, than from resolution (Cavicchia *et al* 2018). It calls for the use of non-hydrostatic higher resolution models better depicting the convection control of the space–time patterns of rainfall extremes (Fumière *et al* 2019). The reliability of model-based studies regarding changes in extremes is anyway a general issue (Bellprat *et al* 2019).

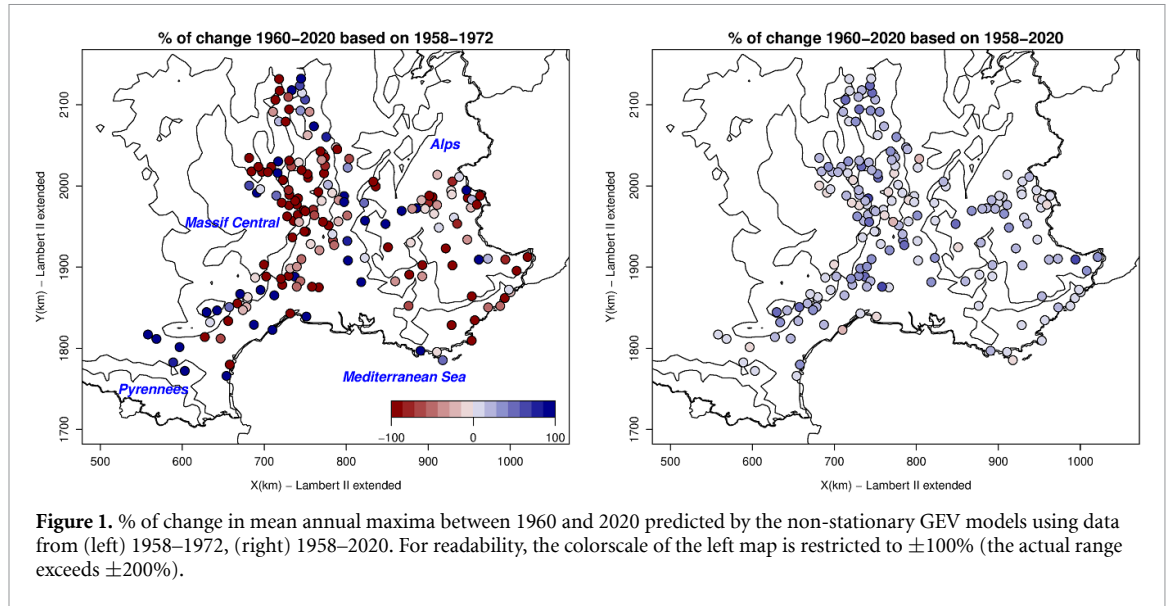
Detecting a change in atmospheric variables, be it from ground data or model outputs, is a problem of signal-to-noise ratio  $S/N$ , the trend or ‘forced’ signal  $S$  being hidden by the atmospheric ‘natural’ variability or ‘noise’  $N$ . This problem was encountered in climate prediction assessment and early recognized as a space–time pattern recognition issue since climate data are multi-dimensional (Hasselmann 1979, Kirchmeier-Young *et al* 2019). Trend identification as well as attribution of extraordinary events (see for instance Vautard *et al* (2015), about the 2014 series of HPEs in the study region) and identification of the time of emergence (ToE) (see for instance the pioneering results of Giorgi and Bi 2009, for the ‘Mediterranean hotspot’) belong to the same class of problems. Attribution and ToE metrics detect a significant change between a reference period of natural variability  $N$ , sometimes coined ‘counterfactual’ or ‘historical’, and a period where the forcing is present  $S + N$ . Different metrics of ToE have been used in previous studies. Giorgi and Bi (2009), Hawkins and Sutton (2012), Maraun (2013), Rojas *et al* (2019), Sui *et al* (2014) define the ToE as the time at which the signal-to-noise ratio  $S/N$  becomes greater than a prescribed value. Mahlstein *et al* (2012), Chadwick *et al* (2019), Gaetani *et al* (2020) define the ToE as the time when  $S + N$  gets statistically different from  $N$ . Kusunoki *et al* (2020) define the ToE as the start of the period in which  $S + N$  consistently exceeds the maximum value of  $N$  obtained from the historical experiment. The frequency share between low- ( $S$ ) and high-frequency ( $N$ ) is anyway quite theoretical in front of a continuous range of scales where intermediate multi-decadal variability related to large scale atmospheric oscillations is difficult to relate to  $S$  or  $N$  (Deser *et al* 2016, Gaetani *et al* 2020). The role of the metrics in change detection is important, but in front of complex space–time patterns, a critical issue is to apply the metrics to appropriate integration domains over space and time in order to amplify the signal to noise ratio and favor trend emergence (Maraun 2013).

Our study aims at using a minimal set of assumptions to show how a network of rain-gauges progressively integrates the variability of yearly maximum point rainfall over its increasing time window of functioning and over its space domain of extension.

The key characteristics of our metrics is (a) to work with point trends, (b) to integrate in space looking at the distribution of point trend diagnoses given by each instrument of a network and (c) to integrate in time over an incremental window size that progressively filters out lower frequencies. We thus assume that the functioning window spans over a large enough time spectrum to progressively filter out the noise  $N$  including some decadal variability and that the instrumental consensus points an homogeneous behavior of  $S$  over a small enough study domain.

The characteristics and assumptions of our metrics are individually present in previous studies but, to our best knowledge, have never been applied together. In all the mentioned studies, the space–time resolution of the raw data depends on the nature of the data, computational or instrumental. Model outputs are gridded and instruments may have a point resolution (rain-gauges) or a gridded resolution (radar) and point data may be converted to grids by interpolation (Haylock *et al* 2008, Gottardi *et al* 2012). Our metrics can apply to a set of points or grid nodes as well. In space, a majority of metrics analyzes the change in average rainfall values or indices over either clusters of instruments (Ribes *et al* 2019), or hotspots and continental regions (Gaetani *et al* 2020), or hydrographic units (Leng *et al* 2016, Zhuan *et al* 2018), or latitude bands (Zhang *et al* 2007). The analysis of a set of point changes following a consensus approach like in our metrics is to our best knowledge only present in some modeling based studies that look at the consensus between models (Hawkins and Sutton 2012, King *et al* 2015, Nguyen *et al* 2018). In time, the most common ways to filter out  $N$  including the multi-decadal variability are (a) to work on average values or indices over seasons (Giorgi and Bi 2009) to years (Chadwick *et al* 2019) and (b) to use large temporal moving windows of chosen width to detect the change (typically 20 years such as in Giorgi and Bi 2009, Gaetani *et al* 2020). To our best knowledge, only one study used incremental windows as in our metrics to show the time evolution of maximum precipitation (see figure 4 of Ribes *et al* 2019)—in the latter, considering the series of spatial weighted average of maxima.

In summary, we basically combine the idea of displaying the diagnostic evolution in time (Ribes *et al* 2019) to a consensus metrics present in some ToE modeling studies (Hawkins and Sutton 2012). Doing so, we avoid choices such as indices and thresholds, co-variables, time window sizes and reference periods. We keep the analysis as close as possible to the raw data characteristics—number of instruments and time length of the series—only submitting the study area (the French Mediterranean Region) and the window increments (1 year) to an arbitrary choice.



**Figure 1.** % of change in mean annual maxima between 1960 and 2020 predicted by the non-stationary GEV models using data from (left) 1958–1972, (right) 1958–2020. For readability, the colorscale of the left map is restricted to  $\pm 100\%$  (the actual range exceeds  $\pm 200\%$ ).

## 2. Data and methods

The studied region corresponds to the southern part of France that is under Mediterranean climatic influence (see figure 1). It is limited to the north by the Massif Central, to the south by the Mediterranean coast from Perpignan to Nice—excluding the Bouche-du-Rhône department that behaves differently, to the west by the Pyrenees and to the east by the southern Alps, with altitude ranging from 0 to more than 3000 m.a.s.l over a surface of 100 000 km<sup>2</sup>. The domain is known to experience severe storms generating devastating flash-floods from various foothill rivers, as occurred in the region of Nîmes in 1988 (southern France, Duclos *et al* 1991), on the Ouvèze River in 1992 (eastern flank of the Alps, Sénési *et al* 1996), on the Aude River in 1999 (north-east of the Pyrenees, Gaume *et al* 2004), on the Gard River in 2002 (southern edge of the Massif Central, Delrieu *et al* 2005), on the Argens River in 2010 (southern edge of the Alps, Ruin *et al* 2014), on the Vésubie River in 2020 (southern Alps, Chochon *et al* 2021). The south-eastern edge of the Massif Central experiences most of the extreme storms and resulting flash-floods (figures 2 of Nuissier *et al* 2008, Blanchet and Creutin 2017, Blanchet *et al* 2018).

Daily rainfall data are acquired by Météo-France. About 1500 daily stations are located in this area but with various lengths of observation. We consider 180 stations featuring at least 60 observed years over the period 1958–2020 and we extract, at each station, the series of annual maxima. The stations are relatively homogeneously spread over the region, with however a larger density along the Massif Central flank (see figure 1).

Trend in the statistics of extreme precipitation is assessed by fitting a non-stationary generalized extreme value (GEV) distribution with cumulative distribution function at year  $t$ :

$$G(r_t; \mu(t), \sigma(t), \xi) = \exp \left\{ - \left[ 1 + \xi \frac{r_t - \mu(t)}{\sigma(t)} \right]^{-1/\xi} \right\}, \quad (1)$$

where  $r_t$  is the annual maximum of a given station,  $\mu(t)$ ,  $\sigma(t)$  and  $\xi$  are the location, scale and shape parameters at year  $t$ . We consider linearly varying location and scale parameters:  $\mu(t) = \mu_0 + \mu_1 t$ ,  $\sigma(t) = \sigma_0 + \sigma_1 t$ . This implies that the mean ( $m_t$ ) and  $T$  year return levels ( $RL_t(T)$ ) are assumed to vary linearly with years:

$$m_t = \mu(t) + \frac{\sigma(t)}{\xi} (\Gamma(1 - \xi) - 1) \quad (\text{for } \xi < 1), \quad (2)$$

$$RL_t(T) = \mu(t) + \frac{\sigma(t)}{\xi} \left[ \left( -\log \left( 1 - \frac{1}{T} \right) \right)^{-\xi} - 1 \right], \quad (3)$$

where  $\Gamma$  is the Gamma function. This model might not be the most parcimonious (Blanchet *et al* 2021a) and this could, e.g. affect significance testing but this is out of concern here since we are only interested in trend values.

The GEV model of equation (1) is fitted by maximum likelihood (Coles 2001) at either station. We consider incremental windows, first estimating the model based on the maxima for 1958–1972, then increasing the window size by 1 year (1958–1973), and so on up to the maximal window 1958–2020. Thus 49 GEV distribution estimates are obtained for each station, each estimation being based on 15 (1958–1972) to 63 (1958–2020) maxima.

Since our interest is to assess the instrumental agreement as time goes on, we compare the predicted changes (in mean or return level) for a common period, which is here arbitrarily chosen as 1960–2020. This is given by  $(m_{2020} - m_{1960})/m_{1960}$  and  $(RL_{2020}(T) - RL_{1960}(T))/RL_{1960}(T)$  with  $m_t$  and

$RL_t(T)$  given by equations (2) and (3). Note that this implies extrapolating in time all models (but the maximal one) till 2020 but this is mathematically-speaking no issue since equations (2) and (3) are parametric functions (so we only have to replace  $t$  by 2020 therein).

We call the ‘consensus curve’ the curve defined by the station median of the predicted changes versus time (i.e. versus the window size). Our goal is the assess whether the consensus curve for the mean or return level converges at some point to a nonzero value, i.e. to estimate the time in the past when an agreement has emerged between most stations to point toward a trend. This definition of emergence based on convergence over incremental windows differs from other studies such as Giorgi and Bi (2009), Trambly and Somot (2018) that assess the TOE based on full series of climate simulations (e.g. from 1950 to 2100). Our TOE can actually be understood as a time when a consensus is reached.

### 3. Results

For illustration, we show in figure 1 the spatial distribution of the % of change in mean annual maxima between 1960 and 2020 predicted by the non-stationary GEV models using data from either 1958–1972, or 1958–2020. The % of change using 15 years of data are very chaotic, with changes varying from  $-100\%$  to  $+100\%$  in few km. When using 63 years, changes are smaller in absolute value but much more homogeneous and very mainly positive.

Figure 2 summarizes such maps by showing the boxplots of % of change between 1960 and 2020 obtained over all incremental windows. The horizontal dashed red line shows a rough estimation of the expected Clausius–Clapeyron response, obtained by combining the Clausius–Clapeyron rate of  $+6.8\% \text{ K}^{-1}$  with the observed annual mean warming over the region of about  $+1.79 \text{ K}$  (Ribes *et al* 2019), giving an expected increase in extremes of about  $12.2\%$  between 1960 and 2020. Note that the expected Clausius–Clapeyron response is an horizontal line in figure 2 because the plots show changes with respect to a common reference period 1960–2020 and hence to a common level of warming. The figure shows that the dispersion of predicted percentage of change between 1960 and 2020 has evolved considerably over time. The data series have indeed become longer over time, gradually covering a period where climate change gets increasingly clearer.

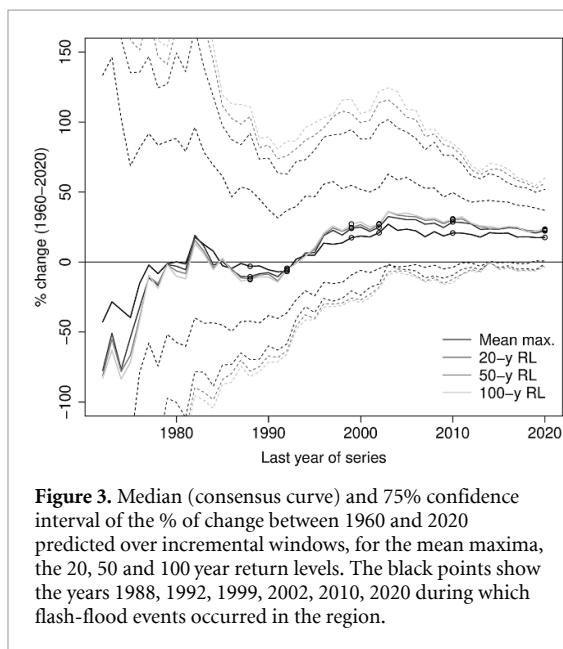
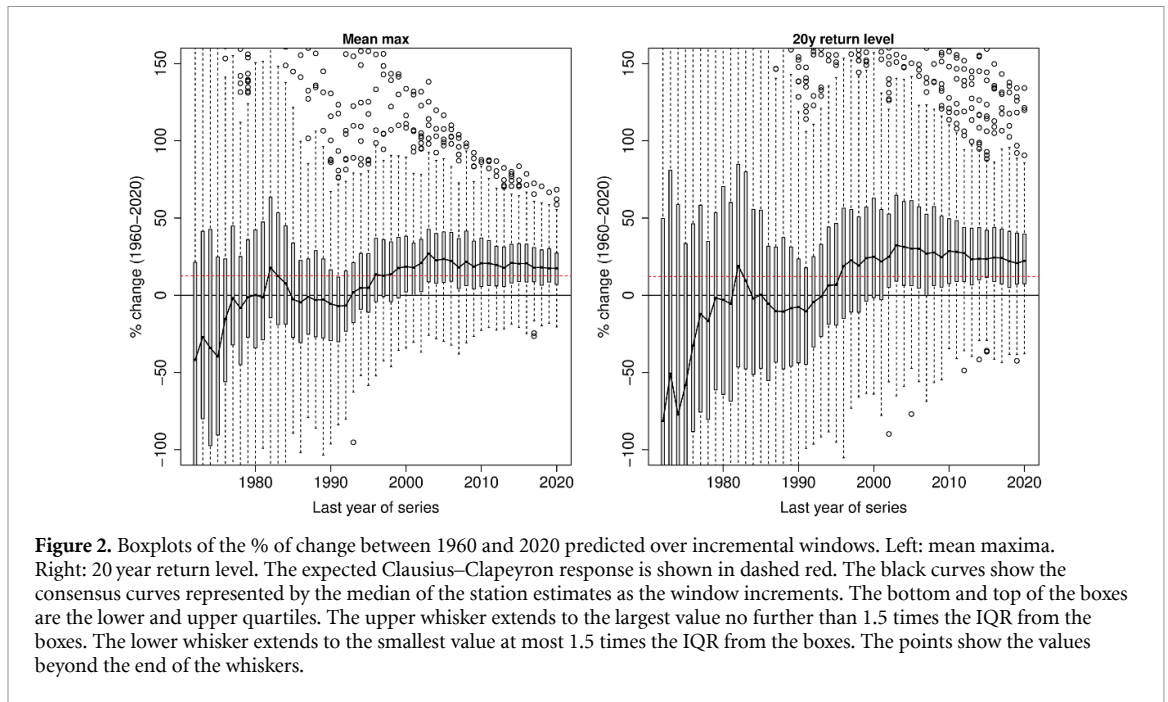
Three periods stand out in the ‘consensus’ of the rain gauges. Until the mid-1980s, the rain gauges gave widely varying opinions. Many of them predicted a decrease in extreme between 1960 and 2020 in proportions ranging from  $0\%$  to  $100\%$ . The data series available—a mere 20 years or so—was too short to

produce reliable statistics. Clearly, the change was not yet perceptible in the Mediterranean region at that time. In the 1990s, a dramatic shift occurred. The divergence of predicted changes between rain gauges was halved as a result of longer observation times. More importantly, the vast majority of rain gauges fell into the same intensification opinion. Since the 2000s, this unanimity has been stable. More than  $80\%$  of the rain gauges predict an increase. This increase tends to tighten around about  $18\%$  for the mean annual maximum and  $22\%$  for the 20 year return level. The latter implies that the 20 year return period of precipitation in 1960 turns out to become a 8 year return period of precipitation in 2020. Furthermore  $75\%$  of the rain gauges exhibit super–Clausius–Clapeyron behavior (i.e. an increase larger than the expected Clausius–Clapeyron response), which is in coherence with Ribes *et al* (2019). In view of these analyses, the intensification of exceptional heavy rainfall appears to be undeniable in the region of interest, and has been for a good 10 years. The stabilization of the consensus curve in figure 2 argues in favor of a TOE around 1995–2000, which is quite consistent with the break date of 1985 identified in the region (Blanchet *et al* 2018, 2021b). This is also consistent with the TOE estimated between 1980 and 2000 in the region in Trambly and Somot (2018) using climate simulations up to 2100.

The consensus curve—and thus the TOE—vary very little whether they are defined from the mean maxima or from the 100 year return levels, as they corresponds to % of changes rather than absolute changes (figure 3). It can also be noted that, although based on convergence of medians, the TOE defined from the consensus curve corresponds to the time when more than two third of the stations agree on positive trends, whatever the return period considered (figure 3).

Another remarkable property of the consensus curve is to be little sensitive to the occurrence of major events, such as in October 1988 (Nîmes disaster, Duclos *et al* 1991), 1992 (Ouvèze River, Sénési *et al* 1996), 1999 (Aude River, Gaume *et al* 2004), 2002 (Gard River, Delrieu *et al* 2005), 2010 (Argens River, Ruin *et al* 2014). The consensus curves obtained by omitting either of these years in the data (i.e. by setting the maxima values of these years to NA) yields to differences no larger than  $5\%$  for the mean maxima and no larger than  $6\%$  for the 20 year return levels. Another remarkable property of the consensus curve is to be little sensitive to the spatial distribution of the stations since it is based on the median.

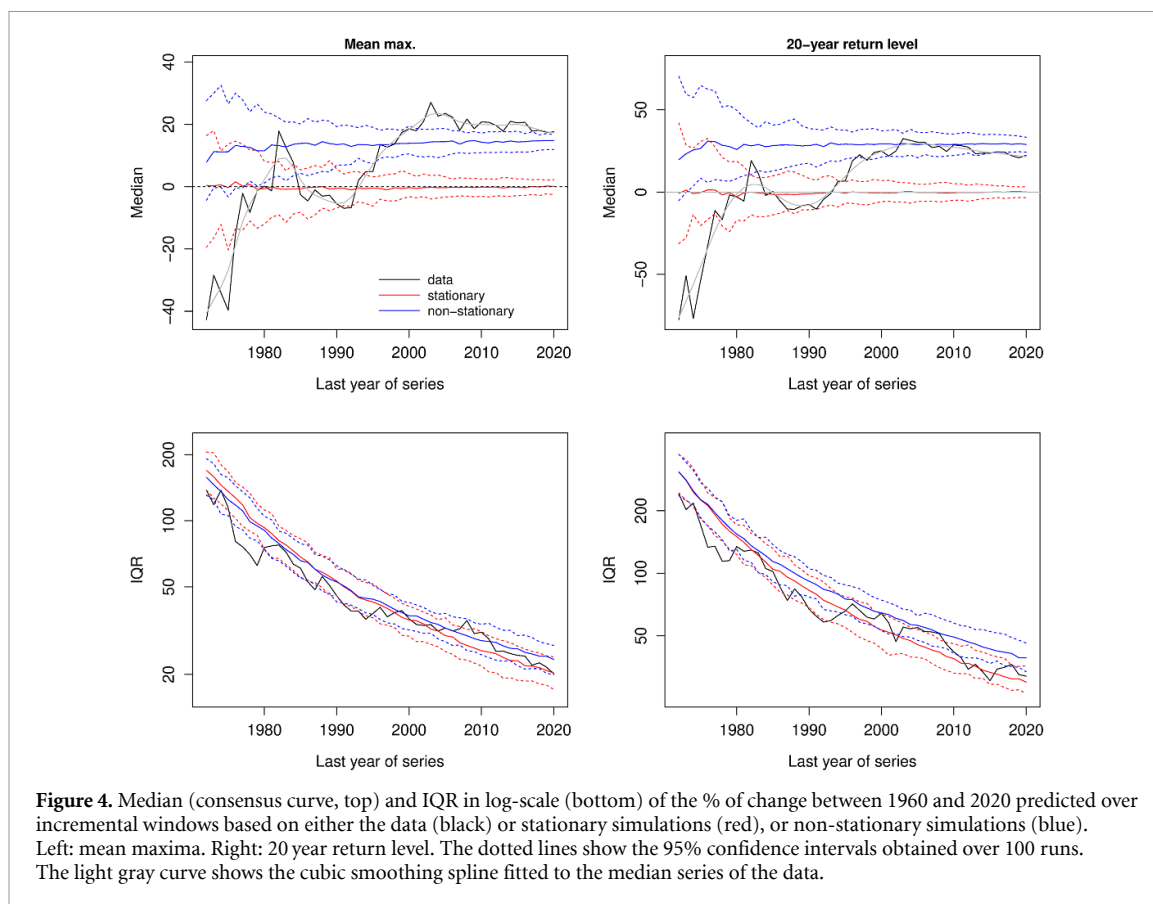
In order to illustrate the respective effects of a stationary noise  $N$  and a multi-decadal signal  $S$  on the presented statistics, we made a simulation exercise. We simulated, at each gauge,  $n$  fictitious annual maximum series drawn independently from



GEV distributions with either the same stationary parameters as the rain gauges, or non-stationary parameters. In the latter case, the four GEV non-stationary parameters are set so that: (a) the average GEV means and variances over 1958–2020 are equal to the empirical means and variances of gauge readings, (b) the percentages of change in mean and 20 year return level are equal to the median values of the percentage of change of the rain gauges obtained over the maximal window (i.e. corresponding to the abscissa 2020 in figure 2).

Figure 4 compares the incremental medians and interquartile ranges (IQR) predicted from both the simulated data ( $n = 100$  runs each) and the observed maxima. The median of the non-stationary series are,

as expected, very close to the rain gauge value in 2020, despite a small bias (slight underestimation of the mean and slight overestimation of the 20 year return level). The median of the stationary series converges to 0, as also expected. It can be noted that, even in this idealized experiment, uncertainty in changes is considerable for the smallest windows: the change in mean maxima (resp. 20 year return levels) varies by  $\pm 20\%$  (resp.  $\pm 50\%$ ) around the true value for the 1950–1972 window. Although the nonstationary GEV framework makes it possible to calculate trends regardless of the length of the series, it is clear that estimates over less than 30 years—say—are unreliable even for the mean maxima. Uncertainty obviously decreases as the window increments, going down to  $\pm 2\%$  for the mean maxima and  $\pm 3\%$  for the 20 year return level with the largest window of 63 years. Differences between the stationary and the non-stationary series are notable—the 95% confidence intervals of the mean and 20 year return level do not overlap when more than 33 years are considered (i.e. using series extending to 1990 or later). The IQR with either the data or the simulations are very similar and super-exponentially decreasing as the series length increases (note the log-scale in the IQR plots of figure 4). Thus the decreasing variability in the boxplots of figure 2 is merely a question of data length. Notably, multi-decadal variability of about 20 years is visible in the median changes based on the data (light gray curve in figure 4), whereas the simulations show more random variability. We note that taking a growing size window shows two main advantages over the fixed (e.g. 20 year) window approach. First it takes the best of the available information at each time step and second it shows the progressive filtering of multi-decadal variability.



#### 4. Conclusion

We have used a consensus approach to show the emergence in the 2000s of an agreement between rain gauges pointing toward an increase in extreme daily precipitation in the French Mediterranean Region since 1960. We have shown that the stations agree to an increase of about 18% in mean maximum precipitation in the region and of about 22% in the 20 year return level, which is considerably larger than the 12% increase expected by Clausius–Clapeyron relationship, but it is coherent with previous studies in the region. We have highlighted that the consensus approach shows various benefits, among which it makes the best use of the available data, it is easy to implement, it is robust to the occurrence of major events without requiring regional methods (Blanchet *et al* 2021a), it is by construction little sensitive to the spatial spreading of the rain gauges, it allows progressive filtering of the multi-decadal variability.

#### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

#### Acknowledgments

This work is part of a collaboration between the University Grenoble Alpes and Grenoble Alpes Métropole, the Metropolitan authority of Grenoble conurbation (deliberation 12 of the Metropolitan

Council of 27 May 2016). Part of this work was funded by the IND-EX project with the support of the Rhône Alpes Region in France. The data used in this paper are maintained by MétéoFrance. They can be downloaded under research agreement from the website: <http://publitheque.meteo.fr/>

#### ORCID iDs

Juliette Blanchet  <https://orcid.org/0000-0001-8088-8895>

Jean-Dominique Creutin  <https://orcid.org/0000-0003-0076-9584>

#### References

- Bellprat O, Guemas V, Doblas-Reyes F and Donat M G 2019 Towards reliable extreme weather and climate event attribution *Nat. Commun.* **10** 1732
- Blanchet J, Blanc A and Creutin J-D 2021a Explaining recent trends in extreme precipitation in the Southwestern Alps by changes in atmospheric influences *Weather Clim. Extremes* **33** 100356
- Blanchet J and Creutin J-D 2017 Co-occurrence of extreme daily rainfall in the French Mediterranean region *Water Resour. Res.* **53** 9330–49
- Blanchet J, Creutin J-D and Blanc A 2021b Retreating winter and strengthening autumn Mediterranean influence on extreme precipitation in the Southwestern Alps over the last 60 years *Environ. Res. Lett.* **16** 034056
- Blanchet J, Molinié G and Touati J 2018 Spatial analysis of trend in extreme daily rainfall in southern France *Clim. Dyn.* **51** 799–812
- Cavicchia L *et al* 2018 Mediterranean extreme precipitation: a multi-model assessment *Clim. Dyn.* **51** 901–13



- Chadwick C, Gironás J, Vicuña S and Meza F 2019 Estimating the local time of emergence of climatic variables using an unbiased mapping of GCMs: an application in semiarid and Mediterranean Chile *J. Hydrometeorol.* **20** 1635–47
- Chochon R, Martin N, Lebourg T and Vidal M 2021 Analysis of extreme precipitation during the Mediterranean event associated with the Alex storm in the Alpes-Maritimes: atmospheric mechanisms and resulting rainfall *Simhydro 2021: Models for Complex and Global Water Issues* (France: Sophia-Antipolis)
- Coles S 2001 *An Introduction to Statistical Modeling of Extreme Values* (Springer Series in Statistics) (London: Springer)
- Colmet-Daage A, Sanchez-Gomez E, Ricci S, Llovel C, Borrell Estupina V, Quintana-Seguí P, Llasat M C and Servat E 2018 Evaluation of uncertainties in mean and extreme precipitation under climate change for Northwestern Mediterranean watersheds from high-resolution Med and Euro-CORDEX ensembles *Hydrol. Earth Syst. Sci.* **22** 673–87
- Delrieu G, Nicol J, Yates E, Kirstetter P-E, Creutin J-D, Anquetin S, Oblé C and Saulnier G-M 2005 The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean hydrometeorological observatory *J. Hydrometeorol.* **6** 34–52
- Deser C, Terray L and Phillips A S 2016 Forced and internal components of winter air temperature trends over North America during the past 50 years: mechanisms and implications *J. Clim.* **29** 2237–58
- Drobinski P *et al* 2014 Hymex: a 10-year multidisciplinary program on the Mediterranean water cycle *Bull. Am. Meteorol. Soc.* **95** 1063–82
- Duclos P, Vidonne O, Beuf P, Perray P and Stoebner A 1991 Flash flood disaster: Nîmes, France, 1988 *Eur. J. Epidemiol.* **7** 365–71
- Ducrocq V, Nuissier O, Ricard D, Lebeaupin C and Thouvenin T 2008 A numerical study of three catastrophic precipitating events over southern France. II: mesoscale triggering and stationarity factors *Q. J. R. Meteorol. Soc.* **134** 131–45
- Fumière Q, Déqué M, Nuissier O, Somot S, Alias A, Caillaud C, Laurantin O and Seity Y 2019 Extreme rainfall in Mediterranean France during the fall: added value of the CNRM-AROME convection-permitting regional climate model *Clim. Dyn.* **55** 77–91
- Gaetani M, Janicot S, Vrac M, Famien A M and Sultan B 2020 Robust assessment of the time of emergence of precipitation change in West Africa *Sci. Rep.* **10** 7670
- Gaume E, Livet M, Desbordes M and Villeneuve J-P 2004 Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999 *J. Hydrol.* **286** 135–54
- Giorgi F and Bi X 2009 Time of emergence (TOE) of GHG-forced precipitation change hot-spots *Geophys. Res. Lett.* **36** L06709
- Gottardi F, Oblé C, Gailhard J and Paquet E 2012 Statistical reanalysis of precipitation fields based on ground network data and weather patterns: application over French mountains *J. Hydrol.* **432–433** 154–67
- Hasselmann K 1979 On the signal-to-noise problem in atmospheric response studies *Meteorology Over the Tropical Oceans*
- Hawkins E and Sutton R 2012 Time of emergence of climate signals *Geophys. Res. Lett.* **39** L01702
- Haylock M R, Hofstra N, Klein Tank A M G, Klok E J, Jones P D and New M 2008 A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006 *J. Geophys. Res.: Atmos.* **113** D20119
- IPCC 2021 *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- King A D, Donat M G, Fischer E M, Hawkins E, Alexander L V, Karoly D J, Dittus A J, Lewis S C and Perkins S E 2015 The timing of anthropogenic emergence in simulated climate extremes *Environ. Res. Lett.* **10** 094015
- Kirchmeier-Young M C, Wan H, Zhang X and Seneviratne S I 2019 Importance of framing for extreme event attribution: the role of spatial and temporal scales *Earth's Future* **7** 1192–204
- Kusunoki S, Ose T and Hosaka M 2020 Emergence of unprecedented climate change in projected future precipitation *Sci. Rep.* **10** 4802
- Leng G, Huang M, Voisin N, Zhang X, Asrar G R and Leung L R 2016 Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming *Environ. Res. Lett.* **11** 114003
- Lutoff C and Durand S 2018 *Mobility in the Face of Extreme Hydrometeorological Events 1: Defining the Relevant Scales of Analysis*. ISTE Editions (Amsterdam: Elsevier)
- Lutoff C and Durand S 2020 *Mobility in the Face of Extreme Hydrometeorological Events 2: Analysis of Adaptation Rhythms*. ISTE Editions (Amsterdam: Elsevier)
- Mahlstein I, Hegerl G and Solomon S 2012 Emerging local warming signals in observational data *Geophys. Res. Lett.* **39** L21711
- Maraun D 2013 When will trends in European mean and heavy daily precipitation emerge? *Environ. Res. Lett.* **8** 014004
- Molinie G, Ceresetti D, Anquetin S, Creutin J D and Boudevillain B 2012 Rainfall regime of a mountainous Mediterranean region: statistical analysis at short time steps *J. Appl. Meteorol. Climatol.* **51** 429–48
- Nguyen T-H, Min S-K, Paik S and Lee D 2018 Time of emergence in regional precipitation changes: an updated assessment using the CMIP5 multi-model ensemble *Clim. Dyn.* **51** 3179–93
- Nuissier O, Ducrocq V, Ricard D, Lebeaupin C and Anquetin S 2008 A numerical study of three catastrophic precipitating events over southern France. I: numerical framework and synoptic ingredients *Q. J. R. Meteorol. Soc.* **134** 111–30
- Ribes A, Thao S, Vautard R, Dubuisson B, Somot S, Colin J, Planton S and Soubeyrou J-M 2019 Observed increase in extreme daily rainfall in the French Mediterranean *Clim. Dyn.* **52** 1095–114
- Rojas M, Lambert F, Ramirez-Villegas J and Challinor A J 2019 Emergence of robust precipitation changes across crop production areas in the 21st century *Proc. Natl Acad. Sci.* **116** 6673–8
- Ruin I *et al* 2014 Social and hydrological responses to extreme precipitations: an interdisciplinary strategy for postflood investigation *Weather Clim. Soc.* **6** 135–53
- Sénési S, Bougeault P, Chêze J-L, Cosentino P and Thepenier R-M 1996 1996: The Vaison-la-Romaine flash flood: mesoscale analysis and predictability issues *Weather Forecast.* **11** 417–42
- Soubeyrou J-M, Neppel L, Veysseire J-M, Tramblay Y, Carreau J and Gouget V 2015 Evolution des précipitations extrêmes en France en contexte de changement climatique *Houille Blanche* **1** 27–33
- Sui Y, Lang X and Jiang D 2014 Time of emergence of climate signals over china under the RCP4.5 scenario *Clim. Change* **125** 265–76
- Tramblay Y, Neppel L, Carreau J and Najib K 2013 Non-stationary frequency analysis of heavy rainfall events in Southern France *Hydrol. Sci. J.* **58** 280–94
- Tramblay Y and Somot S 2018 Future evolution of extreme precipitation in the Mediterranean *Clim. Change* **151** 289–302
- Vautard R, Yiou P, Van Oldenborgh G J, Lenderink G, Thao S, Ribes A, Planton S, Dubuisson B and Soubeyrou J-M 2015 Extreme fall 2014 precipitation in the Cévennes mountains *Bull. Am. Meteorol. Soc.* **96** S56–S60
- Zhang X, Zwiers F W, Hegerl G C, Lambert F H, Gillett N P, Solomon S, Stott P A and Nozawa T 2007 Detection of human influence on twentieth-century precipitation trends *Nature* **448** 461–5
- Zhuan M-J, Chen J, Shen M-X, Xu C-Y, Chen H and Xiong L-H 2018 Timing of human-induced climate change emergence from internal climate variability for hydrological impact studies *Hydrol. Res.* **49** 421–37