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Scientific Editors

Aquatic Ecology of the Mondego River Basin
Global Importance of Local Experience

Coimbra • Imprensa da Universidade

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PRECIPITATION AND THE HYDROLOGY OF THE MONDEGO CATCHMENT: A SCALE – INVARIANT STUDY

Abstract

Precipitation in the Mondego drainage basin, in Portugal, is a highly variable input into the hydrological system of this region, strongly affecting water resources management. Precipitation is a highly non-linear hydrological process that exhibits wide variability over a broad range of time and space scales. The strongly irregular fluctuations of precipitation, which in certain cases lead to catastrophic events, have strong socio-economic impacts, related to the occurrence of floods and droughts, reservoir management policies, etc.

Many approaches to the study of precipitation fail to grasp the extreme variability of this process. The invariance of properties across scales and the multifractality of precipitation may offer an alternative approach to quantify this variability. Thus, to increase our understanding of the precipitation variability in the Mondego basin, this work explores the invariance of properties manifested across scales and the fractal and multifractal behaviour observed in the temporal structure of precipitation, using daily precipitation data from two locations in this catchment: Coimbra and Penhas Douradas. The data cover a period of 54 years. The study is based on spectral analysis, box-counting analysis, and investigation into the scaling of probability distributions and statistical moments of the precipitation intensity. Results show the presence of scale-invariant and multifractal properties in the temporal structure of precipitation.

Introduction

Precipitation exhibits a high non-linear variability over a wide range of time and space scales. This variability involves a large dynamic range, which in certain cases leads to catastrophic events. Precipitation phenomena range from cells (associated with

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cumulus convection), to synoptic areas (frontal systems). Precipitation cells have an area of the order of 1-10 km^2 and lifetimes of several minutes. Synoptic precipitation fields can cover areas of 10^4 km^2 and have a lifetime of one to several days.

Precipitation is the driving agent of many other processes. Its temporal and spatial variability are important issues in many studies and areas of research (e.g. hydrology, hydraulics, agronomy, soil pollution, water resources). However, information on the amount and distribution of precipitation in space and time is often restricted precisely because of this strong temporal and spatial variation, which many approaches to the study of precipitation fail to grasp.

The purpose of this work is to contribute to a better understanding of precipitation in the river Mondego drainage basin, in the Centre of Portugal (Figure 1). The strongly irregular fluctuations of river discharge, in both the Mondego River and its main first-order tributary streams, have led to different actions being taken with respect to the watercourses, aiming at diminishing the effect of hydrological extremes. In the past, until the end of the seventies, frequent flooding of the lower-lying lands near the estuary of the river (downstream of Coimbra, see Figure 1) had strong socio-economical impacts. These floods occurred nearly every year, with calamitous consequences. In the same region, fresh water was also often scarce due to the uneven distribution of precipitation during the year, and intrusion of saline water in the river and in the groundwater.

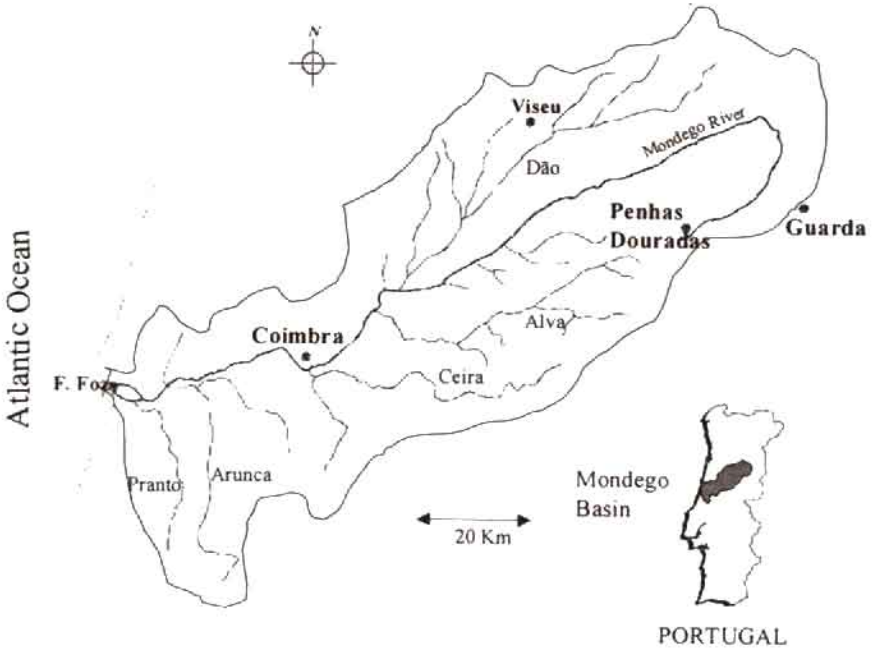

Figure 1. Map of Mainland Portugal localising the Mondego Basin, and an enlarged view of the catchment area locating the River Mondego and its main first-order tributaries, the main cities, and the two meteorological stations used in this study (Coimbra and Penhas Douradas).

These and other problems led to the development of a multipurpose hydro-agricultural project in the Mondego basin. The works carried out in the river and in the lower part of the drainage basin include flood protection works, and irrigation and drainage works. The management of its different components is very much dependent on the highly variable precipitation input into the hydrological system. Some difficulties arise from the lack of knowledge on the temporal and spatial distributions of precipitation in the catchment. For example, hydrological models usually have to conceptualise processes based on simple, often homogeneous, approximations of nature (e.g. precipitation is expressed as a mean over large areas, and as depths over periods of a day). Such generalised conceptualisations often lack sufficient temporal and spatial resolution to permit a detailed modelling of complex hydrological processes.

Recent events (December 2000/January 2001), with catastrophic consequences related to the occurrence of floods in the Lower Mondego region due to several ruptures of the protection dikes of the Mondego River, had a strong socio-economic impact and put pressure on decision makers to re-evaluate the entire project.

An important contribution towards increasing our understanding of the non-linear variability in precipitation is being given by scale-invariant studies of this process. The invariance of properties being maintained across scales can be mathematically investigated using fractal and multifractal theories. These theories offer an alternative to ('conventional') approaches that study one scale independent of the other. Instead, they investigate the presence of certain features of a dynamic system that are independent of scale. The present study uses these theories to investigate the scale-invariant temporal structure of precipitation in the Mondego drainage basin. The work uses daily precipitation data from two locations in the drainage basin, Coimbra and Penhas Douradas, over a period of 54 years.

General description of the Mondego River drainage basin and its hydrology

The Mondego River is the longest watercourse whose entire course lies within Portugal. Its source is in the Serra da Estrela, in Central Portugal, at an altitude of 1,547 m, and it flows into the Atlantic Ocean, near the city of Figueira da Foz, 234 km later (see Figure 1). The average slope of the Mondego riverbed is 0.637% (Lencastre and Franco 1984). The main first-order tributary streams entering the Mondego River are the Dão, on the right bank, and the Pranto, Arunca, Ceira and Alva, on the left bank.

The Mondego drainage basin has an area of approximately 6,645 km^2, being the second biggest river catchment area totally located in Portugal. Its shape is elongated, with its axis oriented approximately NE-SW, and is located approximately between 39°46' N and 40°48' N, and 7°14' W and 8°52' W. The highest altitude in the drainage basin is almost 2,000 m above sea level. The mean altitude is around 375 m.

The climate of the Mondego basin is Mediterranean and strongly influenced by the proximity of the Atlantic Ocean. The Atlantic influence increases the relative humidity of the air and affects temperatures and precipitation. In the summer, low precipitation and high temperature and insolation can occur due to the presence and influence of the Azores high-pressure system. In the winter, many days have precipitation and mild temperature, strongly influenced by the passage of frontal surfaces and depressions moving from West to East, coming from the Atlantic Ocean.

The average annual temperature in the basin is approximately 13 °C. The warmest part of the basin is near the coast (in the Lower Mondego region), where the average annual temperature is around 16 °C. The coldest regions are in the high lands of Estrela and Caramulo Mountains, where the average annual temperature is only 10 °C. Near the coast, the variation of temperature during the year is small because of the influence of the Atlantic Ocean. As the distance to the ocean increases, the temperature range increases. In the Mondego basin, the average temperature for the hottest months of July and August is 19 °C, and for the coldest months of December and January it is 6 °C.

The average annual insolation in the basin is around 2,400 h and the mean annual evapotranspiration is around 720 mm.

The mean annual precipitation in the basin is approximately 1,130 mm. The period from October to March is the humid semester, registering about 70% of the annual precipitation (for the two locations in the basin, see Figure 4(c)). The wettest month is December, with around 160 mm of precipitation. The driest months are July and August, with a monthly precipitation of around 15 mm. In the dry season, months often register zero-precipitation.

Topography has a striking influence on both temperature and precipitation (Figure 2). There is a clear increase in precipitation and decrease in temperature with altitude, as one goes from the lower lands towards the hills.

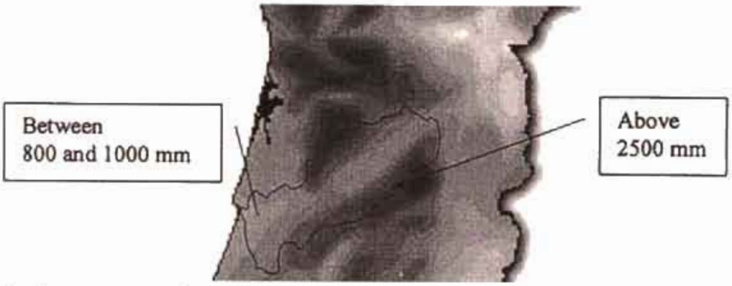

Figure 2. Spatial variation of mean annual precipitation in the Mondego River Basin. The highest values of precipitation (darker areas) are recorded in the mountainous regions of Estrela and Caramulo and the lowest (lighter areas) in the Lower Mondego Region, near the Atlantic coast. (Adapted from DGA 1989)

It is possible to define three hydro-morphologic regions in the Mondego basin, based on different morphologic and climatic characteristics, hydrologic regimes and land use:

- *Upper Mondego*, corresponding to the mountainous region, where the river runs through valleys formed in the ice age. This region includes, among others, parts of the drainage basins of the Dão and Alva tributaries, and the upper section of the Mondego River.

- *Middle Mondego*, which occupies the area lying between the outskirts of the Serra da Estrela mountains and the city of Coimbra. In this part of the Mondego catchment, the riverbed, which initially runs along a narrow valley, progressively broadens. This section of the river contains the outlets of the rivers Dão, Alva, and Ceira.
- *Lower Mondego* corresponds to the last section of the basin between Coimbra and the sea. In this area the river has a wide valley. The main tributaries of the Mondego River in this area are the rivers Arunca, Pranto and Foja.

The total resident population in the Mondego basin is around 680 thousand inhabitants (MA 2000). In this region the land is predominantly occupied by forest. In recent years the area occupied by forest has increased as the agricultural area diminished; forest accounted for 45% of ground cover in 1985 and 54% in 1990.

The Mondego River has a mean annual runoff of approximately 86 m^3/s (403 mm or 2.7×10^9 m^3), at the outlet. The mean runoff of the driest month is around 0.015×10^9 m^3 and of the wettest month is 0.530×10^9 m^3 (MA 2000). The hydrological discharges of the Mondego River and its main first-order tributary streams are extremely irregular. In Coimbra, approximately 40 km from the estuary, the river flow has reached discharges as high as 3,000 m^3/s, in strong contrast with discharges of less than 1 m^3/s, occurring several days a year (natural situation before the human intervention). This has frequently led to flooding, and water supply problems, mainly for agricultural purposes. Flooding is still a problem in the Mondego basin, although several dams have been constructed, and these are able to control the great majority of flood situations in roughly 80% of the basin area. For approximately 20 consecutive years, the regulation and protection scheme managed to control the river discharges against floods. Recent flooding events are leading to a re-evaluation of the project and of its management and maintenance.

The most important hydraulic works in the Mondego basin are the dams at Aguieira, Fronhas, Raiva and the barrage at Coimbra, the Serra da Estrela hydroelectric system, and the irrigation and drainage systems of the Lower Mondego region. The diversity of water uses (e.g. for supplying populations, agriculture, industry, energy production) is extremely important for the economy of the region. In fact, the Mondego basin is the one registering the most extensive use of water resources in Portugal, namely for hydroelectric power (annual production of 360 GWh) and agriculture. The Lower Mondego hydro-agricultural scheme, which includes large irrigation and drainage systems, enhances the economic development of the region, where there are 15,000 ha of good agricultural land.

For mainland Portugal and, in particular, for the Mondego river drainage basin, Figure 3 shows a drought situation recorded in 1945 (Pimenta 1998), classified according to Palmer (1965). The Palmer Drought Severity Index is based on the supply-and-demand concept of the water balance equation, and is calculated using precipitation and temperature data, and the available water content of the soil. The values of the Palmer Index that are indicated in Figure 3 are average values for the year of 1945. Pimenta (1998) and Pimenta and Lima (1999) studied the occurrence of droughts in mainland Portugal, using monthly precipitation and air temperature time series from 70 stations of the Portuguese climatological network, for the period 1941 to 1992. Their study shows that, during this period, there were droughts affecting most of the territory, including the Mondego catchment area. Because of the uneven distribution of precipitation during a year, with the dry season coinciding with the warmest months, the Palmer Index yearly average indicates the occurrence of extremely dry periods within a twelve-month period. These are often linked to important water shortage problems, already mentioned above.

Figure 3. Impact of one of the most severe droughts (year of 1945) observed in Mainland Portugal and in the Mondego Basin, according to the Palmer classification, where: 1 – Extremely dry; 2 – Very dry; 3 – Moderately dry; 4 – Slightly dry; and 5 – Incipient dry. (Adapted from Pimenta and Lima 1999)

The precipitation data from Coimbra and Penhas Douradas

The precipitation data used in the scale-invariant analysis (see below) were recorded at two locations in the river Mondego drainage basin, in Portugal: Coimbra/ Geofísico and Penhas Douradas (Serra da Estrela). The co-ordinates of these stations are approximately 40°12' N and 8°25' W, for Coimbra, and 40°25' N and 7°33' W, for Penhas Douradas. The altitude of the measuring sites is, respectively, 141 m and 1,380 m above mean sea level. Figure 1 shows the location of the measuring stations in the Mondego basin.

The precipitation measuring devices are of the 20-14-G type (according to the classification by Sevruk and Klemm, 1989); they have horizontal openings of 200 cm^2 at 1.5 m height. The gauges were observed daily. The resolution of the measurements is 0.1 mm of precipitation. Trace precipitation of less than 0.1 mm is disregarded and such days are considered dry (zero-precipitation days).

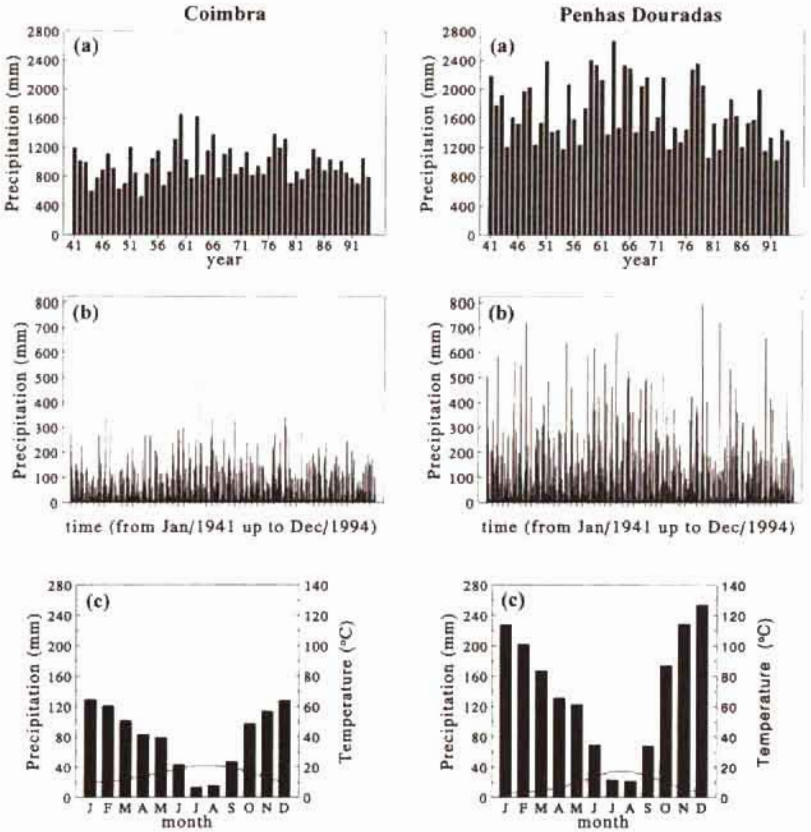

Figure 4. Precipitation in Coimbra and Penhas Douradas, in the Mondego drainage basin, for the years 1941-1994: (a) annual precipitation; (b) monthly precipitation; and (c) average monthly precipitation. Figure (c) also shows the average monthly temperature, for the years 1947-1982.

The precipitation recorded in Coimbra and Penhas Douradas, for the years 1941 to 1994, is shown in Figure 4 and in Table 1. Figure 4(a) shows the annual precipitation. Figure 4(b) shows the monthly precipitation and Figure 4(c) shows the monthly average precipitation. The precipitation recorded in Coimbra and Penhas Douradas illustrates the spatial variability of precipitation in the Mondego basin, where the lower-lying land registers less precipitation, and the higher ground gives higher precipitation figures. Both locations exhibit a marked seasonal distribution of precipitation during the year. In Coimbra, of the 648 months that constitute this sample, 16 months had less than 1 mm of precipitation (roughly 2.5%); among these, there are five months with less than 0.1 mm. In Penhas Douradas, in the same period, there were 24 months with less than 1 mm of precipitation (roughly 3.7% of the sample); among these, there are seven months with less than 0.1 mm of precipitation.

Figure 4(c) also shows the average monthly temperature in Coimbra and Penhas Douradas, recorded from 1947 to 1982. For this period, the mean annual temperature in Coimbra was 15.1 °C and in Penhas Douradas it was 8.9 °C. On average, the coldest month was January, with 9.6 °C in Coimbra and 2.8 °C in Penhas Douradas. In Coimbra, the warmest months were July and August with 20.9 °C, and in Penhas Douradas July was the warmest, with 17.1 °C.

Table 1. Summary of relevant precipitation data from Coimbra and Penhas Douradas, for the period 1941-1994.

Type of precipitation data (1941-1994)	**Measuring stations**	
	Coimbra	**Penhas Douradas**
Mean annual precipitation (coefficient of variation)	976.9 mm (0.24)	1692.2 mm (0.25)
Precipitation in wettest year (wettest year)	1651.4 mm (1960)	2669.3 mm (1963)
Precipitation in driest year (driest year)	524.2 mm (1953)	1023.9 mm (1992)
Average monthly precipitation (coefficient of variation)	81.4 mm (0.90)	141.0 mm (0.99)
Precipitation in wettest month (wettest month)	467.4 mm (November, 1963)	802.6 mm (December, 1978)
Precipitation in driest months (total number of months)	0 mm* (5 months)	0 mm* (7 months)
Average precipitation in wettest month (average wettest month)	129.5 mm (January)	253.8 mm (December)
Average precipitation in driest month (average driest month)	13.7 mm (July)	21.9 mm (August)

* Monthly precipitation below 0.1 mm is considered negligible.

Some aspects of fractal and multifractal theories

The invariance of properties manifested across scales can be investigated mathematically using fractal and multifractal theories. These theories apply to processes and systems that do not have a characteristic scale. Scale-invariance leads to a class of scaling rules (power laws) characterised by scaling exponents. This allows the relationship of variability between different scales to be quantified. Statistical properties of scale-invariant systems at different scales (i.e. on large and small scales) are related by a scale-changing operation that involves only scale ratios.

Scaling theories are developed in a non-dimensional framework, because one is looking for features that are independent of the physical size of the study-object. To non-dimensionalise time measurements, one assumes that the duration of the longest period of interest is equal to 1. If this period has a duration T, then the magnitude of any time interval τ should be divided by T. Any time scale corresponding to τ can then be characterised by a scale ratio λ, with $1/\lambda = \tau / T$. To non-dimensionalise the precipitation intensity on a time scale of resolution λ, the intensity can be divided by the ensemble average intensity of the process. For precipitation this means the climatological average precipitation. Nevertheless, in practice, one generally uses the average intensity of the sample, which corresponds to the largest scale of interest ($\lambda = 1$). Let the (average) precipitation intensity for $\lambda = 1$ be $< R_1 >$, where the angular brackets $< \ >$ mean (ensemble) average. So if the precipitation intensity in a time interval λ^{-1} is R_λ, the corresponding non-dimensional intensity is $\varepsilon_\lambda = R_\lambda / < R_1 >$, hence $< \varepsilon_\lambda > = 1$.

Using fractal theory (Mandelbrot 1977, 1982) one is dealing with simple scaling. Fractal behaviour is determined by one parameter. Fractal studies of the temporal structure of precipitation deal only with the oversimplified binary question of occurrence and non-occurrence of the process. The binary question (i.e. the definition of rainfall occurrence) is generally associated with a precipitation-intensity threshold. The geometric structure that is the 'support' of the precipitation process can be regarded as a fractal object embedded in the 1-dimensional space of time and is defined as the set of precipitation periods observed in a particular location. Its fractal dimension, D, is between 0 and 1. Very roughly, the fractal dimension of a set tells how densely the set occupies the metric space in which it lies. More generally, it tells how frequent a phenomenon is. The fractal dimension of a set can be determined with the box-counting method (e.g. Feder 1988, Hastings and Sugihara 1993).

The need to generalise the scaling properties of physical processes has led to the development of multifractal theory (Hentschel and Procaccia 1983, Grassberger 1983, Schertzer and Lovejoy 1983), dealing not with simple scaling but with multiscaling. It can handle the different intensity levels of processes. Multifractal behaviour is determined not by one, but by an infinity of scaling exponents.

One way to investigate the multifractal temporal structure of the precipitation process is by studying the (multiple) scaling of the probability distributions of the precipitation intensity (e.g. Schertzer and Lovejoy, 1987). The precipitation intensity threshold level is evaluated with the order of singularity γ of the intensities $\varepsilon_\lambda \sim \lambda^\gamma$ (e.g. Frisch and Parisi 1985, Halsey et al. 1986, Schertzer and Lovejoy 1987). The scaling of the probability distributions is given by the exponent function $c(\gamma)$:

$$\Pr(\varepsilon_\lambda \geq \lambda^\gamma) \approx \lambda^{-c(\gamma)} \quad (1)$$

In literature, the function $c(\gamma)$ is called the codimension function. Eq. (1) holds for proportionality constants varying slowly with λ and depending weakly on γ (e.g. Schertzer and Lovejoy 1989, Lovejoy and Schertzer 1991). This statistical characterisation of multifractals arises directly from multiplicative cascade processes (see e.g. Schertzer and Lovejoy 1987). The scaling (power-law) behaviour can be tested with log-log plots of the probability of exceeding different levels of the precipitation intensity ε_λ , observed on scales of differing levels of resolution λ, against the scale ratio λ (e.g. Lavallée et al. 1991).

Another (equivalent) way to investigate the multifractal temporal structure of precipitation is with the statistical moments of the precipitation intensity (Schertzer and Lovejoy 1987). The scaling of the moments of precipitation intensity is described by the exponent function $K(q)$. The notion of moment can be generalised to any real value q. The moments' scaling function $K(q)$ satisfies:

$$< \varepsilon_\lambda{}^{q} > \approx \lambda^{K(q)} \tag{2}$$

where $< \varepsilon_\lambda{}^{q} >$ is the (ensemble) average q^{th} moment of the precipitation on a scale specified by λ. The scaling of the moments can be tested with log-log plots of the average q^{th} moment of precipitation intensity ε_λ, observed on scales of different levels of resolution λ, against the scale ratio λ. The two multifractal scaling exponent functions $c(\gamma)$ and $K(q)$ are (theoretically) non-linear increasing functions (concave functions).

One can also use standard spectral methods and analysis to test for scale-invariance. The most familiar consequence of scaling is the power-law behaviour that is expected in the energy (power) spectra of scaling processes (e.g. Mandelbrot 1982, Schertzer and Lovejoy 1987, Ladoy et al. 1991, Lovejoy and Schertzer 1995):

$$E(\omega) \approx \omega^{-\beta} \tag{3}$$

where ω is the wave-number, $E(\omega)$ is the energy, and β is the spectral exponent. For temporal processes, the wave number can be approximated by $\omega \sim 1/\tau$, with τ being the magnitude of any time interval. Thus, in this application, ω is a frequency. The power-law behaviour of the spectra is expected to occur over a range of wave numbers and might not be observed for small samples.

Scaling and multifractal analysis of daily precipitation data

This Section deals with the analysis of the daily precipitation, over a period of 54 years, from Coimbra and Penhas Douradas, recorded from 1941 to 1994. In the different analyses, given below, the statistics are accumulated for the 54 years covered by the data.

The energy spectra of the daily precipitation at these two locations are plotted in Figure 5. The spectra have been smoothed for high frequencies. The spectral peaks at $\omega \approx 0.0027$ day^{-1} correspond to the annual cycle frequency. The spectra exhibit power-law behaviour that extends from 1 day up to at least one month. The spectral exponent ß (Eq. 3) is estimated as 0.28, for the data from Coimbra, and 0.31, for the data from Penhas Douradas. Parameters ß were estimated from the absolute values of the slopes of the regression lines fitted to the right-hand side scaling regions of the spectra, plotted in log-log axis. For scales larger than one to two months, up to roughly one decade, one can distinguish a rather flat section in the spectra. The scaling regime associated with the range of scales characterised by such a spectral plateau is expected to govern inter- and intra-seasonal variability (Fraedrich and Larnder 1993). This plateau is followed by another section (i.e., for even larger scales), indicating large-scale climatic variability. For other locations, e.g. Ladoy et al. (1991), Fraedrich and Larnder (1993), Tessier et al. (1996) and Svensson et al. (1996) have reported similar results.

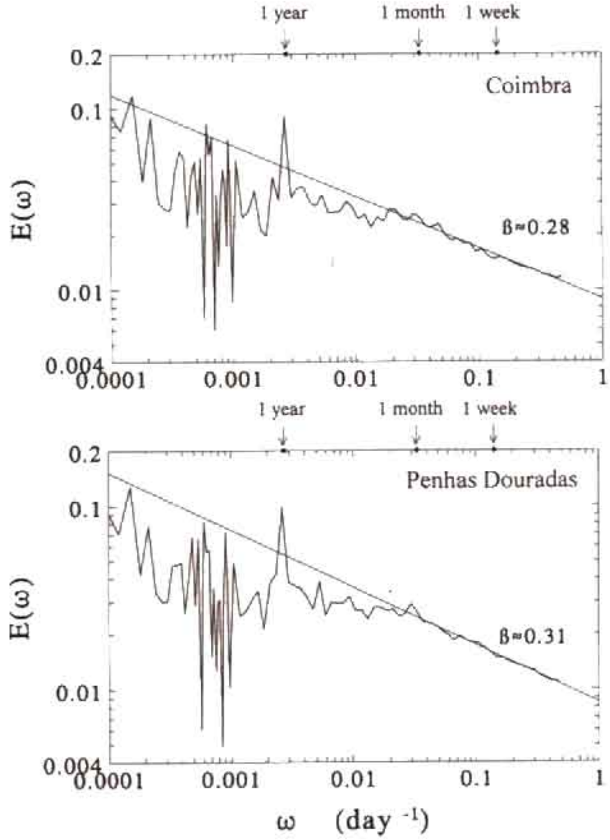

Figure 5. Energy spectra obtained for daily precipitation from Coimbra and Penhas Douradas, from 1941 to 1994.

The box-counting method can be also used to test the scale-invariant temporal structure of precipitation. The application of the box-counting method to precipitation, shown below, is based on a zero-precipitation threshold definition of precipitation occurrences. Figure 6 shows the box-counting plot obtained for the daily precipitation, for time scales from 1 day up to 8.5 months. A fractal dimension, 0.64, characterises precipitation occurrences in Coimbra, on the range of scales from 1 day up to about 13 days. A similar fractal dimension, 0.65, characterises precipitation occurrences in Penhas Douradas, on the range of scales from 1 day up to about 14 days. The fractal dimensions are estimated from the absolute value of the slopes of the regression (heavy) lines fitted to the left-hand side sections of the plots in Figure 6. Analysis of larger time scales is affected by 'saturation', which is a practical problem encountered when applying the box-counting method to precipitation occurrences. The regression (broken) lines fitted to the right-hand side sections of the plots in Figure 6 have (trivially) slope -1.

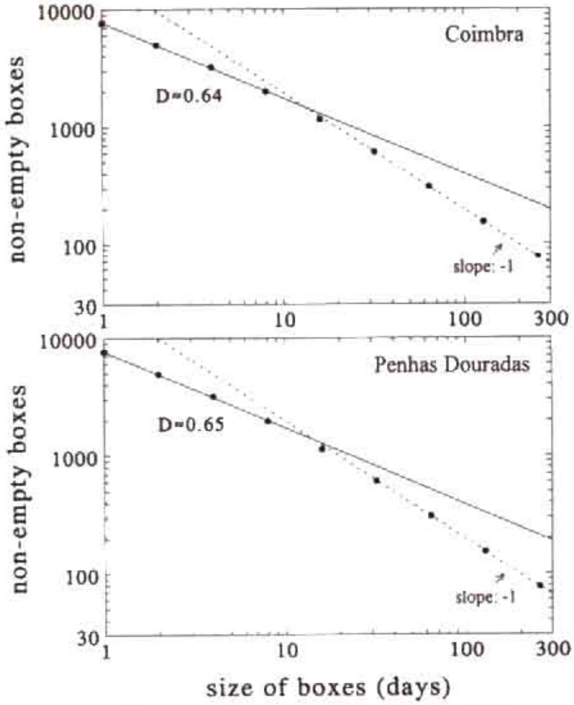

Figure 6. Box-counting plot obtained for daily precipitation from Coimbra and Penhas Douradas, for the period 1941 to 1994. The plot displays time scales from 1 day up to 8.5 months.

Figure 7 shows, for the data from Coimbra and Penhas Douradas, the log-log plot of the probability of exceeding precipitation intensity levels of singularity γ, observed on time scales from 1 day ($\lambda = 256$) up to 8.5 months ($\lambda = 1$), against the scale ratio λ. The orders of singularity γ of the precipitation intensity plotted in Figure 7 are indicated in the legends. The scaling behaviour observed in Figure 7 is maintained from one day up to more than one month. The scaling range observed for Penhas Douradas seems to be larger than for the data from Coimbra. The probability plots in Figure 7 show regression lines fitted to the data that clearly indicate the presence of scale invariance in the temporal structure of precipitation.

Also relative to the data from Coimbra and Penhas Douradas, Figure 8 shows the log-log plot of the average q^{th} moments of precipitation intensity ε_λ on time scales from 1 day ($\lambda = 256$) up to 8.5 months ($\lambda = 1$), against the scale ratio λ. Figure 8(a) shows moments larger than 1 and Figure 8(b) moments smaller than 1. The moments q plotted in Figure 8 are indicated in the legend. For moments larger than 1, the scaling range seems to extend from one day up to about one month, for the data from Coimbra, and up to about 2 months, for the data from Penhas Douradas. One expects that the scaling behaviour for some small moments, which highlight the small intensities of the data, would be affected by an incorrect description of the precipitation process by the data,

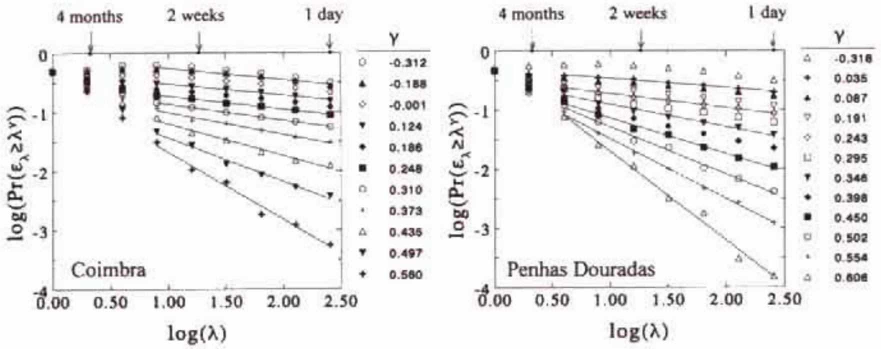

Figure 7. Log-log plot of the probability of exceeding precipitation intensity levels of singularity γ, observed on scales from 1 day ($\lambda = 256$) up to 8.5 months ($\lambda = 1$), against the scale ratio λ. The legend indicates the order of singularity γ of the precipitation intensity ε_λ. The plots are for the data from Coimbra and Penhas Douradas.

over this range of the precipitation dynamics. This could result from the inability of the measuring devices to record precipitation intensities smaller than a characteristic value.

The scaling functions $c(\gamma)$ and $K(q)$, in Eqs. (1) and (2) respectively, which would describe the statistics of precipitation in Coimbra and Penhas Douradas are obtained from the regression lines fitted to the probability plots in Figure 7 and moments' plots in Figure 8, over the relevant range of orders of singularity γ, and moments q of precipitation intensity.

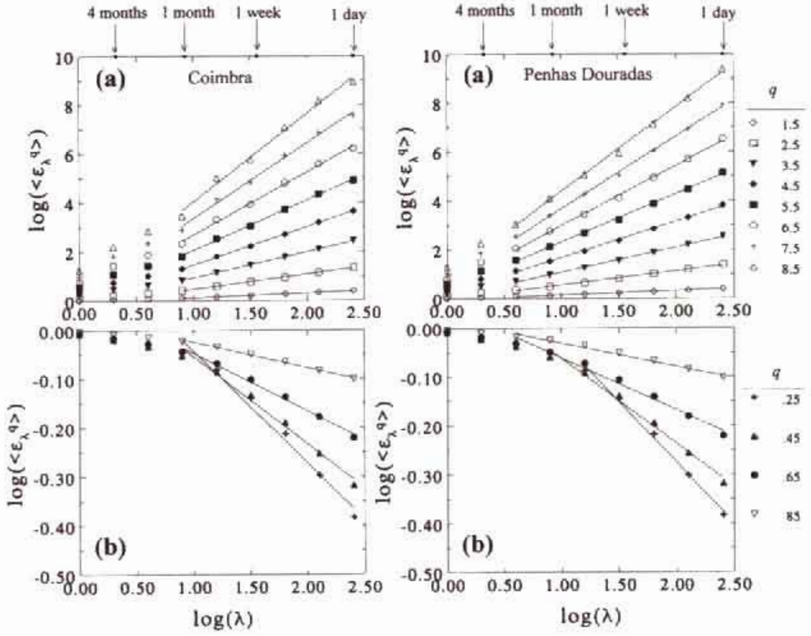

Figure 8. Log-log plot of the average q^{th} moments of the precipitation intensity ε_λ on scales between 1 day ($\lambda = 256$) and 8.5 months ($\lambda = 1$), against the scale ratio λ: (a) for moments larger than 1; and (b) for moments smaller than 1. The plots are for the data from Coimbra and Penhas Douradas.

Concluding remarks

This study shows the presence of scale-invariant and multifractal properties in the temporal structure of precipitation in the Mondego drainage basin. The study used daily precipitation from Coimbra and Penhas Douradas. Scale-invariant and multifractal properties are maintained from one day up to roughly one month. Results obtained for the data sets investigated are consistent with results reported by other researchers, for different precipitation data sets. One can refer to e.g. Ladoy et al. (1991), Hubert and Carbonnel (1991), Hubert (1992), Tessier et al. (1992), Ladoy et al. (1993), Tessier et al. (1993), Hubert et al. (1993), Lima et al. (1993), Olsson and Niemczynowicz (1994), Hubert (1995), Lima and Bogardi (1995), Harris et al. (1996), Svensson et al. (1996), Bendjoudi et al. (1997), Lima (1998, 1999) and Lima and Grasman (1999).

The scale-invariant and multifractal approach to the study of precipitation in the Mondego basin has still not been fully explored. There is still insufficient knowledge about the dependency of the multifractal behaviour of precipitation on climatological and geographical factors (i.e. on precipitation-generating mechanisms). Thus, more research is needed involving the study of precipitation from other locations. Further research should include the analysis of precipitation data from more locations in the Mondego catchment, and also the analysis of higher resolution precipitation time series (e.g. hours, minutes). This will allow us to characterise the precipitation process better. It will also allow us to fully explore the invariance of precipitation properties across scales. Some studies have already shown that this scale invariance is observed down to scales of the order of minutes (e.g. Lima 1998). Such properties permit us to use the statistics of precipitation derived, for example, from daily data to infer the statistics of precipitation at smaller time scales. The expectation is that the multifractal theory and its application in models (e.g. Schertzer and Lovejoy 1987) may be tools that help produce high-resolution synthetic precipitation data that can be used in many hydrological applications and studies (e.g. rainfall-runoff transformation, soil erosion, spread of pollutants, urban drainage). For the Mondego basin, this could greatly assist in water resources studies and management.

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