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

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Abstract. Vb-cyclones propagating from the North-Western Mediterranean Sea (NWMS) into central Europe are often associated with extreme precipitation. This study explores the state and process chain linking the NWMS state and the Vb-cyclone precipitation in the 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 + RCP8.5 future scenario 2006-2099) downscaling the EC-EARTH global climate data set are used for this purpose. The results show 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 three catchments also show good agreement. The simulations for the future period show a basin-average SST warming of $\approx 2.5-3$ K by the end of 21^{st} century, but insignificant changes in Vb-cyclone frequency, mean intensity, and precipitation in the selected catchments. The NWMS sea surface temperature, evaporation, and wind speed anomalies corresponding to the Vb-cyclone precipitation rankings differ between the evaluation and historical simulations. In the evaluation simulation, Vb-cyclone precipitation rankings correspond with sea surface temperature, evaporation, and wind speed anomalies, while in the historical and the future simulation no such correspondence is seen. Especially the Adriatic and Ionian basins in the simulation driven by EC-EARTH show no sensitivity to the Vb-cyclone precipitation over the catchments. The change in the processes between evaluation and historical simulations might be due to the emergence of biases inherited from the driving EC-EARTH global simulation. The future simulation shows no significant process changes compared to the historical simulation.

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

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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 (Hochman et al., 2022; Mathias et al., 2021).

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 (NWMS) 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 (Krug et al., 2022).

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-cyclones 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) and Messmer et al. (2017). Based on a model sensitivity study, vol 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 vol 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; Ho-Hagemann et al., 2015, 2017; Krug et al., 2022).

Krug et al. (2022) analyzed about 1107 Vb-cyclone events simulated by a regional coupled climate model during the period 1901-2010. Their study concluded that the NWMS 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-cyclones, 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. (2021) reported a significant information exchange between the evaporation over the NWMS and Vb-cyclone precipitation over the Odra catchment. Above mentioned studies highlight the NWMS's role in modulating Vb-cyclone intensity.

As the role of the Mediterranean Sea in modulating the Vb-cyclone events is well established in the literature for the historical period, investigating the Vb-cyclone's future projections and the role of the Mediterranean Sea in the warming climate becomes extremely important. Especially, the Mediterranean Sea being a hot spot of climate change, investigating its role in the future Vb-cyclones is also of extreme importance. Using a Global Climate Model (GCM), ECHAM5/OM1, Nissen et al. (2013)

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reported a decrease in the number of Vb-cyclones by the end of the 21^{st} 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 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 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 (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. In terms of Vb-cyclone daily precipitation intensity, a significant increase was reported over Bavaria.

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is an initiative that coordinates scientific groups for high-resolution regional climate data sets (Giorgi, 2006). The regional climate model, Consortium for Small-scale Modelling in Climate Mode (COSMO-CLM, Rockel and Geyer (2008)) 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 (Akhtar et al., 2018). Especially given the importance of the Mediterranean Sea in the evolution of Vb-cyclone events, a realistic and dynamically interactive ocean model is thus necessary.

The COSMO-CLM is coupled to Nucleus for European Modeling of the Ocean (NEMO, Madec (2008)) over the Mediterranean sea (NEMOMED12,Brossier et al. (2011, 2012)) along with a river run-off model, Total Runoff Integrating Pathways (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. (2022). Their study demonstrated the ability of the coupled system in representing the past Vb-cyclone events realistically. Furthermore, Krug et al. (2022) 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 and 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 (Hazeleger et al., 2012) as driving data. The simulation used historical

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greenhouse gas emissions for the historical period 1951-2005 and RCP8.5 forcing scenario for the future period (2006-2099) at 0.11° ($\approx$ 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).

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 their characteristics in the historical period before we proceed to investigate the future Vb-cyclone characteristics. Thereafter the NWMS state in terms of SST, evaporation and 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 NWMS and the Vb-cyclone precipitation over the three catchments we use information theory methods similar to the studies by Pothapakula et al. (2019, 2020); Krug et al. (2021). These studies used information exchange to quantify the Indo-Pacific coupling, the interplay between the Indian Ocean dipole and El-Niño Southern Oscillation with the Indian Monsoon precipitation, and, the role of NWMS 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, in this study we ask the following questions:

1. Does the EC-EARTH driven coupled regional simulation produce Vb-cyclones comparable to the ERA-20C reanalysis driven coupled regional simulation in the historical period.

2. Does the state of the NWMS and the process chain differ between the two simulations in the historical period?

3. Do the characteristics of Vb-cyclones and their associated process chain linking the NWMS change in the future period?

This paper is organized as follows. Section 2 consists of data and methodology describing 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 Vb-cyclones in historical periods, future changes compared with historical period, results representing the state of NWMS and quantification of the process chain linking NWMS and Vb-cyclone precipitation in-terms of information exchange over the three catchments. 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 a regional climate coupled atmosphere and ocean system consisting of atmospheric component COMSO-CLM 5-0-9 and the NEMOMED12 ocean component. 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 (Tiedtke, 1989), and a

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four-category microphysics scheme (Doms and Baldauf, 2011; Doms et al., 2011). The soil-vegetation-atmosphere-transfer sub-model TERRA provided the lower boundary conditions over land (Schrodin and Heise, 2001; Schulz et al., 2016). 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 regional climate coupled atmosphere and ocean system used in this study. The regional version of the NEMO-V3.6 was adapted over the Mediterranean region named NEMOMED12 in the current study. The domain of the NEMOMED12 covers the entire Mediterranean Sea at a horizontal resolution of $\approx$ 7.5 km along with a buffer zone nearby the Atlantic Ocean. A 3D relaxation of the temperature and salinity was performed in the buffer zone so as to realistically simulate the circulation from the Atlantic through the Gibraltar Strait and into the Mediterranean Sea (Sevault et al., 2009). 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 the OASIS-MCT3 coupler (Craig et al., 2017). The coupling fields between the ocean and atmosphere are interpolated and exchanged every three hourly by the coupler.

In addition to the NEMOMED12, the NEMO configuration adapted over the North and Baltic marginal seas was coupled to the atmospheric component COSMO-CLM in a simulation driven by ECMWF twentieth century reanalysis, ERA-20C (Poli et al., 2016). The performance of ERA-20C downscaled simulation in realistically replicating the Vb-cyclone events and their associated precipitation was already reported and analyzed in the study by Krug et al. (2022). Hence in this study, we used the ERA-20C downscaled simulation as a reference for validating the downscaled EC-EARTH simulated Vb-cyclone events and their associated precipitation in the historical period. It is to be noted that though the EC-EARTH driven simulation was only coupled to NEMOMED12, both simulations used same coupling frequency and set-ups over the Mediterranean Sea region. 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. As the Vb-cyclone are rare events, we considered 55 years in the historical and future periods to account for sufficient Vb-cyclone cases.

2.2 Vb-cyclone tracking

For detecting and tracking Vb-cyclones in the two simulations a tracking algorithm developed by Wernli and Schwierz (2006) which was later modified by Sprenger et al. (2017) was used. The mean sea level pressure was used as input for the tracking algorithm (at a 6-hourly interval). 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

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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. (2022).

2.3 Vb-cyclones and North-Western Mediterranean Sea state

After the Vb-cyclone tracking, their frequency of occurrence, track density, minimum central pressure, and precipitation was analyzed. Hence the historical period was taken from 1951-2005 and 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. The linear trend line is computed with the least square regression approximation through R software package (R Core Team, 2013). The track density of the Vb-cyclones represent the probability with which Vb-cyclone centers cross a grid point in the given time period similar to the study by Messmer et al. (2015). The minimum central core pressures obtained from the simulations were plotted using box whiskers. The box whiskers ends at the quartiles, the horizontal line at the center represents the median, and the points/circles are the values more than 1.5 times the interquartile range from the end of the box.

For the Vb-cyclone precipitation analysis, three important catchments i.e., the Danube, Elbe, and Odra were selected. The daily anomalies of precipitation, SST, evaporation and wind speeds were calculated by subtracting the daily value from the daily climatological mean during the respective analysis period to remove the seasonal cycle and to account for possible systematic biases. There after, the spatial and temporal averages of the precipitation over the Danube, Elbe, and Odra were calculated for each Vb-cyclone life time as detected from the tracking algorithm. Similarly, the spatial and temporal averages of the SST, evaporation and wind speeds over the pre-defined uptake region over the NWMS were calculated. The spatially averaged precipitation sum anomaly accumulated during the Vb-cyclone life time over the respective catchments was further ranked according to the intensity indicating the rank of Vb-cyclone events. In other words, the precipitation anomaly during the entire Vb-cyclone life time were ranked and a Vb-cyclone event with highest positive precipitation anomaly was ranked as 1. In addition to the Vb-cyclone precipitation anomaly rankings, the absolute precipitation amounts were also showed.

Corresponding to the Vb-cyclone precipitation anomaly rankings we analyzed the state of the NWMS (7° E, 22° E, 35° N, 46° N) similar to the study by Krug et al. (2022). The corresponding spatially and temporally averaged SST, evaporation, and wind speeds anomalies over this pre-defined region were plotted corresponding to the Vb-cyclone precipitation anomaly rankings. We also showed the moving averages of SST, evaporation, and wind speed anomalies for 10 Vb-cyclones 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. (2022) for analyzing the precipitation rankings and corresponding NWMS state.

2.4 Quantifying process chain between North-Western Mediterranean Sea and Vb-cyclone precipitation

Methods from information theory were recently used in quantifying interactions among sub-systems, especially in climate system applications (Pothapakula et al., 2019, 2020; Krug et al., 2021; 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. Generally, the estimations from TE are free from any underlying assumptions of

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the probability distributions. However, the estimation of TE in non-parametric form is still a challenge and requires rigorous parameter tuning and testing (Kaiser and Schreiber, 2002; Pothapakula et al., 2019).

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, their 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 NWMS and the spatio–temporal averaged precipitation over three catchments during all the detected Vb-cyclone days. Here we bring to the attention of readers that unlike the precipitation rankings where the precipitation anomaly for the entire Vb-cyclone event life time was considered, the information exchange calculations used individual days of all the detected Vb-cyclone events. By considering all the Vb-cyclone days, we aim for robust estimation of information exchange with long time series as proposed in (Pothapakula et al., 2019). Furthermore, it is to be noted that the Granger causality is equivalent to the linear approximation of TE by a factor of 2 (Barnett et al., 2009). Krug et al. (2021) applied the same methodology to quantify the information exchange between the NWMS 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.

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

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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,

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

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 NWMS. The value of τ was taken to be zero and ω as one consistent to the study of Krug et al. (2021). 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 NWMS (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). Though the measure of TE is highly useful, its limitation interms of common drivers influencing the source and target needs to carefully taken into account. For example, while investigating the information exchange between Vb-cyclone daily precipitation and NWMS daily evaporation anomaly, it is assumed that no common driver is influencing the source and target variables (Runge et al., 2019; Pothapakula et al., 2019).

3 Results and discussion

In this section, first, the Vb-cyclone characteristics interms of occurrence, precipitation, minimum sea level pressure are discussed in evaluation, historical and future simulations. Thereafter, we analyze the NWMS state and associated process chain interms of information exchange during these events. Additional analysis which includes the evaluation of the SST's obtained from the two simulations were performed and discussed in the Appendix section.

3.1 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 simulations. For the evaluation simulation, a total of 531 Vb-cyclone events were detected for the period 1951-2005 corresponding to 9.7 Vb-cyclone events per year (standard deviation is 2.1 events per year). In the historical simulation, a total of 557 Vb-cyclone events were detected for the period 1951-2005 corresponding to 10.1 Vb-cyclones per year (standard deviation is 1.6 events per year). The historical simulation slightly overestimated the number of Vb-cyclones by a statistically insignificant amount of 4.8% compared to the evaluation simulation. The blue line in Fig .1 represents the fitted linear regression line and the grey bands represent the 95% confidence interval bands for all the tracked Vb-cyclones each year in various simulations. Overall, the trends revealed to be statistically insignificant in evaluation, historical and future simulations. With respect to the seasonal differences, on average the historical simulation overestimated the Vb-cyclone occurrence by 49% per year in

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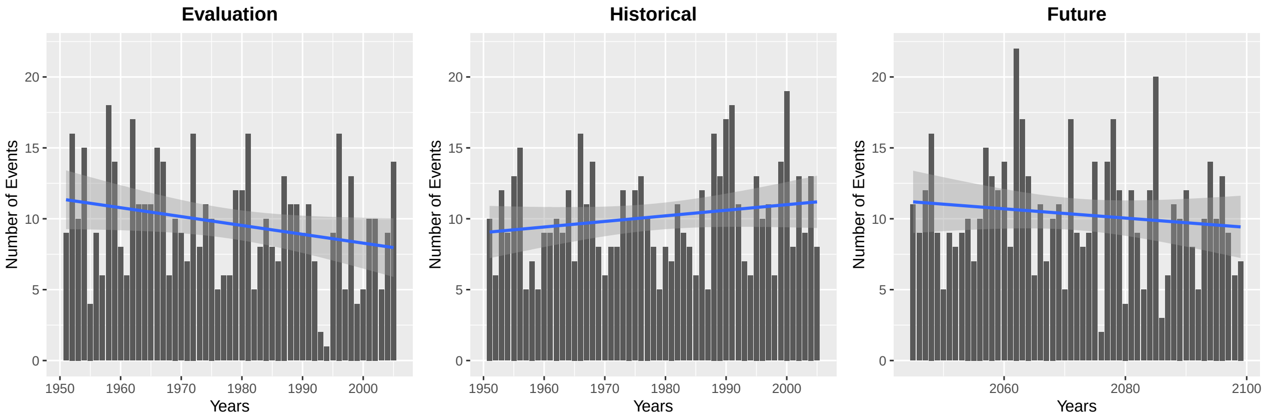

Figure 1. Time series of annual Vb-cyclone event number and their associated linear trends for the evaluation, historical, and future simulations. The shaded intervals correspond to the 95% confidence intervals for the Vb-event trend line.

summer (significant at 95% confidence) while in winter it underestimated Vb-cyclones by 41% per year (significant at 95% confidence) compared to the evaluation simulation (see Fig. S1 in supplementary material). Furthermore, the SST's in the historical simulation during summer season are colder than in the evaluation simulation (see Appendix A) indicating that the Vb-cyclone occurrence's in the historical simulation during summer are determined by some large scale dynamics rather than by the thermodynamic instability created by the Mediterranean SSTs.

In total 567 Vb-cyclones were detected in the future simulation for the period 2045-2099 corresponding to 10.3 Vb-cyclones per year (standard deviation is 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 and trends were revealed in the future simulation compared to historical simulation (Fig. S1 in supplement). This result is contrary to the findings of Mittermeier et al. (2019) , where they reported significant changes in the Vb-cyclone occurrences in the future spring and summer seasons.

A good agreement in the Vb-cyclone track density was also detected between the historical and evaluation simulations (Fig. S2 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 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 in terms of minimum cyclone central pressure also revealed good agreement between the historical and evaluation simulation with respect to the median values (the center line of the box plots in Fig. S3 in supplement), however a discrepancy exists in the outliers, i.e., the extreme values, especially values with greater minimum cyclone central pressures (values > 1020 hPa). This difference might be attributed to the low number of Vb-cyclones detected in the winter season in historical simulation

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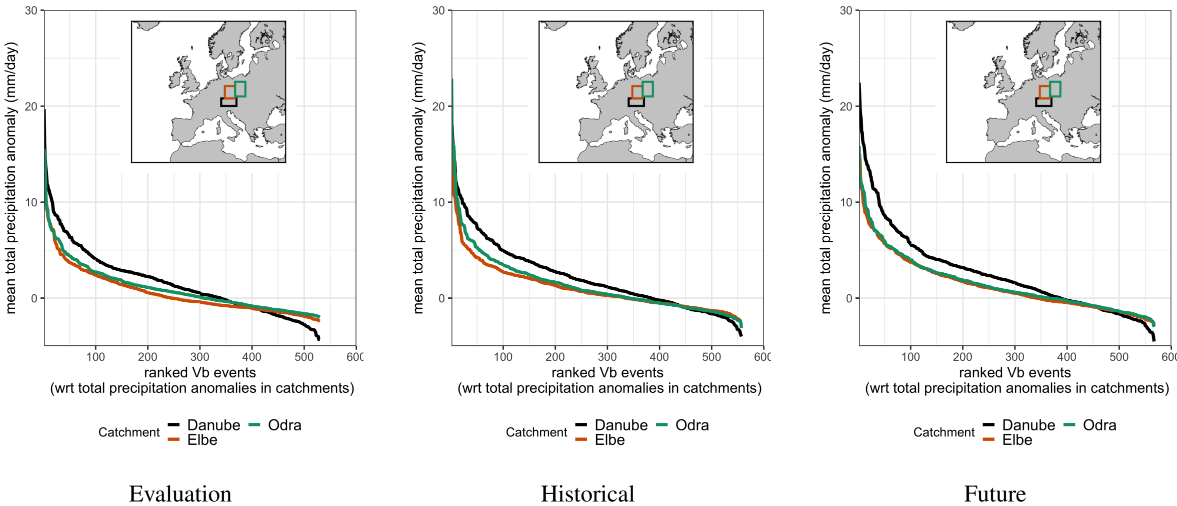

Figure 2. Ranked Vb-cyclone total precipitation anomalies in the Danube, Elbe, and Odra catchments obtained from various simulations.

compared to the evaluation simulation (Fig. S4, winter season box plot). The future simulation indicated no significant changes in the Vb-cyclone minimum central pressures compared to historical simulation, especially with the median values in the box whisker plots. This is also true in all the seasons where no significant changes are observed between the median values of historical and future simulations, however differences are noted in the outliers in all the seasons (Fig. S4 in supplementary material).

Figure 2 shows the Vb-cyclone precipitation anomalies ranked according to their magnitudes (lowest rank for maximum anomaly) in the Danube, Elbe, and Odra river catchments for various simulations. The rankings over the Elbe and Odra catchments in evaluation showed similar anomaly magnitudes due to their close spatial proximity. The Danube catchment showed higher precipitation anomalies in high and medium ranks ($\approx > 400$ ranks) while a higher variability in lower ranks compared to Elbe and Odra in both historical and evaluation simulations. This behavior of Danube was attributed to the presence of complex orography and also to the typical Vb-cyclone pathways (Krug et al., 2022). The similarity between the Elbe and Odra catchments precipitation rankings, high precipitation anomalies in the Danube catchment is also seen from the absolute precipitation amounts (Fig. S5 in supplementary notes). Over all, there is a good agreement between the evaluation and historical simulated precipitation rankings over all the three catchments. 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 evaluation simulation compared to the historical simulation (Fig. S6). The spatial precipitation patterns showed a zonal difference between the historical and evaluation simulation. The precipitation in the historical simulation was slightly greater in magnitude ($\approx$ 1mm/day) in the western part of the domain, while in the eastern domain, there was an under estimation ($\approx$ 1mm/day) (Fig. S7). In the future, all the three catchments show similar precipitation anomaly magnitudes as the historical simulation, but with very slight higher precipitation magnitudes for the top 10 high ranking Vb-cyclone events (Fig. S6). With Vb-cyclone events rankings greater than 10, no significant differences were found in the future precipitation anomalies and

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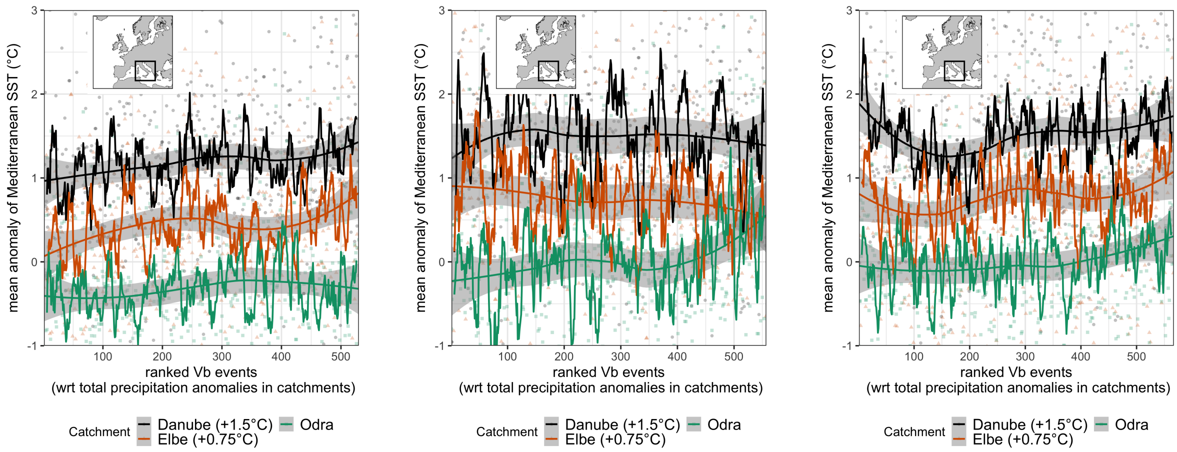

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Figure 3. Sea surface temperature anomalies corresponding to the Vb-cyclone precipitation anomaly rankings in various simulations for Danube, Elbe and Odra catchments. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

magnitudes over the three catchments. The spatial plots of the precipitation show that the future simulation on average shows an insignificant increase of total precipitation by about (≈ 1mm/day) for all the detected Vb-cyclones compared to the historical simulation (Fig. S7).

3.2 North-Western Mediterranean Sea state during the Vb-cyclones and associated process chains

This sub-section presents the state of the SST, evaporation, and wind speed anomalies over the NWMS and associated process chains interms of information exchange.

Figure 3 shows the spatially averaged SST anomalies of the NWMS (domain shown in black rectangle box) with respect to the Vb-cyclone precipitation anomaly rankings. In the evaluation simulation the high precipitation anomalies tend to be realized for low SST anomalies, especially for the Danube and Elbe catchments. This might be attributed to the strong upper sea mixing and evaporative cooling during the Vb-cyclone life time. These cooler anomalies were also partially replicated for the Danube and Odra basins in the historical simulation (≈ 1-100 ranks). In the future simulation the SST cooling was not noticed. Figure 4 presents the spatial distribution of the mean SST anomalies over the NWMS during all the Vb-cyclones. The evaluation simulation on average showed negative SST anomalies in the NWMS. This was expected as the Vb-cyclones usually originate from the NWMS. Though the cooling in the historical simulation was noticed with less magnitude in the north-western domain, no such cooling was seen over the Adriatic sea and Ionian region. This means that the SST's in these regions were not responsive in the historical simulation. This behaviour was also seen in the mean bias plots, where the cooling of the SST's in the historical was underestimated compared to evaluation (Fig. S8 in supplement). The difference between the

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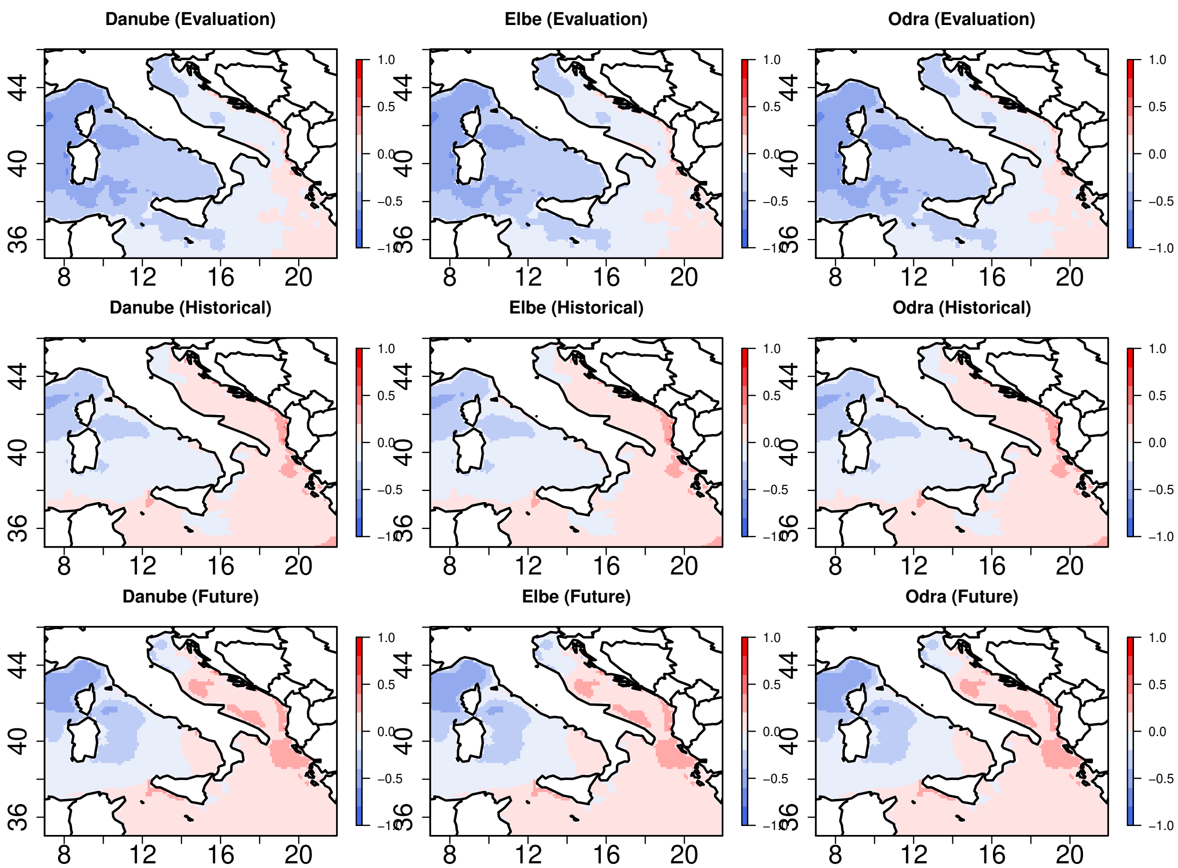

Figure 4. Mean sea surface temperatures anomalies (K) during all the Vb-cyclones in various simulations corresponding to precipitation over Danube, Elbe and Odra catchments.

future and historical simulations on average showed no major differences in the magnitude of SST cooling during the tracked Vb-cyclones indicating no significant changes in the response of SST to the future Vb-cyclone events over the NWMS.

Thereafter, we investigated the information exchange between the SST's and the Vb-cyclone induced precipitation over the three catchments to diagnose the process chains linking the NWMS and Vb-cyclone precipitation (Fig. 5). We noted significant differences in the information exchange spatial locations between the evaluation and historical simulations, especially in the Elbe and Odra catchments. In the historical simulation an underestimation of information exchange between the NWMS and the precipitation over the Elbe, and an overestimation in the information exchange over the Odra catchments was noted indicating that the process linking the SST's and the Vb-cyclone differ between the evaluation and historical simulation. 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, especially over the Odra catchment, a significant reduction in the amount of information exchange is noted.

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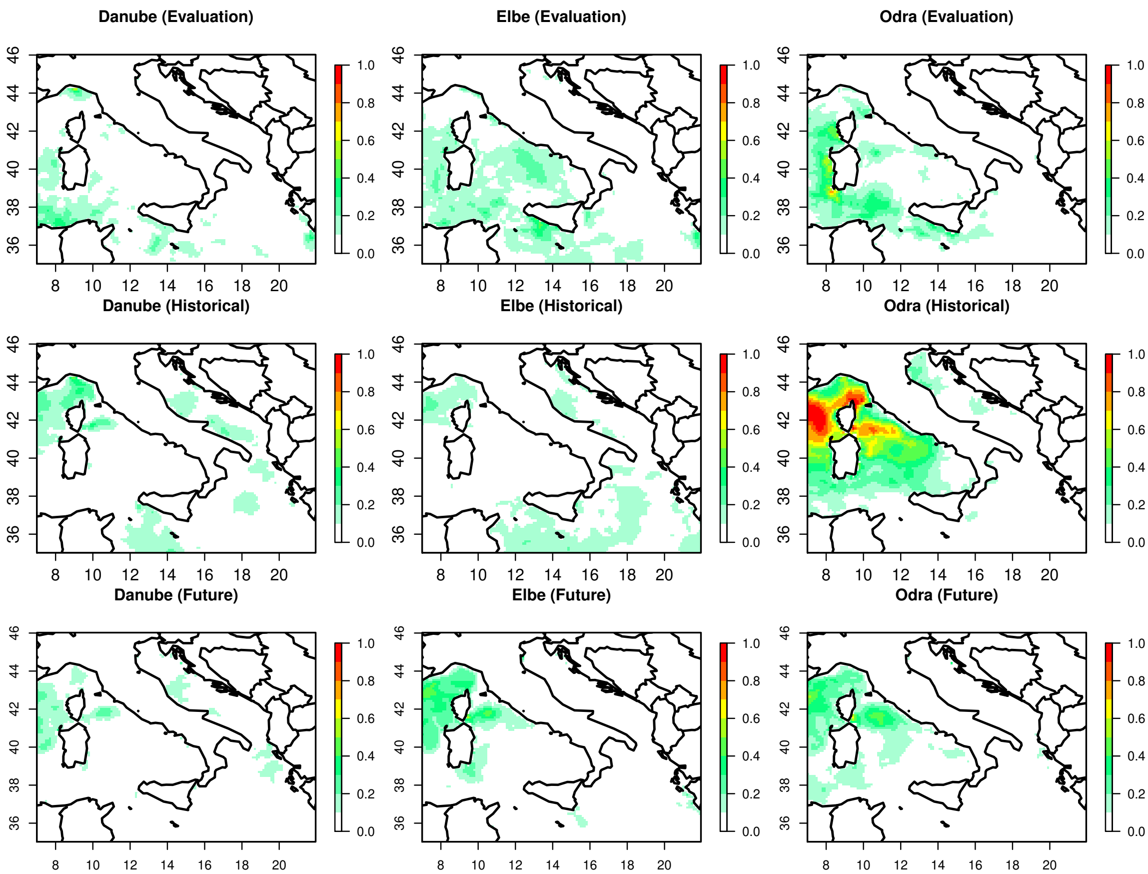

Figure 5. Information exchange ($\times 10^{-2}$ nats) between the SST's and the total precipitation anomalies over the Danube, Elbe and Odra catchments for various simulations. Only 95% significant range is plotted.

Figure 6 shows the evaporation anomalies over the NWMS with respect to the Vb-cyclone precipitation anomaly rankings. In the evaluation simulation the evaporation anomalies corresponded to the precipitation anomaly rankings in all the catchments indicating the dependence of Vb-cyclones on the NWMS moisture. High evaporation anomalies over the NWMS are linked with high ranked precipitation Vb-cyclone events overall the catchments, reiterating the importance of NWMS moisture feeding the Vb-cyclones. This result is consistent with the findings of Messmer et al. (2017) concluding that the moisture from the Mediterranean Sea leads to high atmospheric moisture availability causing an increased precipitation amount over central Europe. The historical simulation however showed no such correspondence between the NWMS evaporation anomalies and the Vb-cyclone precipitation 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. 7 show that on average the magnitude of evaporation over the NWMS was greater in the evaluation simulation compared to the historical simulation during the detected Vb-cyclones. The historical simulation underestimated the evaporation from the NWMS, especially over the Adriatic and Ionian regions. This was further

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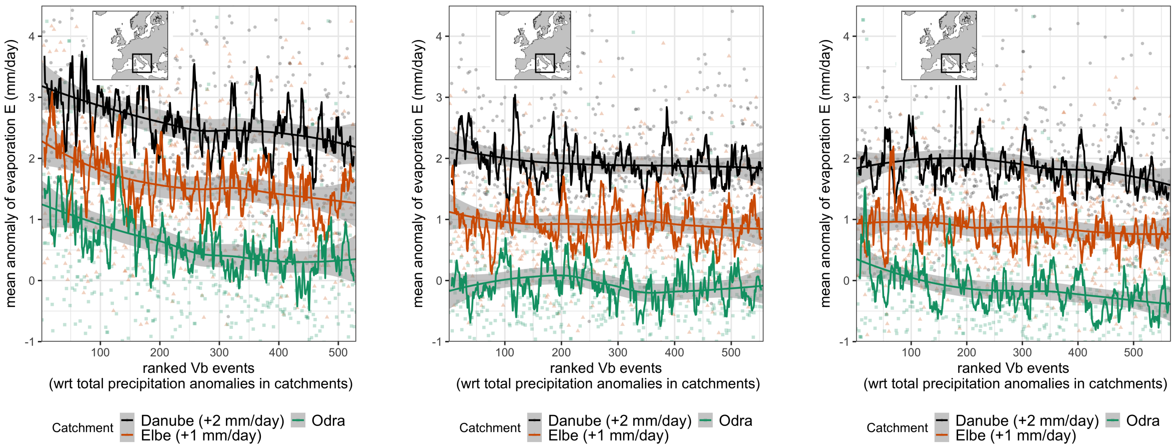

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Figure 6. Evaporation anomalies corresponding to the Vb-cyclone precipitation anomaly ranking in various simulations for Danube, Odra and Elbe catchments. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

evident from the mean bias plots where a large negative bias is noted between the historical and evaluation simulation (Fig. S9 in supplement). The spatial patterns corresponding to the future simulations on average showed no significant changes in the magnitude of evaporation anomalies compared to the historical simulation indicating that the Mediterranean response with respect to the evaporation does not change in the future compared with the historical period.

The information exchange between the evaporation over the NWMS and the Vb-cyclone precipitation over the three catchment's is presented in Fig. 8. We noticed a significant amount of information exchange between the NWMS's evaporation (and also Adriatic Sea for Odra catchment) and the Vb-cyclone precipitation in the evaluation simulation for all the catchments. This result is in line with the findings of Krug et al. (2021) concluding significant information exchange between the NWMS and the Odra catchments for all the detected Vb-cyclones from 1901-2010. However, the historical simulation does not show significant information exchange linking the NWMS and Vb-cyclone precipitation in all the catchments. This indicates that some crucial physical processes linking the evaporation over the NWMS and Vb-cyclone precipitation were missing in the historical simulation. Nevertheless, the precipitation magnitudes over the three catchments are comparable between the evaluation and historical simulation implying that the underestimation of the Mediterranean moisture in the historical simulation is compensated by other moisture sources feeding the Vb-cyclone precipitation. Messmer et al. (2017) found a non-linear response of the Vb-cyclone precipitation with increment and decrement of moisture flux over the Mediterranean Sea. An increase in the Mediterranean moisture flux contributed to about 24% significant increase of Vb-cyclone precipitation, while a decrease in the moisture flux resulted in insignificant decrease in Vb-cyclone precipitation amount. This implies a non-linear compensation effects of atmospheric moisture feeding the Vb-cyclone's, and perhaps this is also the reason for historical simulation compensation effects. However, this needs a detailed investigation. The information exchange spatial locations do vary between

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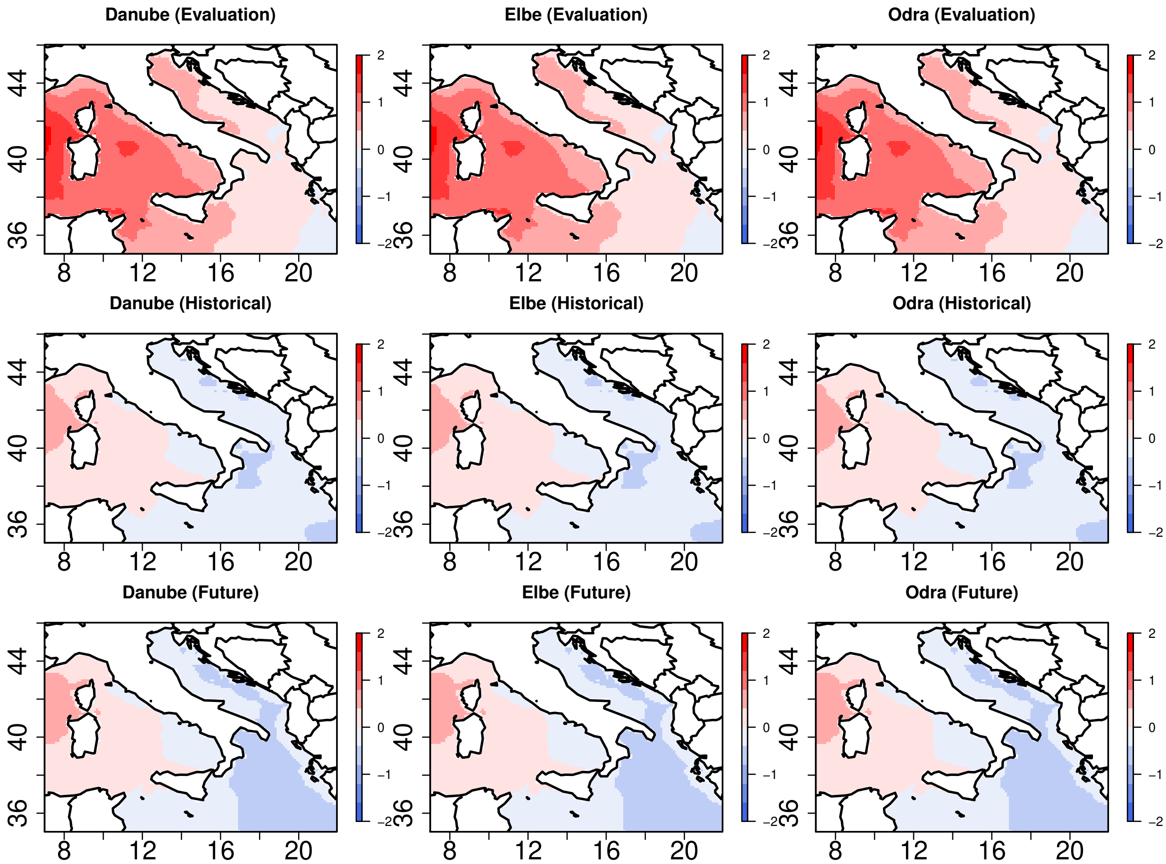

Figure 7. Mean anomaly patterns of evaporation (mm/day) over the Mediterranean Sea from various simulations for all Vb-cyclone events.

the historical and future simulations, but the difference in the magnitudes of information exchange is less compared to the differences between the historical and evaluation simulations. This indicates that the processes linking the NWMS evaporation and the Vb-cyclones are not likely to change in the future.

Figure 9 shows the wind-speed anomalies with respect to the Vb-cyclone precipitation anomaly rankings. The high wind speed anomalies tend to be realized for high precipitation rankings in evaluation simulation. Krug et al. (2022) showed that these strong winds result in the dynamic evaporative forcing over the NWMS fueling the Vb-cyclone precipitation especially during their initial phase. This phenomena also leads to the SST's cooling over the NWMS, which is evident from the results of our evaluation simulation. The increasing trends in wind-speed are also replicated in the historical and future simulations, however the wind speed anomaly magnitudes were slightly lower in historical simulations compared to the evaluation simulation. The future simulation also show a good correspondence in the wind speed anomalies, i.e, high ranked Vb-cyclone events linked with high wind speed anomalies.

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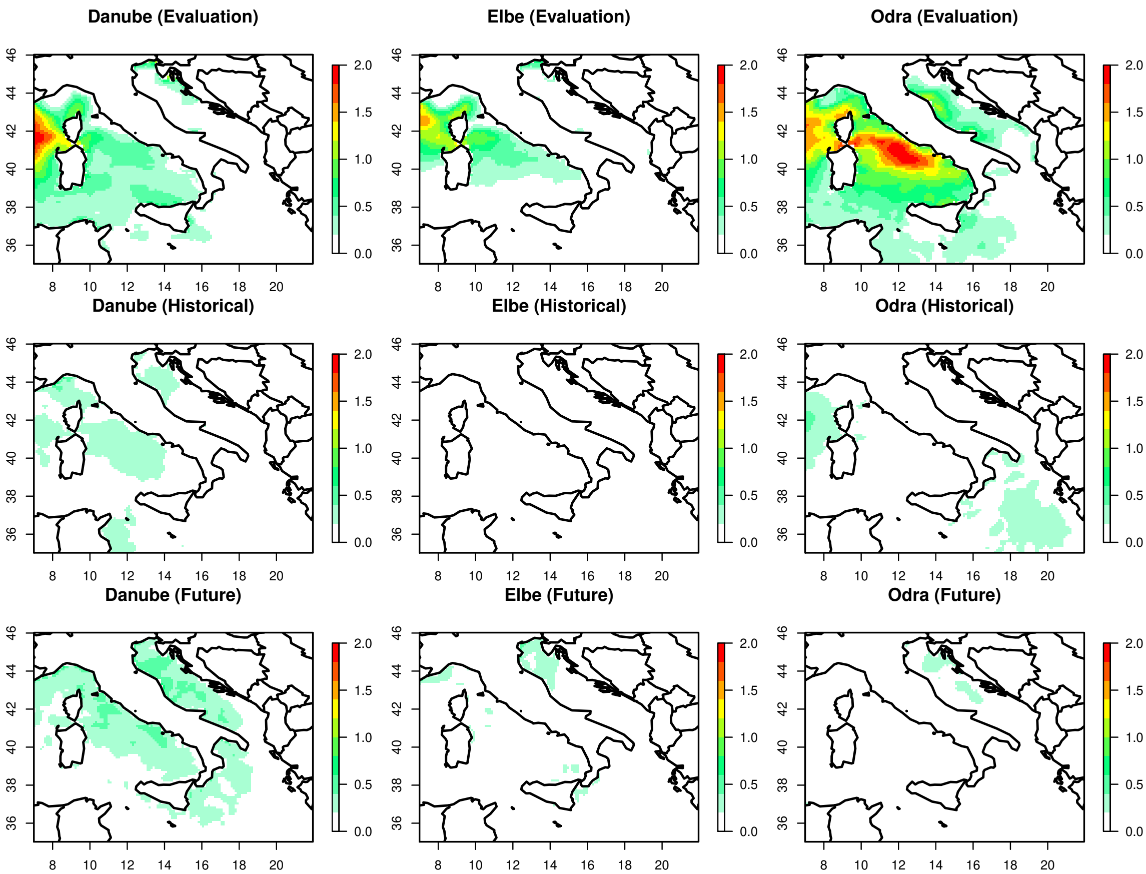

Figure 8. Information exchange ($\times 10^{-2}$ nats) between the evaporation over the Mediterranean Sea and the total precipitation anomalies over the Danube, Elbe and Odra catchments for various simulations. Only 95% significant range is plotted.

The spatial plots of the mean daily wind speed anomalies for all the Vb-cyclones are shown in Fig. 10. On average the wind speed anomaly magnitudes in the evaluation simulation over the NWMS were slightly higher in magnitude compared to the historical simulation (Fig. S10 in supplement). It is to be noted that the differences between the evaluation and historical simulation were greater in magnitudes for the SST anomalies (Fig. 4) and the evaporation anomalies (Fig. 7) over the NWMS compared to the wind speed anomalies differences. Similar to the higher significant SST and evaporation anomaly differences over the Ionian basin and the Adriatic Sea, the wind speed biases are also observed in the historical simulation over these regions compared to evaluation simulation. This implies that some of the crucial feed-backs interms of SST's, evaporation and, wind speed linking the Adriatic Sea and some parts of the Ionian basin are entirely missing in the historical simulation. The future simulation on average showed no significant differences from the historical simulation.

The information exchange spatial locations linking the NWMS wind speed anomalies and the Vb-cyclone precipitation over the three catchments is shown in Fig. 11. Unlike the information exchange patterns linking the NWMS's SST and the evapora-

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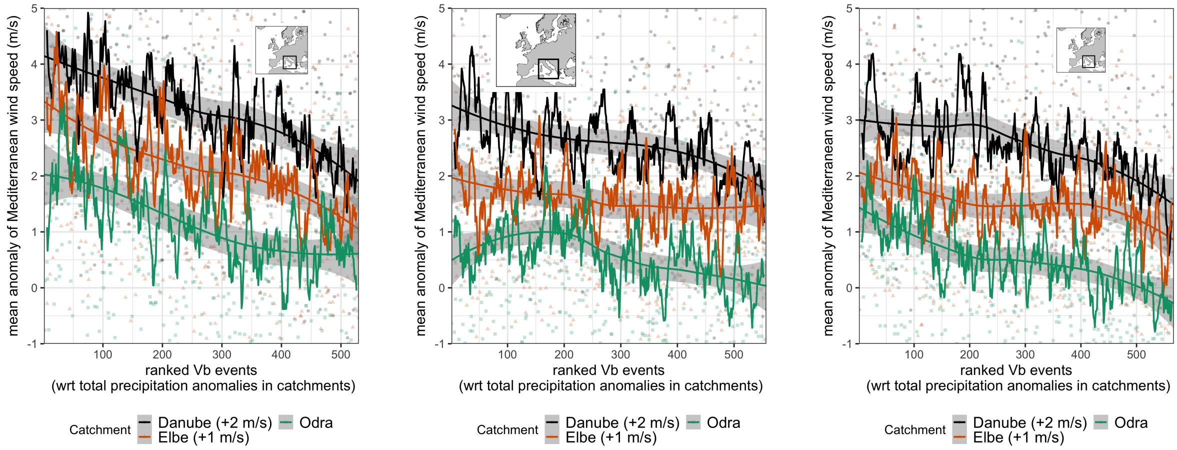

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Figure 9. Wind speed anomalies corresponding to the precipitation anomaly rankings in various simulations for all Vb-cyclones. The lines show the moving average and the LOESS regression. The data for Danube and Elbe catchments were shifted by constant values for improved representation.

tion anomalies to the Vb-cyclone precipitation where significant differences were found between the evaluation and historical simulations, the information exchange patterns linking the wind speed anomalies and Vb-cyclone precipitation showed very similar patterns and magnitudes. This indicates that though the historical simulation captured the process linking wind speed anomalies over the NWMS and Vb-cyclone precipitation, errors in the dynamical evaporative forcing still exist. We found a cold bias in SSTs simulated in the historical simulation which might be causing the unrealistic dynamical evaporative forcing response over the NWMS. Though the same coupled RCM model setup was used for both the historical and evaluation simulation, we see differences in the SST magnitudes. We further investigated plausible reasons for such a behaviour of coupled RCM and a detailed explanation is provided in the Appendix A section. The investigation showed that the coupled RCMs closely follow the SSTs of their driving GCMs. The EC-EARTH GCM used in the historical simulation had a cold bias in the Mediterranean SST, which seemed to be further inherited by the coupled RCM. Furthermore, (Hazeleger et al., 2012) reported biases in surface parameters such as cold surface temperature and surface fluxes in the EC-EARTH GCM simulation. This indicates that the historical simulation must have inherited the simulation biases from its driving GCM, the EC-EARTH, resulting in cold bias of SST and surface air temperatures which influence the evaporation over the NWMS. A study by Pothapakula et al. (2020) reported that the biases from the GCM large scale signals were inherited by the downscaled COSMO-CLM simulations over the South Asia domain resulting in unrealistic process chain linking the Indian Summer Monsoon Rainfall, the Indian Ocean dipole and the El-Niño Southern Oscillation. However, study by Sørland et al. (2018) reported that the RCMs tend to improve the driving GCM biases over Europe, however the RCMs were reported to do a better job in correcting the GCMs when the GCM has a warm bias, compared to a cold bias. Since the historical simulation forced by EC-EARTH is reported to have a cold bias on the surface temperature and sea surface temperatures, it is plausible that the cold biases were inherited by

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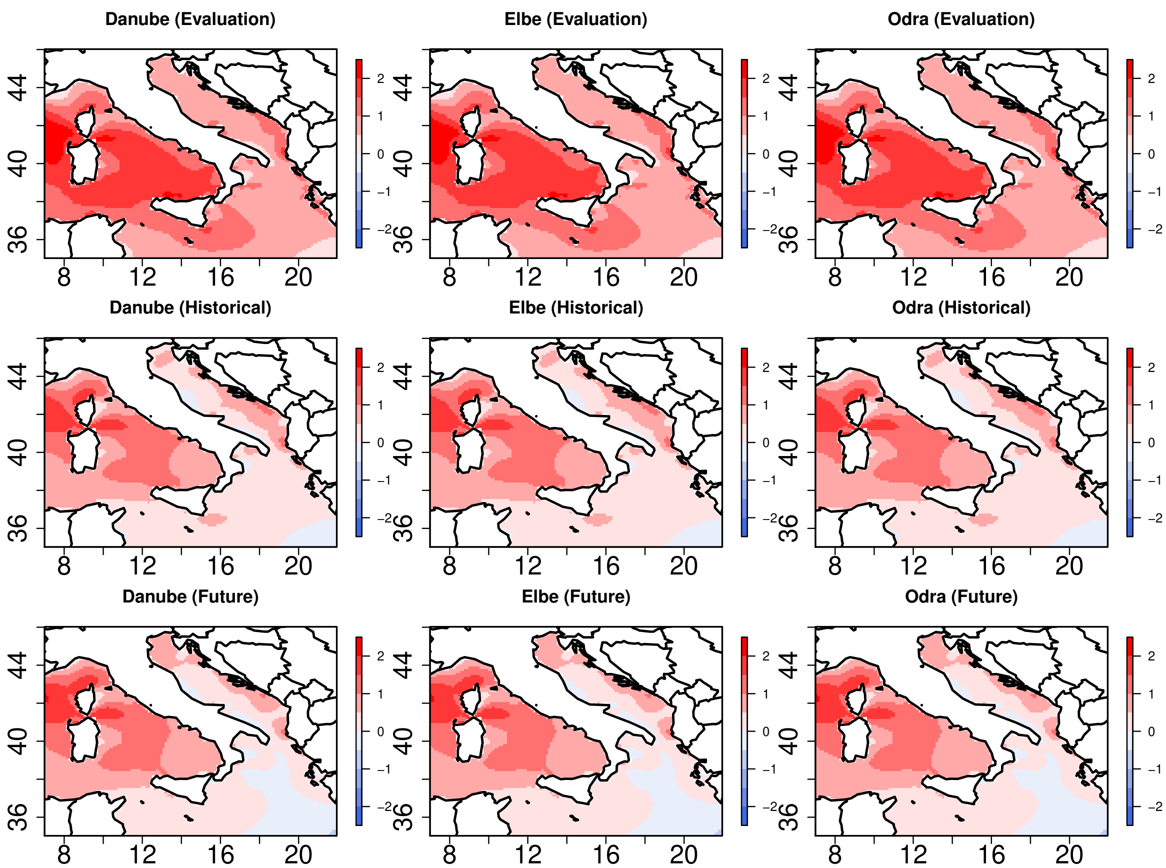

Figure 10. Mean anomalies of wind speed (m/s) over the Mediterranean Sea in the evaluation, historical, and future simulations over Danube, Elbe and Odra catchments for all Vb-cyclone events.

the coupled RCM historical simulation. The information exchange patterns and magnitudes corresponding to the future simulation in Fig. 11 showed no significant differences compared to the historical simulation. This indicates that the future process linking the wind speeds and the Vb-cyclone induced precipitation over the three catchments do not significantly change in the future.

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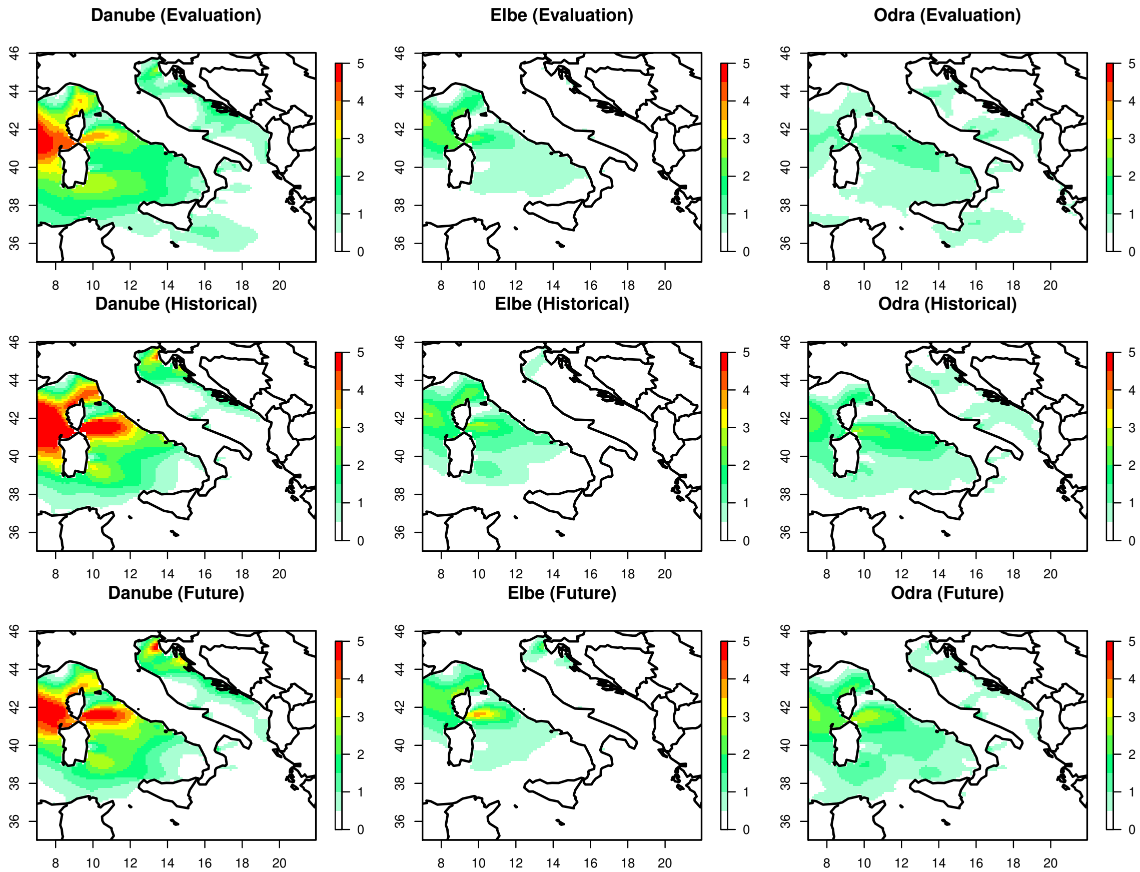

Figure 11. Information exchange ($\times 10^{-2}$ nats) between the wind speed and total precipitation anomalies for various simulations. Only 95% significant range is plotted.

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4 Conclusions

This work focused on the evaluation and projection of Vb-cyclones, the corresponding state and process chains linking the North-West Mediterranean Sea (NWMS) and Vb-cyclone related precipitation in two high resolution coupled regional climate model simulations. One regional simulation was driven by ERA-20C reanalysis (1951-2005) called 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 historical, and from the period 2006-2099 as future simulation.

The results revealed a good agreement in the Vb-cyclone frequency between the evaluation (9.7 events per year) and historical simulations (10.1 events per year) but with significant seasonal differences. This discrepancy in the seasonal cycle of Vb-cyclone occurrences between the evaluation and historical simulation needs a further detailed investigation. The Vb-cyclone track density and intensity in terms of minimum cyclone central pressure showed good agreement between the evaluation and historical simulation. An insignificant increase by 1.8 % in the Vb-cyclone frequency by the end of 21^{st} century was revealed from future simulation. The Vb-cyclone precipitation anomaly magnitude rankings also showed good agreement between the evaluation and historical simulations. Changes in the future Vb-cyclone precipitation anomalies over the three catchments were insignificant.

In investigating the state of NWMS and the Vb-cyclone related precipitation in the Danube, Odra and Elbe catchments, the evaluation simulation showed a correspondence of NWMS SST, evaporation, and windspeed anomalies to the Vb-cyclone precipitation anomaly rankings. Such a correspondence was not detected in the EC-EARTH driven historical simulation. Despite good agreement in the Vb-cyclone frequency, intensity, and precipitation between the evaluation and historical simulation, the state and process chains differ. These differences might be attributed to the emergence of simulation biases inherited from the driving EC-EARTH GCM. Furthermore, (Hazeleger et al., 2012) reported biases in surface parameters such as cold surface temperatures and fluxes, which might be inherited by the coupled RCM resulting in cold SSTs and unrealistic dynamical evaporative response in the historical simulation. Downscaling the EC-EARTH3 (latest version of EC-EARTH) which has smaller bias in the surface air temperatures, SST and surface fluxes (Döscher et al., 2021) might assist in further understanding the state and process chains linking the NWMS and the Vb-cyclone precipitation in historical and future periods.

Code and data availability. 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 including the coupled regional model code can be accessed through 10.5281/zenodo.6585342. The cyclone tracking method is available on request from Michael Sprenger, ETH Zurich. The GUF historical simulation data set is available on ESGF nodes at Deutschen Klimarechenzentrum (DKRZ) Hamburg (https://esgf-data.dkrz.de/projects/esgf-dkrz/).

Author contributions. The concept was proposed by PKP and BA. Funding was acquired by BA. The information theory algorithms were developed by PKP. The Vb-cyclone tracking and the scripts for their rankings were done by AH and further modified and improved by PKP.

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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.

Competing interests. The authors declare that they have no conflict of interest.

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Appendix A: Mediterranean Sea Surface Temperatures in the GCM-RCM chains

To understand the difference in the responses of the Mediterranean Sea in the historical and evaluation simulations, we compared the SST's obtained from the evaluation and historical regional coupled simulations with the UK Met Office's Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST 1.1) with a resolution about 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) with a horizontal resolution of about 0.25° × 0.25° as another source of observational data set. Furthermore, we investigated the SST's as replicated in the GCM-RCM chain for various available coupled simulations in the Med-CORDEX phase II experiments as the simulation used in the current study were a part of Med-CORDEX phase II initiative. The data sets available in the Med-CORDEX data base used in this analysis is shown in TableA1.

The SST data sets from the models in Table A1 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 linearly interpolated onto a common grid prescribed by the Med-CORDEX community named OMED-11i which is approximately 12 km in resolution. Note that simulations used in this study are refered to as Goethe-University Frankfurt (GUF) simulations in this Appendix section.

A1 Evaluation and future projections of Mediterranean SST

Figure A1 (a) shows the temporal evolution of the basin averaged annual Mediterranean SST for various simulations. Comparing the GUF historical and GUF evaluation simulated SST's to the HadISST and OISST observational data sets, we noticed a cold bias (≈ 2 K). This cold bias was more pronounced 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 and summer seasons (Fig. S11 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. 1(a) indicating the inheritance of the GCM SST magnitudes by the respective RCMs. 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 which appears to be inherited by the coupled RCM. 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.

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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. S12 and Fig. S13 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 and GUF historical simulations.

The Mediterranean SST climate change signal is presented in Fig. A1b. 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 RCP8.5 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. S14 in supplement). This results indicate that the GUF simulation captured the future warming signal of the Mediterranean SST inline with the Med-CORDEX ensemble.

Table A1. Regional Climate Models (RCM)/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

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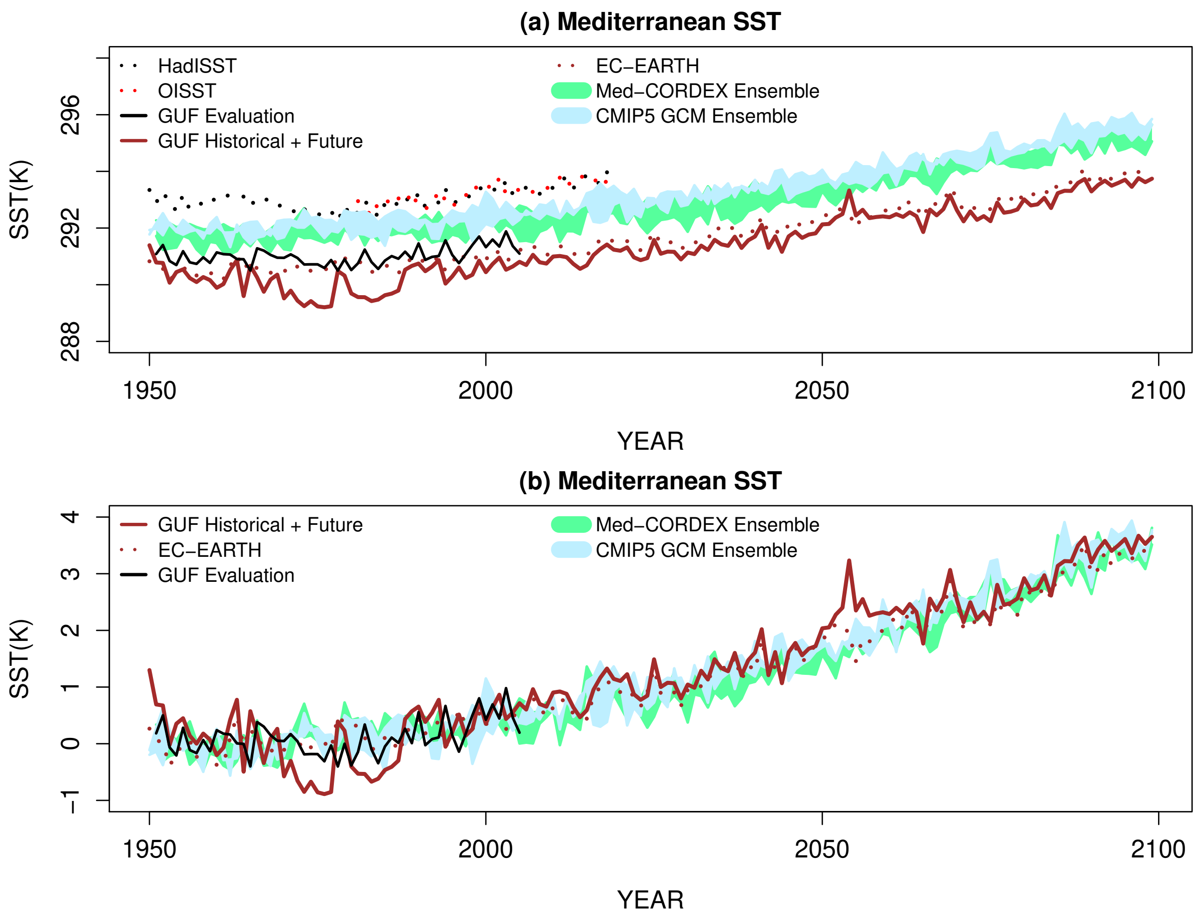

Figure A1. (a) Mediterranean Sea basin averaged annual SST (K) evolution and (b) SST anomalies for the time period 1951-2099 (with reference to historical period 1951-2005) obtained from various simulations along with observational data sets, the HadISST and OISST.

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