

# Extreme Mediterranean cyclones ~~under~~ from pre-industrial to future climate change: impacts on extreme wind, precipitation and compound precipitation–wind events

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**Abstract.** The Mediterranean ~~storm-track is characterized by small but intense cyclones that can cause extreme weather events across the region. Thus the~~ is a major extratropical cyclone hotspot and heavily impacted by climate change. The aim of this study is to investigate the impact of future climate change ~~on~~ with respect to pre-industrial conditions on cyclones which induce extreme wind, precipitation and compounding ~~eyelones~~ precipitation–wind events. Using a regional climate model simulation, we show that the mean cyclone frequency is reduced by roughly a third in the Mediterranean by the end of the 21st century under the representative concentration pathway RCP8.5. For precipitation-type extreme cyclones (EXCs), future projections show increased precipitation during their most intense phase in the western Mediterranean (WMED), whereas precipitation from these cyclones remains similar in the eastern Mediterranean (EMED). Moreover, precipitation EXCs in the EMED are shifted southward, whereas the latitude of precipitation EXCs in the WMED remains unchanged in the future. ~~The intensification of WMED precipitation EXCs in the future is partly explained by a significant increase in diabatically produced PV during their mature phase~~ This intensification is linked to the positioning of future wind speed EXCs at the left exit region of the jet streak, which is itself projected to strengthen under RCP8.5. Wind speed EXCs become more intense in both the WMED and EMED in the future under RCP8.5. The reason for this intensification is that wind speed EXCs in the future are located on the left exit of the jet streak, the latter also being intensified in the future. The future change of compounding precipitation and wind speed cyclones is similar to the individual precipitation and wind speed EXCs, with the exception that wind speed of compounding EXCs is reduced in the EMED. Thus, we find that despite a general reduction of cyclones in the Mediterranean, precipitation and wind speed EXCs intensify in the future in some areas, which implies strong socio-economic consequences for the Mediterranean.

## 1 Introduction

The Mediterranean has long been recognized as one of the most active cyclogenesis regions in the world (Pettersen, 1956). Due to the unique location and topography of the Mediterranean Basin, cyclones in the Mediterranean tend to be of smaller scale,

shorter lifetime, and lower intensity compared to cyclones in the main storm track regions of the Atlantic and Pacific (Trigo, 2006; Campa and Wernli, 2012; Flaounas et al., 2014). Yet, these cyclones can ~~heavily impact~~ have severe impacts on the Mediterranean region ~~as a result of~~ causing heavy precipitation events (Pfahl and Wernli, 2012; Flaounas et al., 2015a; Raveh-Rubin and Wernli, 2015), ~~heavy windstorms~~ intense winds (Nissen et al., 2010; Raveh-Rubin and Wernli, 2015), and coastal floods (Lionello et al., 2019; Ferrarin et al., 2021). When these hazards co-occur as compound extremes, ~~they can have a larger impact than the individual events combined~~ (Martius et al., 2016; Zscheischler et al., 2018; Messmer and Simmonds, 2021; Vakraat and Ho their combined impact can exceed what either hazard would cause individually (Martius et al., 2016; Zscheischler et al., 2018; Messmer and . Given the importance of these high impact weather systems for the Mediterranean, the purpose of this study is to investigate how Mediterranean cyclones change in the future with respect to preindustrial conditions. Thereby, we focus on cyclones, which induce extreme wind, precipitation and compounding precipitation-wind events and investigate which processes explain the changes in such cyclones. Moreover, the Mediterranean is projected to be heavily influenced by future climate change and is defined as a "climate change hotspot" (IPCC, 2021).

~~The impact of climate change on Mediterranean cyclones has been~~

So far, changes of Mediterranean cyclones and their characteristics due to future climate change are extensively studied in global circulation models (GCM) (e.g., Lionello et al., 2002; Raible et al., 2007; Nissen et al., 2014; Hochman et al., 2020; Doensen et al., (GCMs; e.g., Lionello et al., 2002; Raible et al., 2007; Nissen et al., 2014; Hochman et al., 2020; Doensen et al., 2025). For example, Zappa et al. (2015a) showed that CMIP5 models can realistically resolve the cyclone tracks and mean cyclone-related precipitation within the Mediterranean. GCMs also project a robust reduction in future cyclone frequency in the Mediterranean (e.g., Raible et al., 2010; Ulbrich et al., 2013; Nissen et al., 2014). Raible et al. (2010) showed evidence that this reduction is due to a decrease in baroclinicity and an increase in static stability. Nissen et al. (2014) showed that the decrease can also be ~~related~~ attributed to a positive shift in the North Atlantic Oscillation (NAO).

~~In the Mediterranean, a decrease in winter precipitation~~ This decrease in cyclone frequency in winter is interpreted as one major reason for the decrease in mean precipitation in the Mediterranean (Pfahl and Wernli, 2012). This decline in precipitation has already been observed in the 20<sup>th</sup> century (Trigo et al., 2000) and the region is projected to become even drier ~~in~~ during winter in the future (Zappa et al., 2015b). ~~Most of the precipitation in the Mediterranean occurs in the vicinity of a cyclone (Pfahl and Wernli, 2012), and hence this future reduction in precipitation is most likely caused by~~ Thus, global modelling studies agree that cyclone frequency is projected to decrease, inducing a reduction in cyclones. Precipitation extremes occur mostly in the mean precipitation.

Besides the impact of cyclones on mean precipitation, also precipitation extremes are related to cyclones in the Mediterranean. Extreme precipitation events normally occur in autumn in the western Mediterranean and in winter in the eastern Mediterranean (Raveh-Rubin and Wernli, 2015). ~~Reale et al. (2022) showed that cyclone-related precipitation may increase in the western Mediterranean and decrease in the eastern Mediterranean in the future, indicating a discrepancy within the Mediterranean itself. However, Moreover,~~ Chericoni et al. (2025) showed that future extreme cyclone-related precipitation ~~may increase in~~ intensity increases despite a reduction in average cyclone-related total seasonal mean precipitation and the number of extreme cyclones. ~~Wind extremes occur mostly~~ As for precipitation extremes, wind extremes are linked to cyclone activity and

occur in winter for both the western and eastern Mediterranean (Raveh-Rubin and Wernli, 2015). Most climate ~~models-model~~ projections show a decrease in cyclone-related wind speed for the Mediterranean in the future (Zappa et al., 2013; Reale et al., 2022; Dolores-Tesillos et al., 2022), however the confidence of the projections on the impact of climate change on extratropical  
60 cyclone wind speeds is low (Catto et al., 2019). Thus, consensus on cyclone-related extremes in precipitation and wind is still not achieved in climate modelling studies.

~~To interpret these projected shifts in Mediterranean cyclone behaviour, it is essential to analyse the underlying processes. For example, diabatic processes can~~

One reason for the discrepancies in global modelling studies is the representation of relevant processes leading to cyclone-related  
65 extreme events. An important process is the intrusion of stratospheric high potential vorticity (PV) air, which is a primary trigger for cyclogenesis in the Mediterranean (Raveh-Rubin and Flaounas, 2017; Scherrmann et al., 2024). Moreover, diabatic processes substantially enhance the cyclonic circulation in ~~an-extratropical-cyclone~~ extratropical cyclones by low-level ~~potential vorticity (PV)~~ PV production (Davis and Emanuel, 1991). ~~Additionally, intrusion of stratospheric high PV air plays an important role in the formation and dynamics of Mediterranean cyclones (Raveh-Rubin and Flaounas, 2017; Scherrmann et al., 2024)~~  
70 ~~As a result, Mediterranean cyclones are often dominantly~~ the result of an interplay between baroclinicity and diabatically produced PV (~~Homar et al., 2002; Fita et al., 2006~~) (Homar et al., 2002; Fita et al., 2006; Flaounas et al., 2021). Nevertheless, Mediterranean cyclones are less deep than extratropical cyclones in the main storm track regions and only develop PV anomalies of moderate intensity (Campa and Wernli, 2012). ~~Low-level diabatically~~ Diabatically produced PV is ~~often~~ the dominant source of low-level PV in Mediterranean cyclones (Scherrmann et al., 2023), ~~hence~~, Hence, increased latent  
75 heating in a warmer climate ~~may can~~ lead to cyclone intensification due to increased low-level diabatic PV production (~~Büeler and Pfahl, 2019~~), especially impacting as shown in idealized simulations under aquaplanet configurations (Büeler and Pfahl, 2019). This intensification process is responsible for enhanced wind speeds in the warm sector (~~Priestley and Catto, 2022~~) of a cyclone (Dolores-Tesillos et al., 2022). Moreover, Zhang and Colle (2018) suggested in an analysis of the East Coast of North America that future extratropical cyclones ~~may be~~ are less intense in their initial phase due to lower baroclinicity in the atmosphere, but  
80 more intense in their mature phase due to increased diabatically produced PV.

~~A significant amount of explosive Mediterranean cyclones are located in the northwestern Mediterranean due to~~ Another key process is the orographic deformation of the flow of baroclinic waves from the Atlantic generated by the Alps (~~Carniel et al., 2024~~)  
~~Moreover, Raveh-Rubin and Flaounas (2017) found in reanalysis data leading to explosive Mediterranean cyclones in the northwestern Mediterranean (Carniel et al., 2024). Raveh-Rubin and Flaounas (2017) found that the 200 most intense Mediter-~~  
85 ~~anean cyclones are often related to fast-intensifying cyclones in the Atlantic and are precursed by Rossby wave breaking. Also~~ Additionally, cyclones associated with extreme wind speeds in the eastern Mediterranean are frequently located north of a jet streak related to the subtropical jet or a merging of the midlatitude and subtropical jet (Flaounas et al., 2015b; Raveh-Rubin and Wernli, 2015). ~~Prezerakos et al. (2005) conducted~~ This process is illustrated in a case study ~~of an intense cyclone that caused where a cyclone rapidly re-intensifies in heavy rain and winds in the eastern Mediterranean, which rapidly~~  
90 ~~reintensified~~ wind speed after entering the left exit region of the subtropical jet and the right entrance region of the midlatitude jet ~~(Prezerakos et al., 2005)~~.

One big caveat using GCMs, is that the resolution is low. The processes of cyclone intensification, which generate cyclone-related extremes in precipitation and wind speed, involve a wide range of scales. GCM resolutions are often too coarse to represent fully represent these processes and to resolve the complex topography of the Mediterranean and the generally smaller-scale cyclones and their dynamics within the Mediterranean (Flaounas et al., 2013). (Flaounas et al., 2013). Using regional climate models, Reale et al. (2022) showed in contrast to GCM results by Zappa et al. (2015a) that mean cyclone-related precipitation is projected to increase in the northern part of the western Mediterranean and decrease in the eastern Mediterranean, indicating a regional dependence of the response of these events. Schemm (2023) demonstrated that the use of high resolution in climate models is essential for accurately representing diabatic processes in cyclones to produce more realistic cyclone tracks. Hence, studying Mediterranean cyclones within high-resolution regional climate models (RCM) can be is beneficial. For example, Chericoni et al. (2025) showed that the ability to reproduce higher moisture fluxes in their RCM with a 12 km horizontal resolution, lead to higher cyclone-related extreme precipitation. Thus, the purpose of this study is to

Thus, we build on the knowledge discussed above and investigate the impact of future climate change on extreme Mediterranean cyclones and their characteristics using utilizing a high-resolution RCM simulations. We utilize simulation produced by the Weather Research and Forecasting (WRF) model (Skamarock et al., 2021). WRF is used to dynamically downscale the Community Earth System Model (CESM; Hurrell et al., 2013) simulation from 1821 to 2100 (Doensen et al., 2025) to a 20 km horizontal and a 1 hour temporal resolution. The analysis is focussed on wind, precipitation and compounding precipitation-wind extreme cyclones (EXC) in the western and eastern Mediterranean. The future climate change signal is extracted by comparing the last 60 years of the 21st century under the representative concentration pathway (RCP) 8.5 conditions with to the first 60 years of the simulation, representative for pre-industrial conditions.

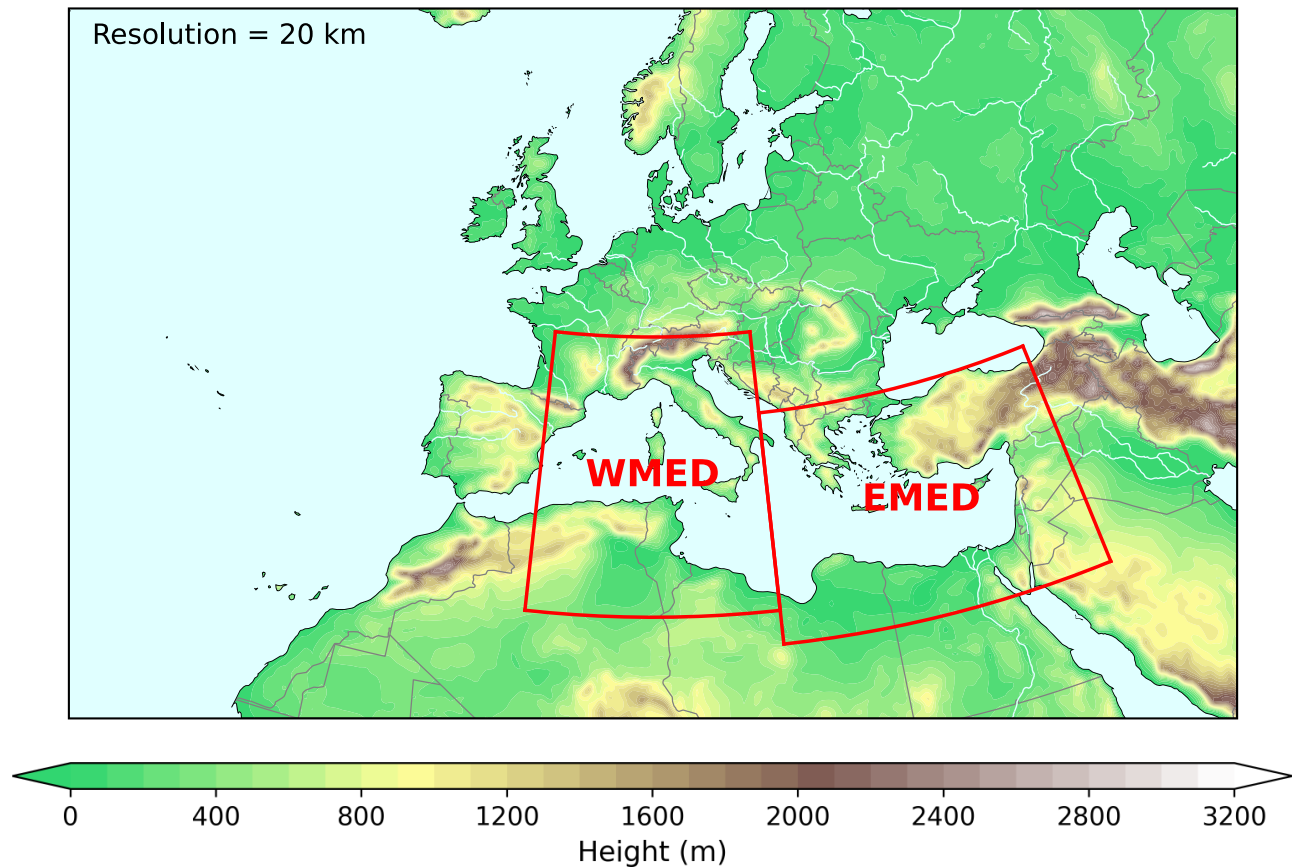
This study is structured as follows. Section 2 describes the models, simulations and methods used. Section 3 presents the results, focussing on extreme precipitation, wind, and compounding cyclones. Then, we discuss the results in a broader context and end with final conclusions in Sect. Section 4.

## 2 Models, simulation and methods

### 2.1 Global and regional climate modelling

To quantify the behaviour of Mediterranean cyclones, we use a model chain from global to regional scales. The global model delivers the initial and boundary conditions for the regional model. The Community Earth System Model (CESM version 1.2.2; Hurrell et al., 2013) serves as global model. Kim et al. (2021) used this model to perform a late Holocene simulation, spanning 3600 years from 1500 BCE until 2100 CE (using the representative concentration pathway RCP8.5 scenario from 2012 to 2100). The output of this simulation has a temporal resolution of 6 hours and a spatial resolution of  $1.9^\circ$  (latitude)  $\times$   $2.5^\circ$  (longitude) in the atmosphere and over land, and a nominal  $1.0^\circ \times 1.0^\circ$  resolution for the ocean and sea ice. The CESM simulation contains 30 vertical levels. In this study, we focus on the period from 1821 CE to 2100 CE (280 years) to capture both the pre-industrial and the future climate.

As RCM, we use the Weather Research and Forecasting (WRF) model version 4.3 (Skamarock et al., 2021) for dynamical  
 125 downscaling. WRF is a mesoscale model that is based on the non-hydrostatic equations and a set of parameterizations to  
 represent sub-grid-scale processes. We used the set of parameterization schemes listed in Table 1. For the Noah-MP land  
 surface model, the phase change of glaciers is turned off, since this option causes numerical instabilities in our simulation.



**Figure 1.** The domain used for the WRF simulation. The two subdomains used for the analysis are highlighted in red: Western (WMED) and eastern Mediterranean (EMED). Shading indicates the height of the model orography in meters above sea level using the WRF topography Global Multi-resolution Terrain Elevation Data (GMTED2010) provided by the United States Geological Survey (Danielson and Gesch, 2011).

The 280 years of the CESM simulation are dynamically downscaled to a horizontal resolution of 20 km and 49 vertical  
 levels. A fixed time step of 120 s is used, and the data is stored with an hourly temporal resolution. To save time, we split up  
 130 the 280 years in roughly 35 year chunks that always overlap for 2 years in time. The 2-year overlap is used as spin-up time for  
 each chunk. Note that the land and atmosphere usually reach equilibrium after 6 to 12 months (Jerez et al., 2020). We use a  
 single-domain setup covering the Euro-Atlantic area (Fig. 1). Nudging to the large scale circulation of the CESM simulation is

switched off, as the main cyclogenesis regions for Mediterranean cyclones are within this domain, and cyclones forming within this domain could develop their own dynamics independent of CESM input data. Although a horizontal resolution of 20 km is insufficient to numerically resolve convective processes, it is sufficient to accurately represent cloud-diabatic processes in fronts and conveyor belts that are crucial features in extratropical cyclones (Willison et al., 2013; Catto et al., 2019).

**Table 1.** Parameterization schemes used for the WRF simulation.

| Parameterization scheme type | Parameterization scheme name                                                        |
|------------------------------|-------------------------------------------------------------------------------------|
| Microphysics                 | Thompson Scheme (Thompson et al., 2008)                                             |
| Shortwave Radiation          | Dudhia Shortwave Scheme (Dudhia, 1989)                                              |
| Longwave Radiation           | RRTM Longwave Scheme (Mlawer et al., 1997)                                          |
| Surface Layer                | Revised MM5 Scheme (Jiménez et al., 2012)                                           |
| Land Surface                 | Noah–MP Land Surface Model (Niu et al., 2011)<br>(without phase change of glaciers) |
| Planetary Boundary Layer     | Yonsei University Scheme (YSU) (Hong et al., 2006)                                  |
| Cumulus                      | Kain–Fritsch Scheme (Kain, 2004)                                                    |

## 2.2 Cyclone tracking algorithm

Extratropical cyclones are tracked with the cyclone tracking algorithm developed by Blender et al. (1997), which is extended by Schneidereit et al. (2010) and Raible et al. (2018). It has been shown that this algorithm can represent cyclones realistically (Raible et al., 2008; Neu et al., 2013; Doensen et al., 2025).

The algorithm tracks minima in the geopotential height field, and we apply it to the hourly 850 hPa geopotential height (Z850) field in WRF. Since tracking cyclones in the lower atmosphere at higher resolution is difficult, ~~because of noise introduced by the~~ due to the complex Mediterranean topography, we regrid the Z850 field of the WRF simulation to  $1^\circ \times 1^\circ$  resolution (roughly 100 km). The regridding excludes weak and unphysical lows. Additionally, we apply a linear smoothing of all grid cells within  $2^\circ$  of one grid cell. With this, we prevent cyclone tracks from being split into multiple tracks. To further ~~define~~ limit the number cyclones, the following criteria of identified local minima must be met:

- A minimum mean gradient of at least 20 geopotential meters (gpm) per 1000 km.
- A minimum mean gradient of 75 gpm per 1000 km at least once during the lifetime of the cyclone.
- Local minima over grid cells with an orography higher than 1000 m above sea level are excluded.
- To connect all the minima of a cyclone track together, a minimum in the following time step is identified with a next-neighbour search. The new minimum of the cyclone one hour later had to be within roughly 40 km of the previous cyclone minimum.
- The minimal lifetime of a cyclone is at least 12 h.

Since the cyclones are tracked on the  $1^\circ \times 1^\circ$  Z850 field, the location of the cyclones often does not match the actual Z850 minimum in the higher 20 km resolution data. Therefore, for every point within the cyclone track, we search for the actual Z850 minimum in the higher resolution Z850 field within a 100 km radius of the original cyclone track point. Next, we assume a cyclone radius of 500 km which corresponds to the average radius found for Mediterranean cyclones (Trigo et al., 1999). We use this cyclone radius to exclude wind speed and precipitation that are not cyclone-related.

### 2.3 ~~Extreme cyclones~~ Definition of cyclone-related extremes

To ~~focus on EXCs in the Mediterranean, we calculate the 95th-percentile precipitation and wind speed within the radius of~~ compute how extreme each cyclone track is, we perform the following procedure for the WMED and EMED respectively:

- ~~To select the most intense wind speed EXCs, we only consider the 95<sup>th</sup>-percentile 850 hPa wind speed (WS850) of all grid cells within the predefined 500 km .The time at which the cyclone radius. This is only done at the time the cyclone reaches its minimum-core minimal sea level pressureis a good indicator of when the cyclone achieves-. The time of minimum core pressure, defined as  $t_{slp}$ , is a solid indication of when a cyclone reaches its highest wind speeds (Pfahl and Sprenger, 2016) and for every cyclone track we assess 850 hPa wind speed (WS850) at this time step (-). Peak precipitation in a cyclone often occurs a couple of hours before (Booth et al., 2018). Hence, for precipitation, we use the rolling-summed 6 hourly speed (Pfahl and Sprenger, 2016).~~  
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- ~~Precipitation generated by Mediterranean cyclones often peaks a few hours before the cyclone reaches its minimum core pressure (Flaounas et al., 2018). Thus, for each timestep we compute the 95<sup>th</sup>-percentile precipitation within the 500 km radius, which is the sum of the precipitation 6-hour accumulated precipitation ( $precip_{6h}$ ) within the cyclone radius. We define  $precip_{6h}$  as the sum 3 -hours before and 2 -hours after a specific time step (hours after each time point within the cyclone track. Eventually, we only retain the highest  $precip_{6h}$ ). The time within the track, when- is the highest, is defined within the cyclone track and define the time at which this occurs as  $t_{precip}$ . Next, EXC extremeness is measured by how many standard deviations-~~  
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- ~~Each track is only considered if at least one point of the track crosses the WMED or EMED, respectively. Also, we ignore all WS850 and  $precip_{6h}$  values that lie outside the predefined coordinates of the WMED and EMED regions. Thus, the cyclone at  $t_{slp}$  and-or  $t_{precip}$  is always located within the WMED and EMED box.~~  
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- ~~Next, we consider all  $precip_{6h}$  values at  $t_{precip}$ -, and all WS850 values at  $t_{slp}$  of the tracks that meet the criteria of the previous point for the whole 280 year period. These values are then normalized by their standard deviation. This step provides a measure of extremeness for  $precip_{6h}$  and WS850 expressed in how many standard deviations they deviate from the mean 95th-percentile precipitation and wind speed across all tracked cyclones over the whole 280-year period. Since of all the tracks. Since the distribution of  $precip_{6h}$  data are typically values is highly skewed, we use a power-law transformation after normalization to make the  $precip_{6h}$  distribution more-Gaussian. Specifically, Gaussian.~~  
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$precip_{6h}$  data. ~~For compounding events, we compute the joint probability distribution of the precipitation and wind speed EXCs and ranked their extremeness based on the joined distribution.~~ A Gaussian distribution is needed to determine the joint distribution for the compounding EXCs.

- 190 – Lastly, cyclones are ranked by their extremeness, measured in standard deviation from the mean. We also do this for the joint distribution of  $precip_{6h}$  and WS850 to quantify the extremeness of precipitation-wind compounding cyclones.

## 2.4 Definition of regions and study periods

To highlight the climatological differences within the Mediterranean, we split up the Mediterranean into two regions (two red boxes in Fig. 1), namely the western Mediterranean (“WMED”, between  $0^{\circ}$  E -  $17.5^{\circ}$  E and  $30^{\circ}$  N -  $47^{\circ}$  N), and the eastern Mediterranean (“EMED”, between  $17.5^{\circ}$  E -  $40^{\circ}$  E and  $28^{\circ}$  N -  $42^{\circ}$  N). All analyses are performed for each region separately.

- 195 To assess the effect of climate change on Mediterranean cyclones, we use two 60-year periods. The first period is defined as all winter half-years (ONDJFM) starting in October 1821 until March 1881 and roughly representing the pre-industrial climate. The second period is defined as all winter half-years from October 2039 until March 2099 representing the future climate under the RCP8.5 scenario. These periods and the EXCs within these periods will be referred to as *past* and *future*, respectively.

- 200 We apply a Kolmogorov-Smirnov (KS) test (An, 1933) in the analyses to test statistical significance at the 5 % level. For the location, we use KS test to see if the median latitude and longitude of the future EXC changes. For the ~~climatology~~seasonality, we use the KS test to examine whether future EXCs occur ~~red~~at different times, ~~by assessing if.~~ This is done by analysing the median day-of-year of each EXC type changed in each region for each region and time period.

## 2.5 Composite analysis

- Finally, a cyclone-centred composite analysis is performed on the 50 most extreme EXCs found in the WMED and EMED,   
205 respectively. ~~This number roughly corresponds to the 5%.~~ We identify roughly 1000 cyclones per period and region. For the composite analysis, we select the 50 most extreme cyclones found for each region in the past and the future, defined with respect to the 95th percentile of precipitation, wind speed, and wind-precipitation compound EXCs. The analysis is performed for cyclones associated with cyclone-related precipitation, wind, and compound extremes, separately.

1. For each cyclone track, we set the reference at time  $t_{slp}$  ~~or for wind speed EXCs and precipitation for wind EXCs ;~~   
210 ~~respectively. Every time step of the track and~~  $t_{precip}$  for precipitation EXCs. Every track timestep after  $t_{slp}$  or  $t_{precip}$  receives a positive index, and the ~~time steps of the track track timesteps~~ before  $t_{slp}$  or  $t_{precip}$  a negative index.
2. For each of the hourly time steps of the cyclone track, all fields are centred at the location of the cyclone, given by its ~~core~~-minimum Z850 (which we use for the tracking). With this approach, the model data for each cyclone track point is independent of its geographical location.
- 215 3. We are only interested in the 12 hours before and after  $t_{slp}$  or  $t_{precip}$  for each cyclone to capture the intensification and ~~decaying~~mature phase of the cyclone.

4. Within this time period, we compute spatial averages ~~from~~of the 50 most extreme EXCs.

We perform the above analysis for the WS850,  $precip_{6h}$ , and the 200 hPa wind speed (WS200) field. Note that some EXC tracks may initialize later than 12 hours before  $t_{slp}$  or  $t_{precip}$ , and may also disappear earlier than 12 hours after  $t_{slp}$  or  $t_{precip}$ . Hence, the composites shown at 12 hours before and after  $t_{precip}$  or  $t_{slp}$  consists of slightly less than 50 EXCs. To compute whether the differences in spatial means for past and future cyclones ~~is~~are statistically significant we apply a Welch's t-test (Welch, 1947) to the spatial composite.

Furthermore, we ~~also~~ compute vertical cross-sections for the 50 most extreme precipitation EXCs ~~, where we vertically interpolated on 21 pressure levels an east-west along an east-west~~ plane through the cyclone core spanning 1600 km in total. For these vertical cross-sections, we ~~computed~~compute PV anomalies, potential temperature ( $\theta$ ) and equivalent potential temperature ( $\theta_e$ ) for 21 pressure levels up to 100 hPa (50 hPa intervals from 100 to 900 hPa and 25 hPa intervals from 900 to 1000 hPa). PV anomalies ~~were~~are computed by subtracting the daily PV climatology, calculated separately for the past and future period, from the instantaneous PV fields. The climatology ~~was~~is derived by averaging PV for each calendar day and applying a centred 31-day running mean.

We also compare some analyses in WRF to ERA5 reanalysis data (Hersbach et al., 2020) for the period October 1981 to March 2011 to capture 30 winter half years. Like in WRF, we track cyclones on 1° resolution in ERA5, but for the EXC composite analysis we use the highest available ERA5 resolution of 0.25°, and regrid the WRF data to the ERA5 resolution for a fair comparison.

### 3 Results

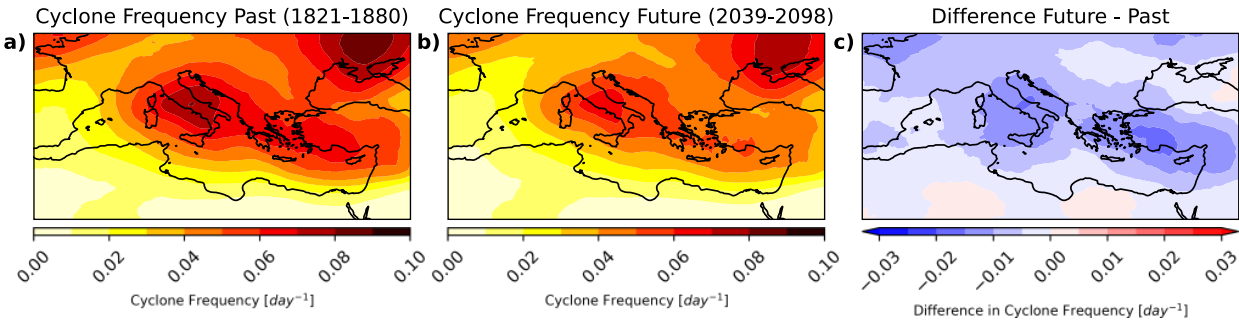
#### 3.1 Climatology of mean and extreme cyclones

~~Here~~First, we characterize the preferred regions of all ~~and extreme~~ cyclones in the Mediterranean. Therefore, we use the cyclone frequency, defined by how often a grid cell is ~~within the~~located within the 500-km radius of a cyclone ~~(defined as 500 km)~~ in the original WRF grid.

~~Enhanced mean cyclone frequency is consistently found in a band spanning from the Tyrrhenian Sea to the Levant with maxima over Italy and northern Greece to the Anatolian Plateau.~~ The comparison of WRF with ERA5 for the time period 1981 to 2010 shows that WRF overestimates the number of cyclones for most of the domain (Fig. S1). This is to some extent expected as WRF is higher resolved. Regionally, the main cyclone hotspots extend from Italy towards the Levant in WRF (Fig. S1a), whereas in ERA5 this is more confined to the region around Italy (Fig. S1b). Thus, biases in cyclone frequency are evident over the eastern Mediterranean and eastern Europe (Fig. 2). These regions ~~S1c), whereas biases over the western Mediterranean are small.~~

Regions of high cyclone frequency exhibit the highest cyclone frequencies in both the past (up to 0.09 cyclones day<sup>-1</sup>; Fig. 2a) and the future (up to 0.07 cyclones day<sup>-1</sup>; Fig. 2b). Comparing the future with the past period, a decrease in cyclone frequency is evident (Fig. 2c). Apart from a few regions in northern Africa, all regions in the Mediterranean show a decline

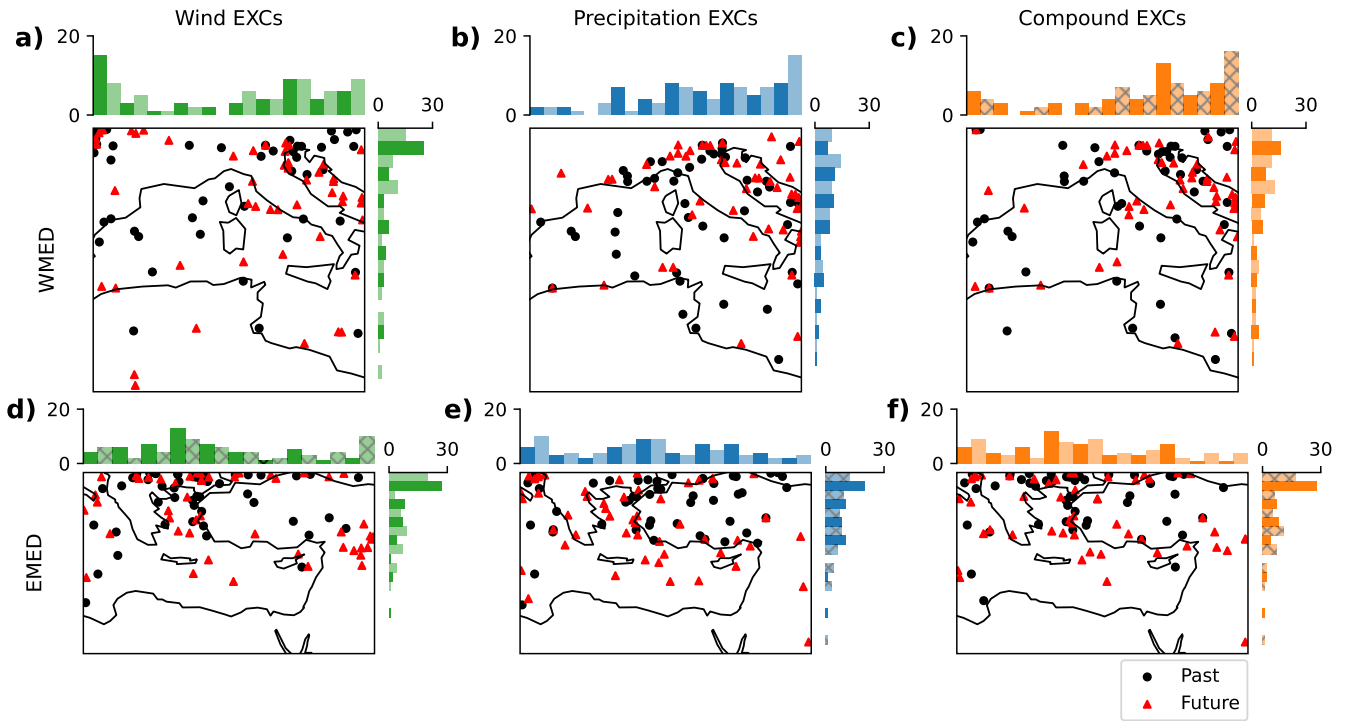
in mean cyclone frequency. This is ~~especially the case over the maxima in~~ particularly true for the hotspot over Italy and the Anatolian Plateau, which show the largest absolute decrease in cyclone frequency (up to  $0.02 \text{ cyclones day}^{-1}$ ), which in relative terms indicates a decrease of roughly one-third.



**Figure 2.** Mean cyclone frequency in the Mediterranean for the past (a; 1821-1880), the future (b; 2039-2098) and the absolute difference between the future and the past (c). Shading shows the number of times ( $\text{day}^{-1}$ ) where a grid cell is within the 500 km radius around a cyclone centre.

~~Concerning extreme cyclones, we show the location~~

Besides the mean cyclone frequency, also the spatial distribution of the 50 most extreme EXCs is analysed. In Fig. 3 the locations of past and future EXCs for each region and each category ~~at (Fig. 3).~~ are shown. In the WMED (Fig. 3a-c), wind speed EXCs are distributed over the entire domain, whereas precipitation and compound EXCs cluster over the warm waters of the Tyrrhenian and Adriatic Sea, and over Northern Italy. Future precipitation EXCs in the WMED (Fig. 3b) ~~seem to~~ occur less often over the Mediterranean and Ligurian Sea. In the EMED (Fig. 3d-f), all EXC types ~~tend to~~ cluster in the Ionian and Aegean Sea, and over northern Greece and the Anatolian Plateau. Future precipitation and compound EXCs (Fig. 3e and 3f) ~~tend to be located more over~~ shift south towards the Mediterranean Sea ~~south of Turkey.~~

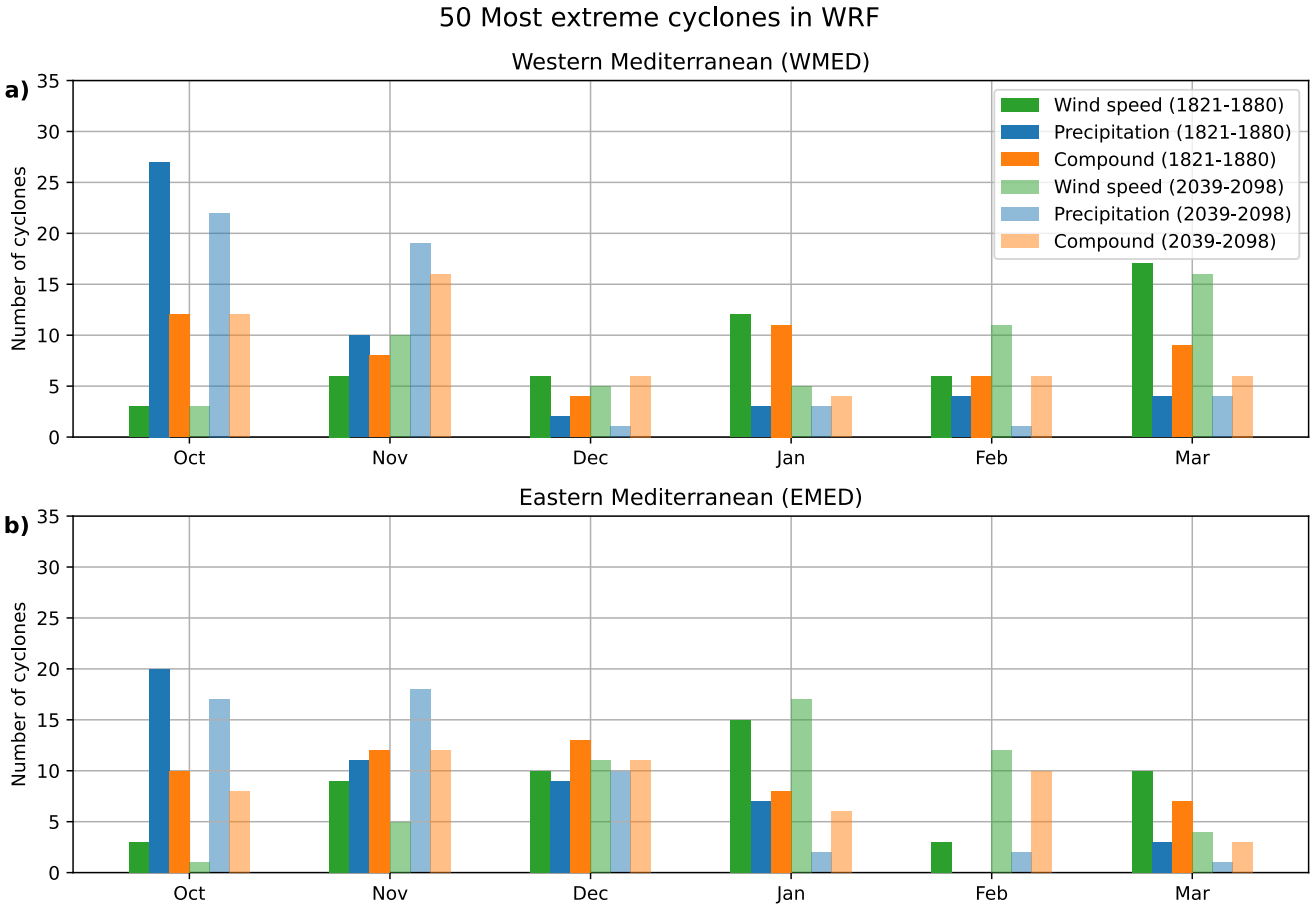


**Figure 3.** Location of 50 most extreme EXCs in WMED (a–c), and EMED (d–f). Shown are locations of wind EXCs (left column), precipitation EXCs (middle column), and compound EXCs (right column) at  $t_{slp}$ . Black circles indicate past EXCs, red triangles indicate future EXCs. The bars indicate the number of cyclones binned in groups of 10 for each longitude and latitude. Green, blue and orange bars indicate wind, precipitation and compounding EXCs, respectively. The lighter shaded bars indicate past EXCs, whereas darker shaded bars indicate future EXCs. Hatched bars indicate a statistically significant change (5% level) in longitude or latitude.

For each subpanel, we also show histograms of the longitudes and latitudes (Fig. 3) to investigate whether the median location of EXCs changes as a result of climate change. Indeed, the southward shift of precipitation and compound EXCs in the EMED in the future is statistically significant at the 5% level. We also find a significant eastward shift of compound EXCs in the WMED in the future (Fig. 3c), and of wind EXCs in the EMED (Fig. 3d). The latter is most likely caused by the future cluster popping up cluster appearing in the Levant in the future.

Besides the spatial changes, we investigated also investigate changes in the monthly occurrence of extreme cyclones seasonality of EXCs during the extended winter season. In Fig. 4, we show the number of EXCs that occur every month of the winter half-year for the WMED and EMED (Fig. 4a) and EMED (Fig. 4b) in the past and the future. Wind and compounding EXCs are distributed occur evenly over the entire winter half-year. Still in both regions. Yet, wind EXCs occur more frequently in the second and colder part of the winter half year, whereas compounding EXCs tend to be are more frequent during the first part beginning of the winter half-year. The occurrence of precipitation EXCs (blue bars) peaks in autumn when the Mediterranean Sea is still warm and evaporation from the sea surface can nourish precipitation of the cyclone, and these

eyelones hardly occur in the second part able to provide moisture to the atmosphere. In the second half of the winter half-year for half year precipitation EXCs become rare in both regions. This decrease The decrease in precipitation EXCs is very abrupt in the central Mediterranean (Fig. 4a), whereas in the eastern Mediterranean it is more gradual (Fig. 4b). WMED, and more gradual in the EMED. Comparing the past with the future distributions during the extended winter EXC distribution, we do not find a statistically significant impact on the median time change in the median time of occurrence of EXCs any EXC type in any region. Thus, the seasonality of extreme cyclones remains unchanged under future RCP8.5 conditions.



**Figure 4.** Number of Mediterranean EXCs per month in the WMED (a) and EMED (b). Green, blue and orange bars show the number of wind, precipitation and compounding EXCs, respectively. Plain bars indicate the number of EXCs in the past (1821–1880), and semi-transparent coloured bars indicate the number of EXCs in the future (2039–2098).

### 3.2 Cyclones associated with extreme precipitation

HereIn this section, we assess the life cycle of the-precipitation EXCs using the-a composite analysis. In Fig. 5, the 50 most extreme precipitation EXCs are shown for the WMED and EMED, assessing past and future EXCs before, at and after their

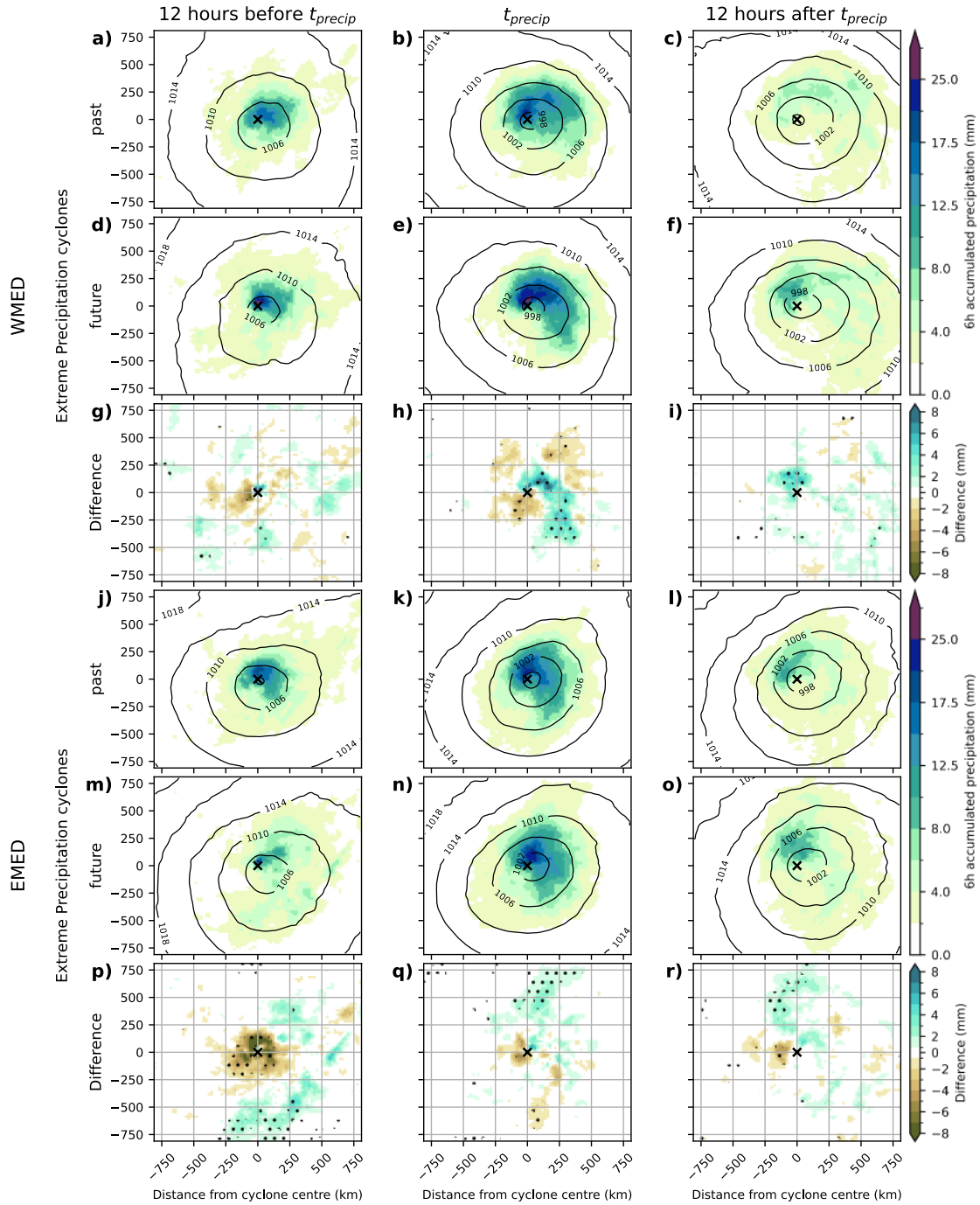
most intense precipitation phase  $t_{precip}$ . In all composites, we see the ~~general~~-structure of a cyclone with a clear minimum in sea level pressure and precipitation bands north and southeast of the EXC ~~center~~centre.

~~We start with~~ First, we analyse the life cycle of past precipitation EXCs (Fig. 5a-c and j-l). 12 hours before  $t_{precip}$  (left column), the highest precipitation is ~~observed mostly located~~ north of the EXC ~~center~~centre in both regions, with the ~~most intense precipitation found highest~~  $precip_{6h}$  ~~values located~~ very close to the EXC ~~center~~centre (Fig. 5a,j). This is in agreement with ERA5 as the comparison for the period 1981-2010 shows, although WRF overestimates  $precip_{6h}$  12 hours before  $t_{precip}$  (Fig. S2).

In the EMED, a precipitation band southeast of the EXC ~~center is visible, possibly indicating centre is present, which indicates~~ the development of frontal structures (Fig. 5j). At  $t_{precip}$  (Fig. 5b,k), precipitation further intensifies and the development of ~~potential frontal structures~~ frontal structures southeast of the cyclone core is evident. Highest ~~precipitation is still observed~~ just  $precip_{6h}$  values are still located north of the EXC centre, with ~~precipitation rates~~  $precip_{6h}$  values up to and exceeding  $25 \text{ mm } 6\text{h}^{-1}$  for past (Fig. 5b) and future (Fig. 5be) EXCs in the WMED ~~respectively., respectively. Again WRF agrees with ERA5, but overestimates  $precip_{6h}$  at  $t_{precip}$  (Fig. S2).~~

In the composites 12 hours after  $t_{precip}$ , ~~precipitation rates significantly decrease~~  $precip_{6h}$  significantly decreases in both regions (Fig. 5c,l). Close to the EXC ~~center, precipitation rates have fallen the most (in the order of centre,  $precip_{6h}$  has fallen by 10 to 15 mm 6h<sup>-1</sup>).~~ Nevertheless, frontal structures are still ~~recognizable~~ apparent in both regions ~~12 hours after. The.~~ The decay process is well simulated as the comparison to ERA5 shows (Fig. S2).

The life cycle of precipitation ~~goes along follows~~ a general intensification of the pressure field. The core pressure of precipitation EXCs falls by 5 hPa ~~comparing the composites at with between~~ 12 hours before  $t_{precip}$  and  $t_{precip}$ . 12 hours after  $t_{precip}$ , the core pressure is still ~~relatively~~ low, which is ~~most likely~~ due to the fact that precipitation peaks before core pressure reaches its minimum.

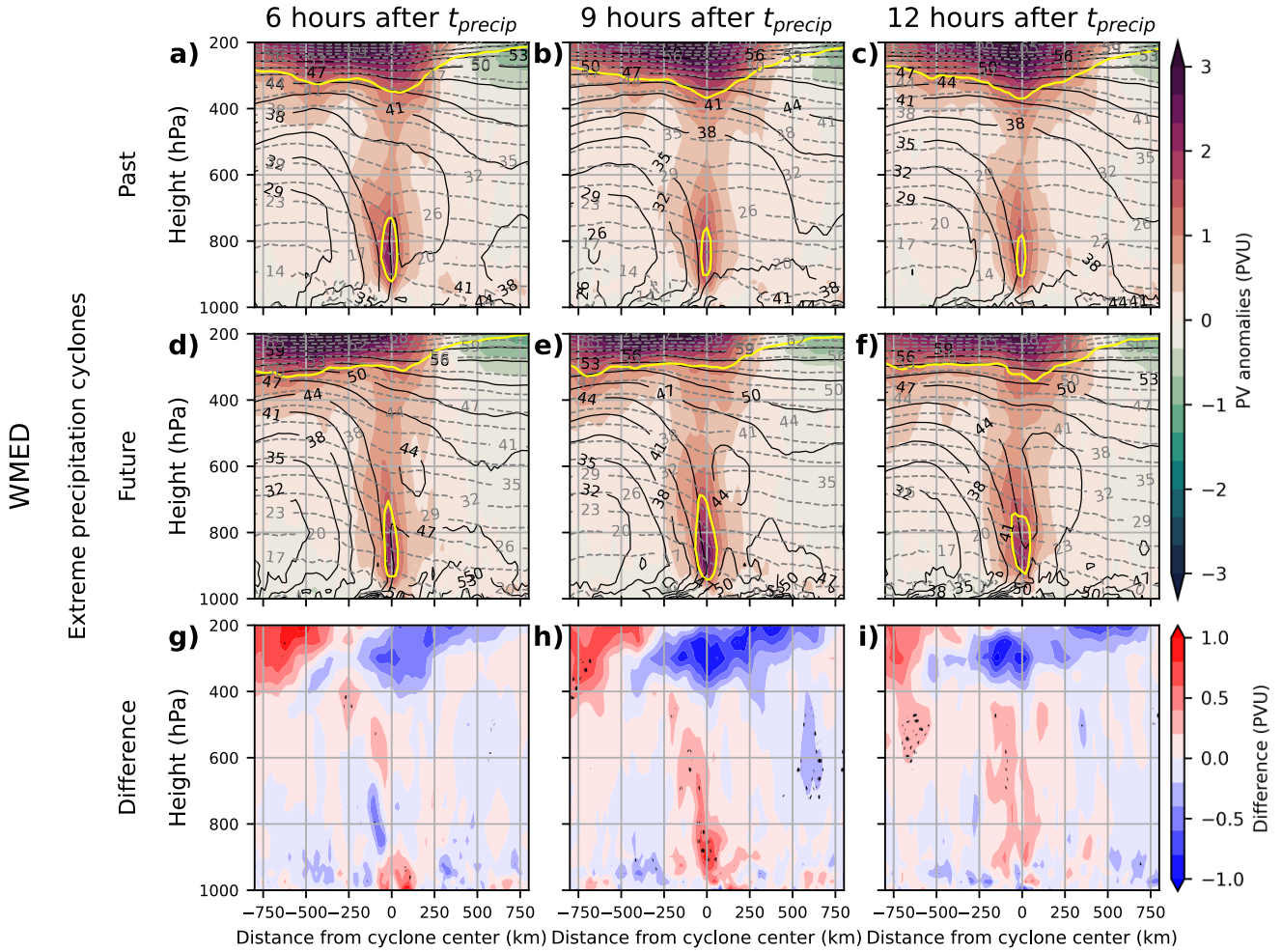


**Figure 5.** A composite of the 50 most extreme precipitation EXCs in the WMED (a–i) and EMED (j–r) showing precip<sub>6h</sub> 6-hourly accumulated precipitation ( $precip_{6h}$ ) in shading. Panels a–c and j–l show composites for the past (1821–1880), panels d–f and m–o show composites for the future (2039–2098), and panels g–i and p–r show the differences between the past and future, where stippling indicates that differences are statistically significant (5% level). Shading indicates mean summed 6-hourly precipitation, and contour Contour lines indicate the mean sea level pressure. The left column shows composites 12 hours before  $t_{precip}$ , the middle column at  $t_{precip}$  and the right column 12 hours after  $t_{precip}$ .

300 The life cycle of future precipitation EXCs show a similar intensification of precipitation process for  $precip_{6h}$  and core pressure for both regions (Fig. 5d–f and m–o). To illustrate the climate change signal in the life cycle, we focus on the difference between past and future EXCs in both regions (Fig. 5g–i and p–r). First, looking at we consider the composites 12 hours before  $t_{precip}$ , we see a considerable decrease in precipitation for future precipitation EXCs. A future decrease of  $precip_{6h}$  around the EXC center centre in both regions appears. In the WMED, the decrease around the core this decrease is rather minor, and  
305 not significant (Fig. 5g). In the EMED (Fig. 5p) the decrease in precipitation reaches,  $precip_{6h}$  decreases up to  $8 \text{ mm } 6\text{h}^{-1}$ , i.e., a decrease of almost half. Notably, precipitation increases significantly further away from the EXC center centre in the EMED. The reduction in precipitation is less apparent at mature state at  $t_{precip}$ . For precipitation EXCs in the WMED (Fig. 5h), a dipole pattern forms with a significant increase in precipitation  $precip_{6h}$  just north of the EXC center centre and within the fronts (frontal zones southeast of the EXC center), and a centre. A significant decrease in precipitation just south of  
310 the EXC center centre appears. The areas where the precipitation increases  $precip_{6h}$  increases also overlap with the areas where precipitation is most intense  $precip_{6h}$  is highest already (Fig. 5b and 5e), hence thus indicating an increase in the impact of future precipitation EXCs at  $t_{precip}$  in the WMED. In the EMED, a general decrease in precipitation decrease in  $precip_{6h}$  is still apparent around the core EXC centre at  $t_{precip}$  (Fig. 5q), although its magnitude the magnitude of the decrease is smaller and the signal does not reach is not statistical significance. Interestingly, the precipitation increase that occurs south of the  
315 EXCs in Fig. 5p disappears, and a precipitation increase north of the EXCs appears. Thus, the results suggest that at  $t_{precip}$ , WMED EXCs tend to produce more and EMED EXCs tend to produce  $precip_{6h}$  increases in precipitation EXCs in the WMED and stays roughly the same amount of precipitation. This difference further amplifies in the EMED. The difference between the regions remains in the composites 12 hours after  $t_{precip}$ . In the WMED, we find a significant increase in precipitation north of the EXC center in the order of  $precip_{6h}$  increase of roughly  $5 \text{ mm } 6\text{h}^{-1}$  north of the EXC centre (Fig. 5i). This is a doubling  
320 compared to past precipitation EXCs (Fig. 5c).

At 12 hours before  $t_{precip}$ , future extreme precipitation EXCs tend to be are slightly less deep in terms of core pressure compared to past precipitation EXCs in both the WMED and the EMED. This suggests that future precipitation EXCs are less intense with respect to pressure before their mature stage, providing a partial answer to why future precipitation rates are less overall  $precip_{6h}$  decreases compared to the past in both regions. At  $t_{precip}$ , precipitation EXCs are equally deep for the past  
325 and future in the WMED where future precipitation EXCs have overcome a slightly larger core pressure difference compared to past cyclones deepen more quickly in 12 hours (Fig. 5a–b vs. Fig. 5d–e). In the meantime, the higher core pressure for future precipitation EXCs persists in the EMED (Fig. 5k vs. Fig. 5n). This partly explains why extreme precipitation could explain why  $precip_{6h}$  in the WMED somewhat increases, in contrast to the EMED. Also 12 hours after  $t_{precip}$ , the difference in core pressure between the WMED and EMED persists.

330 To further explain why future precipitation WMED EXCs tend to be are stronger in their mature phase, we show vertical cross-sections of PV anomalies, potential temperature ( $\theta$ ) and equivalent potential temperature ( $\theta_e$ ) within the composites of Fig. 5. We focus on 6, 9 and 12 hours after  $t_{precip}$ , as differences in PV between past and future EXCs only start to emerge in the mature phase of the cyclone.



**Figure 6.** Vertical ~~cross-section~~cross-section of WMED precipitation EXCs ~~but~~ ranging from 800 km west to 800 km east of the EXC centre, right through the EXC centre. Shading shows PV anomalies [PVU], continuous contour lines show equivalent potential temperature ( $\theta_e$ ) [ $^{\circ}\text{C}$ ] and dashed contour lines show potential temperature ( $\theta$ ) [ $^{\circ}\text{C}$ ]. Shown are past precipitation EXCs (a–c), future precipitation EXCs (d–f) and the difference between the future and past for 6 (left column), 9 (middle column) and 12 hours (right column) after  $t_{precip}$ . Stippling indicates a statistically significant difference (5% level). The yellow line indicates the 2 PVU contour of instantaneous PV.

In all sub-panels of Fig. 6, we find higher ~~values of  $\theta$~~  and  $\theta_e$  ~~values~~ in the right half of the vertical ~~cross-sections~~cross-sections and lower values in the left half, highlighting the warm and cold sector of the EXCs, respectively. In the warm sector,  $\theta$  and  $\theta_e$  ~~diverge more strongly~~differ more than in the cold sector, indicating the ~~abundance of moisture~~greater moisture content of the warm sector. Besides, the negative vertical gradients in  $\theta_e$  in the lower part of the troposphere (e.g. in the right-hand side of Fig. 6e) points to convective instability~~-, which can contribute to  $precip_{6h}$  that we observe in Fig. 5~~. Both  $\theta$  and  $\theta_e$  increase for future EXCs (Fig. 6a–c) vs. Fig. 6d–f), but  $\theta_e$  in the warm sector increases up to 9  $^{\circ}\text{C}$ , showing a combined increase

340 in temperature and moisture in the atmosphere in the future, which further explains the increase in precipitation of EXCs in WMED.

Looking at PV anomalies, we also find future changes in ~~its vertical structure~~ the vertical structure of PV (Fig. 6). In all composites around 300 hPa, we identify high PV air in excess of 2 PVU (indicated by the yellow line) indicating the ~~stratosphere~~ stratospheric air masses. The high PV anomalies above the yellow line indicate a lowering of the tropopause in the vicinity of precipitation EXC. This is in contrast to the upper atmosphere east of the cyclone centre, which is dominated by negative PV anomalies indicating a higher than usual tropopause. Additionally, so-called PV towers ~~with high PV anomalies are present near~~ extend though the entire troposphere are present in the cyclone centre (Fig. 6). These PV towers consist of high-PV stratospheric air intruding into the top of the PV tower, and diabatically produced PV in the lower troposphere. ~~These~~ The lower part of the PV towers exhibit sufficiently large ~~potential vorticity air masses~~ PV values such that the 2 PVU line ~~even becomes visible~~ appears in all composites. ~~Generally~~ Overall, we see the same structures also for precipitation EXCs in the EMED (Fig. S6a–f).

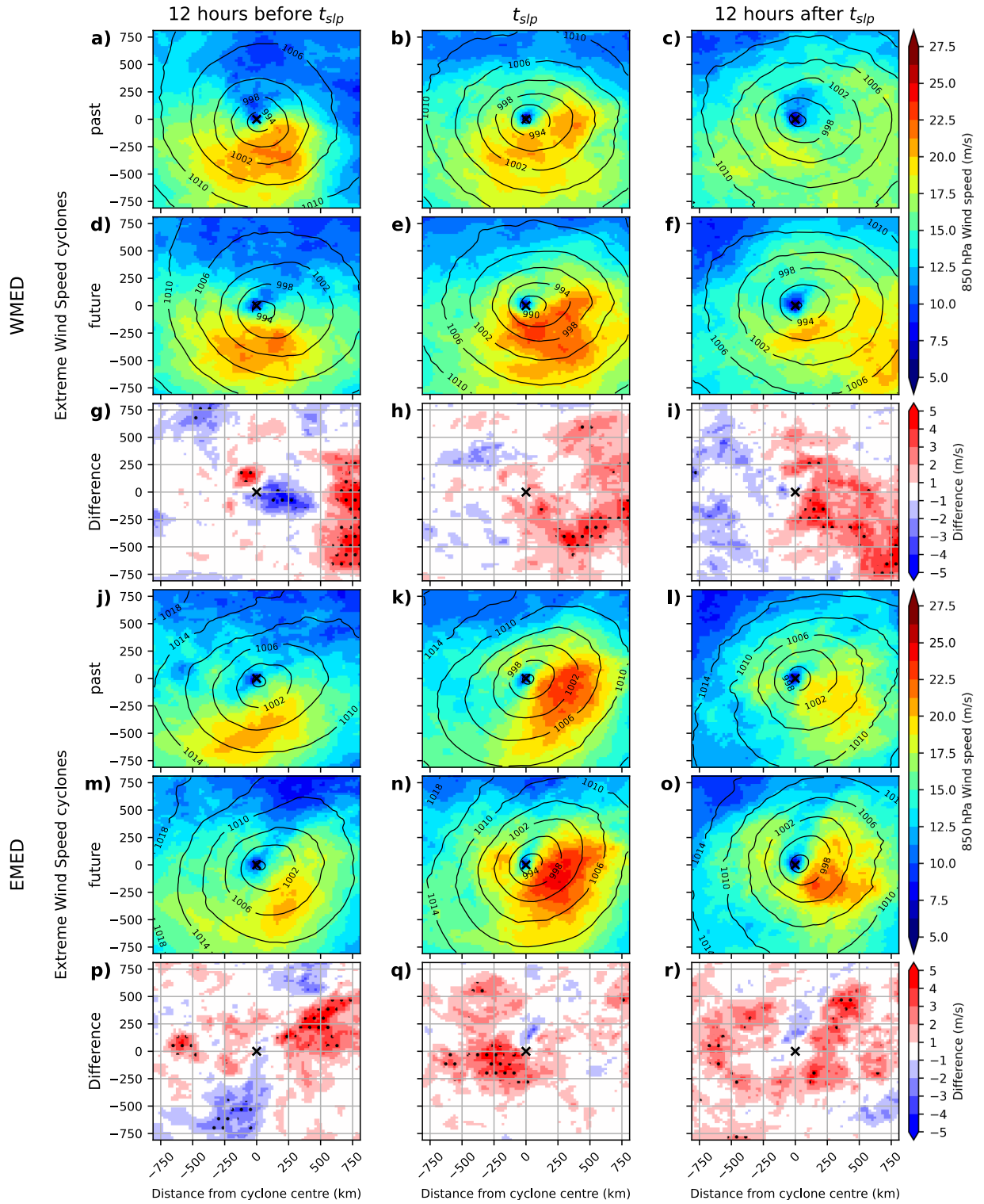
~~When looking at~~ Considering the future differences in Fig. 6g–i, we see a ~~general~~ decrease of PV near the tropopause in the warm sector, indicating the lifting of the tropopause ~~in general~~. In the cold sector, PV increases near the tropopause, which indicates stronger PV advection from the stratosphere and is also indicative of a more intense baroclinic cyclone. Interpretations should be taken with care, though, as the changes observed near the tropopause are ~~not or barely~~ at most marginally statistically significant (at the 5% level). Still, ~~it should be noted that we do not see~~ this enhanced advection of high PV air for precipitation EXCs ~~is not found~~ in the EMED (Fig. S6g–i). ~~Generally, the~~ The PV values within the lower part of the PV tower increase for future precipitation EXCs (Fig. 6g–i). This is ~~especially the case~~ particularly apparent at 9 hours and to a lesser extent at 12 hours after  $t_{precip}$  (Fig. 6h and Fig. 6i) with increases up to 1 PVU. Although the increase is ~~statistically not very robust~~ marginally significant, this still indicates an increase of up to 50% in instantaneous PV in Fig. 6h. This is most likely due to an increase in diabatically produced low-level PV as a result of more moisture and hence higher ~~condensation for latent heat release in~~ future WMED precipitation EXCs. This may enhance the cyclonic circulation and provide a mechanism of why future WMED precipitation EXCs exhibit a stronger intensification and stay more intense in their mature phase. We also see an increase of PV in the PV towers associated with future precipitation EXCs in the EMED, but this increase is clearly less robust (Fig. S6g–i).

### 3.3 Cyclones associated with wind extremes

In this section, we investigate the life cycle of the wind EXCs, following a similar strategy as ~~for~~ with precipitation EXCs. ~~Using again the composite analysis of the 50 most extreme events~~ In Fig. (Fig. 7), we find that the highest ~~wind speeds~~ WS850 values are generally located just south or southeast of the EXC ~~center~~ centre with WS850 values of up to  $25 \text{ ms}^{-1}$ . Minimum core pressure falls below 990 hPa in most composites, and core pressures are generally up to 10 hPa lower than for precipitation EXCs ~~with higher pressure gradients as well~~. Also, the isobar spacing is wider, indicating a weaker pressure gradient.

The ~~development of the life cycle of~~ past wind EXCs and ~~the its~~ associated wind field is shown in Fig. 7a–c and Fig. 7j–l. ~~At~~ 12 hours before  $t_{slp}$  (left column), the wind EXCs ~~already deepened substantially~~ is already substantially deep, and the

wind field is strongest south and southeast of the core. ~~EXCs~~ The comparison with ERA5 for the period 1981-2010 shows  
375 that WRF represents this state but overestimates WS850 in wind speed EXCs (Fig. S3). EXCs in the WMED (Fig. 7a and 7d)  
~~tend to be are~~ slightly deeper and more intense than wind EXCs in the EMED (Fig. 7j and 7m). At  $t_{slp}$  (middle column), the  
wind EXCs has deepened around 4 hPa in all composites. The wind field has clearly intensified and expanded, especially in the  
EMED. Wind EXCs in the WMED are slightly deeper than in the EMED (roughly by 4 hPa), and achieve higher ~~wind speeds~~  
WS850 values in the EMED. A ~~striking~~ difference between the two regions is that wind EXCs in the EMED have a much  
380 more southwest-northeast orientation than in the WMED. WRF agrees with ERA5 but shows an even stronger overestimation  
of WS850 in wind speed EXCs by up to 6-8 m s<sup>-1</sup> than hours before  $t_{slp}$  (Fig. S3). 12 hours after  $t_{slp}$  (right column), the  
core pressure of the EXC has increased ~~slightly~~, and the wind field has shrunk in size and intensity ~~substantially~~. We also see  
a general shift of the remaining wind field towards the east relative to the EXC centre compared to the composites 12 hours  
before  $t_{slp}$ , especially in the WMED. ~~The wind field WS850~~ in the EMED (Fig. 7l and 7o), is slightly ~~stronger than the wind~~  
385 ~~field higher than~~ in the WMED (Fig. 7c and 7f) by about 2-3 ~~ms~~ m s<sup>-1</sup> at  $t_{slp}$ . Again the general decay behaviour of WRF is  
resembling ERA5 but the overestimation of WS850 in wind speed EXCs persists (Fig. S3).



**Figure 7.** Same as Fig. 5, but now for 850 hPa wind speed ([WS850](#)). The left column now indicates 12 hours before  $t_{slp}$ , the middle column at  $t_{slp}$ , and the right columns 12 hours after  $t_{slp}$ .

The life cycle of future wind EXCs intensifies in a similar way as the one of past wind EXCs (Fig. Fig. 7). To extract the future climate change signal, we show the difference between the past and the future (Fig. 7g-i and p-r). 12 hours before  $t_{slp}$  (left column), in the WMED (Fig. 7g) we find a complex pattern of WS850 changes near the EXC center, with opposing anomalies largely offsetting each other. 750 km east of the EXC center, the wind speed is significantly increased by up to  $4 \text{ ms}^{-1}$  in the future. In the EMED, we also find a complex pattern in wind speed differences between the past and future (Fig. 7p) which is different to the WMED. The EMED wind cyclones show an increase in wind speed west and east of the cyclone core and a decrease south of the cyclone core. This is mainly due to differences in wind field orientation, as the analysis of the shape of past and future EXCs (Fig. 7j,m) suggests.

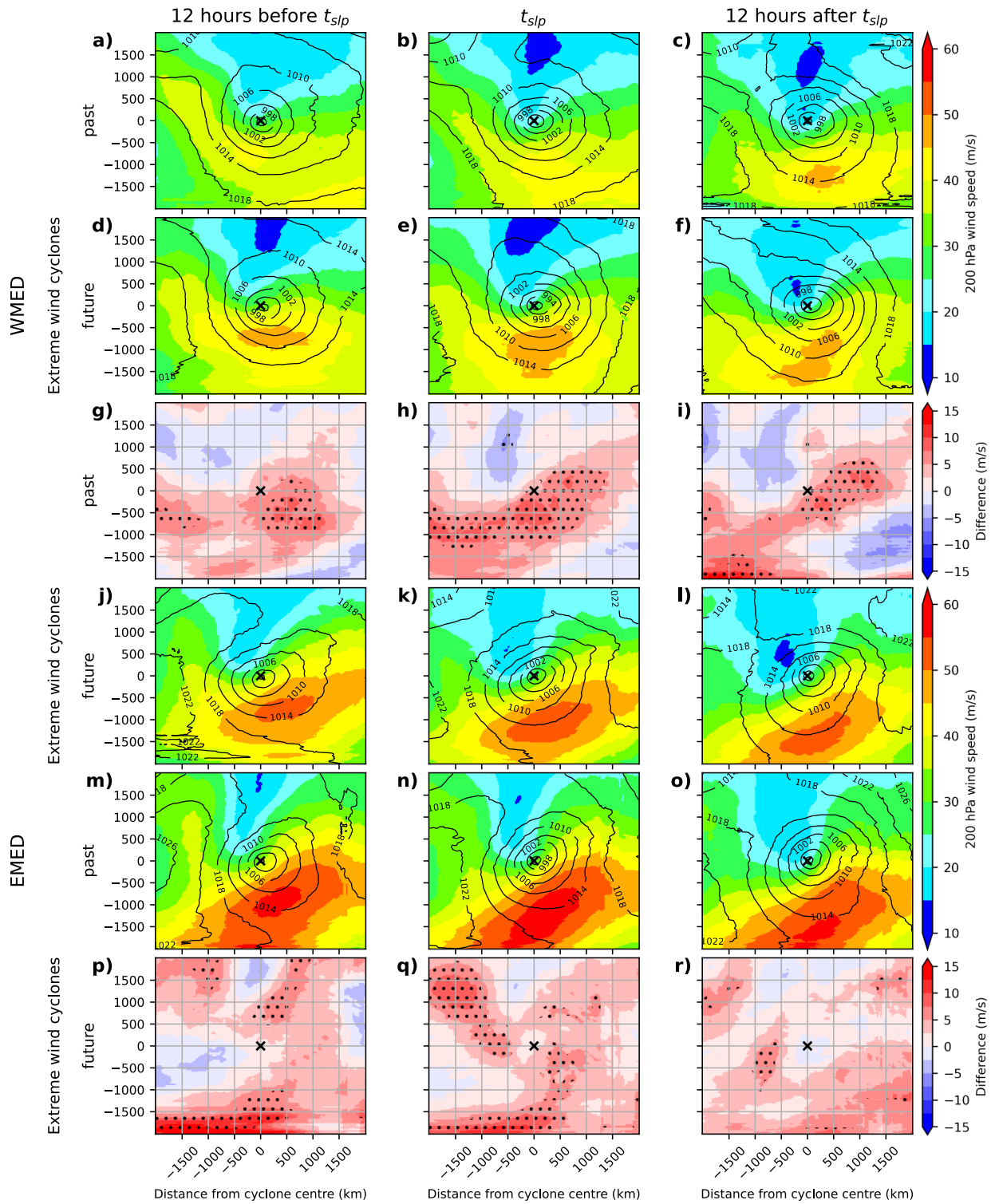
At  $t_{slp}$  (middle column), we see a more ~~uniform~~axisymmetric pattern in wind speed differences. In the WMED, ~~a general increase in wind speed~~an increase in WS850 appears (Fig. 7h) ~~that is consistent along the composite~~, with a significant increase in ~~wind speed~~WS850 in the southeastern quadrant of the composite, which is also the quadrant with the highest ~~wind speeds~~WS850 overall. Only in the western half of the EXC do we observe a ~~slight decrease in wind speed~~decrease in WS850, but this decrease is not statistically significant. Unlike the WMED, in the EMED we observe a statistically significant increase in wind speed in the western half of the EXC composite (Fig. 7q). Comparing the shape of the wind field between past and future EXCs (Fig. 7k,n), this increase is mainly induced by a small wind field just west of the core for future EXCs. Apart from that, the wind fields stay similar in size and intensity.

~~At~~ 12 hours after  $t_{slp}$  (right column), the ~~difference patterns~~differences are similar to the ones at  $t_{slp}$ . Again, we see a ~~statistically~~ significant increase in ~~wind speed~~WS850 in the southeastern quadrant ~~of the WMED EXCs in the WMED~~ and a non-significant decrease in the western half of the ~~WMED EXCs~~composite in the WMED (Fig. 7i). In the EMED, we see a significant increase just south of the EXC ~~center~~centre (Fig. 7r). Note that the magnitude of these differences is equal to the ones at  $t_{slp}$  (Fig. 7h and 7q) but occur at lower overall ~~wind speeds~~WS850 values, so the relative difference between past and future wind EXCs 12 hours after  $t_{slp}$  is greater compared to  $t_{slp}$ .

At 12 hours before  $t_{slp}$ , past and future EXCs in both regions have roughly the same core pressure. At  $t_{slp}$ , future cyclones deepen more and core pressure for EXCs in both regions is lower than for past cyclones (roughly 4 hPa). This difference persists 12 hours after  $t_{slp}$ , where the differences in core pressure increase ~~even~~ further. This provides a partial explanation of why wind speed EXCs ~~appear~~are stronger in their mature phase.

To further understand why wind EXCs in the future ~~tend to be~~are stronger in their most intense and mature phase, we investigate the jet stream as a potential driver. In Fig. 8, we apply the same composite analysis as in Fig. 7, but now to wind speed at 200 hPa (WS200). ~~With this, we characterize~~characterizing the strength and location of the jet stream relative to the wind EXCs. The analysis shows that WS200 values are ~~generally~~ the highest about 1000 km south of the EXC ~~center~~centre, indicating that ~~the wind~~ EXCs are usually located on the northern edge of the jet. Furthermore, another branch of high WS200 values is present west of the EXC centre, especially 12 hours before  $t_{slp}$  and at  $t_{slp}$ . This ~~is a hint that a branch of~~likely reflects the polar jet ~~merges~~merging with the subtropical jet. Generally, WS200 ~~values are much~~is higher in the EMED (exceeding  $60 \text{ ms m s}^{-1}$ ) compared to the WMED (up to  $50 \text{ ms m s}^{-1}$ ). ~~A likely explanation for this is~~This is most likely caused by the more southern location of the EMED region (Fig. 3) and ~~hence~~thus EXCs tend to be located closer to the subtropical jet.

Considering all composites, a ~~jet speed maximum is positioned~~ maximum in WS200 is located just south of the EXC centre, ~~indicating which has the typical shape~~ a jet streak. ~~At~~ 12 hours before  $t_{slp}$ , the EXC is located right above the jet streak maximum, where ~~potential effects of the jet stream neither aid nor inhibit the development of the EXC~~ the jet streak neither  
425 aids nor inhibits EXC development at this stage. At  $t_{slp}$ , the EXC moves towards the left exit of the jet streak, which is the region where upper air divergence leads to rising air motions and hence can ~~prolong EXC intensity in its mature face~~. ~~At~~ provide favourable conditions for a cyclone. 12 hours after  $t_{slp}$ , the EXC has moved further east relative to the jet streak and is now ~~positioned clearly~~ clearly positioned in the left-exit region of the jet streak. This ~~behaviour~~ is especially evident for wind EXCs in the EMED (Fig. 7j–o).



**Figure 8.** Same as Fig. 7, but now for 200 hPa wind speed (WS200). Note that the area away from the centre domain of the composites has expanded from 750 km to 2000 km.

430 ~~Considering WS200 related to future Wind EXCs in the WMED Fig. 7g-i~~ In the future, we see ~~a general an~~ increase in WS200 for both regions at all time steps ~~-(Fig. 7g-i)~~. Consequentially, for wind ~~speed~~-EXCs in the WMED the jet streak ~~clearly~~ appears at all time steps in the future (Fig. 8d-f) in contrast to the past (Fig. 8a-c). The jet streak maximum wind speed is up to 10 ~~msm s~~<sup>-1</sup> higher compared to ~~the~~ past wind EXCs in the WMED and mostly statistically significant across all time steps (Fig. 8g-i). This eventually leads to ~~a future EXC that~~ future conditions where a wind EXC is located in the left exit of a  
435 stronger jet streak in its mature phase (Fig. 8e-f).

In the EMED, we also identify an increase in WS200 within the jet stream across all time steps in Fig. 8p-r of up to 10 ~~msm s~~<sup>-1</sup>. In this region, we also see a significant increase in WS200 northwest of the EXC ~~center~~centre, indicating an increase in strength of the polar jet, especially at  $t_{slp}$  (Fig. 8q). ~~Despite the increase in WS200 south of the EXC center (resembling the merged polar and subtropical jet)~~ However, this increase is only significant at  $t_{slp}$  (Fig. 8q). Nevertheless, we ~~also~~ find future  
440 mature wind speed EXCs in the EMED in the left exit of a ~~partially~~-stronger jet streak. This means that future EXCs in the EMED would also benefit from ~~stronger rising air motions and could thus stay more extreme and sustain high wind speeds in EXCs~~ a more favourable position in the jet streak.

### 3.4 Cyclones associated with compound precipitation and wind extremes

Lastly, we investigate the life cycle of precipitation and wind speed in compounding EXCs. For ~~precipitation~~- $precip_{6h}$  within  
445 compounding EXCs (Fig. S4), we largely see the same patterns as for precipitation EXCs (Fig. 5). ~~Precipitation~~- $precip_{6h}$  increases as the cyclone intensifies and decreases strongly again in its mature stage. ~~Precipitation~~- $precip_{6h}$  is slightly less intense than for precipitation EXCs and compounding EXCs have a lower core pressure (in the order of 4 hPa) ~~to accommodate~~ consistent with higher wind speeds. Also, future  $precip_{6h}$  changes for compound EXCs are very similar to precipitation EXCs. However, compound EXCs in the EMED ~~tend to~~ get even drier than precipitation EXCs in the future (Fig. S4p-r).

450 Wind speeds in compounding EXCs (Fig. S5) are of similar intensity at  $t_{slp}$  compared to wind speed EXCs in Fig. 7. The wind field is ~~of slightly smaller size~~ slightly smaller though. 12 hours before  $t_{slp}$ , ~~wind speeds~~-WS850 of compounding EXCs ~~are slightly is~~ lower compared to wind speed EXCs in both regions (left column of Fig. S5). 12 hours after  $t_{slp}$ , ~~EMED compounding EXCs are significantly less intense than~~ WS850 is significantly lower than in EMED wind speed EXCs, but of similar intensity in the WMED (left column of Fig. S5). Compound EXC core pressure is very similar to wind speed EXCs  
455 at  $t_{slp}$  and 12 hours after  $t_{slp}$ , but slightly higher 12 hours before  $t_{slp}$ . The increase in WS850 in future compound EXCs is ~~slightly~~-less in the WMED ~~as~~ compared to wind speed EXCs in the WMED (Fig. S5g-i). However, for compound EXCs in the EMED we see a large future decrease in wind speed (Fig. S5p-r), which is ~~almost~~ contrary to what we observe for future wind speed EXCs (Fig. 7p-r).

## 4 Discussion and conclusion

460 The aim of this study is to assess changes in wind, precipitation and compounding extreme cyclone characteristics in the Mediterranean by comparing pre-industrial with future conditions under RCP8.5. Thereby, we dynamically downscale an existing global model simulation to a resolution of 20 km with WRF for the period 1821 CE to 2100 CE.

We find that WRF reproduces the main cyclone hotspots and these results are in line with previous studies (Homar et al., 2007; Raible et al., 2010; Campins et al., 2011). We also find that ~~future future~~ WRF reproduces cyclone frequency in the ~~Mediterranean is Mediterranean is~~ western Mediterranean well compared to ERA5, whereas it is overestimated in the eastern Mediterranean. Future cyclone frequency in the Mediterranean is reduced by roughly one-third under RCP8.5 conditions. Such a decrease in cyclone frequency in the Mediterranean is also evident in earlier implemented GCMs (Lionello et al., 2002; Bengtsson et al., 2006; Raible et al., 2010; Ulbrich et al., 2013), CMIP5 (Zappa et al., 2015a; Hochman et al., 2017), and CMIP6 model simulations (Priestley and Catto, 2022) as well as RCM simulations (Reale et al., 2022). ~~It is thus encouraging that the RCM simulation of this study reproduces this signal. This is, however, to some extent expected as cyclones that form within our domain are still mostly driven by the large-scale weather systems (e.g. pressure systems, jet stream) forced by the global model (Doensen et al., 2025), and hence our RCM likely resembles this. It is thus encouraging that the RCM simulation of this study reproduces this signal. This is, however, to some extent expected as cyclones that form within our domain are still mostly driven by the large-scale weather systems (e.g. pressure systems, jet stream) forced by the global model (Doensen et al., 2025), and hence our RCM likely resembles this.~~

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~~Besides mean changes, this study focuses on changes in extremes associated with Mediterranean cyclones. Besides mean changes, this study focuses on changes in extremes associated with Mediterranean cyclones.~~ Besides mean changes, this study focuses on changes in extremes associated with Mediterranean cyclones. WRF captures the structure of both precipitation and wind EXCs seen in ERA5 but systematically overestimates their intensity, especially in the EMED, while reproducing ~~core pressure well. A further possible contributor to the overestimation of  $precip_{6h}$  and WS850 in the EMED is that WRF produces more cyclones there. In a previous study, we found that wind EXCs are less extreme in the EMED compared to the WMED in the driving CESM model (Doensen et al., 2025). However, CESM strongly underestimates cyclone frequency in the Mediterranean, which WRF captures considerably better. By improving both the frequency and the structural representation of these systems, the dynamical downscaling enables us to study extreme Mediterranean cyclones in much more detail, demonstrating that it substantially improves their representation.~~

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The location and seasonality of the EXCs are consistent with previous literature. We find that precipitation EXCs occur predominantly over the Mediterranean Sea, whereas wind speed EXCs also occur frequently over land. This agrees with Raveh-Rubin and Wernli (2015), who found that precipitation extremes in the Mediterranean are most likely located over the sea while gust extremes are more likely over land. Similarly, the precipitation–wind compound EXCs occur mainly over the sea, in agreement with Portal et al. (2024). The seasonality is likewise consistent with earlier work. Khodayar et al. (2025) showed that precipitation-related damages peak in autumn, plausibly reflecting cyclone-related precipitation, although we do not observe the peak in precipitation extremes in winter in the eastern Mediterranean as shown by Raveh-Rubin and Wernli (2015)

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. Doiteau et al. (2024) found that deep Mediterranean cyclones, capable of producing intense winds, are distributed evenly from November to March. The latter matches the even distribution of wind speed EXCs we detect across the winter half year.

495 Despite no significant change in EXC seasonality, precipitation and compound EXCs in the EMED are shifted southward over the warmer Mediterranean Sea in the future, whereas the average latitude of precipitation EXCs in the WMED shows no significant change.

Our findings show that cyclones associated with extreme precipitation respond differently in the future in the two subregions, with an increase in extreme precipitation in the WMED and no ~~substantial~~ ~~substantial~~ significant difference in the EMED. This

500 is remarkable, ~~as as~~ since CMIP5 simulations project a significant future decrease in mean winter-time precipitation over most of the Mediterranean ~~, except for the northern Mediterranean close to the Alps (Zappa et al., 2015b; Reale et al., 2022)~~ ~~. Extreme precipitation associated with cyclones show a similar response in CMIP5 simulations (Zappa et al., 2015a) and in the RCMs (Reale et al., 2022), although there is quite some spread between the models in the magnitude of the change. Chericoni et al. (2025), except for the northern Mediterranean close to the Alps (Zappa et al., 2015b; Reale et al., 2022). Extreme~~

505 ~~precipitation associated with cyclones show a similar response in CMIP5 simulations (Zappa et al., 2015a) and in the RCMs (Reale et al., 2022), although there is quite some spread between the models in the magnitude of the change (Zappa et al., 2015b)~~ . Yet, the increase in precipitation we find for EXCs in the WMED matches the findings by Reale et al. (2022) who also found an increase in mean cyclone-related precipitation for the northern Mediterranean. Chericoni et al. (2025) However, in our work the precipitation EXCs in the EMED show no significant change in precipitation. This does not coincide with the

510 decrease in mean cyclone-related precipitation found by Zappa et al. (2015a) and Reale et al. (2022). Nevertheless, extreme cyclone-related precipitation in the Mediterranean responds differently to climate change than mean seasonal precipitation (Chericoni et al., 2025). The EMED most likely reflects this decoupling of extreme from mean precipitation. Chericoni et al. (2025) further showed that RCMs more realistically represent wind patterns and air-sea fluxes ~~better, resulting better, resulting~~ . This results in higher extreme cyclone-related precipitation ~~than in than in compared to~~ CMIP6 models and thus illustrates the

515 necessity to use high spatial resolution to understand the impact of future climate change on Mediterranean cyclones and the associated extremes as done in this study. ~~Despite no shift in EXC climatology, one difference of the two subregions is that precipitation and compound EXCs in the EMED are shifted southward over the warmer Mediterranean Sea in the future, whereas the average latitude of precipitation EXCs in the WMED remain unchanged in the future. Moreover, the~~ Despite no shift in EXC climatology, one difference of the two subregions is that precipitation and compound EXCs in the EMED are

520 shifted southward over the warmer Mediterranean Sea in the future, whereas the average latitude of precipitation EXCs in the WMED remain unchanged in the future. Moreover, the

The increase in PV for WMED precipitation EXCs during their mature phase ~~is to some extent significant. This is to some extent significant. This marginally significant. The~~ increase in PV ~~is partially located around the tropopause in the cold sector indicating a stronger~~ is partially located around the tropopause in the cold sector indicating a stronger ~~near the tropopause~~ west of the cyclone core indicates a lowering of the tropopause and thus a more intense baroclinic cyclone, and within the

525 PV tower in the lower troposphere indicating more diabatic heating. This behaviour is and within the PV tower in the lower troposphere indicating more diabatic heating. This behaviour is through the interaction of the upper-level PV anomaly with

the low-level circulation (Hoskins et al., 1985). The increase in low-level PV is most likely caused by increased latent heating, and is also found for extreme cyclones in extreme cyclones in cyclones in warmer climates in idealized simulations (Pfahl et al., 2015; Sinclair et al., 2020). Zhang and Colle (2018) Zhang and Colle (2018) Precipitation and wind EXCs in our work become more intense at their peak intensity and in their mature phase, whereas we detect little change or a decrease in intensity before their peak intensity. This behaviour is similar to Zhang and Colle (2018), who used WRF to study future extratropical cyclones over eastern North America and the western Atlantic at a similar resolution to ours-ours-our simulation (0.2°). They found that found that also found that cyclones in their initial phase ,cyclones are weaker due to climate change, but due to latent heating, they develop , cyclones are weaker due to climatechange, but due to latent heating, they develop are weaker in a warmer climate, whereas future cyclones develop more rapidly and eventually become stronger than cyclones in the past. This is a similar behavior to the precipitation EXCs in our study, and highlights the impact of latent heating in future warming scenarios. stronger than cyclones in the past. This is a similar behavior to the precipitation EXCs in our study, and highlights the impact of latent heating in future warming scenarios more intense due to increased latent heating.

The assessment of cyclones associated with extreme wind shows The assessment of cyclones associated with extreme wind shows We find that wind EXCs are of similar intensity are of similar intensity in the WMED and EMED in our WRF simulation. This finding is in contrast to the driving CESM simulation, where wind EXCs are weaker in the EMED than in the WMED (Doensen et al., 2025). This discrepancy is likely due to rather coarse resolution of 1.9° (latitude) × 2.5° (longitude), which is too coarse to reproduce extratropical cyclones in the Mediterranean in an accurate way, as highlighted in Flaounas et al. (2013). Thus, we demonstrate that the dynamical downscaling substantially improves the representation of Mediterranean cyclones. in our WRF simulation. This finding is in contrast to the driving CESM simulation, where wind EXCs are weaker in the EMED than in the WMED (Doensen et al., 2025). This discrepancy is likely due to rather coarse resolution of 1.9° (latitude) × 2.5° (longitude), which is too coarse to reproduce extratropical cyclones in the Mediterranean in an accurate way, as highlighted in Flaounas et al. (2013). Thus, we demonstrate that the dynamical downscaling substantially improves the representation of Mediterranean cyclones.

Concerning climate change, we find a robust Concerning climate change, we find a robust are equally intense in our simulation, and we find a significant increase in wind speed of extreme cyclones in the entire Mediterranean, especially especially also during the mature phase of the EXCs. Compared to the existing literature, the confidence in climate projections related to Compared to the existing literature, the confidence in climate projections related to Reale et al. (2022) found an increase in mean cyclone-related wind speed around Italy, and a decrease in the rest of the Mediterranean. However, Chericoni et al. (2025) , found an increase in mean cyclone-related wind speed for intense cyclones for almost all regions in the Mediterranean, which agrees with our results. Yet, confidence in future climate projections for cyclone-related wind speed is still low (Catto et al., 2019). Moreover, Schemm (2023) demonstrated that the use of kilometer-scale climate models may be essential for accurately representing future cyclone tracks, which significantly impact the locations that are impacted most by cyclones. still low (Catto et al., 2019). Moreover, Schemm (2023) demonstrated that the use of kilometer-scale climate models may be essential for accurately representing future cyclone tracks, which significantly impact the locations that are impacted most by cyclones low (Catto et al., 2019) and thus should be interpreted with care. Note also, that most of the existing literature discuss cyclones as

~~a whole discuss cyclones as a whole~~ discusses mean changes in Mediterranean cyclones, whereas the focus of this study is on extremes. We explain the intensification of wind EXCs in the future projection by changes in the jet stream over the Mediterranean, showing that the wind EXCs extremes. We explain the intensification of wind EXCs in the future projection by changes in the jet stream over the Mediterranean, showing that the extreme cyclones. In the future the subtropical jet intensifies, and consequently future wind EXCs are located in the left-exit of an intensified jet streak in the future in the future. In particular, this is found in the mature phase of wind EXCs in the WMED and EMED. Flaounas et al. (2015b) suggested that Mediterranean extreme Mediterranean extreme extreme Mediterranean wind cyclones often co-occur with a strong jet streak south of the cyclone. They also suggested that barotropic shear provided by the subtropical jet aids the baroclinic life cycle of a cyclone. Moreover, Raveh-Rubin and Wernli (2015) showed that precipitation extremes in the eastern Mediterranean often co-occur with the merging of the midlatitude and subtropical jet in this region, causing cyclogenesis or cyclone intensification. Prezerakos et al. (2005) performed a thorough analysis on thorough analysis on detailed case study analysis of the mechanisms behind the cyclone jet the cyclone jet this cyclone jet co-occurrence in a case study in a case study, showing that an extreme cyclone over the eastern Mediterranean that revived when it was that revived when it was underwent a resurgence in intensity when located in the left exit of the subtropical jet and the right entrance of the midlatitude jet. However, Flaounas et al. (2022) acknowledged that this cyclone-jet co-occurrence has not been studied extensively. Thus, our study contributes to fill this gap by highlighting the importance of the jet position and strength in intensifying extreme wind cyclones in the Mediterranean.

Furthermore, we investigate the behavior behaviour of cyclones associated with compound extreme precipitation and wind. The location of the highest precipitation agrees well with the results of Rousseau-Rizzi et al. (2024), although the location of the most intense winds in WRF is shifted to the east compared to their work. We find that precipitation associated with compound event resemble event resemble EXCs resembles the climate change signal of precipitation EXCs in both regions of the Mediterranean. However, the wind speed of compound EXCs in the EMED show a strong future reductions show a strong future reduction shows a future reduction in intensity. This is in contrast to the intensification of wind speed EXCs in the future.

To conclude, this work offers a comprehensive analysis on the impact of climate change on extreme cyclones and their characteristics in the Mediterranean utilizing a 280 year long dynamically downscaled regional simulation. Our results show evidence that future extreme cyclones will intensify with respect to precipitation and wind speed (most notably in the western Mediterranean) despite a projected reduction in cyclone frequency. Future extreme cyclones tend to be weaker in their initial phase, but intensify more rapidly and remain stronger in their peak and mature phase. Such developments could exacerbate the socioeconomic impacts of cyclones, compounding the effects of climate change in a region projected to be already among the most severely affected worldwide in a region projected to be already among the most severely affected worldwide. Still, one shortcoming is that we only use a single member simulation. Future work using ensembles from RCMs ensembles from RCMs RCM ensemble simulations or km-scale GCMs could further solidify our understanding of future extreme cyclones in the Mediterranean.

(Doensen et al., 2025). We also find that wind EXCs in ERA5 are weaker in the EMED. This discrepancy is likely due to rather coarse resolution of  $1.9^\circ$  (latitude)  $\times$   $2.5^\circ$  (longitude), which is too coarse to reproduce extratropical cyclones in

the Mediterranean in an accurate way, as highlighted in Flaounas et al. (2013). Thus, we demonstrate that the dynamical downscaling substantially improves the representation of Mediterranean cyclones.

600 *Code availability.* The cyclone tracking was performed with the detection and tracking scheme of Blender et al. (1997) and is available on request. The other analysis steps were performed with python scripts. As they are standard methods, they are not uploaded to a repository. These scripts are available on request.

*Data availability.* Post-processed WRF data used for the study are available at <https://doi.org/10.5281/zenodo.17965187> Complete WRF data are locally stored and are available upon request

## Appendix A

### 605 A1

*Author contributions.* OD, MM, and CCR contributed to the design of the study. OD carried out the WRF simulations. OD performed the principal analysis and wrote the manuscript under the supervision of CCR. MM, EDT and CCR provided critical feedback on the results and drafted the manuscript together with OD. All authors contributed to the writing and scientific discussion.

*Competing interests.* The authors declare no conflict of interest.

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