Article

Hydrometeorological extremes in a warmer climate. A local scale assessment for the island of Crete.

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Abstract: A future warmer atmosphere indicates that precipitation will increase as a consequence of the higher humidity concentrations. According to the Clausius-Clapeyron relationship precipitation increase by a factor of 7% per degree of warming. However, recent studies have shown that increase in precipitation extremes can exceed this scaling rate. In this regard we focus on the flash flood prone area of Crete by analysing high resolution precipitation records form a dense network of meteorological stations to see if the relationship of precipitation and dew point temperature lies within the Clausius-Clapeyron theory. We then use simulation outputs of a "present day event" from a set of very high resolution (about 2 km grid spacing) convective permitting regional climate models (CPRCM) to see if the models are able to capture intense convection and thus accurately simulate extreme precipitation events over Crete. A second set of simulations for the present day event, but with a perturbation of +2^{o}C, was used to examine intensity changes and to see what similar events might look like in a future weather. We finally focus on a high impact flash flood event occurred on 17 October 2006 and we study changes in hydrological impacts. The developed information can advance local scale knowledge in the context of climate change adaptation and appropriate risk management.

Keywords: hydrological extremes; flash floods; climate change; precipitation; peak discharge

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1. Introduction

One of the staple findings in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [1] is that the warming of the climate system is unequivocal, with many of the recently observed changes to be unprecedented over decades to millennia. It has been discussed that the global annual mean precipitation is constrained by the energy balance in the atmosphere [2]. However, with an increasing global mean temperature trend over the 21st century, it is virtually certain (probability > 99%) that in the long term, global precipitation will also increase on average [3]. In theory, the Clausius–Clapeyron (CC) equation estimates that in the range of typical lower troposphere temperatures, the saturation vapor pressure increases by a rate of 7%/K of temperature increase [4]. This relationship gives a useful indication about the magnitude of expected changes in future precipitation rates in a warmer atmosphere [2,5]. However, for shorter temporal scales, many studies have examined CC rates derived from high resolution precipitation records (rain gauges, rain radars) or climate model simulations, showing that the obtained scaling rate may by far exceed the CC theory. As for example, recent studies by Bao et al., [6] and Manola et al., [7] have shown that increase in precipitation extremes can exceed this scaling rate in Australia and the Netherlands, respectively. These findings are of increased importance, as changes in short-duration precipitation extremes can cause significant changes in the probability of extreme hydrologic events [8].

To manage the risk of high impact rainfall-runoff events in the context of climate change adaptation, local scale knowledge is required, being sufficiently reliable and custom-tailored to support decision making. Crete is a semi-arid island located in the eastern Mediterranean with complex and steep topography, prone to high impact, localized very intense, convective rainfall and highly seasonal precipitation patterns [9]. Such an event occurred on 17 October 2006 in Almirida region [10] at the western part of the Island. The total measured rainfall for the event was approximately 200 mm with the majority of precipitation occuring within 7 hours. This precipitation accumulation correspond to a 100-yr return period event and resulted to a flash flood with a unit peak dischare of the order of 8 $m^3 s^{-1} km^{-2}$ at a watershed of 25 km^2 (peak discharge ~ 200 $m^3 s^{-1}$). The downstream part of the watershed experienced severe unexpected flooding leading to one casualty and extended damages to property and infrastructure.

In this study, we assess the effect of the saturation vapor pressure increase to the precipitation intensity based on high temporal resolution data from meteorological stations and we compare our estimates with the rate of the CC theory. To obtain the correlation, we use data of precipitation and dew point temperature from 30 weather stations located in the island of Crete. The resulting precipitation intensity – dew point temperature relationship derived from observations is then used to scale/offset the extreme precipitation event of 17 October 2006, to higher dew temperatures (a virsual storm event of a warmer climate). Our results are also compared with simulations performed by three convection permitting regional climate models (CPRCM) used to simulate the same storm event. The simulations were conducted under the refrence climate and under future conditions, by applying a +2°C warming perturbation to the boundaries. The high resolution CPRCMs were able to adequately capture the main features (timing, magnitude and location) of the intense precipitation. The precipitation fields resulted from patern scaling based on observed data and from the high resolution CPRCM simulations are used to drive a spatially distributed setup of HEC-HMS hydrological model, simulating the Almirida flash flood event. Comparative results of the present day and the 2°C warmer climate are obtained and discussed.

2. Results

2.1. Precipitation intensity as a function of the dew-point temperature

The relationship between the precipitation intensity (mm h^{-1}), calculated by hourly accumulations at a 10minute recording time ster, and the dew point temperature (°C) is shown in **Figure 1**, for each season. The results show a diverse scaling behavior for each season, which is related to the different nature of precipitation occurrence (convective/stratiform/orographic). For Crete, during the cold winter months, the majority of the precipitation is occurring in the form of stratiform and orographic and less on convective. In contrast, during the summer months the rare precipitation occurence is usually triggered by increased evaporation over the warm Mediterranean sea, causing convection patterns with high convective available potential energy that can result to torrential rainfall and locally severe thunderstorms. This explains the higher rates of change in the JJA (**Figure 1d**). In the September to November period, both forms of precipitation occur, hence the slope of the correlation is milder than the summer. In **Figure 2**, is the same as **Figure 1a** but with higher detail in terms of precipitation percentiles. **Table 1** includes the slopes for each precipitation percentile illustrated in **Figure 2**.

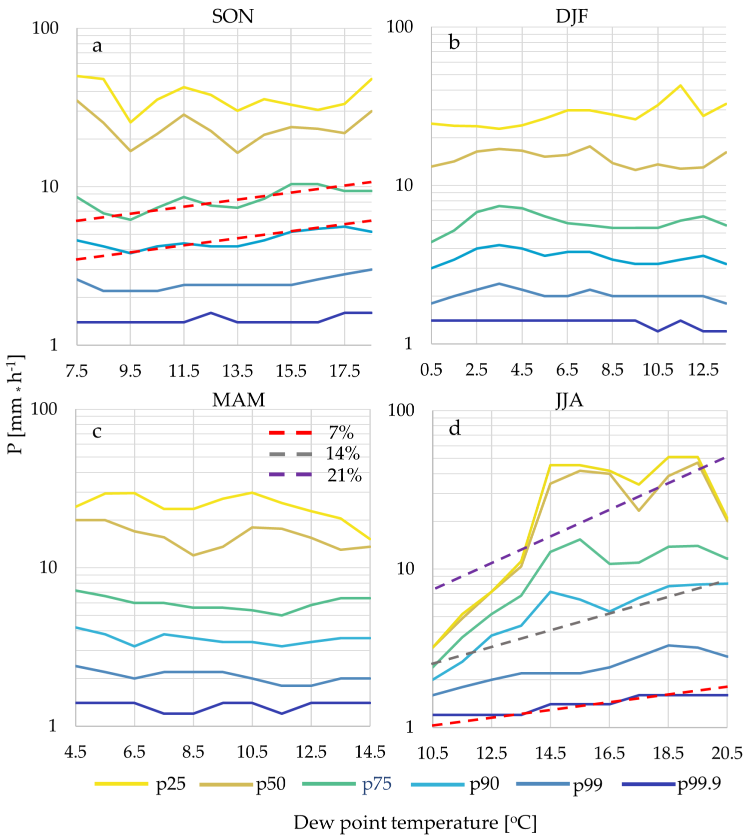

Figure 1. Precipitaiton intensity as a function of dew point temperature for September to November (a), December to February (b), March to May (c) and June to August (d), for different percentiles (25th to 99.9th). Dashed lines represent the 7%, 14% and 21% of positive correlation, or 1, 2, 3 times the CC ratio.

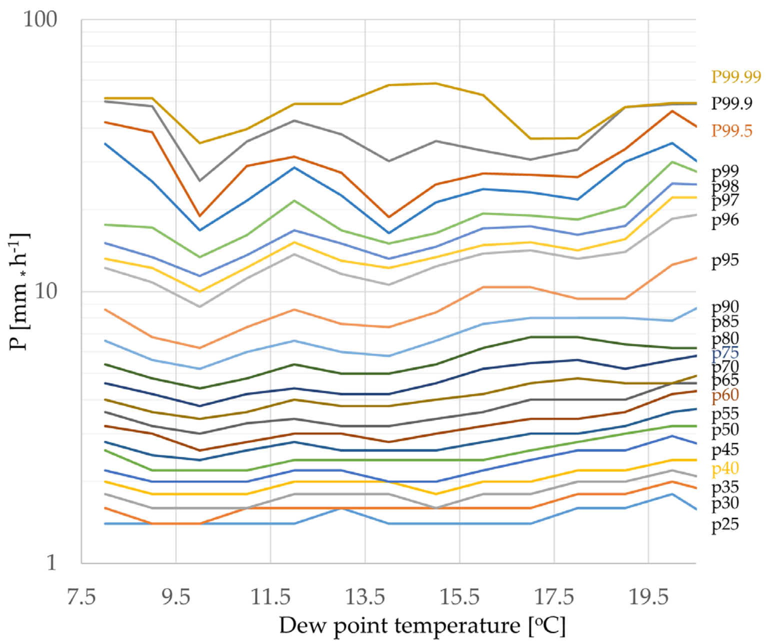

Figure 2. Precipitaiton intensity as a function of dew point temperature for September to November, for different percentiles (25th to 99.99th).

Table 1. Rate of change in precipitation for each degree of dew point temperature change.

Percentile	Slope [% C^{-1}]	Percentile	Slope [% C^{-1}]
25	0.015	80	0.151
30	0.031	85	0.253
35	0.034	90	0.429
40	0.040	95	0.562
45	0.057	96	0.654
50	0.069	97	0.735
55	0.081	98	0.707
60	0.098	99	0.209
65	0.103	99.5	0.216
70	0.110	99.9	0.250
75	0.142	99.99	-0.012

The established relationships between precipitation and dew point temperature are used to scale the precipitation of the 17 October 2006 reference event to a +2°C event. Comparison of the referece climate and the scaled future precipitation is shown in **Figure 3**. The scaled observations at +2°C show a 12% increase in the total accumulated precipitation with a 47% increase in the 15min peak precipitation. The CPRCM runs (also shown in **Figure 3**) simulate a 30% (HCLIM), 17% (HARMONIE) and -7% (WRF) change in the total depth of the precipitation for the +2°C climate. The respective changes in the peak 15min precipitation were estimated at 40%, 35% and 40%. Absolute values of precipitation are shown in **Table 2**.

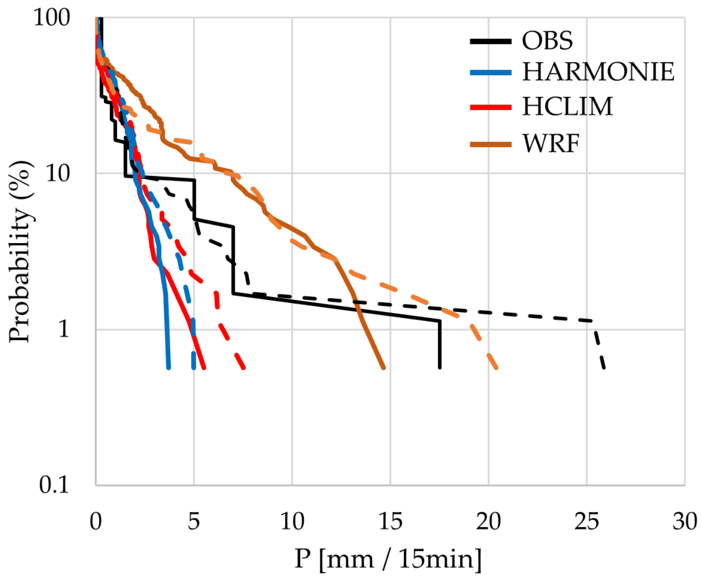

Figure 3. Probability distributions of precipitation. The solid lines correspond to the present day simulations while the dashed lines to the +2°C weather.

Table 2. Changes in total precipitation at event scale (*for the 17th of Ocober) and maximum 15 minute accumulated precipitation for the present day and the +2°C climate.

	OBS	OBS^{+2}	HCLI	HCLI^{+2}	HAR	HAR^{+2}	WRF	WRF^{+2}
Total* precipitation depth (mm)	193	216	124	160	147	172	355	328
Max 15 minute precipitation (mm)	17.5	25.9	5.5	7.5	3.7	5.0	14.7	20.4

2.2. Hydrological simualtions comparison

The different precipitation realizations for the present day and the warmer climate were used to drive a calibrated rainfall-runoff model for simulation of the hydrologic response of the flash flood event. The results show significant increase in the peak discharge due to a potential +2ºC warming. The simulation of the scaled observations at +2ºC shown a 36% increase in the peak discharge. Similar changes also derived from the perturbed simulations at +2ºC CPRCM, with an increase in the peak discharge by 47% (HCLIM), 49% (HARMONIE) and (WRF) 20%. The hydrological simulations driven by the WRF data were found to be closer to the observations, in terms of magnitude and timing of the peak discharge.

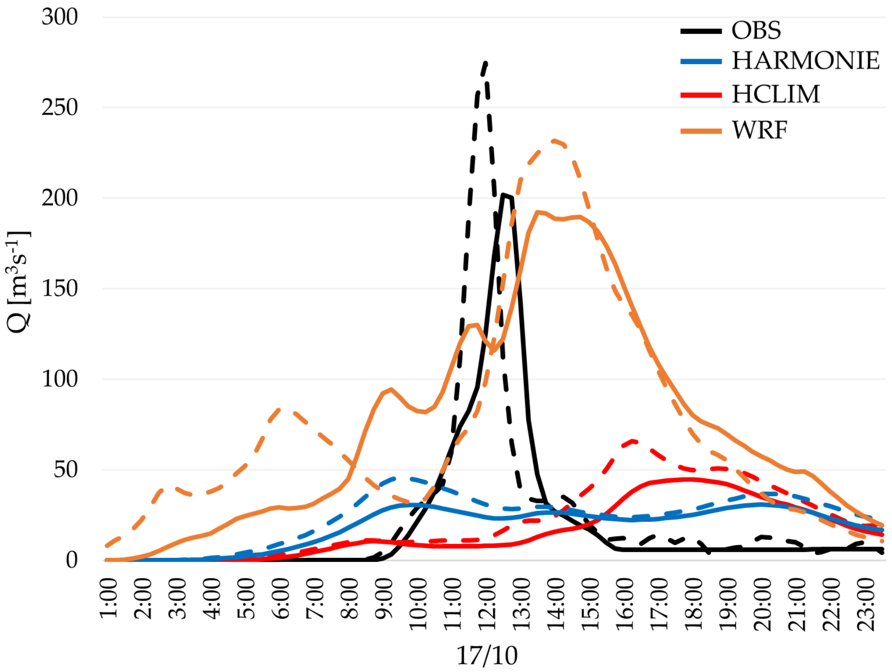

Figure 4. Flash flood events runoff hydrographs. The full lines represent the present day simulation while the dashed lines shows results from the warmer atmosphere.

3. Discussion

The analysis of the precipitation intensity and the dew point temperature shown diverse results for the different seasons that were analyzed. This is in line with [7], which denotes that the correlation can vary with region, season, duration, and form of precipitation, and is different for low and high temperatures, ranging from below CC rate or exceeding it by far.

While large discrepancies were found among the CPRCM simulations of the reference climate, the estimated relative changes in +2ºC total precipitation and peak intensity were found to be consistent. Moreover, they were found to be consistent with the relative changes estimated between the observed data and the scaled +2ºC observations. The agreement in the relative changes is more important than the agreement in absolute values, as the latter is highly sensitive to the boundary conditions of each model setup.

The results of the hydrological simulations revealed significant increases in the flood peak that can consecutively result to higher maximum depth and wider flood inundation. The increased precipitation intensity also affected the timing of the peak discharge.

4. Materials and Methods

Precipitation and dew point temperature observations were obtained from 30 weather stations operating at the island of Crete (10 minute gauging frequency). The operation period of each station varied between 0.1 and 5.6 years. The total length of the data from all weather stations, used to establish the precipitation – temperature correlation was 101years of records. The correlation was assessed using the methodology of [7], that considers hourly precipitation data and dew point temperature, four hours prior the precipitation occurrence.

The CPRCM data were provided by HARMONIE (SMHI), HCLIM (KNMI) and WRF(UNI) models.

- HARMONIE is a NWP model framework that contains a suite of physical parameterization packages, developed to be applicable to convective permitting resolutions of ~2 km. Details about the model can be found in [11].
- HCLIM is a different version of HARMONIE that runs in climate model setting using different physics package [12] that enables the model to be run at very high horizontal resolution while retaining the convection parameterization.
- WRF - Weather Research and Forecasting Model (WRF) version employed by Uni Research is a fully non-hydrostatic modeling system with the ability to resolve strongly nonlinear small scale processes. Details about the model setup can be found in [13].

The hydrological simulations were performed with HEC – HMS 4.2 model. The model was set up using a variant of Clark's unit hydrograph technique to accommodate spatially distributed rainfall data. The model was calibrated to simulate the peak discharge as it was reported in [14].

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Conflicts of Interest: The authors declare no conflict of interest.

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