

Large-Scale Drivers of Widespread Extreme Precipitation in Europe: Insights from High-Resolution Regional Climate Model Simulations

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(Manuscript received 20 March 2024, in final form 21 October 2024, accepted 9 December 2024)

ABSTRACT: Although regional climate models (RCMs) have made significant advancements in simulating the spatiotemporal characteristics of precipitation and understanding mechanisms of precipitation changes over recent decades, concerns persist regarding their ability to accurately represent the large-scale atmospheric conditions associated with climate extremes. In light of this, the present study evaluates the performance of high-resolution RCM simulations in representing the characteristics of widespread extreme precipitation events and their associated large-scale synoptic systems across different complex orographic precipitation regimes in the Mediterranean and the European North Atlantic regions during 1980–2010. The RCM simulations are performed in the framework of the European-Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) at a horizontal resolution of approximately 12 km ($0.11^\circ \times 0.11^\circ$) and constitute so-called evaluation experiments, i.e., simulations forced by large-scale information from a reanalysis. A set of high-resolution quality-controlled observational precipitation datasets compiled from higher density rain gauge station networks, along with E-OBS data, is used to evaluate the precipitation simulated by the RCMs. We found that the RCMs reproduced the observed total number and intensity of widespread extreme precipitation events to a great extent; however, there is variation or spread in the results among different RCMs. The study also emphasized the critical importance of systematically addressing model-specific discrepancies, as these variations can amplify intermodel spread and potentially lead to misleading conclusions. The general synoptic patterns that characterize widespread extreme precipitation include trough–ridge patterns with cyclonic features, advection of warm and moist air promoting rising motion, and enhanced moisture transport into the regions. Also, atmospheric river–like patterns of moisture transport originating from the Atlantic Ocean are identified, particularly in the European North Atlantic regions, and with contributions from the Mediterranean Sea in the Mediterranean regions. While RCMs reproduced the large-scale synoptic spatial patterns observed in ERA5 to a great extent, intermodel differences are evident in the spatial patterns and their magnitudes. We concluded that when driven by the same forcing, the RCMs, despite their many mutual differences, are, on the whole, capable in providing a robust and converging result when it comes to widespread extreme precipitation events.

KEYWORDS: Atmosphere; Europe; Atmospheric circulation; Hydrometeorology; Climate models; Diagnostics

1. Introduction

Spatiotemporal variability of precipitation, particularly its extremes resulting in droughts and flooding, has a significant impact on humans and ecosystems across various regions of the world. In the European region, floods and landslides associated with heavy precipitation have been identified as the most common and widespread natural disasters (Barredo 2009; Zolina et al. 2014; Zolina 2014; Paprotny et al. 2018; Mohr et al. 2023), thereby inflicting the largest economic

losses at a cost of U.S. \$377.5 billion over the past 50 years (WMO 2021). Therefore, a better understanding of the spatiotemporal variability of high-impact precipitation events and their drivers is crucial for assessing and minimizing risks to economic and societal activities. On the other hand, the identification of the sources of moisture fueling extreme precipitation remains a challenging issue with vital implications for predictions of high-impact events. Over the past few years, there has been growing scientific interest in investigating the mechanisms leading to high-impact precipitation, as well as in improving the ability of models to predict and project such events in a changing climate.

In particular, extreme precipitation events, which eventually lead to flash floods and landslides, have been much more frequent in some parts of the Mediterranean region compared to the rest of Europe (Gaume et al. 2009; Ricard et al. 2012; Ulbrich et al. 2012; Llasat et al. 2013; Cavicchia et al. 2018; Blöschl et al. 2019). Observations and reanalyses revealed that most events in the Mediterranean region mainly occur during the autumn and winter seasons (Raveh-Rubin and Wernli 2015; Cavicchia et al. 2018). This region has also been recognized as an important climate change hotspot that responds strongly to global warming (Giorgi 2006; Ranasinghe et al. 2021). Extreme precipitation events over the Mediterranean

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JHM-D-24-0035.s1>.

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DOI: 10.1175/JHM-D-24-0035.1

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TABLE 1. RCM simulations analyzed in this study. More detailed information about the model configurations for all RCMs can be obtained from Table 2 in [Petrovic et al. \(2022\)](#).

Institution	Model	References
Centre National de Recherches Météorologiques (CNRM; France)	ALADIN63	Daniel et al. (2019)
Helmholtz-Zentrum Geesthacht, Climate Service Center Germany (GERICS; Germany)	REMO2015	Pietikäinen et al. (2018)
Eidgenössische Technische Hochschule (ETH) Zurich, Switzerland in collaboration with the Climate Limited-area Modeling Community (CLM-Community)	COSMO-crCLIM	Rockel et al. (2008)
International Centre for Theoretical Physics (ICTP; Italy)	RegCM4-6	Giorgi et al. (2012)
Royal Netherlands Meteorological Institute (KNMI; Netherlands)	RACMO22E	Van Meijgaard et al. (2012)
Swedish Meteorological and Hydrological Institute, Rossby Centre (SMHI; Sweden)	RCA4	Tamoffo et al. (2019)

region are closely associated with the mesoscale-convective systems modulated by larger-scale synoptic circulation patterns ([Toreti et al. 2016](#); [Khodayar et al. 2021](#)). Besides the Mediterranean region, parts of the European North Atlantic region, such as the western coast of Norway ([Stohl et al. 2008](#); [Azad and Sorteberg 2017](#)) and the northwest Iberian Peninsula ([Gómez-Gesteira et al. 2011](#); [Eiras-Barca et al. 2018](#)), are also subject to flood-inducing heavy precipitation events and subsequent hydrological hazards, particularly during the autumn and winter seasons. Heavy precipitation over the European North Atlantic coastal sectors is often associated with atmospheric rivers (ARs) accompanied by the North Atlantic extratropical cyclones ([Stohl et al. 2008](#); [Gómez-Gesteira et al. 2011](#); [Santos et al. 2016](#); [Azad and Sorteberg 2017](#); [Eiras-Barca et al. 2018](#); [Gavrikov et al. 2020](#); [Michel et al. 2021](#)). On the other hand, problems associated with in situ data across Europe, including challenges related to availability of station data, missing values in rain gauge records, spatial inhomogeneity, and quality, underscore the importance of models as essential complements. In fact, models serve as crucial complements to in situ data by expanding spatial coverage, filling gaps, addressing quality issues, and providing a more holistic understanding of complex systems.

In the context of modeling approaches, global climate models (GCMs) have been widely used to study the spatiotemporal variability of precipitation, including its extremes, and the underlying mechanisms associated with synoptic and mesoscale processes. Over the last two to three decades, regional climate models (RCMs) have proven to be essential tools for dynamical downscaling of GCMs at high spatial resolutions over different regions of the globe. This allows for a more accurate representation of complex orographic processes, surface heterogeneities, land surface processes/feedback, and mesoscale atmospheric phenomena that are challenging to simulate using coarser-resolution GCMs ([Wang et al. 2004](#); [Giorgi 2006](#); [Jacob et al. 2014](#); [Prein et al. 2016](#); [Giorgi 2019](#); [Shahi et al. 2022](#)). While RCMs have made significant progress in simulating the spatiotemporal variability of precipitation, concerns still remain about their accuracy in representing extremes and the ability to adequately account for the large-scale and regional processes associated with these extremes. It was found that the observed large-scale atmospheric patterns related to climate extremes in the Mediterranean region are not accurately reproduced by the RCMs ([Flocas et al. 2011](#)). In light of this, it is crucial to assess the capability of current-generation RCMs in capturing

large-scale atmospheric conditions associated with climate extremes and we endeavor to progress toward this objective in this paper. We provide here insights into the performance of high-resolution EURO-CORDEX RCM simulations conducted in reanalysis-driven evaluation experiments ([Petrovic et al. 2022](#)) in representing the spatiotemporal variability of widespread extreme precipitation and their underlying large-scale atmospheric processes. The results from this study aim to illuminate the usefulness of model output obtained from recent high-resolution RCM simulations for understanding the spatiotemporal variability of widespread events of extreme precipitation over Europe.

The paper is organized as follows. Data and methods used in this study are described in [section 2](#). In [section 3](#), the detailed results of the characteristics of widespread extreme precipitation events (WSEPEs) and their associated large-scale synoptic features are presented. Finally, [section 4](#) provides a summary and conclusions of the results.

2. Data and methodology

a. Data

The RCM simulations within the EURO-CORDEX framework analyzed in this study are detailed in [Table 1](#). EURO-CORDEX is a part of the international CORDEX initiative of the World Climate Research Program (WCRP) and consists of a multimodel ensemble of simulations at a horizontal resolution of approximately 12 km ($0.11^\circ \times 0.11^\circ$) covering the European domain ([Jacob et al. 2020](#); [Petrovic et al. 2022](#)). Analyzed RCM simulations are produced in the framework of an evaluation experiment, here driven by the ERA-Interim reanalysis ([Dee et al. 2011](#)), as opposed to historical and scenario experiments in which RCM simulations are forced by output from GCMs. The latest reanalysis, i.e., ERA5 from the European Centre for Medium-Range Weather Forecasts (ECMWF) at a horizontal resolution of approximately 31 km is also used ([Hersbach et al. 2020](#)). The main purpose of incorporating ERA5 in this analysis is to explore the atmospheric mechanisms driving widespread extreme precipitation events, as well as to compare the results obtained from the RCM simulations and to quantify the effect of spatial resolution in the representation of extreme events. ERA5 demonstrated significant improvements in precipitation characteristics compared to ERA-Interim and other reanalysis datasets, such as MERRA-2 and JRA-55 ([Hassler and Lauer 2021](#)).

A recent version 27.0e of the E-OBS daily gridded land-only precipitation dataset, at a resolution of approximately 11 km ($0.1^\circ \times 0.1^\circ$), provided by the European Climate Assessment and Dataset (ECA&D) project, is used as a baseline data to evaluate the model-simulated precipitation (Cornes et al. 2018). However, a recent study by Vautard et al. (2020) highlighted that uncertainties associated with E-OBS can reach up to 35% in mountainous regions. The deficiencies associated with the E-OBS were also demonstrated by Zolina et al. (2014) and Prein et al. (2016). In light of this, several region-specific high-resolution precipitation products compiled from a higher density rain gauge station network than E-OBS are also utilized. These are as follows: 1) Alpine Precipitation Grid Dataset (EURO4M-APGD; Isotta et al. 2014) is a high-resolution ($5\text{ km} \times 5\text{ km}$ grid) daily precipitation data derived from in situ measurements at more than 8500 rain gauge stations covering the entire Alpine region and its nearby/surrounding areas. It was developed within the framework of the European Reanalysis and Observations for Monitoring (EURO4M) initiative. 2) seNorge_2018 is a high-resolution daily precipitation dataset covering Norway and parts of Finland, Sweden, and Russia on a $1\text{ km} \times 1\text{ km}$ grid. It is based on MET Norway's climate data and is presented in Lussana et al. (2019). 3) Iberia01 is a gridded dataset of daily precipitation available on a $10\text{ km} \times 10\text{ km}$ grid spacing, covering Spain and Portugal (Herrera et al. 2019). This dataset is based on a dense network of thousands (total of 3761) of rain gauge stations from the Spanish Meteorological Agency (AEMET), the Portuguese Institute for Sea and Atmosphere (IPMA), and the Portuguese Environmental Agency (APA). 4) SAFRAN is a daily precipitation product based on 3675 rain gauges stations and is available on an $8\text{ km} \times 8\text{ km}$ grid spacing over France (Quintana-Seguí et al. 2008; Vidal et al. 2010). Also, all the observational datasets are regridded onto the RCM grid using the conservative remapping. The analysis is conducted for the period of 1980–2010. However, the EURO4M-APGD precipitation dataset is available only until 2008. Therefore, E-OBS values are retained for the last 2 years.

b. Methodology

In this work, WSEPEs for a given domain (i.e., Fig. 1) are defined as the days when daily precipitation exceeds both the $R99p$ and $R99p_{\text{reg}}$ thresholds in at least 20% of the domain's grid points. Here, $R99p$ represents the 99th percentile of precipitation on wet days as defined by the Intergovernmental Panel on Climate Change (IPCC; Sillmann and Roeckner 2008), while $R99p_{\text{reg}}$ is an area-averaged $R99p$ value over the domain. A wet day is defined as a day with more than 1 mm of precipitation. This implies that widespread extreme events cover a sufficiently large area and can cause large-scale hydrological consequences. A single threshold (e.g., $R99p$) applied to all points for defining regionally WSEPEs may not be effective because, in some locations, the $R99p$ value can be too low. An additional condition (at least 20% of grid points showing $R99p$ higher than $R99p_{\text{reg}}$) implies a representative measure which is not influenced by locally low precipitation in some locations. Our approach allows for filtering out sporadic extreme

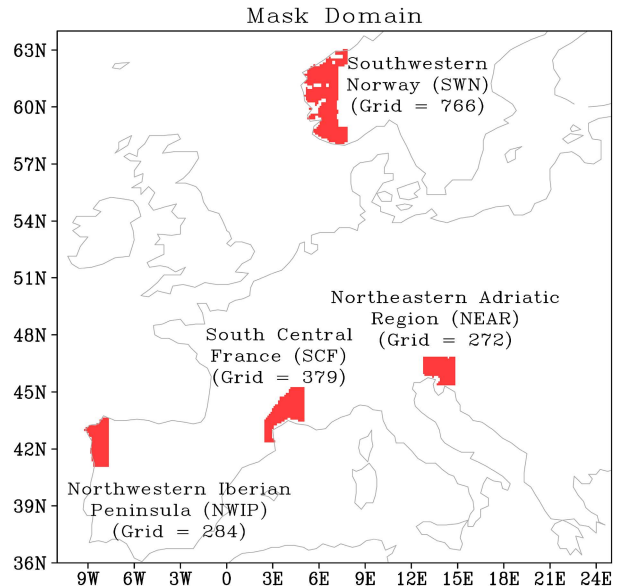


FIG. 1. Mask domains (highlighted in red) where WSEPEs are calculated.

events that show large spatial heterogeneity due to localized factors. This approach guaranties that the identified events have a substantial impact on the hydroclimate and potential implications for flooding and related risks and allows us to better understand their underlying atmospheric driving mechanisms. Several studies have employed similar criteria to identify widespread extreme precipitation events (Roxy et al. 2017; Nikumbh et al. 2019; Messmer and Simmonds 2021; Shahi and Rai 2023).

Due to the unavailability of datasets of many variables (e.g., the unavailability of winds and humidity data at pressure levels limits our analysis of vertically integrated moisture transport and its convergence) for the majority of the RCM simulations in the EURO-CORDEX public domain, attempts are made to investigate the atmospheric driving mechanisms of WSEPEs using 850- and 200-hPa winds, 500-hPa geopotential height, mean sea level pressure (MSLP), and 850-hPa equivalent potential temperature. Furthermore, total column vertically integrated water vapor (IWV) is also considered, as it is a crucial parameter for understanding of moisture source for widespread extreme precipitation. IWV is defined as the total amount of water vapor present in a vertical atmospheric column from Earth's surface to the top of the atmosphere and is also known as precipitable water content (Yuan et al. 2021). This IWV variable is directly sourced from the EURO-CORDEX and ERA5 public domains. Additionally, the calculation of vertically integrated moisture transport and its convergence for ERA5 is performed to investigate the total moisture influx into the study domains during WSEPEs, using the moisture budget equation described in Shahi et al. (2022).

3. Characteristics of WSEPEs

The regional analysis of WSEPEs and their atmospheric driving mechanisms is performed for the regions characterized

by complex orographic precipitation regimes across Europe. Our investigation focuses over two Mediterranean regions [i.e., south-central France (SCF) and northeastern Adriatic region (NEAR)] as well as two European North Atlantic sectors [i.e., northwestern Iberian Peninsula (NWIP) and southwestern Norway (SWN)], as shown in Fig. 1. In general, extreme events in the Mediterranean region (Raveh-Rubin and Wernli 2015; Cavicchia et al. 2018) and the selected European North Atlantic sectors (Gómez-Gesteira et al. 2011; Eiras-Barca et al. 2018; Stohl et al. 2008; Azad and Sorteberg 2017) are more frequent during the autumn and winter seasons, primarily due to the influence of synoptic-scale circulation patterns, as already discussed in the introduction section. Therefore, our analysis is limited to these two seasons. The selected regions have been identified as highly susceptible to extreme precipitation events in numerous studies provided in the introduction section, as also evident from Fig. S1 in the online supplemental material. It is widely established that heavy precipitation events and resulting flash floods, with tragic consequences, are common in the coastal regions along the Mediterranean, particularly in the SCF and NEAR regions. Therefore, assessing the capabilities of modern era high-resolution model simulations in relation to the mechanisms associated with these extremes is of paramount importance. This also applies to the selected region within the European North Atlantic sectors.

a. WSEPE statistics

The identification of WSEPEs is carried out for all datasets using the criteria outlined in the methodology section. The area-averaged R99p value over the selected domains for both seasons is illustrated in Fig. S2a, with the relative differences depicted in Fig. 2a. Relative differences in E-OBS and RCMs are calculated with respect to the high-resolution quality-controlled observational product of each domain. The intermodel variation in R99p precipitation intensity produced by RCMs is evident. It is noteworthy to observe reductions of up to 15%, 10%, and 21% in E-OBS precipitation magnitude compared to the high-resolution observational product in the SCF/NEAR, SWN, and NWIP regions during the autumn season, respectively (Fig. 2a). Similarly, reductions of up to 10% and 22% are identified in the SCF/NEAR and SWN/NWIP regions during the winter season, respectively. This difference in precipitation might be due to differences in the resolution of both products, as well as other factors such as the density of rain gauge stations and the interpolation methods used in constructing these datasets. This discrepancy raises questions about the confidence we can place in results when E-OBS precipitation is used to validate the model simulated precipitation.

On the other hand, most of the models exhibit a dry bias, even when compared with E-OBS, in the SCF and NEAR regions during the autumn season (Fig. 2a). However, during the winter, half of the models demonstrate closer agreement with the high-resolution observational data than with E-OBS in both regions. In the SWN region, half of the models show estimates closer to seNorge than E-OBS, while in the NWIP region, most models align better with Iberia01 than E-OBS during both seasons. In all RCMs, RegCM4-6 is found to have

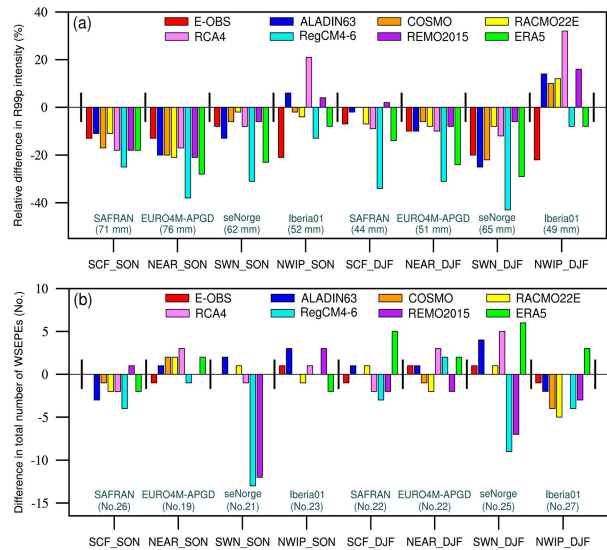


FIG. 2. (a) Relative differences in the area-averaged 99th percentile of wet-day precipitation (R99p; %) and (b) differences in the total number of WSEPEs (No.) in E-OBS and RCMs with respect to different observational products over each region. Actual values from the different observational products for each region are also provided.

lower precipitation estimates in all regions except for the NWIP region, where RCA4 shows a noticeable overestimation of precipitation compared to Iberia01. The reduced precipitation estimates by RegCM4-6 compared to all other models may be due to the domain size considered for RegCM4-6 simulation, as well as other factors such as the physical parameterization used in its configuration. It is found that the domain size is slightly larger for RegCM4-6 configuration compared to all other models' configurations. Several studies have demonstrated that the selection of domain size has a significant impact on the simulation of precipitation (e.g., Vannitsem and Chomé 2005; Leduc and Laprise 2009; Suga et al. 2021). Even when compared with E-OBS, ERA5 exhibits a dry bias in all regions except for the NWIP region, where its estimates are closer to those from Iberia01. Furthermore, we calculated the standard deviation of the relative difference in R99p intensity from RCMs, with and without including RegCM4-6, to assess the spread in the magnitude of precipitation among the models, as shown in Fig. S3 (in red). It is evident that the reduced precipitation estimates by the RegCM4-6 model lead to an increase in spread when included in the standard deviation calculation. Figure S3 shows a relatively small variance/spread in R99p precipitation estimates among the RCMs, with the exception of RegCM4-6, indicating a higher level of reliability and agreement in the results produced/simulated by the RCMs. However, a spread of up to 14% is noted when including RegCM4-6, which could eventually lead to misleading results.

A total of more than 20 events are obtained for all regions using high-resolution observational data of each domain for both seasons, except for the NEAR region during the SON season, where the total number of events is 19 (Fig. 2b; Fig. S2b). It is also noted that the SCF region experiences slightly more events

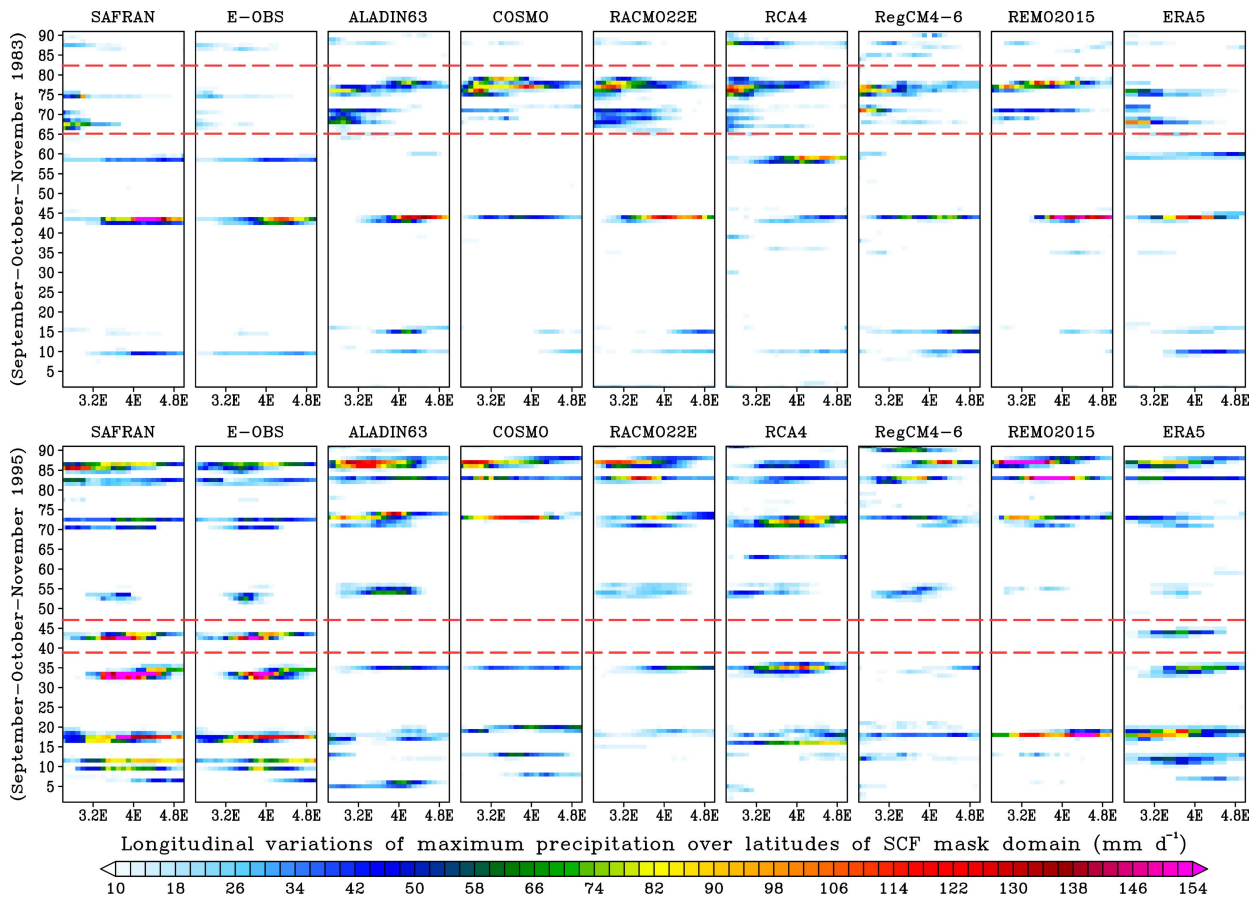


FIG. 3. Longitudinal variations of maximum precipitation over latitudes of the SCF mask domain (mm day^{-1}) from SAFRAN, E-OBS, RCMs, and ERA5. The upper and lower panels show the results for the months of September–November in 1983 and 1995, respectively.

in autumn than in winter, while the opposite is true for all other regions (Fig. 2b; Fig. S2b). E-OBS has the same number of events as the observational data in the SCF and SWN regions during the autumn season, while a difference of one event between both products is found for all other regions in autumn and for all regions in winter. Most of the RCMs, as well as ERA5, simulated almost the same number of events compared to observations, with some differences in the number of events in some regions. Particularly, in the SWN region, the models RegCM4-6 and REMO2015 have considerably fewer events compared to the observations. Furthermore, it is found that the spread of events among the RCMs, with (without) including the RegCM4-6, is up to two in all regions except for the SWN region, where it increases to up to seven (six) events (Fig. S3; in blue). The higher spread in the SWN region is attributed to the REMO2015 model when the RegCM4-6 model is not included in the standard deviation calculation. On the other hand, the dates of identified events from E-OBS are similar to those from the high-resolution observational product of each region, with only a few dates (1–2) showing a 1-day lead/lag time difference (Fig. S2c). ERA5 accurately detected around 45%–50% of the observed event dates, and this value increases to approximately 70% in the case of the SCF region during the DJF season. In the case of RCMs, some correctly reproduced around 30%–40% of

observed event dates, and this value increases to approximately 45% for the NEAR_SON region. However, the percentage increases by 5%–15% when considering the model's skill by taking into account a 1-day lagged (lead/lag) in observed dates.

Longitudinal variations of maximum precipitation across latitudes of the SCF region, for example, during September–November (SON) for 1983 and 1995 (Fig. 3), provide some insight into observed disparities in precipitation extremes between observations and models. In 1983, a clear overestimation of precipitation by RCMs can be seen during days 67–79 (6–18 November). This is also evident to some extent in ERA5, highlighting the occurrence of extreme events that are not present in observations but are simulated by the models. On the other hand, the precipitation extremes seen in September–October 1995 are significantly underestimated by the RCMs. Even the observed extremes during days 42–43 (12–13 October) are not detectable in the RCMs, highlighting the occurrence of extreme events that are present in the observations but not simulated by the RCMs. However, these extremes are at least visible in ERA5, albeit with lower intensity, but better than the RCMs.

b. Analysis of composite patterns

Figure 4 demonstrates the composites of daily mean precipitation during WSEPEs across all four regions for both

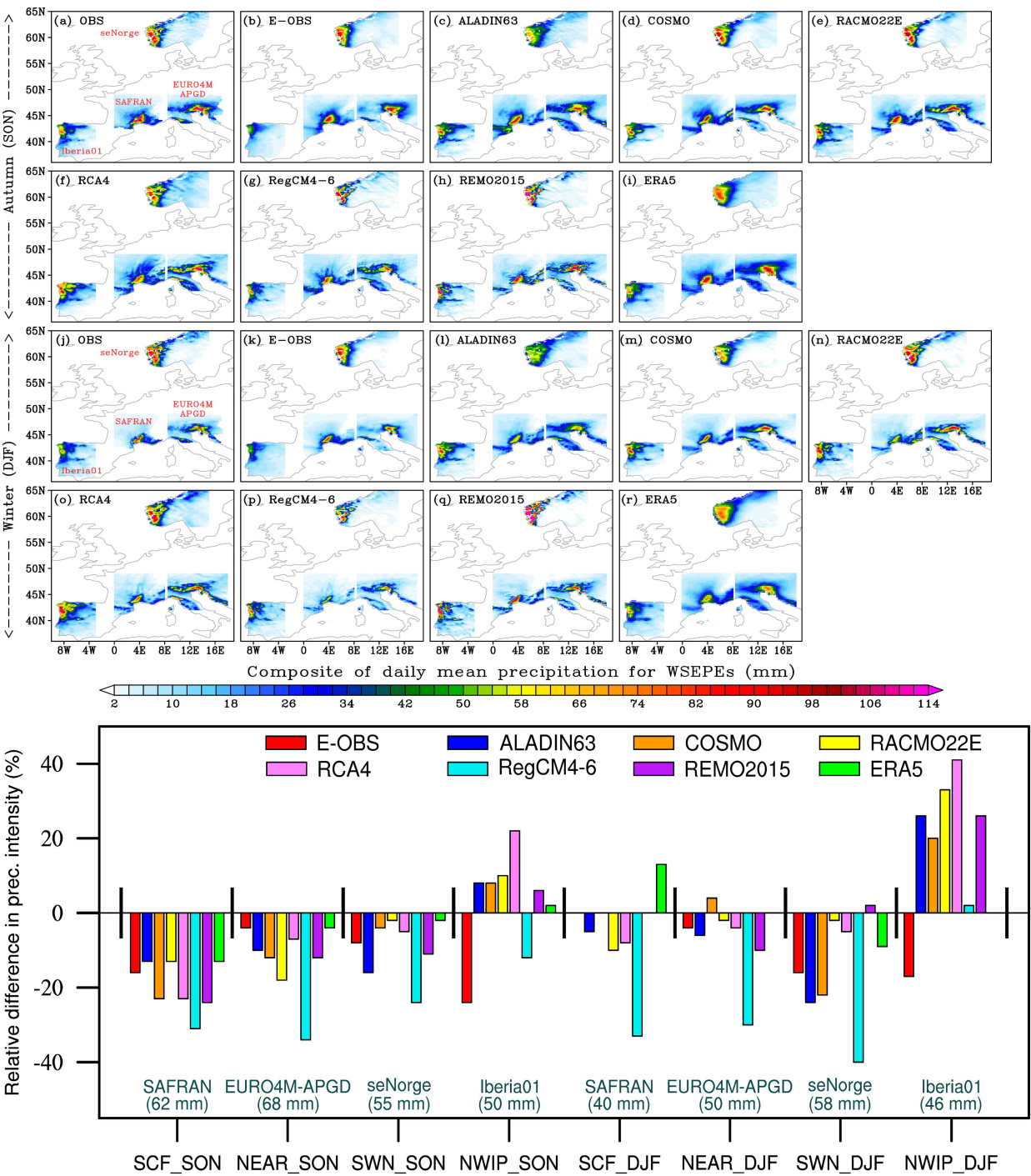


FIG. 4. Composite of mean precipitation (mm; shaded) for WSEPEs in each region from observations and RCMs. The upper and lower panels of the shaded plot show results for the autumn and winter seasons, respectively. The area-averaged values over each mask domain along with the relative difference in E-OBS and RCMs with respect to different observational products of each region are also presented using a bar plot.

seasons from high-resolution observational products, E-OBS, and RCMs. The composite maps are shown over larger domains in order to better demonstrate the spatial extent of identified events. The composite analysis for each region of each dataset is conducted using their respective extreme days. The highest precipitation during WSEPEs of both seasons in the NWIP (SWN) region is seen along the northern border between Spain and Portugal (Vestland county in Norway)

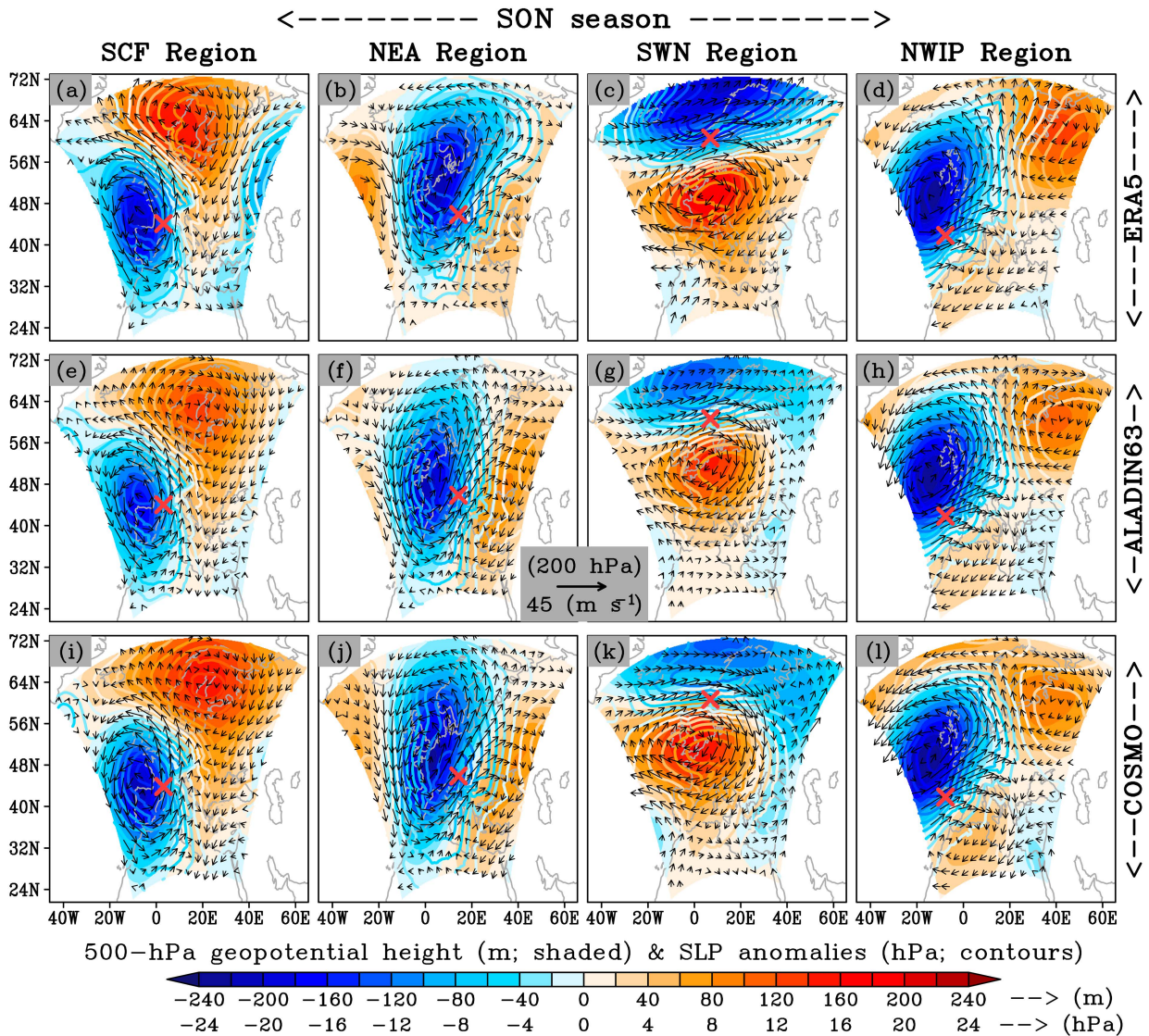


FIG. 5. Composite of 500-hPa geopotential height (m; shaded), 200-hPa wind vectors (m s^{-1} ; arrows), and sea level pressure (hPa; color contours) anomalies for WSEPs in each region during the autumn season from ERA5, ALADIN63, and COSMO RCMs. Red crosses indicate regions where widespread extreme precipitation is assessed.

(Figs. 4a,b,j,k). In the SCF region, the highest amount of precipitation is noted along the southeast edge of the Massif Central (i.e., Cévennes mountain range), and in the NEAR region, the central Slovenia experiences the highest amount of precipitation during WSEPs (Figs. 4a,b,j,k). The area-averaged precipitation amounts over all four masked domains from all the datasets are depicted in Fig. S2d, and relative differences in E-OBS and RCMs with respect to the high-resolution quality-controlled observational product of each domain are illustrated in Fig. 4, using a bar plot. The precipitation variability is largely comparable to what we observed in the case of R99p, albeit with some differences in magnitudes. It is noted that the total mean precipitation shown by the high-resolution observational product is better reproduced by ERA5 than by E-OBS, and this holds true for all

the regions except for the SCF_DJF where an overestimation of precipitation by ERA5 is observed. On the other hand, intermodel spread in precipitation intensity of WSEPs among the RCMs is evident in all regions (Fig. 4 and Fig. S3), with some models showing precipitation estimates closer to those from the high-resolution observational product than E-OBS.

To associate WSEPs with their driving mechanisms, we built composites of 500-hPa geopotential height, 200-hPa winds, sea level pressure anomalies, 850-hPa equivalent potential temperature and wind anomalies, and the mean vertically integrated water vapor, using widespread extreme days from all four regions. The composite analysis for each dataset is conducted using their respective extreme days. Results from ERA5, ALADIN63, and COSMO are depicted in Figs. 5 and 6 and Fig. S4 and for autumn

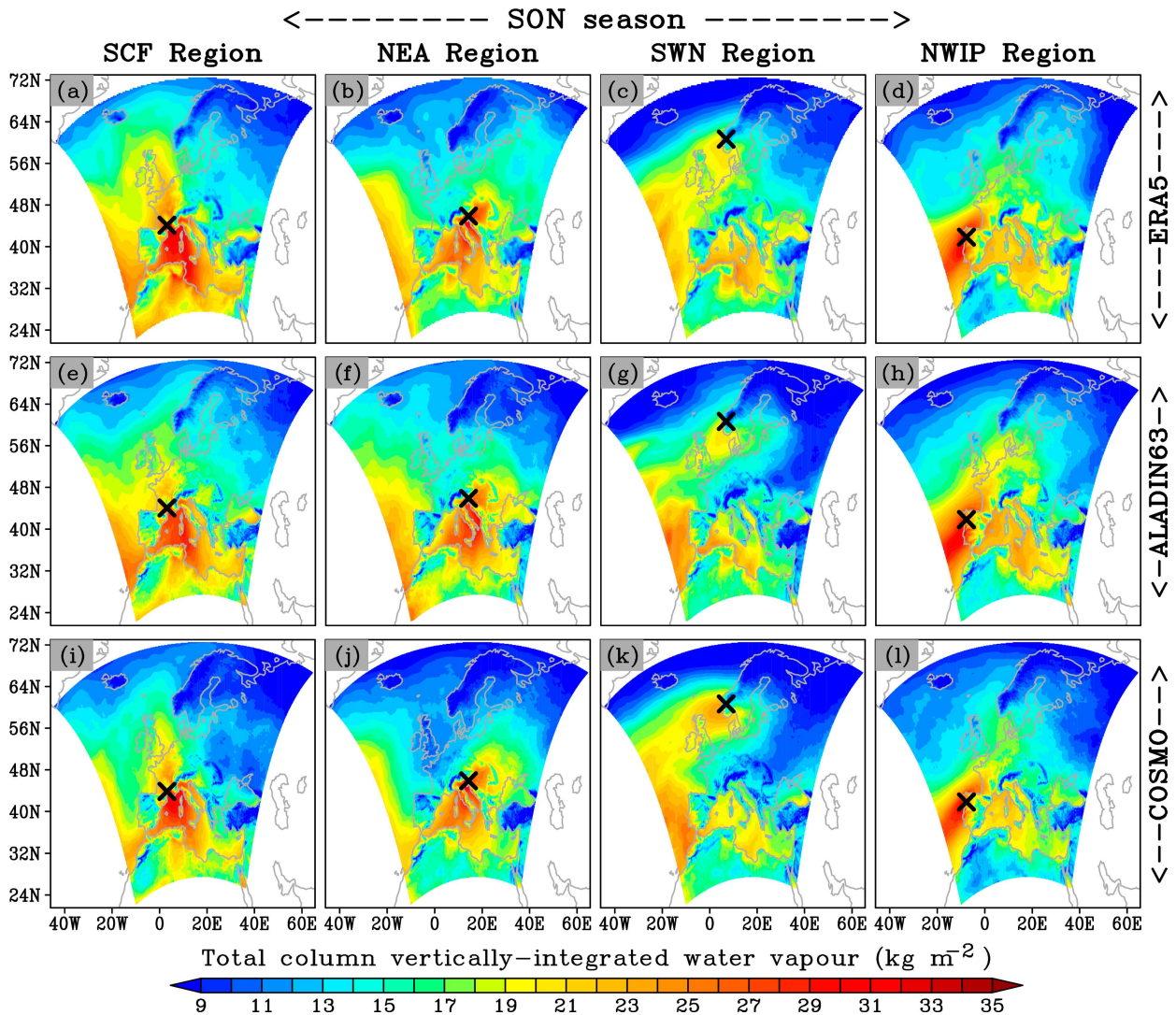


FIG. 6. Composite of total column vertically-integrated IWV (kg m^{-2} ; shaded) for WSEPEs in each region during the autumn season from ERA5, ALADIN63, and COSMO RCMs. Black crosses indicate regions where widespread extreme precipitation is assessed.

and Figs. 7 and 8 and Fig. S5 for winter. Similarly, results from the remaining four models (i.e., RACMO22E, RCA4, RegCM4-6, and REMO2015) are illustrated in Figs. S6–S8 for autumn and Figs. S9–S11 for winter. The vertically integrated moisture transport (VIMT) and its convergence are also computed using only ERA5 data due to the unavailability of the required variables at the pressure level for this calculation in EURO-CORDEX simulations, as depicted in Fig. 9.

c. Large-scale atmospheric patterns for WSEPEs and their attendant mechanisms

We consider two regions for discussion at a time. First, we discuss the results of ERA5 and RCMs for the regions belonging to the Mediterranean basin (i.e., the SCF and NEAR regions). Subsequently, we focus on the regions associated with the European North Atlantic sector (i.e., the NWIP and SWN regions). Following this, we discuss the results of VIMT

and its convergence obtained from ERA5, followed by notes on the physical mechanisms and the results of the column-integrated condensed (liquid + ice) water path obtained from RCM simulations and ERA5.

1) THE SCF AND NEAR REGIONS

The ERA5 results indicate that the occurrence of WSEPEs in the SCF region is linked to large-scale differences in 500-hPa height anomalies across Europe, which is manifested as a trough–ridge dipole pattern (Fig. 5a). This distinctive pattern is characterized by negative $\sim 200\text{-m}$ height anomalies (indicating a trough; low pressure system) over western Europe, centered over the northwestern Iberian Peninsula (with a slight tilt toward the northwest), and positive $\sim 200\text{-m}$ height anomalies (indicating a ridge; high pressure system) centered over the Nordic region (Fig. 5a). This pattern results in an intense south-easterly cyclonic flow with strong low-level advection of warm

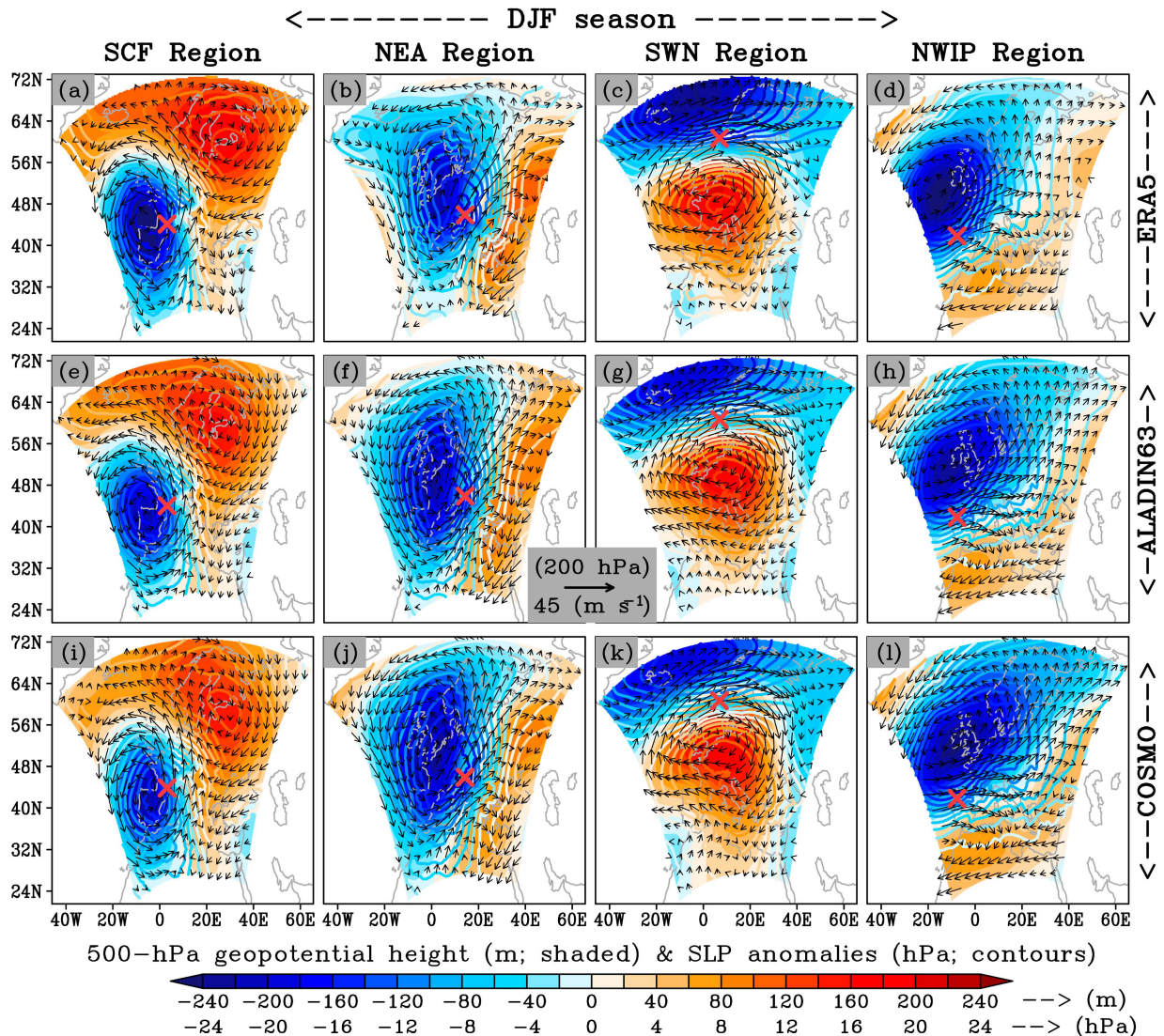


FIG. 7. Composite of 500-hPa geopotential height (m; shaded), 200-hPa wind vectors (m s^{-1} ; arrows), and sea level pressure (hPa; color contours) anomalies for WSEPEs in each region during the winter season from ERA5, ALADIN63, and COSMO RCMs. Red crosses indicate regions where widespread extreme precipitation is assessed.

and moist air from the Mediterranean toward the SCF region, affecting this area (Fig. 5a and Fig. S4a). On the other hand, WSEPEs in the NEAR region are associated with the presence of a cutoff low system centered over northwestern Europe (with a slight tilt toward the northeast), positioned between two blocking highs located to the west and east of the cut-off-low system (Fig. 5b). This blocking pattern induces a strong southwesterly cyclonic flow of moist and warm air from the Mediterranean toward the Adriatic region (Fig. 5b and Fig. S4b). Enhanced moisture transport, resulting from favorable synoptic circulation, can also be observed in both regions (Figs. 6a,b). It is also apparent that both regions are influenced by V-shaped cyclonic features collocated with a trough observed in these areas, suggesting that the synoptic-scale pattern drives the moisture transport over these regions.

In both regions, moist and warm air advection is wrapping cyclonically around the low-pressure center associated with the warm conveyor belt (WCB; Harrold 1973), with a cold front trailing behind it (Figs. S4a,b). This pattern has been tied to widespread extreme precipitation as demonstrated by Pfahl et al. (2014), Wandel et al. (2021), and Oertel et al. (2023), who have established that the WCB refers to warm and moist airstreams in extratropical cyclones, leading to the formation of widespread clouds and heavy precipitation. The results demonstrate that the RCMs largely reproduce the large-scale features associated with WSEPEs in both regions, as obtained from ERA5 (see the first two columns of Fig. 5 and Figs. S4, S6, and S7). However, intermodel differences are evident in both the spatial patterns and their magnitudes. For instance, a displacement in the observed position of the ridge in the SCF

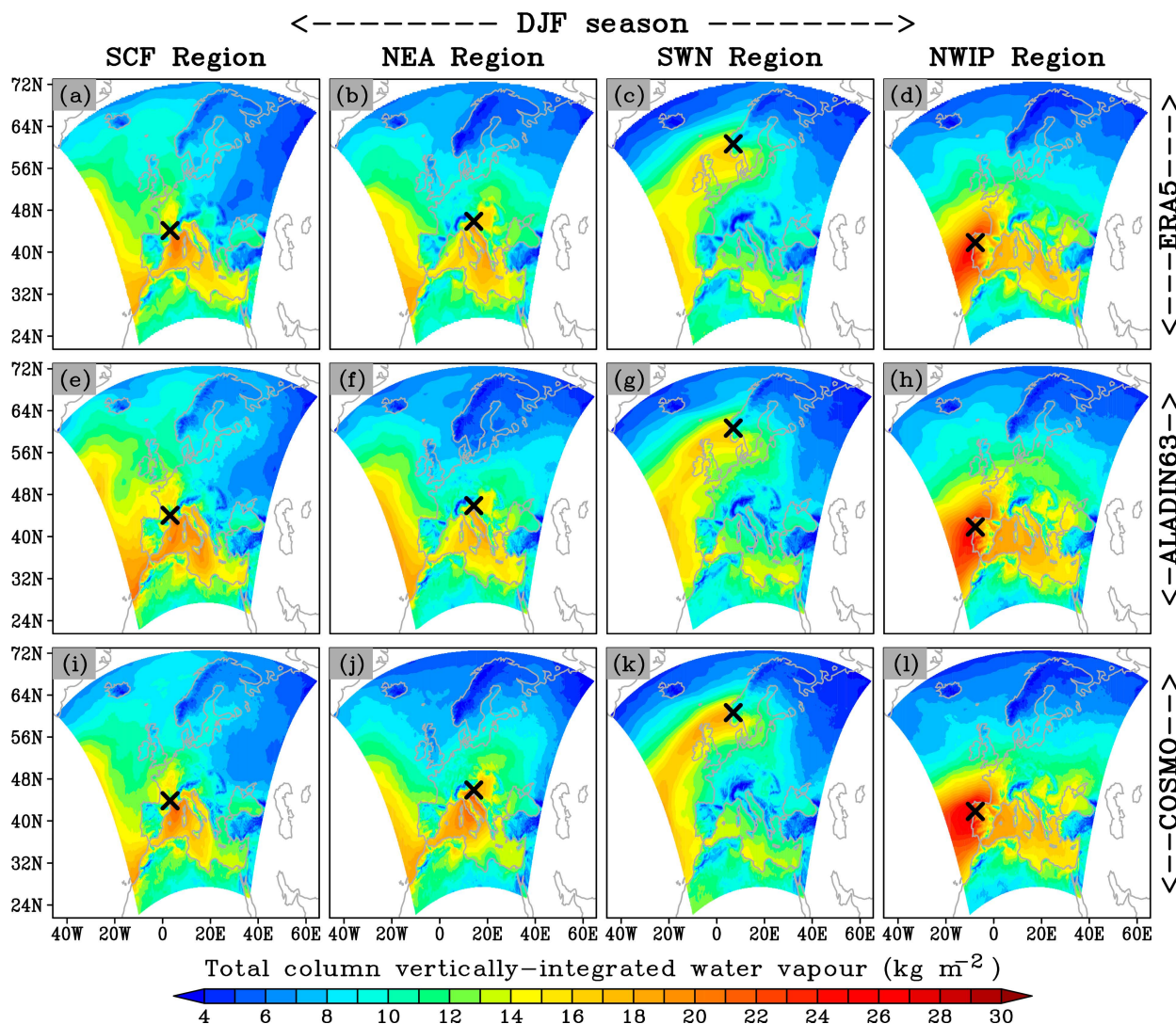


FIG. 8. Composite of total column vertically IYW (kg m^{-2} ; shaded) for WSEPEs in each region during the winter season from ERA5, ALADIN63, and COSMO RCMs. Black crosses indicate regions where widespread extreme precipitation is assessed.

region is noted in RegCM4-6 and RACMO22E models, compared to all other models (Figs. S6e,m).

The large-scale synoptic systems obtained during the winter season are consistent with those found during the autumn season, and this holds true for both the SCF and NEAR regions. However, the composite anomalies of large-scale synoptic fields are slightly more pronounced in the winter season (Fig. 7 and Fig. S9) compared to the autumn season (Fig. 5 and Fig. S6). On the other hand, the amount of moisture in both regions is higher in autumn (Fig. 6 and Fig. S8) compared to winter (Fig. 8 and Fig. S11; mean values are shown in Fig. S12). This is also evident from Figs. 9a, 9b, 9e, and 9f, which show the total mean vertically integrated water vapor transport from ERA5 data (mean values are given in Table 2). The presence of larger amounts of water vapor in autumn compared to winter is most probably due to the generally higher temperatures in autumn than in winter (on average), as it is

well established that the size of water vapor column (i.e., amount of water vapor present in a vertical column of the atmosphere) and its transport are strongly related to temperature.

The observed higher precipitation in autumn compared to winter may be linked to variations in the amount of moisture content obtained between the two seasons (Fig. 4 and Fig. S12). This relationship is well reproduced by the RCMs; however, intermodel differences among the RCMs are evident (Fig. 4 and Fig. S12). Recently, Kunkel et al. (2020) demonstrated that for the continental United States, extreme precipitation amounts generally scale linearly with the water vapor content in an atmospheric column. Furthermore, for a similar set of extreme precipitation events used in Kunkel et al. (2020), Kunkel et al. (2012) found that large-scale weather systems, including tropical and extratropical cyclones (and their associated fronts), were directly linked to most extreme precipitation events. However, when water

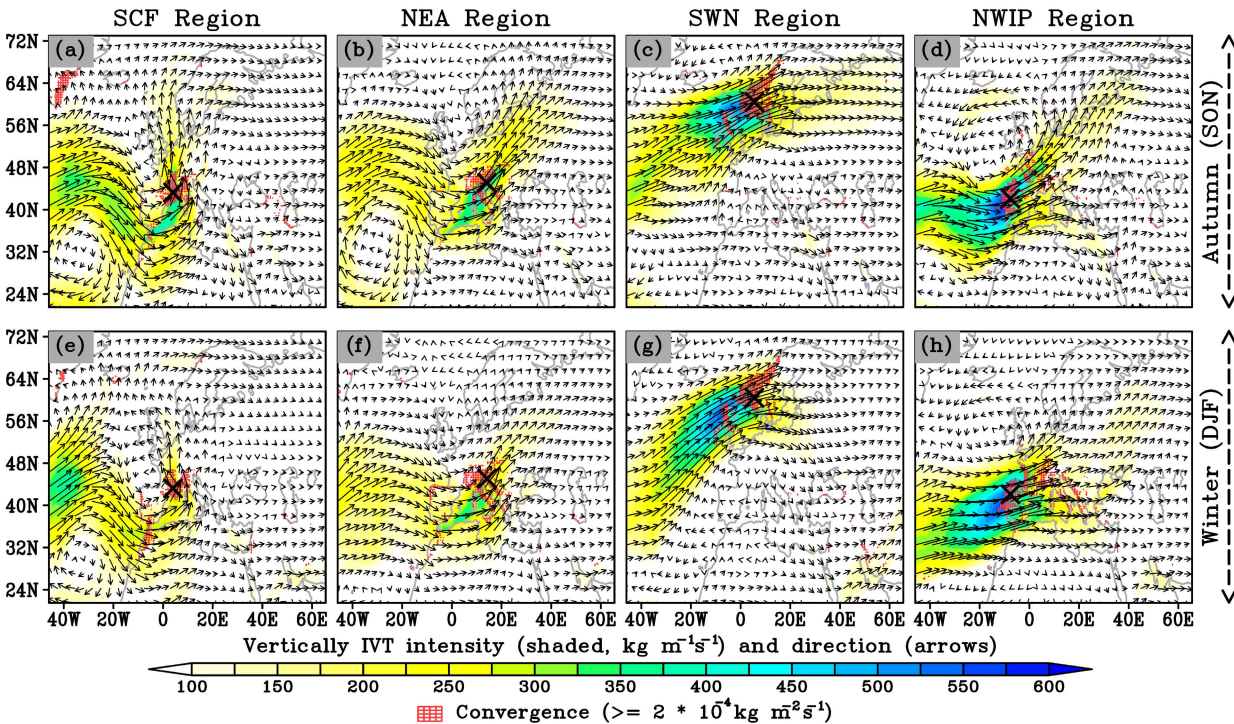


FIG. 9. Composite of vertically integrated mean water vapor transport (IVT) intensity (shaded; $\text{kg m}^{-1} \text{s}^{-1}$), direction (arrows), and convergence ($\geq 2 \times 10^{-4} \text{ kg m}^{-2} \text{s}^{-1}$) indicated by red hatches for WSEPEs in each region from ERA5. The upper and lower panels show results obtained from the autumn and winter seasons, respectively. Black crosses indicate regions where widespread extreme precipitation is assessed.

vapor content is particularly high, increases in precipitable water can produce a disproportionately large increase in extreme precipitation amounts (Kunkel et al. 2020). Specifically, Kunkel et al. (2020) concluded that while it was necessary that a weather system caused upward motion and initiated precipitation, the amount of precipitation was dependent on water vapor content and not the magnitude of upward motion. To assess whether the amounts of water vapor column are high compared to the reference (or background) values, we calculated the water vapor column anomalies. Since the mean water vapor column patterns have already been presented for all models, this calculation is performed solely for ERA5 data. The anomalies are determined by subtracting the daily climatology values for the 1980–2010 period from the daily mean values. The area-averaged water vapor anomalies during WSEPEs over the SCF, NEAR, SWN, and NWIP masked domains for the SON (DJF) season are 9.55 (6.65), 9.10 (6.34), 6.98 (6.10), and 10.51 (9.61) kg m^{-2} , respectively.

TABLE 2. Magnitude of area-averaged total mean vertically IYW transport ($\text{kg m}^{-1} \text{s}^{-1}$) over four masked domains.

Regions	Autumn	Winter
SCF	399	282
NEAR	406	271
SWN	338	314
NWIP	476	446

These results clearly indicate that the water vapor column amounts are high compared to the reference values, demonstrating the relationship between the amount of water vapor and the amount of precipitation, thus supporting our hypothesis/results. Furthermore, higher water vapor column anomalies in autumn compared to winter, particularly over the SCF and NEAR regions, are evident. However, a detailed investigation of this phenomenon is challenging and will be addressed in a separate paper.

In summary, synoptic patterns that characterize widespread extreme precipitation over the SCF (NEAR) region include trough–ridge dipole patterns, strong southeasterly (southwesterly) winds, advection of warm air promoting rising motion (Holton 2004), and positive moisture advection over the region. It appears that the Atlantic Ocean, with contributions from the Mediterranean Sea, is the main source of moisture for the extreme precipitation in both regions (Figs. 9a,b,e,f). This will be studied in detail in future work, with a greater emphasis on investigating the relationship between extreme precipitation and atmospheric rivers through modeling simulations.

2) THE SWN AND NWIP REGIONS

The composite map of the 500-hPa geopotential height anomalies from ERA5 during WSEPEs in the SWN region reveals a dipole-like pattern with a pronounced trough centered over the Nordic region and the Norwegian Sea and a ridge over western Europe (Fig. 5c). This pattern is associated

TABLE 3. Mechanisms leading to the formation of WSEPEs in each region during both seasons, as noted from ERA5.

Regions	Notes on mechanism (ERA5)
SCF	WSEPEs are associated with a blocking pattern that extends meridionally from central Europe to the Nordic region (i.e., a ridge of high pressure) and low pressure anomalies (i.e., a trough) over the North Atlantic to the west of Europe.
NEAR	WSEPEs are associated with a cutoff low system centered over northwestern Europe, with a slight tilt toward the northeast.
SWN	WSEPEs are associated with the positive phase of the NAO, characterized by synoptic high pressure anomalies centered over western Europe and low pressure anomalies centered over the Nordic region and the Norwegian Sea.
NWIP	WSEPEs are associated with a low pressure system centered over the North Atlantic and the British Isles, surrounded (trapped) by areas of high pressure.

with the positive phase of the North Atlantic Oscillation (NAO), which strengthens the advection of warm and moist air from the southwest Atlantic Ocean toward western Norway (Fig. 5c and Fig. S4c). These conditions collectively establish a favorable setup for synoptically forced precipitation over the SWN region (Sodemann and Stohl 2013; Michel et al. 2021). The observed large-scale patterns are well simulated by the RCMs (Fig. 5, Figs. S4, S6 and S7). In the winter season, one can observe a slightly more pronounced (compared to autumn) trough–ridge pattern with a larger spatial extent (Fig. 7 and Fig. S9). Consequently, this leads to a more pronounced wind flow oriented in a southwest–northeastward direction over the SWN region. On the other hand, both ERA5 and RCMs show a slightly higher amount of moisture flux over the SWN region in autumn (Fig. 6 and Fig. S8) compared to winter (Fig. 8 and Fig. S11; mean values are shown in Fig. S12), as is also evident from Table 2. This difference in moisture content may account for the slight variation in precipitation obtained between the two seasons, although this is not true for all RCMs (Fig. 4 and Fig. S12). Furthermore, elongated and narrow bands of integrated moisture flux extending from the Atlantic Ocean to western Scandinavia are observed (Figs. 9c,g). This suggests that widespread extreme precipitation in the SWN region is associated with ARs, in line with earlier findings (Sodemann and Stohl 2013; Gavrikov et al. 2020; Michel et al. 2021).

The ERA5 results indicate that WSEPEs during the autumn season in the NWIP region are associated with a strong trough located around the North Atlantic and the British Isles (followed by cyclogenesis), which appears to be trapped by the surrounding blocking high systems (Fig. 5d). This cyclonic trough, accompanied by blocking ridges, supports a strong jet stream on its southern flank (warm conveyor belt) from the Atlantic Ocean toward the northwestern Iberian Peninsula (Fig. 5d and Fig. S4d). Furthermore, this southwesterly cyclonic flow intensifies the advection of warm and moist air, transporting moisture from the Atlantic Ocean toward the northwestern Iberian Peninsula (peak over the NWIP region; Figs. 5d and 6d, Fig. S4d). Collectively, these conditions culminate in the occurrence of heavy precipitation over the NWIP region. The WSEPEs during the winter season are associated with a slightly more pronounced trough centered around the British Isles, with ridges on its northern and southern edges (Fig. 7d). The winter season showcases synoptic-scale conditions akin to those observed during the autumn season, such as a warm conveyor belt associated with a

cyclonic trough that transports warm and moist air toward the northwestern Iberian Peninsula and enhanced water vapor moisture flux over this region (Figs. 7d and 8d, Fig. S5d). It is found that RCMs greatly reproduce the observed large-scale synoptic spatial patterns; however, intermodel differences are evident in the spatial patterns as well as in the magnitudes of these patterns (Figs. 5–8, Figs. S4–S11). On the other hand, elongated and narrow bands of integrated water vapor moisture flux extending from the Atlantic Ocean to the NWIP region, oriented in a southwest–northeastward direction (Figs. 9d,h), suggest that widespread extreme precipitation events in this region are associated with ARs. This pattern of ARs has also been observed in earlier studies (Eiras-Barca et al. 2018; Ghasemifar et al. 2020).

3) ATMOSPHERIC MOISTURE TRANSPORT FROM ERA5

In this section, we present a detailed analysis of moisture sources and transport pathways during WSEPEs across all examined regions. The analysis of the VIMT from ERA5 reveals an atmospheric river–like pattern of moisture transport originating from the Atlantic Ocean in all analyzed regions (Fig. 9). The moisture transport over the SCF (NEAR) region is evidently controlled by northwesterly–southeasterly (northwesterly–southwesterly) flows originating from a well-established anticyclonic feature over the southeastern Atlantic Ocean (Figs. 9a,b,e,f). In fact, this anticyclonic feature promotes enhanced moisture transport from the Atlantic Ocean toward both regions, resulting in precipitation due to convergence, and is aligned with the observed trough–ridge patterns (Figs. 5a,b and 7a,b). Regarding the SWN region, a pronounced southwest–northeastward flow of moisture from the Atlantic Ocean toward southwestern Scandinavia, resulting in large-scale convergence and precipitation over that region, is clearly seen in Figs. 9c and 9g. This system is associated with the observed trough–ridge patterns (NAO+; Figs. 5c and 7c) and is consistent with previous studies (Sodemann and Stohl 2013; Michel et al. 2021). On the other hand, the NWIP region is influenced by a cyclonic feature with westerly flows that transport moisture from the Atlantic Ocean hitting the NWIP region (Figs. 9d,h), and this pattern is collocated with an observed trough located around the British Isles (Figs. 5d and 7d). This result is in line with the findings of Eiras-Barca et al. (2018). The clear difference in VIMT magnitude between the two seasons in the SCF and NEAR regions may account for the observed variation in precipitation between these seasons (Table 2; Fig. 4).

In summary, the Atlantic Ocean emerges as a primary moisture source for widespread extreme precipitation events in all four analyzed regions.

4) NOTES ON THE PHYSICAL MECHANISMS

Here, we have summarized the key physical mechanisms leading to the formation of WSEPEs in a tabular format (Table 3). While previous analyses have shown that RCMs largely reproduce the large-scale synoptic patterns observed in ERA5 data [i.e., sections 3c(1) and 3c(2)], we now perform a correlation analysis to further elaborate (summarize) these findings. We have calculated the pattern correlation between ERA5 and the RCMs for the 500-hPa geopotential height and the mean sea level pressure (see Fig. 10), as these parameters are commonly used to understand and explain the large-scale atmospheric processes associated with extreme weather events. The RCM datasets were regridded to ERA5 grid for this correlation calculation.

It is evident from Fig. 10 that the atmospheric processes during the WSEPEs noted in ERA5 are well captured by the RCMs ($r \geq 0.9$ for most of the regions). However, some RCMs exhibit slightly lower correlation ($0.75 \leq r \leq 0.86$) for the mean sea level pressure in the NEAR region during the DJF season. Furthermore, during the SON season, RCA4, RegCM4, and REMO2015 exhibit correlations smaller than 0.7 for the mean sea level pressure in the NEAR region. Overall, we can conclude that the RCMs, despite their many mutual differences, are capable of robustly representing the atmospheric processes leading to WSEPEs across all four study regions.

5) CONDENSED WATER PATH FROM RCMs

As previously noted, the moisture content is nearly identical across all models for each analyzed region. However, variations in moisture content are noted between the different analyzed regions. Given this, it would be interesting to investigate whether the column-integrated condensed (liquid + ice) water path shows a similar behavior. The composites of the mean column-integrated condensed (liquid + ice) water path from the RCM simulations and ERA5 during WSEPEs are plotted in Fig. 11. As can be seen from Fig. 11, noticeable intermodel variations in the amount of condensed water content are evident. The amount of condensed water content simulated by RegCM4-6 is considerably less compared to ERA5 and all other RCMs, which might explain the identified difference in precipitation estimates between RegCM4-6 and all other models. Furthermore, the higher amount of condensed water content in autumn compared to winter across the SCF and NEAR regions, as evident in both ERA5 and RCMs, might elucidate the identified variations in precipitation between these seasons in both regions (Fig. 11). As we know, during extreme precipitation events, the condensed water path increases significantly due to the intense condensation of atmospheric moisture. This process is driven by synoptic scale and/or orographic lifting of humid air, which transport large amounts of water vapor to higher altitudes where it condenses or freezes into liquid droplets and ice

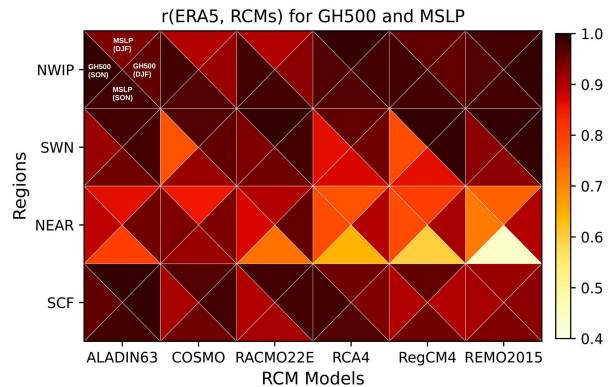


FIG. 10. The pattern correlation between ERA5 and the RCMs for the 500-hPa geopotential height (GH500) and the MSLP is shown using a heatmap. Each cell of the heatmap is divided into four triangles. The west and south triangles show the results of GH500 and MSLP for the SON season, respectively. Similarly, the east and north triangles show the results of GH500 and MSLP for the DJF season, respectively. All correlation values are statistically significant at the 99% confidence level (based on the t test).

particles. These hydrometeors (liquid + ice) then grow through collision and coalescence processes, where tiny droplets or ice crystals collide and merge, forming larger particles (Pruppacher and Klett 2010; Heymsfield et al. 2020). Eventually, these particles become too heavy to be supported by the updrafts, leading to their fall as precipitation. Therefore, even though the instantaneous amount of cloud liquid water and cloud ice may be small compared to the total accumulated precipitation, they are crucial in modulating the rate and efficiency of precipitation formation during extreme events. However, variations in the amount of condensed water content do not always align/correspond with variations in precipitation estimates, as evident in some analyzed regions (Fig. 11). Furthermore, the significant overestimation of condensed water content by RACMO22E and the underestimation by RegCM4-6, compared to ERA5 and all other RCMs across all analyzed regions for both seasons, highlights the need for a comprehensive investigation into the microphysical processes involved in cloud formation and precipitation in the models.

4. Summary and conclusions

In this study, we have analyzed the representativeness of the characteristics of widespread extreme precipitation events (WSEPEs) and their associated large-scale atmospheric conditions in a number of high-resolution RCM simulations using several high-resolution observational precipitation products, as well as the recent ERA5 reanalysis. The RCM simulations are evaluation experiments driven by ERA-Interim reanalysis at a horizontal resolution of approximately 12 km ($0.11^\circ \times 0.11^\circ$) in the framework of EURO-CORDEX. The analysis focuses on four complex orographic European regions, characterized by extreme precipitation. Specifically, two of these regions are located along the northern coast of the Mediterranean (i.e., the SCF and NEAR regions), while the other two are exposed

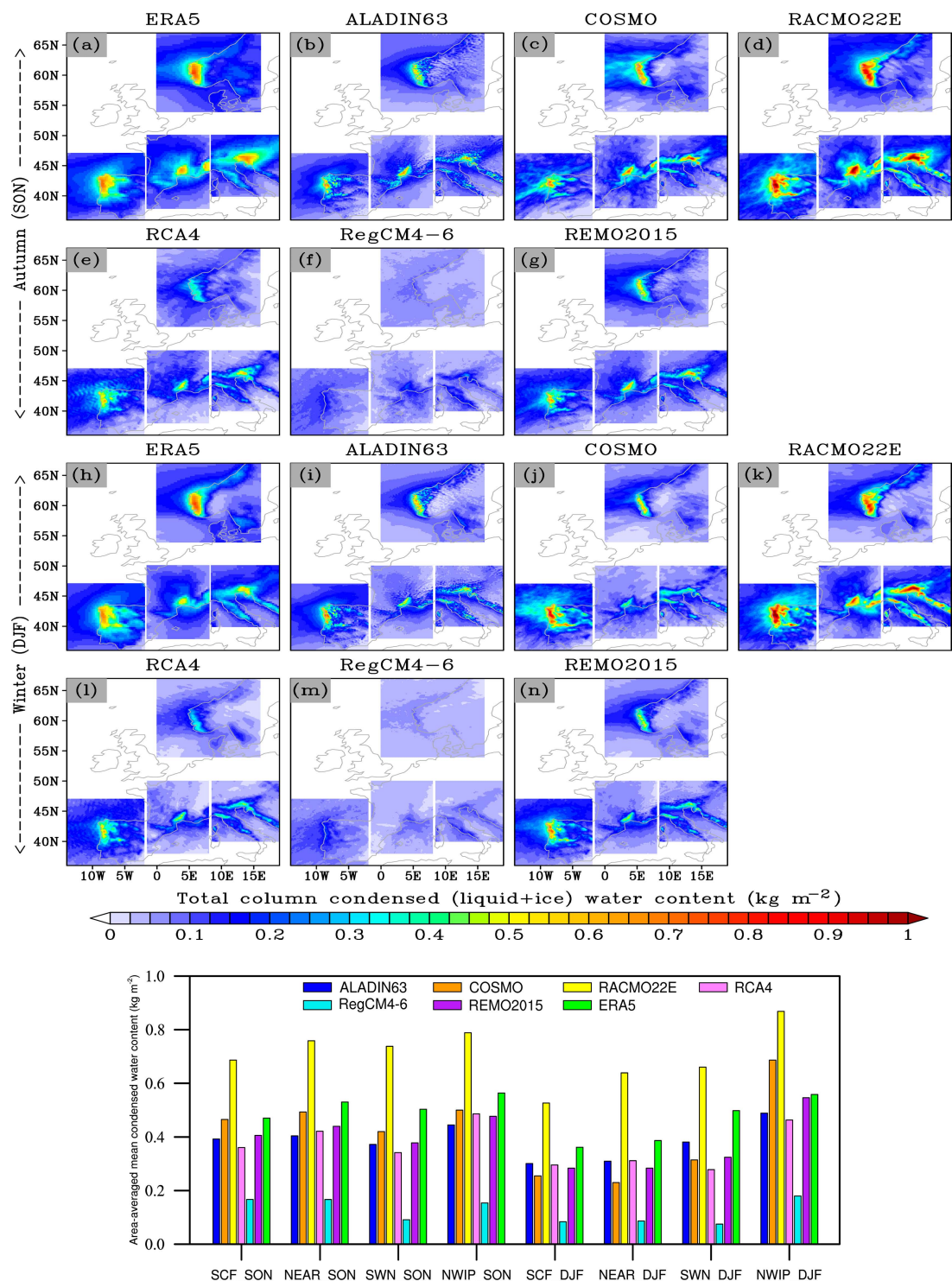


FIG. 11. Composite of mean total column-integrated condensed (liquid + ice) water path (kg m^{-2} ; shaded) for WSEPEs in each region from ERA5 and RCMs. The upper and lower panels of the shaded plot show results for the autumn and winter seasons, respectively. Area-averaged values over each masked domain are also presented using a bar plot.

to processes in the European North Atlantic sectors (i.e., the NWIP and SWN regions). These selected regions have been found to be predominantly vulnerable to extreme precipitation events, mostly in the autumn and winter seasons. Therefore, our analysis is specifically considered for these two seasons. The high-resolution quality-controlled observational product compiled from higher density rain gauge station networks available over each region, along with the E-OBS precipitation data, is used to evaluate the model-simulated precipitation.

We found that the RCMs largely reproduced the observed total number of WSEPEs, with a spread of up to two events among the models in all four analyzed regions, except for the SWN region. In this region, these two models (i.e., RegCM4-6 and REMO2015) notably have fewer events, which eventually lead to an increase in the spread among the models. It is furthermore found that ERA5 outperformed the RCMs in representing the dates of observed events. A noteworthy reduction of up to 25% in precipitation intensity during WSEPEs in the E-OBS, compared to high-resolution observational data, is observed in some regions. The observed precipitation during WSEPEs is notably more intense in autumn compared to winter over the SCF and NEAR regions and is well reproduced by both ERA5 and the RCMs. On the other hand, RegCM4-6 yields lower precipitation estimates compared to all other models across all regions, except for the NWIP region, where RCA4 demonstrates a noticeable overestimation of observed precipitation. This suggests that conducting a multimodel study without examining the outcomes from each model individually may lead to misleading conclusions, especially if one of the models has a significant bias. The relatively small inter-model spread in precipitation intensity of WSEPEs among the RCMs (with the exception of RegCM4-6), when driven by the same forcing, indicates a high level of agreement/consistency among the models. Furthermore, models that perform best in one region may not necessarily excel in all other regions, highlighting the importance of regional-specific model assessments.

The ERA5 results indicate that the occurrence of WSEPEs in the SCF region is associated with a blocking pattern that extends meridionally from central Europe to the Nordic region (i.e., a ridge of high pressure) and low pressure anomalies (i.e., a trough) over the North Atlantic to the west of Europe, while the WSEPEs in the NEAR region are associated with a cutoff low system centered over northwestern Europe. These patterns lead to the advection of moisture-laden air (resembling an atmospheric river-like pattern of moisture transport) originating from the Atlantic Ocean, with contributions from the Mediterranean Sea, resulting in enhanced moisture transport in these regions and precipitation due to convergence. In the SWN region, WSEPEs are associated with the positive phase of the NAO (Sodemann and Stohl 2013; Michel et al. 2021), characterized by a trough centered over the Nordic region and the Norwegian Sea, and a ridge over western Europe. This pattern promotes the transport of moisture-laden warm air originating from the Atlantic Ocean into this region, leading to precipitation due to convergence. On the other hand, the NWIP region is dominated by a

cyclonic feature collocated with a trough centered around the North Atlantic and the British Isles. This setup promotes the advection of moisture-laden warm air originating from the Atlantic Ocean toward this region, resulting in precipitation due to convergence. The Atlantic Ocean is identified as the primary moisture source with an atmospheric river-like pattern for heavy precipitation during the WSEPEs in both the SWN and NWIP regions, in line with previous studies (Sodemann and Stohl 2013; Gavrikov et al. 2020; Michel et al. 2021; Eiras-Barca et al. 2018). Furthermore, the higher amount of moisture content in autumn, compared to winter, particularly over the SCF and NEAR regions, may elucidate the observed variations in precipitation during these seasons in both regions.

It is noted that all RCMs to a large extent reproduced the large-scale synoptic spatial patterns observed in ERA5 for both seasons across all four analyzed regions. However, inter-model differences are evident in both the spatial patterns and their magnitudes. Despite these differences, all RCMs simulated nearly the same amount of moisture content in each analyzed region. This suggests that the obtained variations in precipitation estimates among the RCMs for “an analyzed region” may not solely be related to issues with the driving model (i.e., initial and boundary conditions) but could also be associated to uncertainties with the physical parameterizations and associated processes. For example, noticeable differences in precipitation estimates are identified between RegCM4-6 and all other models, while the amount of moisture produced by RegCM4-6 is similar to that derived from all other models. It is furthermore found that the amount of condensed water content simulated by RegCM4-6 is considerably less compared to all other models, which might explain the identified difference in precipitation estimates between RegCM4-6 and all other models. Here, we cannot draw unequivocally firm conclusions due to uncertainties and limitations in our current understanding of the microphysical processes involved in cloud formation and precipitation, as well as their representation in the models. Furthermore, the significant overestimation of condensed water content by RACMO22E compared to all other models highlights the need for a comprehensive investigation into the physical parameterizations and processes involved. The large amounts in RACMO22E were already pointed out by Roebeling and Van Meijgaard (2009), who found an on average 30% overestimation of RACMO cloud condensed water path compared to satellite inferred amounts. However, a detailed investigation with modeling experiments utilizing physical parameterizations is required to fully understand and support our hypotheses.

In summary, while the RCM ability to simulate large-scale synoptic patterns enhances confidence in their application for regional climate studies, their results should be interpreted in conjunction with observations, global models, and other tools to ensure comprehensive and accurate evaluations of regional climate variability. On the other hand, the improved representation of extreme precipitation in ERA5 encourages conducting RCM simulations at high resolution using lateral boundary conditions (LBCs) from this reanalysis dataset to further explore the effects of model resolution and physical parameterizations. Such evaluation experiments are being conducted in the next phase of CORDEX.

In light of the upcoming next generation of RCM intercomparison experiments for Europe, we provide three specific recommendations. First, we recommend the adoption of a uniform domain size for all RCM simulations under consideration. For instance, the RegCM4-6 model configuration has a slightly larger domain size than all other models analyzed in this study, which may account for some differences in the outcomes/results. Standardizing the domain size would facilitate direct comparisons among models and mitigate potential biases related to domain-specific effects. Second, it would be beneficial if the CORDEX community could enrich the output by providing additional important diagnostic variables [e.g., convective available potential energy (CAPE), convective inhibition (CIN), omega (vertical velocity), vertically integrated moisture transport and its convergence, etc.]. This can be realized/accomplished by either developing and incorporating relevant packages/tools or making datasets available at all pressure or model levels. This is extremely useful for a detailed process-based understanding of the spatiotemporal variability of precipitation. Last, we urge/encourage the CORDEX community to consider implementing coupled atmosphere–ocean–land surface–sea ice regional Earth system models (RESMs). Such an implementation is essential for understanding the complexities of coupled climate systems and their responses at local and regional scales.

Acknowledgments. This research was supported/funded by the Coastal Ocean Sustainability in Changing Climate (COAST) project funded through the Belmont Forum Foundation (Grant Agreement C7H-ANR20B69). OZ was supported through the MIPT development program (Priority-2030). SG and OZ benefited from projects FMWE-2024-0017 and 075-15-2021-577 by the RF Ministry of Science and Higher Education. The authors express their gratitude to all climate modeling groups for their dedicated efforts in computing and providing the simulation datasets in the frame of the European branch of the international Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) program sponsored by the World Climate Research Programme (WCRP). We acknowledge the E-OBS dataset from the EU-FP6 project UERRA (<http://www.uerra.eu>) and the Copernicus Climate Change Service and the data providers in the European Climate Assessment and Dataset (ECA&D) project (<https://www.ecad.eu>). The authors would like to acknowledge the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing fifth generation ERA5 reanalysis data. Furthermore, the authors thank MeteoSwiss for providing us with Alpine precipitation grid dataset (EURO4M-APGD).

The authors declare that they have no conflicts of interest. Namendra Kumar Shahi performed the roles of conceptualization, data curation, formal analysis, methodology, investigation, software, validation, visualization, and writing original draft. Olga Zolina performed the roles of conceptualization, funding acquisition, project administration, review, and suggestions. Sergey K. Gulev performed the roles of funding acquisition, project administration, review, and suggestions.

Data availability statement. EURO-CORDEX datasets used in this work are freely available on the WCRP website under ESGF: <https://cordex.org/>. E-OBS daily precipitation data can be obtained from the following link: <https://www.ecad.eu/download/ensembles/download.php>. ERA5 datasets can be found at Copernicus site: <https://cds.climate.copernicus.eu/datasets>. The analysis codes that support the findings of this study are available from the corresponding author upon reasonable request.

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