Evaluation and Projection of Vb-Cyclones and Associated North-Western Mediterranean Sea State in Regional Coupled Climate Simulations

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Evaluation and projection of Vb-cyclones and associated North-Western Mediterranean Sea state in regional coupled climate simulations

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Abstract Vb-cyclones propagating from the North-Western Mediterranean Sea into Central Europe are often associated with extreme precipitation. This study explores the state & process chains linking the North-Western Mediterranean Sea and the Vb-event precipitation in Danube, Elbe, and Odra catchments in regional coupled atmosphere-ocean climate simulations with COSMO-CLM+NEMO. Two high-resolution simulations, an evaluation simulation (1951-2005) downscaling the centennial ERA-20C reanalysis and a continuous simulation (historical 1951-2005 + RCP-8.5 future scenario 2006-2099) downscaling the EC-EARTH global climate RCP-8.5 projection are used for this purpose. Sea surface temperature (SST) validation with observations over the Mediterranean Sea reveals a cold bias ($\approx 1 - 1.5$ K) in the historical & evaluation simulations. There is a good agreement in mean annual Vb-cyclone frequency between the evaluation (9.7 events/year) and the historical (10.1 events/year) simulations. But, there are significant discrepancies in the seasonal cycle. The mean cyclone intensity measured with minimum central pressure, track density, and precipitation rankings in the catchments also show good agreement. A basin-average SST warming of $\approx 2.5 - 3$ K, but insignificant changes in Vb-frequency, mean intensity, and precipitation in the catchments are projected by the end of the 21^{st} century. The North-Western Mediterranean SST, evaporation, and wind speed anomalies corresponding to the precipitation rankings over the three catchments & associated process chains differ between the evaluation & historical simulations. In the evaluation simulation, Vb-cyclone precipitation rankings correspond with SST, evaporation, and wind speed anomalies, while in the historical & the future simulation no such correspondence is seen. Especially the Adriatic & Ionian basins show no sensitivity to the Vb events in the EC-EARTH driven simulation. The change in the processes might be

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because of the emergence of simulation biases inherited from the driving EC-EARTH global simulation.

Keywords Regional Coupled Climate Modeling; · Vb-Cyclones · Precipitation · Air-Sea Interactions

1 Introduction

Observational and modeling studies relating to the global temperature and precipitation changes provide confidence in the current ongoing global warming (Stocker et al, 2013). Changes in the extreme weather and climate events such as warm/cold days and nights, heat waves, droughts, heavy precipitation events induced by the anthropogenic global warming were observed in the last century (Fischer et al, 2013; Wilcox and Donner, 2007; Trenberth, 1999; Nishant and Sherwood, 2021; Beniston et al, 2007; Seneviratne et al, 2012). Specifically, short-term precipitation extremes often result in heavy damage to infrastructure and life, and hence are in need of further investigations.

Over Central Europe, extra-tropical cyclones named Vb-cyclones are often associated with extreme precipitation, especially in the summer season (Hofstätter et al, 2018; Blöschl et al, 2013). These Vb-cyclones develop over the North-Western Mediterranean Sea typically over the Gulf of Lions and travel northeastward through the eastern Alps to Central Europe (van Bebber, 1891; Messmer et al, 2015). Often, extreme precipitation occurring in the catchments of Danube, Elbe and Odra is linked to the Vb-cyclones.

Though the occurrence of Vb-cyclones is rare (typically about 4-10 events on average per year) they are of considerable importance due to the extreme precipitation they bring to Central and Eastern Europe (Hofstätter et al, 2016; Messmer et al, 2015). These events occur throughout the year with a peak frequency in spring (Hofstätter et al, 2016, 2018). The Vb-events are typically fed from the evaporation over continental land and nearby oceans. For example, enhanced evaporation over the Mediterranean Sea and subsequent increase of available total water content in the atmosphere during Vb-cyclones was studied by Hofstätter and Chimani (2012) & Messmer et al (2017). Based on a model sensitivity study, Volosciuk et al (2016) reported an increase in precipitation by 17% over Central Europe with warmer sea surface temperatures (SST) over the Mediterranean Sea compared with a simulation run by average Mediterranean SST for the period 1970-1999. Results from Volosciuk et al (2016) relied on a stand-alone coarse-resolution global atmosphere model without dynamic coupling of the ocean, missing crucial air-sea feedback processes. The role of the Mediterranean Sea in enhancing the August 2002 flood in the early stages was shown in Sodemann et al (2009); James et al (2004); Gangoiti et al (2011). Furthermore, a sensitivity study by Messmer et al (2017) confirmed the Mediterranean Sea role in supplying moisture to Vb-cyclones. However, other studies concluded that the moisture transport from the North Atlantic, Black Sea, continental moisture are major sources contributing to

the precipitable water for Vb-cyclones (James et al, 2004; Gangoiti et al, 2011; Krug et al, 2021a).

Krug et al (2021a) analyzed about 1107 Vb-cyclone events simulated by a regional coupled climate model during the period 1901-2010. Their study concluded that the North-Western Mediterranean Sea played an active role in the early stage intensification of the Vb-cyclones and also in pre-moistening the continental land. Furthermore, high precipitation Vb-cyclone events were associated with anomalously high dynamically driven evaporation. However, with Lagrangian moisture source diagnostics on selected 16 Vb-events, their study revealed that continental moisture recycling, the North Sea, the Baltic Sea, the North Atlantic, and the Black Sea were major sources of moisture supply to the Vb-cyclones. Krug et al (2021b) reported a significant information exchange between the evaporation over the North-Western Mediterranean Sea and Vb-cyclone precipitation over the Odra catchment. Above mentioned studies highlight the North-Western Mediterranean Sea's role.

Though the Vb-cyclone events and the role of the Mediterranean Sea as a moisture source were investigated in the past studies, the Vb-cyclone's future projections and the role played by the Mediterranean Sea in the warming climate are yet to be investigated. Especially, the Mediterranean Sea being a hot spot of climate change, investigating its role in the future Vb-cyclones is of extreme importance. Using a global climate model (GCM), ECHAM5/OM1, Nissen et al (2013) reported a decrease in the number of Vb-cyclones by the end of the 21st century but an increase in precipitation amount by 16% compared to the present. Messmer et al (2020), investigated the climate change impacts on Vb-cyclone characteristics using a global climate model, i.e., Community Earth System Model (CESM) ensemble simulations. Their results confirmed a minor decrease in the frequency of Vb-cyclones from 2.9 to 2.6 Vb-cyclones per year by the end of 21^{st} century. They also found a subtle eastward shift in the Vb-cyclone frequency pattern. Furthermore, by downscaling the 10 heaviest precipitation Vb-cyclone events with the Weather Research and Forecasting (WRF) model in future and historical periods, they reported insignificant changes in the total precipitation amount. It is to be noted that the study by Messmer et al (2020) downscaled only 10 Vb-cyclone heavy precipitation events in the past and future periods.

To simulate mesoscale systems such as the Vb-cyclones and analyze their climatic characteristics, high-resolution regional climate model simulations in long centennial periods are desirable. Mittermeier et al (2019) using a Canadian Regional Climate Model Large Ensemble (CRCM5-LE) (Leduc et al, 2019) at a resolution of about 12 km (0.11°) studied future Vb-cyclone frequency and precipitation changes over Bavaria from 1950-2099. They reported a non-significant increase in the absolute number of Vb-cyclones per year in the future period. Also, a significant decrease in future summer Vb-cyclone frequency and increase in spring. A significant increase in daily precipitation intensity was also reported over Bavaria.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is an initiative that coordinates scientific groups for such high-resolution re-

gional climate data sets (Giorgi, 2006). The regional climate model COSMO-CLM is used for dynamically downscaling GCMs over various CORDEX domains (Asharaf and Ahrens, 2015; Russo et al, 2020; Drobinski et al, 2020; Evans et al, 2021). The added value of such high-resolution simulations was well documented in the studies by Schlemmer et al (2018); Imamovic et al (2019); Panosetti et al (2019); Hentgen et al (2019); Brogli et al (2019); Sørland et al (2021). However, the COSMO-CLM often uses prescribed SSTs from the driving GCMs which are handicapped by their coarse resolution and unrealistic air-sea dynamic interactions. Especially given the importance of the Mediterranean Sea in the evolution of Vb-cyclone events, a realistic and dynamically interactive ocean model is thus important.

The COSMO-CLM is coupled to Nucleus for European Modeling of the Ocean (NEMO) over the Mediterranean sea (NEMOMED12) along with a river run-off model TRIP to make the regional system dynamically interactive (Akhtar et al, 2018). The added value of such a coupled regional system was reported by Kelemen et al (2019) on the representation of European continental precipitation. Furthermore, Primo et al (2019) reported the added value in terms of extreme air temperatures. This coupled system was earlier used to study Vb-cyclones in the historical period by Akhtar et al (2019) and Krug et al (2021a). Their study demonstrated the ability of the coupled system in representing the past Vb-cyclone events realistically. Furthermore, Krug et al (2021a) analyzed the total precipitation sums of a few selected Vb-cyclone events (1901–2010) simulated by the coupled system driven by the ERA-20C reanalysis. They reported that the coupled system precipitation patterns & magnitudes agree well with the CRU (Harris et al, 2020) and the E-OBS (Cornes et al, 2018) precipitation observational data sets.

In the current study, we apply the regional climate coupled model (COSMO-CLM–NEMOMED12–TRIP) for the period 1951-2099 continuously using the EC-EARTH GCM as driving data. The simulation used historical greenhouse gas emissions for the historical period 1951-2005 and RCP-8.5 forcing scenario for the future period (2006-2099) at 0.11° (≈ 12 km) horizontal resolution. This simulation was a part of the coordinated activity by various institutions within the Med-CORDEX phase-II framework. The Med-CORDEX focuses on coordinated multi-model and multi-scenario studies covering the Mediterranean region with high resolution coupled regional climate models (Ruti et al, 2016). As the Mediterranean Sea plays an important role during the Vb-cyclone events, first we compared the Mediterranean SST of our coupled simulations with observations (for the historical period) along with the Med-CORDEX ensemble members.

We evaluate the EC-EARTH driven regional climate simulation with the ECMWF twentieth century reanalysis (ERA-20C) driven coupled regional climate simulation for Vb-cyclone frequency and characteristics in the historical period before we proceed to investigate the future Vb-cyclone characteristics. Thereafter the North-Western Mediterranean Sea state in terms of SST, evaporation & wind speed corresponding to the Vb-cyclone precipitation over the three catchments, the Danube, Elbe and Odra in the two simulations

is analyzed. Finally to quantify the process chain linking the North-Western Mediterranean Sea and the Vb-precipitation over the three catchments we use information theory methods similar to the studies by Pothapakula et al (2019, 2020); Krug et al (2021b). These studies used information exchange to quantify the Indo-Pacific coupling, the interplay between the Indian Ocean dipole & El-Niño southern oscillations with the Indian Monsoon precipitation, and, the role of North-Western Mediterranean Sea evaporation during the Vb-cyclone precipitation over Odra catchment. More details about these methods and the simulations are explained in the data and methodology section.

Specifically, we ask the following questions in this study:

1. Is the SST from the regional coupled simulation driven by the EC-EARTH GCM comparable to the observed SST in the historical period. Furthermore, does it produce future SST climate signals in line with the Med-CORDEX phase-II ensemble?

2. Does the EC-EARTH driven coupled regional simulation produce Vb-events comparable to the ERA-20C reanalysis driven coupled regional simulation in the historical period. Do the Vb-cyclones change in the future?

3. Does the state of the North-Western Mediterranean Sea and the process chain differ between the two simulations in the historical period & in the future period?

This paper is organized as follows. Section 2 consists of data and methodology which describes the climate models, the Vb-cyclone tracking, and a brief introduction to information theory methods. Thereafter, we present the results and discussion in Section 3 which includes validation of the EC-EARTH driven SST, the Vb-cyclones in historical and future periods. Results representing the state of North-Western Mediterranean Sea & quantifying the process chain interms of information exchange to the Vb-cyclone precipitation over the three catchments are also presented in this section. Finally, some conclusions and outlook are given in Section 4.

2 Data and Methods

2.1 Regional Coupled Climate Model Setup

The dynamical downscaling was performed with the regional climate model COMSO-CLM 5-0-9 (Rockel and Geyer, 2008) as the atmospheric component (Sevault et al, 2014). The COSMO-CLM is a non-hydrostatic regional model designed for applications across various spatial and temporal scales. The governing equations were numerically solved by the Runga Kutta time-stepping scheme (Wicker and Skamarock, 2002). It used the Arakawa-C grid in rotated geographical coordinates and follows terrain sigma vertical coordinates. The horizontal resolution of COSMO-CLM was about 0.11° and used 40 vertical layers representing about 22.7 km of the atmospheric column. The applied physical parameterizations included the Ritter and Geleyn (1992) radiative scheme, the Tiedtke convection scheme, and a four-category microphysics

scheme (Doms and Baldauf, 2011; Doms et al, 2011). The soil-vegetation-atmosphere-transfer sub-model (TERRA-ML) provided the lower boundary conditions over land. The current simulation used the AeroCom Global AOD data (Kinne et al, 2006) to represent the aerosol properties. The initial and the lateral boundary files were taken from the EC-EARTH available through the SMHI Sweden (Hazeleger et al, 2012). The lateral boundary files were updated every 6 hours for the entire simulation period (1951-2099).

The NEMOMED12 is the ocean component of the coupled regional climate system (Sevault et al, 2014). The regional version of the NEMO-V2.6 was adapted over the Mediterranean region named NEMOMED12. The domain of the NEMOMED12 covers the entire Mediterranean Sea at a horizontal resolution of $\approx$ 7.5km along with a buffer zone nearby the Atlantic Ocean. A 3D relaxation of the temperature and salinity was performed at the buffer zone so as to realistically simulate the circulation from the Atlantic through the strait and into the Mediterranean Sea. The Black sea was parameterized such that the resultant net balance of the water budget is added into the Mediterranean Sea. The water budget was closed through the Total Runoff Integrating Pathways (TRIP) model (Oki and Sud, 1998) which supplies freshwater influx at the Mediterranean river mouths. For more information on the NEMOMED12 readers are advised to refer Somot et al (2008); Sevault et al (2014). The coupling of the sub-components in the regional coupled system was done by OASIS-MCT3 coupler (Valcke, 2013).

We also discussed the results from a simulation with similar set-up (in addition to the Mediterranean Sea, North & Baltic Sea were additionally coupled) but driven by the ECMWF twentieth century reanalysis, ERA-20C (Poli et al, 2016). The performance of ERA-20C downscaled simulation in realistically replicating the Vb-cyclone events & their associated precipitation was already reported and analyzed in the study by Krug et al (2021a). Hence in this study, we used the ERA-20C downscaled simulation as a reference for validating the downscaled EC-EARTH simulated Vb-cyclone events & their associated precipitation in the historical period. From hereafter the downscaled simulation driven by ERA-20C is referred to as evaluation simulation, the downscaled EC-EARTH simulation in the historical period (1951-2005) as historical simulation, and finally the future period (2045-2099) of downscaled EC-EARTH simulation as a future simulation. Each of these simulations covered a period of 55 years.

2.2 Observational data sets and Med-CORDEX ensemble members

To validate the SST obtained from the evaluation & historical regional coupled simulations, we used the UK Met Office's Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST 1.1) (Rayner et al, 2003) in the historical period. In addition, we also used the NOAA Optimum Interpolation (OI) SST V2 (Reynolds et al, 2002) as another source of observational data set. Furthermore, as our downscaled simulation with EC-EARTH was a part of

coordinated activity contributing to the Med-CRODEX phase II simulations, we also used the SST data sets available from the Med-CORDEX phase-II database to evaluate our simulations. The institutions and the models are described in Table 1.

Table 1: RCMs/observations descriptions for SST evaluation over the Mediterranean Sea.

RCM Modeling Institution	**Acronym**	**driving model**
University of Belgrade	EBUPOM2c	MPI-ESM-LR
CNRM Meteo-France,Toulouse	CNRM-RCSM4	CNRM-CM5
Helmholtz-Zentrum Hereon, Geesthacht	GERICS-AWI-ROM44	MPI-ESM-LR
Helmholtz-Zentrum Hereon, Geesthacht	GERICS-AWI-ROM22	MPI-ESM-LR
Goethe-University Frankfurt (GUF)	CLMcom-GUF-CCLM5-0-9-NEMOMED12-3-6	EC-EARTH
Observations and Reanalysis data sets		
HadISST	–	–
OISST	–	–
Goethe-University Frankfurt (GUF)	CLMcom-GUF-CCLM5-0-9-NEMOMED12-3-6-NEMO-NORDIC-3.3	ERA-20C

The SST data sets from the models in Table 1 are available through the Med-CORDEX website (https://www.medcordex.eu). The University of Belgrade used the Princeton Ocean Model (POM) as the regional ocean component and the limited area model Eta/NCEP for the atmospheric component (Djurdjevic and Rajkovic, 2008), the Centre National de Recherches Meteorologiques (CNRM), Meteo France used the NEMOMED8 as the ocean model and the ALADIN-Climate model as the atmospheric component (Sevault et al, 2014). The GERICS-AWI Helmholtz-Zentrum Hereon Geesthacht, Climate Service Center Germany used the MPIOM developed at the Max Planck Institute for Meteorology (Hamburg, Germany) as the ocean component and REMO as the atmospheric component. All the SST data sets were interpolated onto a common grid prescribed by the Med-CORDEX community named OMED-11i which is approximately 12 km in resolution. Note that simulations obtained from the Med-CORDEX database were used only for evaluating the SST signal from our Goethe-University Frankfurt (GUF) simulations.

2.3 Vb-Cyclone tracking

For detecting & tracking Vb-cyclones we used a tracking algorithm developed by Wernli and Schwierz (2006) which was later modified by Sprenger et al (2017). We used the mean sea level pressure output from the dynamically downscaled ERA-20C, GUF evaluation simulation, the EC-EARTH driven GUF historical and future simulation as an input for the tracking algorithm (at a 6-hourly interval). Initially, within the domain, 25° W–45° E and 25° N–75° N, closed isobars were tracked and the deepest pressure within the closed isobar was considered to be the cyclone center. Thereafter, the next following track point cyclone center was selected by a guess on the past displacement

vector within a search of radius 1000 km. The tracking algorithm considers all the cyclones crossing the 47° N latitude and between the longitudes, 12° E and 22° E with a lifetime greater than 24 hours (Hofstätter et al, 2016; Wernli and Schwierz, 2006). For more details regarding the tracking algorithm, the readers are directed to refer Krug et al (2021a).

2.4 Vb-cyclones & North-Western Mediterranean Sea state

After the Vb-cyclone tracking in GUF simulations, we analyzed their frequency of occurrence, track density, minimum central pressure, and precipitation. As the Vb-cyclone are rare events, we considered 55 years in the historical and future periods to account for sufficient Vb-cyclone cases. Hence the historical period was taken from 1951-2005 & the future period from 2045-2099 in this study. The number of Vb-cyclone events per year along with their linear trends and respective 95% confidence intervals was analyzed in the GUF evaluation, historical, and future simulations. The minimum central core pressures obtained from the simulations were plotted using box whiskers.

For the Vb-precipitation analysis, we selected three important catchments i.e., the Danube, Elbe, and Odra (shown as rectangles in black, orange, and green colors respectively in Figure 3). The area-averaged precipitation sum anomaly accumulated during the Vb-cyclone days over these catchments was further ranked according to the intensity. The precipitation sum anomaly during the Vb-event was calculated by subtracting the day sum with the climatology day sum precipitation in the GUF evaluation, historical, and future simulations respectively. In addition to the Vb-cyclone precipitation anomaly rankings, we also showed the absolute precipitation amounts.

Corresponding to the Vb-cyclone precipitation anomaly rankings we analyzed the state of the North-Western Mediterranean Sea (7° E, 22° E, 35° N, 46° N) similar to the study by Krug et al (2021a). The corresponding spatially and temporally averaged SST, evaporation, and wind speeds anomalies over this region were plotted corresponding to the Vb-cyclone precipitation anomaly rankings in GUF evaluation, historical, and future simulations. We also showed the moving averages of SST, evaporation, and wind speed anomalies for 10 Vb-events with the Local Polynomial Regression Fitting (LOESS) lines corresponding to the precipitation anomalies over the Danube, Elbe, and Odra catchments. We adapted the methodology as in Krug et al (2021a) for analyzing the precipitation rankings and corresponding North-Western Mediterranean Sea state.

2.5 Quantifying process chain between North-Western Mediterranean Sea & Vb-cyclone precipitation

Methods from information theory were recently used in quantifying interactions among sub-systems, especially in climate (Pothapakula et al, 2019, 2020;

Krug et al, 2021b; Ruddell et al, 2019). Transfer entropy (TE) was especially used in detecting and quantifying the direction of information exchange between two or more sub-systems. Unlike correlation, TE is an asymmetrical measure. Furthermore, the estimations from TE are free from any underlying assumptions of the probability distributions. Though the TE is a useful measure, its estimation is still a challenge.

A study by Pothapakula et al (2019) tested various TE estimators on idealized and real climate test cases along with the sensitivity of these estimators on time series length. Their results showed that the TE-linear which assumes Gaussianity is robust in revealing the system dynamics. While the non-linear estimations like TE Kraskov, Kernel gave reliable results, free-tuning parameters such as the number of nearest neighbors, kernel width were tested and tuned for reliable estimations.

In this study, we used the robust TE-linear estimation to quantify the process chain in terms of information exchange between the North-Western Mediterranean Sea and the spatio–temporal averaged precipitation over three catchments during the detected Vb-events. Krug et al (2021b) applied the same methodology to quantify the information exchange between the North-Western Mediterranean Sea and the precipitation over Odra catchments during Vb-cyclones.

At the heart of the information theory lies the concept of Entropy (H). The Entropy quantifies the uncertainty of a random variable X (Shannon, 1948) and is defined as,

$$H(X) = -\sum_{x} p(x) \log p(x), \tag{1}$$

where $p(x)$ represents the probability of a state of the random variable X. The summation goes through all the states of the random variable quantifying the average uncertainty of X. The units of entropy are generally expressed in nats when natural logarithm is used, whereas in the units of bits if the logarithm to the base of 10 is used. In this study, all the results quantifying information exchange were expressed in the units of nats.

Mutual information (MI) is defined as the average uncertainty reduction in the random variable X provided by the knowledge of random variable Y or vice-versa.

$$MI_{XY} = \sum_{x,y} p(x,y) \log \frac{p(x,y)}{p(x)p(y)}, \tag{2}$$

Where the $p(x, y)$ represents the joint probability of a state corresponding to the random variables X and Y. The MI is a symmetric quantity and thus can not detect the direction of information exchange.

The TE builds upon the MI measure and is defined as mutual information between the future target variable X and the whole past of the source Y^- conditioned on the whole past of the target variable X^-. The TE is an asymmetric measure giving directional information exchange.

$$TE_{Y->X} = MI(X; Y^{-}|X^{-}). \quad (3)$$

Due to computational complexity in the estimation of joint probability densities, the whole past of the source and target random variables are reduced as follows,

$$TE_{Y->X} = MI(X; Y_{t-\tau}|X_{t-\omega}), \quad (4)$$

where τ and ω represents the time lags of the history of source and target variables. The values of the τ and ω are generally chosen depending on the system dynamics. For more detailed review on TE and its estimation refer to Pothapakula et al (2019).

In this study, we chose the target variable to be the spatial averaged daily precipitation anomaly over the respective catchments during a Vb-cyclone event and the source being the simultaneous state of SST, evaporation or wind speed anomalies over the North-Western Mediterranean Sea. The value of τ was taken to be zero and ω as one consistent to the study of Krug et al (2021b). The TE measure in this study quantifies the reduction in uncertainty about the present state of precipitation in the respective catchment while knowing the state of North-Western Mediterranean Sea (SST, evaporation or wind speed) during the same day given the knowledge of one day precipitation persistence in the catchment region. Significance tests with permuted surrogates were conducted for information exchange values (Lizier, 2014; Pothapakula et al, 2019). As the measure of TE is highly sensitive to the time series length, the Vb-cyclone events detected within 55 year period were used instead of a typical 30 year period.

3 Results and discussion

In this section, first, the SST's obtained from the GUF historical simulation, GUF evaluation simulation, and additionally the Med-CORDEX phase-II ensemble members are compared against observations. Thereafter, we discuss the simulated climate change signal of the Mediterranean SST. Thereafter, the Vb-cyclone detection in the GUF historical & evaluation simulations along with GUF future simulation will be discussed. Finally we analyze the North-Western Mediterranean Sea state and associated process chain interms of information exchange during these events.

3.1 Evaluation & future projections of Mediterranean SST

Figure 1a shows the temporal evolution of the basin averaged annual Mediterranean SST for various simulations. Comparing the GUF historical & GUF evaluation simulated SST's to the HadISST & OISST observational data sets, we noticed a cold bias ($\approx$ 1 – 1.5 K). This cold bias was more pronounced

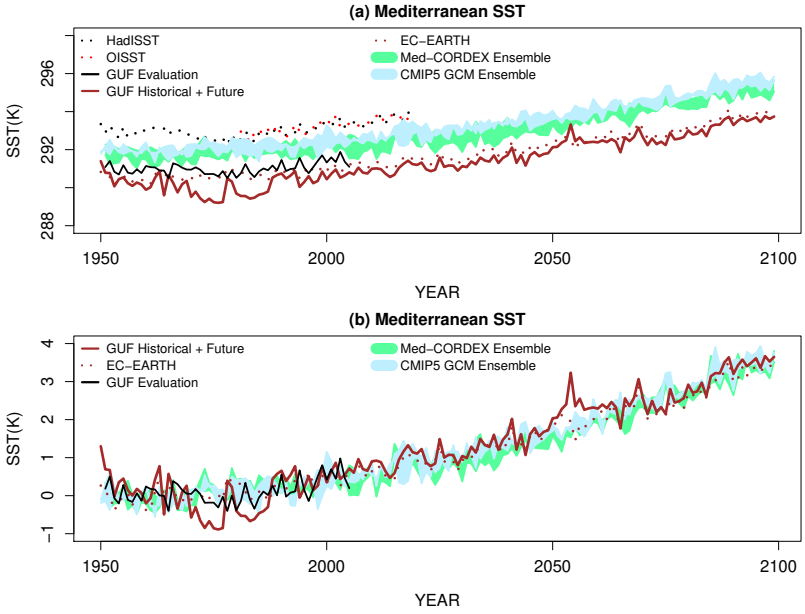


Fig. 1: (a) Mediterranean Sea basin averaged annual SST (K) evolution and (b) SST anomalies for the time period 1951-2099 (with reference to historical period 1951-2005) obtained from various simulations along with observational data sets, the HadISST & OISST.

in the GUF historical compared to the GUF evaluation simulation. This may be attributed to a more realistic atmospheric forcing by COSMO-CLM on the ocean model NEMOMED12 in the evaluation simulation compared to historical simulation. The Med-CORDEX phase-II ensemble also simulated a cold bias, but a smaller one compared with GUF simulations. A closer look into the seasonal cycle revealed that almost all the simulations had a cold bias in the spring & summer seasons (Fig. S1 in supplementary material). It was interesting to note the close correspondence of the driving GCM's and the downscaled simulated SST time evolution in Fig. 1a. The global model, EC-EARTH's SST was colder than the other considered CMIP5 GCM SST's, hence, this explains the comparably larger cold bias of the GUF historical simulation. Furthermore, a narrow spread in the Med-CORDEX ensemble and CMIP5 GCM ensemble was identified. Selection of only two GCM's for downscaling, i.e., the MPI-ESM-LR and CNRM from the CMIP5 simulations so far might the reason for such a narrow spread.

A closer look into the spatial SST and the bias plots in historical period revealed that the cold bias was present throughout the Mediterranean Sea (Fig. S2 & Fig. S3 in supplement). Especially the south-eastern warm pool

was not very well captured by the GUF simulations and also by the Med-CORDEX ensemble members. However, overall important SST patterns (e.g., the warm eastern pool in the Levantine compared to the western cold pool over the North-Western Mediterranean) of the Mediterranean Sea were well captured by the GUF evaluation & GUF historical simulations.

The Mediterranean SST climate change signal is presented in Fig. 1b. The SST anomaly was calculated with respect to the reference period 1951-2005. Almost all the simulations agreed very well that the basin averaged Mediterranean SST will warm $\approx$ 2.5 K – 3 K under the RCP-8.5 scenario by the end of 21^{st} century. This warming of the Mediterranean Sea is consistent with the findings by Soto-Navarro et al (2020). Spatial climate change SST patterns in GUF and the Med-CORDEX ensemble simulations reveal a homogeneous warming throughout the Mediterranean Sea (Fig. S4 in supplement). As the GUF simulations captured the SST signals and spatial patterns in-line with the observations & Med-CORDEX ensemble in the historical & future periods, we proceed further to explore the Vb-cyclones, the North-Western Mediterranean Sea state and associated process chains in the subsequent sections.

3.2 Vb-cyclones in the historical and future periods

In this sub-section, we present and discuss the results obtained from Vb-cyclone tracking in various GUF simulations. For the GUF evaluation simulation, a total of 531 Vb-cyclone events were detected for the period 1951-2005 corresponding to 9.7 (standard deviation $\approx$ 2.1 events per year) Vb-cyclone events per year. In the GUF historical simulation, a total of 557 Vb-cyclone events were detected for the period 1951-2005 corresponding to 10.1 Vb-events per year (standard deviation $\approx$ 1.6 events per year). The GUF historical simulation slightly overestimated the number of Vb-events by a statistically insignificant amount of 4.8% compared to the GUF evaluation. With respect to the seasonal differences, on average the GUF historical simulation overestimated the Vb-cyclone occurrence by 49% per year in summer (significant at 95% confidence) while in winter it underestimated Vb-cyclones by 41% per year (significant at 95% confidence) compared to GUF evaluation. No significant trends were revealed in GUF historical & evaluation simulations for the whole period (Fig .2).

In total 567 Vb-cyclones were detected in the GUF future simulation for the period 2045-2099 corresponding to 10.3 Vb-cyclones per year (standard deviation $\approx$ 2.3 events per year). This indicates an increase by 1.8% Vb-cyclones events per year in the future period compared to the historical period. Standard student's t-test analysis revealed that this percentage increase was insignificant. This result is consistent with the findings by Mittermeier et al (2019) where an insignificant percentage increase of Vb-cyclone frequency in the far future was reported with 0.11° resolution stand-alone regional climate model. No significant changes in the Vb-cyclone seasonal frequency & trends

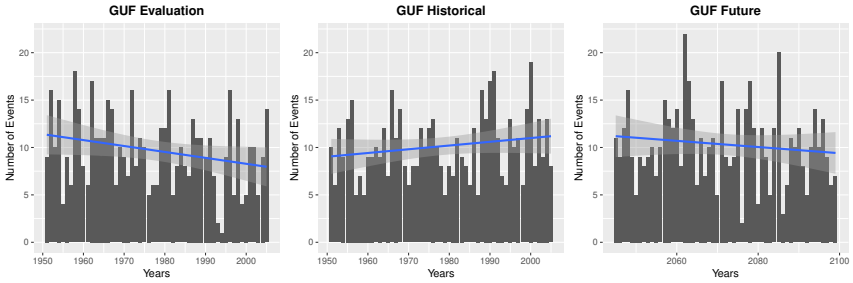
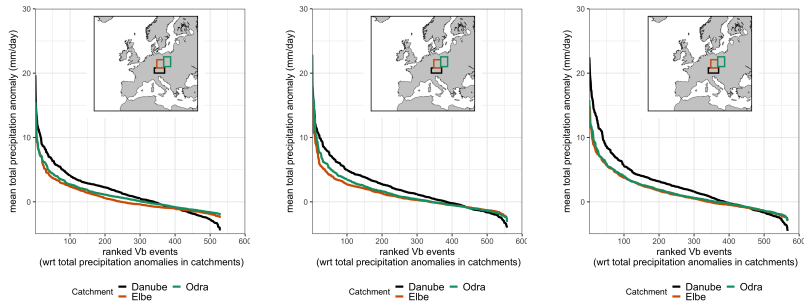


Fig. 2: Time series of annual Vb-cyclone event number and their associated trends for the GUF evaluation, historical, and future simulations. The shaded intervals correspond to the 95% confidence intervals for the Vb-event trend line.



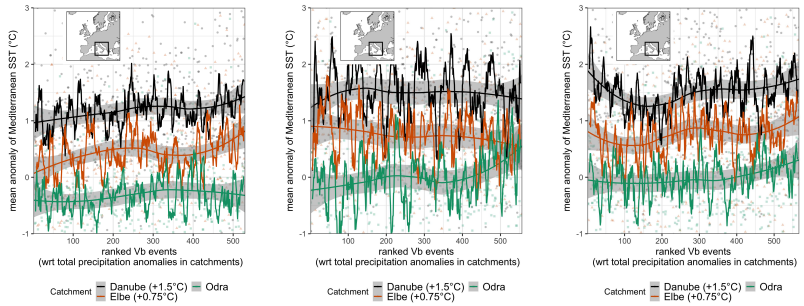
(a) GUF Evaluation (b) GUF Historical (c) GUF Future

Fig. 3: Ranked Vb-cyclone total precipitation anomalies in the Danube, Elbe, and Odra catchments obtained from various GUF simulations.

were revealed in the future simulation compared to historical simulation (Fig. S5 in supplement).

A good agreement in the Vb-cyclone track density was also detected between the GUF historical & GUF evaluation (Fig. S6 in supplement). However, a minor underestimation of $\approx 1\%$ of the Vb-cyclone centers over the eastern flanks of the Alps and a very slight overestimation over Italy was noted in the GUF historical simulation. In the simulated future, the Vb-cyclones travelled further north-eastwards compared to the historical period (also reported in Messmer et al (2020). The Vb-cyclones intensity interms of mean minimum cyclone central pressure also revealed good agreement between the GUF historical & GUF evaluation simulation (Fig. S7 & Fig. S8 in supplement). The GUF future simulation indicated no significant changes in the Vb-cyclone mean minimum central pressures in the future compared to historical simulation.

Figure 3 shows the Vb-cyclone precipitation anomalies ranked according to their magnitudes (lowest rank for maximum anomaly) in the Danube, Elbe,



(a) GUF Evaluation (b) GUF Historical (c) GUF Future

Fig. 4: Sea surface temperature anomalies corresponding to the Vb-cyclone precipitation anomaly rankings in various GUF simulations for Danube, Elbe and Odra catchments. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

and Odra river catchments for various GUF simulations. The rankings over the Elbe & Odra catchments in GUF evaluation showed similar anomaly magnitudes due to their close spatial proximity. The Danube catchment showed higher precipitation anomalies in high & medium ranks ($\approx > 400$ ranks) while a higher variability in lower ranks compared to Elbe & Odra. This behavior of Danube was attributed to the presence of complex orography and also to the typical Vb-cyclone pathways (Krug et al (2021a)). There is a good agreement between the GUF evaluation & GUF historical simulated precipitation rankings over all three catchments. Furthermore, a good agreement in absolute precipitation amounts and in the spatial precipitation patterns were found between the GUF historical & GUF evaluation (Fig. S9 & Fig. S10 in supplement). However the precipitation magnitudes for a few high-ranked events ($\approx$ 1-20 ranks) were greater ($\approx$ 0.5, 0.45, 0.25 mm/day) in the Danube, Elbe, and Odra catchments respectively in GUF evaluation simulation. No significant differences were found in the future precipitation anomalies and magnitudes (Fig. S10 & Fig. S11 in supplement).

3.3 North-Western Mediterranean Sea state during the Vb-cyclones & associated process chains

This sub-section presents the state of the SST, evaporation, and wind speed anomalies over the North-Western Mediterranean Sea & associated process chains interms of information exchange.

Figure 4 shows the spatially averaged SST anomalies of the North-Western Mediterranean Sea (domain shown in black rectangle box) with respect to the Vb-cyclone precipitation anomaly rankings. In the GUF evaluation simulation the high precipitation anomalies tend to be realized for low SST anomalies,

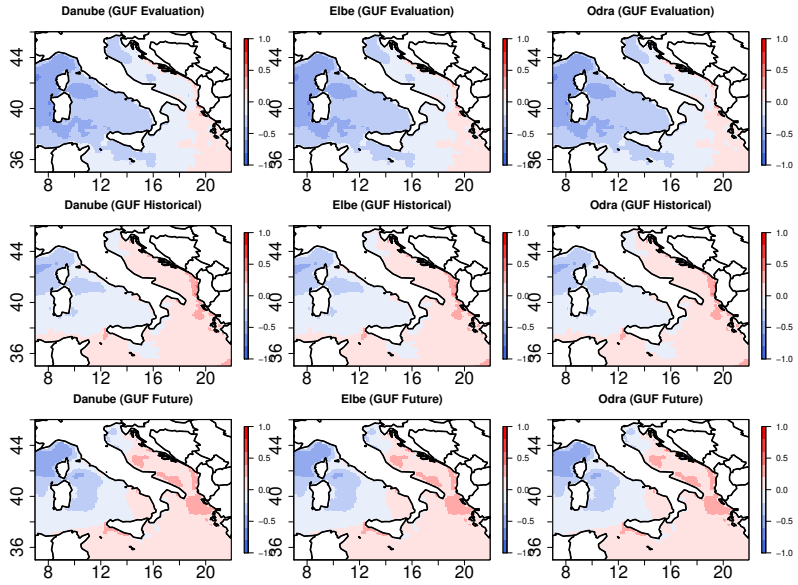


Fig. 5: Mean sea surface temperatures anomalies (K) during all the Vb-cyclones in various GUF simulations corresponding to precipitation over Danube, Elbe and Odra catchments.

especially for the Danube and Elbe catchments. This might be attributed to the strong upper sea mixing and evaporative cooling. These cooler anomalies were also partially replicated for the Danube & Odra basins in the GUF historical ($\approx$ 1-100 ranks). In the GUF future simulation the SST cooling was not noticed. Figure 5 presents the spatial distribution of the mean SST anomalies over the North-Western Mediterranean Sea during all the Vb-events. The GUF evaluation simulation on average showed negative SST anomalies in the North-Western Mediterranean Sea. This was expected as the Vb-cyclones usually originate from the North-Western Mediterranean Sea. Though the cooling in the GUF historical simulation was noticed with less magnitude in the North-Western domain, no such cooling was seen over the Adriatic sea & Ionian region. This means that the SST's in these regions were not responsive in the GUF historical simulation. This behaviour was also seen in the bias plots, where the cooling of the SST's in the GUF historical was underestimated compared to GUF evaluation (Fig. S12 in supplement). The difference between the future and historical simulations on average showed no major differences in the magnitude of SST cooling during Vb-cyclones.

Thereafter, we investigated the information exchange between the SST's and the Vb-cyclone precipitation over the three catchments to diagnose the process chains (Fig. 6). We noted differences in the information exchange spatial locations between the GUF evaluation & historical simulations, especially

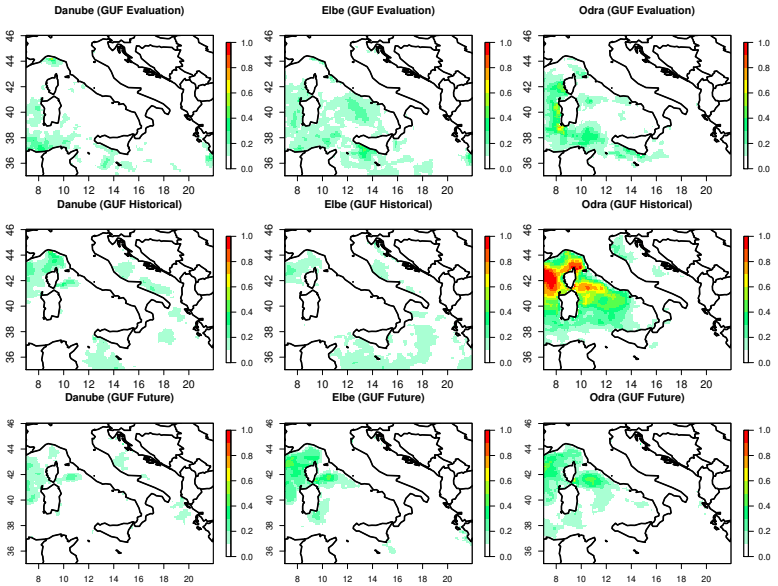
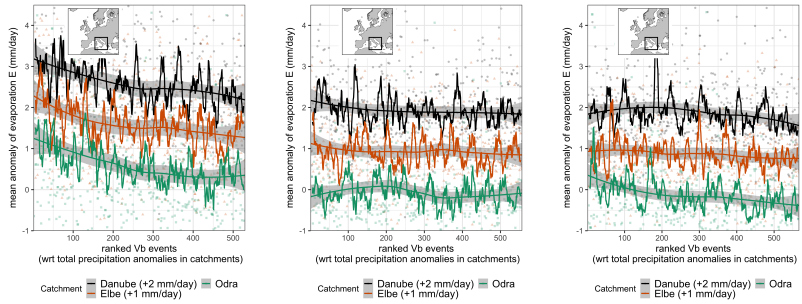


Fig. 6: Information exchange ($\times 10^{-2}$ nats) between the SST's and the total precipitation anomalies over the Danube, Elbe and Odra catchments for various GUF simulations. Only 95% significant range is plotted.

in the Elbe and Odra catchments. In the GUF historical simulation an underestimation of information exchange between the North-Western Mediterranean and the precipitation over the Elbe, and an overestimation in the information exchange over the Odra catchments was seen. The spatial locations of the information exchange in the future simulation remained the same as in historical simulation, but with minor changes in the magnitude of information exchange.

Figure 7 shows the evaporation anomalies over the North-Western Mediterranean Sea. In the GUF evaluation simulation the evaporation anomalies corresponded to the precipitation anomaly rankings in all the catchments indicating the dependence of Vb-cyclones on the North-Western Mediterranean Sea moisture. The GUF historical simulation shows no such correspondence except for only a minor increase in the anomalies of evaporation over the Danube and Elbe catchment (high ranks, $\approx >$ 100 ranks). The spatial plots in Fig. 8 show that on average the evaporation over the North-Western Mediterranean sea was underestimated in the GUF historical simulation during the Vb-events, specially, over the Adriatic & Ionian regions. This was further evident from the bias plots (Fig. S13 in supplement). The spatial patterns corresponding to the GUF future simulations on average showed no changes in the magnitude of evaporation anomalies compared to the historical period.

The information exchange between the evaporation over the North-Western Mediterranean Sea and the Vb-cyclone precipitation over the three catch-



(a) GUF Evaluation (b) GUF Historical (c) GUF Future

Fig. 7: Evaporation anomalies corresponding to the Vb-cyclone precipitation anomaly ranking in various GUF simulations for Danube, Odra and Elbe catchments. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

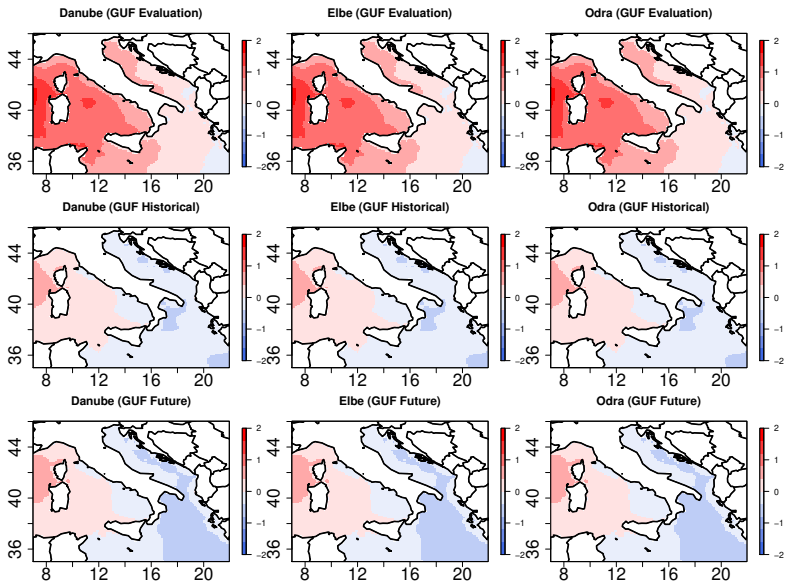


Fig. 8: Mean anomaly patterns of evaporation (mm/day) over the Mediterranean Sea from various GUF simulations for all Vb-cyclone events.

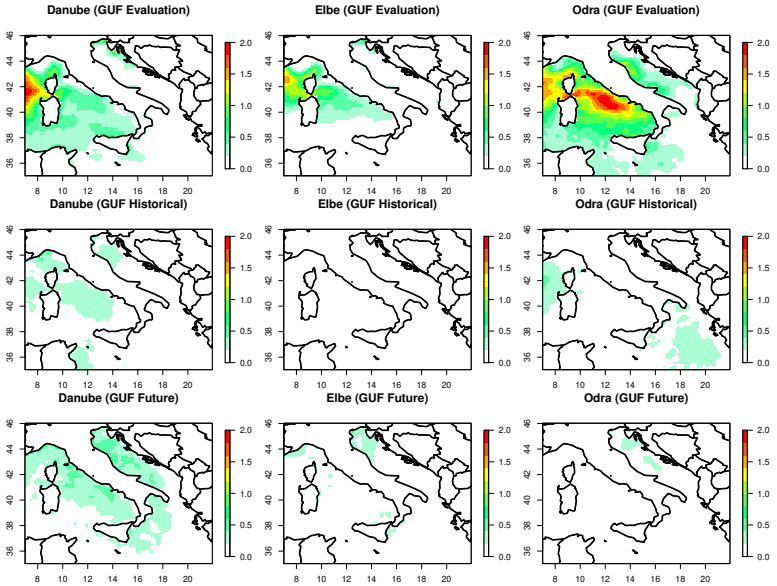
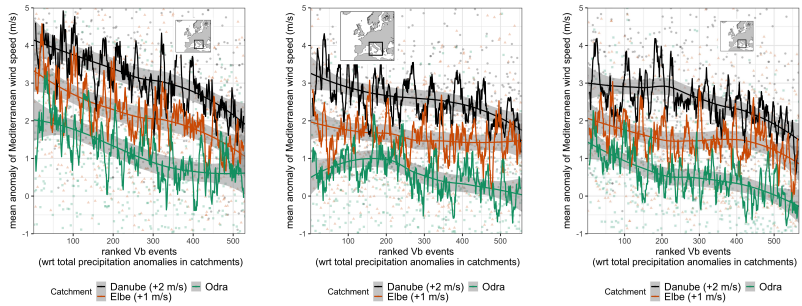


Fig. 9: Information exchange ($\times 10^{-2}$ nats) between the evaporation over the Mediterranean Sea and the total precipitation anomalies over the Danube, Elbe and Odra catchments for various GUF simulations. Only 95% significant range is plotted.

ment's is presented in Fig. 9. We noticed significant information exchange between the North-West Mediterranean basin evaporation (and also Adriatic Sea for Odra catchment) and the Vb-cyclone precipitation in GUF evaluation simulation for all the catchments. This behavior was not replicated in the GUF historical simulation. This indicates that some crucial physical process linking the evaporation and Vb-cyclone precipitation were missing in GUF historical simulation. The information exchange spatial locations do vary between the GUF historical & GUF future but the difference in magnitudes of information exchange is less compared to the differences between the GUF historical & GUF evaluation simulations.

Figure 10 shows the wind-speed anomalies corresponding to the Vb-cyclone precipitation anomaly rankings. The high wind speed anomalies tend to be realized for high precipitation rankings in GUF evaluation simulation. Krug et al (2021a) showed that these strong winds enhance the evaporation over the Mediterranean Sea fueling the Vb-cyclones especially during their initial phase. The increasing trends in wind-speed were also replicated in the GUF historical & GUF future simulations. However, the wind speed anomaly magnitudes were lower in GUF historical & future compared to the GUF evaluation simulation.

The spatial plots of the mean daily wind speed anomalies are shown in Fig. 11. On average the wind speed anomaly magnitudes in the GUF eval-



(a) GUF Evaluation (b) GUF Historical (c) GUF Future

Fig. 10: Wind speed anomalies corresponding to the precipitation anomaly rankings in various GUF simulations for all Vb-events. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

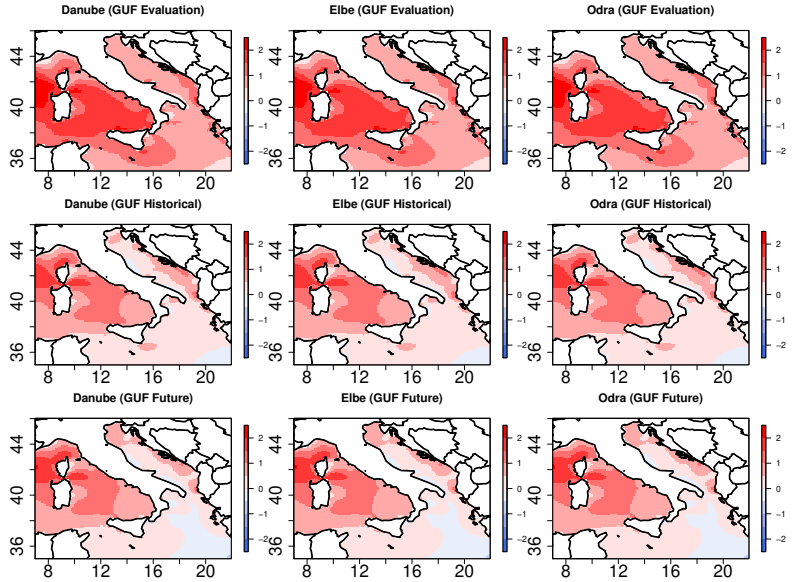


Fig. 11: Mean anomalies of wind speed (m/s) over the Mediterranean Sea in the GUF evaluation, historical, and future simulations over Danube, Elbe and Odra catchments for all Vb-cyclone events.

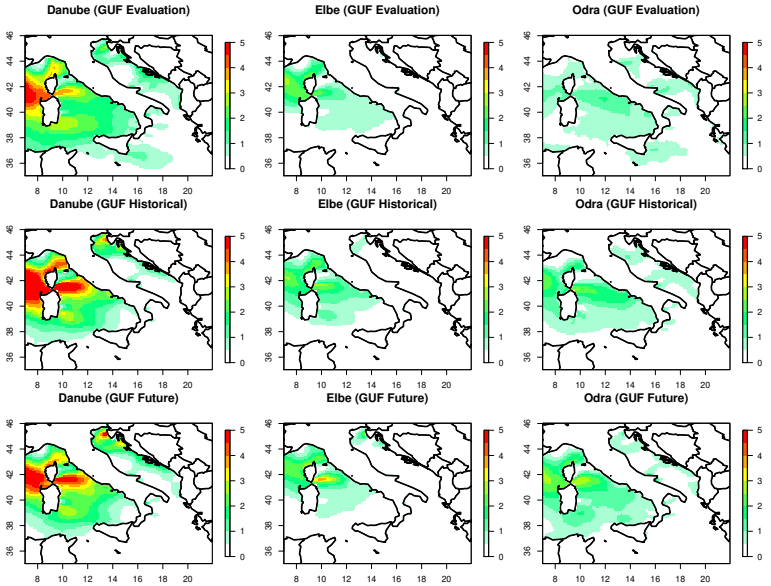


Fig. 12: Information exchange ($\times 10^{-2}$ nats) between the wind speed and total precipitation anomalies for various GUF simulations. Only 95% significant range is plotted.

uation simulation over the North-Western Mediterranean Sea were higher in magnitude compared to the GUF historical simulation. Also the spatial extent of the high magnitude winds during the Vb-cyclones extended from the North-Western Mediterranean Sea down to Ionian basin and the Adriatic Sea. This behavior was not replicated in the GUF historical simulation. This was further evident and conclusive from the bias plot (Fig. S14 in supplement). This evidence further indicates that during the Vb-cyclones in GUF historical simulation, the Adriatic and some parts of the Ionian basin were missing crucial feed-backs from the North-Western Mediterranean Sea. On average the difference in the magnitudes between the GUF future & GUF historical were very less compared with the difference between the GUF historical & GUF evaluation. The information exchange spatial locations and magnitude between the wind speed and the Vb-cyclone precipitation anomalies matched well in the GUF evaluation & GUF historical simulations compared with the SST and evaporation patterns (Fig. 12). A minor difference was noted between the GUF future and GUF historical simulations.

4 Conclusions

The current work focused on the Vb-cyclones and the corresponding North-Western Mediterranean Sea state & process chains as simulated in two coupled regional climate model simulations. One regional simulation was driven by ERA-20C reanalysis (1951-2005) called GUF evaluation, and the other simulation was driven by EC-EARTH for the period 1951-2099. The simulation for the period 1951-2005 was referred as GUF historical, and from the period 2006-2099 as GUF future.

The results revealed that GUF historical, GUF evaluation & the Med-CORDEX ensemble members considered in our study were cold ($\approx 1 - 1.5$ K) compared to the HadISST and OISST observation based datasets during the period 1951-2005. However, the major Mediterranean Sea SST patterns were well captured by the GUF simulations. All the regional climate simulated basin averaged SSTs closely followed the GCM simulated SST values reiterating the importance of the choice of the driving GCM which is dynamically downscaled. All the Med-CORDEX ensemble members agreed on the Mediterranean basin averaged SST warming of $\approx 2.5 - 3$ K by the end of the 21^{st} century under the RCP-8.5 scenario compared to the historical period.

A good agreement was found in the Vb-cyclone frequency between the GUF evaluation (9.7 events per year) & GUF historical simulations (10.1 events per year). Also, the Vb-cyclone track density and intensity in terms of minimum cyclone central pressure showed good agreement. Moreover, the Vb-cyclone precipitation anomaly magnitude rankings also showed good agreement between the GUF evaluation & historical simulations. An insignificant increase by 1.8 % in the Vb-cyclone frequency by the end of 21^{st} century was revealed from GUF future simulation. Changes in the future Vb precipitation anomalies over the three catchments were also insignificant.

In the GUF evaluation simulation the North-Western Mediterranean SST, evaporation, and windspeed anomalies corresponded to the Vb-cyclone precipitation anomaly rankings. Such a correspondence was not detected in the EC-EARTH driven historical simulation. Despite similarities in the model set-up (same regional atmosphere/ocean model components and set-ups over Mediterranean Sea) & good agreement in the Vb-cyclone frequency, intensity, and precipitation between the GUF evaluation & GUF historical simulation, the North-Western Mediterranean Sea state and process chains differ. These differences might be attributed to the emergence of simulation biases inherited from the driving EC-EARTH GCM, e.g., cold surface & sea surface temperatures over the Mediterranean compared to ERA-20C forcing. A study by Pothapakula et al (2020) showed that the biases in the driving GCMs emerged into the regional climate simulations resulting in unrealistic process chains. Downscaling the EC-EARTH3 (latest version of EC-EARTH) which has smaller bias in the surface air temperatures, SST (Döscher et al, 2021) might assist in further understanding the state and process chains linking the North-West Mediterranean Sea and the Vb-cyclone precipitation in historical & future periods.

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Declarations

- **Availability of data and materials:** The SST data can be obtained from the Med-CORDEX data base, https://www.medcordex.eu . The analysis is done in R and all the codes used in this paper can be accessed through 10.5281/zenodo.5753360. The cyclone tracking method is available on request from Michael Sprenger.
- **Conflict of interest:** All the authors declare no conflict of interest.
- **Authors contribution** The concept was proposed by BA. Funding was acquired by BA. The information theory algorithms were developed by PKP. The RCM simulations were performed by AOH and PKP with the assistance from TK. The paper was written by PKP and reviewed by all the authors. All authors have read and approved the final paper.

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