Characterization of historical rainfall patterns: linear segmentation and quadratic bifurcation

With an application to the city of Perpignan (France)

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Characterization of historical rainfall patterns: linear segmentation and quadratic bifurcation

Application to the Perpignan series (1951–2025)

Jacques Blanchart
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Abstract
This article proposes a method for characterizing rainfall transitions based on historical series. Two synthetic parameters are analyzed: the annual or seasonal amount of rainfall (RR) and the median of daily rainfall (m). This median is estimated by means of a log-logistic adjustment (Fisk), ensuring a robust measurement of the daily rainfall distribution. Two complementary approaches are used to detect changes:
(i) a linear segmentation into a maximum of five schemes, selected according to the AIC/BIC information criteria[1] ;
(ii) a quadratic bifurcation.
The results make it possible to highlight transition periods on the series studied. The Perpignan historical series is used as a case study, and avenues for extension to other regions and other detection tools are discussed.

1. Introduction

For several decades, climate research has developed a large set of methods to detect transitions and breaks in time series.
Robust statistical approaches, such as those proposed by Lanzante (Lanzante, 1996) have laid the foundations for nonparametric and outlier-resistant detection, paving the way for a detailed analysis of discontinuities in instrumental data (e.g. radiosonde series).
More recently, authors such as Rodionov (Rodoniov, 2004) have perfected these techniques with sequential algorithms for detecting change in averages (STARS), while a European multidisciplinary team (Scheffer, 2009) has broadened the conceptual field by introducing the notion of alternative attractors and tipping points in complex systems, whether ecological, climatic or social.
Finally, a relatively comprehensive review of the techniques used for temporal analysis was conducted by a team from the *School of Electrical Engineering & Computer Science* at the University of Washington (Aminikhanghahi, 2017). It leads to a "generic" modelling in which each series is assumed to be *piecewise stationary*, i.e. made up of segments separated by one or more regime changes within which the statistical properties remain constant.
Although the methodologies differ (breakthrough tests, CUSUM, Bayesian approaches, dynamic optimization, etc.), they all share the same logic: looking for transition signals in systems with slow and noisy dynamics. In other words, represent a phenomenon as an alternation of periods of stability and rupture.

[1] AIC: Akaike Information Criterion
BIC: Bayesian Information Criterion, Bayesian Information Criterion (or Bayesian Schwarz Criterion)

The University of Washington study plays an important unifying role: it shows that most breakage detection methods can be reduced, explicitly or implicitly, to an optimization paradigm consisting of finding the segmentation that balances fidelity to the signal and simplicity of the model:

$$\min_{T \in S_x} V(T, x) + \mathrm{pen}(T)$$

where (S_x) is the set of possible segmentations, (V) corresponds to the adjustment cost (or lack thereof) of the segmentation, and (pen) is a penalty term intended to avoid over-slicing.

A group of mathematicians and statisticians has carried out a study specific to climate series (Reeves, 2006) which focuses on the search for plateaus or a pair of linear segments. A global architecture of models makes it possible to identify linear segments, plateaus and fractures, but also notes that progressive drifts or small amplitude failures are not easily detected.

In this very rich set of tools and with this paradigm in mind, it seemed efficient to us to choose a method that would allow us to identify the best possible combination of stability/rupture sequences among a family of models and, for the sake of verification, to accompany it with a method that would clearly identify the beginning of a simple bifurcation or a more frank break.

2. Data and parameters

We will illustrate our approach using rainfall data from the weather station (Météo France) in Perpignan (France) (station 66136001).
We therefore have complete rainfall data since 1951.
However, we will often choose 1980 as the starting year of the calculation to be able to compare stations with each other, many of them not going back that far.
The baseline data we will use is the daily rainfall amount (RR) for all available meteorological years.
The amount of annual (or seasonal) rainfall (RR) is therefore obtained by a simple summation.
To this extensive quantity we will add another intensive one, namely the median (m) of the distribution of rainfall during the year. We thus join another study devoted to temperature by trying to characterize the climate (annual or seasonal) of a locality with as few climatic parametersd as possible (Blanchart, 2025).
As for the median, many studies offer statistical distributions adapted to various situations. After analyzing several series of weather data from France, we opted for the simplest possible distribution, i.e. log-logistics distribution (Fisk) for the cumulative distribution function (CDF) of daily rainfall:

$$F(x) = \frac{1}{1 + (\frac{\alpha}{x})^{\beta}}$$

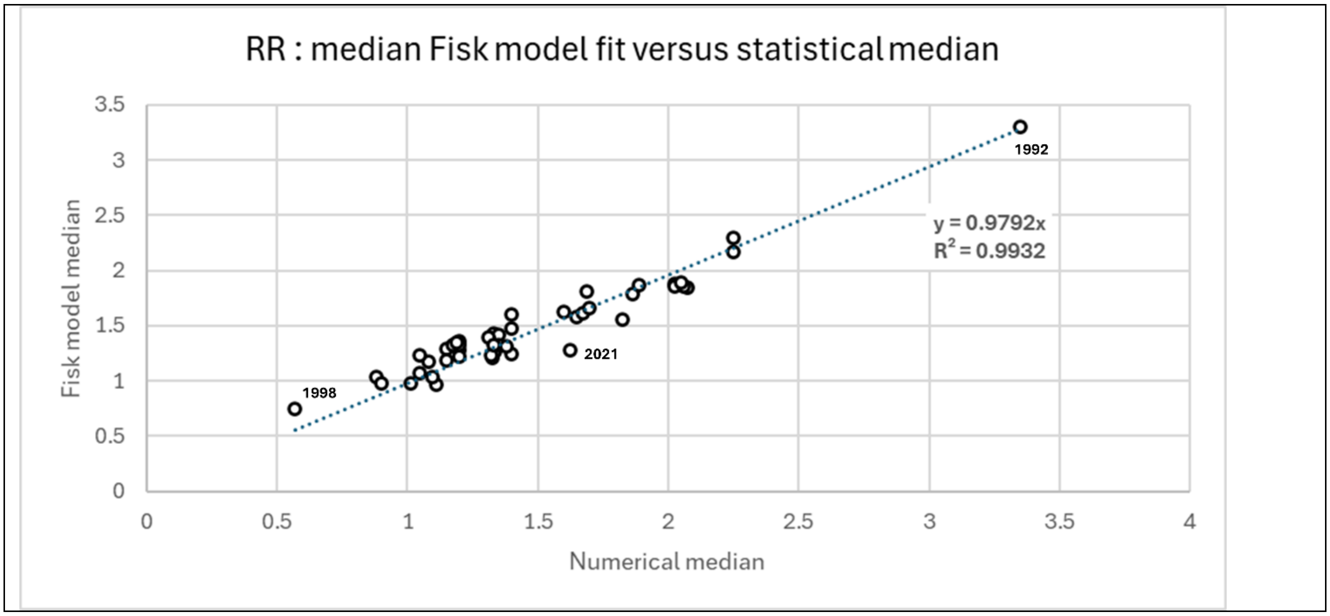
This two-parameter distribution always has (α) as its median.
We tested the simplest forms (β=1) and (β=2) on many stations, compared the AIC/BIC criteria and the form (α=1) appeared to be preferred in the sense of these criteria:

We have therefore systematically used the simple form:

$$F(x) = \frac{x}{x + m}$$

where, as noted above, (m) is the median of the distribution.

For the Perpignan station, and to ensure that this model is sufficiently accurate, we compared the result obtained by a regression on the Fisk distribution function (CDF) with the numerical median:



We observe an excellent correlation, which confirms that the simpler model leads to a good estimate of the median rainfall for the year.
When we approach more refined statistical techniques (segment regressions, search for regime breaks,...), we will return to statistical medians, which no longer smooth out the results.
Nevertheless, we will retain the calculation of the median using the log-logistic model because the difference between the two results is also indicative of an event such as a break or a smooth bifurcation.
In conclusion, we will retain two essential parameters for the study of annual precipitation patterns: an extensive quantity, i.e. the annual amount of rainfall (RR) and an intensive one, i.e. the median of the statistical distribution of daily rainfall (m), (m-num) for the statistical value and/or (m_mod) for the value from the model.

3. Methods

3.1 Linear Segments

From the CUSUM method it was retained that it was possible to visualize the major regimes of a time series. We have programmed a variant which consists of a division of the series into linear segments to identify periods of homogeneous trend (MULTIREG program). We define models consisting of 1 to 5 segments, with the breakpoints between the segments being calculated to minimize the sum of the squares of the gaps. Each model defined in this way is selected based on the AIC/BIC criteria

The MULTIREG program with selection of the best number of segments via AIC/BIC can be considered as an improved and formalized version of the CUSUM: it retains the idea of detecting regime changes in the time series but replaces heuristic decisions with an objective statistical criterion. In addition, it directly provides the regression coefficients for each segment, allowing the annual increase or decrease in rainfall for each detected regime to be estimated.

3.2 Quadratic break model

As far as the changes in the trajectory of these parameters are concerned, we have been struck by the regular appearance of transitions that are neither ruptures, nor inflections, nor plateaus, but appearances of moderate transitions.
We then developed a simple model of gradual transition applied to the annual climate series of (RR) and (m). The model is based on a parabolic shape with progressive breakage:

$$y(t) = a.t + b \qquad si\ t \leq t_0$$
$$y(t) = a.t + b + k.(t - t_0)^2 \qquad si\ t > t_0$$

where:

- y = (RR) or (m)
- a is the average linear trend (steady growth or decrease),
- b the basic level,
- k the drift factor introducing a gradual acceleration or deceleration,
- t_0 the date of the start of the progressive termination.

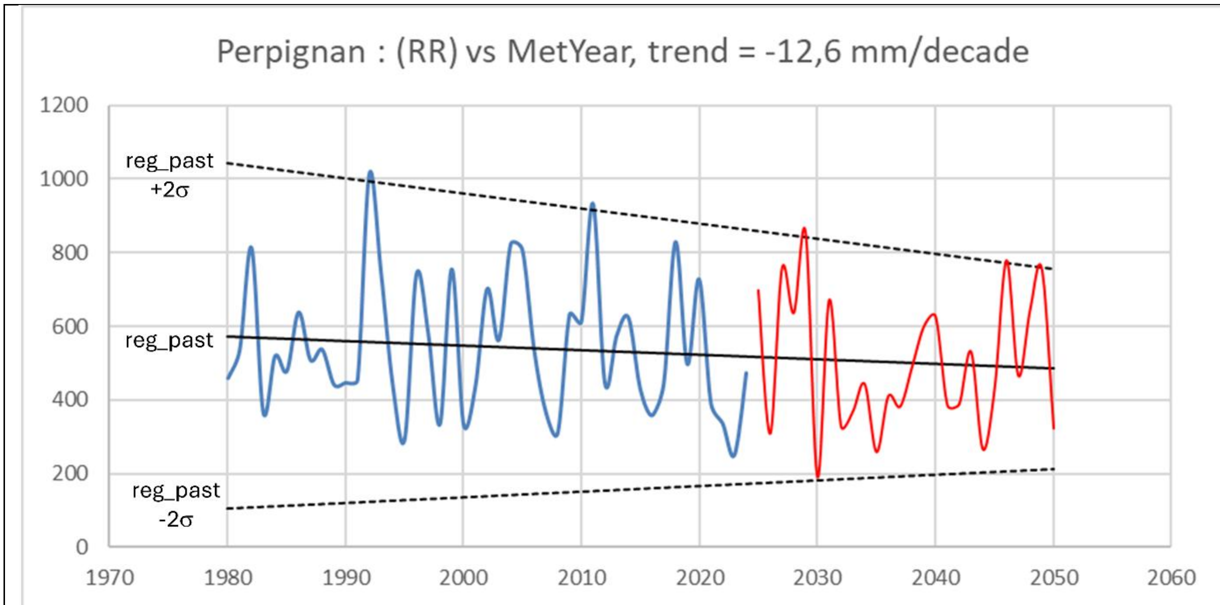
When k = 0, the series remains purely linear; When k ≠ 0, a progressive curvature appears, reflecting a transition in the climate regime. This model, which we call the Quadratic Break Model (BombScan program), offers a continuous, non-segmented alternative to classical break detection. It makes it possible to identify phases of slow acceleration or stabilization in rainfall series, and to monitor their evolution over time.
For each final year of calculation, a multiple regression is carried out between the starting year (1951) and the year in question. The parameters (a, b, k, t_0) are fitted by least squares minimization, according to the quadratic formula above.
The variation of (k) over time is then analyzed as an indicator of gradual transition and thus characterize in a more detailed way the break identified by the segmentation.
This model is still in its infancy because it is sensitive to local fluctuations and chosen thresholds.

4. Results

4.1.- Exploratory phase

It is always useful to carry out an initial exploratory phase to visualize the general evolution of the parameters.

Thus, if we do a single linear regression on the set of data of (RR), we obtain this graph:



MetYear = meteorological year, Dec 1st of year(x-1) until Nov 30th of year (x)

After performing the regression, it is easy to assess the normality of the fluctuation distribution and its standard deviation. If desired, we can thus extend the behavior of the parameter until 2050 by a simple random selection in this distribution (red curve).

If we extend this development until 2050, we can see that we can go down to 200 mm of annual rainfall with a probability of 95%.

It is extremely important to emphasize that the results of this 2025-2050 extension (random draw) are neither a forecast nor a prediction but a simple projection that illustrates what is "possible" (but neither "foreseeable" nor "probable").

In the case of Perpignan, the annual amount of rainfall decreases at a rate of 12.6 mm per decade and that fluctuations are decreasing.

But it is important to highlight the fact that the calculation period is of fundamental importance.

This result changes completely if only more recent data are available at the station.

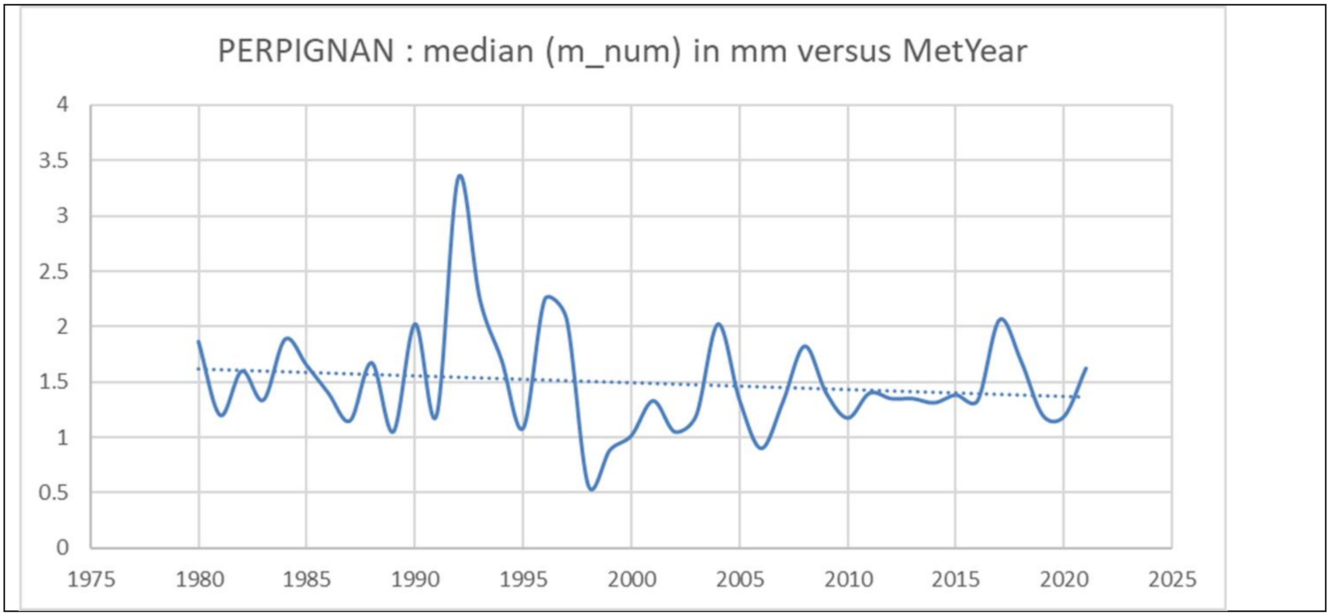
If we look at the previous graph, we can see that since 2020, we have had four consecutive years of significant decline with a slight increase in 2024. We can therefore wonder if the amount of rain in Perpignan is not "collapsing".

The same calculation was therefore made, considering that data were only available since 1990, 2000 and 2010. Here is the result:

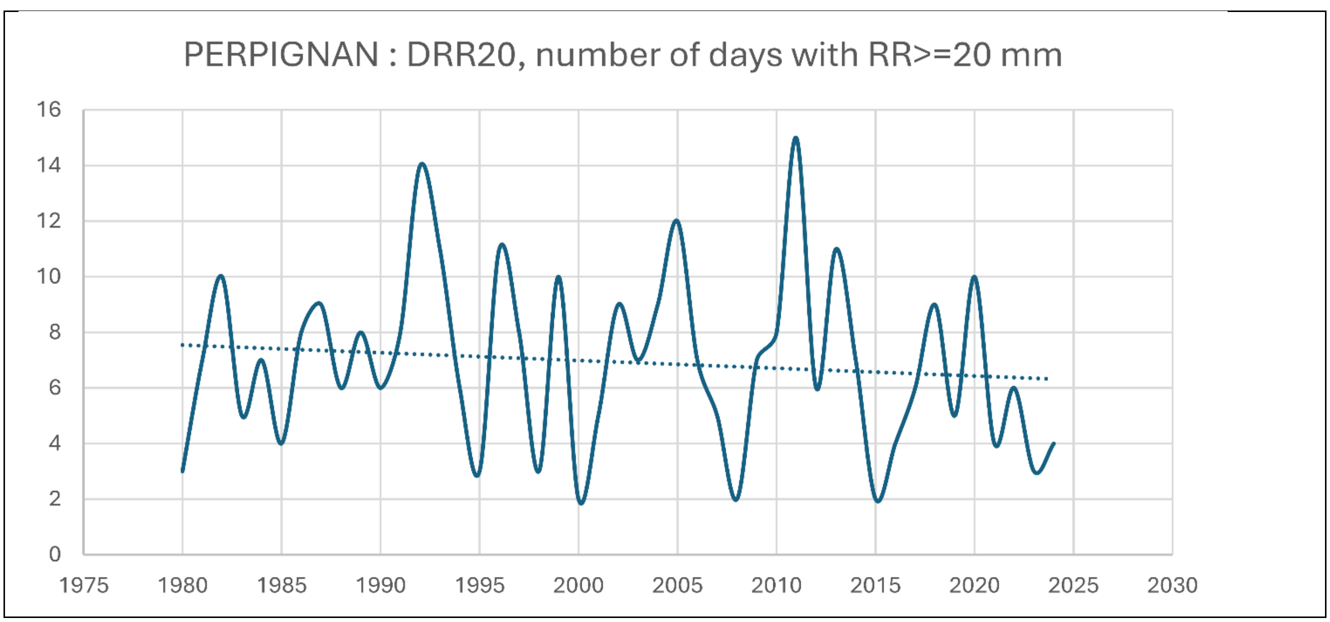
Data	Evolution of (RR)
1980-2024	**-12.6** mm/decade
1990-2024	**-35.4** mm/decade
2000-2024	**-54.5** mm/decade
2010-2024	**- 193** mm/decade

One would be tempted to believe in a form of evolution leading to total aridification.
This illustrates once again the recurrent problem of the calculation period which can become a "reference period" when comparing results from different stations or models.
We have therefore opted for a more detailed analysis (levels, ruptures, segmentations, etc.), but also by developing a model fine enough to detect progressive bifurcations during the main rainfall regime, which would make it possible to identify the best form of evolution (see paragraph 4.2).

In the same way, if we examine the evolution of the median (m), we obtain:



At first glance, there is therefore a decrease in the total amount of rainfall associated with a slight decrease in the median rainfall, thus without an increase in intense rainfall.
This is also in line with the evolution of the number of days of intense rain (RR>=20 mm)



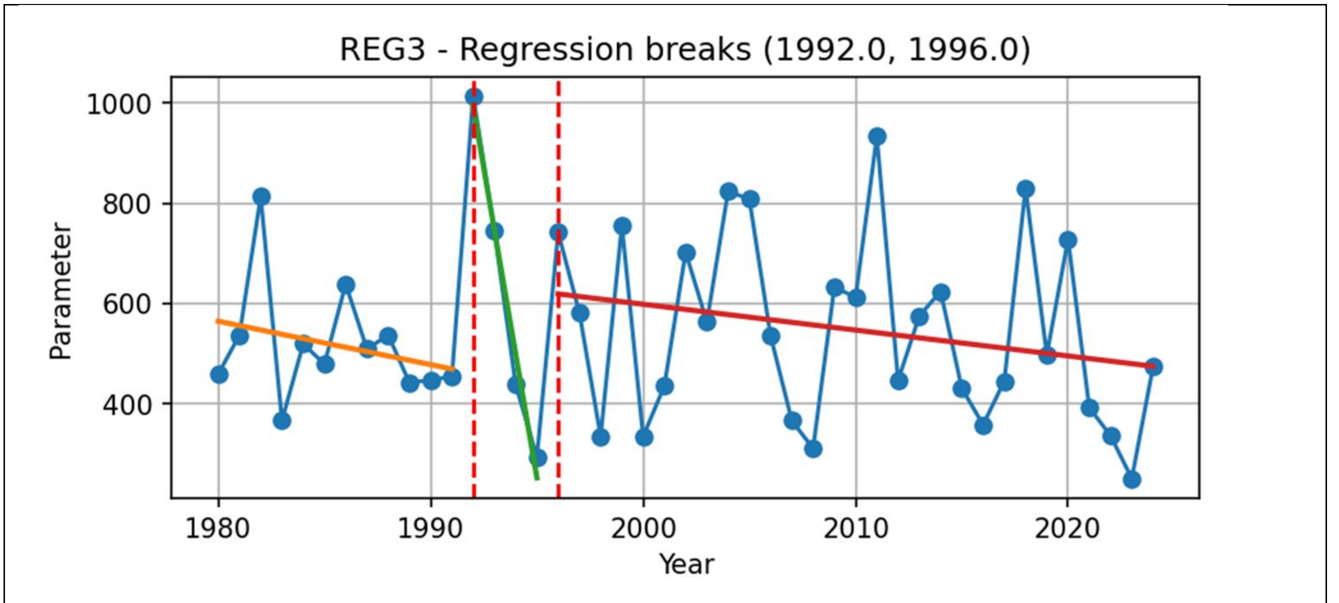
There is therefore a general decrease in the median rainfall, reflecting a greater frequency of light rainfall, which does not exclude the occasional appearance of years of intense rain.
Here too, a more precise analysis of the temporal sequences will be carried out.

4.2.- Analysis phase

After identifying the main trends, it appears that rainfall patterns cannot be explained solely by global warming, which is more monotonous. The distribution of precipitation is the result of a combination of atmospheric and oceanic factors: barometric variations, large-scale circulation, alternating depressions and anticyclones, local convective phenomena, regional oscillations and sea surface temperature anomalies. Climate change does not intervene as an additional forcing that modifies the existing balance between these processes, amplifying contrasts and interannual variability.
Beyond a real physical model, a simple statistical approach can only find its place if it is based on the identification of bifurcations or breaks in climatic regimes.
It is in this context that the two techniques we introduced above and applied to (RR) and (m) are inscribed.

a. (RR)

The MULTIREG programme applied to the period 1980-2024 gives the best[2] adjustment for a sequence of 3 segments:



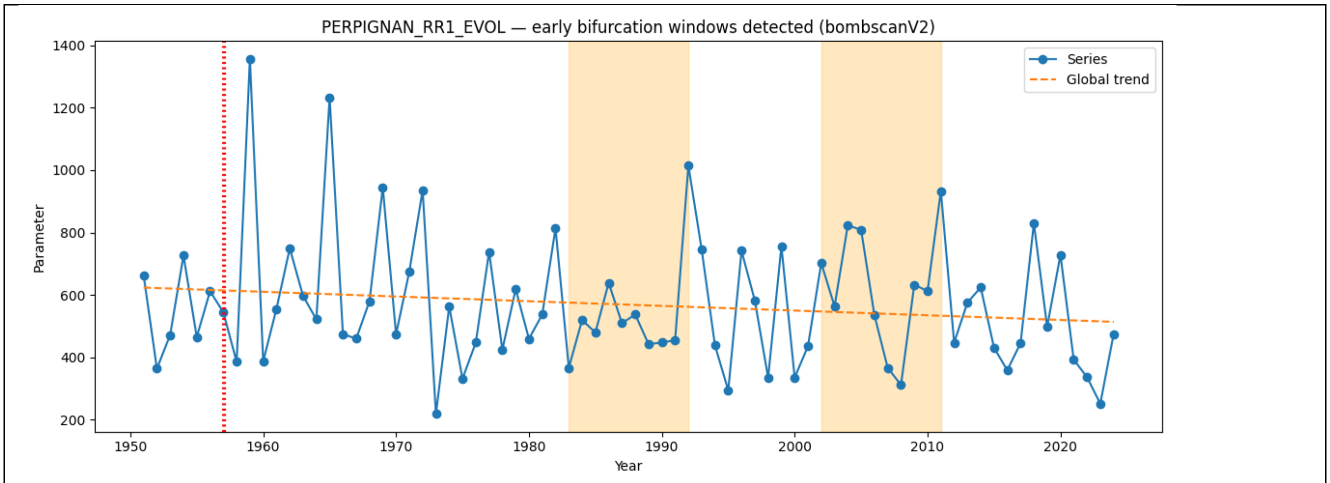
REG3 is the most plausible model (best fit with 3 segments)

We can therefore see two "stable" regimes spaced out by a transition period from 1992 to 1996 where after a sharp rise in (RR) in 1992, there is a fall in 1995 (up/down transition). The last segment shows a steady decrease in rainfall of 52 mm/decade.

[2] "best" = in the sense of Akaike or Bayes.

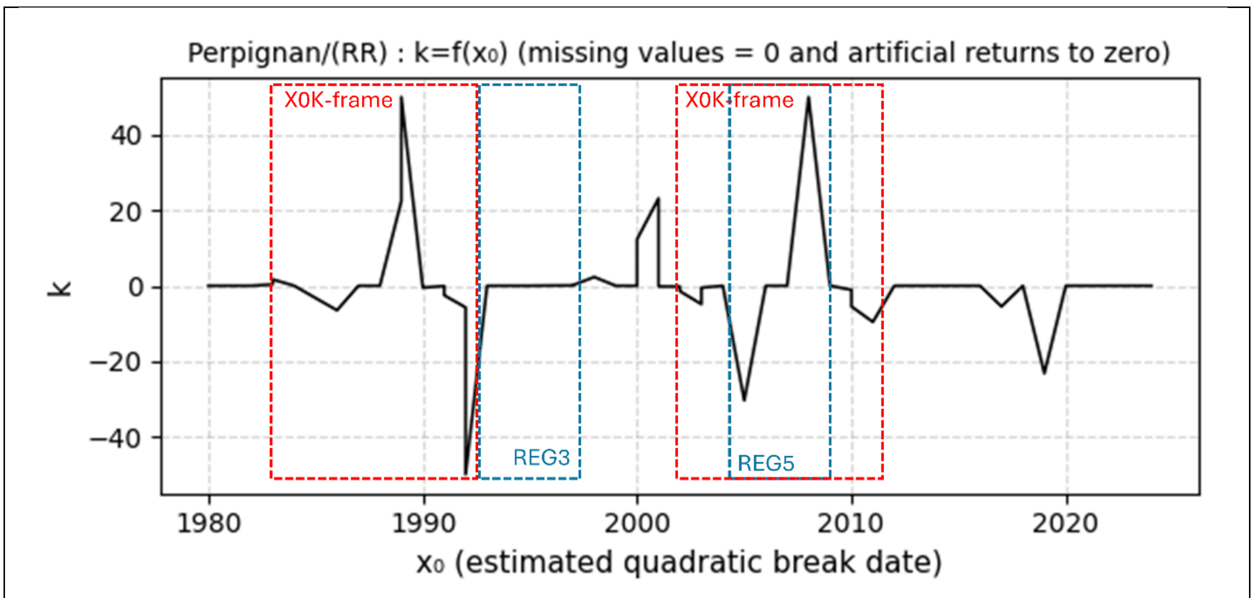
Calculation of bifurcations (BombScan and X0K programs)

The BombScan programs and its X0K add-in perform the quadratic bifurcation model and give the results of the following graph.
The first program works on the whole history with its general trend and looks for the large areas where bifurcations have appeared since 1951:



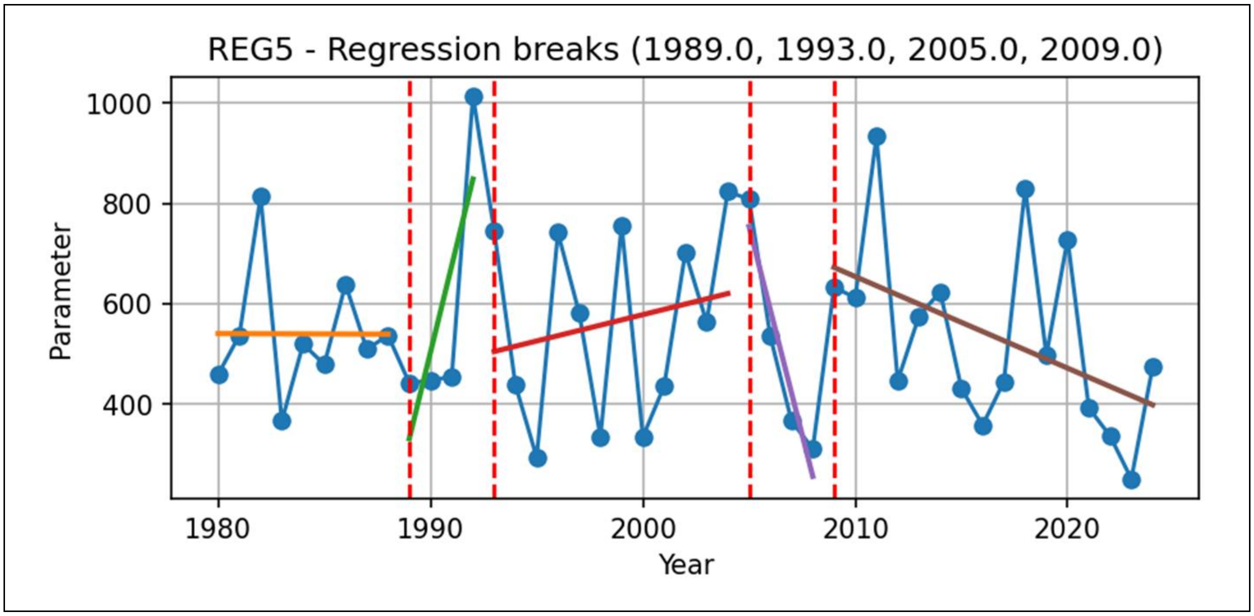
The colored windows indicate periods when significant quadratic bifurcations occur.
They are called: "X0K frames" remembering the algorithm used.

In this first analysis, we therefore have two windows where significant bifurcations took place: 1983-1992 with a peak in rain in 1989 and 2002-2011
The X0K program will refine and determine the bifurcation velocities (k) as a function of the corresponding year (x0). On the graph below we can see the two pairs of peaks, up/down in the first window and down/up in the second window.
The REG3 window of the transition identified by the MULTIREG model has been plotted on this graph.



(k) is the speed of the bifurcations. Peaks at 50 indicate a fast bifurcation, likely a rupture. Less than 20, soft bifurcations are plausible.

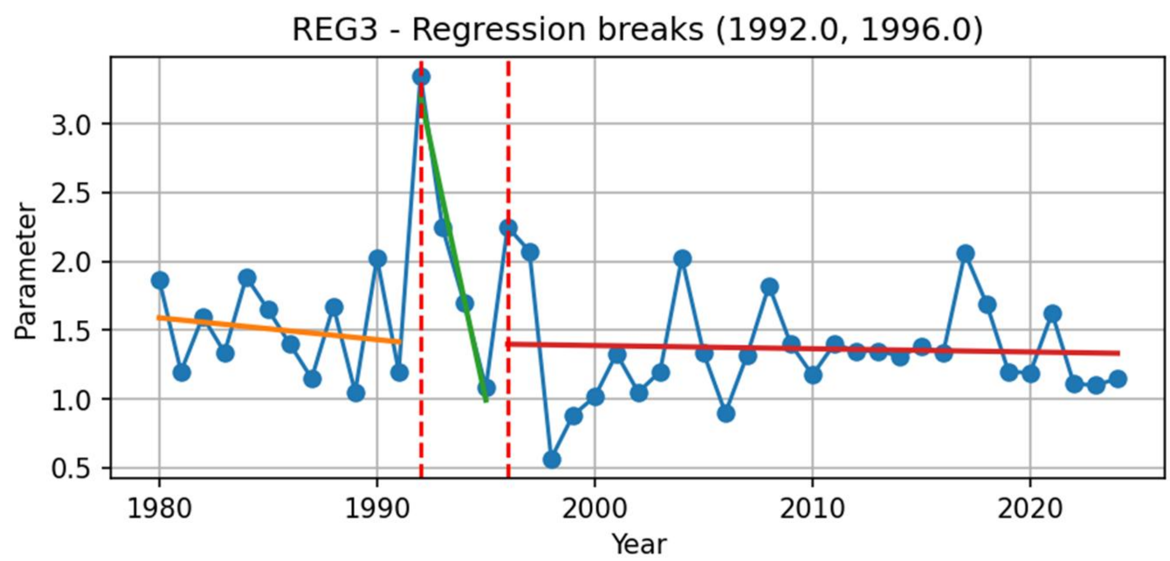
In fact, the REG3 regression window should be shifted and it will be necessary to develop a better knowledge of the appearance of bifurcations (see Perspectives, Simulations).
On the other hand, you must switch to a more complex model (REG5) to locate the second X0K window. In this configuration, we find the up/down and down/up configurations of the X0K windows.



This raises the question of the choice of model to identify bifurcations. The AIC/BIC criterion argues for a single transition, in this case REG3 to choose the model as part of one of the description of major trends, but a multi-model analysis favors an iterative approach to identify secondary bifurcations. We will talk about this again in paragraph 5.

b. (m)

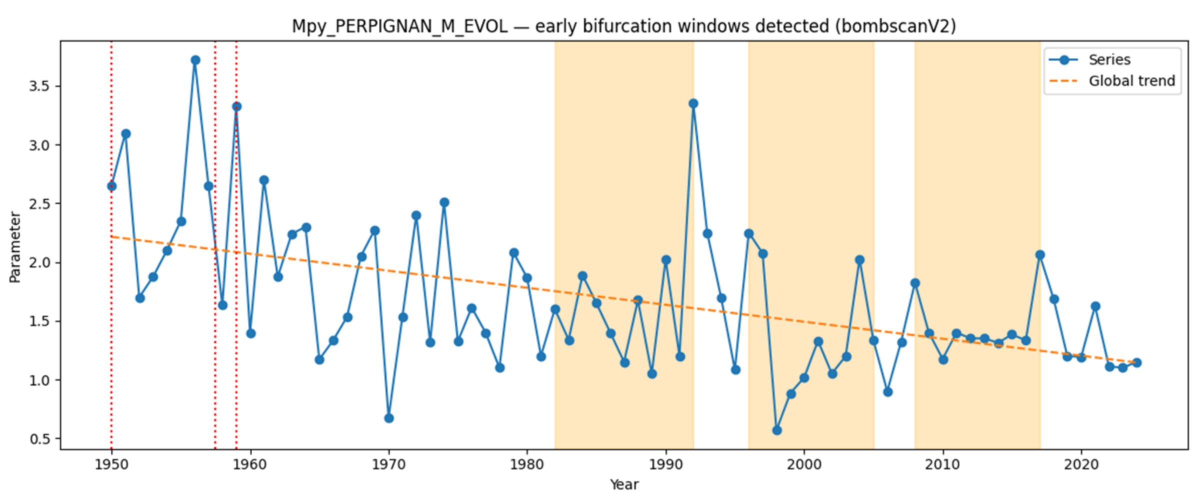
The MULTIREG and BombScan-X0K programs applied to (m) also give the best fit for a sequence of 3 segments, with exactly the same sequence 1992-1996 as the main transition:



Parameter is (m), REG3 is the "best fit" model (AIC and BIC).

There is a slight variation in the median rainfall here, which leads us to believe that there will be no general intensification of rainfall in Perpignan.

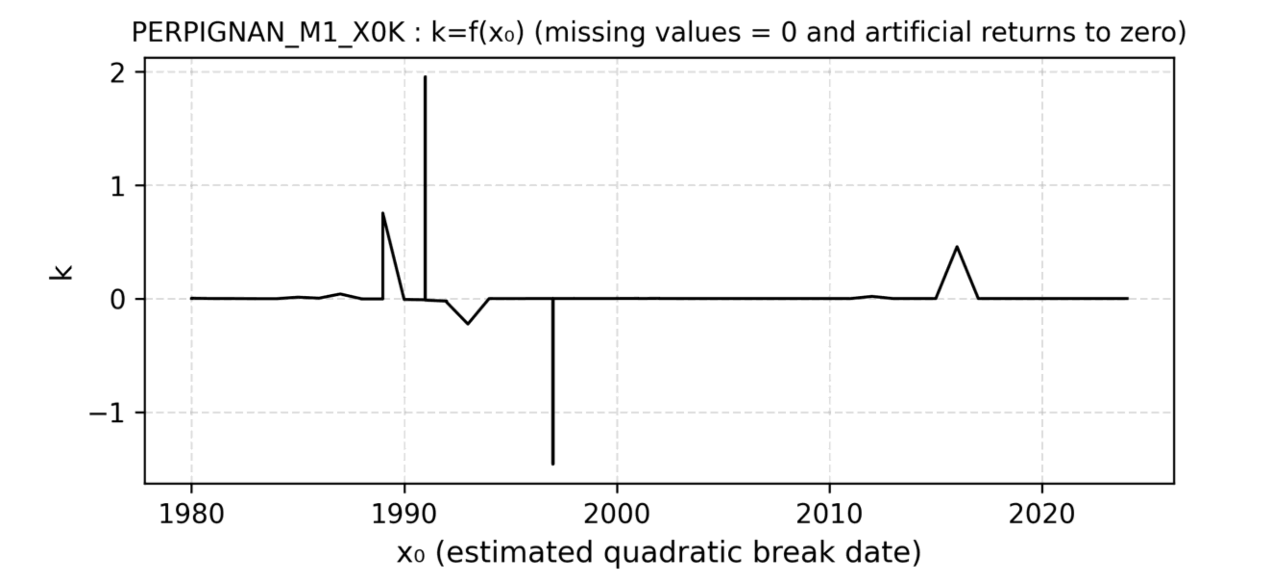
The general identification of the zones with bifurcations/ruptures since 1951 gives the following result:



The colored windows indicate periods when significant quadratic bifurcations occur.
They are called: "X0K frames" according to the algorithm used.

What is interesting in this graph is the appearance of two additional frames compared to the 1992-1996 break identified by linear segmentation. But we will see that these bifurcations are slight in the period 1980-2024.

The X0K add-on gives the following graph :



(k) is the speed of the bifurcations. Peaks are very low, indicating soft bifurcations of the median (m).

This graph shows not only bifurcations identified by the REG3 segmentation (1992-1996), but also lagged or small bifurcations.
In any case, the median rainfall in Perpignan did not change much after 1980.

5. Discussion

Here is a summary table of the results obtained on (RR) and (m) from the two methods MULTIREG and BombScan.
For segment regression, only the most plausible model should be used, but the use of more segment models shows that some transitions between new segments do correspond to weaker transitions or bifurcations.

(RR)

MULTIREG method	AIC ranking	MULTIREG frames	break scan frames	break scan start	break scan end
RR – REG3	1	**1992-1996**	**1983-1992**	**1988-**	**1993**
RR – REG4	2	<1990 + **2005-2009**	**2002-2011**	**2004**	**2008**
RR – REG5	3	**1989-1993** + **2006-2009**			
Small bifurcations not detected by MULTIREG			**1989-2002, 2017-2024**		

(m)

MULTIREG method	AIC ranking	MULTIREG frames	break scan frames	break scan start	break scan end
RR – REG3	1	**1992-1996**	**1982-1992**	**1991**	**1997**
RR – REG4	2	**1989-1992** + **1992-2001**	**1996-2005**	perhaps 2nd peak 1997	
RR – REG5	3	REG4 + **2018-2024**	**2018-2017**	**2015**	**2017**
Small bifurcations not detected by MULTIREG			2018-2024 is a low (k) transition		

Generally speaking, during the period **1992-1996** with a first detection of bifurcation around 1988, there was a significant transition in the regime in Perpignan both for the total amount of annual rainfall (RR) and for the annual median (m) of rainfall.

The following **2004-2009** transition on (RR) is not accompanied by a regime change for the median.

Finally, more gradual bifurcations can be reported for (RR) around **2018** (beginning of the drought period?) and for (m) around **2016**.

The combination of two parameters (RR) and (m) and two methods, segment regression (MULTIREG) and the search for bifurcations in established regimes (BombScan) makes it possible to identify and characterize changes in rainfall patterns.

It should be emphasized that the results of these algorithms are highly dependent on the choice of parameters and empirical thresholds.

On the other hand, we will not risk associating climatic events with these figures (see next chapter "Prospects").

In any case, we have opened the door to extensions and improvements of this general method.

6. Prospects

Everything that has been presented in this article has methodological weaknesses. Linear segment and quadratic bifurcation approaches rely on arbitrary parameter choices and do not guarantee exhaustive or optimal detection of changes. These limitations are similar to those highlighted by Aminikhanghahi and Cook (2017) on classical change detection methods: lack of systematic comparison between methods, difficulty in processing long series with multiple variations, and sensitivity to the choice of thresholds and parameters.

In this context, several paths are available to us to extend and strengthen this study:

1) **Addition of algorithms**: CUSUM, K-means seasonal profiles,...
The application of CUSUM would allow for the statistical and cumulative detection of points of change, providing a robust complement to the transitions identified here. The PELT (Pruned Exact Linear Time) method, used here to speed up certain calculations, could be tested to automatically segment series while optimizing a global criterion, limiting the arbitrariness of segmentations.
The identification of seasonal patterns that we have already used in local climate reporting will be processed by the K-means algorithm, an unsupervised automatic classification method. This will allow us to group years with similar seasonal forms (e.g. very dry seasons concentrated in summer, or rain spread out all year round, etc.). Synchronous transitions may or may not be observed between the base profiles and the events affecting (RR) and (m).

2) **Simulation**
We plan to develop a full simulation software to explore in depth the transitions between "stable → bifurcation → break" climate regimes. By combining models of disturbances followed by collapses or bifurcations with the noise of annual fluctuations, the system will produce outputs to identify — and, if necessary, quantify via artificial intelligence methods — the causal relationships between perturbative events and regimes detected by MULTIREG, Bombscan and X0K.

3) **Relevance criterion (AIC, BIC)**
We recalled in the introduction that the selection of the most plausible model can be formulated in a general way as an optimization:

$$\min_{T \in S_x} \; V(T, x) + \mathrm{pen}(T)$$

where (V) measures the fit quality of a segmentation, and (pen) controls the complexity of the model to avoid over-slicing.
In the work presented here, we mainly use the AIC and BIC criteria, which are instantiations of this general scheme:

- the adjustment term is given by $\mathrm{n.ln}\,(\mathrm{RSS/n})$
- the penalty depends on the number of segments, weighted by (2k) for the AIC criterion and (k.ln(n)) for the BIC criterion.

Although robust and widely used, these criteria were designed within a general framework, with no specificity for weather and climate time series. A natural perspective would therefore be to examine whether it is possible to adapt or modulate these penalty functions, to better take into account the particular properties of these data (autocorrelation, persistent seasonality, slow trends, non-Gaussian

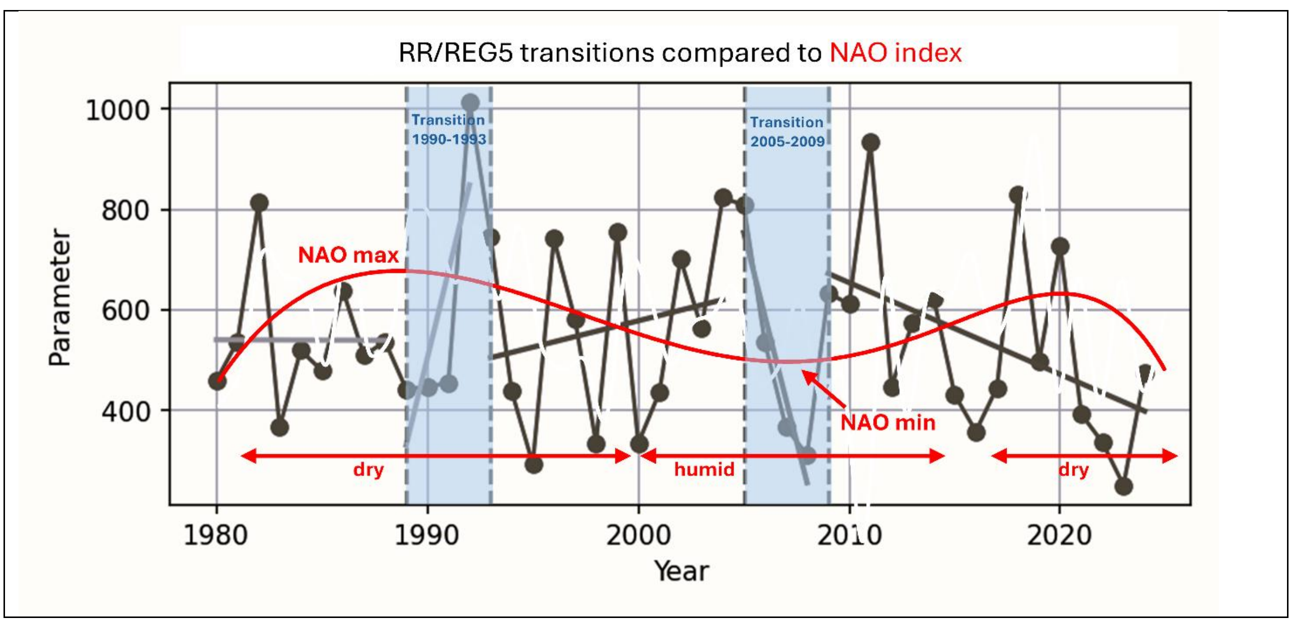
distributions, etc.). Such adaptation could lead to a more relevant criterion for discriminating real climatic disruptions from natural fluctuations.
In any case, these criteria indicate that in the case of Perpignan the REG3 model is the most plausible in the Akaike sense for both parameters (RR) and (m). This should not prevent us from examining other models to identify minor events, and even to consider an "average model".

4) **Comparative framework**
By applying this general method to a set of stations located in the same territory, it will become possible to validate or discard, on a quantitative basis, the conjectures resulting from observation. This system will also provide a comparative framework for measuring the effect of environmental factors such as altitude, topography or distance from the sea on the transition between climatic regimes.

(5) **the search for causality: Pinatubo, ENSO, NAO,...**
The search for causality naturally falls under climatological and meteorological expertise. A statistical analysis, on the other hand, does not claim to explain physical mechanisms: it highlights regularities, correlations and temporal correspondences that can guide investigations.

As such, the REG5 segmentation applied to precipitation (RR) can be compared to the evolution of the NAO (North Atlantic Oscillation) index. The NAO index measures the atmospheric pressure contrast between the Azores High and the Icelandic Low. In the positive phase, the reinforcement of these centers of action intensifies the westerly zonal circulation, deflecting the humidity towards northern Europe and making the Mediterranean drier. In the negative phase, the attenuation of this pressure gradient allows low-pressure systems to reach the south, increasing rainfall in the Mediterranean — often in the form of intense episodes — while northern Europe dries out.

The superposition of the NAO index and the REG5 model applied to the series of (RR) is not intended to establish a causal link, but to underline the strong relationship between the structural changes observed. This proximity suggests that the transitions identified in precipitation could — a hypothesis to be explored — be partially modulated by the atmospheric dynamics of the North Atlantic.



The situation should be interpreted with caution, but the (RR) curve shows a series of drier years from 1980 to 2000. A transition took place around 1990 to a wetter period from about 2005 to 2015. During this second period, a transition takes place with a steady decrease in rainfall (third segment) to a dry period.

(6) 25-year projections
Exploratory projections to 2050 can be considered by combining (RR) and (m) values from linear regressions with random sampling incorporating the uncertainty estimated by the standard deviation on sliding windows of these parameters. This method is not a complete climate model: it is only intended to simulate plausible trajectories, quantify the margins of uncertainty, and illustrate the sensitivity of the results to different model choices.

A first application to the annual amount of rainfall (RR) highlights several orders of magnitude depending on the chosen model.
In simple regression (REG1), the trend indicates a decrease of 12.6 mm per decade.
The change in the estimation period, especially when the time window is restricted, can however lead to much more pessimistic projections, up to scenarios of almost total aridification.
Using only the most likely model (REG3), the projection leads to a decrease of 52 mm per decade, starting with 600 mm around the year 2000.

Other scenarios could be built by combining the averaging model with an explicit modelling of variations in the NAO index or other climate oscillations (ENSO in particular). These approaches would make it possible to integrate both long-term dynamics and interannual atmospheric modulation into prospective exercises.

(7) Other parameters
Beyond the methods presented, it would be possible to combine several approaches in a comparative framework, to jointly assess the robustness and coherence of the transitions detected. A natural extension would consist of integrating other rainfall parameters, such as maximum rainfall intensity, extreme indicators and drought indices. Taking them into account would make it possible to document not only changes in the mean, but also the evolution of the distribution of rare events — essential elements in the characterization of local climatic regimes.

In addition, the difference between the numerical median and the median estimated by the log-logistic model could be an additional indicator. This difference could reflect the evolution of the internal structure of the precipitation distribution (frequency of low rainfall, change in scale of intense events), and thus provide an independent signal reinforcing or nuanced the transitions identified by (RR) and (m).

7. Conclusion

At this stage, the objective is not to propose a definitive theoretical framework, but to establish a methodological basis for identifying, comparing and interpreting rainfall transitions from historical series. The results show that a combination of synthetic parameters (RR, m) and transition models (linear segmentation and quadratic bifurcation) makes it possible to highlight coherent and repetitive breaks according to the territory studied. The median of daily rainfall can either be estimated by a log-logistic adjustment, ensuring a robust representation of the distribution, or calculated numerically.

Although there is still room for improvement, these approaches deliver a major result: significant rainfall changes can be detected without resorting to complex models, simply from well-chosen synthetic indicators. The Perpignan series illustrates this potential, and the future integration of additional tools — such as CUSUM, PELT, indicators of extremes, or exploratory projections — should strengthen the comparative robustness of diagnostics.

This work thus represents a first step in the construction of an evolving set of algorithms intended to characterize the rainfall patterns of a territory and to identify the climatic avatars likely to mark their transitions. The perspectives presented in paragraph 6 outline the way forward to expand, test and consolidate this approach.

Finally, it should be noted that the Python implementation of all the models makes it possible to obtain complete results in a very short time, without any other resource than a personal computer, which opens the way to their replication and evaluation on a wide range of territories.

As far as Perpignan is concerned, we can remember:

- The existence of a clear bifurcation of regime between 1992 and 1996, affecting both the amount of annual rainfall (RR) and the median of daily rainfall.
- A possible bifurcation of precipitation (RR) between 2005 and 2009, with low plausibility.
- The possibility that these two regime changes are related to the NAO oscillator.
- The emergence of a bifurcation in 2020, accompanied by a period of drought.
- That today, the most plausible model indicates a decrease in rainfall of about 50 mm per decade, with no significant change in the median of daily rainfall.

Methodological Note – Computation and Python Environment

All calculations, aggregations, and model fittings presented in this study were performed using standard Python scientific libraries for data analysis and statistical processing of climatic series.
The analyses were conducted in a Python environment (version ≥ 3.10) under JupyterLab and Thonny editor.
The main libraries used are listed below:

Library	**Purpose in the scripts**	**Notes**
pandas	Data loading, manipulation and export (CSV, Excel)	Core component for time-series processing
numpy	Numerical computations (log, power, means, variance, random sampling, arrays)	Used directly and indirectly by most statistical routines
scipy *(scipy.stats)*	Log-logistic (Fisk) fitting, optimisation and cumulative distribution functions (CDF)	Used to estimate the median of the rainfall distribution
State models	Linear regressions, model fitting, and AIC/BIC computation	Main engine for models REG1–REG5
matplotlib	Visualisation of rainfall series, segmentation, NAO index and projections	Primary plotting library
openpyxl	Excel read/write support and creation of additional worksheets	Used to store results in xlsx format
scikit-learn (sklearn)	Optional — used in some exploratory segmentation / metrics tests	Not a core dependency, but already present in several trials
random / numpy.random	Random draws for exploratory projections and uncertainty sampling	Supports Monte-Carlo-style scenarios
OS/Pathlib	File path management	Used in standalone scripts
warnings	Suppression of statistical warnings during model fitting	Improves readability of console outputs

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Note on the collaboration with GPT-5

This study was developed through an ongoing collaboration with GPT-5's conversational scientific assistance. These exchanges allowed us to progressively explore and consolidate the model, test several variants, and arrive at a coherent theoretical framework based on numerous but largely unformalized intuitions. This experience illustrates the emergence of a hybrid research approach, combining human intuition and computational assistance. In particular, the development of the Python programs was significantly accelerated by this interaction.

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Conflict of interest
None

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