EXTREME VALUE MODELLING OF DAILY AREAL RAINFALL OVER MEDITERRANEAN CATCHMENTS IN A CHANGING CLIMATE

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Abstract

Heavy rainfall events during the fall season are causing extended damages in Southern France catchments. A peaks-over-threshold model is developed for the extreme daily areal rainfall occurrence and magnitude in the fall over six Mediterranean catchments in Southern France. The main driver of the heavy rainfall events observed in this region is the humidity flux from the Mediterranean Sea. Reanalysis data are used to compute the daily humidity flux (FHUM) during the period 1958-2008, to be included as a covariate in the model parameters. Results indicate that the introduction of FHUM as a covariate in the model parameters can improve the modelling of extreme areal precipitation. The seasonal average of FHUM can improve the modelling of the seasonal occurrences of heavy rainfall events, while the daily FHUM values can improve the modelling of the events magnitudes. In addition, an ensemble of simulations produced by five different general circulation models are used to compute FHUM in future climate and hence to evaluate the impact of climate change on the heavy rainfall distribution in the selected catchments. This ensemble of climate models allows the evaluation of the uncertainties of climate projections. By comparison to the reference period 1960-1990, all models projects an amplification of mean seasonal FHUM from the Mediterranean Sea during the projection period 2070-2099, on average by +22%. This increase in the humidity flux leads to an increase in the number of heavy rainfall events, from an ensemble average of 2.55 events during the fall season in present climate to 3.57 events projected for the period 2070-2099. However, the projected changes have limited impacts on the magnitude of extreme events, with a 5% increase in the median of 100-year quantiles.

1- INTRODUCTION

For the next century, future climate projections carried out with climate models show an amplification of precipitation extremes associated with a decrease of precipitation totals in the Mediterranean basin (Alpert et al., 2002; Gibelin and Déqué, 2003; Goubanova and Li, 2007; Gao et al., 2008; Somot et al., 2008; Ricard et al., 2009, Sanchez-Gomez et al., 2009). Therefore, it becomes necessary to assess and quantify the possible changes in extreme rainfall events to evaluate their impacts on the hydrology of Mediterranean catchments. Several studies have analyzed the possible trends and future changes in extreme precipitation using point rainfall (Beguería et al., 2010) or rainfall averaged over various domain sizes (Neppel et al., 1997, Kyselŷ et al., 2010). However to our knowledge no study has developed extreme value analysis at the catchment scale in the Mediterranean region to evaluate the possible changes.

In hydrology, areal rainfall statistics are more relevant than point rainfall statistics for most applications, in particular for flood modeling and management (Lebel & Laborde, 1988). A good knowledge of the amount of rainfall intercepted by a catchment during the heaviest rainfall events is required for the correct estimation of flood volume. Furthermore, the mean areal rainfall over a catchment is the main input variable of rainfall-runoff hydrological models, employed for flood forecasting or the design of hydraulic structures (Andréassian et al., 2004; Moulin et al., 2009). Estimations of areal rainfall are usually obtained using spatial interpolation techniques such as kriging (Singh and Birsoy, 1975; Lebel et al., 1987; Kieffer-Weisse and Bois, 2002; Ruelland et al., 2008). Some studies have analyzed the statistical distribution of areal rainfall to estimate the return periods of extremes, using conventional frequency analyses techniques (Skaugen et al., 1996; Neppel et al., 1997; Neppel et al., 2006). The areal rainfall distribution can also be directly derived from the punctual distributions

(Buishand, 1991; Lebel & Laborde, 1988). Following this approach, the estimation of extreme areal rainfall depths using Extreme Value distributions is also possible (Coles and Tawn, 1996, Buishand et al., 2008, Overeem et al., 2010).

The frequency analysis methods relying on the Extreme Value Theory are widely used to relate the magnitude of extreme events (e.g. heavy rainfall, floods) to a probability of occurrence (Stedinger et al., 1993). Nevertheless, in the context of climate change the standard frequency analysis techniques need to be adapted (Khaliq et al., 2006; El Adlouni et al., 2007). One way to take into account the non-stationarity signal in the frequency models is to make their parameters dependent on time or on climatic covariates (Katz et al, 2002; Fowler et al., 2007). If a low frequency covariate is included in a model with time-dependent parameters, it becomes possible to assess the risk of extreme events on a seasonal or yearly basis (El Adlouni et al., 2007). The most appropriate covariates can be identified from the past climate records, using observations or reanalysis data. These covariates are then computed for the future climate, using the outputs of general circulation models in order to produce scenarios (Johnson and Sharma, 2009). A growing number of studies have considered the use of covariates into non-stationary frequency models for extreme point precipitation (Aissaoui-Fqayeh et al., 2009; Friederichs, 2010; Kallache et al., 2010; Maraun et al., 2010). In particular, several studies have shown the efficiency of atmospheric humidity and moisture flux as covariates for daily rainfall modeling and downscaling (Cavazos and Hewitson, 2005; Fowler et al., 2007; Bliefernicht and Bárdossy, 2007; Wang and Zhang, 2008; Mehrotra and Sharma, 2009; Tryhorn and DeGaetano, 2010; Yang et al., 2010).

The goal of the present study is to develop a model with climatic covariate information for the magnitude and the occurrence of extreme areal rainfall events in Mediterranean catchments. The study area is the southern French Mediterranean region, where catastrophic flash floods caused by intense rainfall events are the main natural hazard (Delrieu et al., 2005; Boudevillain et al., 2009). Several studies have already shown that heavy rainfall events in the study area were linked with the existence of a strong anomaly of moist and warm air associated with a strong convergent southeasterly low-level flow over the region (Ducrocq et al., 2007; Nuissier et al., 2007; Funatsu et al., 2009; Boudevillain et al., 2009). This feature is robust enough to be captured by the reanalysis data at a relatively large spatial scale (Joly et al., 2009). One question that is addressed in the present paper is whether the use of covariates describing the humidity flux from the Mediterranean Sea can improve the frequency modeling of heavy rainfalls in this region. In this study, the humidity flux from the Mediterranean Sea is computed from reanalysis data and tested as a covariate in a non-stationary peaks-over-thresholds model for extreme areal rainfall for six watersheds. Then, an ensemble of simulations produced by different general circulation models are used to compute the humidity flux in future climate and to evaluate the impact of climate change on the heavy rainfall distribution in the selected catchments. The data and methods are presented in section 2 and 3, the modelling results and the projections in the future climate are presented in section 4.

2- STUDY AREA AND DATASETS

2.1 Rainfall database and selected catchments

We include in this study six watersheds, all located in the south-eastern border of the Cévennes mountainous area in Southern France (Fig. 1). The catchment sizes range from 795 km² for the Vidourle catchment, to 2585 km² for the Herault catchment. These watersheds are often hit by catastrophic flash floods caused by intense rainfall events, such as the event of

September 2002 (Delrieu et al., 2005). Daily rain gauge data from 398 stations provided by Météo-France were used, covering the period 1958 to 2008. The number of rain gauge records available in the catchments varies from year to year, as shown in table 1. The rain gauge density range from 6.6 rain gauge per 100 km² (Vidourle) to 1.74 rain gauge per 100 km² (Herault), depending on the year. The daily records are spatially interpolated using the Thiessen Polygons interpolation method.

In a preliminary study, other interpolation methods such as cubic spline or bloc-kriging techniques have been compared with the rainfall data available in the selected catchments. The results, not shown in the present study, indicate a very good agreement in the areal rainfall estimation between the different methods.. This result is in accordance with previous studies of Lebel et al. (1987) or Kieffer-Weisse and Bois (2002) who obtained very similar interpolation results using different methods when considering a dense network of rain gauge as it is the case in the present work. Consequently, only the Thiessen method is retained, since it is a simple method to implement with low computation time. The interpolated rainfall fields were averaged on the selected catchments in order to provide time series of areal rainfall.

The days exceeding the thresholds corresponding to the long term 95^{th}, 97^{th}, 98^{th} and 99^{th} percentiles computed on wet days (when P>1mm) during the fall season (September, October and November) were extracted. The heaviest rainfall events and devastating floods are usually observed during the fall in this region (Delrieu et al., 2005).. Since the average duration of the heavy precipitation events in the study area is about 29 hours (Boudevillain et al., 2009), the daily areal rainfall provides a fair representation of the rainfall depths during extreme events in these catchments. To remove serial dependence between the selected events (i.e. with threshold exceedances several consecutive days), a minimum of 2 days between consecutive events was respected. Only the maximum of threshold exceedances occurring during consecutive days was selected.

2.2 Humidity flux in present and future climate

2.2.1 Reanalysis data

The NCEP reanalysis data (Kalnay et al., 1996) are used to estimate the humidity flux from the Mediterranean Sea, which is the main climatic influence on heavy rainfall events observed in southern France and detectable at the synoptic scale as shown in previous studies (Funatsu et al., 2009; Boudevillain et al., 2009; Joly et al., 2009; Duffourg and Ducrocq, 2011). Reanalysis data from the four 2.5°x2.5° grid cells covering the region were extracted (Fig. 2), at daily time step during the observation period 1958-2008. The variables retrieved are the specific humidity (SHUM) and the U (zonal) and V (meridional) wind components at 925 hPa. The humidity flux (FHUM) originating from the Mediterranean Sea was computed as the product of wind magnitude from the second quadrant (south-east) and specific humidity at 925 hPa for the same grid point, located south-eastern to the catchments (noted [D] on Fig.2). This procedure is repeated for each time step of the observation period to derive a reference daily time series of FHUM.

2.2.2 General circulation model data

An ensemble of 5 coupled atmosphere ocean global circulation models (AOGCMs) from the ENSEMBLE Stream 2 experiment (Johns et al., 2011) are selected (Table 2). These models feature some of the latest developments of climate modeling, by the inclusion of atmospheric, oceanic and land use models. Some AOGCMs also include a carbon cycle (DMIEH5C, MPEH5C and HadCM3C) or aerosol transport and chemistry models (EGMAM2 and HadCM3C). The selected models are capable of reproducing the same climate variables as those produced by the NCEP reanalysis at daily time steps, with a similar spatial resolution. The A1B scenario was chosen for the simulations because it forecasts a strong increase in greenhouse gas emissions which is consistent with real emission growth. Also, the AIB scenario has been used often so it makes our work comparable with earlier climate modeling work. Data outputs for the historical period and A1B scenario for the period 2000–2099 are available in the Climate and Environmental Retrieval and Archive (CERA) database in Hamburg (http://cera-www.dkrz.de/).

The FHUM variable is computed with the outputs of SHUM, U and V winds components at 925 hPa obtained with the different AOGCMs, for the control period 1960-1990 and for two projection periods 2020-2050 and 2070-2099. Climate models are not perfect reproductions of the reality and consequently there is a need to evaluate and correct their outputs using past observations records (Déqué, 2007). In the present study, the CDF-t approach developed by Michelangeli et al. (2009) is used to correct FHUM computed from AOGCMs with FHUM computed from NCEP reanalysis during the observation period 1960-1990. The CDF-t approach belongs to the family of the quantile-matching methods (Michelangeli et al. 2009; Kallache et al., 2011), dealing with the cumulative distribution function (CDF) of the variable of interest. It is based on a non-parametric transformation T, which allows to correct the modeled CDF (FHUM computed from AOGCMs) with the reference CDF (FHUM computed from the NCEP reanalysis) during the control period. Then, the same transformation T is applied to the projection periods 2020-2050 and 2070-2099, with the hypothesis that the model bias will remain the same in future climate. For the full description of the CDF-t approach, see Michelangeli et al. (2009) and a free R package is available on the CRAN website (http://cran.r-project.org/web/packages/CDFt/index.html).

3- NON-STATIONARY PEAKS-OVER-THRESHOLD MODELLING

3.1 Model description

The POT approach allows the joint characterization of the frequency and magnitude of extreme events, which is useful in a non-stationary context of climate change since it permits assessing the changes in frequency as well as in magnitude (Jacob et al., 2009). In this study, the POT approach is applied to the areal rainfall in the six previously described catchments. For high thresholds, the occurrence of threshold exceedances is assumed to follow a Poisson process and the magnitudes of exceedances a Generalized Pareto (GP) distribution, which can be adapted for the non-stationary context (Coles, 2001, Beguería et al., 2010). The estimation of the model parameters in the present study is done via the Maximum Likelihood Estimation (MLE) method. The MLE approach is general and flexible, and can be easily extended to encompass regression relationships between data and other explanatory variables (Coles, 2001; El Adlouni et al., 2007; Aissaoui-Fqayeh et al., 2009).

The n occurrences for a given time period follow a Poisson distribution, whose probability distribution function (pdf) is given by:

$$f(n,\lambda) = \exp^{-\lambda} \frac{\lambda^n}{n!} \qquad (1)$$

n is a non-negative integer (n =0,1,2,3..) and λ is a positive real number which represents the average occurrence rate. In the present study, it is the mean number of daily precipitation amounts that exceeds a certain threshold during the fall season. The parameter λ corresponds to both the mean number of exceedances per year and the variance and can be estimated from the sample mean. In the stationary case, λ is constant. In a non-stationary context, the intensity of the Poisson process could vary in time and be related to a time-dependent covariate *x*:

$$\lambda(x_t) = \exp(a_1 x_t + b_2) \qquad (2)$$

The a_1 and b_1 parameters are model parameters, estimated by MLE.

The three parameter GP distribution models the magnitudes of the threshold exceedances. The GP distribution has the following cumulative distribution function (Madsen et al., 1997):

$$F(q) = 1 - \left(1 - \kappa \frac{q - q_0}{\alpha}\right)^{-1/\kappa} \qquad \kappa \neq 0 \qquad (3)$$

$$F(q) = 1 - \exp\left(-\frac{q - q_0}{\alpha}\right) \qquad \kappa = 0$$

Where q is the value of a given threshold exceedance, α is the scale parameter, κ the shape parameter of the GP distribution and q_0 the threshold level. The threshold level is determined a priori, only the scale and shape parameters of the GP need to be estimated from the sample. A non-stationarity feature can also be incorporated in the GP distribution, usually in the scale parameter (Coles, 2001, Khaliq et al., 2006). The non-stationarity can also be incorporated into the shape parameter but it is not a common practice as the estimation of the shape parameter is difficult, in particular when considering covariates (Coles, 2001; Renard et al.,; 2006, Pujol et al., 2007). In the present paper, only a dependency on the scale parameter is considered:

$$\alpha(y_t) = \exp(a_2 y_t + b_2) \tag{4}$$

Where *y* is a covariate, a_2 and b_2 are model parameters, estimated by MLE.

Finally, using the parameters of the Poisson and GP distributions and inverting Eq. 1, it is possible to derive the q_T event that is the event corresponding to the exceedance probability $1/T$ (Madsen et al., 1997):

$$q_T = q_0 + \frac{\alpha}{\kappa}\left[(\lambda T)^{\kappa} - 1\right] \qquad \kappa \neq 0 \tag{5}$$

$$q_T = q_0 + \alpha(\ln \lambda T) \qquad \kappa = 0$$

In the stationary case, a unique quantile q_T is computed using the parameter values. For the non-stationary case, the q_T quantile is a function of the covariates used for the Poisson and GP model parameters. As the covariates considered are time-dependent, in the non-stationary case the q_T quantiles are also time-dependent.

3.2 Comparison between stationary and non-stationary models

The Poisson process was either considered stationary (model P_0) or with a log-linear dependency of the λ parameter with a covariate x_t (model P_1). Similarly, the GP distribution was considered stationary with constant scale and shape parameters (model GP_0) or with a log-linear dependency on the scale parameter (α) with a covariate y_t (GP_1). The deviance test based on the log-likelihood difference is chosen to compare the models, M_0 and M_1. The method of the deviance test is to compare the validity of the model M_1 against the model M_0, based on the deviance statistic (El Adlouni et al., 2007, Coles, 2001):

$$D = 2\left\{l_n^*(M_1) - l_n^*(M_0)\right\} \qquad (5)$$

Where $l_n^*(M)$ is the maximized log-likelihood function of the model M computed on n observations. The D-statistic is distributed according to a chi-square distribution, with υ degrees of freedom, where υ is the difference between the number of parameters of the M_1 and M_0 models. D is larger than this critical value, the model M_1 is more adequate at representing the data than the model M_0.

4 RESULTS

4.1 Trend analysis and threshold selection

The stationarity of the heavy rainfall events in time has been first evaluated to check the possible dependences of the model parameters with time. A trend analysis is undertaken on the seasonal number and the magnitude of precipitation extremes. This analysis was performed using two methods: the non-parametric Mann-Kendall statistical test for trend detection and the deviance statistic, computed between a stationary model and a non-stationary model using time as a covariate. The results indicate no significant upward or downward trend at the 5% significant level for the extreme daily areal rainfall frequency or magnitude during the period 1958 to 2008, in all the selected catchments. This result is in accordance with those obtained by Neppel et al., (2003) on the heavy rainfall occurrence between 1958 and 2002 in the same region.

The validity of threshold values for the POT model needs to be checked: if the threshold is too low, it violates the asymptotic basis of the model, leading to bias, and if the threshold is too high, it generates too few excesses, leading to high variance (Coles, 2001, Katz et al., 2002). The most suitable threshold to be used in the POT model is selected on the basis of the mean residual life plot, based on the average of threshold exceedances for different thresholds values (Beguería et al., 2010) and a GP distribution fit over a range of different thresholds values (Coles, 2001). For all catchments the 95th percentile (Figure 3) is selected, with a number of threshold exceedances during the fall varying from 2.23 (Vidourle) to 2.71 (Ardeche) leading to 107 (Vidourle) to 149 (Ardèche) events. This selection of events includes all the heaviest rainfall that occurred in the region and some of which led to catastrophic floods, as for example the events of September 8th and 9th 2002 (Delrieu et al., 2005) with more than 250 mm/d of areal precipitation in three of six catchments (see Fig. 3). The values taken by the 95th percentile show a good regional consistency among the catchments, with areal precipitation ranging from 30.3 mm to 46.6 mm, the highest value, for the Ardèche catchment.

4.2 Non-stationary POT modeling of extreme areal rainfall with humidity flux

The FHUM, computed from NCEP reanalysis, is tested as a covariate in the non-stationary POT model. The deviance test results (Table 3) indicates that the λ parameter of the occurrence process can be related to the seasonal average of FHUM to improve the frequency model, with significant deviance scores (with $D > 3.841$) in all the catchments. Figure 4 show for the Hérault catchment the scatter plot of the number of the events together with the relationship fitted with MLE between the λ_{ns} parameter and the FHUM average in fall. On the other hand, the FHUM variable computed at seasonal or even monthly time scales is not found to improve the GP model (results not shown). Only daily values of FHUM, corresponding to the events dates, provides significant deviance scores (with $D > 3.841$, except for the Vidourle catchment) when related to the scale parameter of the GP distributions (Table 3). On Figure 5 is shown for the Hérault catchment the scattered relationship between daily FHUM values and the corresponding event magnitudes. Consequently, if the seasonal rate of occurrence for the extreme rainfall can be related to seasonal patterns of humidity flux, the magnitude and therefore the severity of the events can only be related to daily temporal variations in air humidity. The influence of short term variations of climatic factors on the magnitude of extreme rainfall in the same region has been already documented (Nuissier et al., 2008; Ducrocq et al., 2008; Sanchez-Gomez et al., 2008; Boudevillain et al., 2009). Duffourg and Ducrocq (2011) observed that in most cases, the moisture feeding the heavy precipitating systems in Southern France crosses the northwestern part of the Mediterranean basin in a lapse of 5 to 10 hours. This limits the predictability of the rainfall amounts in the long term with low-frequency covariates (computed on a seasonal or annual basis). Indeed, to make future projections from climate model outputs, there is a need to incorporate in the non-stationary models time-averaged covariates, since climate models are better at producing a climatology rather than a day-to-day chronology.

The proposed POT model associates: (1) a GP model with stationary parameters and (2) a non stationary Poisson model, with its λ_{ns} parameter related to the average FHUM in fall. The model parameters are given in table 4 together with the equations of the relationships between

λ_{ns} and FHUM. The Figure 6 shows the quantile-quantile plots of the stationary GP distribution for each catchment to evaluate the quality of the model fit. A perfect fit is indicated if all crosses follow the diagonal line illustrated in the scatter plots. The larger the differences between the crosses and the line, the poorer the quality of the model fit. The Figure 5 shows that the differences are small between the observed and modeled values, even for the largest events. The GP distribution parameters (Table 3) indicates a heavy tailed behaviour (with $\kappa > 0$) for 3 catchments (Ceze, Gard, Vidourle) and an exponential behaviour ($\kappa = 0$) for the 3 others (Ardeche, Herault, Orb). The scale parameter varies from 22.6 to 30.4. With a non-stationary Poisson model, it becomes possible to compute quantiles for the different values taken by the covariate, here the FHUM average during the fall season.

Non-stationary quantiles corresponding to a 100-year return period have been computed for the Hérault catchment (Fig. 7) and compared with the 100-year quantile computed with a classical stationary model. The non-stationary quantile values are ranging from 181.5 mm to 223.05 mm, corresponding to a 10% variation compared to the stationary quantile value, 199.2 mm. This result illustrate the effects of taking into account the non-stationarity signals into frequency modeling: models can provide a range of possible values for a given quantile instead of a single quantile that may not be fully representative of the climatic variations observed. The values taken by the non-stationary quantiles of Figure 7 appear not significantly different from the stationary quantile during the reference period: the range of variability is comparable to the confidence interval obtained for the stationary quantile using a standard bootstrap procedure, with its 90% confidence interval between 176.14 and 223.93 mm. However, there is a need to better assess the effects of sampling uncertainties on the use of climatic covariates into non-stationary models. The method of maximum likelihood may not converge when the sample size is small or when a large number of parameters is considered, leading to unrealistic shape parameter values and large confidence intervals in particular for long return periods. Other methods such as the Bayesian approach (Ouarda and El Adlouni, 2011) might be more suited for the purpose of analyzing and quantifying the uncertainties in a non-stationary context (Renard et al., 2006).

4.3 Future changes in the humidity flux projected by AOGCM and consequences on extreme rainfall events

The variables SHUM and the U and V wind components at the 925 hPa level are retrieved in the 5 selected AOGCMs over the area corresponding to the south-eastern NCEP grid pixel covering the Mediterranean Sea. The FHUM variable is computed for the periods 1960-1990, 2020-2050 and 2070-2099. The FHUM computed with the different AOGCMs is first compared with FHUM computed with NCEP reanalysis during the reference period 1960-1990. The quantiles-quantiles plots are shown on the Figure 8. The best models at reproducing the FHUM distribution in fall are the MPE and DMI, while a large overestimation of FHUM is observed with the HAD model. The model outputs are corrected following the CDF-t approach of Michelangeli et al. (2009). It can be seen on Figure 8 that the correction is able to remove most of the bias of the FHUM variable from the AOGCMs with respect to the NCEP reanalysis data, except for the highest values. The same bias correction is then applied to the projected period 2020-2050 and 2070-2099. The average seasonal FHUM of a projection period is compared to the average seasonal FHUM of the reference period by calculating the relative difference between both values. The result of this comparison is illustrated in Figure 9 for all models and both projection periods. A future increase of average seasonal FHUM is indicated by positive values. Negative values indicate a decrease. There are large uncertainties between the different models in respect to projections of average seasonal FHUM. For the time period 2020-2050, no clear signal can be identified in the different AOGCMs: some models exhibit an upward trend and some others a downward trend. Likewise, several studies indicated that the response of the hydrological variables to global warming starts to be statistically significant only from 2050 onward (Sanchez-Gomez et al., 2009). However, there is a clearer signal for the period 2070-2099 with all models indicating an increase of the humidity flux from the Mediterranean Sea, in average by +22%. The statistical significance of the changes in the mean between 1960-1990 and 2070-2099 is assessed by applying the *t*-test. At the 5% level, the changes are significant for the DMI, EGMAM and MPE models. This finding is similar to the 20% increase of the humidity flux found for the same period by Ricard et al. (2009) using a mesoscale dynamic model. If we considers only the two better models at reproducing seasonal FHUM during the reference period (the MPE and DMI models), the projected increase for 2070-2099 would be of +35%.

With the relationships established between the parameters λ_{ns} and FHUM (Table 4) it becomes possible to assess the future changes in the extreme rainfall distribution under the hypothesis that the relationships observed will be unchanged in the future. For all the catchments, the multi-model mean projected increase of FHUM in the fall (+22%), leads to an increase of the number of threshold exceedances. Over all the catchments, the mean number of events in fall during the reference period 1960-1990 is 2.55, whereas for the period 2070-2099 the mean number of events is 3.57. It is possible to compute quantiles for the periods 1960-1990 and 2070-2099 with a non-stationary λ_{ns} parameter, computed on a seasonal basis (Table 4). Figure 10 shows the box-plots of the 100-year quantiles in the Herault catchment, computed with the corrected FHUM from the different AOGCMs, for the reference period 1960-1990 and for the projection period 2070-2099. For all models, the quantiles computed for the period 2070-2099 are larger than the quantiles obtained for the period 1960-1990. On average for all catchments and model projections, the median of the quantiles is increased by 5% for 2070-2099 by comparison to the reference period 1960-1990. The whole distribution is shifted toward higher values, associated with an increase in the variability for some models. However, these changes are most certainly not significant since they remain within the range of the estimation uncertainties for the 100-year quantiles (Fig.7).

5 SUMMARY AND CONCLUSIONS

This study considered a non-stationary extreme value modelling for areal rainfall at the catchment scale, which is the relevant scale for most of hydrological applications. A peaks-over-threshold model for heavy rainfall events has been applied on six Mediterranean catchments, combining a Poisson distribution for the occurrence process and a GP distribution for the magnitude of the events. No temporal trends in the magnitude or in the occurrence of extreme daily areal precipitation can be observed in the selected catchments during the period 1958-2008. The introduction of a covariate describing the humidity flux from the Mediterranean Sea improves the modelling of the occurrence and the magnitude of extreme rainfall events, as indicated by the deviance test results. The Poisson distribution parameter, describing the seasonal number of events, can be related to the FHUM average in the fall season, while for the GP distribution daily FHUM variations appear to exert an influence on the events magnitude. The model parameters and the relationships obtained between the rate of occurrence of heavy rainfall events and FHUM are very similar in the different catchments. Therefore it could be worthwhile to include more catchments along the Mediterranean coast to see if a regional analysis could be undertaken to identify relationships at a regional scale between large scale humidity flux and the heavy rainfall event distributions.

With such a model it becomes possible to estimate the future changes in the distribution of heavy rainfall events, by the analysis of the future change of the values taken by the covariates. The outputs of 5 AOGCMs have been compared to analyze the possible changes in the humidity flux from the Mediterranean Sea between a reference period 1960-1990 and two projections period 2020-2050 and 2070-2099. No clear trends can be identified for the period 2020-2050 while for the period 2070-2099, despite large differences between the models, all of them project an increase in the humidity flux, in average by +22%. The relationships established in past climate records between the model parameters and FHUM can serve to estimate the future distribution of heavy rainfall events, under the hypothesis that these relationships will be conserved in the future climate. On average for all catchments, this upward trend found in the humidity flux leads to an increase of the seasonal number of precipitation events above the 95^{th} percentile. This change in occurrence has however limited impacts on the magnitude of extreme events, since the 100-year quantiles values are increased only by 5%.

In this paper, only the case where the seasonal number of events is dependent of one covariate was considered. Other non-stationary cases, with different types of dependences between model parameters and covariates, or the introduction of several different covariates in the model need to be tested to improve the relationships obtained. In particular, there is a need to identify and to test other potential covariates that could improve the modelling of the events magnitudes in the GP model. Climatic indexes or tele-connections could be considered to that end, in particular at smaller scales: regional climate models could provide meaningful covariates at less than 50 km resolution. In this study, only was considered an ensemble average of different climate model projections. Other approaches also exist and should be tested, taking into account model efficiency in reproducing the variable of interest, in order to weight the different projections. With the growing number of climate projections becoming available, there is no consensus yet on the best choice of metrics and diagnostics of performance (Tebaldi and Knutti, 2007). Coupling extreme value models with the appropriate explanatory climatic covariates (humidity fluxes, weather patterns etc.) provides means of physical interpretation of the extreme phenomenon's observed. Non-stationary extreme value models with climatic covariates can thus be useful tools to assess the future changes in the extreme rainfall distribution and quantiles, to be used for the design of engineering structures such as dams, reservoirs, and flood mitigation works.

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TABLES

Table 1: Selected catchments	Size (km²)	Number of rain gauges	Rain gauge density (Number/100km²)	95th percentile of areal rainfall (mm/d)
Herault	2585	45-71	1.74-2.74	31.5
Ardeche	2376	50-95	2.1-3.99	43.63
Gard	1996	40-81	2-4.05	36.91
Orb	1596	30-48	1.87-3	30.38
Ceze	1552	35-60	2.25-3.86	35.81
Vidourle	795	30-53	3.77-6.66	36.03

Table 2: AOGCMs selectedAcronym	Institution	Model	Spatial resolution (lat x lon)	Reference
CNRM	Centre National de Recherches Meteorologiques, CNRM-GAME, France	CNRM-CM3.3	2.8° x 2.8°	Salas-Mélia et al. 2005)
DMI	Danish Climate Centre, Danish Meteorological Institute, Denmark	DMIEH5C	3.6° x 3.6°	Roeckner et al. (2006)
EGMAM	Institute for Meteorology, Freie Universitat Berlin, Germany	EGMAM2	3.6° x 3.6°	Huebener et al. (2007)
HAD	Hadley Centre, Met Office, United Kingdom	HadCM3C	2.5° x 3.7°	Johns et al. (2003)
MPE	Max Planck Institute for Meteorology, Germany	MPEH5C	3.6° x 3.6°	Roeckner et al. (2006)

Table 3: Deviance score tests (in bold the significant scores at the 5% level)

Catchments	Deviance between P_0 and P_1 with mean FHUM during the fall season as covariate	Deviance between GP_0 and GP_1 with daily FHUM values as covariate
Herault	**10,14**	***11,46***
Ardeche	**13,99**	***5,78***
Gard	**13,69**	***4,42***
Orb	**13,3**	***21,73***
Ceze	**11,17**	***4,4***
Vidourle	**12,07**	0,45

Table 4: POT model parameters

Catchments	Poisson model parameters	GP model parameters	
	λ_{ns}	α	κ
Herault	exp(73.09FHUM-4.86)	30,4	0
Ardeche	exp(80.01FHUM-4.9)	27,86	0
Gard	exp(82.64FHUM-4.97)	26,83	0,05
Orb	exp(85.33FHUM-5.13)	29,75	0
Ceze	exp(78.35FHUM-4.95)	22,69	0,09
Vidourle	exp(86.36FHUM-5.2)	24,37	0,09

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Figure 1: Map of the selected catchments in southern France

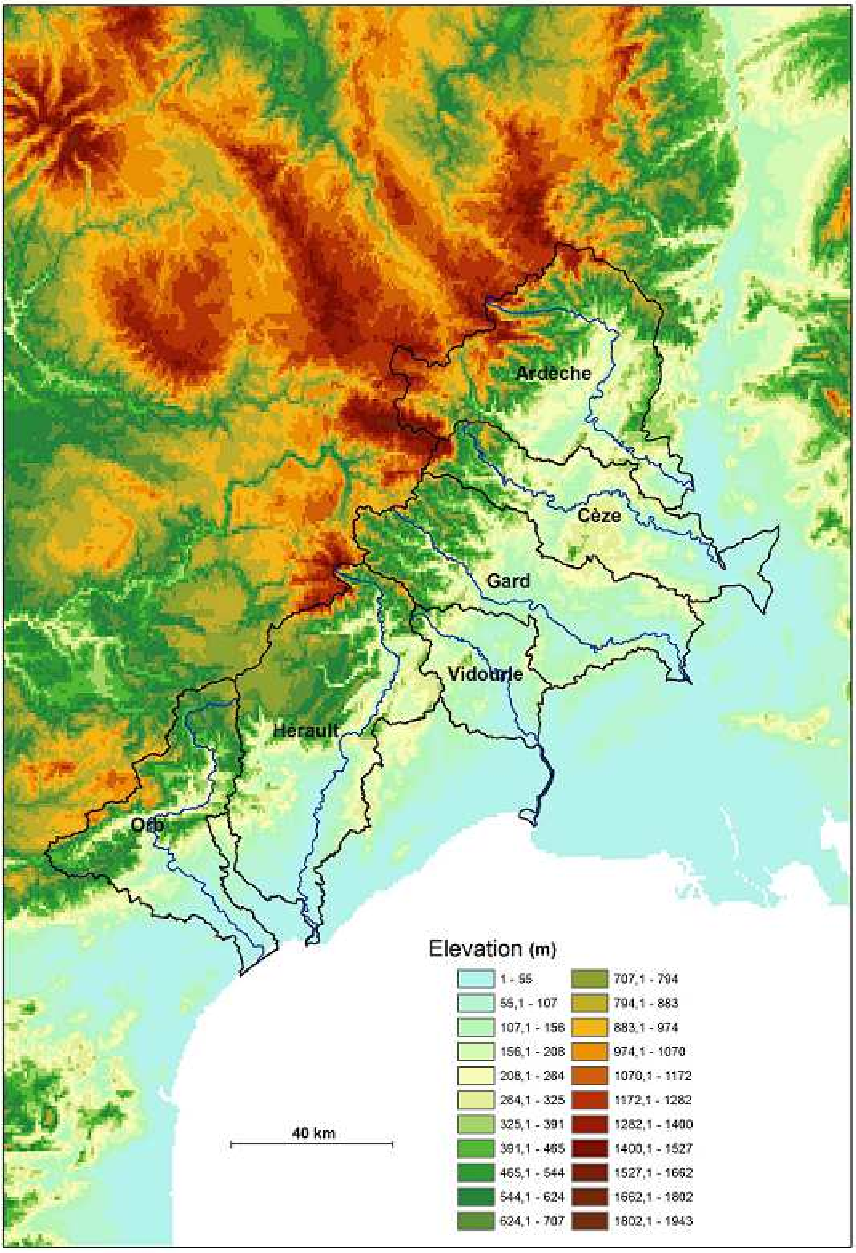

Figure 2: NCEP Grid cells (A, B, C, D) and rain gauge stations over the study area

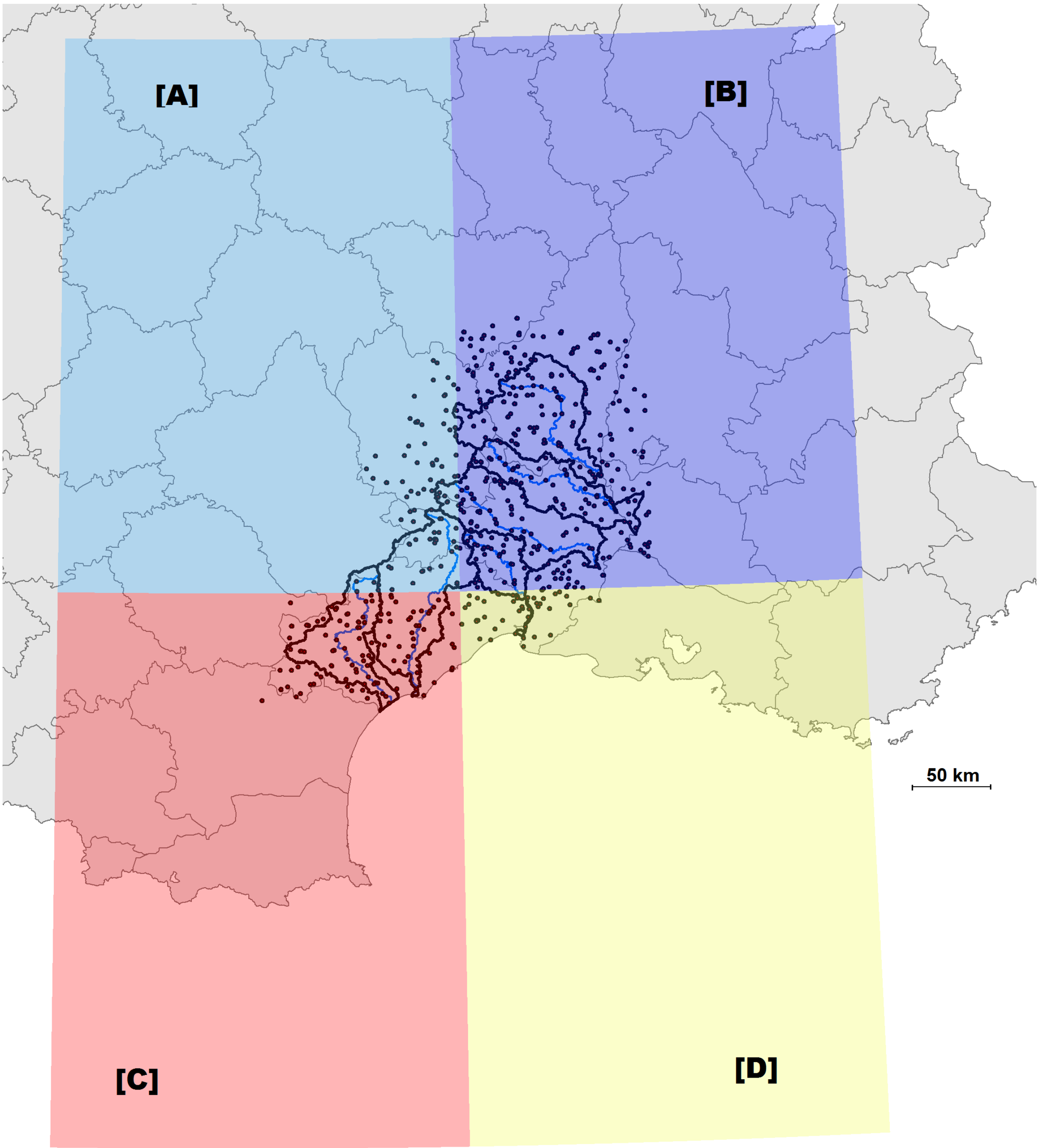

Figure 3: Selected rainfall events above the 95th percentile for each catchment during the period 1958-2008

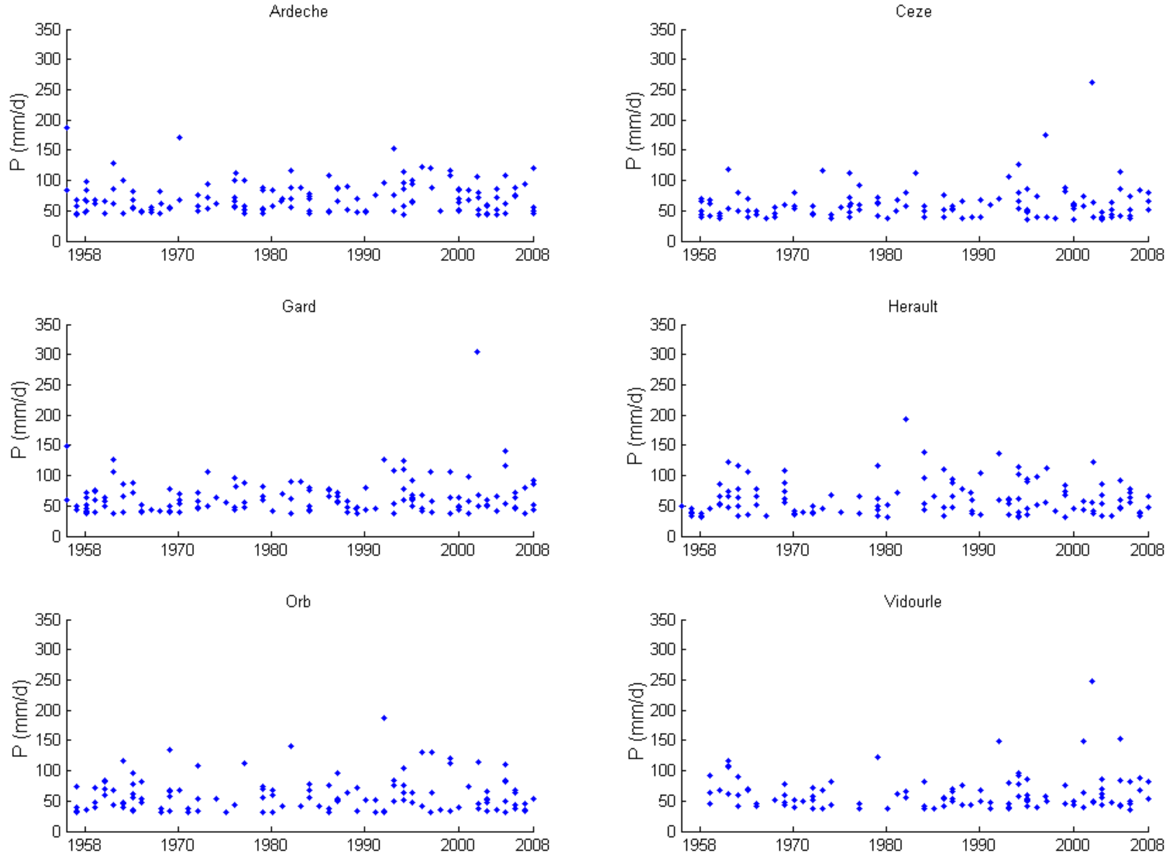

Figure 4: Occurrence of extreme precipitation events and mean FHUM (from NCEP) during the fall season for the Hérault catchment. The line represents the fitted relationship via MLE between the λ parameter.and FHUM seasonal values.

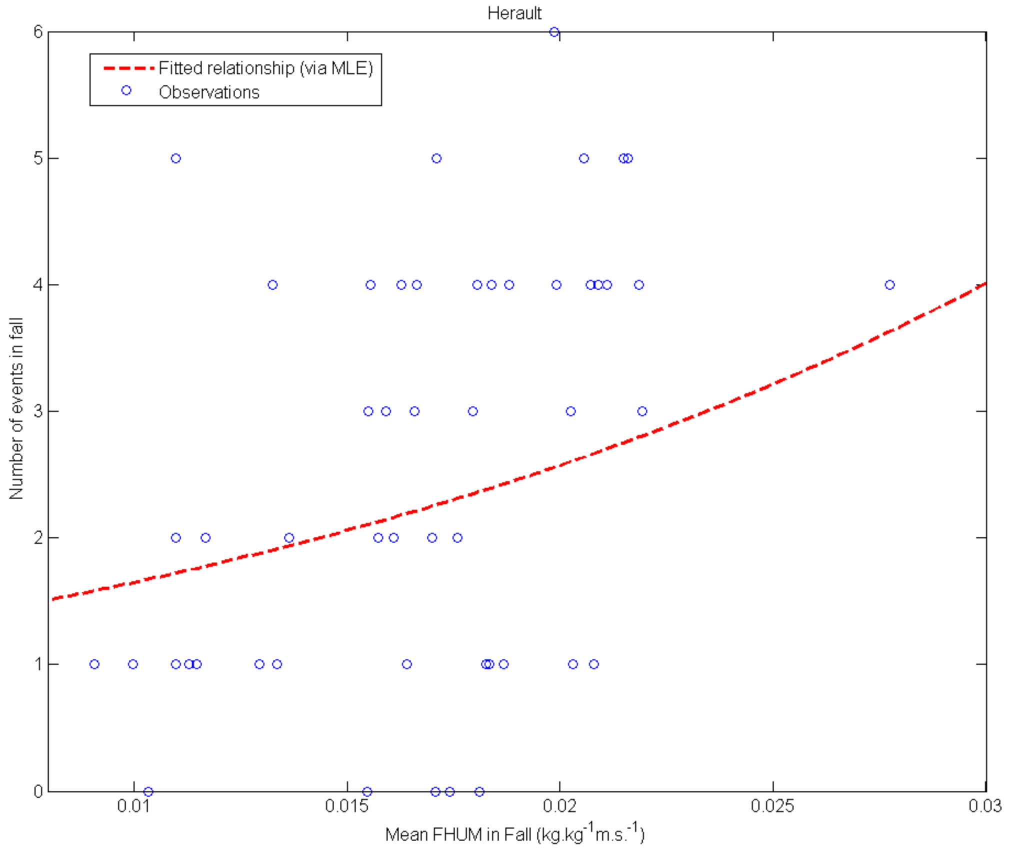

Figure 5: Daily magnitude of extreme precipitation events and FHUM (from NCEP) for the Hérault catchment. The line represents the fitted relationship via MLE between the scale parameter.and FHUM daily values.

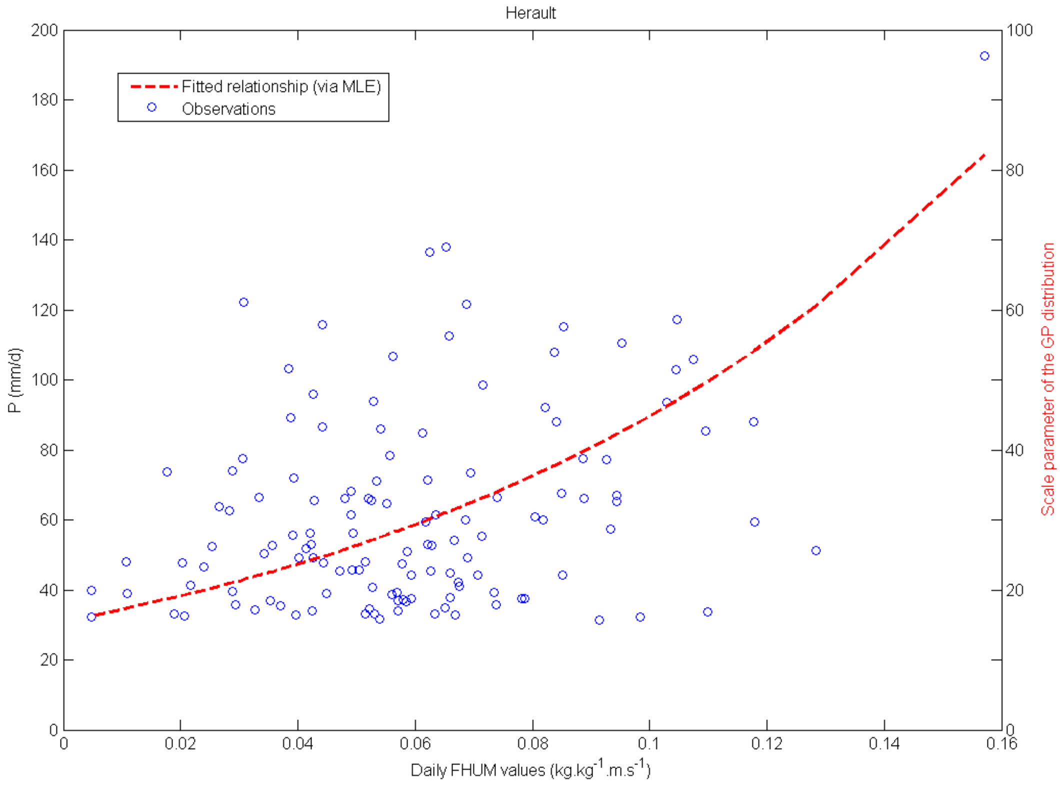

Figure 6: Quantile-quantile plots of the GP distribution fit to the exceedances of the 95th percentile in the 6 catchments

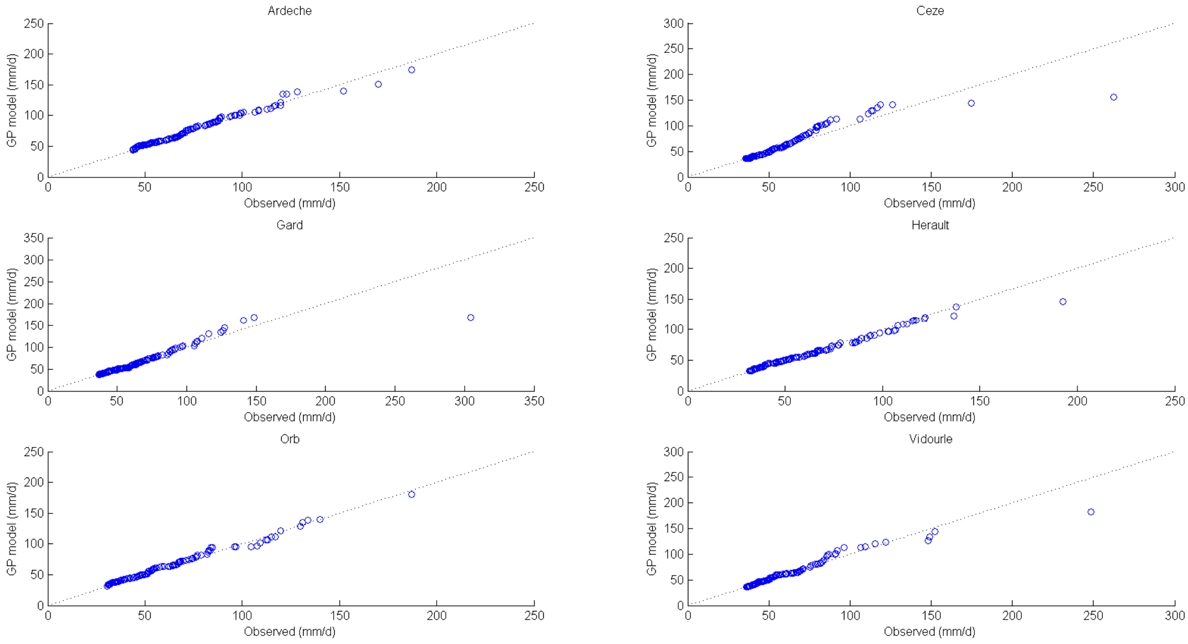

Figure 7: Non-stationary 100-year quantiles versus the stationary quantile for the Hérault catchment, with the 90% confidence intervals obtained by boostrap.

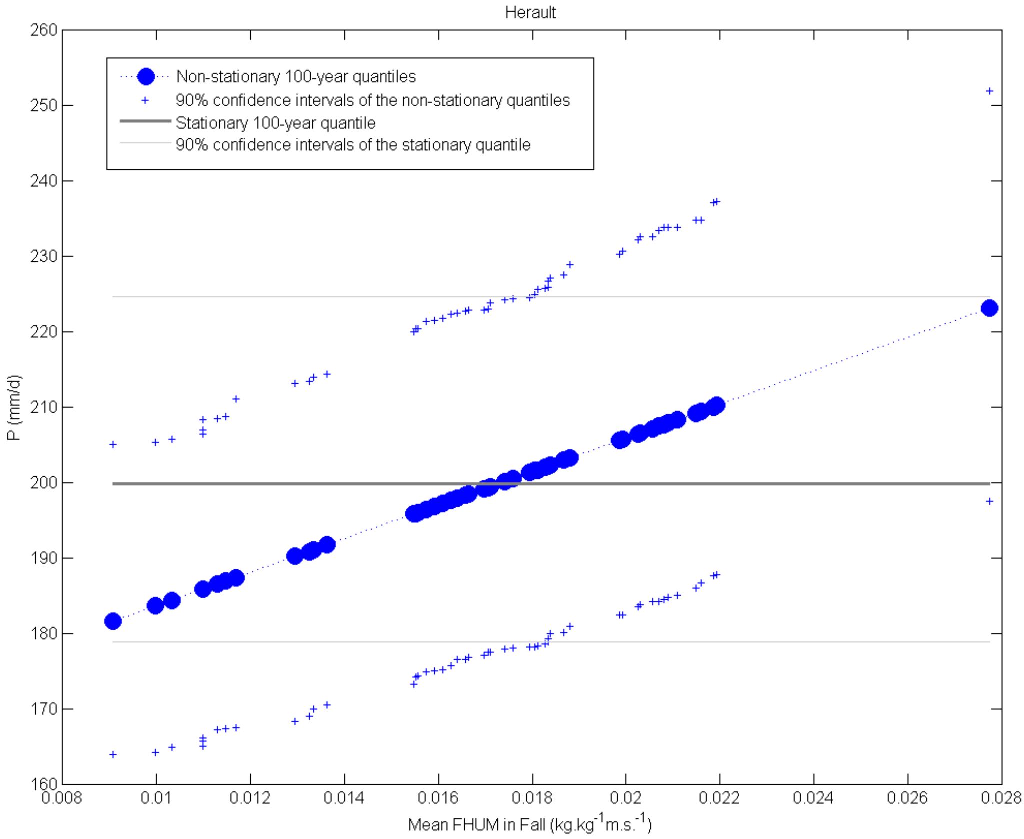

Figure 8: Quantile-quantile plots comparing the original and corrected distributions of FHUM computed from the 5 AOGCMs with FHUM computed from NCEP reanalysis for the fall season.

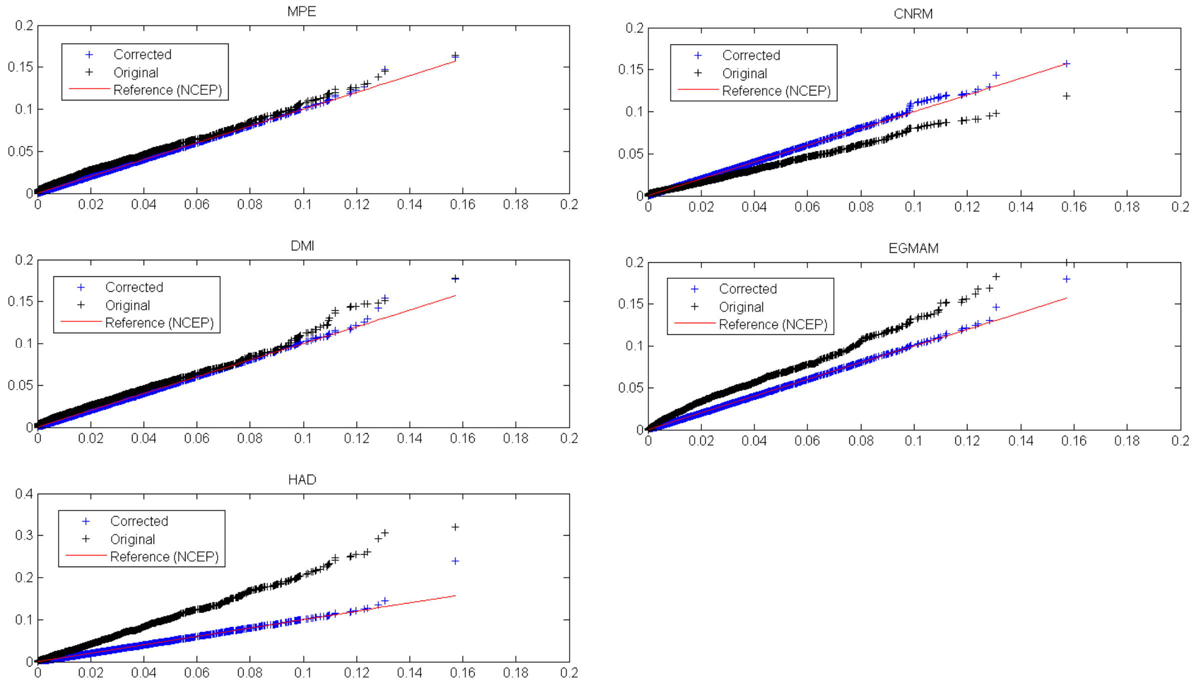

Figure 9: Relative changes of FHUM in fall between the reference period 1960-1990 and the two future periods 2020-2050 and 2070-2099 computed by the different AOGCMs

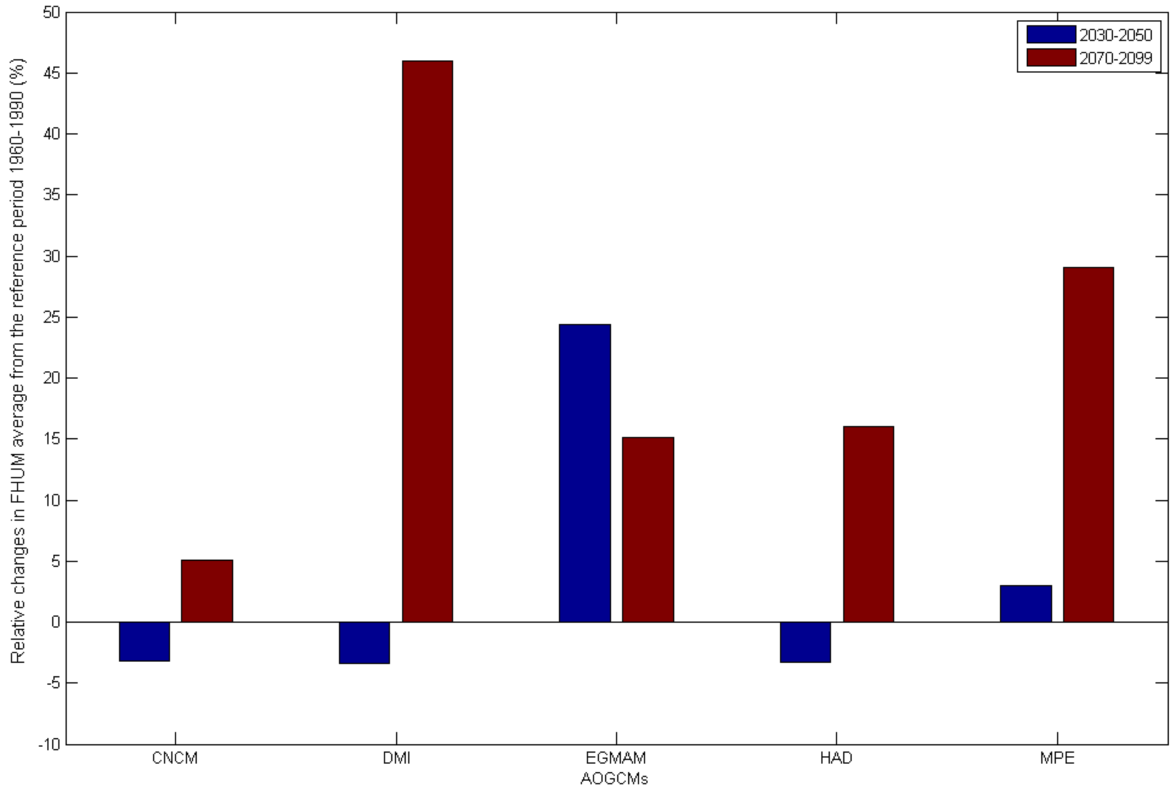

Figure 10: Quantiles corresponding to a 100-year return period in the Hérault catchment, computed with FHUM from the 5 AOGCMs during the periods 1960-1990 and 2070-2099. The boxes have lines at the lower quartile, median, and upper quartile values, the whiskers extend from each end to the most extreme values. The different colors indicate the different AOGCMs.