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Atmospheric blocks modulate the odds of heavy precipitation events in Europe

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Abstract

A statistical link is presented between atmospheric blocks in the Euro-Atlantic sector and the frequency of regional-scale heavy precipitation events in Europe. Changes in the odds of European 1-, 3- and 5-day accumulation heavy precipitation in the presence of a block are investigated for different geographical locations of blocks and for summer and winter. The results show a significant modulation of the odds of heavy precipitation events during blocking episodes over the North-Atlantic and Europe. Blocks located further east have only limited effects on the odds of heavy precipitation events over Europe. The spatial patterns are very diverse and are strongly dependent on the location of the blocks and on the season. Generally, the odds of heavy precipitation events are reduced in the area of the blocking anticyclone and increased in the areas southwest to southeast of it and in some cases also north of it. Often areas with increased odds of heavy precipitation coincide with the location of the storm track.

Keywords Atmospheric blocking · Heavy precipitation · Europe · Odds ratio

1 Introduction

Atmospheric blocks with a lifetime of several days to weeks, a large spatial extent, and a stationary character strongly influence regional weather (e.g., Rex 1950a, b). This includes a modulation of the frequency of a variety of extreme weather events (see Woollings et al. 2018 for a short review). Close links have been established between blocks and high and low temperature extremes (e.g., Trigo et al. 2004; Sillmann and Croci-Maspoli 2009; Pfahl and Wernli 2012; Schneidereit et al. 2012; Brunner et al. 2017; Schaller et al. 2018), as well as dry spells (Buehler et al. 2011).

The connection between blocks and mean precipitation is well established. A composite study of six blocking events by Rex (1950a, b) documents a decrease of both summer and winter mean precipitation during Euro-Atlantic blocking periods over most of the European continent. Only the northwestern Scandinavian coast, parts of the Iberian Peninsula, and parts of the Balkan regions received above average precipitation during these blocking episodes. Rex attributed the spatial changes in the precipitation to a meridional shift of the storm track caused by the block. Hence the link between blocking and precipitation is indirect. Blocks are often associated with highly amplified upper level troughs (Altenhoff et al. 2008) that are conducive to heavy precipitation (e.g., Grazzini 2007; Martius et al. 2008; Nuissier et al. 2011) they modulate the pathways, the propagation speed, and the stationarity of cyclones in their surroundings (e.g., Rex 1950a; Swanson 2002; Nakamura and Huang 2018) and thereby modulate the location of the precipitation associated with the warm conveyor belts and fronts of these cyclones (e.g., Catto and Pfahl 2013; Pfahl et al. 2014). In addition fronts are linked to areas of high atmospheric moisture transport (e.g., Ralph et al. 2004) that can be relevant for heavy precipitation (e.g., Neiman et al. 2008; Sousa et al. 2016). A potential link between atmospheric blocks and heavy precipitation in Europe emerging through these links is the topic of our paper.

An important modulation of the mean precipitation in Europe by blocking has been described in several studies. Trigo et al. (2004) analysed 63 winter blocking episodes over central Europe and their effect on mean precipitation using the NCEP/NCAR reanalysis data set. They observed

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three latitudinal bands with distinct precipitation anomalies. Precipitation was above average during Euro-Atlantic blocking episodes over northern Scandinavia, the Iberian Peninsula, the western Mediterranean, and northern Africa. Precipitation was below average in eastern Europe. An increase in mean precipitation over southern Europe during Euro-Atlantic winter blocking episodes was confirmed using high resolution precipitation data (E-OBS) (Yao and Luo 2014; Sousa et al. 2017). The longitudinal position of blocking influences the European precipitation distribution. Winter blocking at the longitude of Greenland is associated with the strongest increase of mean precipitation in southern Europe (Yao and Luo 2014). An increase of precipitation along the Norwegian Atlantic coast is observed during eastern Atlantic and European winter blocking episodes (Yao and Luo 2014).

There are seasonal differences in the mean precipitation anomaly patterns during blocking episodes. The increase in precipitation along the Norwegian Atlantic coast associated with eastern Atlantic blocking, for example, is not observed during the summer months (Sousa et al. 2017) and the entire precipitation anomaly pattern is generally shifted poleward in summer compared to winter.

So far, the link between blocks and multiday heavy precipitation has received little scientific attention. Evidence on the influence of blocks on the formation heavy precipitation events in their surroundings mainly comes from case-studies (e.g., Samel and Liang 2003; Grams et al. 2014; Piaget et al. 2015). Using a high-resolution European precipitation climatology, Sousa et al. (2017) evaluated changes in the mean daily precipitation distribution for six grid boxes over central and southern Europe in the presence of a block between 1950 and 2012. For the northern grid boxes, they observe a shift towards more frequent low intensity precipitation days during Atlantic blocking and for the southern grid boxes an increase in the frequency of high intensity precipitation.

In addition to the heavy precipitation events, also several cases of floods have been related to the occurrence of blocks. A prominent example is the Pakistan flood in August 2010 that was related to a very strong and persistent block over Russia (e.g., Hong et al. 2011; Lau and Kim 2012; Schneidereit et al. 2012; Martius et al. 2013). A 50-year climatological analysis of heavy precipitation events in Pakistan revealed, that two out of the five predominant atmospheric circulation types during these heavy precipitation events were associated with persistent blocking over Russia and a neighbouring trough west of Pakistan (Yamada et al. 2016). Similar upper-level flow configurations with up- or downstream blocks and troughs in the region of the heavy precipitation were also observed in October 2000 for the floods in Great Britain (Krishnamurti et al. 2003), Spain (Homar et al. 2002), Italy (Gabella and Mantonvani 2001; Xoplaki et al. 2012) and Switzerland (Barton et al. 2016; Lenggenhager et al. 2018) and for many historical flood events in Switzerland (Stucki et al. 2012).

Multi-day heavy precipitation events are important drivers of major flood events (e.g., Stucki et al. 2012; Froidevaux et al. 2015). Blocks, through their persistence and longevity, might particularly affect the occurrence frequency of such multi-day heavy precipitation events as the blocks can slow down the propagation speed of individual cyclonic systems (e.g., van Oldenborgh et al. 2017; Lenggenhager et al. 2018).

However, a climatological analysis of the co-occurrence of blocks and regional-scale multi-day heavy precipitation events in Europe is to the best of our knowledge still incomplete. In this study, we fill this gap by addressing the modulation of the odds of heavy precipitation during blocking events, and we investigate if the same seasonal and regional patterns hold for mean precipitation as well as for extreme precipitation. Specifically, we aim at providing a comprehensive overview of the change in the odds of flood-relevant regional-scale, multi-day heavy precipitation events in Europe during blocking episodes. Changes in the odds of 1-day, 3-day and 5-day heavy precipitation events (above the 95th and the 98th percentile) will be evaluated for all seasons separately and for blocking events in five different longitudinal bands in the Euro-Atlantic sector. Additionally, an analysis of the variation of the respective heavy precipitation events in the winter and summer seasons is conducted.

The paper is organised as follows in Sect. 2 the data sets and the statistical model are introduced, in Sect. 3 first the seasonal variation of the multi-day heavy precipitation events is discussed and then the changes in the odds of these events in the presence of blocking. The paper closes with discussion in Sect. 4 and conclusions in Sect. 5.

2 Data and methods

Precipitation and potential vorticity (PV) on different pressure levels were calculated from the ERA-Interim reanalysis dataset (Dee et al. 2011) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). We used data interpolated to a regular horizontal grid (1° longitude by 1° latitude) at six-hourly resolution and included all the data from January 1979 to December 2015.

2.1 Precipitation: data, spatial and temporal aggregation and temporal de-clustering

While the absolute values of precipitation from gridded reanalysis data are known to be of limited accuracy (Sun et al. 2018), the ERA-interim precipitation data is fairly well suited for studying the spatial distribution of precipitation (Donat et al. 2014). The advantage of using the ERA-Interim over a higher-resolution observation-based gridded precipitation data product is that precipitation is fully consistent with the large-scale flow. Here we are interested in large-scale, 1- to multi-day heavy precipitation events and we use several measures for this. The total precipitation (including snow, stratiform and convective precipitation) is first aggregated to daily precipitation accumulations (from 09 to 09 UTC) and then further into 3-day and 5-day running accumulations. Then three spatial aggregations are applied (accumulations at one grid point, mean over 3×3 grid points and mean over 5×5 grid points). From these daily values, including the non-precipitation days, high percentiles (95th, 98th and 99th) are calculated for each grid-point for the whole year as well as for each season separately.

For the statistical analysis, we performed a de-clustering of the heavy precipitation time series because the 3-day and 5-day time series contain non-independent events from the running accumulation calculations. Consecutive heavy precipitation days are regarded as belonging to the same event and only the day with highest precipitation accumulation is considered for the statistical analysis. For 3-day accumulation events to be regarded as independent, we ask for at least 1 day with precipitation accumulations below the respective percentile threshold. Five-day accumulation events, however, need to have at least 2 days below the threshold to be regarded as independent. This declustering results in a substantial reduction in the number of events, for example in the winter season the 1-day accumulation 95th percentile mean sample contains 167 days, the 3-day accumulation 95th percentile sample contains 78 days and the 5-day accumulation sample contains 53 days.

To account for the spatial dependence of the precipitation fields the false discovery rate procedure after Benjamini and Hochberg (1995) is applied. The test corrects *p* value thresholds that indicate statistical significance by considering the number of falsely rejected null hypotheses by multiple testing. Details on the methodology and its importance for spatial data can be found in Wilks (2016).

2.2 Blocks: objective identification and blocking region definition

The definition of blocks in literature is very diverse (e.g., Barriopedro et al. 2006; Woollings et al. 2018). Here, blocks are identified following the methodology of Schwierz et al. (2004). This identification algorithm defines blocks as quasi-stationary upper tropospheric features with strong negative PV anomalies. Following their approach, we use vertically averaged PV anomalies between 500 and 150 hPa. The anomalies are calculated with respect to the climatological 30-day running mean at the same date of the years 1979–2015. The anomaly fields are then smoothed with a 2-day running mean filter and anomalies below -1.3 pvu are tracked over time. Features with an anomaly of more than -1.3 pvu that persist for a minimum of 5 days with a spatial overlap of at least 70% between two 6-h time steps are identified as blocks.

For the statistical analysis of the co-occurrence of blocks and precipitation, we define five different blocking locations in the Euro-Atlantic sector each covering 30° in longitude and the latitudes between 45°N and 75°N from 60°W to 90°E (see Sects. 3.3.1 to 3.3.4). Every day when a blocking centre (location of the maximum intensity) lies within one of the grid boxes, that day is considered as blocked in this region.

The composite cyclone density during the blocking days is shown as proxy for the location of the storm tracks. The density composites are derived from a cyclone climatology (Wernli et al. 2006; Sprenger et al. 2017). The outline of a cyclone is defined to be the outermost closed line of constant sea level pressure surrounding at least one local minimum sea level pressure.

2.3 Odds-ratio

To quantify the statistical link between blocks and the occurrence of heavy precipitation events in Europe we conducted a logistic regression (Eq. 1) at every grid point over Europe:

$$\mathrm{logit}(\mathrm{p(t)}) = \ln \frac{\mathrm{p(t)}}{1 - \mathrm{p(t)}} \beta_0 + \beta_1 x(t) \tag{1}$$

where x(t) is a binary time series indicating the presence (x = 1) or absence (x = 0) of a block at time t in one of the six regions (the model is applied six times, once for each blocking region) and p: = P(y(t) = 1|x(t)) is the probability of observing a heavy precipitation event at the grid point given the presence or absence of a block at one of the 6 locations (see Mahlstein et al. 2012 for further details). This method was chosen, because of the binary character of the data (event, no event/block, no block).

The method assumes the predictand (in our case the heavy precipitation events) to be binomially distributed. This implies that (1) the probability of the events does not change over time (stationarity) and (2) the events are independent (Wilks 2006). Given the seasonality in the precipitation events and the temporal dependence of our time series by multi-day running means, these requirements are not met, initially. To come as close as possible to these assumptions, two simple measures were taken. First, we applied the logistic regression to each season separately, because we have a strong seasonal cycle in the occurrence of extremes at a certain grid point. For reasons of brevity, the analysis is limited to the summer (JJA) and winter (DJF) seasons. Second, we de-clustered the heavy precipitation events (see Sect. 2.1).

The odds ratio, i.e., the ratio of the odds of a heavy precipitation event during block periods to the odds of a heavy precipitation event during no-block periods is obtained by exponentiating the regression coefficient β_1 (Eq. 1). The odds ratio was calculated for every grid point in central Europe and is shown and discussed subsequently. An odds ratio smaller than one indicates a decrease in the odds of observing a heavy precipitation event while an odds ratio bigger than one indicates an increase of the odds of observing a heavy precipitation event.

3 Results

The results are organised in the following way. First, the spatial and temporal variability of heavy precipitation in Europe is presented (Sect. 3.1), then the climatological mean and the seasonal variability of the blocking frequencies are shown (Sect. 3.2) and last, the statistical relation between blocks and heavy precipitation is examined (Sect. 3.3).

3.1 Spatial and temporal variability of 1-day, 3-day and 5-day heavy precipitation

Absolute values of heavy precipitation in Europe are spatially highly variable. While in some regions (e.g., eastern Spain) the 95th all-year percentile of daily ERA-Interim precipitation accumulation (3×3 grid points averaged) amounts to 4–8 mm, in south-western Norway the values are three to four times larger amounting to approximately 20 mm (Fig. 1a). This spatial relation remains constant for longer accumulation periods (3 days and 5 days, Fig. 1a–c) and with increasing percentile thresholds (Fig. 1d–i). The spatial relation also remains when comparing a different precipitation data set (not shown), the absolute values, however, depend on the spatial resolution of the precipitation data set (e.g., Thackeray et al. 2018; Sun et al. 2018).

Generally, the largest precipitation values are found in mountainous areas in the exit regions of the storm tracks in western Europe (e.g., western Norway, Scotland and the north-western part of the Iberian Peninsula) and in the Alps. The lowest values are found in north-eastern Europe, the western UK and western Spain. While an increase in the accumulation time leads to an increase in the precipitation amounts, the spatial pattern of the precipitation percentile values remains quite similar. The spatial distribution of the precipitation percentile values remains very similar with increasing precipitation severity (Fig. 1). We therefore mainly focus on results for the 95th and the 99th percentile threshold (moderate extremes and extremes).

Heavy precipitation varies strongly with season over Europe (Fig. 3). Considering only spring (MAM) months, the 95th percentile of the 3×3 grid-point smoothed 3-day precipitation accumulation is highest (up to 42 mm) over south-western Norway (Fig. 3a). The maximum values in summer (JJA) are located over the eastern Alps (40 mm), over continental eastern Europe and over eastern Norway (up to 35 mm). The minimum values are located over the Mediterranean (Fig. 3b). In autumn (SON) and winter (DJF), three areas with high precipitation values emerge: western Norway (up to 65 mm), the Alps (up to 42 mm) and the north-western part of the Iberian Peninsula (up to 42 mm).

The seasonal cycle can also be illustrated by the fraction of days in which the 95th all-year percentile (3-day accumulation, 3×3 grid-points smoothing, before de-clustering) is exceeded in each season (Fig. 4). In the Mediterranean heavy precipitation is most frequent in autumn (western Mediterranean) and winter (eastern Mediterranean). Over eastern Fenno-Scandinavia and eastern Europe heavy precipitation is also frequent in summer. Along the Atlantic coast heavy precipitation is most frequent in autumn and winter. A similar seasonal cycle is also found for 1-day and 5-day precipitation accumulations and for the 98th and 99th percentile (not shown).

The previous results are based on data that was smoothed by taking a 3×3 grid-points average. The results are similar for the non-smoothed and the 5×5 grid-points smoothed data (not shown). With an increasing size of the filter the spatial differences become smaller. The high values become lower, the low values become higher and the spatial structure is more homogeneous (Fig. 2). The seasonal cycle of the extremes does not change much with increasing smoothing filters sizes (not shown).

In summary a strong seasonal cycle of heavy precipitation is observed that varies geographically within Europe. Therefore, it is important to consider each season separately for the subsequent analyses of this study.

3.2 Euro-Atlantic blocking climatology

The highest all-year blocking frequency over the Atlantic basin and Europe and is located at ~ 30°W/60°N (Fig. 5). In 9–10% of all 6-h time steps between 1979 and 2015 blocking occurred in this region. There is a strong seasonal cycle in the blocking frequency (Fig. 6). In spring (MAM), the main blocked region over the North-Atlantic is shifted further west compared to winter with two maxima at 40°W/55°N and 55°W/65°N with frequencies of 10–11%. In addition, there is a weak frequency maximum in the eastern Russian region with 6–7% blocks.

In summer (JJA), the blocking frequency is generally lowest. The blocks over the North-Atlantic occur further east compared to spring in an area around ~ 20°W/55°N. Additionally a third high-latitude maximum is found at ~ 180°E/85°N. Over the North-Atlantic, a block is detected only 8–9% of the time. The summer blocking frequency minimum is partly due to the

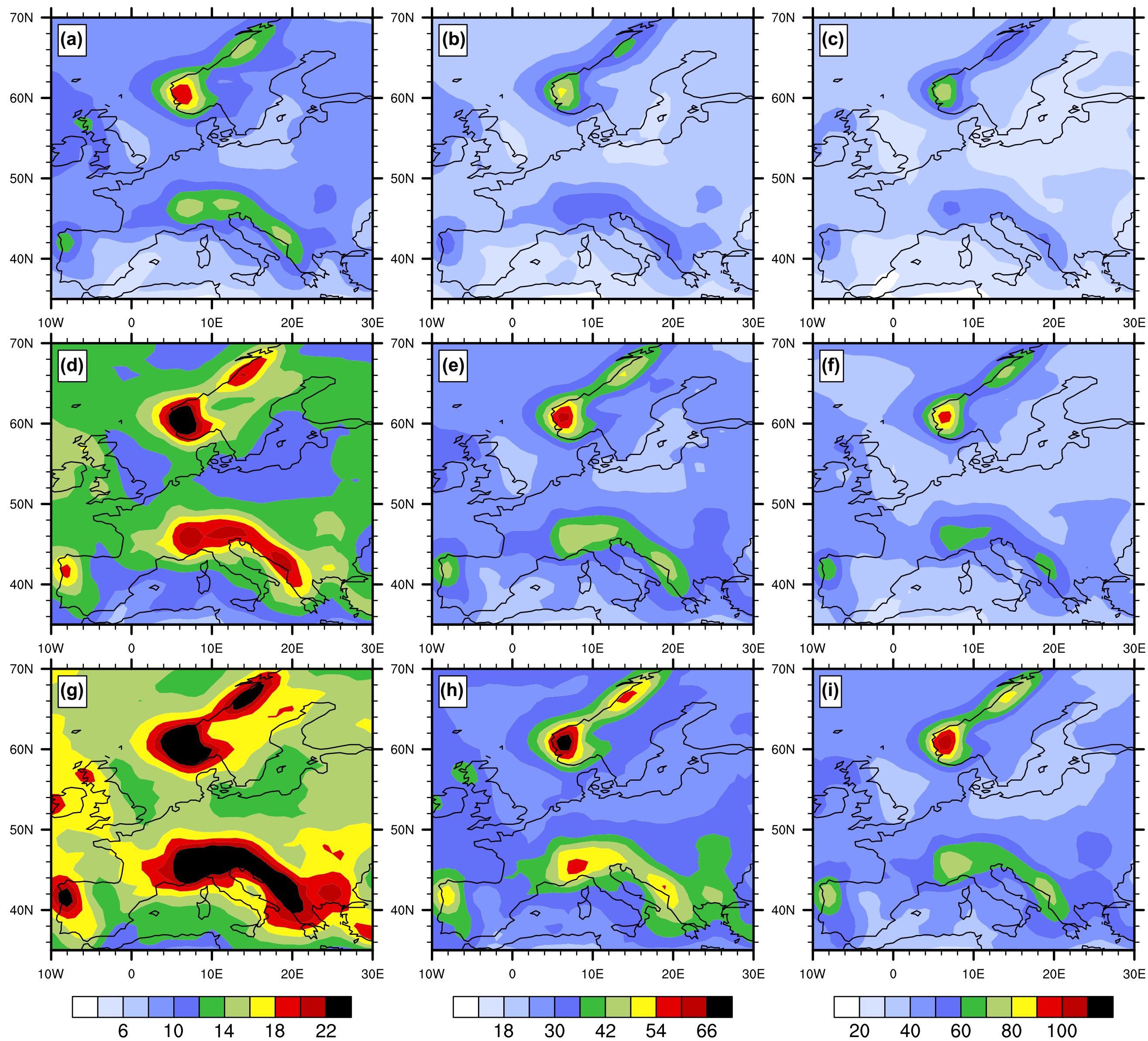


Fig. 1 95th (**a–c**), 98th (**d–f**) and 99th (**g–i**) all-year percentile of 1-day (**a**, **d**, **g**), 3-day (**b**, **e**, **h**) and 5-day (**c**, **f**, **i**) precipitation accumulations (mm) smoothed with a 3 × 3 grid points moving window in the ERA-Interim period from 1979 to 2015

constant PV anomaly threshold that we use in the blocking detection algorithm (Villiger 2017).

The highest frequency of blocks is found in autumn (SON). Over the North-Atlantic (~30°W/60°N) they are detected on more than 12% of the time steps. During winter (DJF), the frequencies are in the same range (11–12%) and the blocking frequency maximum over the North-Atlantic is located slightly further west (~35°W/60°N) than in autumn.

3.3 Statistical relation between blocking and heavy precipitation

Next, we investigate the statistical link between blocks in different regions of the Euro-Atlantic sector and the occurrence of moderately extreme (> 95th seasonal percentile) and extreme (> 99th seasonal percentile) precipitation events in Europe. To that end, we calculate odds-ratios, that indicate

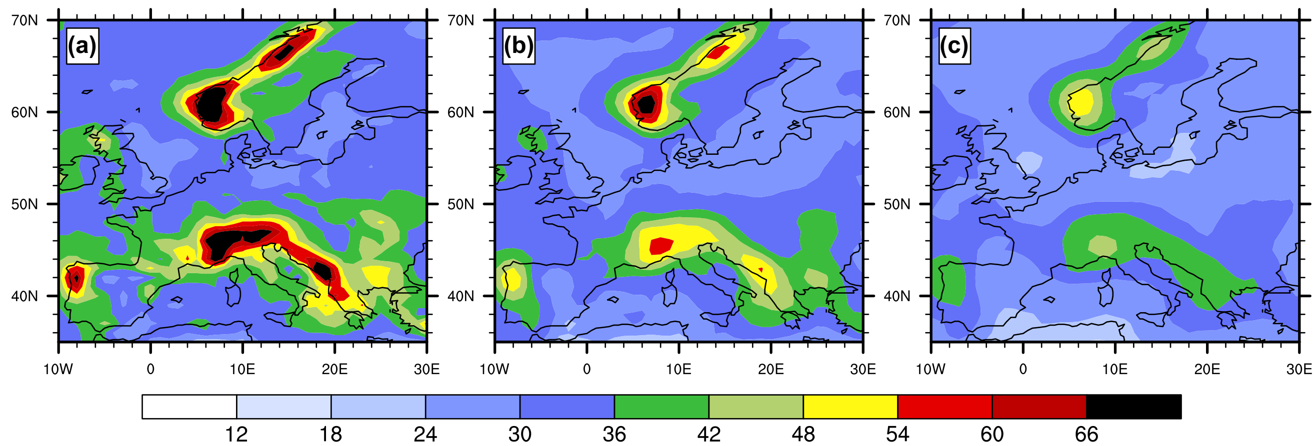


Fig. 2 99th all-year percentile of the 3-day precipitation accumulation (mm) in the ERA-Interim period from 1979 to 2015 **a** without spatial smoothing, **b** 3 × 3 grid points smoothed and **c** 5 × 5 grid points smoothed

changes in the odds of an extreme precipitation event at every grid-point, given a block in a specific region during summer and winter, respectively. In the following sections, we only present results of the 3 × 3 grid points smoothed precipitation. Generally, the results are qualitatively similar for all spatial smoothing windows, but the statistically significant areas increase with a larger smoothing window, i.e., for larger spatial aggregations.

3.3.1 Blocking in the western North-Atlantic sector

The upper-level flow in boreal summer (JJA) during days with blocks in the western North-Atlantic (ATLW) sector (60°W–30°W) is characterized by a ridge over the central North-Atlantic at 40°W and a weak broad trough centred at 10°W (Fig. 7a). A weak storm track is located south of the blocked areas and extends from the central Atlantic across the northern British Isles and across Scandinavia (Fig. 7a). Blocking in the ATLW sector is associated with an elongated band of increased odds of moderate 1-day precipitation extremes (1.5–2.5 times higher than without blocking) between 10°W/45°N and 10°E/55°N along the European Atlantic coast and along the southwest coast of England along the eastern edge of the upper-level trough, while over large parts of central Europe, the odds for 95th percentile 1-day precipitation extremes are reduced (Fig. 8a). A similar pattern is visible in the moderate 3-day precipitation extremes, but no statistical significance was found (Fig. 8b). An even stronger increase in the odds of these moderate extremes is observed for the moderate 5-day events over central Europe (Fig. 8c). The maximum increase of the odds is shifted eastward compared to the 1-day accumulations and is located over the European continent (Fig. 8c). The highest values of the odds ratios and statistical significance is located over France with odds ratios of up to 3.5. The south-eastern European area with decreased odds is also shifted east for the 5-day accumulation compared to the 1-day accumulation.

The spatial distribution of the odds of extreme precipitation exceeding the 99th percentile is comparable for all accumulation periods to those of the moderate 95th percentile, but the absolute odds ratio values are higher compared to the moderate extremes (up to 3 for the 1-day events, 4 for the 3-day events and > 5 for the 5-day events). However, none of the regions shows a significant change of the odds (not shown).

In winter the composite blocking frequency reaches maximum values of 40–50% south of Greenland at 40°W (Fig. 7b). The low values show that there is a strong variability in the exact location and/or spatial extent of the blocks. The upper-level flow during days with blocks in the ALTW is characterized by a ridge over the central Atlantic at 40°W and a zonal flow over Europe. The storm track is strongest over Scandinavia with a secondary maximum over the Mediterranean (Fig. 7b). This flow is associated with increased odds of 1-day, 3-day and 5-day moderate precipitation extremes over central and eastern Europe and the Iberian Peninsula (Fig. 8d-f). The moderate 1-day extremes are 1.5–2.5 times more likely over southern Portugal, northern-eastern Spain, and central Europe (5–30°E/40–62°N). This pattern is even stronger for longer-lasting events, with an increase of the odds of up to 3.5. A similar pattern is observed for the more extreme precipitation events (> 99th percentile) of all durations with higher odds ratio values (2–5) than the moderate extremes but only very localised regions of statistical significance (not shown).

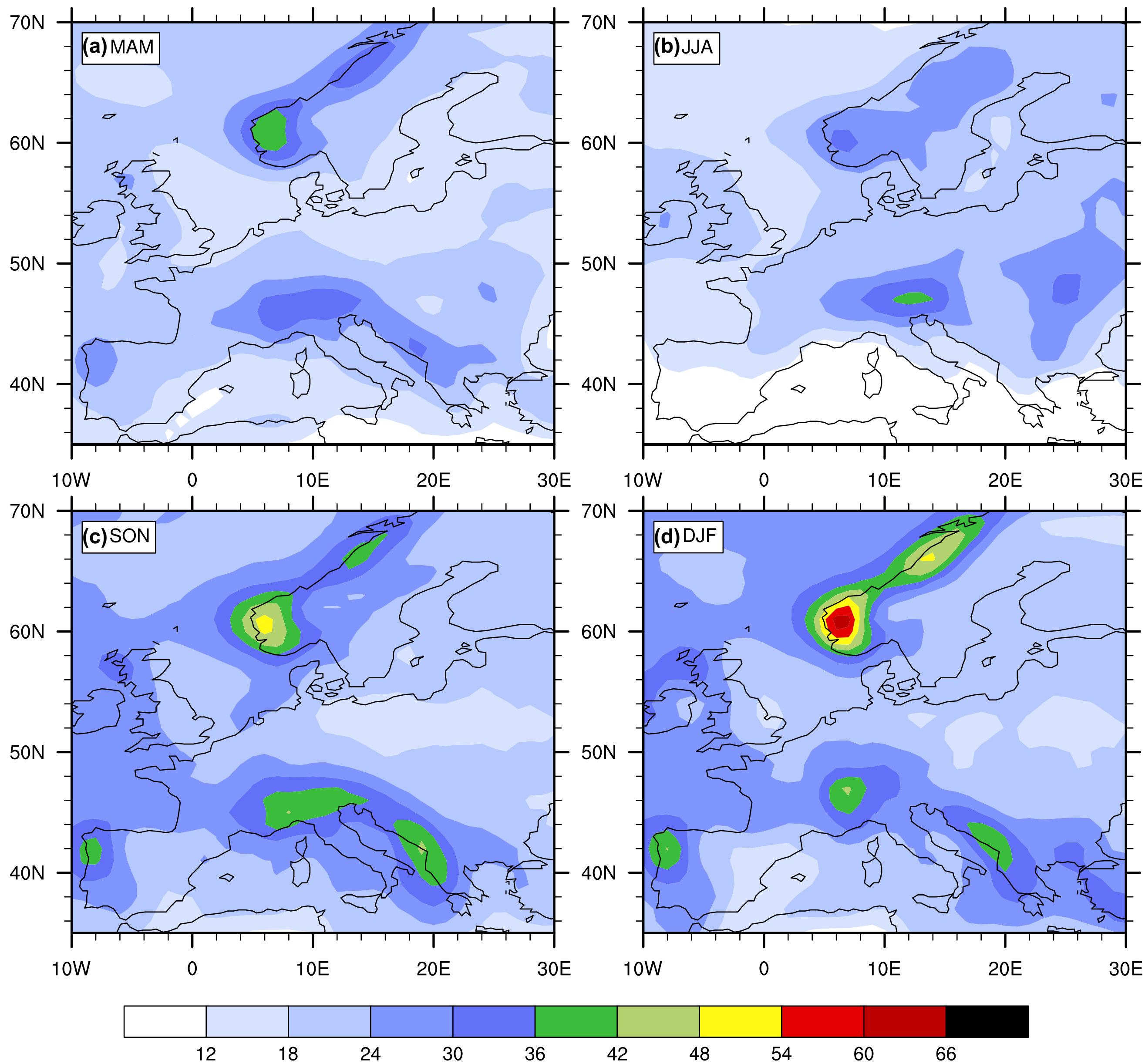


Fig. 3 95th seasonal percentile of the 3 × 3 grid points smoothed 3-day precipitation accumulation (mm) for **a** spring, **b** summer, **c** autumn and **d** winter in the ERA-Interim period from 1979 to 2015

3.3.2 Blocking in the eastern North-Atlantic sector

The upper-level flow during summer days with blocks in the eastern North-Atlantic (ATLE) sector (30°W–0°W) is characterized by a ridge over the eastern Atlantic at 15°W and a downstream broad trough centred at 10°E (Fig. 9a). The weak storm tracks are interrupted and displace northward in the blocked area and extend downstream of the blocked area across Scandinavia. This flow configuration is associated with a dipole pattern in the odds ratios of all the analysed moderate extreme precipitation events (Fig. 10a–c). While the odds are smaller in the region of the block, i.e., over the UK, southern Scandinavia and Denmark, the odds for moderate extreme events are higher in southern and eastern Europe. The odds ratios are highest for 5-day events (up to 3.5 for moderate extreme events). The odds ratios are smallest for the moderate extreme 1-day events but are statistically significant over most of Europe (Fig. 10a).

In winter the composite blocking frequency reaches maximum values of 50–60% at 15°W (Fig. 9b). The upper-level flow during days with blocks in the ATLE sector is characterized by a ridge over the eastern North-Atlantic at 15°W and a downstream cyclonically overturning trough over Europe (Fig. 9b). The storm tracks are weakened in

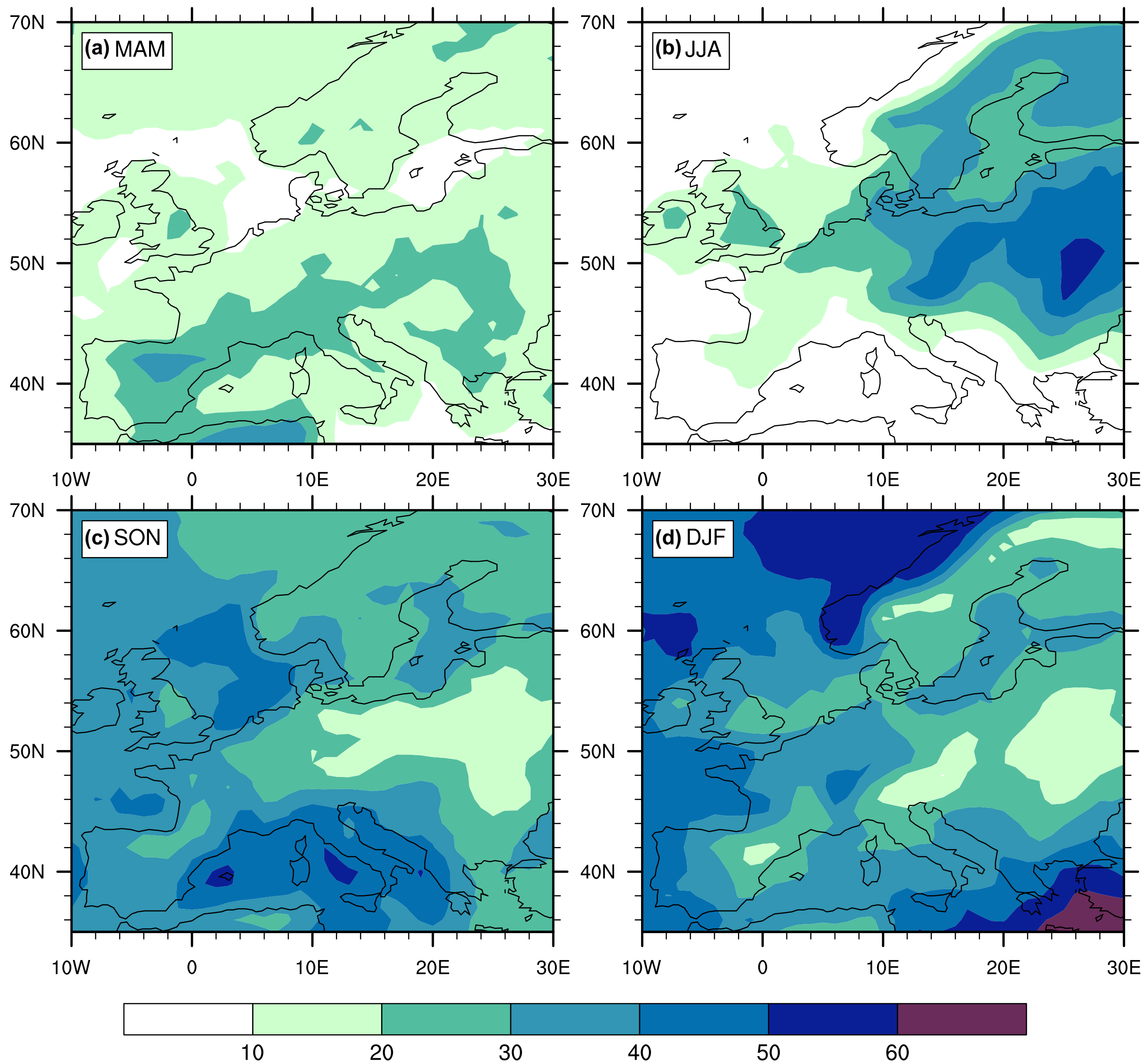


Fig. 4 Fraction (%) of events occurring during each season (**a** spring, **b** summer, **c** autumn and **d** winter) with precipitation above the 95th all-year percentile of the 3 × 3 grid point smoothed 3-day precipitation accumulation in the ERA-Interim period from 1979 to 2015

the blocked area and shifted northward. A weak storm track extends downstream of the blocked area north of Scandinavia and a weak storm frequency maximum is situated over the central and eastern Mediterranean. This flow configuration is associated with a tripole pattern in the odds ratios of moderate precipitation extremes (Fig. 10d–f). A strong increase in the odds of moderate precipitation extremes of all analysed durations is found over the Norwegian Atlantic coast. This area is exposed to many storms, because of a northward shift of the storm track around the blocking high (Fig. 9b). A decrease in the odds is found over the north-western part of Europe (10°W/40°N–20°E/65°N). Over the eastern Mediterranean along the downstream flank of the upper-level trough the odds for precipitation extremes are also increased (Fig. 10d–f).

3.3.3 Blocking in the European sector

The upper-level flow during summer days with blocks in the European (EURO) sector (0°W–30°W) is characterized by an anticyclonically overturning ridge-trough couplet centred at 15°E–20°E (Fig. 11a). The storm tracks are located north of blocked area and extend downstream of the blocked area over northern tip of Scandinavia. This flow is associated

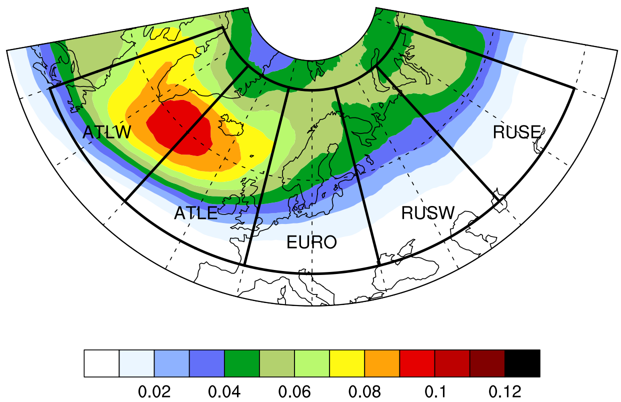


Fig. 5 All-year blocking frequency (after Schwierz et al. 2004) in the Euro-Atlantic region during the ERA-Interim period from 1979 to 2015. The boxes indicate the location of the five blocking regions used for Sect. 3.3

with a statistically significant decrease in the odds of moderate 1-day precipitation extremes over northern Europe and a significant increase over central and southern Europe (odds ratio 1.5–3) (Fig. 12a). Also, between 5°W and 5°E and 60°N to 70°N a region with odds ratios of more than 1.5 is detected (Fig. 12a). This region is even more pronounced in the extreme (> 99th percentile) 1-day events with odds ratio values of 2–5 and the region extends south to 50°N (not statistically significant, not shown). This area with increased odds of precipitation extremes is likely affected by the cyclones passing north of the blocks (Fig. 11a).

In winter the composite blocking frequency reaches maximum values of 30–40% at 10°E (Fig. 11b). The upper-level flow on days with blocks in the EURO sector is characterized by a ridge over the Europe at 10°E and an upstream cyclonically overturning trough at 10°W and a downstream anticyclonically overturning trough over eastern Europe (Fig. 11b). This flow is associated with low odds of moderate precipitation extremes over most of Europe (Fig. 12d–f). The odds of moderate precipitation extremes are increased only over the central and eastern Mediterranean and along the northern Norwegian coast. Along the Norwegian coast the odds are very high, with values of 4–5 for the moderate 1-day extremes (Fig. 12d). Interestingly and similarly to the summer composites, the odds ratios over Norway decrease from 1-day to 3-day and 5-day accumulation events.

3.3.4 Blocking in the western Russian sector

The upper-level flow during days with blocks in the western Russian (RUSW) sector (30°W–60°W) is characterized by a ridge over the eastern Europe and Russia at 45°E and an upstream cyclonically tilted trough over Europe (Fig. 13). A local cyclone frequency maximum is present over Scandinavia. This flow is associated with a strong west–east gradient in the odds ratios of moderate

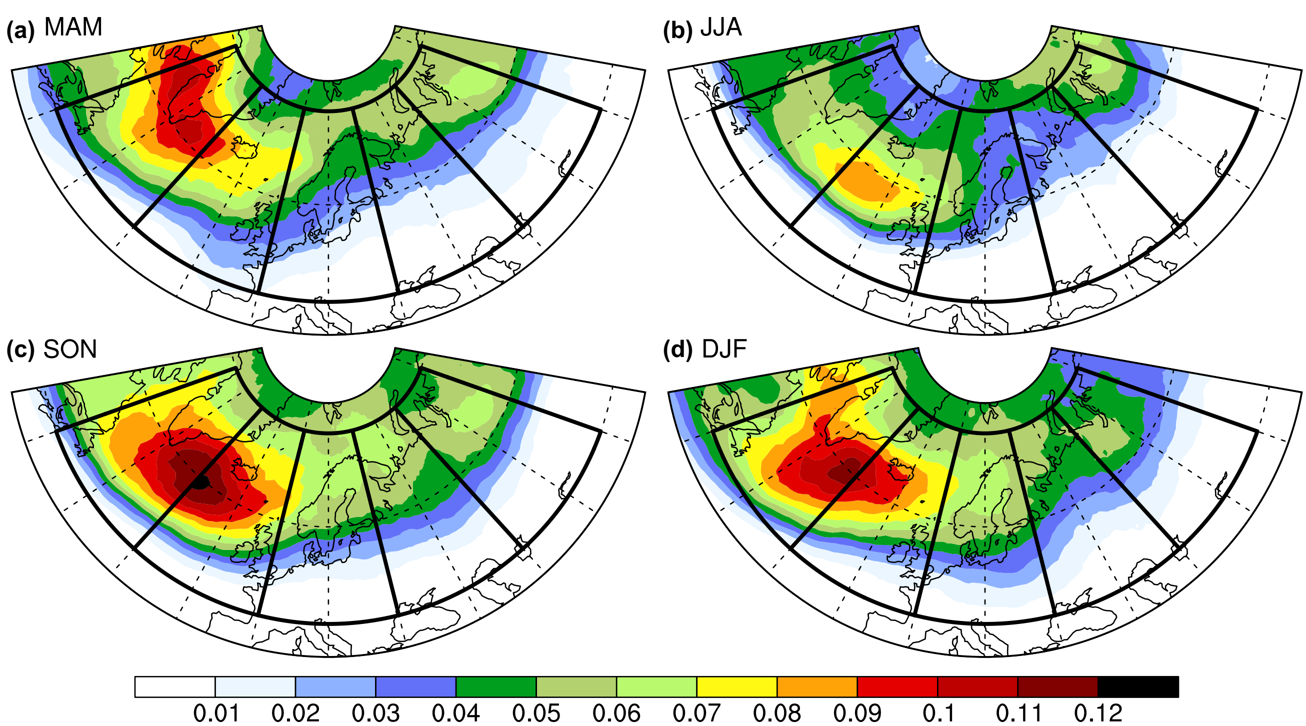


Fig. 6 Seasonal blocking frequency (after Schwierz et al. 2004) in the North-Atlantic region during the ERA-Interim period from 1979 to 2015. The boxes indicate the location of the five blocking regions used for Sect. 3.3

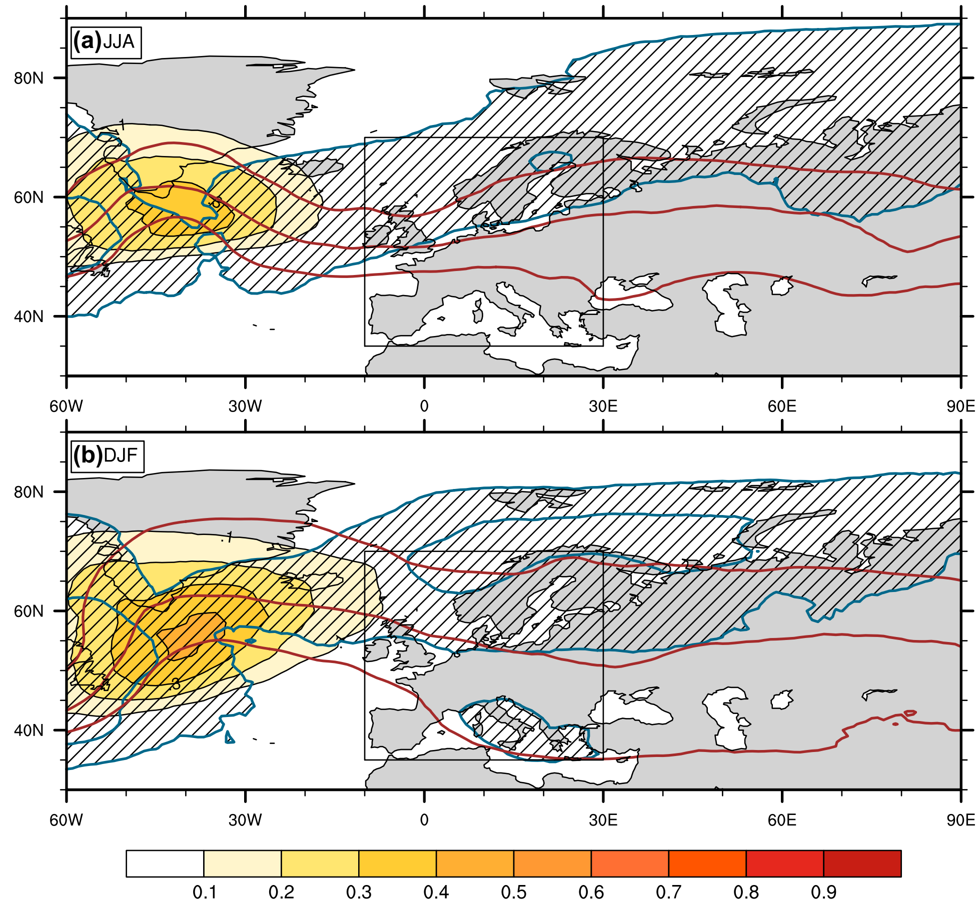


Fig. 7 Composite blocking frequency (colour shading), vertically averaged PV (brown contours, 2, 2.5 and 3 pvu) and cyclone frequency (blue hatching and contours, in steps of 10%) during **a** summer (JJA) and **b** winter (DJF) blocking in the western North-Atlantic sector (60°W–30°W)

precipitation extremes (Fig. 14). While the odds of moderate precipitation extremes are lower in western Europe, the odds are higher over Scandinavia just upstream of the blocked area. This signal is, however, only statistically significant for the 1-day precipitation extremes (Fig. 14a). Moderate 1-day extremes are 2–4 times more probable over large areas between 10°E–30°E and 50°N–70°N, with higher odds ratio values in the north of the area. In contrast to blocks in the regions further west, western Russian blocks have a statistically significant influence both on the odds of moderate extreme (> 95th percentile) and extreme (> 99th percentile) 1-day events (not shown). Extreme 1-day events are 3–5 times more likely during RUSW blocks over large parts of eastern European (east of 10°E). In contrast to the summer blocks, during winter blocks no significant influence on the odds of extreme precipitation over Europe is found (not shown).

We have also investigated the effect of blocking located further east over Russia. There are no significant changes in the odds of heavy precipitation over Europe associated with blocks over the eastern Russian sector (60°W–90°W) (not shown).

4 Discussion

A statistically significant link between the odds of heavy precipitation and the longitudinal location of blocks in Euro-Atlantic sector is found. A western Atlantic block significantly influences the odds of heavy precipitation events of 1- to 5-day duration, by modulating the general flow. While in summer the presence of a block increases the odds of heavy precipitation mainly along the European Atlantic coast, in winter the odds increase over most of central Europe. The odds ratio for both seasons lies between 1.5 and 2.5. A shift towards the continent is found in the location of increased odds between the 1-day and the 5-day accumulation events in summer. We can only speculate about possible explanations for this difference in location. The 1-day precipitation odds ratio maxima are located along the southern edge of the storm track and along the eastern flank of a very weak upper-level trough and might be related to the passage of mobile fronts. Indeed, Schemm et al. (2017) find a strong link between fronts over Europe and precipitation extremes and Catto and Pfahl (2013) find

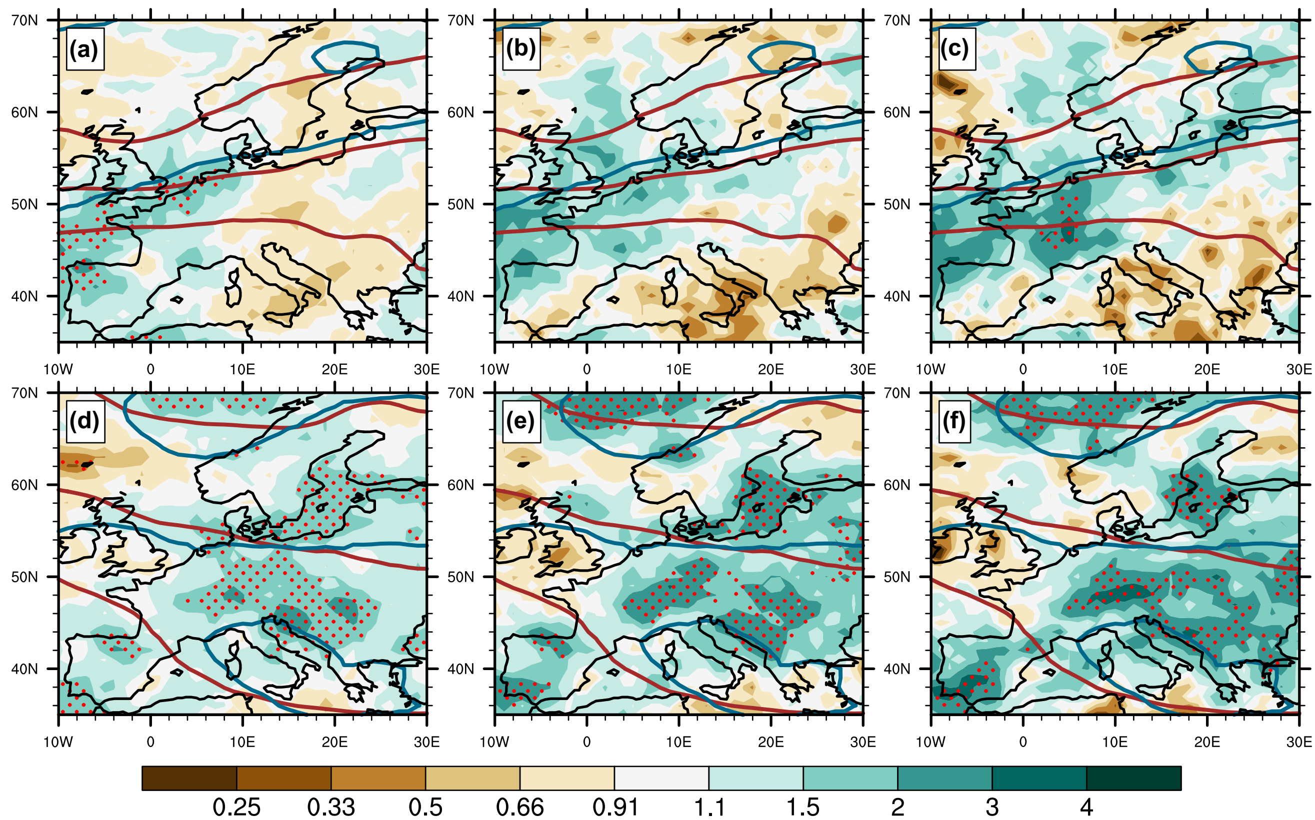


Fig. 8 Odds ratio of moderately extreme 1-day (**a**, **d**), 3-day (**b**, **e**) and 5-day (**c**, **f**) precipitation events between days with blocks in the western North-Atlantic sector (60°W–30°W) and days without blocks in this region for JJA (**a**–**c**) and DJF (**d**–**f**). The lines indicate the composite vertically averaged PV (brown, 2, 2.5, 3 pvu) and cyclone frequency (blue, 10%, 20%). The red dots indicate statistically significant areas on a 95th percentile level

that between 60 and 70% of 6-h ERA-interim precipitation extremes over central Europe are linked to fronts. The 5-day precipitation odds ratio maximum is located further east over France, Germany and Switzerland. This signal might be related to consecutive days with intense prefrontal thunderstorms potentially associated with more stationary fronts. An analysis combining objectively identified fronts (e.g., Schemm et al. 2018) with extreme 5-day summer precipitation over central Europe would be needed to substantiate this hypothesis.

An eastern Atlantic block is associated with decreased odds of heavy precipitation for all accumulations in the region of the block and increased odds south-west and north of it. In summer, the block is located further north than in winter, which means that the increased odds north of the block are not in the study region, while in winter the Norwegian east-coast is strongly affected. The influence of the eastern North-Atlantic block on central European heavy precipitation is generally stronger compared to the western North-Atlantic block, the largest statistically significant odds ratios are detected for moderate 5-day summer precipitation extremes (up to 3.5). In summer, all heavy precipitation events show a significant change in the odds, while in winter the signal is significant only for the 1-day events.

It is interesting to compare our results to the findings of Yao and Luo (2014), even though the regions and the definition of blocks are slightly different. Most of the western North-Atlantic blocks and probably also some of the eastern Atlantic blocks are referred to as "Greenland blocks" by Yao and Luo (2014). Comparing their results of mean precipitation to our results of the heavy precipitation, we see that the locations that show positive winter precipitation anomalies during Greenland blocks corresponds quite well to the regions with increased odds for heavy precipitation during eastern Atlantic blocks in this study, suggesting that part of the increase in mean precipitation is due to an increase in the extremes.

European blocks are associated with a decreased chance of heavy precipitation in the region of the block and south of it. Increased odds are located west of the blocks. Southern Europe faces increased odds of heavy precipitation. Significant results west of the block are, however, only found for 1-day heavy precipitation events for both seasons with odds ratio values of up to 3 in summer and up to 5 in winter. In

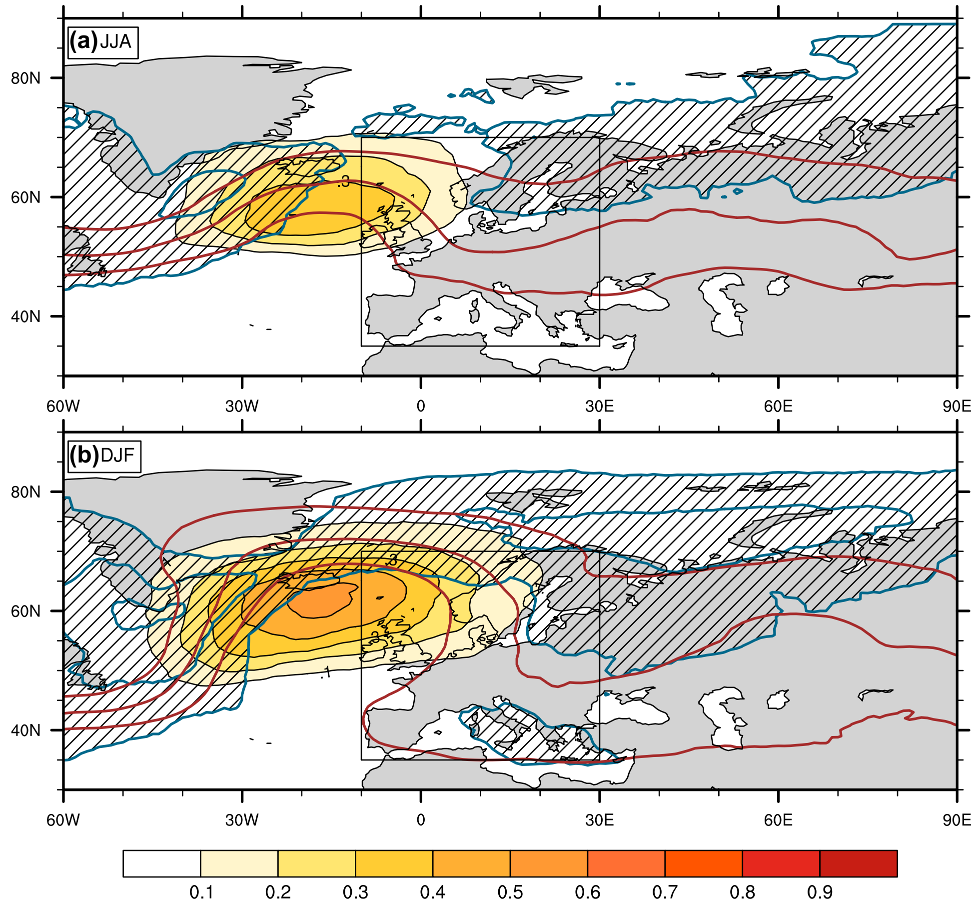


Fig. 9 The same as Fig. 7 but for the eastern North-Atlantic sector (30°W–0°E)

winter the largest influence is seen north of the block along the Norwegian west-coast. The odds ratios over Norway decrease with increasing accumulation periods. A possible interpretation is the frequent passage of low-pressure systems in this area that can foster 1-day precipitation extremes but that the systems are too mobile to significantly contribute to 5-day accumulation extremes. A similar alternative explanation is the non-stationarity of the blocks. The blocking detection requires 70% spatial overlap from one time step to the next allowing for some primarily eastward movement of the block (Croci-Maspoli 2005, Fig. 5.9) and this could also be detrimental for extremes with the longer accumulation periods. The increased odds over southern Europe are in good accordance with the results of Sousa et al. (2017) and support their finding that the increase in southern European mean precipitation during blocks is mainly influenced by the increased frequency of upper percentile precipitation events. Interestingly, Sousa et al. (2017) attribute the increased precipitation south of the block to a weaker static stability of this region.

Western Russian blocks during the summer season are accompanied by increased odds of moderate and extreme 1-day precipitation events over eastern Europe (east of 10°E). For the extreme precipitation events the odds ratios vary between 3 and 5 over large parts of eastern Europe. An explanation for the increased odds in moderate precipitation extremes over Scandinavia and the Baltic states could be the trough upstream of the block and the associated surface cyclone maximum. While on the western flank of the trough, dry conditions prevail, on the eastern flank quasi-geostrophic lifting is expected and the odds of heavy precipitation are increased in contrast to all the other blocking locations, the western Russian block also show statistically significant results for the 99th percentile extreme events. For longer accumulation periods as well as winter blocks there are no significant changes in the odds of the precipitation events. The increased odds for extreme precipitation do not reflect the results of Yao and Luo (2014) for mean winter precipitation, who find a statistically significant decrease of precipitation during "eastern Europe" blocks, which should roughly correspond to our western Atlantic blocks. This could point to a decrease in the lower and medium percentile precipitation as a main reason for the reduction in mean precipitation. However, as different blocking indices are used, some of the eastern European events could also belong to our European category.

Summarising, we find the general pattern of changes of the heavy precipitation and the extreme precipitation

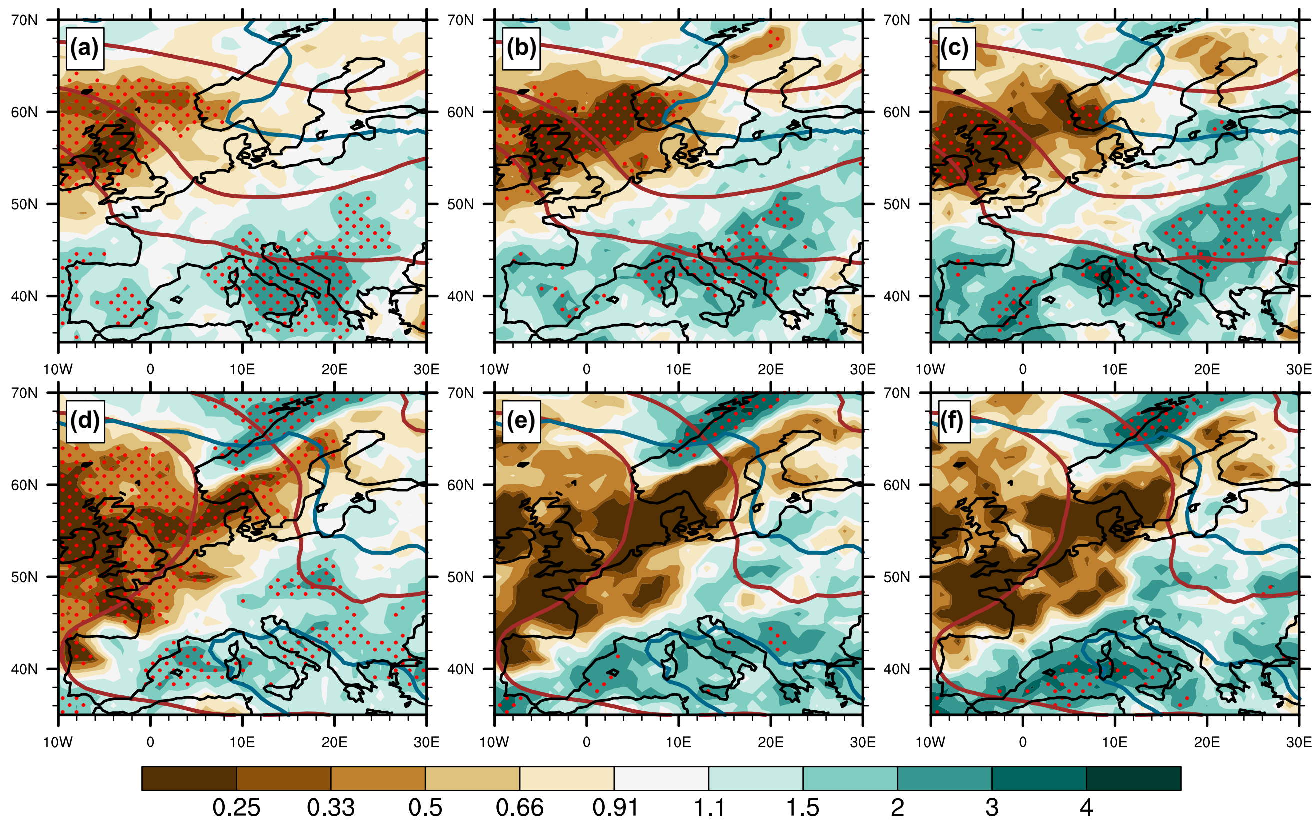


Fig. 10 The same as Fig. 8 but for the eastern North-Atlantic sector (30°W–0°E)

events to agree quite well with the pattern of changes of mean precipitation described by Sousa et al. (2017). In areas where they find a reduction in mean precipitation (central and northern Europe, following the latitudinal band of the blocks), we also see a reduction of the odds of the heavy precipitation and in regions where they find an increase in the mean precipitation (southern Europe and depending on the season also the Norwegian Atlantic coast) we also observe increased odds for heavy precipitation events.

5 Conclusions

The modulation of the odds of 1-day, 3-day and 5-day accumulation heavy precipitation events (95th and 99th local seasonal percentiles) in central Europe by blocking anticyclones is investigated. The odds of moderate extreme events (95th percentile) are changed significantly during blocking episodes. The specific spatial patterns of the changed odds of heavy precipitation vary with season, the location of the blocking anticyclones, and to a certain degree with the accumulation period. Blocks in the North Atlantic and in the central European sector have a significant influence on the odds of both winter and summer heavy precipitation events in central Europe. Blocks located downstream of central Europe have only limited influence on the frequency of European heavy precipitation events.

Generally, the odds ratio is below one, i.e., the chance of heavy precipitation decreases, in the blocked area and is higher than one, i.e., the chance of heavy precipitation increases, in areas southeast to southwest of the blocks and in some cases also northwest of the block. The patterns in the spatial distribution of odds ratio can for most constellations be related to the position of the storm tracks relative to the blocks modulated by the local topography. Increased chances of heavy precipitation are co-located with areas of frequent cyclone passages. Notable exceptions occur in summer and for the 5-day accumulations where the direct link to cyclone tracks is not always obvious. In the future, it would be interesting to look more detailed at the processes that link blocks and 5-day accumulation heavy precipitation events.

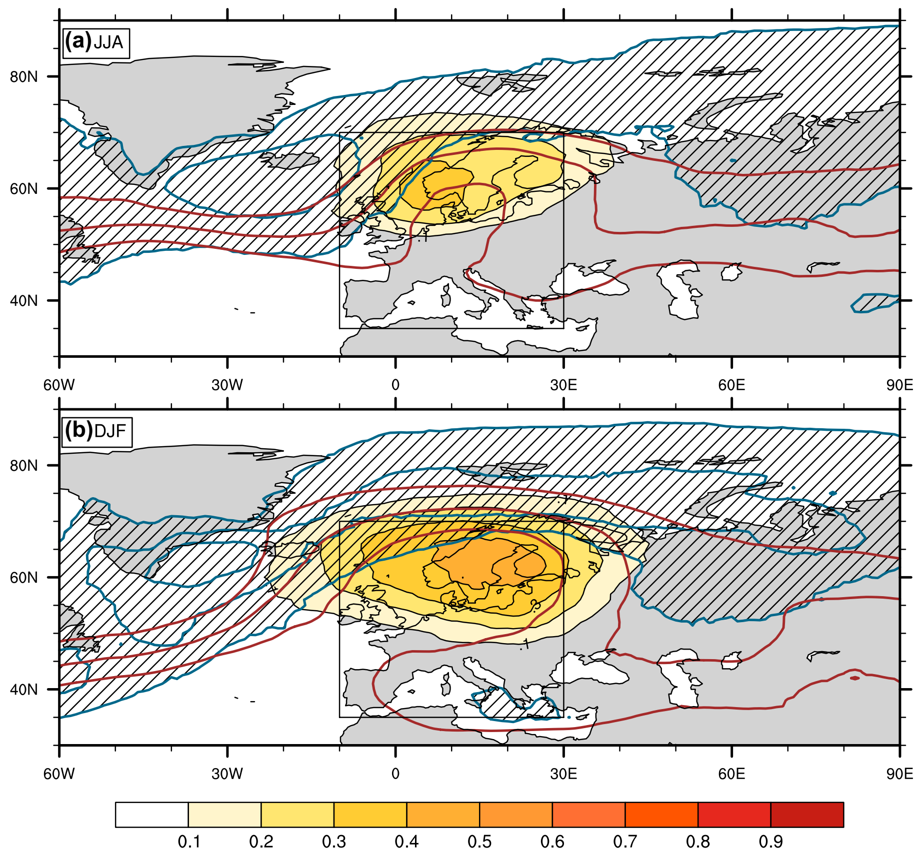


Fig. 11 The same as Fig. 7 but for the European sector (0°W–30°E)

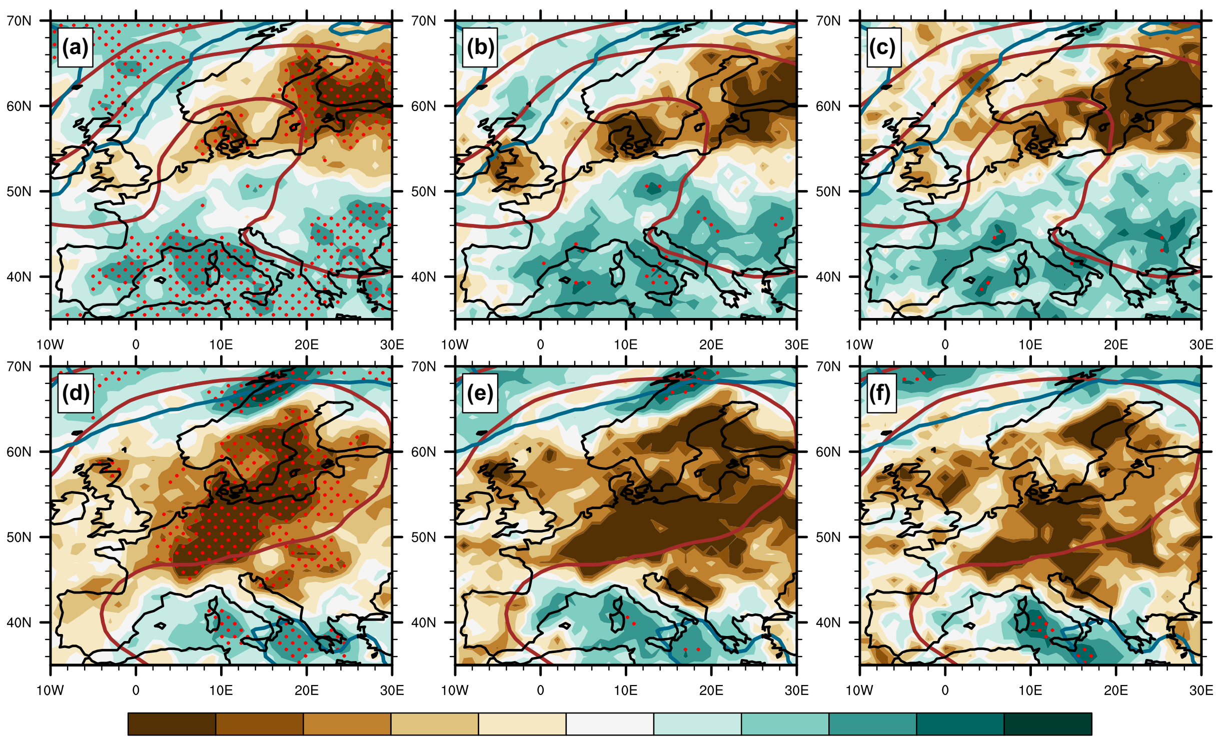
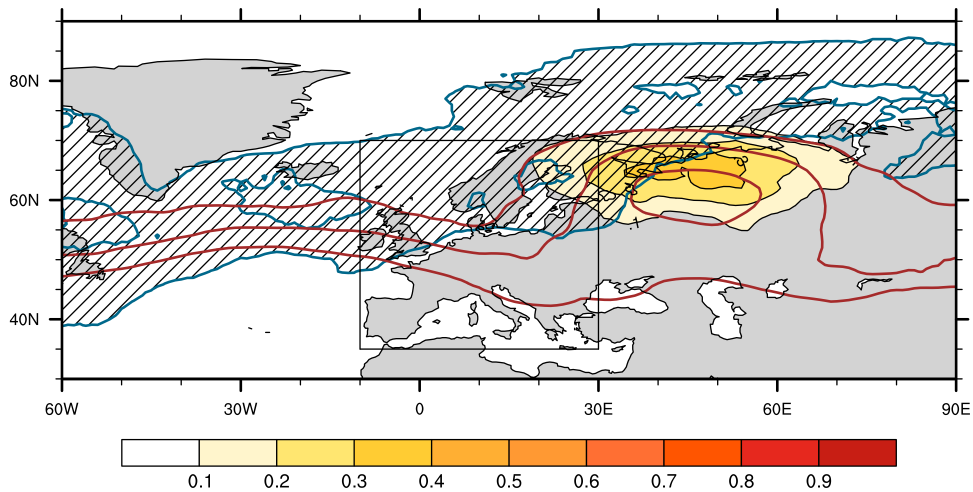


Fig. 12 The same as Fig. 8 but for the European sector (0°W–30°E)

Fig. 13 Composite blocking frequency (colour shading), vertically averaged PV (brown contours, 2, 2.5 and 3pvu) and cyclone frequency (blue hatching and contours, in steps of 10%) during summer (JJA) blocking in the western Russian sector (30°E–60°E)



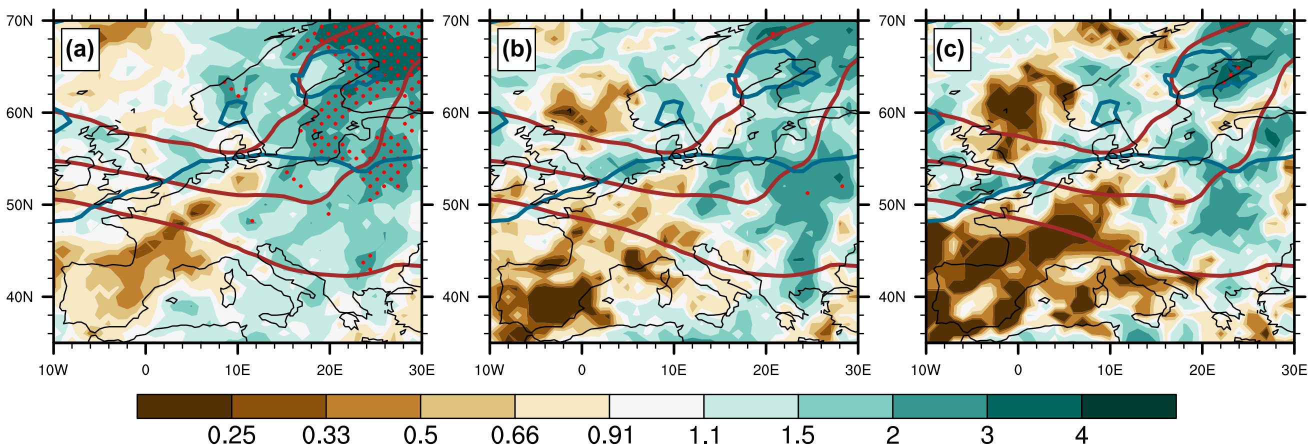


Fig. 14 Odds ratio of moderately extreme 1-day (**a**), 3-day (**b**) and 5-day (**c**) precipitation events between days with blocks in the western Russian sector (30°E–60°E) and days without blocks in this region for JJA. The lines indicate the composite vertically averaged PV (brown, 2, 2.5, 3 pvu) and cyclone frequency (blue, 10%, 20%)

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical standards This study was funded by the Swiss National Science Foundation (Grant number 156059).

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