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Statistical comparison of observed temperature and rainfall extremes with climate model outputs

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The use of climate models as a decision tool

- There is an increasing demand for 21st century predictions of the climate on a regional scale, fuelled by concerns about the impact of climate change on water resources.
- Climate models are considered as sophisticated tools able to simulate climatic conditions, not only regarding the future, but also the past and the present (Randall et al., 2007). Despite their extensive use, predictions of future climate based on General Circulation Models (GCMs) continue to be debatable and raise considerable controversies on the argument that their verifiability cannot be proven at the moment.
- Studies which address these subjects are largely based on the performance and the projections of the GCMs for the 21th century, whose utility has shifted from general mitigation policies to site and case-specific water management decisions and hydrological applications (Kundzewicz & Stakhiv, 2010). Extreme events such as floods and heat waves have displaced the interest of climate models evaluation from monthly and annual mean values to daily time series evaluation (Frich et al., 2002; Alexander et al., 2006).
- These potential extended uses demand a great level of accuracy at finer spatial and temporal scales, which is not currently possessed by GCMs. It is generally questionable whether the general circulation models, which are aimed to reproduce the main climatic features at broad scales, can be adapted to meet these demands.

The Mediterranean: a hot spot of climate change

Amongst all regions, the Mediterranean area is regarded as one of the hot spots of climate change (Giorgi, 2006; Diffenbaugh et al., 2007) that is expected to suffer from more intense extreme events.

Mediterranean water resources in a global change scenario

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Mediterranean areas of both southern Europe and North Africa are subject to dramatic changes that will affect the sustainability, quantity, quality, and management of water resources. Most climate models forecast an increase in temperature and a decrease in precipitation at the end of the 21st century. This will enhance stress on natural forests and shrubs, and will result in more water consumption, evapotranspiration, and probably interception, ... nspiration, ... ons will be

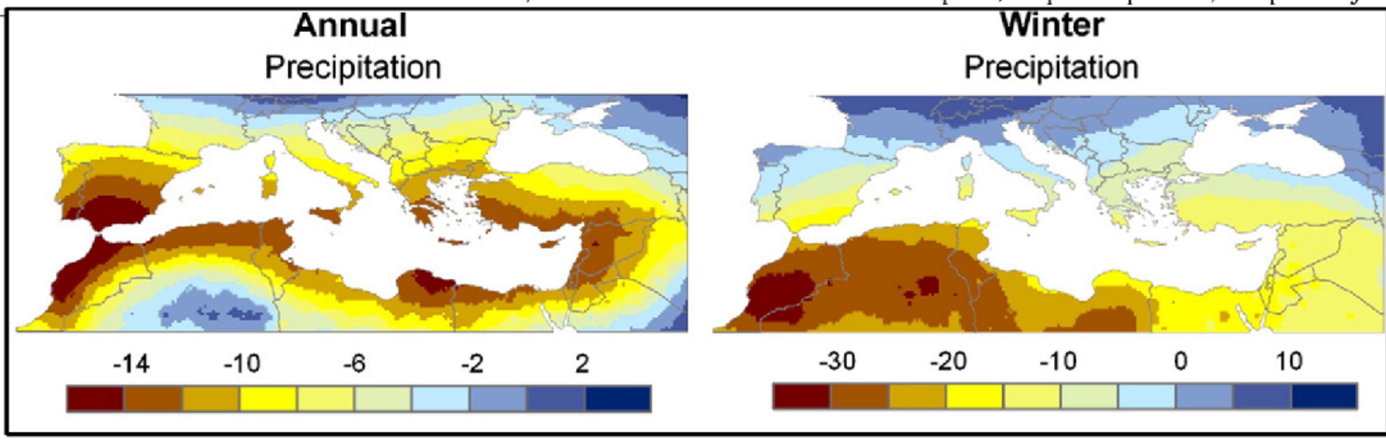


Fig. 1: The predictions of climate models are extensively used as a basis for the evaluation of the impact of climate change on water resources. In this example publication, Garcia-Ruiz et al. (2011) utilize the outcome of model projections in the Mediterranean region in order to assess the subsequent changes in water resources and ecosystems. The abstract of the publication is shown, along with a figure depicting mean annual and winter precipitation changes (P, %) projected for the Mediterranean region between 2040-2070 in comparison to 1960–1990 by nine general circulation models.

Stations used for the point analysis

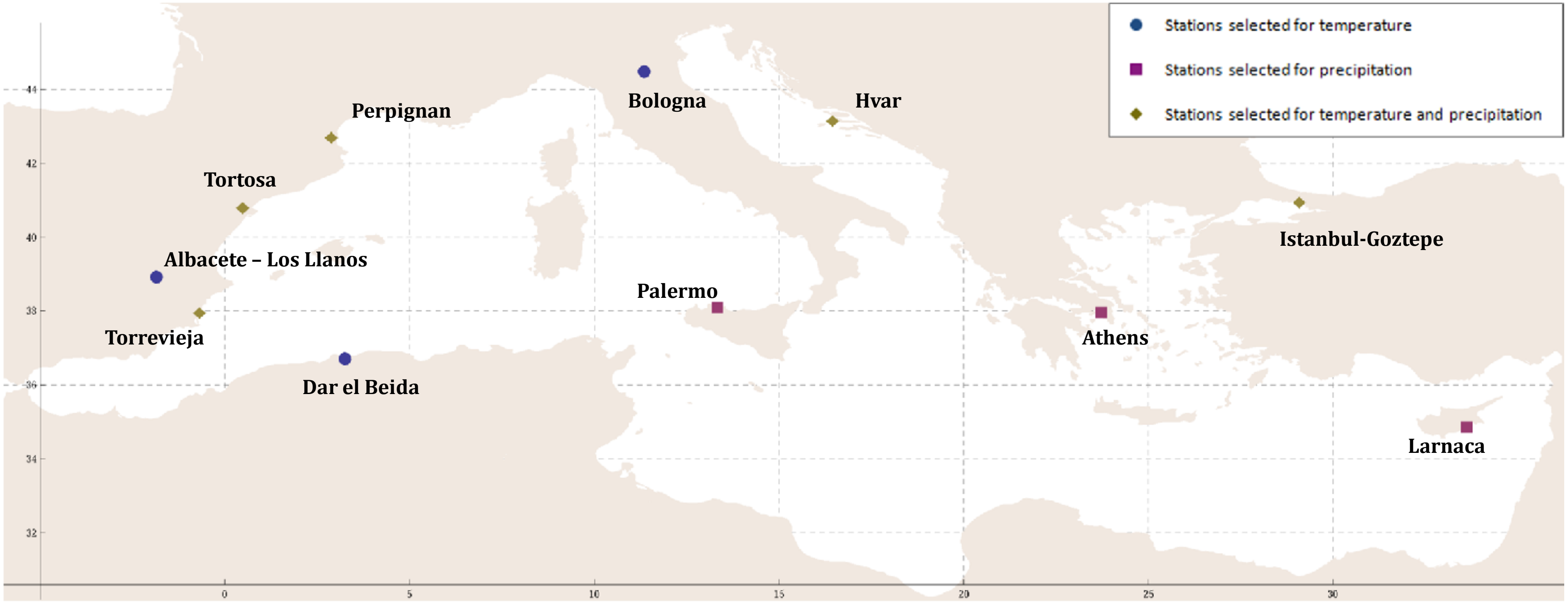


Table 1: Meteorological stations used in the analysis

Stations	Country	Coordinates - Elevation	Precipitation		Temperature	
			Years of data	Time span	Years of data	Time span
Albacete - Los Llanos	Spain	38.95N, -1.85E, 704m	-	-	105	1901-2010
Athens	Greece	37.58N, 23.43E, 95m	111	1900-2010	-	-
Bologna	Italy	44.50N, 11.35E, 53m	-	-	194	1814-2007
Dar el Beida	Algeria	36.72N, 3.25E, 25m	-	-	71	1940-2010
Hvar	Croatia	43.17N, 16.45E, 20m	111	1900-2010	75	1930-2008
Istanbul-Goztepe	Turkey	40.97N, 29.08E, 33m	77	1929-2004	75	1929-2003
Larnaca	Cyprus	34.88N, 33.63E, 1m	94	1916-2009	-	-
Palermo	Italy	38.11N, 13.35E, 37m	157	1852-2008	-	-
Perpignan	France	42.73N, 2.87E, 43m	99	1901-1999	108	1901-2010
Torrevieja	Spain	37.97N, -0.70E, 1m	73	1927-1999	73	1927-1999
Tortosa	Spain	40.82N, 0.48E, 48m	89	1910-1999	70	1941-2010

The stations were selected based on the following criteria:

- Time series longer than 70 years, having as few missing data as possible
- Raw data without having been subjected to modifications
- Even geographical distribution
- Availability of data on the internet

Sources: http://climexp.knmi.nl/ and National Observatory of Athens

Selection of climate models

Three AR4 models have been selected (CGCM3, ECHAM5, CSIRO), based on the following criteria:
- Coverage of past periods with adequate length of time series
- Availability of daily temperature and precipitation data on the internet

Regarding the simulation runs, the past period up to 2000 was covered by the 20C3M scenario, which spans from the mid-19th to the end of the 20th century. The first decade of the 21st century could not be covered by 20C3M, so outputs for the SRES A2 scenario were chosen instead. The SRES scenarios depend on assumptions on population growth, economic development and technological changes, and they are initialized from the end of the 20C3M scenario.

Table 2: Climate models and scenarios used in the analysis

IPCC Report	Name	Developed by	Resolution (°) in latitude and longitude	Grid Points, latitude x longitude	Years	Scenarios used	
						20C3M	SRES A2
AR4	ECHAM5	Max-Planck Institute for meteorology & Deutsches Klimarechenzentrum	1.9 x1.9	96x192	1860-2000	✓	×
AR4	CSIRO	Australia's Commonwealth Scientific and Industrial Research Organisation	1.9 x1.9	96x192	1871-2010	✓	✓
AR4	CGCM3-T63	Canadian Centre for Climate Modelling and Analysis	2.81 X 2.81	64x128	1850-2010	✓	✓

Sources: http://www.cccma.ec.gc.ca/cgi-bin/data/cgcm3/cgcm3_a2 and https://esg.llnl.gov:8443/index.jsp
Acknowledgement: The NetCDF files were handled using the Unidata/UCAR software

Interpolation of climate model outputs for point comparison

- In order to compare the observed time series with the climate model outputs, the four grid points closest to the station of interest were interpolated.
- The Best Linear Unbiased Estimation technique (BLUE) has been successfully used in previous analyses (e.g. Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010). However, it is suitable only for large time scales (monthly and beyond). Specifically, it fails to aggregate the daily gridded time series and smooths out the extreme values.
- A non-linear transformation was thus introduced in order to generate the model interpolated time series, by optimizing its coefficients. The transformed time series for each grid point is:

$$y_i = (a + x_i)^c \qquad (1)$$

where x_i are the climate model outputs for the four nearest grid points, and α, c are non-negative coefficients.

The transformation is used with the BLUE interpolator:

$$\tilde{y} = \sum_{i=1}^{4} \lambda_i \cdot y_i \qquad (2)$$

where λ_i are weighting coefficients , non-negative for physical consistency and $\lambda_1+\lambda_2+\lambda_3+\lambda_4=1$ for unbiasedness.

Combining the two equations we obtain:

$$\tilde{x} = y^{-1} = \left(\sum_{i=1}^{4} \lambda_i \cdot (a + x_i)^c\right)^{1/c} - a \qquad (3)$$

where $\tilde{x}$ is the optimized model interpolated time series of the daily values.

Optimization was implemented by minimizing the error function

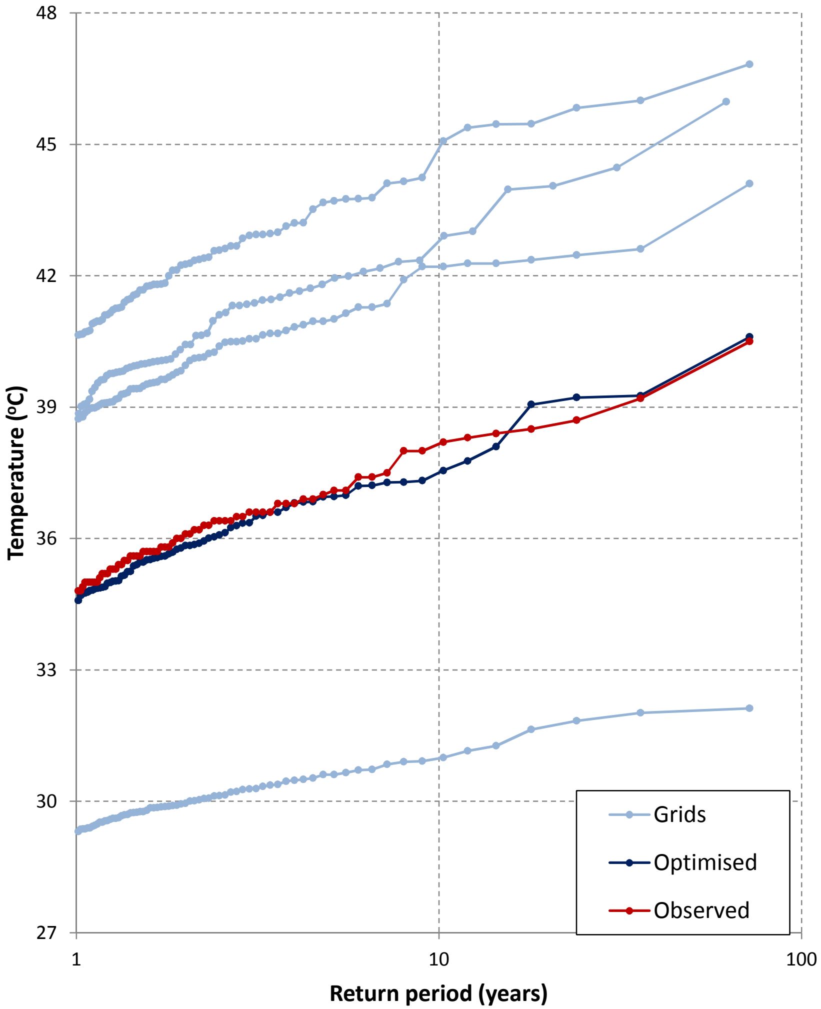
$$Er = e^2 + (e_m^2 + e_s^2) \cdot q \qquad (4)$$

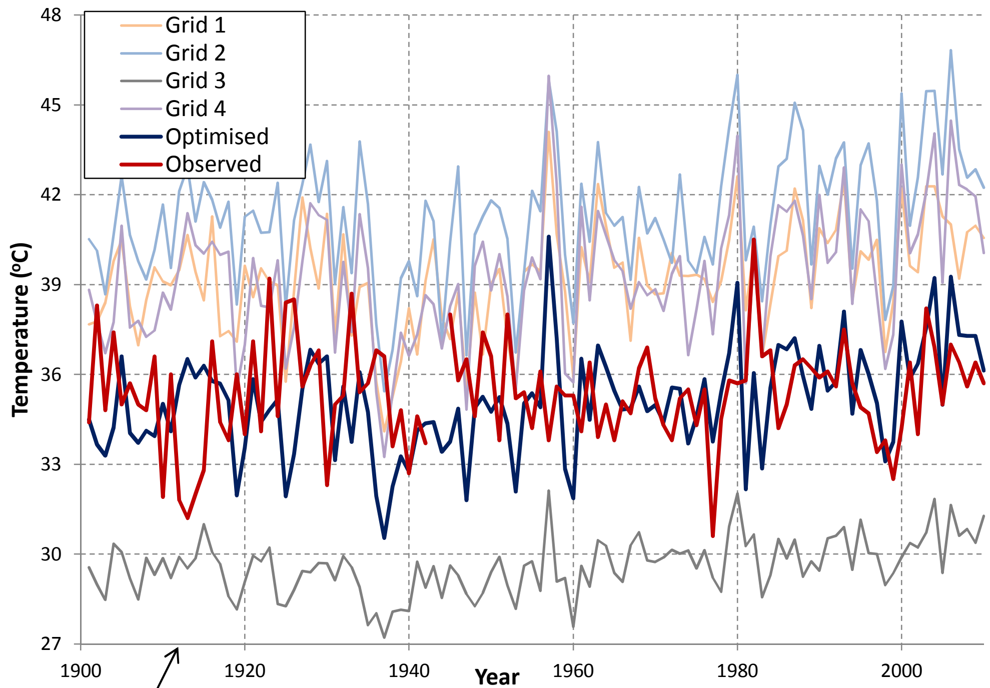
where e^2 is the mean square error in prediction, and e_m and e_s are the errors in prediction of mean value and standard deviation, respectively. We penalize the difference from mean value and standard deviation by multiplying with a large number (q); in our study we consider q = 1000.

Justification of the methodology (1)

The employment of this method allows the modelled time series to fit the historical ones as closely as possible, whereas other common methods of spatial interpolation with fixed weights produced larger errors and smaller efficiencies on the broad scales of the GCM grids (Koutsoyiannis et al., 2008).

Annual maximum daily high temperature at Perpignan station for the CSIRO model





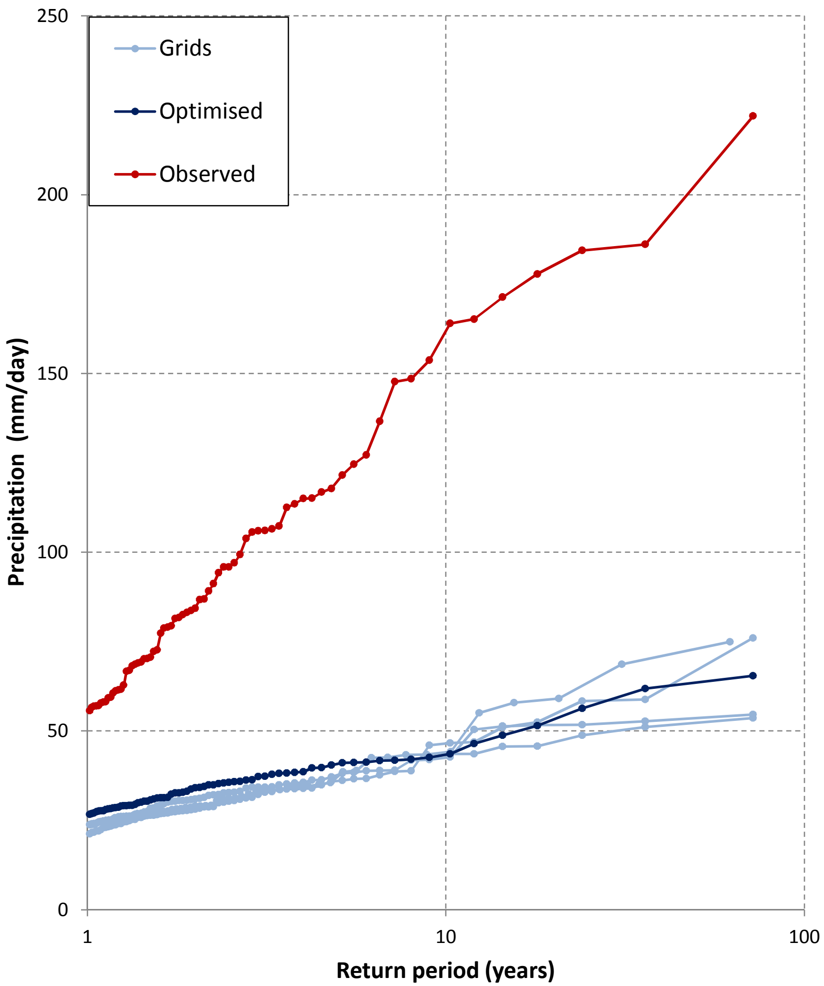
Observed, simulated at nearest 4 GCM grid points, and interpolated (at the station location), annual daily maximum temperature time series.

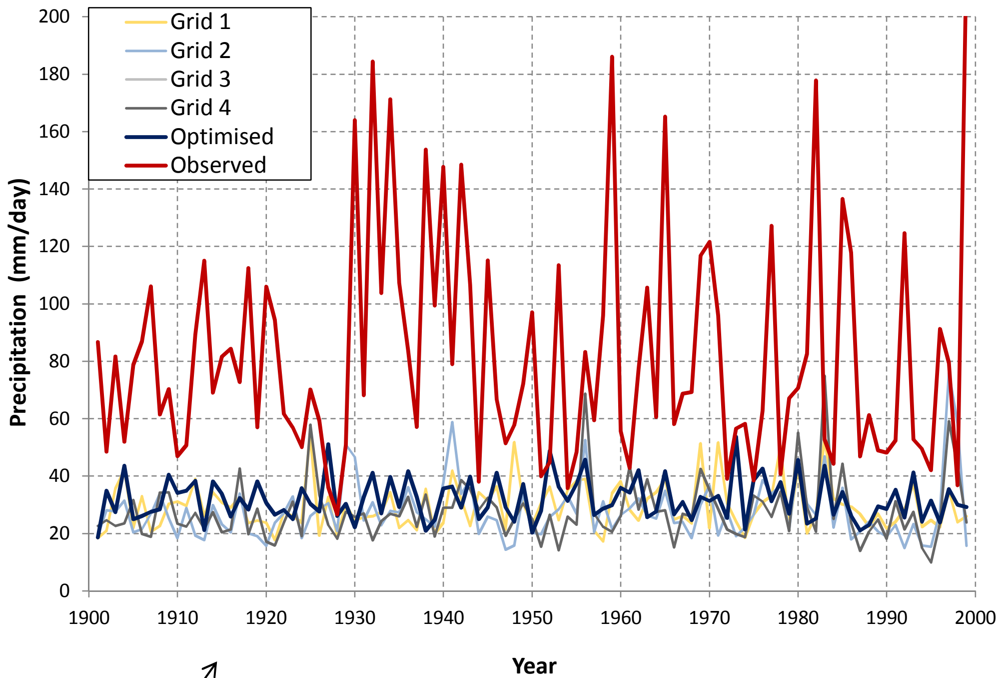
Empirical distribution of observed, simulated at grid points and interpolated time series.

Justification of the methodology (2)

While the methodology is the same in both variables, decent fitting cannot be achieved in precipitation, due to the systematic underestimation of extreme daily rainfall from all models, which is apparent in the gridded data. Consequently, the results of the optimization in that case will still diverge, regardless of the transformation.

Annual maximum daily precipitation at Perpignan station for the CSIRO model

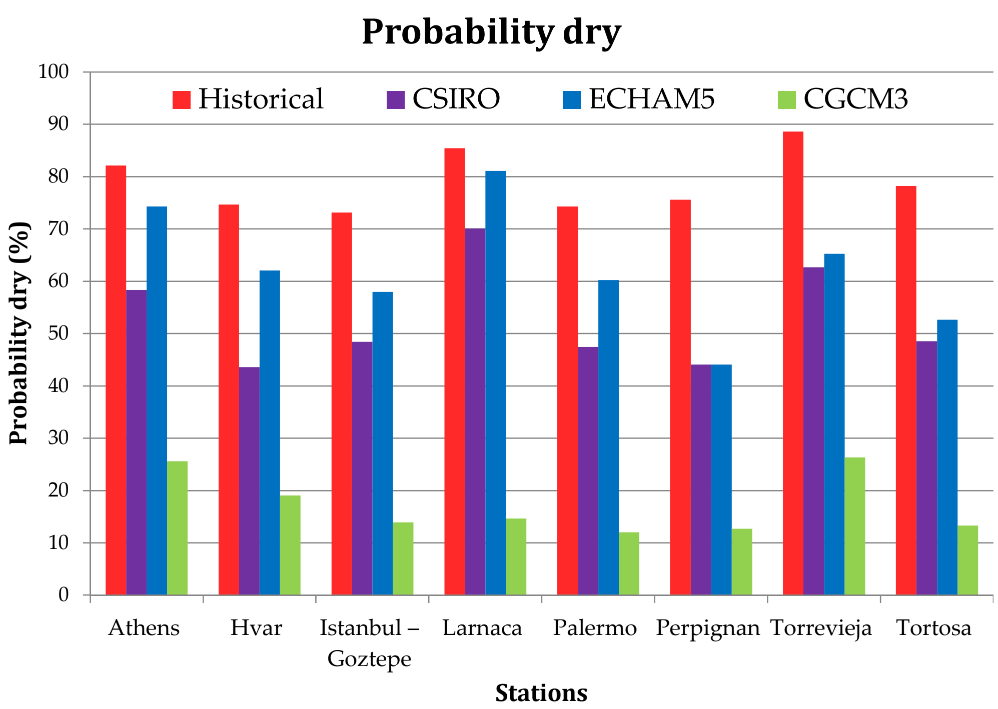




Observed, simulated at nearest 4 GCM grid points, and interpolated (at the station location), annual daily maximum precipitation time series.

Empirical distribution of observed, simulated at grid points and interpolated time series.

Statistical indices of observed time series



- Assuming a rainfall depth threshold of 0.1 mm/day, the probability dry of observed and modelled time series was calculated, which allows the inter-comparison of rainfall frequency among the three models, as well as a comparison with reality.
- It can be easily observed that all models significantly underestimate the probability dry for the period of study. The wet days appear to be much more frequent than the ones observed in reality.
- Out of the three models, ECHAM5 has the least rainfall intensity underestimation (reducing the actual probability by appox. 33% on average).
- CGCM3 has the poorest performance, with an average reduction of probability dry by 78%.

	Daily time series						Annual maximum time series					
	Correlation Coefficient			Efficiency Coefficient			Correlation Coefficient			Efficiency Coefficient		
	CSIRO	ECHAM5	CGCM3	CSIRO	ECHAM5	CGCM3	CSIRO	ECHAM5	CGCM3	CSIRO	ECHAM5	CGCM3
Temperature	0.797	0.741	0.801	-7.380	-57.378	-13.176	0.069	0.023	0.039	-1.389	-42.961	-3.467
Precipitation	0.040	0.030	0.030	-0.203	-0.241	-0.145	-0.025	-0.018	0.064	-2.224	-1.895	-2.661

The performance of the GCMs, quantified by the correlation and efficiency of coefficients*, is poor. The only exception is the satisfactory correlation of daily temperatures, which indicates that the models capture the annual seasonality of the temperature variation (but not that of rainfall). It is obvious from the quantitative results that the climate models cannot reproduce the historical time sequence of events. Therefore, even though their nature is deterministic, their functionality could be paralleled to a random number generator , which retains (as will be seen next) only some of the statistical characteristics of the observed temperatures.

* The correlation and efficiency coefficients are the averages of all the stations.

Comparison of empirical distribution with distributions of maxima

We fit distribution functions of maxima to the daily annual maximum observed data. The following distributions are used:

• **Generalized extreme value distribution** (GEV)

$$\mathrm{H}(x) = e^{-\left(1+\frac{\kappa \cdot x}{\lambda}-\kappa\cdot\psi\right)^{-1/\kappa}} \qquad \kappa\cdot x \geq \kappa\cdot\lambda\cdot\psi-\lambda$$

where κ, ψ, λ are shape, location and scale parameters, respectively.

• **Gumbel distribution** is the special case of GEV with $\kappa = 0$.

$$\mathrm{H}(x) = e^{-e^{-\left(\frac{x}{\lambda}-\psi\right)}} \qquad -\infty < x < \infty$$

• **Fréchet distribution** is the special case of GEV with $\kappa\,\psi = 1$

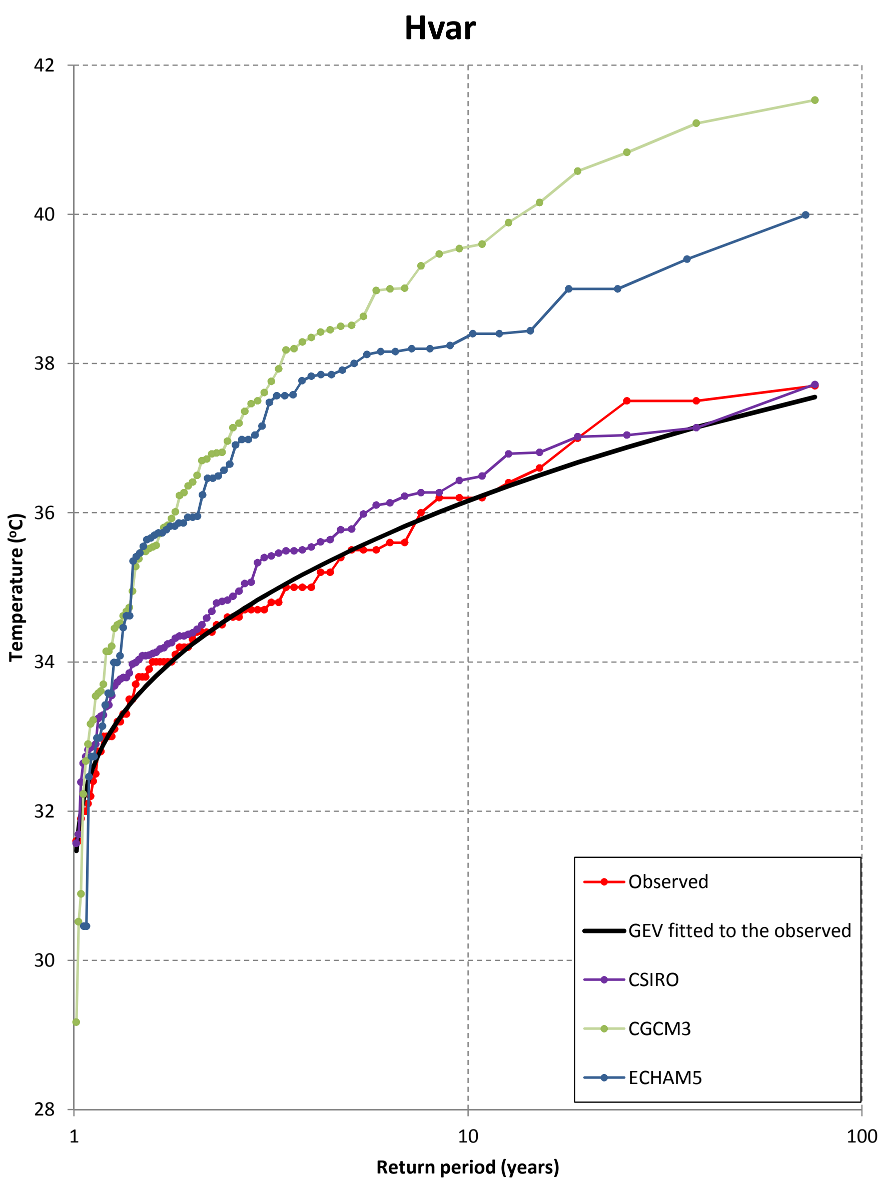
$$H(x) = e^{-\left(\frac{\kappa\cdot x}{\lambda}\right)^{1/\kappa}} \qquad x \geq 0$$

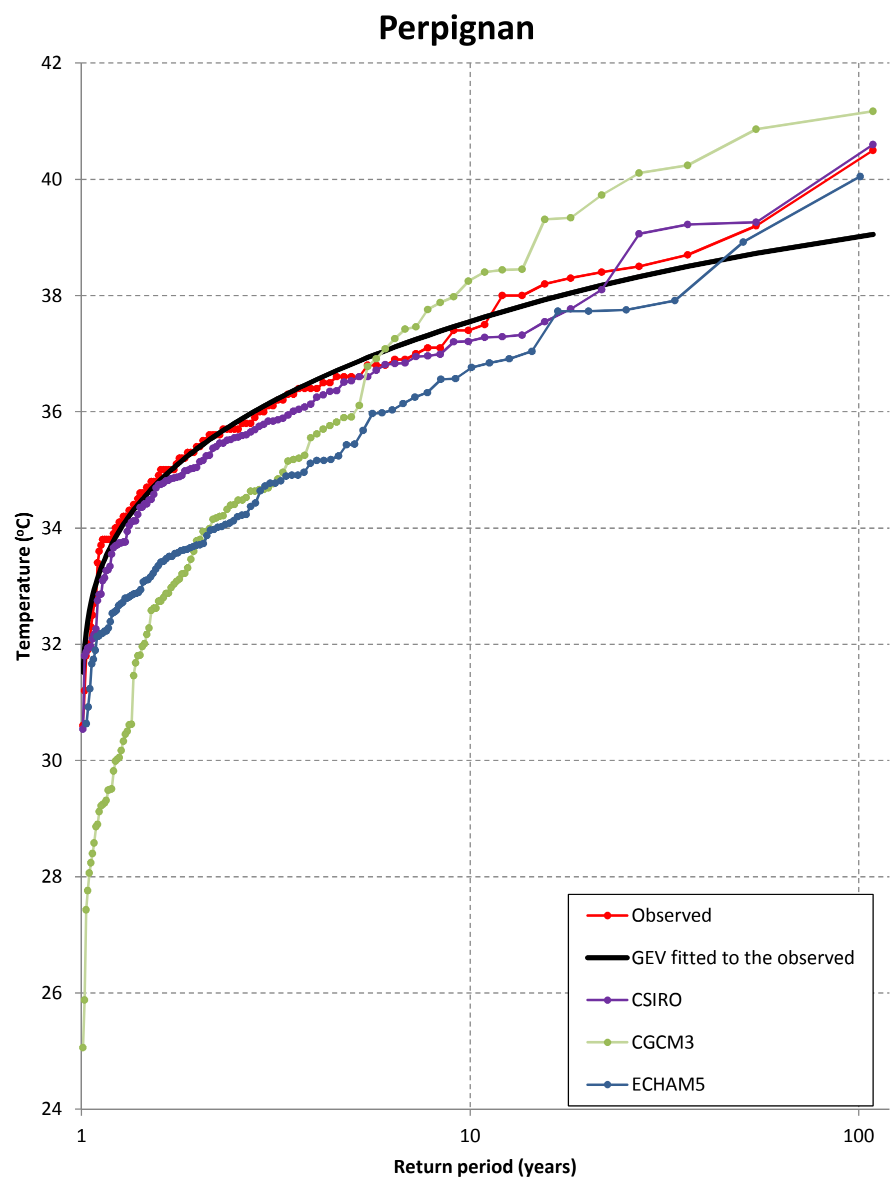
• Koutsoyiannis (2004) proposes the use of the GEV distribution as an alternative closer to reality, especially for large return periods (T >50 years). Our analysis confirmed that GEV distribution with 3 parameters fits the data better, even though we have few data values with T > 50 years.

• The GEV parameters are estimated using L-Moments, since the most important parameter is κ, which determines the behaviour of the distribution tail.

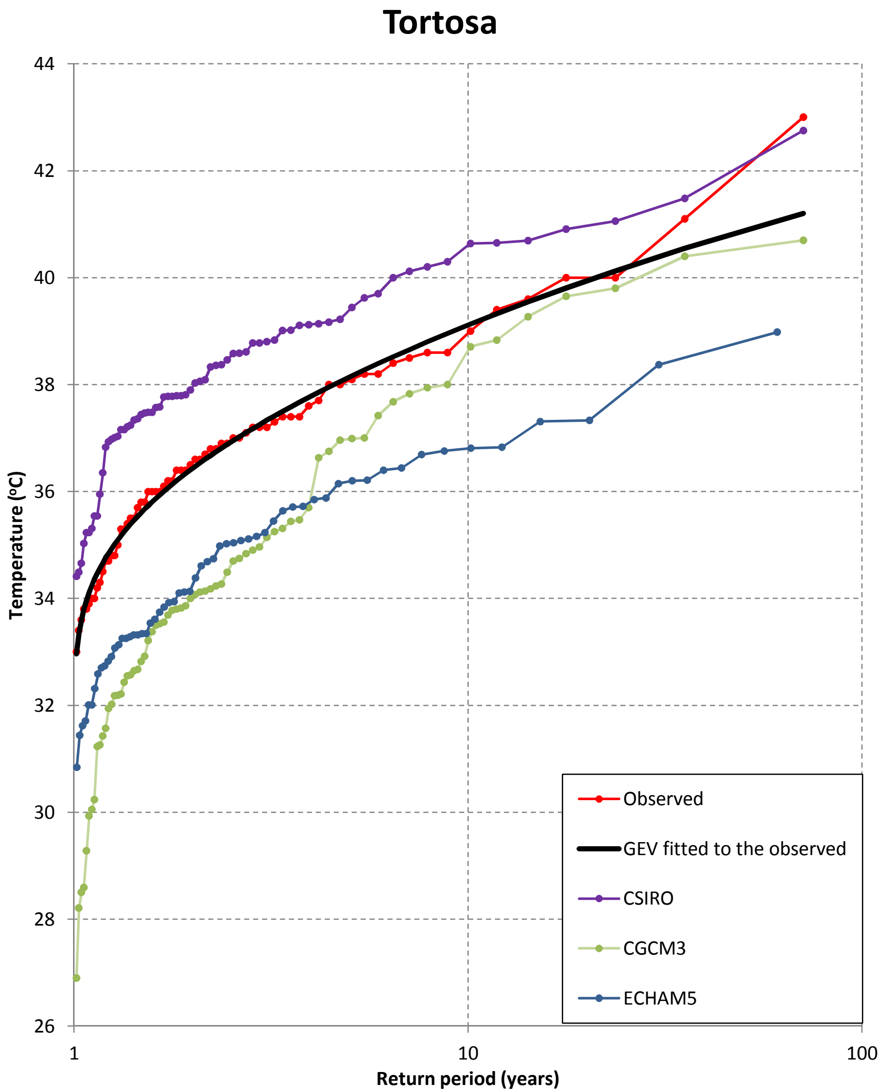
Acknowledgement: The parameters in each distribution were estimated with the Hydrognomon software. (www.hydrognomon.org)

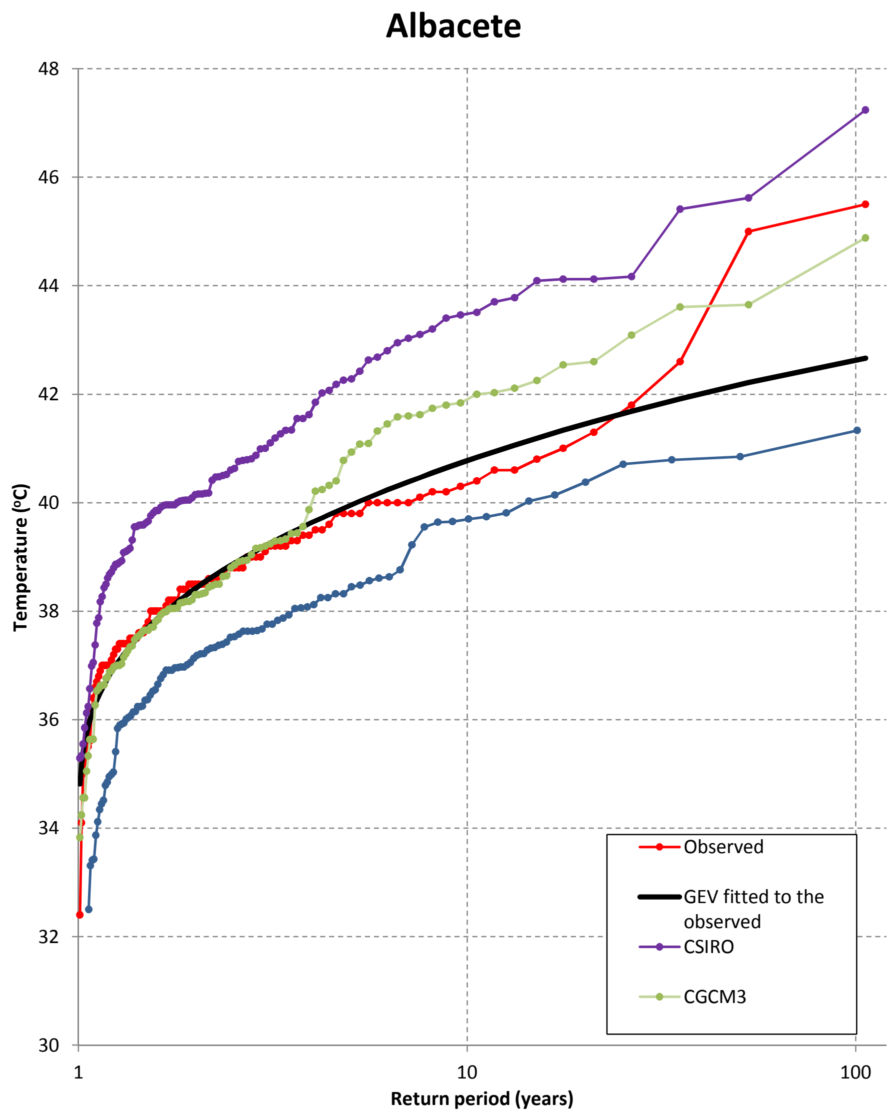
Annual maximum temperature (1)





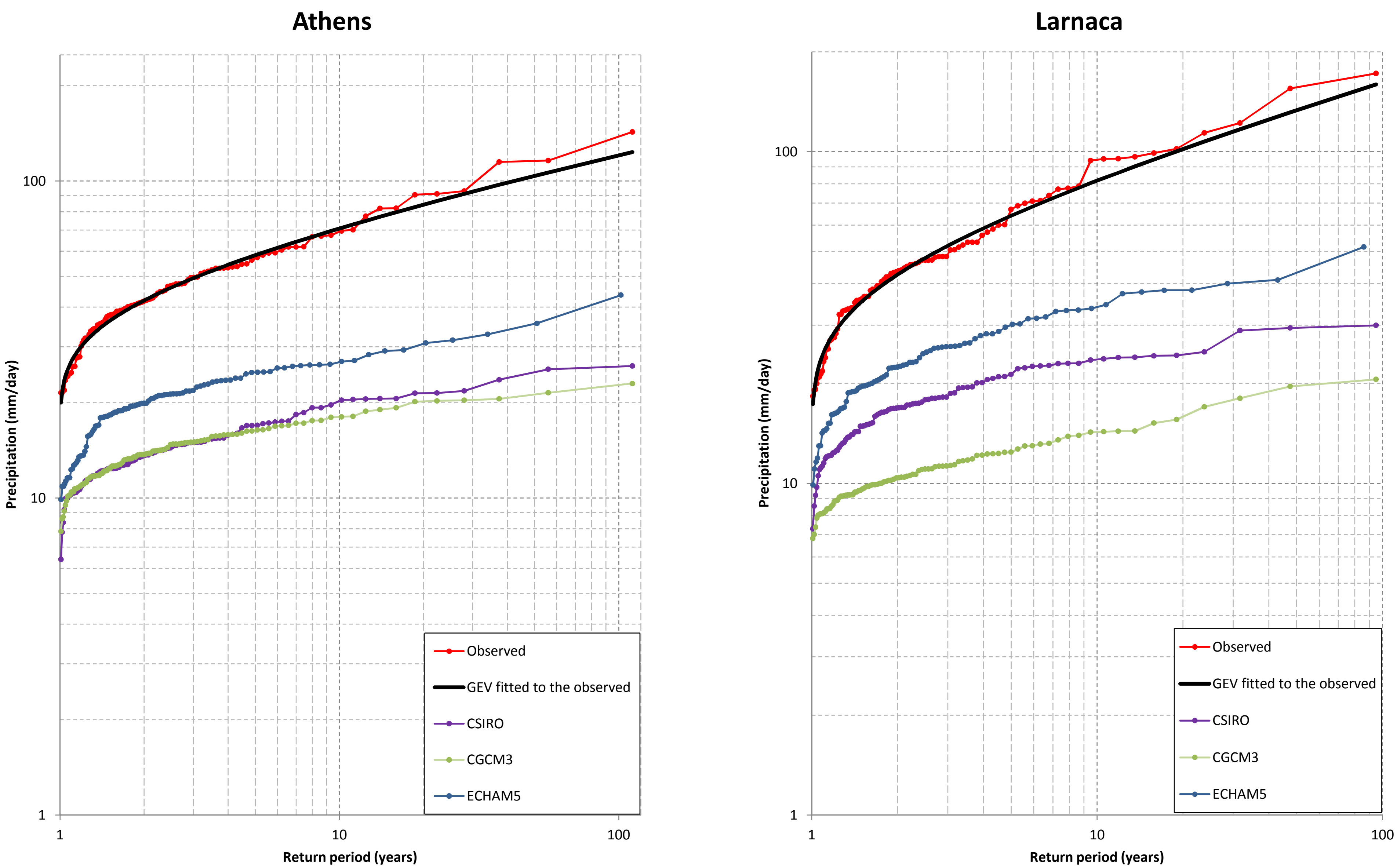
Annual maximum temperature (2)



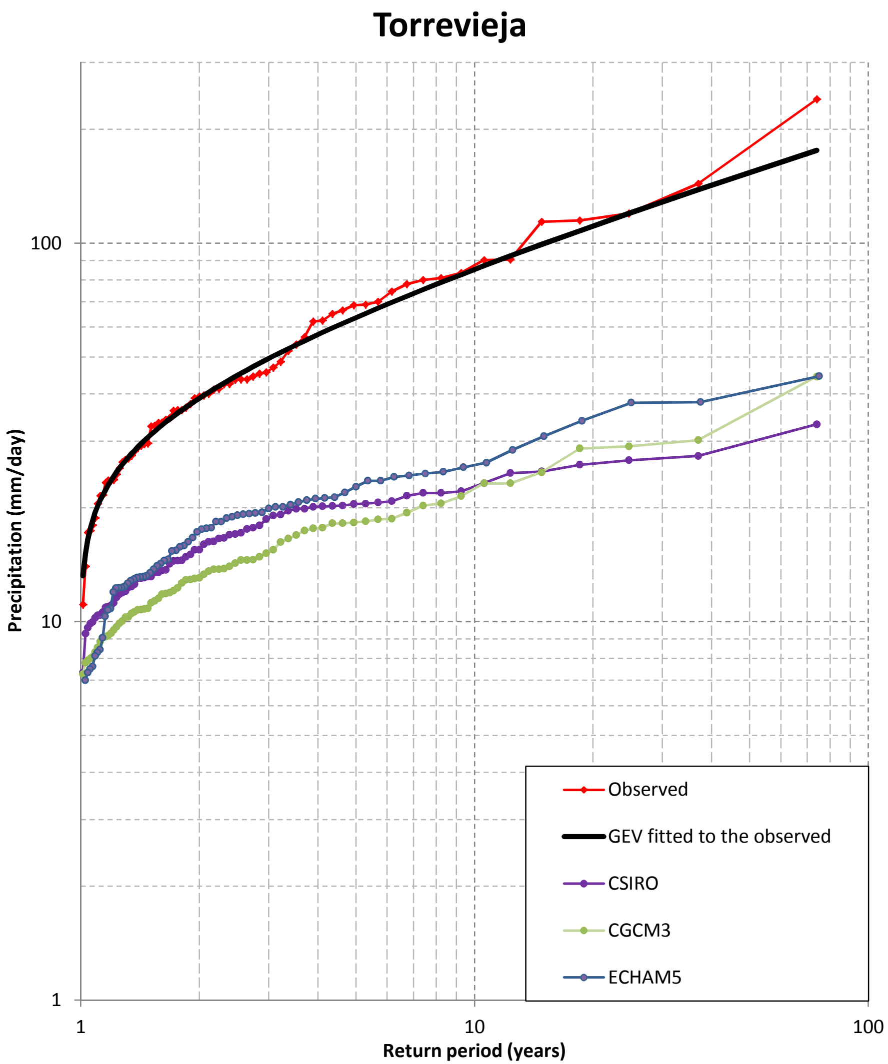


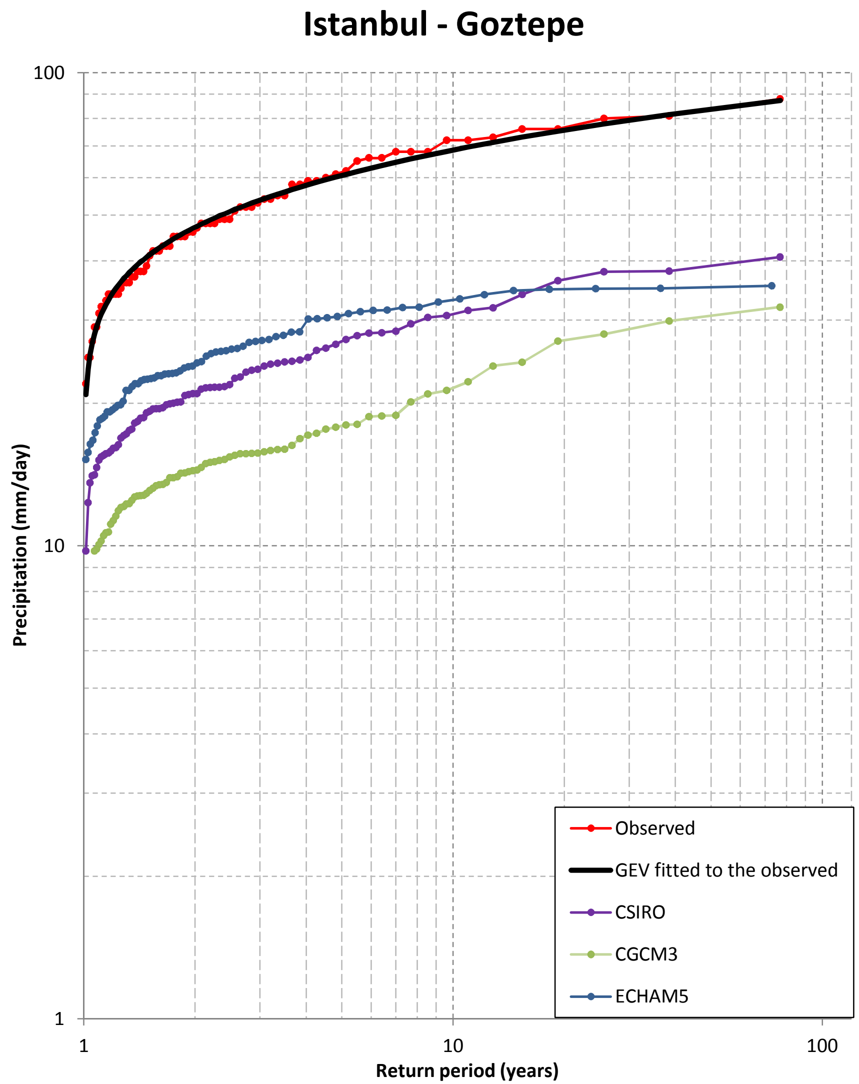
The overall performance of the GCMs is decent, even though the annual daily maximum temperatures vary and there are remarkable differences between the inter-comparison of climate models.

Annual maximum precipitation (1)



Annual maximum precipitation (2)

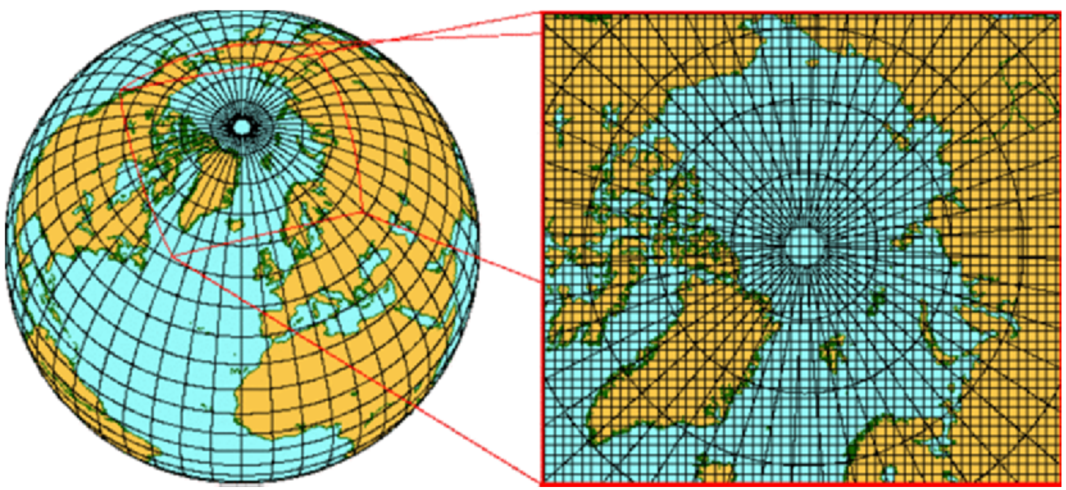




The GCM performance regarding the rainfall extremes is poor in all cases. The rainfall intensity is strongly underestimated. We also observe that the GEV distribution successfully fits the observed data in both variables.

Modelling challenges and alternative approaches

- The issue of discrepancy between observed and modelled rainfall is well-known in the climate modeling community, and has been dealt with a plethora of dynamical and statistical downscaling techniques with mixed results (e.g. Giorgi and Mearns, 1991, Kidson and Thompson, 1997, Tolika et al., 2008). Model extensions with finer computational grids have been utilized (Regional models – RCMs), and even more trendy approaches such as neural networks (Crane & Hewitson, 1998) have been employed as refined modeling strategies.
- However, one should note that, even if these efforts are successful at reproducing observations at smaller scales, most of these methods are based on the GCMs for the initial data and boundary conditions. Hence, any inaccuracies and discrepancies are conveyed to smaller scales.



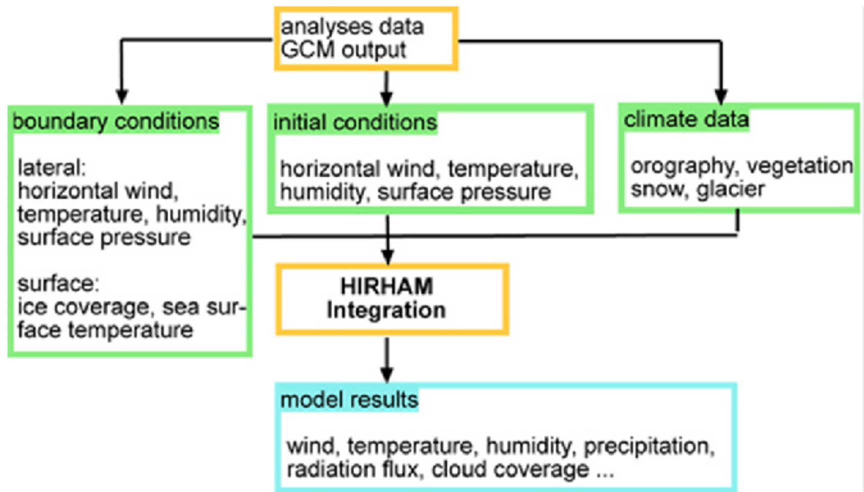


Fig. 2: The image on the left depicts the usual grid spaces of a general circulation model (~ 3.75° left) and a regional climate model for the Arctic (~ 0.5° right). At each case only every second grid line is shown. The image on the right depicts the flowchart of the regional atmospheric model HIRHAM. Regional models are based on the initial conditions and boundary conditions of GCMs in order to make a more detailed estimation of climate indices over a specified region. **Source of the images:** http://www.awi.de//en/home/

Conclusions

- The quantitative results depict the inability of climate models to reproduce the actual (historical) temporal variation of rainfall and temperature, and in particular, the occurrence of extreme events.

- In temperature they reproduce the seasonality and statistical characteristics of maxima, thus behaving like typical random number generators.

- In rainfall they do not reproduce seasonality neither the statistical behaviour of daily maxima.

- More specifically, in rainfall extremes, GCMs consistently err by up to an order of magnitude. A systematic overestimation of the rainfall frequency is observed, along with a severe underestimation of the rainfall intensity in all studied locations.

So, are models ready for "prime time" in water resources?

- The current suite of GCMs is not developed to provide the level of accuracy required for hydrological applications, and this is quite apparent from our results in daily rainfall extremes.

- These findings are not unprecedented to the hydrological and water-management community:

Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t911751996

Are climate models "ready for prime time" in water resources management applications, or is more research needed?
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Our response to the question posed in the title of this editorial is that, while they are getting better, climate models are not (up to) ready for "prime time" yet, at least for direct application to water management problems. Much more research needs to be done, and models need to be improved considerably before they

adopted. The GCM projections are not directly applicable to solve important practical questions. Clearly, further work is needed in the area of GCM testing and refinement, so that climate model results can be applied, in a more persuasive way, to real problems.
Trenberth (2010) soberly assesses the transient

Reasonable concerns have already been raised about the misuse of model outputs for water management applications. In this characteristic editorial paper, Kundzewicz & Stakhiv (2010) address this issue in detail. Similar scientific concerns have already been raised by Koutsoyiannis (2008, 2010).

- Despite the constant promotion and the resulting shift of water scientists towards such extended uses and adaptations, the key issue remains: **Climate model outputs should not be used extensively and injudiciously for hydrological and water management applications.**
- GCMs have been found to perform poorly on monthly to climatic scales (Anagnostopoulos et al., 2010, Nyego-Origamoi et al., 2010), and it is even more doubtful whether they can provide a credible basis on finer scales for prediction of future flood regimes.
- According to Koutsoyiannis (2010) this may not be a defect of current climate models, but may reflect the intrinsically unpredictable character of climate.

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