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

~~"Extreme wet-cold compound events investigationunder climate change in Greece~~

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Abstract. This paper aims to study wet-cold compound events (WCCEs) inover Greece for the wet and cold season November-April, since these events may affect directly human activities for short or longer periods as no similar research has been conducted for the country studying the past and future development of these compound events. WCCEs are divided in two different daily compound events (Maximum Temperature (TX-) -Accumulated Precipitation (RR~~)~~) and (Minimum Temperature (TN-) – Accumulated Precipitation (RR)) ~~and two different approaches~~ using fixed thresholds (RR over 20 mm/day and Temperature under 0 ºC) ~~and percentile (RR over 95th and Temperature under 5th) thresholds~~. Observational data from the Hellenic National Meteorology Service (HNMS) and simulation data from reanalysis and ~~EUROCORDEX~~EURO-CORDEX models were used in the study for the historical period 1980-2004. The Ensemble mean of the s~~S~~imulation datasets from projection models were employed for the near future period (2025-2049) to study the impact of climate change on the occurrence of WCCEs under ~~RCP~~Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios. Following data processing and validation of the models, the potential changes in the distribution of WCCEs in the future were investigated based on the projected and historical simulations. WCCEs determined by fixed thresholds were mostly found over high altitudes with TN-RR events exhibiting a future tendency to reduce particularly under RCP 8.5 scenario and TX-RR exhibiting similar reduction of probabilities for both scenarios. ~~On the other hand, WCCEs obtained with percentile thresholds, were distributed mostly in Eastern Greece and Crete while their changes differed significantly among models.~~

1. Introduction

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

Recent studies have been conducted on the examination of wet-cold compound events (WCCEs) that concern monthly extreme values of temperature and precipitation and the correlation of these variables (Lemus-Canovas, 2022; Chukwudum and Nadarajah, 2022; Lhotka and Kyselý, 2021; Wu et al., 2019). The purpose of this article is the study of extreme ~~wet-cold compound events (~~WCCEs~~)~~ on daily basis in Greece during the historical period (1980-2004) and how the occurrence of these events will be affected by climate change~~. using projection data from and~~. It has been reported that WCCEs affect the

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region of the Mediterranean Sea, including Greece (Zhang et al., 2021). Studies using only observational data at some locations (Lazoglou and Anagnostopoulou, 2019), or modeled data mostly over the broader region of the Mediterranean Sea (Vogel et al., 2021; Hochman et al., 2021; de Luca et al., 2020), concerning WCCEs have been conducted in the past, not depicting analytically WCCEs in Greece, which is attempted in this work.

The examined events belong to the first category of the definition of compound events from IPCC since they refer to the simultaneous exceedance of precipitation and temperature thresholds. WCCEs ~~can~~may have negative impact on people's lives by causing electricity blackouts, affecting agriculture with heavy snowfall or freezing rain and~~,~~ blocking transportation because of closed roads, railways or even airports (Houston et al., 2006; Llasat et al., 2014; Vajda et al., 2014). On the other hand, most of the available freshwater in the country comes from melted mountain snow during spring or summer. Finally, eco-systems, especially on mountains, may be ~~harmed~~affected by the absence of snow that climate change may cause (Demiroglu et al., 2015; Pestereva et al., 2012; Trujillo et al., 2012; García-Ruiz et al., 2011). ~~Moreover, Athens, a city of more than 4 million inhabitants, experienced in two consecutive years snowstorms (16, 17 February 2021 and 24 January 2022), which caused great problems in road traffic and electricity failures.. Historically, such events occur infrequently in the region and it is the first time that snow depth exceeds 15cm twice in a period of eleven months in the city center. At other parts of Greece such events are more frequent, and this is shown in the present study.~~

~~This work extends further and more meticulously the study of Markantonis et al., (2021) about daily minimum temperature and accumulated precipitation WCCEs. The motivation is the absence of such similar study concerning the country, with few exceptions that used only observational data at some locations (Lazoglou and Anagnostopoulou, 2019), or modeled data mostly over the broader region of Mediterranean Sea lacking detailed analysis for Greece (Vogel et al., 2021; Hochman et al., 2021; de Luca et al., 2020).~~ The ~~first~~greatest part of the study concerns the historical period between 1980 and 2004, because of the availability of quality controlled daily observational data for minimum temperature (TN), maximum temperature (TX) and accumulated precipitation (RR). H~~Th~~ence, for that period, we use observational data from 21 Hellenic National Meteorological Service (HNMS) stations, to~~for the~~ validat~~eion of~~ EURO-CORDEX Regional Climate Models (RCMs), provided by the Copernicus Climate Change Service ~~of EUs Copernicus Program~~ and the projection model dataset produced in-house. In addition to the models, two reanalysis products are included, as the closest to true past climate conditions in regions with no or scarce observations (Moalafhi et al., 2016). More information about the observational and model datasets is ~~shown~~presented in Section 2. Section 3 highlights the applied methodology while Section 4 ~~presents~~displays WCCEs observed in stations and station cells of the models and Section 5 contains Reanalysis and projections Ensemble mean ~~the comparison of model data~~ WCCEs probabilities spatial distribution for the historical period~~with observations~~. Section ~~5~~,6 details the results about the difference in WCCEs probabilities between the historical and ~~for the historical period and the projected changes by each model for~~ the near future period between 2025 and 2049 for two greenhouse gas concentration scenarios, RCP 4.5 and RCP 8.5.

2. Data

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

1. HNMS observations

HNMS provides freely observational data from 21 stations for the purpose of scientific research. (http://www.emy.gr/emy/el/services/paroxi-ipiresion-elefthera-dedomena). The data have been formally evaluated by HNMS and the timeseries show no missing or distorted values. In particular, the

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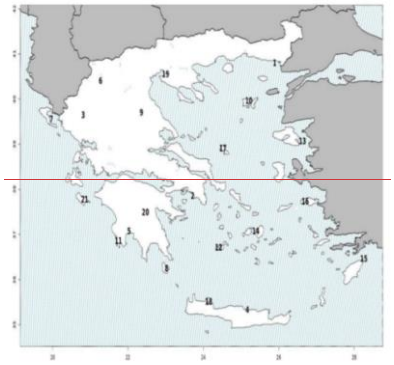
timeseries available for the historical period 1980-2004 have a 3-hour temporal resolution and from these values we have extracted the daily values of TN, TX and RR. Figure 1 shows the position of the stations while Table A1 of Appendix A provides details on the characteristics of the stations~~.~~. We have used the observational data to validate the model datasets ~~with regard to~~regarding the WCCEs for the historical period.



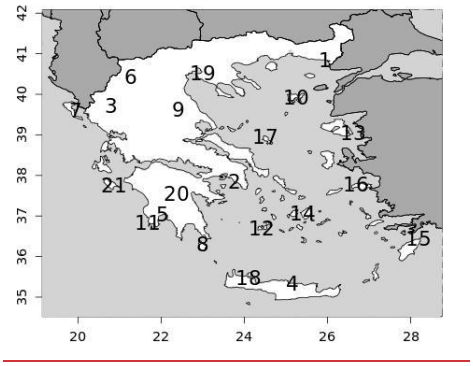


Figure 1: Map of HNMS stations. The numbers correspond to those in Table A1 (Appendix A).

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2.2 Reanalysis models

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

~~1.~~ 2.3 GCM / RCM models

To observe possible alterations of ~~wet-cold-compound-events~~WCCEs occurrence probability in the future period 2025-2049 compared to the historical period, we employed data from RCM simulations driven by GCMs. In this regard, we obtained data from 5 models included in the EURO-CORDEX initiative provided by the Copernicus Program. All chosen EURO-CORDEX models with available daily data were selected because they have ~~a~~the finest spatial resolution of 0.11º x 0.11º ~~and available daily data for both RCP scenarios~~ and have been tested in (Cardoso et al., 2019). Information on the regional and parent models and their acronyms used herewith is given in Table 1. In addition to the EURO-CORDEX model data, we have used dynamically downscaled data from the EC-EARTH GCM to high spatial resolution of 5km x 5km for the area of Greece using WRF (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
Climate Limited-Area Modelling Community	(Rockel et al., 2008)	CLMcom-CLM-CCLM4-8-17	MOHC-HadGEM2-ES	CLMcom	0.11
Swedish Meteorological and Hydrological Institute	(Samuelsson et al., 2016)	SMHI-RCA4	MPI-M-MPI-ESM-LR	SMHI	0.11
Danish Meteorological Institute	(Christensen, 2006)	DMI-HIRHAM5	NCC-NorESM1-M	DMI	0.11
EREL (NCSRD)	(Politi et al. 2020, 2022)	ARW-WRF	EC-EARTH	WRF_EC	0.05

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

~~3.~~ 3. Methodology

~~The process we followed in this work is briefly presented in the flowchart of Figure 2. The light blue steps form the main flow of the approach that mainly include the selection of the compound events based on threshold criteria, validation of the obtained compounds against observational data, and calculation of ththeir occurrence probabilities. The models' validation part is a previous step to the exhibition of modeled data and is added on the data processing step. At the validation step we also compare univariate 20-year return levels using two different approaches, Peaks Over Threshold (POT) and Block Maxima or Minima (BM), further described in section 4.2.2. The calculated probabilities of WCCEs using all models in the historical period have been validated against observations. The yellow boxes describe the results displayed at each step.~~

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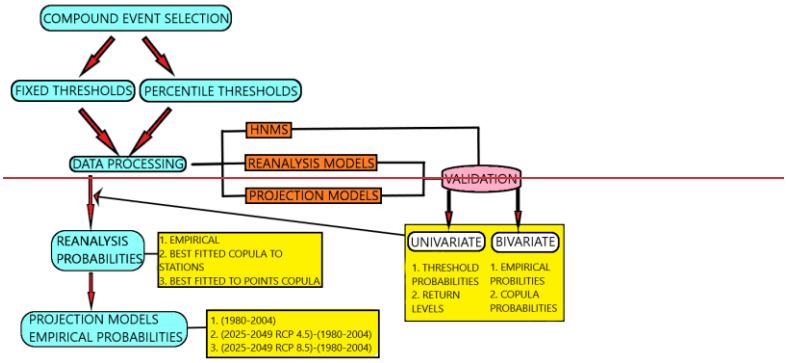

~~**Figure 2: WCCEs methodology process flowchart.**~~

The first step in this study is the validation of the projection and reanalysis models against observations. Moreover, the ensemble of the 6 projection models is also exhibited We choose as the Ensemble resolution that of the CORDEX models since 5 of them share the same spatial resolution. The only model in need of regridding is WRF_EC. We follow the nearest neighbor method to upscale WRF_EC from 5 km to 11 km

~~In the later sections,~~ In addition, ~~w~~we use box-plots to depict the ability of the models to simulate observational data WCCEs probabilities for the historical period at the cells that include meteorological stations. The box-plots consist of the colored box, where in the band near the middle of the box is the median, the bottom and top of each color box are the 25th (Q1) and 75th ~~**Σφάλμα! Η αναφορά της υπερ-σύνδεσης δεν είναι έγκυρη.**~~(Q3) percentile (BL) percentile The lower limit of the whisker (LLW) is calculated by LW= Q1-1.5*BL and the ~~end~~supper limit (ULW) by UW= Q3+1.5*BL. The length of the whiskers ~~are the 1.5 times~~(WL) is calculated as the difference between ~~the 25th~~ULW and LLW~~75th~~ ~~**Σφάλμα! Η αναφορά της υπερ-σύνδεσης δεν είναι έγκυρη.**~~s ~~(WL)~~. Any value out of this range is marked by a black point in the plot. The validation is conducted after the elevation bias correction of temperature at the cells of the models containing the stations. The cells of the stations are found using the nearest neighbor approach and the temperature bias correction temperature is the following:

$$T_s = T_m + 0.06*(H_m - H_s) \quad (1)$$

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

3.1 Compound event selection

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

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The WCCEs, which are examined on daily basis, are divided in two types of synchronous events, TX-RR and TN-RR and studied using ~~two different approaches, (1) the percentile threshold and (2)~~ the fixed threshold approach (Table 2). ~~For the first method the thresholds are the 95th percentile of RR distribution and the 5th percentile of TN and TX distribution. This approach examines the threshold for each variable at each station or grid point.~~ Thise ~~second~~ approach considers the fixed threshold of 20 mm/day for RR and 0 °C for TN and TX for all stations or grid points, as recommended by the Commission for Climatology (CCl), the World Climate Research Programme (WCRP) of the Climate Variability and Predictability Component (CLIVAR) project and the Expert Team for Climate Change Detection and Indices (ETCCDI). TN equal to or under 0 °C indicates Frost Days (FD), while TX equal or under 0 °C Iced Days (ID) (Fonseca et al., 2016). ~~Firstly, we compare the univariate exceedance probabilities and then the bivariate ones. The difference between the two methods is that the percentile approach calculates the probability that an event considered extreme for the study area occurs, while the second that an event considered already extreme occurs.~~ The thresholds examined have been proposed in various works~~studies~~ for ~~both univariate and bivariate cases~~ studying extreme events (Raziei et al., 2014; Tošić and Unkašević, 2013; Anagnostopoulou and Tolika, 2012; Pongrácz et al., 2009; Kundzewicz et al., 2006; Moberg et al., 2006)..

THRESHOLDS	RR	TN	TX	WCCE
FIXED	>= 20 mm/day **(RR20)**	<= 0 ºC **(FD)**	<= 0 ºC **(ID)**	**1. (RR20-FD)** **2. (RR20-ID)**
~~**PERCENTILE**~~	~~>= 95th **(RR95p)**~~	~~<= 5th **(TN5p)**~~	~~<= 5th **(TX5p)**~~	~~**1. (RR95p-TN5p)**~~ ~~**1. (RR95p-TX5p)**~~

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

3.2 WCCEs probability calculation

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

The best fitting copula selection for each timeseries is examined~~done~~ using the R programming language function BiCopSelect as suggested in (Zhou et al., 2019)~~, included in the~~ package VineCopula (Schepsmeier et al., 2013). The appropriate bivariate copula for each dataset is chosen~~,~~ by the function, from a multitude of 40 different copula families ~~-~~using the Akaike Information Criterion (AIC) (Akaike, 1974) and Bayesian Information Criterion (BIC) (Schwarz, 1978), and the copula chosen for each station and model dataset is shown in Appendix B (Tables B1 and B2). Copulas are used in plenty of studies that investigate the dependence between two different climate variables and the joint probability of compound events (Tavakol et al., 2020; Dzupire et al., 2020; Pandey et al., 2018; Cong and Brady, 2012; Abraj and Hewaarachchi, 2021).

As mentioned in Nelsen, (2007), a bivariate copula is a bivariate distribution function where margins 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 $C(1,v)=v$. Let X and Y be random variables with a joint distribution function $F(x,y)=Pr(X \leq x, Y \leq y)$ and continuous marginal distribution functions $F_1(x)=Pr(X \leq x)$ and $F_2(y)=Pr(Y \leq y)$, respectively. By Sklar's theorem (Sklar, 1959), one obtains a unique representation

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$$F(x,y) = C\{F_1(x),F_2(y)\} \quad (2)(1)$$

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

$$F(x,y) = Pr(X>=x,Y<=y) = C(u,v) \quad (3)(2)$$

Besides copula probabilities, we also show the Kendall rank correlation and tail dependence (χ) between the variables (RR_TN) and (RR_TX) to examine the dependence between the variables over all the range and tails of the distribution.

The Kendall rank correlation coefficient evaluates the degree of similarity between two sets of ranks given to a same set of objects (Abdi, 2007) and we prefer it from other correlation types because it provides a distribution free test of independence and a measure of the strength of dependence between two variables. Kendall's tau (τ) is given by Eq. 3, and has a range [-1, 1]:

$$\tau = (Nc - Nd) / (n*(n-1)/2 \quad (3)$$

where, Nc is the number of concordant pairs and Nd the number of discordant pairs.

Tail dependence describes the limiting proportion that one margin exceeds a certain threshold given that the other margin has already exceeded that threshold that has a range [0, 1]. In R, we use the function taildep from package extRemes (Gilleland and Katz, 2016) for the threshold u=0.95 to calculate Chi (χ). Chi is calculated by:

$$chi(u) = Pr[Y > G^{-1}(u) \mid X > F^{-1}(u)] = Pr[V > u \mid U > u], \quad (4)$$

where (U, V) = (F(X), G(Y)) -i.e., the copula.

4. WCCEs assessment in HNMS stations

1. Results in observation locations

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

we firstly examine the dependence between the variables based on the HNMS data and using these data we calculate the probability of WCCEs applying both empirical and copula approaches. Then, we use the HNMS data to validate both reanalysis and projection models during the historical period.

"EVENT"=POSITIVE PROBABILITY		OBSERVATION EVENT	
		YES	NO
MODEL EVENT	YES	A	B
	NO	C	D

Table 2: Contingency table where "A" is the number of event forecasts that correspond to event observations, or the number of hits, Entry "B" is the number of event forecasts that do not correspond to observed events, or the number of false alarms, Entry "C" is the number of no-event forecasts corresponding to observed events, or the number of misses, Entry "D" is the

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number of no-event forecasts corresponding to no events observed, or the number of correct rejections.

~~1. HNMS WCCE climatology~~

4.1 RR20FD

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

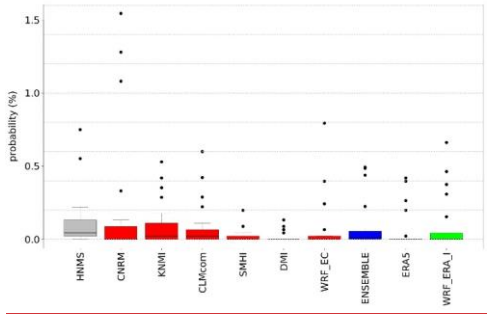

Figure 2: Box-plot presenting RR20FD empirical method probabilities for observations and models.

	HNMS	CNRM	KNMI	CLMcom	SMHI	DMI	WRF_EC	ENSEMBLE	ERA5	WRF_ERA_I
MEAN	**0.1177**	0.2217	0.0977	0.0899	0.0252	0.0158	0.0935	**0.0906**	0.0620	0.098
SD	**0.1912**	0.4641	0.1600	0.1622	0.0480	0.0364	0.2034	**0.1674**	0.1347	0.188
BIAS		-0.1040	0.0199	0.0277	0.0924	0.1019	0.0242	**0.0270**	0.0557	0.018
RMSE		0.3410	0.1216	0.0929	0.1718	0.2029	0.1131	**0.0989**	0.1273	0.111
COR		0.7958	0.7689	0.8804	0.9183	0.4000	0.8371	**0.8604**	0.7949	0.823
CSI		0.4762	0.5500	0.5000	0.4000	0.1905	0.3500	**0.6842**	0.2381	0.400

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

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Μορφοποιήθηκε: Στοιχισμένο στο κέντρο
Μορφοποιημένος πίνακας
Μορφοποίησε: Γραμματοσειρά: 8 στ.
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Μορφοποίησε: Γραμματοσειρά: 8 στ.
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Μορφοποίησε: Γραμματοσειρά: 8 στ.
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Μορφοποίησε: Γραμματοσειρά: 8 στ.
Μορφοποίησε: Γραμματοσειρά: 8 στ., Όχι Έντονα
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Μορφοποίησε: Αγγλικά (Ηνωμένων Πολιτειών)
Μορφοποίησε: Γραμματοσειρά: Όχι Έντονα
Μορφοποίησε: Γραμματοσειρά: Όχι Έντονα

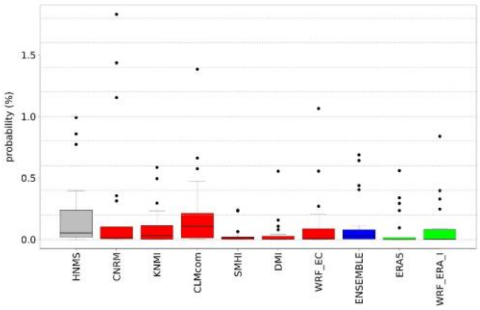


Figure 3: Box-plot presenting RR20FD copula method probabilities for observations and models.

	HNMS	*CNRM*	*KNMI*	*CLMcom*	*SMHI*	*DMI*	*WRF_EC*	*ENSEMBLE*	*ERA5*	*WRF_E…*
MEAN	**0.2032**	0.2592	0.1030	0.2096	0.0341	0.0495	0.1130	**0.1281**	0.0742	0.099
SD	**0.3014**	0.5283	0.1686	0.3323	0.0689	0.1232	0.2558	**0.2160**	0.1524	0.205
BIAS		-0.0560	0.1002	-0.0064	0.1691	0.1537	0.0902	**0.0751**	0.1290	0.103
RMSE		0.2493	0.1891	0.2672	0.2962	0.2743	0.1573	**0.1320**	0.2129	0.169
COR		0.9671	0.9079	0.6307	0.8053	0.6979	0.9004	**0.9610**	0.9140	0.923
CSI		0.8889	0.9444	1.0000	0.9474	0.6190	0.7500	**1.0000**	0.5238	0.700

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

Figure 3 presents the tail dependence for the two different types of compound events examined. Only two stations in Crete show minor dependence between the variables at the tails of the distributions. Figure 4

Figure 4 shows that (RR20-FD) events display higher numbers are located mostly in the mainland, while RR95p-TN5p in the Aegean Sea area. At several stations, there is a difference between the empirical and the copula approach, which in stations usually overestimates the total number of WCCEs.

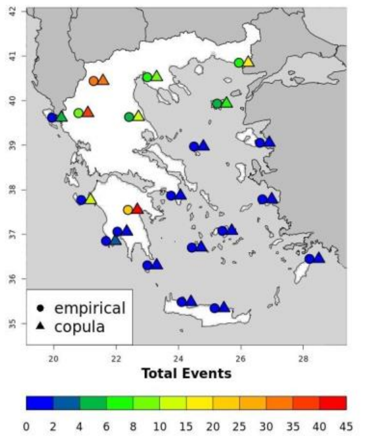


Figure 4: Total number of RR20FD WCCEs (1980-2004). Circles symbolize empirical and triangles the copula method.

4.2 RR20ID

RR20ID events yield, as expected, lower probabilities than RR20FD events as observed in Figures 5 and 6. Most observations and models yield zero probabilities, hence validation of models for these events is limited. Empirical method exhibits only two stations with events in the historical period for the empirical method (Figure 7).

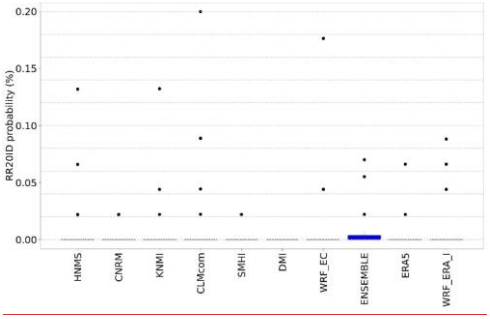
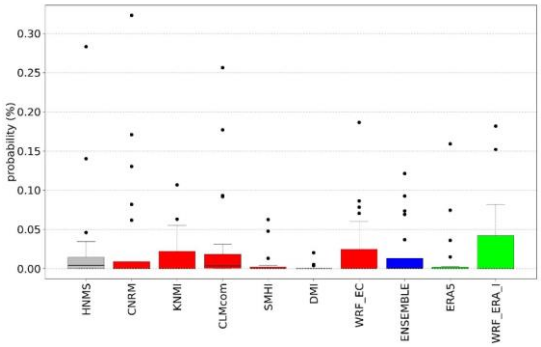


Figure 5: Box-plot presenting RR20ID empirical method probabilities for observations and models.

	HNMS	CNRM	KNMI	CLMcom	SMHI	DMI	WRF_EC	ENSEMBLE	ERA5	WRF_E
MEAN	**0.0115**	0.0032	0.0095	0.0212	0.0011	0.0000	0.0126	**0.0079**	0.0042	0.014
SD	**0.0316**	0.0079	0.0301	0.0494	0.0048	0.0000	0.0398	**0.0191**	0.0150	0.028
BIAS		0.0084	0.0021	0.0096	0.0105	0.0115	0.0011	**0.0036**	0.0073	0.003
RMSE		0.0263	0.0068	0.0280	0.0288	0.0329	0.0330	**0.0157**	0.0220	0.023
COR		0.8185	0.9782	0.8692	0.8738	NA	0.5733	**0.9256**	0.8149	0.699
CSI		0.1429	0.1429	0.1111	0.0476	0.0000	0.1000	**0.1667**	0.0500	0.157

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



Μορφοποίησε

Figure 6: Box-plot presenting RR20ID copula method probabilities for observations and models.

	HNMS	CNRM	KNMI	CLMcom	SMHI	DMI	WRF_EC	ENSEMBLE	ERA5	WRF_E
MEAN	**0.0282**	0.0378	0.0169	0.0344	0.0066	0.0017	0.0249	**2.040E-02**	0.0138	0.027
SD	**0.0663**	0.0811	0.0303	0.0676	0.0166	0.0046	0.0473	**3.640E-02**	0.0377	0.052
BIAS		-0.0097	0.0112	-0.0062	0.0215	0.0264	0.0032	**0.0078**	0.0144	0.000
RMSE		0.0532	0.0493	0.0598	0.0565	0.0691	0.0489	**0.0443**	0.0420	0.033
COR		0.7534	0.7228	0.5861	0.8202	0.2291	0.6594	**0.7712**	0.8370	0.854
CSI		0.4000	0.3810	0.7857	0.4737	0.3333	0.4211	0.7857	0.2857	0.35

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

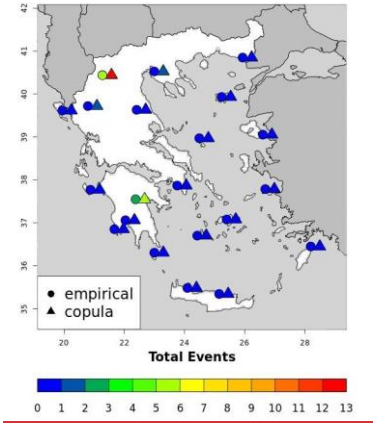


Figure 7: Total number of RR20ID WCCEs (1980-2004). Circles symbolize empirical and triangles the copula method.

4.3 Observations-models comparison conclusions

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

~~In Figure 5a only two stations show a significant number of RR20-ID events. At the percentile threshold approach (Figure 5b), we observe few WCCEs using the empirical method, while all stations show a significant number of WCCEs using the copula method.~~

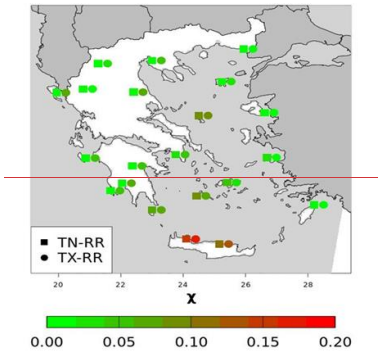


Figure 3: Tail dependence (χ) for TN-RR (squares) and TX-RR (circles).

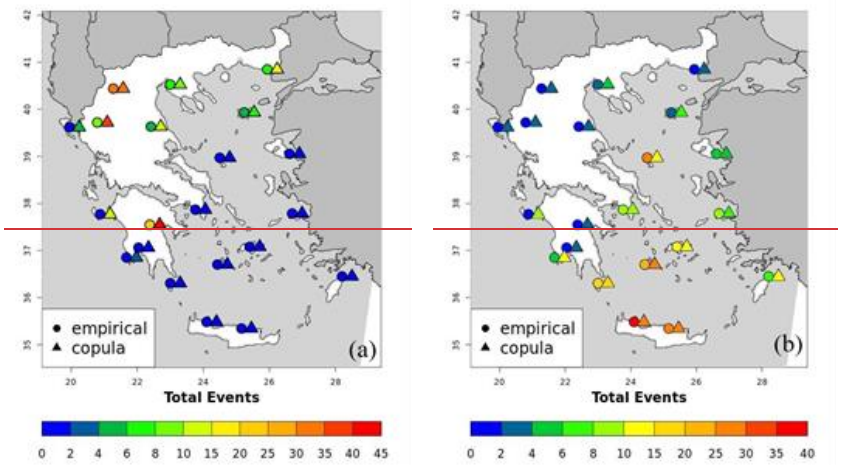
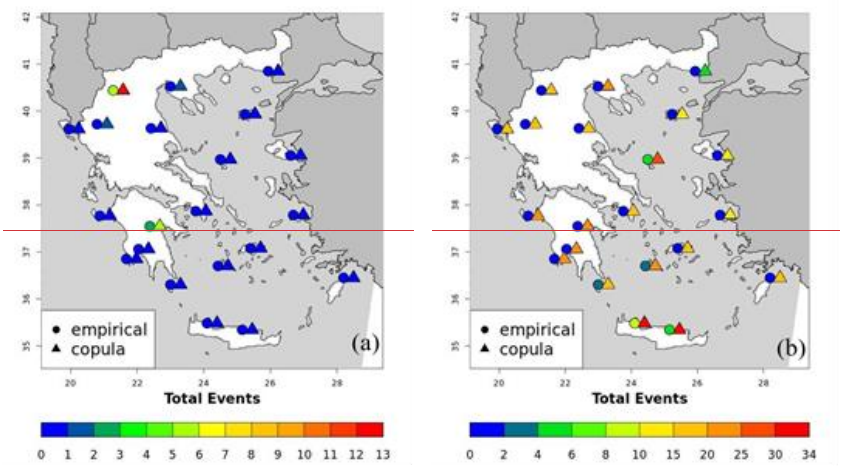


Figure 4: Total number of WCCEs (1980-2004) for (a) RR20-FD and (b) RR95p-TN5p.

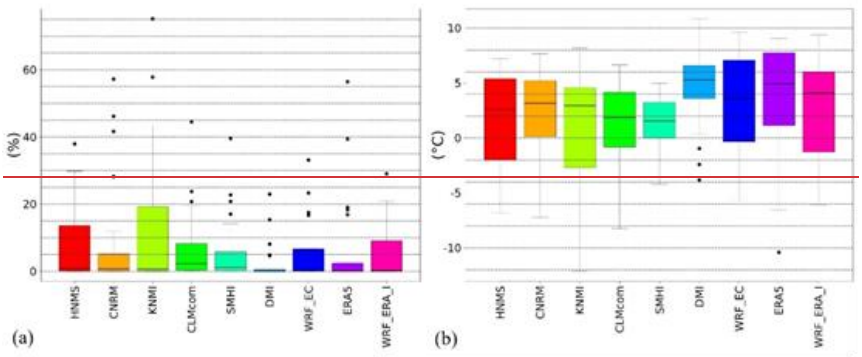


~~**Figure 5: Total number of WCCEs (1980-2004) for (a) RR20-ID and (b)RR95p-TX5p.**~~

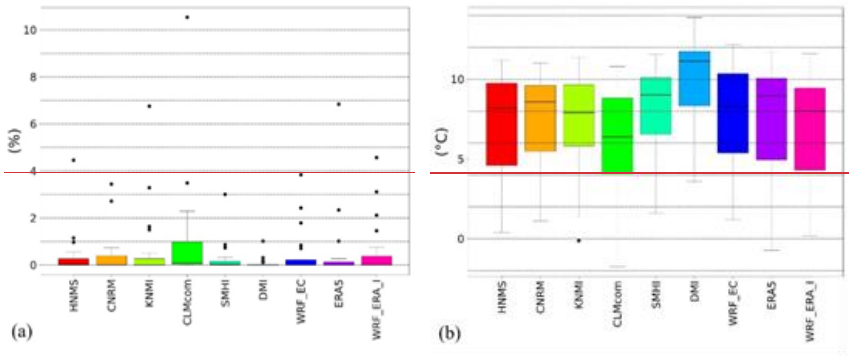
~~2. Univariate validation~~

~~Both reanalysis and projections models are compared to observational data for each variable and for the WCCEs probabilities. Figures 6-8 present the mean values and the standard deviation for stations and the respective models' grid points. The corresponding values for each station are shown in Tables S1-S3 and S5-S7 from Supplementary material.~~

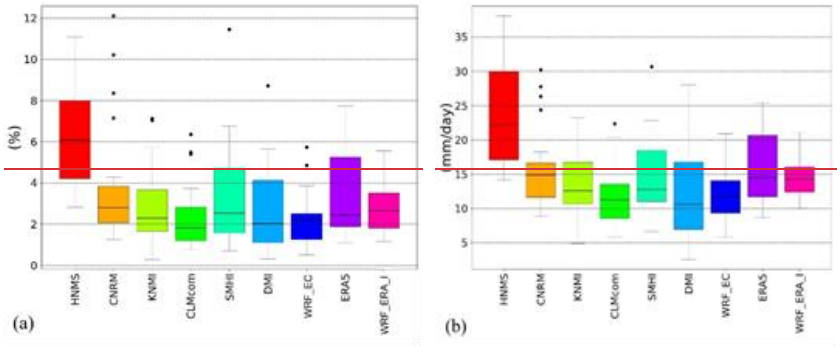
~~4.2.1 Thresholds & Probabilities~~



~~**Figure 6: Boxplots of (a) FD probability and (b)TN5p threshold.**~~



~~**Figure 7: Boxplots of (a) ID probability and (b)TX5p threshold.**~~



~~**Figure 8: Boxplots of (a) RR20 probability and (b)RR95p threshold.**~~

~~For TN and TX (Figures 6 and 7, respectively) seems to be a good concordance of most models mean values with the HNMS data, although there are differences in the range of BL and WL between the models. The model that mostly overestimates TX5p and TN5p thresholds is DMI. For RR (Figure 8), all models underestimate extreme values compared to HNMS with ERA5 being closer to observations.~~

~~4.2.2 Return levels~~

~~Another way to compare extreme values is the calculation of return levels. As mentioned in methodology we use two approaches, (BM) and (POT). For BM we use the annual maximum or minimum value of the variable that results in the loss of information, because there is available only one value per year. BM samples tend to follow the GEV distribution, according to The Fisher–Tippett–Gnedenko theorem (Fisher and Tippett, 1928; Gnedenko, 1943). For BM we fit the GEV by applying the method 'Lmoments' using the function fevd from R package extRemes.~~

~~On the other hand, POT has the advantage of examining more values per year with the chosen condition that the values above the right threshold are considered as extreme (Balkema and Haan, 1974; James Pickands, 1975). The approach is to select as threshold the 90th percentile of the variable distribution (Bommier, 2014). Also, in order to achieve that each extreme value is independent from another, we use a conservative 5-day threshold declustering (Coles, 2001), securing that there are no extreme values affected by the same synoptic system. For POT we fit the Generalized Pareto (GP) distribution, which corresponds to the tail distribution of the GEV (Goda, 2018). As suggested in~~

Poschlod, (2021), we use Maximum Likelihood Estimation (MLE) as an optimization algorithm to fit the GP to the declustered timeseries, using again the extRemes package.

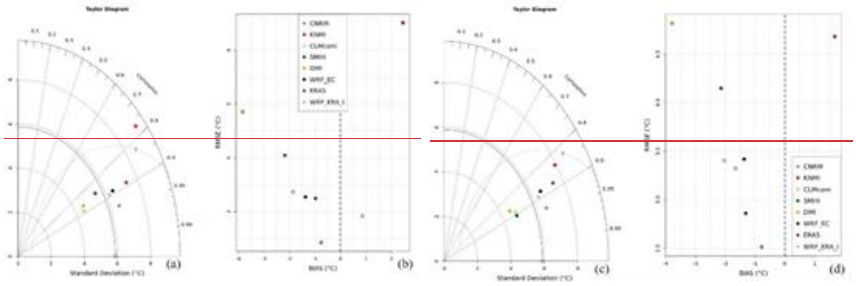


Figure 9: Taylor diagram for TN 20 years return level using (a) POT and (c) BM approach. RMSE-BIAS plots for (b) POT and (d) BM.

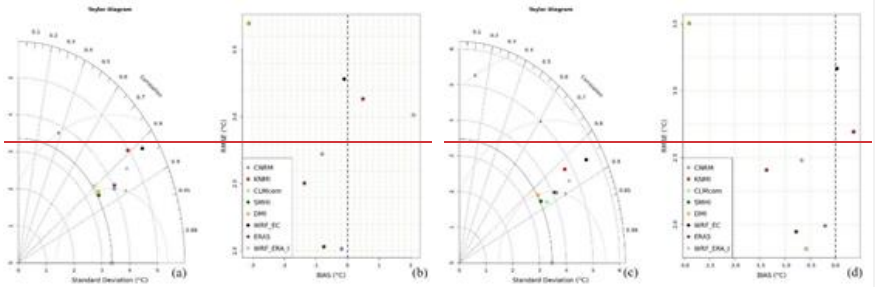


Figure 10: Taylor diagram for TX 20 years return level using (a) POT and (c) BM approach. RMSE-BIAS plots for (b) POT and (d) BM.

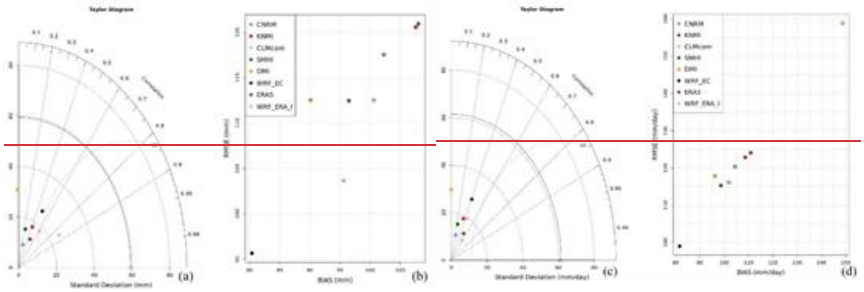


Figure 11: Taylor diagram for RR 20 years return level using (a) POT and (c) BM approach. RMSE-BIAS plots for (b) POT and (d) BM.

Figures 9 and 10 show that the CNRM is the model closer to HNMS TN and TX 20 years return level. Figure 11 yields that WRF_ERA_I has the highest correlation to observations, while WRF_EC the best RMSE-BIAS relation to observations. The values used to produce Figures 9-11 can be found in Tables S11-S16 from Supplementary material.

Bivariate

3. validation

The bivariate validation of the models is conducted by the empirical and copula methods for the WCCEs at the stations. Figures 12 and 13 summarize the results from Supplementary material Tables S4, S5 and S9, S10, respectively.

1. Empirical approach

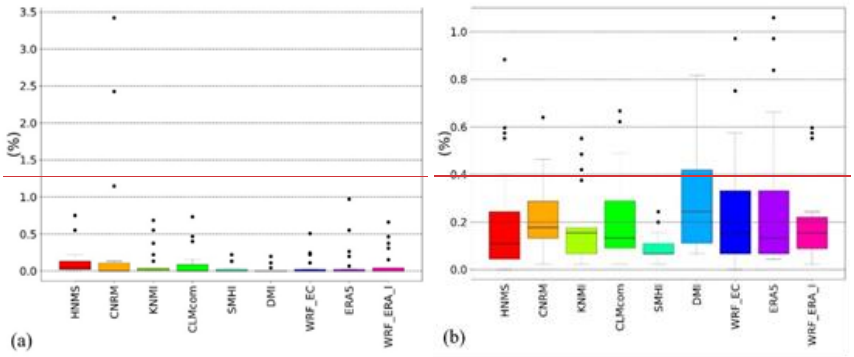


Figure 12: Boxplots of probabilities for (a) RR20-FD and (b) RR95p-TN5p WCCEs.

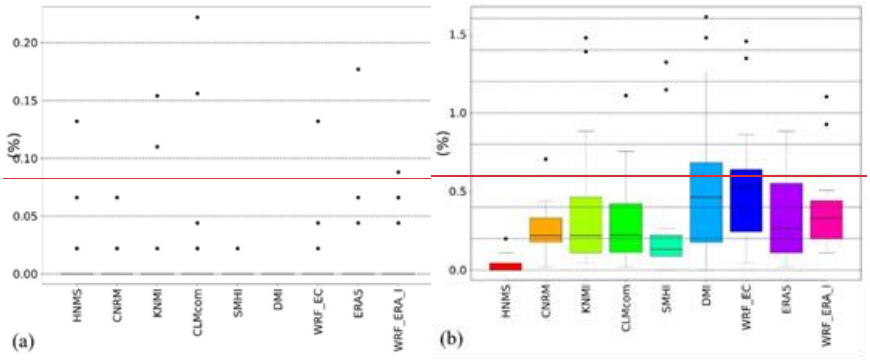
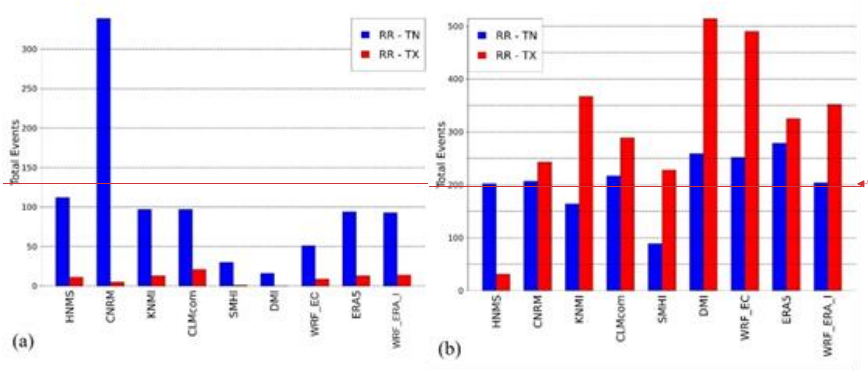


Figure 13: Boxplots of probabilities for (a) RR20-ID and (b) RR95p-TX5p WCCEs.

In Figure 12a, HNMS-BL is greater than all models, although a number of models show values greater than the WL of observations, with CNRM yielding the most extreme values, with 3 cases of more than 1% probability. RR95p-TN5p events probabilities from models are close or over the mean values and BL of HNMS except for the case of SMHI which shows smaller values (Figure 12b). From Figure 13a we find that RR20-ID events are extremely rare at the locations of the stations with few exceptions. DMI exhibits zero events, while the largest probabilities are exhibited by CLMcom with four non-zero probabilities points . In Figure 13b, we see that all models overestimate the probabilities of RR95p-TX5p events with DMI showing the highest probabilities and SMHI the closer to HNMS agreement.

Μορφοποιήθηκε: Εσοχή: Αριστερά: 1,9 εκ., Χωρίς κουκκίδες ή αρίθμηση

Μορφοποιήθηκε: Εσοχή: Αριστερά: 2,54 εκ., Χωρίς κουκκίδες ή αρίθμηση



Μορφοποιήθηκε: Αριστερά

Figure 14: Bar plots of total number of WCCEs for (a) fixed and (b) percentile thresholds for the 1980-2004 period.

In Figure 14, we present a quantitative comparison of the total number of compound events that are counted for all stations and the corresponding grid **points** for each model. For fixed thresholds, most models show good agreement with the HNMS data except of CNRM which overestimates the amount of total WCCEs for the RR-TN case. Also, SMHI and DMI and to a lesser extent WRF_EC underestimate significantly the number of total events for both types. With the percentile threshold approach all models overestimate the number of WCCEs for the RR-TX case, while for the RR-TN case most models are close to the HNMS total number of WCCEs, except of SMHI which underestimates it.

2. Copula approach

Μορφοποιήθηκε: Εσοχή: Αριστερά: 2,54 εκ., Χωρίς κουκκίδες ή αρίθμηση

The best-fitted copulas fixed and percentiles probabilities for each model dataset are compared to the respective HNMS station best-fitted copula in Figures 15 and 16, respectively. We use Taylor diagrams and RMSE-BIAS plots to observe which models are closer to the WCCEs probabilities calculated for the HNMS data.

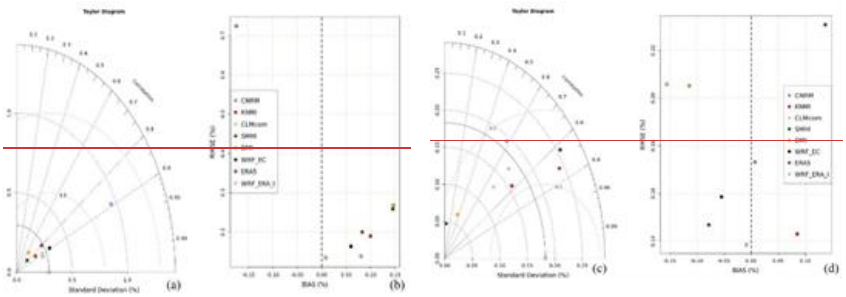
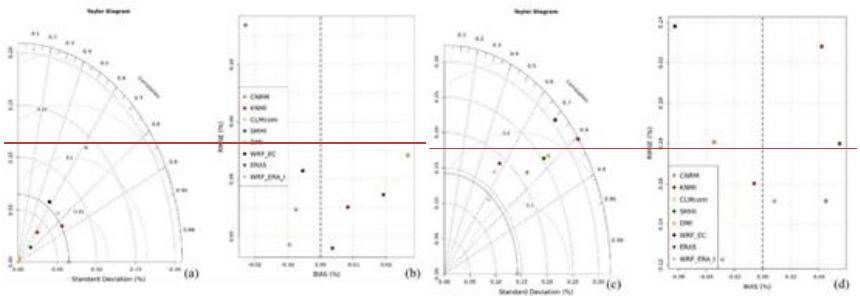


Figure 15: Taylor diagram of WCCEs copula probabilities for (a) RR20-FD and (c) RR95p-TN5p. RMSE-BIAS plots of WCCEs copula probabilities for (b) RR20-FD and (d) RR95p-TN5p.



~~**Figure 16: Taylor diagram of WCCEs copula probabilities for (a) RR20-ID and (c) RR95p-TX5p. RMSE-BIAS plots of WCCEs copula probabilities for (b) RR20-ID and (d) RR95p-TX5p.**~~

~~Figures 15 and 16 show that models agree more with observations on fixed thresholds WCCEs than the percentiles ones, where there is a broader deviation of correlation to observations. Probabilities for WCCEs are generally close to zero for observations and models, therefore RMSE and BIAS values are also almost zero. The values for each station are presented analytically in Tables S19-S22 from the Supplementary material.~~

~~2.~~ 5. Historical period ~~M~~models ~~WCCEs on maps~~

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

~~1.~~ 5.1 Reanalysis

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

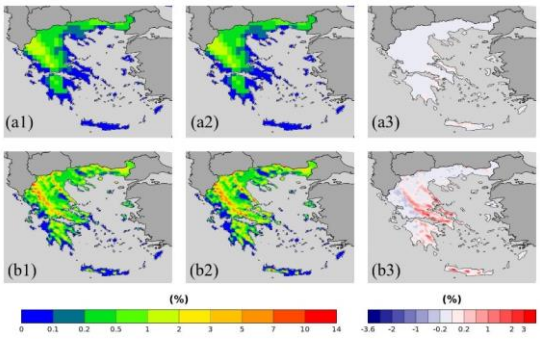


Figure 8: RR20FD probabilities for (a) ERA5 and (b) WRF_ERA_I produced by (1) Empirical and (2) Copula and (3) = (2) –(1).

Μορφοποιήθηκε: Χωρίς κουκκίδες ή αρίθμηση

Μορφοποιήθηκε: Πλήρης

Μορφοποιήθηκε: Εσοχή: Αριστερά: 1,27 εκ., Χωρίς κουκκίδες ή αρίθμηση

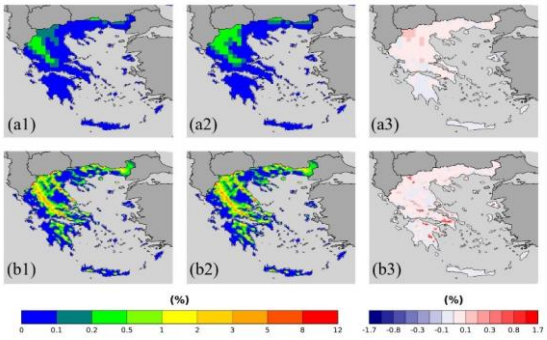


Figure 9: RR20ID probabilities for (a) ERA5 and (b) WRF_ERA_I produced by (1) Empirical and (2) Copula and (3) = (2) –(1).

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

5.2 Projections Ensemble

Figures 10 and 11 yield that Ensemble mean displays similar to WRF_ERA_I spatial distribution of WCCEs. RR20FD and RR20ID probabilities reach 10.8% and 5.4% respectively. The copula method yield higher probabilities for both methods in mountainous regions with greater difference displayed for RR20ID events in thr Pindus mountain range and RR20FD exhibiting greater spatial distribution in differences between the two methods.

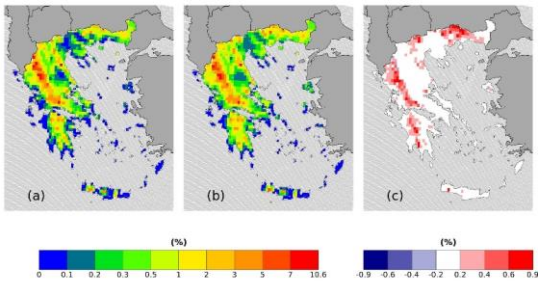


Figure 10: RR20FD Ensemble probabilities for (a) Empirical and (b) Copula method. (c)=(b)-(a).

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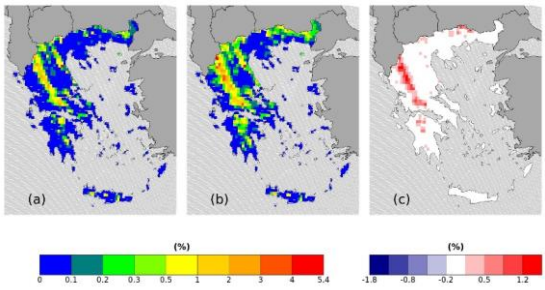

Figure 11: RR20ID Ensemble probabilities for (a) Empirical and (b) Copula method. (c)=(b)-(a).

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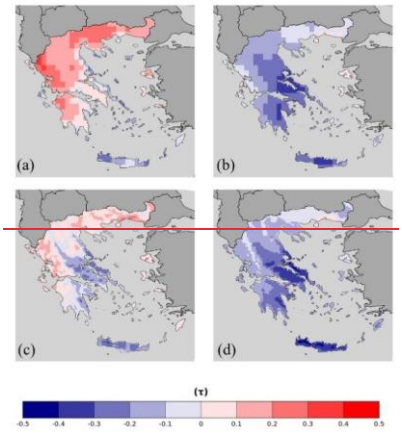
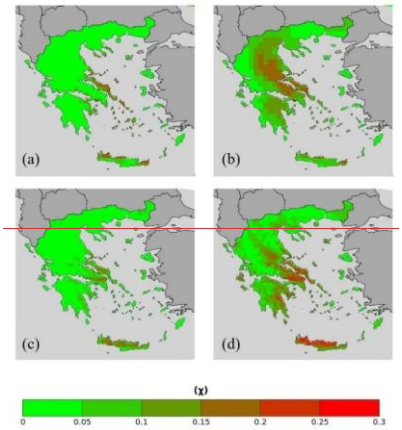
~~Data from reanalysis models provide us with information on the WCCEs for the historical period, at places with no available observational data. Thus, we will examine the probability of WCCEs using three different methods for the reanalysis data. (1) The empirical probability method, (2) the probability calculated by the most common copula from the total of the 21 HNMS stations and (3) the best fitted copula at each grid point of the model. For comparison, we show the differences between each pair of methods. The reason to show the second method is to examine its ability to resemble the empirical method, since it is computationally much faster than method (3). In Tables B1 and B2 of Appendix B it is shown that the best fitted copula for HNMS timeseries is the Rotated BB8 270 degrees for (-TN, RR) bivariate distribution and the Survival BB8 for (-TX, RR) bivariate distribution. In both cases, the copulas are chosen for 10 out of the 21 stations. In the appendix, the univariate probabilities and thresholds are also shown. Firstly, we show the Kendall rank correlation (τ) (Figure 17) and then the tail dependence (χ) (Figure 18) between the variables. For the sake of brevity, we refer to the three methods as (A), (B) and (C).~~



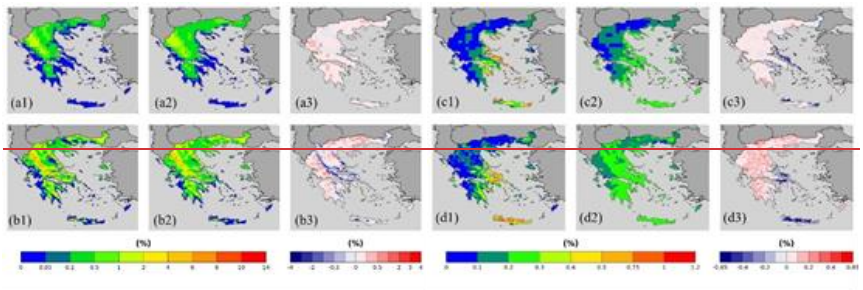
~~Figure 17: Kendall rank correlation (τ) between (a, c) TN-RR and (b, d) TX-RR and (a, b) ERA-5 and (c, d) WRF_ERA_I.~~



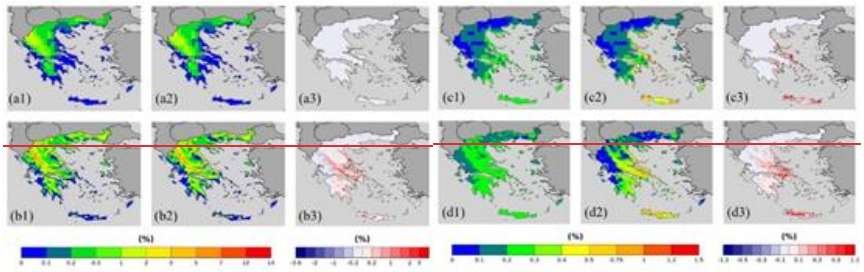
~~**Figure 18: Tail dependence (χ) at 95% between (a, c) TN-RR and (b, d) TX-RR and (a, b) ERA 5 and (c, d) WRF_ERA_I.**~~

~~Figure 17 shows that there is little correlation between the variables with TN-RR having mostly slight positive correlation (17a, 17c), while more negative correlation reaching to -0.5 is calculated for TX-RR (17b, 17d). From tail dependence for the 5 % of the distributions in Figure 18, we see that TX-RR (18a, 18c) are more dependent from TN-RR (18b, 18d) in more regions of the map. Values reach up to 0.3 mainly for TX-RR in eastern Greece and Crete. Also, Figures S1-S3 in th supplementary material present the univariate thresholds and probabilities for RR, TN and TX using the reanalysis datasets (ERA5 and WRF_ERA_I).~~

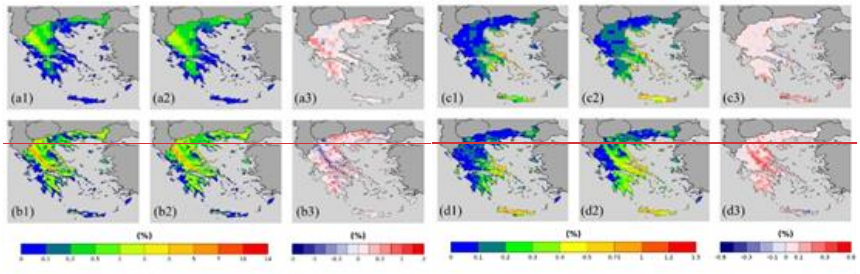
~~**1. TN-RR WCCEs**~~



~~**Figure 19: (a, b) RR20-FD and (c, d) RR95p-TN5p WCCEs probabilities. (a, c) ERA 5 and (b, d) WRF_ERA_I. Column (1) is method A, (2) method B and (3) = (2) – (1).**~~



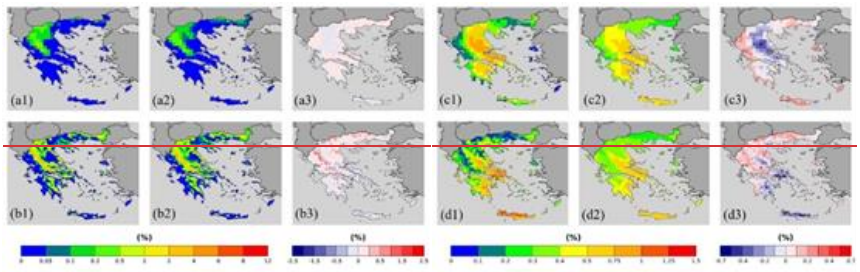
~~**Figure 20: (a, b) RR20-FD and (c, d) RR95p-TN5p-WCCEs probabilities. (a, c) ERA-5 and (b, d) WRF_ERA_I. Column (1) is method B, (2) method C and (3) = (2) – (1).**~~



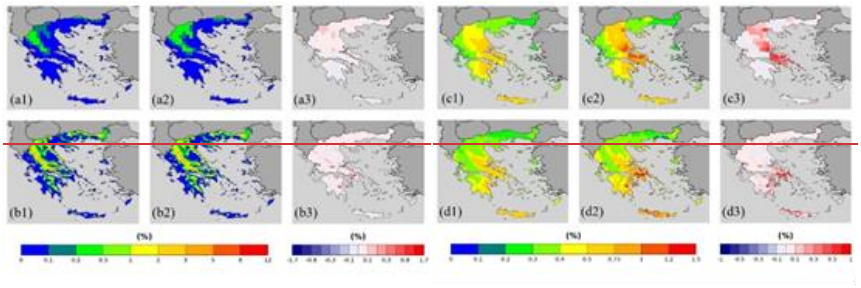
~~**Figure 21: (a, b) RR20-FD and (c, d) RR95p-TN5p-WCCEs probabilities. (a, c) ERA-5 and (b, d) WRF_ERA_I. Column (1) is method A, (2) method C and (3) = (2) – (1).**~~

~~From Figures 19 and 20 we observe that method B underestimates the extreme value probabilities compared to methods A and C. On the other hand, method B exhibits less non-zero values compared to method A. In Figure 21, we see that method C mostly overestimates WCCEs compared to method A, especially for RR95p-TN5p and WRF_ERA_I. RR20-FD events reach at most extreme probabilities of 14%, while for RR95p-TN5p the highest probabilities range between 1.2% and 1.5%.~~

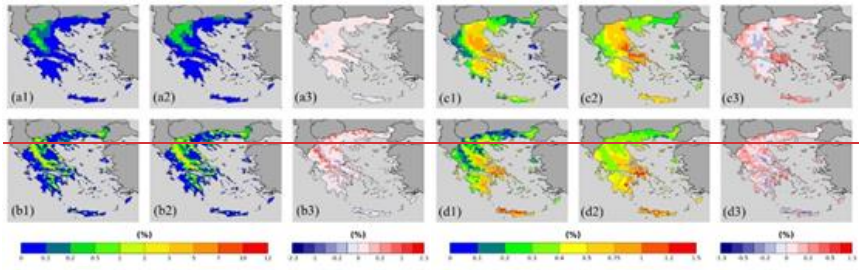
~~**2. TX-RR-WCCEs**~~



~~**Figure 22: (a, b) RR20-ID and (c, d) RR95p-TX5p-WCCEs probabilities. (a, c) ERA-5 and (b, d) WRF_ERA_I. Column (1) is method A, (2) method B and (3) = (2) – (1).**~~



~~Figure 23: (a, b) RR20-ID and (c, d) RR95p-TX5p WCCEs probabilities. (a, c) ERA-5 and (b, d) WRF_ERA_I. Column (1) is method B, (2) method C and (3) = (2) – (1).~~



~~Figure 24: (a, b) RR20-ID and (c, d) RR95p-TX5p WCCEs probabilities. (a, c) ERA-5 and (b, d) WRF_ERA_I. Column (1) is method A, (2) method C and (3) = (2) – (1).~~

~~Figures 22-24 show that RR20-ID events exhibit lower probabilities than RR20-FD events reaching 10% to 12%. RR95p-TX5p reach 1.5% at the most extreme values, which are distributed at a greater area than RR95p-TN5p. On the other hand, method C exhibits the highest probabilities for both approaches events.~~

6. Past-Future Ensemble differences~~Projections comparison~~

~~We compare the historical period probabilities with the probabilities determined for the future scenarios RCP 4.5 and RCP 8.5 for the 2025-2049 period by applying both fixed thresholds and percentiles.~~ This section displays the differences of the Ensemble mean WCCEs probabilities, calculated for the empirical and the copula method, compared to the past probabilities presented in the previous section. The differences mapped are statistically significant at 95% level using the Student's t-test (Goulden, 1939) comparing 25 annual values of the timeseries. ~~We have applied the empirical method to calculate the probabilities of the WCCEs.~~

6.1 RR20FD

~~1.~~

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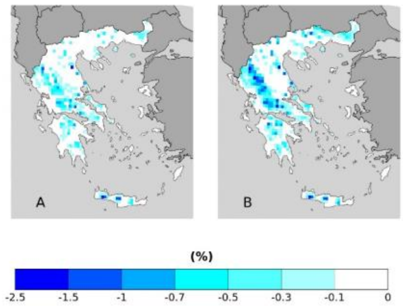

Figure 12: RR20FD empirical method probability differences of future-past periods for (A) RCP4.5 and (B) RCP8.5 scenarios.

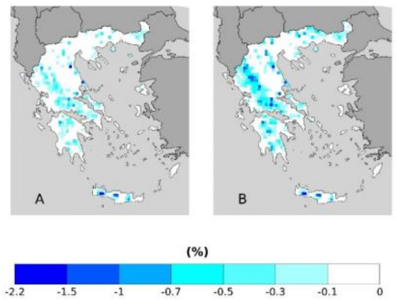

Figure 13: RR20FD copula method probability differences of future-past periods for (A) RCP4.5 and (B) RCP8.5 scenarios.

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

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

From the results displayed in Figures 12 and 13 and in Table 7 RCP4.5 and RCP8.5 scenarios for the probabilities of the RR20FD events probabilities we observe that in all cases future scenarios yield only negative values meaning the reduction of RR20FD events in 2025-2049 period compared to 1980-2004 period in all mountainous regions of Greece. RCP8.5 yields greater reduction of RR20FD probabilities than the RCP4.5 scenario both in spatial distribution and extreme values. The empirical method exhibits a greater reduction for the RCP8.5 scenario, although for RCP4.5 scenario both methods yield similar results.

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6.2 RR20ID

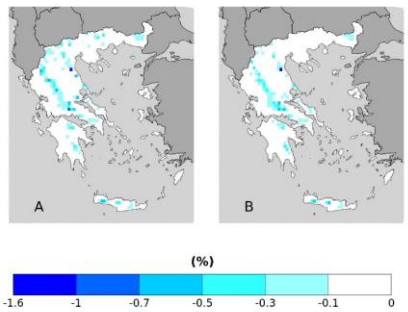

Figure 14: RR20ID empirical method probability differences of future-past periods for (A) RCP4.5 and (B) RCP8.5 scenarios.

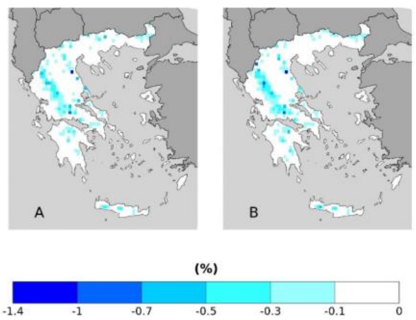

Figure 15: RR20ID copula method probability differences of future-past periods for (A) RCP4.5 and (B) RCP8.5 scenarios.

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

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

Similarly to RR20FD, RR20ID events probabilities yield only zero or negative differences compared to the past for both scenarios. Empirical and copula methods yield similar results in distribution and extreme values. For both methods, the RCP4.5 scenario tends to higher reduction of RR20ID probabilities than RCP8.5 as observed in Table 8.~~The six projection models we previously evaluated, are used here to study their behavior in the calculation of the probabilities of WCCEs. We compare the~~

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historical period probabilities with the probabilities determined for the future scenarios RCP 4.5 and RCP 8.5 for the 2025-2049 period by applying both fixed thresholds and percentiles. The differences mapped are statistically significant at 95% level using the Student's t-test (Goulden, 1939) comparing 25 annual values of the timeseries. We have applied the empirical method to calculate the probabilities of the WCCEs. Univariate thresholds and probabilities are shown in Figures S4-S6 of the supplementary material.

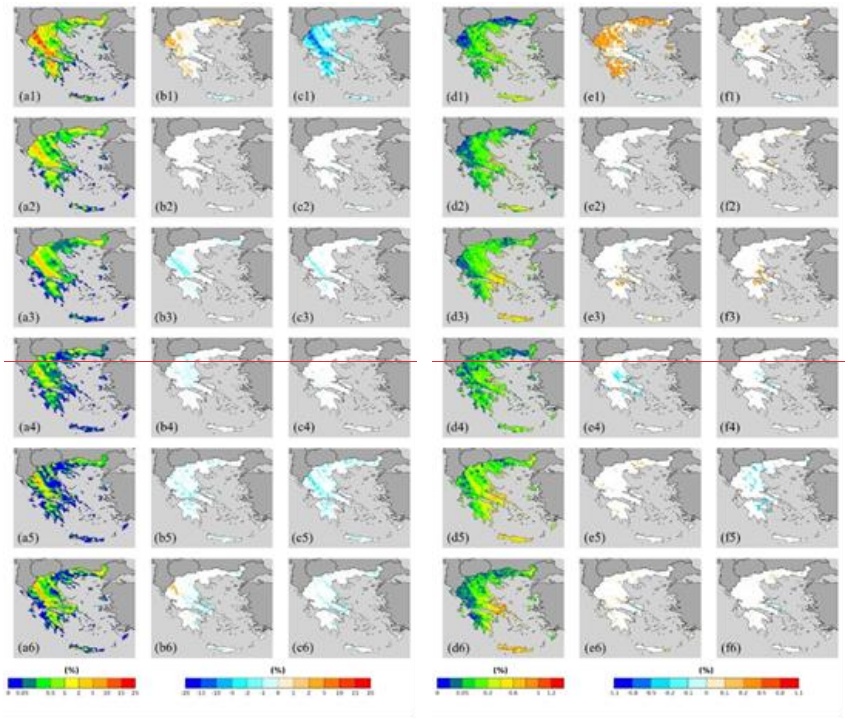

Figure 25: (a-c) RR20-FD and (d-f) RR95p-TN5p probabilities. Models 1: CNRM, 2: KNMI, 3: CLMcom, 4: SMHI, 5: DMI, 6: WRF_EC. (a, d) 1980-2004, (b, c) (2025-2049 RCP 4.5) – (1980-2004) and (c, f) (2025-2049 RCP 8.5) – (1980-2004).

We see from Figure 25a that RR20-FD events probabilities may reach 25% particularly for CNRM, which also exhibits the greatest changes in the future, being mostly positive for RCP4.5 and extremely negative (up to -20%) for RCP8.5. Other models calculate fewer extreme probabilities for RR20-FD events and less extreme changes in the future being mostly negative and found in mountainous areas. RR95P-TN5p events displayed in Figure 25d reach up to 1.5% only for WRF_EC. The rest of the models reach most extreme values in the range of 0.4% to 1%. Most models do not display significant changes in the future, except of CNRM which shows positive changes that spread extensively over Greece.

Figure 26: (a-c) RR20-ID and (d-f) RR95p-TX5p probabilities. Models 1: CNRM, 2: KNMI, 3: CLMcom, 4: SMHI, 5: DMI, 6: WRF_EC. (a, d) 1980-2004, (b, c) (2025-2049 RCP 4.5) – (1980-2004) and (c, f) (2025-2049 RCP 8.5) – (1980-2004).

Figure 26a shows that RR20-ID events are limited to mountainous areas. Again, CNRM exhibits in few areas the most extreme values ranged between 10% to 20%. Similar values are, also exhibited by WRF_EC. These models display the most extreme reduction of the probabilities in the future, reaching 10% to 15 % in the case of CNRM and RCP8.5. WRF_EC, DMI and to a lesser degree KNMI in Figure 26d, yield the most extreme probabilities for RR95p-TX5p events that reach 1%. The most notable changes are displayed by CNRM under RCP4.5, which shows increases in western and northern parts of the country and significant decreases in eastern areas and Crete.

Conclusions

This work presents for the first time to our knowledge an extensive study of wet-cold compound events in Greece for the historical and future periods of 1980-2004 and 2025-2049, respectively. Models' data from the EUROCORDEX initiative of 0.11° resolution and reanalysis data (ERA5 and ERA-Interim dynamically downscaled to 5km^2) were used and validated for the determined WCCEs against the formally available observational datasets by HNMS for the country. The number of events and their probabilities of occurrence were determined by applying a~~two different approaches,~~ fixed thresholds approach~~ and percentiles~~. Then, the bivariate validation of the models' datasets against observations was performed for the determined bivariate thresholds~~ (univariate and bivariate) and the 20 years return levels using blog maxima and POT methods.~~. The ~~probability~~probabilities of WCCEs ~~was~~were computed using the empirical method and the best-fitted copula for the bivariate timeseries for observational data, reanalysis, projection models and the Ensemble of the projection models. Copulas yield higher extreme events probabilities for most of the cases considering the dependence between

temperature and precipitation ~~Moreover, for the reanalysis data, we applied the approach of the most common copula of the 21 observational stations.~~

~~Even though reanalysis and projection models seemed to underestimate extreme precipitation, thus leading to less extreme events, both helped to map the geographical distribution of WCCEs over Greece. All models agreed that for the historical period, more events by the fixed threshold approach were found over mountainous regions while the percentile approach yielded more WCCEs over the eastern parts of the country and Crete.~~Although, there is an absence of stations over mountainous areas we trust the results produced by models since bivariate validation shows good agreement between observations and models. This trust is enhanced by the fact that winter period systems that affect large areas crossing the country from north to south or from west to east (Cartalis et al., 2010) and therefore recorded by available stations. Also, in the cold period of the year convective precipitation forced by orography is limited hence the doubt that the models do not simulate extreme rainfall in winter is reduced. Moreover, the use of the Ensemble mean of the models reduces the probability of models' overestimation or underestimation of extreme events occurrences.

~~Furthermore, the projected changes in the number of WCCEs were investigated under RCP 4.5 and RCP 8.5. Significant changes were obtained using the fixed threshold method over mountainous areas which showed a potential reduction of the number of compound events particularly under RCP 8.5. The application of the percentile method yielded reduced changes in the probabilities of wet-cold compounds than the fixed threshold approach while the models showcased higher disagreement among them concerning the changes.~~

The reduction of RR20-FD and RR20-ID WCCEs on mountains that the Ensemble of~~most~~ projection models ~~predicted for~~predict in the future, might ~~mean~~contribute to less heavy snowfall events and possibly less accumulated snow depth. If such a scenario will be verified, Greece faces the threat of losing the main sources of fresh water that come from melted mountain snow during spring or early summer in the near future. The rise of temperature due to global warming is the main factor for the reduction of WCCEs (Supplementary Figures S5-S7), thus similar mountainous regions in other parts of the planet face similar danger considering the unique characteristics of each area. ~~The change of WCCEs for RR95p (TN5p or TX5p) does not necessarily translate to a corresponding change of snowfall events, since the temperature percentile thresholds are for several occasions higher than 0 °C. Snow events may occur at higher temperatures, however in this study we examined the amount of precipitation and not its type. Next future steps could focus on the investigation of the synoptic systems that cause wet-cold compound events in the area of interest. The higher resolution reanalysis and projection simulations used in the study, WRF_ERA_I and WRF_EC, exhibited with greater detail the distribution of WCCEs, highlighting the need for high resolution model data for areas with diverse topography like Greece.~~

Acknowledgments

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Code and data availability

Code and results data available upon request.

Author contributions

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

Competing interests

The authors declare that they have no conflict of interest.

Appendix ~~A~~

NUMBER	LOCATION	ID	LATITUDE	LONGITUDE	ELEVATION (m)
1	Alexandroupoli	16627	40.85	25.917	4
2	Elliniko	16716	37.8877	23.7333	10
3	Ioannina	16642	39.7	20.817	483
4	Irakleio	16754	35.339	25.174	39
5	Kalamata	16726	37.067	22.017	6
6	Kastoria	16614	40.45	21.28	660.95
7	Kerkira	16641	39.603	19.912	1
8	Kithira	16743	36.2833	23.0167	167
9	Larisa	16648	39.65	22.417	73
10	Limnos	16650	39.9167	25.2333	4
11	Methoni	16734	36.8333	21.7	34
12	Milos	16738	36.7167	24.45	183
13	Mitilini	16667	39.059	26.596	4
14	Naxos	16732	37.1	25.383	9
15	Rhodes	16749	36.42896	28.21661	95
16	Samos	16723	37.79368	26.68199	10
17	Skyros	16684	38.9676	24.4872	12
18	Souda	16746	35.4833	24.1167	151
19	Thessaloniki	16622	40.517	22.967	2
20	Tripoli	16710	37.527	22.401	651
21	Zakinthos	16719	37.751	20.887	5

Μορφοποιημένος πίνακας

Table A1: HNMS stations information.

~~Appendix B~~

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830 ~~Table B1: (-TN, RR) best-fitted Copula for each station timeseries.~~

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Μορφοποιημένος πίνακας

834 ~~Table B2: (-TX, RR) best-fitted Copula for each station timeseries.~~