

1 Investigation of the extreme wet-cold compound events changes between 2025-2049 and  
2 1980-2004 using regional simulations in Greece

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7 **Abstract.** This paper aims to study wet-cold compound events (WCCEs) in Greece for the wet and  
8 cold season November-April since these events may affect directly human activities for short or longer  
9 periods as no similar research has been conducted for the country studying the past and future  
10 development of these compound events. WCCEs are divided into two different daily compound events  
11 (Maximum Temperature (TX) -Accumulated Precipitation (RR)) and (Minimum Temperature (TN) –  
12 Accumulated Precipitation (RR)) using fixed thresholds (RR over 20 mm/day and Temperature under 0  
13 °C). Observational data from the Hellenic National Meteorology Service (HNMS) and simulation data  
14 from reanalysis and EURO-CORDEX models were used in the study for the historical period 1980-  
15 2004. The Ensemble mean of the simulation datasets from projection models was employed for the  
16 near future period (2025-2049) to study the impact of climate change on the occurrence of WCCEs  
17 under the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios. Following data  
18 processing and validation of the models, the potential changes in the distribution of WCCEs in the  
19 future were investigated based on the projected and historical simulations. WCCEs determined by fixed  
20 thresholds were mostly found over high altitudes with TN-RR events exhibiting a future tendency to  
21 reduce particularly under the RCP 8.5 scenario and TX-RR exhibiting similar reduction of probabilities  
22 for both scenarios.

23

## 24 1. Introduction

25 Extreme weather events and their linkage to climate change is a matter of high concern for many  
26 scientific groups (Zanocco et al., 2018; Konisky et al., 2016; Curtis et al., 2017). In the last decade,  
27 numerous scientific studies focused on the causes, frequency and impacts of extreme compound events  
28 (e.g. Aghakouchak et al., 2020; Singh et al., 2021; Sadegh et al., 2018; Zscheischler et al., 2017;  
29 Zscheischler and Seneviratne, 2017; Zscheischler et al., 2018). As mentioned in the Intergovernmental  
30 Panel on Climate Change report on “Managing the risks of extreme events and disasters to advance  
31 climate change adaptation” (IPCC SREX) (Ref 7, p. 118) compound events are defined as: (1) two or  
32 more extreme events occurring simultaneously or successively, (2) combinations of extreme events  
33 with underlying conditions that amplify the impact of the events, or (3) combination of events that are  
34 not themselves extremes but lead to an extreme event or impact when combined (Leonard et al., 2014).

35 Recent studies have been conducted on the examination of wet-cold compound events (WCCEs) that  
36 concern daily values of temperature and precipitation and the correlation of these variables  
37 (Chukwudum and Nadarajah, 2022; Lhotka and Kyselý, 2021), while other studies focus on the  
38 occurrence of monthly WCCEs for the historical period (Wu et al., 2019; Lemus-Canovas, 2022)  
39 However, the purpose of this article is the study of fixed thresholds extreme WCCEs on daily basis in  
40 Greece during the historical period (1980-2004) and how the likelihood of these events will be affected  
41 by climate change, during the period 2025-2049. It has been reported that WCCEs affect the region of  
42 the Mediterranean Basin, including Greece (Zhang et al., 2021). Studies using only observational data  
43 at some locations (Lazoglou and Anagnostopoulou, 2019), or modeled data mostly over the broader  
44 region of the Mediterranean Sea (Vogel et al., 2021; Hochman et al., 2021; de Luca et al., 2020),  
45 concerning WCCEs have been conducted in the past, but not depicting analytically WCCEs in Greece,  
46 a country that as a part of the Mediterranean Basin is considered a “Climate change hotspot” (Ali et al.,  
47 2022). This work attempts to fill this void on the effects of climate change on WCCEs in Greece.

48 The examined events belong to the first category of the definition of compound events from IPCC  
49 since they refer to the simultaneous exceedance of precipitation and temperature thresholds. WCCEs  
50 may have a negative impact on people’s lives by causing electricity blackouts, affecting agriculture  
51 with heavy snowfall or freezing rain and blocking transportation because of closed roads, railways or  
52 even airports (Houston et al., 2006; Llasat et al., 2014; Vajda et al., 2014). On the other hand, most of  
53 the available freshwater in the country comes from melted mountain snow during spring or summer.  
54 Finally, eco-systems, especially in mountains, may be affected by the absence of snow that climate  
55 change may cause (Demiroglu et al., 2015; Pestereva et al., 2012; Trujillo et al., 2012; García-Ruiz et  
56 al., 2011).

57 The first part of the study concerns the historical period between 1980 and 2004, because of the  
58 availability of quality-controlled daily observational data for minimum temperature (TN), maximum  
59 temperature (TX) and accumulated precipitation (RR). Hence, for that period, we use observational  
60 data from 21 Hellenic National Meteorological Service (HNMS) stations, to validate EURO-CORDEX  
61 Regional Climate Models (RCMs), provided by the Copernicus Climate Change Service and the  
62 projection model dataset produced in-house. In addition to the models, two reanalysis products are  
63 included, as the closest to “true” past climate conditions in regions with no or scarce observations  
64 (Moalafhi et al., 2016). More information about the observational and model datasets is presented in  
65 Section 2. Section 3 highlights the applied methodology while Section 4 displays WCCEs observed in  
66 stations and station cells of the models and Section 5 discusses the reanalysis and projections Ensemble  
67 mean WCCEs probabilities spatial distribution for the historical period. Section 6 details the results of  
68 the difference in WCCEs probabilities between the historical and the near future period between 2025  
69 and 2049 for two greenhouse gas concentration scenarios, RCP 4.5 and RCP 8.5.

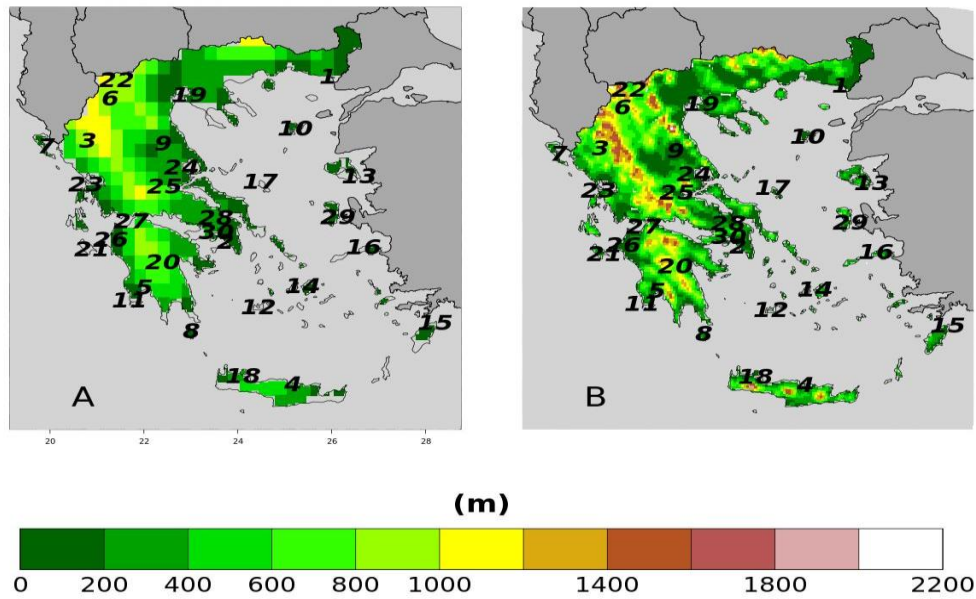
## 70 **2. Data**

71 In this Section, we present the datasets that provide the observational and simulation data produced by  
72 projection and reanalysis models.

### 73 **2.1. HNMS observations**

74 HNMS provides freely observational data from 21 stations for the purpose of scientific research  
75 (<http://www.emy.gr/emyl/el/services/paroxi-ipiresion-elfthera-dedomena>). The data have been  
76 formally evaluated by HNMS and the timeseries show no missing or distorted values. In particular, the  
77 timeseries available for the historical period 1980-2004 have a 3-hour temporal resolution and from  
78 these values, we have extracted the daily values of TN, TX and RR. Moreover, stations 22-30 which  
79 also belong to the network of HNMS stations contain observations in the period 1980-2004, although  
80 none of the stations covers all observational days in the period. The datasets of these stations were  
81 extracted by the National Centers for Environmental Information of National Oceanic and Atmospheric  
82 Administration. We selected stations that contain at least 20 years of observations. Figure 1 shows the  
83 position of the stations on the orography of ERA5 and WRF, while Table A1 of the Appendix provides  
84 details on the characteristics of the stations. We have used observational data to validate the model  
85 datasets regarding the WCCEs for the historical period.

86



87

88 **Figure 1: Map of HNMS stations on orography of (A) ERA5 and (B) WRF-ERAinterim. The**  
 89 **numbers correspond to those in Table A1 (Appendix).**

90 **2.2. Reanalysis models**

91 We have used two reanalysis models due to the lack of spatially and temporally complete direct  
 92 observations, to study consistently the WCCEs in Greece in the historical period. The first model is the  
 93 latest available reanalysis product ERA 5 from the European Centre for Medium-Range Weather  
 94 Forecasts (ECMWF) of spatial resolution ~30km x 30km (Hersbach et al., 2020). The second  
 95 reanalysis model, built in the Environmental Research Laboratory (EREL) of the National Center of  
 96 Scientific Research ‘Demokritos’ (NCSR-D) WRF\_ERA\_I, has been produced by dynamically  
 97 downscaling ERA-INTERIM using the Weather Research Forecast (WRF) model (v3.6.1) from 80km  
 98 x 80km to 5km x 5km (Politi et al., 2021, 2020, 2018).

99 **2.3. GCM / RCM models**

100 To observe possible alterations of WCCEs occurrence probability in the future period 2025-2049  
 101 compared to the historical period, we employed data from RCM simulations driven by GCMs. In this  
 102 regard, we obtained data from 5 models included in the EURO-CORDEX initiative provided by the  
 103 Copernicus Program. All chosen EURO-CORDEX models with available daily data for both RCP  
 104 scenarios were selected because they have the finest spatial resolution of 0.11° x 0.11°, and have also  
 105 been tested in Cardoso et al, (2019). Information on the regional and parent models and their acronyms  
 106 used herewith is given in Table 1. In addition to the EURO-CORDEX model data, we have used  
 107 dynamically downscaled data from the EC-EARTH GCM to a high spatial resolution of 5km x 5km for  
 108 the area of Greece using the WRF model (Politi et al., 2020, 2022).

Institution	Reference	Regional Model	Forcing model	Acronym	Resolution (°)
Météo-France / Centre National de Recherches Météorologiques	(Spiridonov et al., n.d.)	ALADIN63	CNRM- CERFACS- CNRM-CM5	CNRM	0.11
Koninklijk Nederlands Meteorologisch Instituut	(van Meijgaard et al., 2008)	KNMI- RACMO22E	ICHEC-EC- EARTH	KNMI	0.11

<b>Climate Limited-Area Modelling Community</b>	(Rockel et al., 2008)	CLMcom-CLM-CCLM4-8-17	MOHC-HadGEM2-ES	CLMcom	0.11
<b>Swedish Meteorological and Hydrological Institute</b>	(Samuelsson et al., 2016)	SMHI-RCA4	MPI-M-MPI-ESM-LR	SMHI	0.11
<b>Danish Meteorological Institute</b>	(Christensen, 2006)	DMI-HIRHAM5	NCC-NorESM1-M	DMI	0.11
<b>EREL (NCSRD)</b>	(Politi et al. 2020, 2022)	ARW-WRF	EC-EARTH	WRF_EC	0.05

109

110 **Table 1: EURO-CORDEX and EREL-NCSRD simulation models information.**

111

112 **3. Methodology**

113 The first step in this study is the validation of the projection and reanalysis models against  
114 observations. Moreover, the ensemble of the 6 projection models is also exhibited. We choose as the  
115 Ensemble resolution of the CORDEX models since 5 of them share the same spatial resolution. The  
116 only model in need of regridding is WRF\_EC. We follow the nearest neighbor method to upscale  
117 WRF\_EC from 5 km to 11 km. In addition, we use box-plots to depict the ability of the models to  
118 simulate observational data WCCEs probabilities for the historical period at the cells that include  
119 meteorological stations. The box plots consist of the colored box, where in the band near the middle of  
120 the box is the median, bottom and top of each color box are the 25<sup>th</sup> (Q1) and 75<sup>th</sup> (Q3) percentiles (BL  
121 percentile. The lower limit of the whisker (LLW) is calculated by  $LLW = Q1 - 1.5 * BL$  and the upper limit  
122 (ULW) by  $ULW = Q3 + 1.5 * BL$ . The length of the whiskers (WL) is calculated as the difference between  
123 ULW and LLW. Any value out of this range is marked by a black point in the plot. The validation is  
124 conducted after the elevation bias correction of temperature at the cells of the models containing the  
125 stations. The cells of the stations are found using the nearest neighbor approach and the temperature  
126 bias correction temperature is the following:

127 
$$T_s = T_m + 0.006 * (H_m - H_s) \quad (1)$$

128 In equation (1),  $T_s$  is the temperature of the cell after the elevation bias correction,  $T_m$  is the  
129 temperature provided by the model,  $H_m$  is the cell elevation and  $H_s$  is the elevation of the HNMS  
130 station.

131 **3.1. Compound event selection**

132 According to HNMS, the meteorological year can be split into two climate periods  
133 (<http://emy.gr/emy/el/climatology/climatology>). The cold and wet period extends on average from mid-  
134 October to the end of March, and the warm-dry period occurs during the rest of the year. Since the  
135 study is focused on the extreme WCCEs, we examine the period between November and April, since  
136 according to the HNMS observations, April exhibits lower temperatures than October and more rainy  
137 days. Moreover, it is not uncommon for the northern parts of Greece, especially mountainous areas, to  
138 be affected by snowfalls during April. This leads to the creation of a timeseries of 4532 daily values for  
139 the historical period and 4531 for the future period. CLMcom considers that each month is consisted of  
140 30 days, thus leading to 4500 values for each period. Also, DMI considers that a calendar year has 365  
141 days, thus each period examined has 4525 values.

142 The WCCEs, which are examined on daily basis, are divided into two types of synchronous events,  
143 TX-RR and TN-RR and studied using the fixed threshold approach (Table 2). This approach considers  
144 the fixed threshold of 20 mm/day for RR and 0 °C for TN and TX for all stations or grid points, as  
145 recommended by the Commission for Climatology (CCI), the World Climate Research Programme

146 (WCRP) of the Climate Variability and Predictability Component (CLIVAR) project and the Expert  
 147 Team for Climate Change Detection and Indices (ETCCDI). TN equal to or under 0 °C indicates Frost  
 148 Days (FD), while TX equal to or under 0 °C indicates Iced Days (ID) (Fonseca et al., 2016). The  
 149 thresholds examined have been proposed in various works for studying extreme events (Raziei et al.,  
 150 2014; Tošić and Unkašević, 2013; Anagnostopoulou and Tolika, 2012; Pongrácz et al., 2009;  
 151 Kundzewicz et al., 2006; Moberg et al., 2006).

THRESHOLDS	RR	TN	TX	WCCE	
FIXED	>= 20 mm/day	<= 0 °C (FD)	<= 0 °C (ID)	1.	(RR20-FD)
	(RR20)			2.	(RR20-ID)

152

153 **Table 2: Univariate thresholds and the compound events examined in the study.**

154 **3.2. WCCEs probability calculation**

155 The WCCEs probabilities are calculated by applying two different methods. The first is the empirical  
 156 approach counting the events from the timeseries and dividing by the total number of days to find the  
 157 percentage (%) of the occurrence probability. For the second method, we use the copula approach for  
 158 the HNMS observations and model comparison and to map the differences between the two methods  
 159 for the reanalysis and projection of model data. Compared to copula, an empirical method has a higher  
 160 uncertainty when calculating the probability of extreme events (Hao et al., 2018; Tavakol et al., 2020;  
 161 Zscheischler and Seneviratne, 2017). The purpose of using two different methods is to investigate  
 162 whether the copula method underestimates or overestimates the WCCEs.

163 The best fitting copula selection for each timeseries is examined using the R programming language  
 164 function BiCopSelect as suggested in (Zhou et al., 2019) package VineCopula (Schepsmeier et al.,  
 165 2013). The appropriate bivariate copula for each dataset is chosen by the function, from a multitude of  
 166 40 different copula families using the Akaike Information Criterion (AIC) (Akaike, 1974) and  
 167 Bayesian Information Criterion (BIC), and the copula chosen for each station and model dataset is  
 168 shown in Appendix B (Tables B1 and B2). Copulas are used in plenty of studies that investigate the  
 169 dependence between two different climate variables and the joint probability of compound events  
 170 (Tavakol et al., 2020; Dzipire et al., 2020; Pandey et al., 2018; Cong and Brady, 2012; Abraj and  
 171 Henaarachchi, 2021).

172 As mentioned in Nelsen, (2007), a bivariate copula is a bivariate distribution function where margins  
 173 are uniform on the unit interval [0, 1]. A bivariate copula is a map  $C:[0,1]^2 \rightarrow [0,1]$  with  $C(u,1)=u$  and  
 174  $C(1,v)=v$ . Let  $X$  and  $Y$  be random variables with a joint distribution function  $F(x,y)=\Pr(X \leq x, Y \leq y)$  and  
 175 continuous marginal distribution functions  $F_1(x)=\Pr(X \leq x)$  and  $F_2(y)=\Pr(Y \leq y)$ , respectively. By Sklar's  
 176 theorem (Sklar, 1959), one obtains a unique representation as follows:

177 
$$F(x,y) = C\{F_1(x), F_2(y)\} \tag{2}$$

178 For the two random variables of  $X$  (e.g., precipitation) and  $Y$  (e.g., temperature) with cumulative  
 179 distribution functions (CDFs)  $F_1(x)=\Pr(X >= x)$  and  $F_2(y)=\Pr(Y <= y)$ , the bivariate joint distribution  
 180 function or copula ( $C$ ) can be written as:

181 
$$F(x,y) = \Pr(X >= x, Y <= y) = C(u,v) \tag{3}$$

182 **4. WCCEs assessment in HNMS stations**

183 In this section, the models are validated against observations both for the empirical and the copula  
 184 method. WCCEs probabilities for each station and model are presented in the supplementary material.  
 185 BIAS and RMSE along with the Critical Success Index (CSI) are used for the validation. CSI is  
 186 calculated as  $CSI=A/(A+B+C)$ .  $A$ ,  $B$  and  $C$  symbolize elements from the contingency table (Table 2)  
 187 that occur from comparing zero and non-zero probabilities in stations with the corresponding model  
 188 cells. Also, the total number of events calculated for both methods from observational data is presented  
 189 for each station.

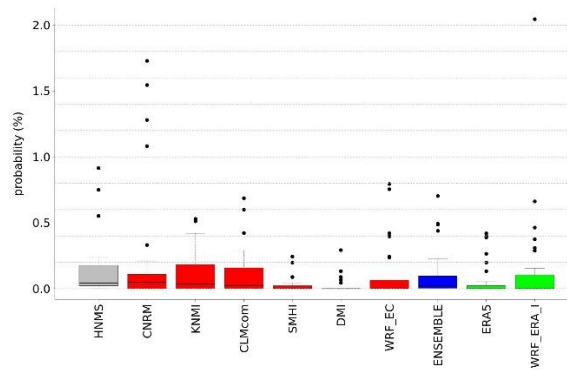
"EVENT"=POSITIVE PROBABILITY		OBSERVATION EVENT	
		YES	NO
MODEL EVENT	YES	<b>A</b>	<b>B</b>
	NO	<b>C</b>	<b>D</b>

190 **Table 2: Contingency table where "A" is the number of event forecasts that correspond to event**  
191 **observations or the number of hits. Entry "B" is the number of event forecasts that do not**  
192 **correspond to observed events or the number of false alarms. Entry "C" is the number of no-**  
193 **event forecasts corresponding to observed events or the number of misses. Entry "D" is the**  
194 **number of no-event forecasts corresponding to no events observed or the number of correct**  
195 **rejections.**

196 **4.1. RR20FD**

197 Probability values for each station are presented in Supplementary (Tables S1-S4) as well as the  
198 contingency tables (Tables S7-S10) from which CSI is calculated. ERA5 and WRF\_ERA\_I are  
199 reanalysis products and exhibited for comparison reasons. The copulas selected by Bicopselect for each  
200 observational and modeled timeseries are also presented in Supplementary (Tables S5-S6).

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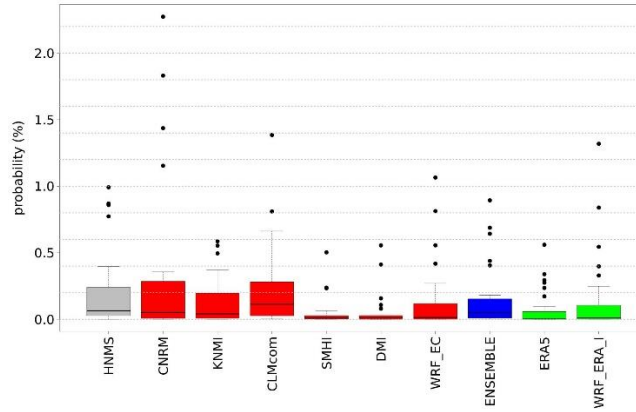


202

203 **Figure 2: Box-plot presenting RR20FD empirical method probabilities for observations and**  
204 **models.**

	<i>HNMS</i>	<i>CNRM</i>	<i>KNMI</i>	<i>CLMcom</i>	<i>SMHI</i>	<i>DMI</i>	<i>WRF_EC</i>	<i>ENSEMBLE</i>	<i>ERA5</i>	<i>WRF_ERA_I</i>
<i>MEAN</i>	<b>0.1382</b>	0.2361	0.1168	0.1116	0.0267	0.0208	0.1143	<b>0.1044</b>	0.0625	0.1535
<i>SD</i>	<b>0.2211</b>	0.4821	0.1590	0.1781	0.0581	0.0600	0.2216	<b>0.1813</b>	0.1311	0.3935
<i>BIAS</i>		-0.0979	0.0214	0.0266	0.1115	0.1174	0.0239	<b>0.0338</b>	0.0756	-0.0154
<i>RMSE</i>		0.3234	0.1298	0.0922	0.2003	0.2148	0.1222	<b>0.0975</b>	0.1536	0.2319
<i>COR</i>		0.8583	0.8138	0.9211	0.9194	0.7177	0.8484	<b>0.9118</b>	0.8210	0.8523
<i>CSI</i>		0.6071	0.6667	0.6296	0.3214	0.1667	0.3793	<b>0.7692</b>	0.2667	0.4483

205 **Table 3: Table exhibiting mean (MEAN) station RR20FD empirical probabilities (%) for**  
206 **observations and models, standard deviation (SD), bias (BIAS), rmse (RMSE), Pearson**  
207 **correlation (COR) and CSI of models against observations.**



208

209 **Figure 3: Box-plot presenting RR20FD copula method probabilities for observations and models.**

	<i>HNMS</i>	<i>CNRM</i>	<i>KNMI</i>	<i>CLMcom</i>	<i>SMHI</i>	<i>DMI</i>	<i>WRF_EC</i>	<i>ENSEMBLE</i>	<i>ERA5</i>	<i>WRF_ERA_I</i>
<i>MEAN</i>	<b>0.2016</b>	0.2974	0.1291	0.2129	0.0448	0.0528	0.1338	<b>0.1451</b>	0.0699	0.1455
<i>SD</i>	<b>0.2864</b>	0.5802	0.1715	0.3031	0.1042	0.1237	0.2580	<b>0.2310</b>	0.1368	0.2939
<i>BIAS</i>		-0.0959	0.0725	-0.0113	0.1568	0.1488	0.0678	<b>0.0565</b>	0.1317	0.0561
<i>RMSE</i>		0.3334	0.1720	0.2264	0.2646	0.2530	0.1458	<b>0.1139</b>	0.2165	0.1788
<i>COR</i>		0.9422	0.8782	0.6968	0.7688	0.7620	0.8888	<b>0.9467</b>	0.8955	0.8233
<i>CSI</i>		0.9259	0.9629	1	0.9643	0.7333	0.8276	<b>1</b>	0.6333	0.7931

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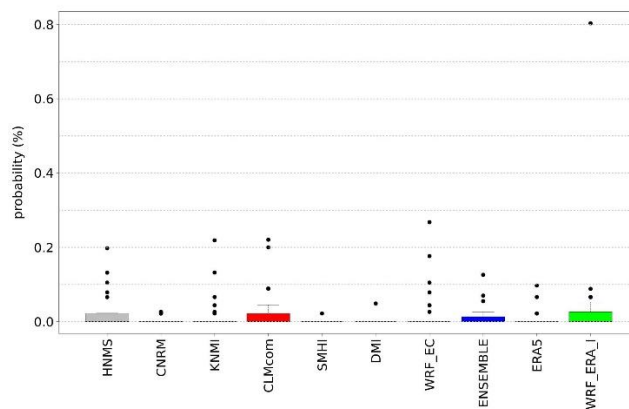
211 **Table 4: Table exhibiting mean (MEAN) RR20FD copula station probabilities (%) for**  
 212 **observations and models, standard deviation (SD), bias (BIAS), rmse (RMSE), Pearson**  
 213 **correlation (COR) and CSI of models against observations.**

213

214 **4.2. RR20ID**

215 RR20ID events yield, as expected, lower probabilities than RR20FD events as observed in Figures 4  
 216 and 5. Most observations and models yield zero probabilities, hence validation of models for these  
 217 events is limited. The empirical method exhibits eight stations with non-zero probabilities in the  
 218 historical period (Supplementary).

219



220

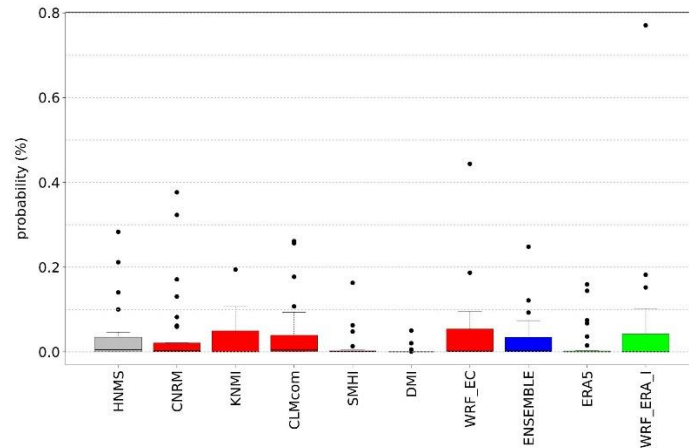
221 **Figure 4: Box-plot presenting RR20ID empirical method probabilities for observations and**  
 222 **models.**

<i>HNMS</i>	<i>CNRM</i>	<i>KNMI</i>	<i>CLMcom</i>	<i>SMHI</i>	<i>DMI</i>	<i>WRF_EC</i>	<i>ENSEMBLE</i>	<i>ERA5</i>	<i>WRF_ERA_I</i>
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<i>MEAN</i>	<b>0.0331</b>	0.0430	0.0240	0.0397	0.0104	0.0029	0.0388	<b>0.0265</b>	0.0167	0.0493
<i>SD</i>	<b>0.0669</b>	0.0933	0.0440	0.0725	0.0320	0.0098	0.0876	<b>0.0524</b>	0.0413	0.1441
<i>BIAS</i>		-0.0099	0.0091	-0.0065	0.0228	0.0303	-0.0057	<b>0.0067</b>	0.0164	-0.0161
<i>RMSE</i>		0.0568	0.0466	0.0556	0.0522	0.0682	0.0636	<b>0.0419</b>	0.0438	0.1084
<i>COR</i>		0.7961	0.7212	0.6780	0.7506	0.5380	0.6829	<b>0.7776</b>	0.8101	0.6928
<i>CSI</i>		0.1071	0.2000	0.1923	0.0333	0.0333	0.1481	<b>0.2400</b>	0.1034	0.1538

223 **Table 5: Table exhibiting mean (MEAN) RR20ID empirical probabilities station probabilities**  
 224 **(%) for observations and models, standard deviation (SD), bias (BIAS), rmse (RMSE), Pearson**  
 225 **correlation (COR) and CSI of models against observations.**



226  
 227 **Figure 5: Box-plot presenting RR20ID copula method probabilities for observations and models.**

	<i>HNMS</i>	<i>CNRM</i>	<i>KNMI</i>	<i>CLMcom</i>	<i>SMHI</i>	<i>DMI</i>	<i>WRF_EC</i>	<i>ENSEMBLE</i>	<i>ERA5</i>	<i>WRF_ERA_I</i>
<i>MEAN</i>	<b>0.0282</b>	0.0378	0.0169	0.0344	0.0066	0.0017	0.0249	<b>0.0204</b>	0.0138	0.0274
<i>SD</i>	<b>0.0663</b>	0.0811	0.0303	0.0676	0.0166	0.0046	0.0473	<b>0.0364</b>	0.0377	0.0524
<i>BIAS</i>		-0.0097	0.0112	-0.0062	0.0215	0.0264	0.0032	<b>0.0078</b>	0.0144	0.0008
<i>RMSE</i>		0.0532	0.0493	0.0598	0.0565	0.0691	0.0489	<b>0.0443</b>	0.0420	0.0339
<i>COR</i>		0.7534	0.7228	0.5861	0.8202	0.2291	0.6594	<b>0.7712</b>	0.8370	0.8540
<i>CSI</i>		0.5000	0.4333	0.8095	0.5357	0.2667	0.5000	<b>0.8095</b>	0.2667	0.4286

228 **Table 6: Table exhibiting mean (MEAN) RR20ID copula probabilities station probabilities (%)**  
 229 **for observations and models, standard deviation (SD), bias (BIAS), rmse (RMSE), Pearson**  
 230 **correlation (COR) and CSI of models against observations.**

### 231 4.3. Observations-models comparison conclusions

232 The events examined are rare among the available stations for the historical period. Copulas  
 233 considering the dependence between the variables yield greater probabilities than the empirical method.  
 234 More stations with non-zero probabilities enable more accurate validation of the models. To minimize  
 235 uncertainties, smooth extreme underestimations or overestimations of WCCE probabilities that each  
 236 model yields, and because ENSEMBLE shows better consistency among the projection models'  
 237 statistical indices, we use it for further analysis in the study.

### 238 5. Historical period models WCCEs on maps

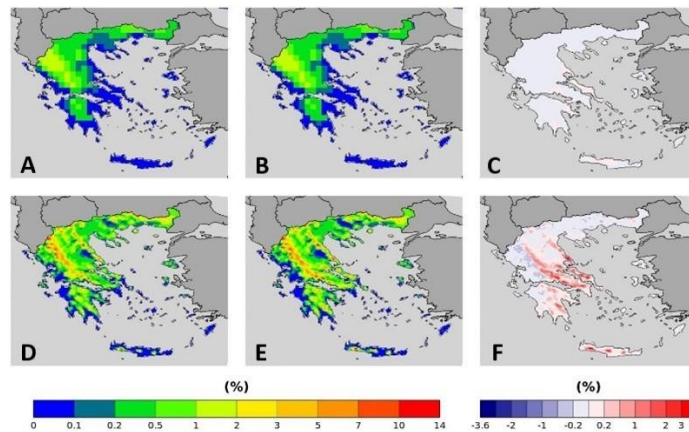
239 In this section, WCCEs spatial distribution probabilities are compared between empirical and copula  
 240 methods. This procedure is conducted separately for the two reanalysis products and the Ensemble  
 241 mean of the projection models.



242 **5.1. Reanalysis**

243 ERA5 and WRF\_ERA\_I WCCEs spatial distribution probabilities in Greece are displayed in this  
 244 section. We display both reanalysis products, although ERA5 is the most recently developed reanalysis  
 245 product, we exhibit also WRF\_ERA\_I since its much finer spatial resolution is more appropriate for the  
 246 complex topography of Greece with many mountains and islands.

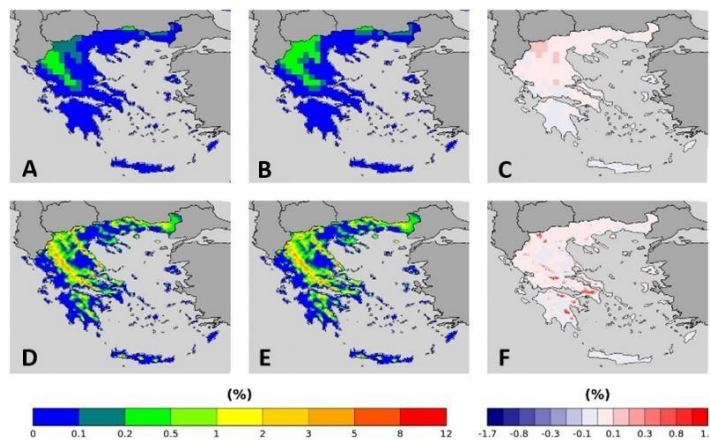
247



248

249 **Figure 6: RR20FD probabilities for (A, B, C) ERA5 and (D, E, F) WRF\_ERA\_I produced by (A,**  
 250 **D) Empirical and (B, E) Copula and © = (B)–(A) and (F)=(E)-(D).**

251



252

253 **Figure 7: RR20ID probabilities for (A, B, C) ERA5 and (D, E, F) WRF\_ERA\_I produced by (A,**  
 254 **D) Empirical and (B, E) Copula a©(C) = (B)–(A) and (F) = (E)-(D).**

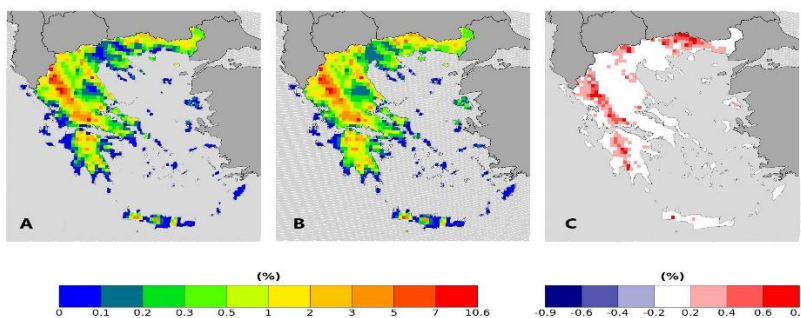
255 Both reanalysis products yield greater WCCEs probabilities in the Pindus mountains, although due to  
 256 its finer spatial resolution, WRF\_ERA\_I display high probabilities at other mountainous regions  
 257 located in Crete, Peloponnese, Evia Island and others. Also, in both WCCEs copula method yields  
 258 higher probabilities, especially for WRF\_ERA\_I and the RR20FD case. Moreover, WRF\_ERA\_I  
 259 displays a greater range than ERA5 with RR20FD probabilities reaching 14% and RR20ID 12%  
 260 compared to 6% and 2% of ERA5 respectively.

261 **5.2. Projections Ensemble**

262 Figures 8 and 9 yield that the Ensemble mean displays similar to the WRF\_ERA\_I spatial distributions  
 263 of WCCEs. RR20FD and RR20ID probabilities reach 10.8% and 5.4% respectively. The copula  
 264 method yields higher probabilities for both methods in mountainous regions with greater differences

265 displayed for RR20ID events in the Pindos mountain range and RR20FD exhibiting greater spatial  
 266 distribution in differences between the two methods.

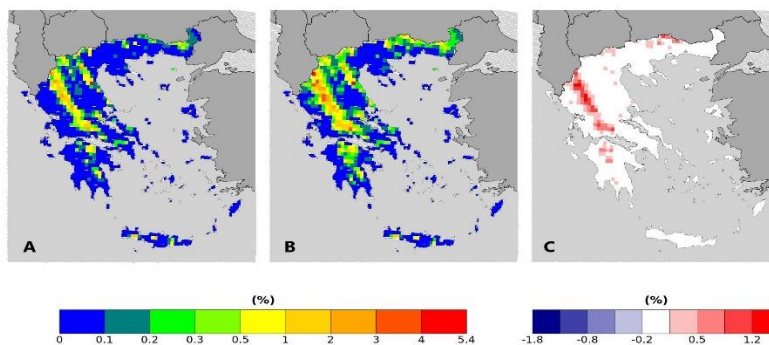
267



268

269 **Figure 8: RR20FD Ensemble probabilities for (A) Empirical and (B) Copula method. (C)=(B)-**  
 270 **(A).**

271



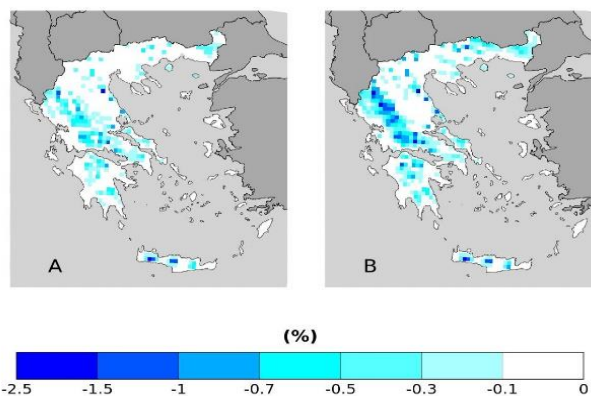
272

273 **Figure 9: RR20ID Ensemble probabilities for (A) Empirical and (B) Copula method. (C)=(B)-(A).**

274 **6. Past-Future Ensemble differences**

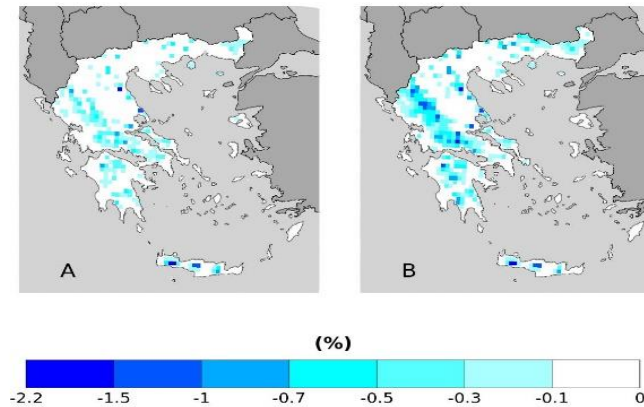
275 This section displays the differences of the Ensemble mean WCCEs probabilities, calculated for the  
 276 empirical and the copula method, compared to the past probabilities presented in the previous section.  
 277 The differences mapped are statistically significant at a 95% level using the Student's t-test (Goulden,  
 278 1939) comparing 25 annual values of the timeseries.

279 **6.1. RR20FD**



280

281 **Figure 10: RR20FD empirical method probability differences of future-past periods for (A)**  
 282 **RCP4.5 and (B) RCP8.5 scenarios.**



283

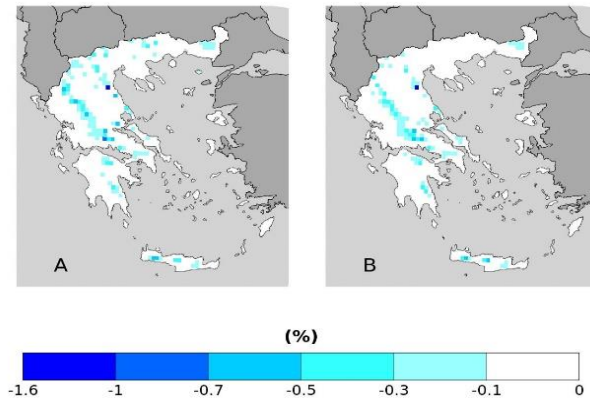
284 **Figure 11: RR20FD copula method probability differences of future-past periods for (A) RCP4.5**  
 285 **and (B) RCP8.5 scenarios.**

	<i>Empirical RCP4.5</i>	<i>Empirical RCP8.5</i>	<i>Copula RCP4.5</i>	<i>Copula RCP8.5</i>
$0 \leq N_c < 0.1$	34	31	64	57
$-0.1 \leq N_c < -0.3$	112	154	112	131
$-0.3 \leq N_c < -0.5$	63	65	53	81
$-0.5 \leq N_c < -0.7$	31	48	16	47
$-0.7 \leq N_c < -1$	12	34	6	24
$-1 \leq N_c < -1.5$	5	18	3	11
$N_c \leq -1.5$	2	5	3	4
<i>MAX D</i>	-1.8063 %	-2.4988 %	-1.9500 %	-2.1392 %

286 **Table 7: ENSEMBLE Number of cells (Nc) in each category of probability difference (%) for**  
 287 **RR20FD for empirical and copula method. MAX D denotes the maximum negative difference**  
 288 **between future and past periods. Nv concerns only cells with statistically significant difference.**

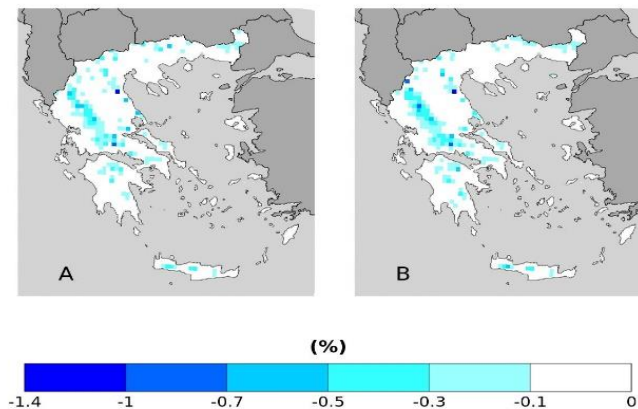
289 From the results displayed in Figures 10 and 11 and in Table 7 RCP4.5 and RCP8.5 scenarios for the  
 290 probabilities of the RR20FD events, we observe that in all cases future scenarios yield only negative  
 291 values, meaning the reduction of RR20FD events in the 2025-2049 period compared to 1980-2004  
 292 period in all mountainous regions of Greece. RCP8.5 yields a greater reduction of RR20FD  
 293 probabilities than the RCP4.5 scenario both in spatial distribution and extreme values. The empirical  
 294 method exhibits a greater reduction for the RCP8.5 scenario, although for the RCP4.5 scenario both  
 295 methods yield similar results.

296 **6.2. RR20ID**



297

298 **Figure 12: RR20ID empirical method probability differences of future-past periods for (A)**  
 299 **RCP4.5 and (B) RCP8.5 scenarios.**



300

301 **Figure 13: RR20ID copula method probability differences of future-past periods for (A) RCP4.5**  
 302 **and (B) RCP8.5 scenarios.**

	<i>Empirical RCP4.5</i>	<i>Empirical RCP8.5</i>	<i>Copula RCP4.5</i>	<i>Copula RCP8.5</i>
$0 \leq N_c < -0.1$	193	229	166	210
$-0.1 \leq N_c < -0.3$	81	71	96	109
$-0.3 \leq N_c < -0.5$	23	20	33	37
$-0.5 \leq N_c < -0.7$	9	5	9	7
$-0.7 \leq N_c < -1$	1	0	1	3
$N_c \leq -1$	1	1	1	1
<i>MAX D</i>	-1.5536	-1.0593	-1.3425	-1.1362

303 **Table 8: ENSEMBLE Number of cells (Nc) in each category of probability difference (%) for**  
 304 **RR20ID for empirical and copula method. MAX D denotes the maximum negative difference**  
 305 **between future and past periods. Nv concerns only cells with statistically significant difference.**

306 Similarly, to RR20FD, RR20ID events probabilities yield only zero or negative differences compared  
 307 to the past for both scenarios. Empirical and copula methods yield similar results in distribution and  
 308 extreme values. For both methods, the RCP4.5 scenario tends to higher reduction of RR20ID  
 309 probabilities than RCP8.5, as observed in Table 8.

310 The results for both scenarios and events show that independently from the choice of scenario, the  
 311 probabilities of the events are expected to reduce almost equally in the near future (2025-2049)  
 312 compared to the past period (1980-2004).

313 **7. Discussion and Conclusions**

314 This work presents for the first time to our knowledge an extensive study of wet-cold compound events  
315 in Greece for the historical and future periods of 1980-2004 and 2025-2049, respectively. Models' data  
316 from the EUROCORDER initiative of 0.11° resolution and reanalysis data (ERA5 and ERA-Interim  
317 dynamically downscaled to 5km<sup>2</sup>) were used and validated for the determined WCCEs against the  
318 formally available observational datasets by HNMS for the country. The number of events and their  
319 probabilities of occurrence were determined by applying a fixed thresholds approach. Then, the  
320 bivariate validation of the models' datasets against observations was performed for the determined  
321 bivariate thresholds. The probabilities of WCCEs were computed using the empirical method and the  
322 best-fitted copula for the bivariate timeseries for observational data, reanalysis, projection models and  
323 the Ensemble of the projection models. Copulas yield higher extreme events probabilities for most of  
324 the cases considering the dependence between temperature and precipitation.

325 Although uncertainties may rise on the impact of WCCEs on mountainous areas due to the absence of  
326 observations on altitudes higher than 1000 meters, we trust the results yielded by the Ensemble.  
327 Besides the satisfying results from the bivariate validation, this trust is enhanced by the fact that winter  
328 period systems affect large areas crossing the country from north to south or from west to east (Cartalis  
329 et al., 2010) and therefore recorded by available stations. Also, in the cold period of the year,  
330 convective precipitation forced by orography is limited hence the doubt that the models do not simulate  
331 extreme rainfall in winter is reduced. Moreover, the use of the Ensemble mean of the models reduces  
332 the uncertainties in models' ability to simulate the probability of the occurrence of extreme events. The  
333 reduction of RR20-FD and RR20-ID WCCEs on mountains that the Ensemble of projection models  
334 predict in the future, might contribute to less heavy snowfall events and possibly less accumulated  
335 snow depth. If such a scenario will be verified, Greece faces the threat of losing the main sources of  
336 fresh water that come from melted mountain snow during spring or early summer in the near future  
337 period. The rise of temperature due to global warming is the main factor for the reduction of WCCEs  
338 (Supplementary Figures S5-S7), while also possible changes in patterns of teleconnections may affect  
339 winter conditions in Greek mountains, similar to NAO (North Atlantic Oscillation) pattern affecting  
340 Pindos mountains (López-Moreno et al., 2011) or the positive phase of EAWR (East Atlantic-Western  
341 Russia) pattern that leads to cold air advection from the north towards the southern part of Europe and  
342 the eastern Mediterranean region (Ionita, 2014). Still, understanding extreme events on complex  
343 terrains demands greater effort from the scientific community to enable solid predictions on the impact  
344 of climate change on the occurrence of these events.

345 **Acknowledgments**

346 The authors acknowledge partial funding by the project “National Research Network for Climate  
347 Change and its Impacts, (CLIMPACT - 105658/17-10-2019)” of the Ministry of Development, GSRT,  
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545 **Code and data availability**

546 Code and results data available upon request.

547 **Author contributions**

548 IM has worked on conceptualization, methodology, validation, visualization, investigation, writing  
549 review and editing. AS, DV and IK contributed on conceptualization, review and supervision. All  
550 authors have read and agreed to the published version of the manuscript.

551 **Competing interests**

552 The authors declare that they have no conflict of interest.

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554 **Appendix**

NUMBER	LOCATION	ID	LATITUDE	LONGITUDE	ELEVATION (m)	YEARS
1	Alexandroupoli	16627	40.85	25.917	4	1980-2004
2	Elliniko	16716	37.8877	23.7333	10	1980-2004
3	Ioannina	16642	39.7	20.817	483	1980-2004
4	Irakleio	16754	35.339	25.174	39	1980-2004
5	Kalamata	16726	37.067	22.017	6	1980-2004

6	Kastoria	16614	40.45	21.28	660.95	1980-2004
7	Kerkira	16641	39.603	19.912	1	1980-2004
8	Kithira	16743	36.2833	23.0167	167	1980-2004
9	Larisa	16648	39.65	22.417	73	1980-2004
10	Limnos	16650	39.9167	25.2333	4	1980-2004
11	Methoni	16734	36.8333	21.7	34	1980-2004
12	Milos	16738	36.7167	24.45	183	1980-2004
13	Mitilini	16667	39.059	26.596	4	1980-2004
14	Naxos	16732	37.1	25.383	9	1980-2004
15	Rhodes	16749	36.42896	28.21661	95	1980-2004
16	Samos	16723	37.79368	26.68199	10	1980-2004
17	Skyros	16684	38.9676	24.4872	12	1980-2004
18	Souda	16746	35.4833	24.1167	151	1980-2004
19	Thessaloniki	16622	40.517	22.967	2	1980-2004
20	Tripoli	16710	37.527	22.401	651	1980-2004
21	Zakynthos	16719	37.751	20.887	5	1980-2004
22	Florina	16613	40.78	21.43	619	1980-2002
23	Aktio	16643	38.919	20.772	2	1980-2004
24	Anchialos	16665	39.217	22.8	19	1980-2000
25	Lamia	16675	38.883	22.433	12	1980-2004
26	Andravida	16682	37.92	21.293	10	1980-2004
27	Patras	16689	38.25	21.733	2	1980-1999
28	Tanagra	16699	38.317	23.533	140	1980-2000
29	Chios	16706	38.333	26.133	5	1980-2000
30	Elefsis	16718	38.064	23.556	20	1980-2000

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556 **Table A1: HNMS stations information.**

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