Atmospheric moisture sources for the river Rhine under present and future climate conditions

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Abstract

As it is expected that the river Rhine catchment will experience severe droughts in the future, it is important to get to know its moisture sources. This is done by analysing the behaviour of evaporation and precipitation and the transport of atmospheric moisture using present and future simulations of one high-resolution global climate model. Furthermore, the atmospheric moisture sources from which the evaporation result in precipitation over the Rhine catchment are determined. To do so, the Eulerian backward tracking model WAM2-Layers (Van der Ent, 2014) is used with present simulations (2002-2006) and future simulations (2094-2098) of EC-Earth (Hazeleger et al., 2012). After backtracking, it is found that especially during present winters, Evaporation that Contributes to Precipitation over the Rhine catchment (*ECPR*) predominantly is supplied from the North-Atlantic ocean. In present summer, the contribution of evaporation from West-Europe also becomes important. In future winter the North-Atlantic ocean is found to supply 5% less of the total precipitation over the Rhine catchment. The Source Contribution to Precipitation over the Rhine catchment (*SCPR*) of the other source-regions does not differ more than 1% with present winters. For future summer, the major suppliers (North-Atlantic ocean and West-Europe), show a decrease of 3% in *SCPR* relative to present summers. However, on an absolute scale, this decrease in supply from the North-Atlantic ocean and West-Europe is large (respectively 10 and 7 mm/month decrease), indicating drier future summers. In addition, the moisture sources of the Rhine during the dry summer of 2018 have been determined. It is found that during this summer, the *SCPR* from the North-Atlantic ocean was low, resulting in an even drier summer than predicted for future summers.

Contents

1. Introduction

Human society is becoming increasingly reliant on freshwater resources like rivers and other types of open water areas (Gimeno et al., 2012). The moisture supply to these areas is partly regulated by the amount of precipitation, which is dependent on (local) evaporation and moisture advection (Gimeno et al., 2012). Investigating evaporation and atmospheric moisture transport on different spatial scales is the basis for locating so-called atmospheric moisture sources for specific areas. Locating the origin of precipitation makes it possible to investigate the dependency of specific areas on these atmospheric moisture sources. It is of our interest to investigate the atmospheric moisture sources for precipitation which falls in the catchment area of the river Rhine. This area is chosen as the locations of the moisture sources for this specific area are still unknown. This is a pressing issue, since the water level of the river Rhine reached historically low values in the Netherlands during the year 2018 (Waterpeilen.nl, 2019) and Van der Linden et al. (2019) found that droughts are likely to increase for this area in the future.

Moisture advection towards the Rhine catchment is subject to global atmospheric moisture flow. On a global scale, evaporation over oceans is found to be larger than evaporation over continents (Gimeno et al., 2012). However, continental precipitation is found to originate also to a large extent from evaporation over a continent (Shukla and Mintz, 1982). Van der Ent performed a research which estimated the continental precipitation which is derived from continental evaporative sources to be 40% of the total precipitation over land (Van der Ent, 2014). Consequently, the other 60% is originating from evaporation over oceans. Europe is found to be a large supplier of continental evaporation, although the evaporated moisture is not precipitated over Europe but on another continent (Van der Ent, 2014). On the other hand, moisture is also transported to Europe from other continents, indicating moisture transport from North America (Van der Ent, 2014). Precipitation over the Rhine catchment is expected to originate mainly from the west, as the predominant wind-direction over West-Europe is westerly (Murray and Johnson, 1952) and evaporation over the North-Atlantic ocean is high (between 800 and 1600 mm/year (Yu, 2007)). However, to some extent, precipitation over the Rhine catchment is also supplied by local evaporation as Van der Ent (2014) found a connection between evaporation and precipitation on a regional scale. He defined the *regional recycling of evaporation* as the moisture that evaporates over a region and also precipitates over the same region (Van der Ent, 2014*).* However, the actual contribution of local evaporation to the Rhine catchment is unknown, as it has not been studied yet.

When investigating the origin of precipitation over the Rhine catchment, it is important to include the perspective of climate change. Global warming will affect the magnitude of evaporation and moisture transport, which therefore are likely to change the occurrence and intensity of precipitation events in the nearby future (Trenberth, 2011). On a global scale, Yu and Weller (2007) found that evaporation already has increased over the oceans in the previous decades. Laîné et al. (2014) found this positive trend also for future climate, although for the North-Atlantic ocean a decrease in evaporation was observed. According to Feng and Fu (2013), evaporation over global drylands tends to increase potentially as a result of a growing evaporative demand of the atmosphere due to an increased air temperature. However, the major reason to include and analyse future climate scenarios is that for the Rhine-Meuse drainage area, extreme droughts are expected to occur more often in the future (Van der Linden et al., 2019; Samaniego et al., 2018; Ruosteenoja et al., 2018). Van der Linden et al. (2019) found that this is caused by the positive feedback between (the lack of) evapotranspiration and precipitation, which enhances the occurrence of extreme droughts and warm extremes. Droughts even become the normal climatological state, when simulating the future climate with a high spatial resolution (25km x 25km). The droughts become severe during summer due to both a limited amount of rainfall and dry soil moisture conditions already in spring (Van der Linden et al., 2019).

Getting insight in the atmospheric moisture flow on a global and local scale, will make it possible to investigate the atmospheric moisture supply towards the river Rhine. The evaporative sources which provide the moisture for the precipitation over the river Rhine catchment are identified and located. This is done by the use of a backward tracking method (see section 2.2) for both present and future climate, since the moisture sources will probably change due to global warming. The main research question is: Where does precipitation over the Rhine catchment originate from regarding present and future climate scenarios?

Three sub-questions are defined:

- What is the general precipitation, wind and evaporation pattern in the study area for present and future climate?
- Which areas are main evaporative sources for the precipitation in the catchment area of the river Rhine for present and future climate?
- How was the moisture supply in the summer of 2018, when there was severe drought over the Rhine catchment?

2. Methodology

2.1 Theoretical background

The atmospheric water balance of one grid cell depends on the amount of precipitation and evaporation in a grid cell together with the moisture transport over the boundaries of the cell. A surplus of evaporation relative to precipitation implies that moisture will be transported out of the grid cell in the direction which corresponds with the dominant wind-direction. In a multiple horizontal layer grid, convection and subsidence are probable causes of vertical moisture exchange between the layers. Analysing the transport of atmospheric moisture is based on the principle of solving water balances for different grid cells per time step. The formula for calculating the atmospheric moisture storage change over time is:

$$\frac{\delta S_k}{\delta t} = \frac{\delta (S_k u)}{\delta x} + \frac{\delta (S_k v)}{\delta y} + E_k - P_k + F_{v,k} \, [L^3 T^{-1}] \text{ , (Van der Ent, 2014)} \qquad (2.1)$$

where $S_k u$ and $S_k v$ are the atmospheric moisture advection in respectively the x and y-direction integrated over layer k.

$$S_k u = \int_{p_{k,top}}^{p_{k,bottom}} (q * u) \, dp \text{ ,} \qquad (2.2)$$

$$S_k v = \int_{p_{k,top}}^{p_{k,bottom}} (q * v) \, dp \text{ .} \qquad (2.3)$$

So in equation 2.1, the $\frac{\delta (S_k u)}{\delta x}$ and $\frac{\delta (S_k v)}{\delta y}$ terms represent the change of atmospheric moisture transport over respectively the west-east and south-north boundaries of a grid cell. $\frac{\delta S_k}{\delta t}$ is the atmospheric moisture storage change over time, E_k is evaporation entering layer k, P_k is precipitation leaving layer k and $F_{v,k}$ is the vertical moisture transport either leaving or entering layer k (Van der Ent, 2014). F_v is regarded as the closure term of the equation. For further details, see section 2.3 of the work of Van der Ent (2014).

Tracking moisture is done by tagging specific cells and follow these over time. When interested in the origin of precipitation, cells with precipitation in the area of interest are selected and tracked back until the moment of evaporation. This method is called backward tracking. The tagged water cells get a separate water balance:

$$\frac{\delta S_{g,k}}{\delta t} = \frac{\delta (S_{g,k} u)}{\delta x} + \frac{\delta (S_{g,k} v)}{\delta y} + E_{g,k} - P_{g,k} + F_{v,k,g} \, [L^3 T^{-1}] \text{ , (Van der Ent, 2014)} \qquad (2.4)$$

where subscript g represents the tag. Except for the tag, the terms are the same as in equation 2.1. More details can be found in section 2.4 of Van der Ent (2014).

2.2 WAM-2layers

For the study a model developed by Van der Ent (2014) is used. The model is called Water Accounting Model (WAM) - 2layers, which is an offline Eulerian numerical atmospheric moisture tracking model. Numerical atmospheric moisture tracking models are often implemented in Global Climate Models and contribute to the understanding of how moisture moves and is transformed as it passes through the atmosphere (Gimeno et al., 2012). The numerical tracking models can operate both with Lagrangian and Eulerian tagging techniques. The advantage of Eulerian tagging techniques is that the specific origin and destination of advected moisture can be determined (Gimeno et al., 2012). An important assumption in the WAM-2layers model is that the atmosphere is divided in two well mixed layers: a top layer and a bottom layer. The pressure at the division between the top and bottom layer is chosen as such that the wind shear between the two layers is best captured (van der Ent, 2014).

$$p_{\text{division}} = 7438.803 + 0.728786 \times p_{\text{surface}} \; [\text{Pa}]$$, (van der Ent, 2014) (2.5)

The use of only two layers reduces the computational costs considerably, while providing nearly identical results as a highly advanced online multiple layer model (Van der Ent et al., 2013). The atmospheric moisture flow pattern is thus calculated based on the integral of moisture and wind over only two layers (eq. 2.2 and 2.3). Before the model is able to track moisture, it needs to get the horizontal atmospheric moisture flow pattern as a function of space and time. This is done by solving the water balance per grid cell for each time step as explained in section 2.1. The atmospheric moisture content of a grid cell combined with the wind direction and the magnitude of the wind speed indicate the magnitude of the horizontal transport between grid cells.

The model is able to select and track moisture from a specific area by tagging the moisture which evaporated or precipitated over the corresponding grid cells (section 2.1). Based on the horizontal fluxes, the model can determine which fraction of the tagged moisture was (will be) in which grid cell on the previous (next) time step. Consequently, for each grid cell precipitation is subtracted from evaporation to find out which fraction of the tagged moisture was achieved by horizontal transport and which fraction origins from evaporation or precipitation within the cell.

When tracking evaporation from a specific source area, the model uses a forward tracking function. If interested in the origin of precipitation over a fixed sink area, the model uses a backward tracking function. Forward tracking implies that evaporation is followed forward in time (source to sink), while backward tracking refers to tracing precipitation back in time (sink to source). In case of backward tracking, the output is a spatial distribution of evaporated atmospheric moisture which will precipitate in a predefined region. In this study, backward tracking is performed and the predefined region will be the catchment area of the river Rhine (Figure 2.1).

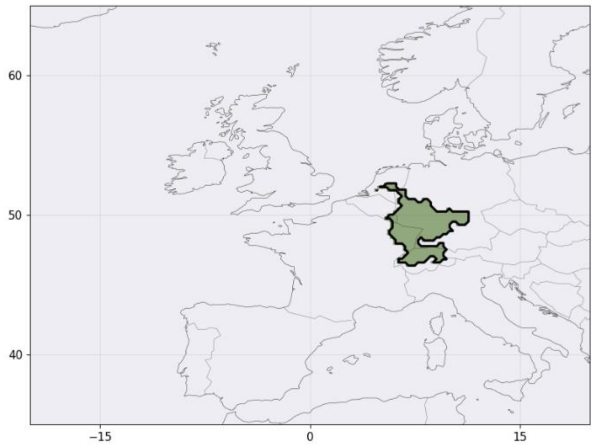

Figure 2.1: River Rhine catchment

2.3 Data

2.3.1 EC-Earth

The data for this study is retrieved from EC-Earth, which is a new Earth system model based on the operational forecast system of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hazeleger et al., 2012). EC-Earth combines weather and climate prediction together with Earth-system science (Hazeleger et al., 2010) and simulates runs which are probable to occur regarding the prevailing climatic conditions. EC-Earth is an atmosphere only model, which implies that the hydrology at the surface is simplified. Land surface conditions are modelled by the use of H-TESSEL (Balsamo et al., 2009) and the sea surface temperature is prescribed as a boundary condition. To accurately simulate the climate, greenhouse gas concentrations, aerosol concentrations and sea surface temperatures are used as input values. Hazeleger et al. (2012) found that the model performs well in simulating the dynamic variables, but performs less in simulating surface temperature and fluxes. Nevertheless, Hazeleger et al. (2012) concludes by stating that the model performs well in comparison to other coupled models with similar complexity.

Simulations of EC-earth for the years 2002-2006 and 2094-2098 are used. For the simulation of 2002-2006, the input values of the greenhouse gas and aerosol concentration were based on observations (Haarsma et al., 2013). The values for the sea surface temperature were based on data from National Oceanic and Atmospheric Administration (NOAA, 2018). For future climate, the greenhouse gas and aerosol concentration were derived from the RCP4.5 scenario (Van Vuuren et al., 2011). Sea surface temperatures were calculated by adding the projected ensemble mean change of the 17 members of the coupled climate model ECHAM5/MPI-OM (Sterl et al., 2008). Further details regarding the input for the climate simulations can be found in Van der Linden et al. (2019) and Haarsma et al. (2013).

Six runs have been simulated per period and these data are available for use. In total two times 30 years of data are available: six times five years of data for present climate (2002-2006) and for future climate (2094-2098). The two different periods are chosen like this, since they cover a period of several decades which is needed when analysing the possible displacement of atmospheric moisture sources due to global warming. Since climate is defined as the weather conditions prevailing in an area over a period of 30 to 35 years, enough data are available to draw conclusions from. The data consist out of variables which are obtained at five pressure levels and variables which are measured close to the surface. Wind speed and humidity are obtained at five pressure levels every sixth hour of a day. Precipitation, evaporation, humidity at 2 meters height, wind speed at 10 meters height and surface pressure are obtained every third hour of a day (Table 2.1). Evaporation and precipitation are accumulated quantities, while the other variables such as wind and specific humidity are instantaneous. The data are available on a 25km by 25km grid scale. The resolution of the input data is based on its value at the equator, as the grid size is dependent on the latitude.

2.3.2 ERA-5

ERA-5 data for the year 2018 are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Berrisford et al., 2009). Similar as for EC-earth data, ERA-5 consist out of variables which are obtained either at pressure levels or at a single surface level. Wind speed and humidity on each pressure level are obtained with a 6-hourly resolution. Humidity at 2 meters height, wind speed at 10 meters height and surface pressure are obtained on a 3-hourly basis. Precipitation and evaporation are hourly accumulated quantities (Table 2.1). The spatial resolution of ERA5 is 30 x 30 km^2 at the equator. ERA-5 data will be used to analyse the evaporative moisture sources during the summer drought in 2018 for the catchment area of the river Rhine.

Table 2.1: Input variables as obtained from EC-earth and ERA5. Pressure levels are at 850, 700, 500, 300 and 200 hPa

Variables	**Units**	**Level**	**Time resolution**	
			EC-Earth	*ERA5*
Evaporation	m3	Surface	3-hourly	hourly
Specific humidity	m3	Surface (2m)	3-hourly	3-hourly
Precipitation	m3	Surface	3-hourly	hourly
Surface pressure	Pa	Surface	3-hourly	3-hourly
Wind speed (u)	m/s	Surface (10m)	3-hourly	3-hourly
Wind speed (v)	m/s	Surface (10m)	3-hourly	3-hourly
Specific humidity	m3	Pressure levels	6-hourly	6-hourly
Wind speed (u)	m/s	Pressure levels	6-hourly	6-hourly
Wind speed (v)	m/s	Pressure levels	6-hourly	6-hourly

2.4 Study area

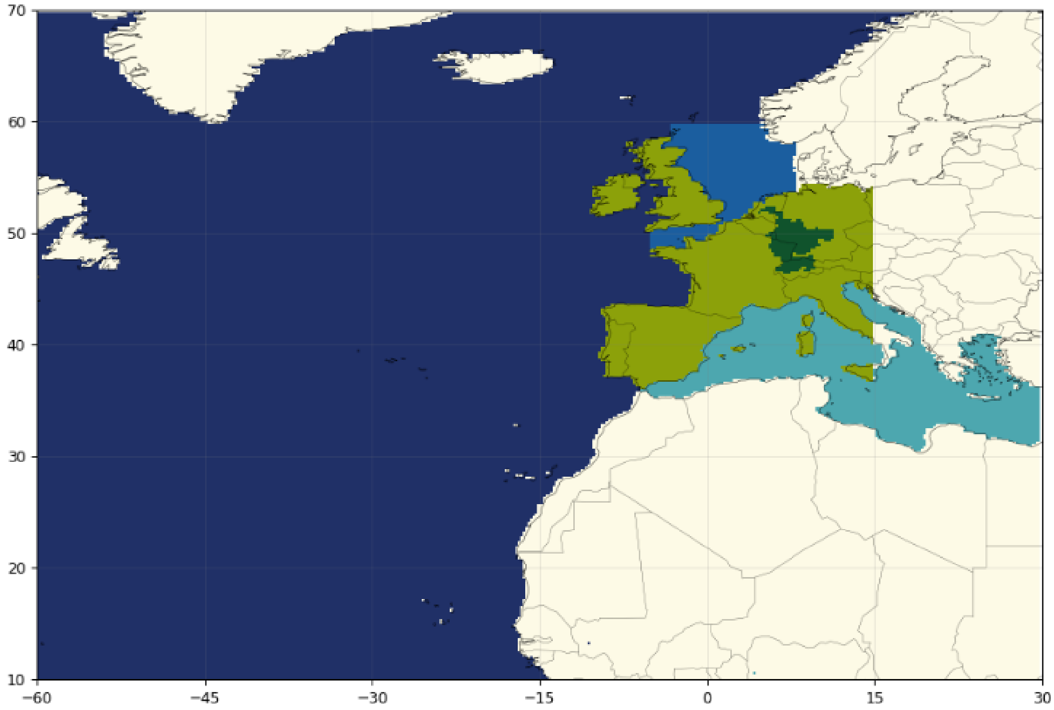

Figure 2.2: Study area, including the five source-regions for which the contribution of evaporation to precipitation over the Rhine catchment is quantified: Rhine (darkgreen), West-Europe (light-green), North-Atlantic ocean (darkblue), North-Sea (blue) and Mediterranean Sea (light-blue).

The domain over which precipitation over the Rhine catchment is tracked back in time is visible in Figure 2.2. Note that relative to the Rhine catchment, the domain is extended much more to the west than to the east. Since the dominant wind direction over West-Europe is westerly, it is more relevant to extend the study area to the west than to the east. The domain ranges between the longitudes 60°W, 30°E and the latitudes 10°N, 70°N. When precipitation over the Rhine catchment would originate from outside the domain, it is regarded as a loss term on the corresponding boundary of the domain. For example, if there is a very strong westerly during a certain season and moisture is supplied from Canada, the loss term on the west-side of the domain is large. The colours denote the different source-regions over which Evaporation that Contributes to Precipitation (*ECPR)* over the Rhine catchment is quantified. These regions are chosen based on the hypothesis that precipitation will originate west from the Rhine catchment and based on their distance from the Rhine catchment. First of all, the Rhine catchment is analysed since it gives insight in the local feedback between evaporation and precipitation. Secondly, moisture supply from West-Europe (west of 15°E) is quantified as this gives insight in the amount of *ECPR* which originates from a continental area. Next, the Mediterranean-sea and the North-sea, which are located close to the Rhine catchment, are defined as source-regions although their contribution might be low due to their small sizes. Finally, the moisture supply from over the Atlantic ocean is quantified as this is expected to be a major supplier due to both its size and its westward orientation. For the remaining areas (denoted by a white colour), it is expected that their atmospheric moisture supply towards the Rhine catchment is low. Therefore, these regions are not regarded as being source-regions.

2.5 Definitions

The research which is conducted, contains several statistical parameters and physical concepts. In Table 2.2 the definitions of these parameters and concepts are listed in alphabetical order.

Table 2.2: Definitions of concepts and parameters. Based on the work of Van der Ent (2014).

Concept or parameter	**Definition or formula**
ECPR	Evaporation that Contributes to Precipitation over the river Rhine catchment.
Regional recycling of evaporation	Moisture that evaporates over a region and also precipitates over the same region (Van der Ent, 2014).
RER	Regional Evaporative Recycling. $$RER \equiv \frac{\text{Amount of regional ECPR}}{\text{Total amount of precipitation in Rhine catchment}}\ x\ 100$$
SCPR	Source Contribution to Precipitation over the river Rhine catchment. $$SCPR \equiv \frac{\text{ECPR summed over a sourceregion}}{\text{Total amount of precipitation in Rhine catchment}}\ x\ 100$$

2.6 Experimental set-up

It is the aim of this study to locate the origin of the precipitation over the Rhine catchment and to link the observed *ECPR* pattern to existing climatological patterns. The analyses are performed twofold: for present and future climate conditions.

In order to describe the climate in the study area, precipitation, evaporation and wind data from EC-earth are analysed on a spatial scale. Precipitation is only analysed for West-Europe. Wind speed and direction are analysed for the whole study area (60 W, 30°E to 10°N, 70°N), as these are the driving force behind moisture transport. Consequently, evaporation is also analysed for the whole study area, as it is likely that evaporation is advected from over a wide region.

Spatial patterns of Evaporation that Contributes to Precipitation over the Rhine catchment (*ECPR*) for present and future climate are created by running the WAM-2layers model for EC-earth data. As WAM-2layers requires data on only two pressure levels with a fixed temporal resolution, EC-earth data are first pre-processed. Humidity and wind speed are obtained at five pressure levels (Table 2.1). These variables are merged in order to get values for only two layers, which WAM-2layers requires. EC-earth data on pressure levels are available on a six-hourly basis, while data on single levels are obtained every third hour. Therefore, data on single levels is converted as such that all data have a temporal resolution of 6 hours. However, in WAM-2layers the water balances are solved every 10 minutes. For this reason the input data are linearly interpolated to make it possible to run the model with a temporal resolution of 10 minutes.

Since the data all have the same resolution, WAM-2layers can be run. As a first step, the horizontal fluxes and states for all grid cells are calculated every 10 minutes. Secondly, precipitation over the Rhine catchment is continuously selected and tracked back in time, resulting in a value of *ECPR* for each grid cell. Thirdly, the time interval between evaporation and precipitation of *ECPR* is calculated. Finally, monthly average values of *ECPR* are calculated. The scripts are run per single present or future member. For the analyses the different members are combined to get output averaged for present and future climate.

ECPR is analysed spatially over the entire study area and quantitatively per source-region (section 2.4) both on an absolute and relative scale. The relative contribution per source-region is calculated by dividing the total *ECPR* over a source-region by the total amount of precipitation over the Rhine catchment. This shows what percentage of evaporated moisture of a certain source-region precipitates over the Rhine catchment: the so called *SCPR*. Finally, it is investigated what the Regional Evaporative Recycling (*RER)* for the Rhine catchment is.

The analysis of the drought in 2018, the third sub-question, requires a real-time dataset, which is not available in EC-Earth. Therefore ERA-5 data are used, obtained from the ECMWF. The pre-processing steps are similar to those as taken for EC-earth, since the main difference regarding the dimensions and resolutions of the data is its spatial resolution. Compared with EC-earth, ERA-5 data are a bit coarser and therefore the amount of grid cells in longitudinal and latitudinal direction is adapted in WAM-2layers. The other difference is that precipitation and evaporation data are stored as the cumulative value over the previous hour, which is different from EC-earth, where they were stored as the sum over the entire time interval (three hours). Therefore precipitation and evaporation values are first obtained every hour and afterwards summed to get six-hourly values. After pre-processing, the input data are linearly interpolated, the horizontal fluxes and states are calculated every 10 minutes, the precipitation over the Rhine catchment is selected and tracked back in time, the time interval between evaporation and precipitation of *ECPR* is calculated and monthly average values of *ECPR* are calculated. Afterwards, the spatial pattern of *ECPR* is analysed and the *SCPR* and *RER* of the summer of 2018 are calculated and compared with the present and future summer in EC-earth climate.

3. The components of the atmospheric water balance in present and future climate

In this chapter the climatological patterns for precipitation, wind and evaporation are investigated as they determine the atmospheric water balance and thereby the atmospheric moisture flow pattern within the study area. The build-up in this chapter is based on the concept of backtracking: precipitation, which is selected over the Rhine, follows a certain path back in time, which mainly relies on the wind-direction, until it is evaporated at a certain place. The precipitation pattern is only shown for West-Europe as it is the precipitation over the Rhine catchment which is of our interest. The wind and evaporation patterns are shown for the entire study area, since it is expected that atmospheric moisture is advected from over a wide region. The patterns are analysed for winter and summer (December, January, February and June, July, August respectively), both for present and future climate as simulated by EC-earth.

3.1 Precipitation

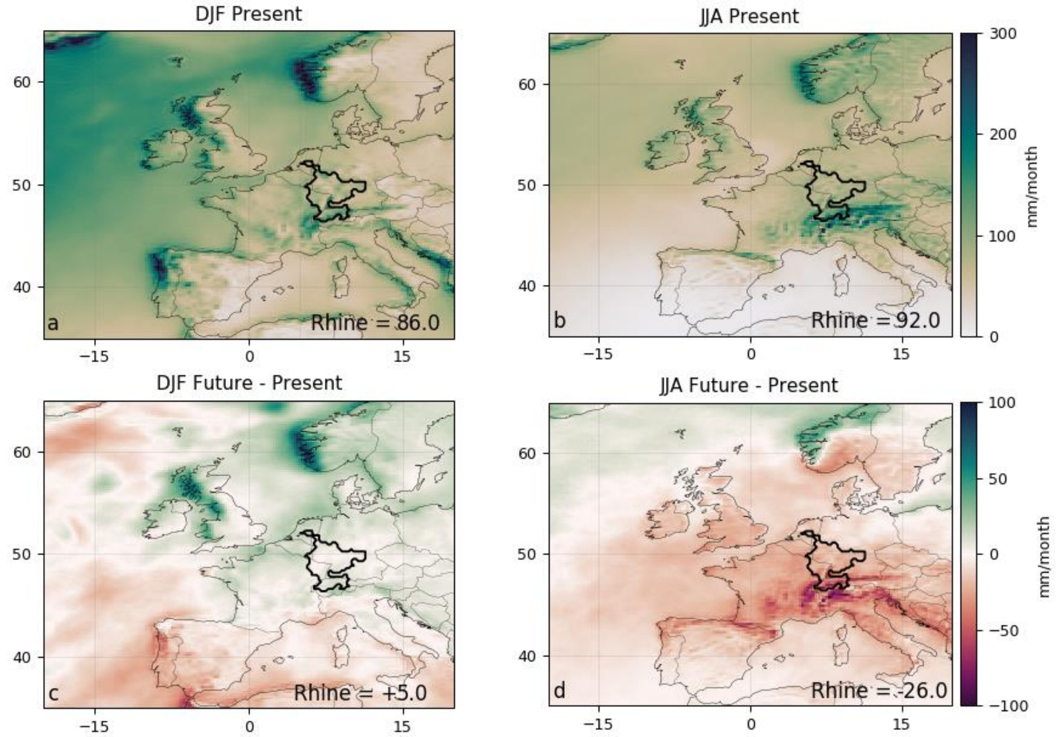

Figure 3.1: Precipitation over West-Europe for winter and summer for present climate (a and b, resp.) and the absolute difference with the future climate (c and d, resp.). Note that the units are in millimeter per month. The black line denotes the boundary of the Rhine catchment.

Precipitation is very heterogeneously distributed over West-Europe. In general the magnitude of precipitation is larger in winter than in summer. This is most pronounced over the Atlantic ocean as the magnitude is tens of millimeters per month higher during winter. Over West-Europe, apart from the coastal regions, the difference between winter and summer precipitation is almost zero. However, the precipitation averaged over the Rhine catchment is slightly more in summer than in winter (92 and 86 mm/month resp.)(Figure 3.1a and b).

The change of precipitation towards the future is different in winter and summer. Where for winter the main changes between future and present climate are relatively small and limited to the western coastal regions, for summer the changes are larger and cover a big part of West-Europe. Besides, future winter precipitation over the Rhine catchment tends to increase slightly (5 mm/month), whereas summer precipitation decreases with 26 mm/month, which is more than a quarter of its present magnitude (Figure 3.1c and d). The main reasons for the drop in summer precipitation in the future are a decrease in evaporation over Europe due to drier soils (Van der Linden et al., 2019; Samaniego et al., 2018) and a decrease in evaporation over the North-Atlantic ocean (Laîné et al., 2014). These drops in evaporation are further discussed in section 3.3.

3.2 Wind pattern

3.2.1 Wind direction

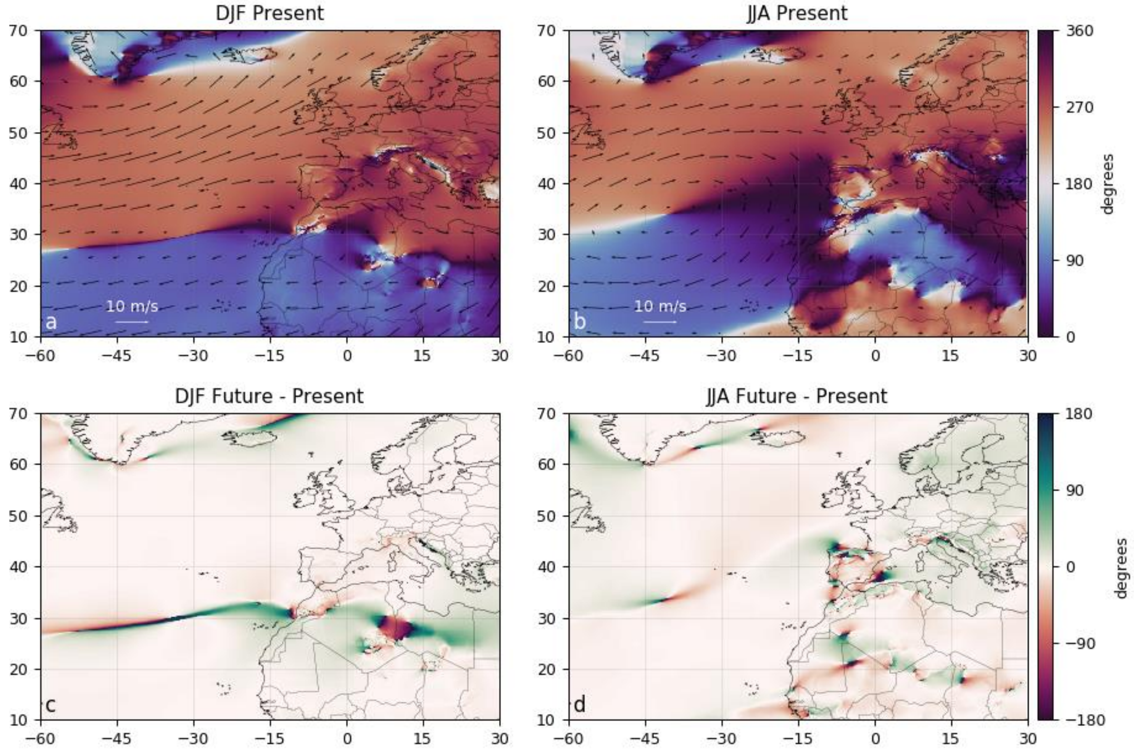

Figure 3.2: Wind direction in degrees for winter (a) and summer (b) at 850 hPa for present climate. The quivers indicate wind direction as well as the magnitude of the velocity. Note that the colour bar is cyclic which results in one colour for northerly winds. Changes in wind direction for the future climate are also shown for winter (c) and summer (d). Positive values indicate a clockwise shift in wind direction (e.g. Northerly -> Easterly).

The wind direction changes with 180 degrees between the north and south part of the domain. The easterly winds, below 30°N, are the so-called trade winds, which continuously flow towards the intertropical convergence zone. The westerly winds, above 30°N, are called the westerlies and are dominating in the mid-latitudes. The distinction between the trade and the westerly winds is known to be the subtropical high. Local anomalies in the general pattern are mainly caused by mountainous regions such as the Alps and Atlas. In perspective of moisture advection to Europe, especially the region above 30°N is important. The westerlies are expected to be important for the moisture advection over Europe as they transport moisture evaporated over the Atlantic ocean towards Europe. Differences between winter and summer are most significant close to the subtropical high. During winter evaporation from a larger area can be supplied to Europe as the flow field of the westerlies extends more south. In contrast, during summer the moisture supply might be less due to the large northerly flow before the coasts of Portugal and Morocco (Figure 3.2a and b). These differences close to the subtropical high are related to the position of the Inter Tropical Convergence Zone (ITCZ). The ITCZ and consequently the subtropical high move southward during winter, which results in an extended flow field of the westerlies. During summer the ITCZ and subtropical high shift northwards, by which the flow towards Europe is limited (Schneider et al., 2014).

Regarding the future wind pattern, the wind direction changes relative to the present are relatively small. During winter, the trade winds extend some degrees north close to the African coast (Figure 3.2c). In summer the main difference is that the westerly winds over the Atlantic ocean turn some degrees counter clockwise; which implies that they become somewhat more southerly (Figure 3.2d). The northward extension of the trade winds in the Hadley cell (circulation between 0 and 30°N on the northern hemisphere), as found for future winter climate, is related to global warming. Levine and Schneider (2015) found that the Hadley circulation widens as the effective static stability increases, which occurs during global warming. Due to the extension, the surface of the flow field of the westerlies decreases, resulting in a smaller area over which evaporation is transported towards the Rhine catchment during future winters.

3.2.2 Wind speed

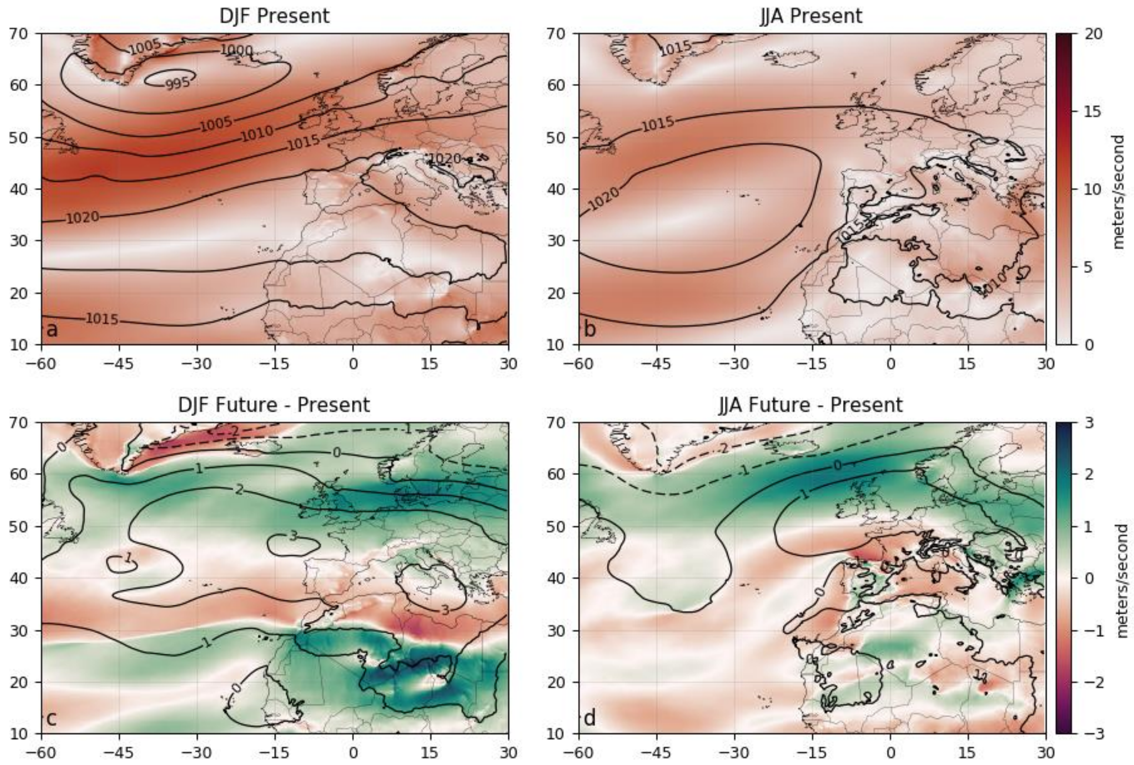

Figure 3.3: Wind speed in meters per second for winter (a) and summer (b) average scale at 850 hPa for present climate together with contour lines of mean sea level pressure (MSLP)(hPa). Changes in wind speed for the future climate (m/s) are also shown for winter (c) and summer (d) together with the differences in MSLP (hPa).

Wind speed has an effect on both the magnitude of evaporation (mainly over water surfaces) and the advection of moisture (Yu, 2007). In general, wind speed has the largest magnitude over the Atlantic ocean while it is weak over land. During present winters, trade and westerly winds have velocities of respectively 7 m/s and 15 m/s over the Atlantic ocean. Over land these values drop to 3 m/s and 7 m/s (Africa and Europe respectively). The large magnitude of westerlies in winter over the Atlantic ocean correlates well with the stronger gradients in MSLP over the same area (Figure 3.3a). During summer, the westerlies are dropped in velocity to 7 m/s, which correlates with the weaker MSLP gradient (Figure 3.3b).

Future climate shows stronger wind speeds for both winter and summer in the northern part of the study area (between 50 and 60°N). In winter, an increase of about 2 m/s is present over the area ranging from the North Sea to eastern Europe. Consequently, the differences in MSLP are relatively strong over the same area. Just north of the subtropical high, wind speeds are dropping with 1 m/s (Figure 3.3c). During summer, the strongest increase in wind speed (2 m/s) is found between Iceland

and England, again correlating with strong differences in MSLP. However, in south-western Europe, a decrease of 1 m/s is observed (Figure 3.3d).

3.3 Evaporation pattern

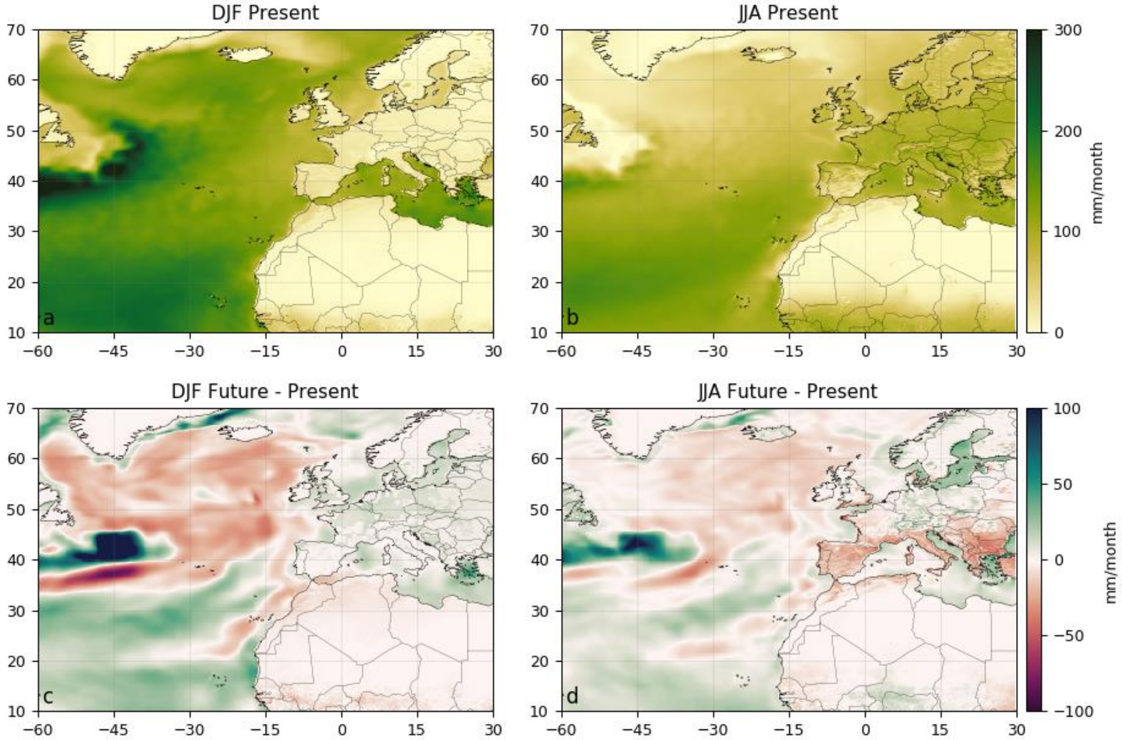

Figure 3.4: Evaporation pattern over the study area for winter (a) and summer (b) in present climate. Besides, the absolute difference in evaporation between future and present climate for winter (c) and summer (d) are shown. Units are in millimeter per month.

Regarding present climatological conditions, evaporation shows strongly differing values when comparing summer and winter both over land and ocean. In winter, evaporation over land is almost zero, whereas over the Atlantic ocean up to 300 mm/month is evaporated. During summer time, the pattern is more homogeneous: evaporation amounts over Europe are around 100 mm/month and evaporation over the Atlantic ocean ranges between 50 and 150 mm/month (Figure 3.4a and b). Higher evaporation rates over the Atlantic ocean during winter are caused by higher wind speeds (section 3.2) and a stronger exchange coefficient due to lower air temperatures, relative to the warmer sea surface. The latter is also the reason for the high evaporation at the warm Gulf stream (40°N, 45°W). Evaporation is high since the air is transported from over the relatively cold sea surface at the cold Gulf stream just north-west. As soon as the cold air flows over the warmer sea surface, the humidity contrast becomes large and evaporation will be large as well. Finally, the higher evaporation rates over Europe during summer are caused by higher surface temperatures (Schmugge and Andre, 2012).

Differences between future and present evaporation values are strongest over the Atlantic Ocean. Especially on the west side (42°N, 45°W), evaporation tends to increase with more than 100 mm/month. Apart from that region, evaporation over the Atlantic Ocean above a latitude of 35°N decreases with approximately 40 mm per month. Below 35°N, the region where trade winds dominate, it is shown that evaporation will increase in the future (Figure 3.4c). For the summer, the changes over the Atlantic ocean are similar to those in winter but less extreme. Besides, over southern Europe evaporation decreases with approximately 30 mm/month (Figure 3.4d).

The latter is explained by Van der Linden et al. (2019) who found that evapotranspiration in future summers will decrease as a result of a local soil moisture feedback. Enhanced evapotranspiration in spring results in a consecutive soil moisture decrease which limits the evapotranspiration in summer as such that the absolute amount of precipitation decreases (Van der Linden et al., 2019). The decrease in evaporation over the Atlantic ocean (above 35°N) is related to the fact that air just above the sea surface will warm faster due to global warming than the sea surface itself (Laîné et al., 2014). Hereby both the exchange coefficient and the humidity contrast at the surface are reduced, and consequently also the surface evaporation. This effect is found to be stronger for future winters than summers. Below 35°N, the positive effect of direct thermal heating is becoming dominant, since it is located closer to the equator, and therefore evaporation is enhanced (Laîné et al., 2014). Finally, the strong increase in evaporation in the warm Gulf stream (42°N, 45°W), is explained by an increase of the sea surface temperature (SST) at that location, which is stronger than the increase in SST in the cold Gulf stream, located just north-west (Alexander et al., 2018). This temperature difference intensifies evaporation which is caused by the advection of cold air over the warm Gulf stream at (42°N, 45°W).

4. Moisture sources of the river Rhine catchment in present and future climate

Precipitation over the Rhine catchment is tracked back and analysed for both winter and summer under present and future climate conditions. First, it is investigated how much precipitation originates from inside and outside the study area. Secondly, the absolute magnitude of Evaporation that Contributes to Precipitation over the river Rhine catchment (*ECPR*) is assessed by analysing a spatial distribution over the study area and by quantifying the *ECPR* per source-region. Thirdly, the spatial distribution of *ECPR* is analysed independent of the amount of precipitation and the *SCPR* is calculated for each source-region. The Source Contribution to Precipitation over the Rhine catchment *(SCPR)* indicates what percentage of the total precipitation is supplied by a specific source-region.

4.1 Validation moisture sources

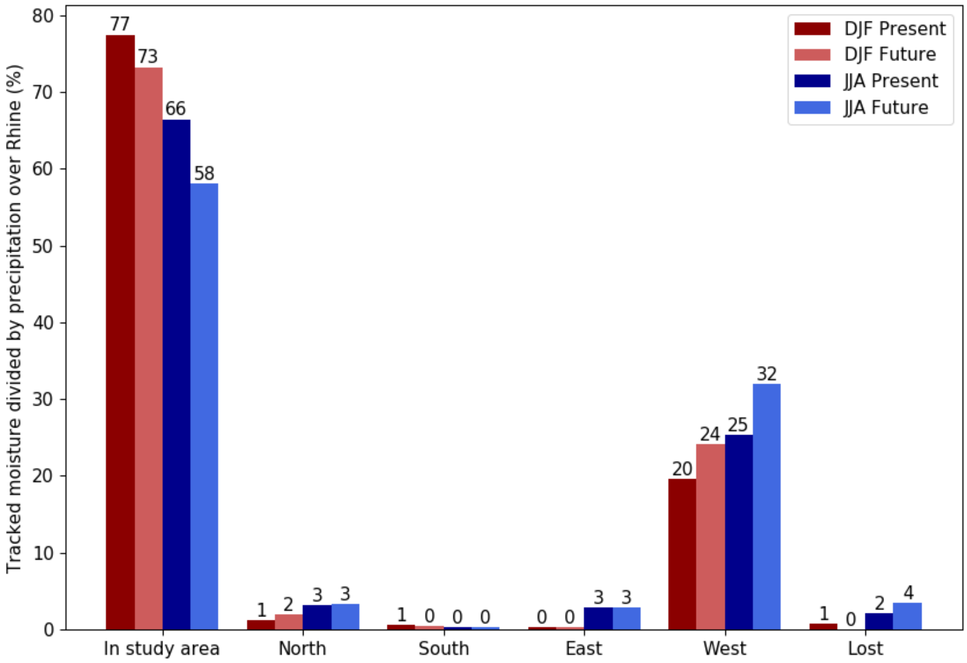

Figure 4.1: The amount of ECPR which is found to originate from inside the study area (see Figure 2.2 in Methodology), from over the boundaries, or which is 'lost', for winter and summer, present and future climate. All terms should add up to 100%, as the 'lost' term is the closure term.

Ideally, all precipitation over the Rhine catchment would be tracked. This would be the case when a global domain is used. However, to reduce computational costs the tracking is performed for the study area indicated in Figure 2.2. The result of performing the moisture tracking on a limited domain, is that tracked moisture to some extent originates from outside the boundaries. Figure 4.1 shows how much water is transported over respectively the North, South, East and West border, where the West border has the biggest contribution. 25% of the precipitation over the Rhine catchment, originates west from the 60°W border. For the future, it is not surprising that relative to the present, more moisture is originating west from the study area, since the wind speeds of the westerlies are found to increase (see 3.2.2). However, regarding the differences between summer and winter, on first sight it is unexpected that during summer more moisture originates from outside the western boundary. As evaporation over land is found to be higher and the fact that the wind speed of the westerlies is lower during summers, relatively more precipitation is expected to originate from over Europe itself and less from the west. However, based on the findings of Van der Ent (2014), summer precipitation over West-European countries does originate partly from evaporation over North-America. This would explain the large amount of moisture which is tracked on the west border. Nevertheless, the large west-term implies that the study area could have been extended more to the west, in order to get more detail on the origin of precipitation over the Rhine catchment over North-America.

4.2 Absolute contribution of ECPR

4.2.1 Spatial distribution of ECPR

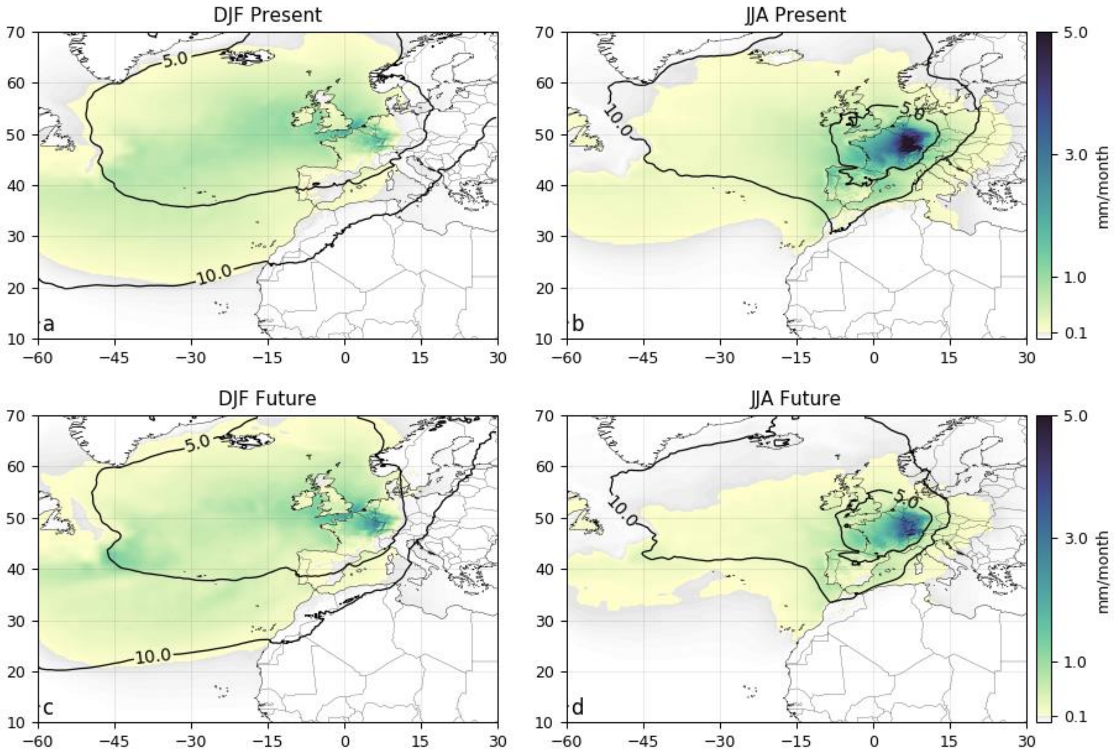

Figure 4.2: Absolute amount of ECPR for present and future climate averaged over winter (resp., a and c) and summer (resp., b and d). Note that only ECPR of 0.1 and higher is shown. Units are in millimeter per month. Besides, time contours are shown (days), which indicate the time interval between the moment of evaporation and the moment of precipitation over the Rhine catchment.

The largest moisture sources resulting in precipitation over the Rhine catchment are found west of the Rhine basin. This was expected since the westerlies are dominant in the mid-latitudes (section 3.2) and therefore are driving the atmospheric moisture transport. During present winters, much more precipitation is originally evaporated over the Atlantic ocean, whereas during summer relatively more precipitation originates from over West-Europe. This corresponds with the findings in section 3.3, in which it was shown that during winter, evaporation is high over the Atlantic ocean and during summer evaporation is relatively high over continental Europe. *ECPR* reaches the Rhine basin much quicker during winter than during summer. Where in winters the moisture from over a large part of the Atlantic ocean is transported within 5 days towards the Rhine, in summer this travel time is doubled (Figure 4.2a and b). The longer travel time of *ECPR* during summer, which is mainly caused by lower wind speeds (section 3.2.2), might also cause evaporation over the Atlantic ocean to precipitate before it reaches the Rhine catchment, although that has not been studied yet.

The changes in spatial distribution of *ECPR* between present and future differ strongly per season. For winter, besides the slight increase in *ECPR* over West-Europe, the changes are limited. However, in summer, a clear drop in the amount of *ECPR* is visible, both over the Atlantic ocean as over West-Europe (Figure 4.2d). This was expected based on the finding that summer precipitation is going to decrease in the future (section 3.1). A reason for this drop is the decrease in evaporation over the Atlantic ocean and Europe (section 3.3).

4.2.2 ECPR quantified per source-region

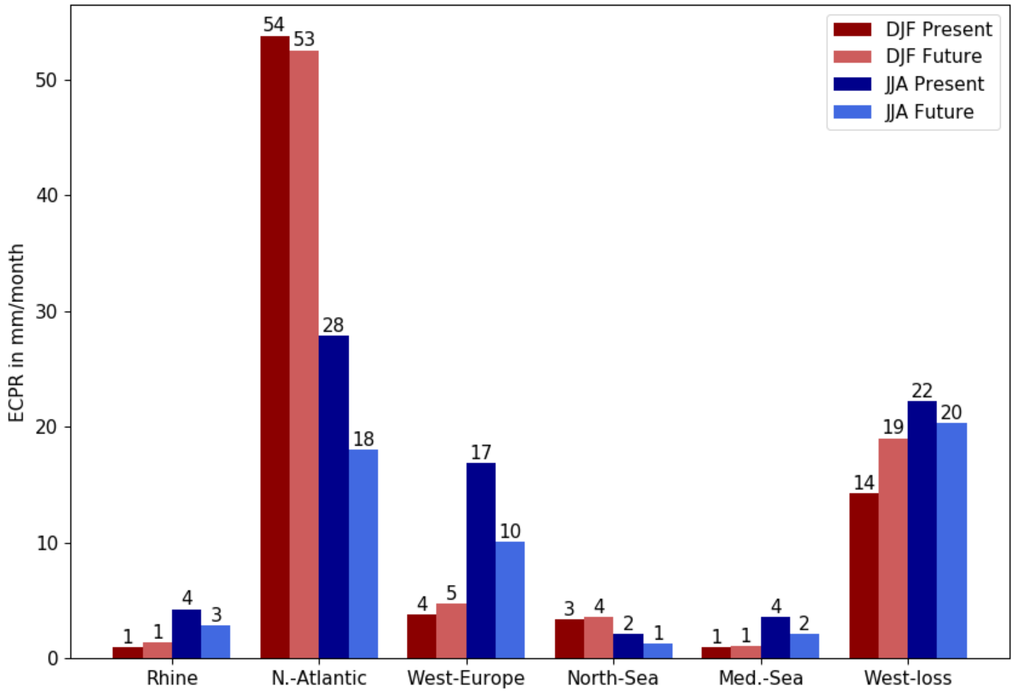

Figure 4.3: Moisture supply of different source-regions to the precipitation over the Rhine catchment for winter and summer. Units are in mm/month.

In line with the findings in the previous section, the North-Atlantic ocean is found to dominate the atmospheric moisture supply towards the Rhine catchment during present winters, as it supplies every month 54 mm of moisture. In contrast, West-Europe, the North-Sea, the Mediterranean-Sea and the Rhine together, supply only roughly 9 mm every month (Figure 4.3). This big difference is partly explained by the size of the source-regions: the North-Atlantic ocean covers a much larger area than the other regions and is therefore also able to supply more moisture. Despite this size difference, moisture supply during summer is totally different, especially for the North-Atlantic ocean and West-Europe. Over the North-Atlantic ocean and over West-Europe, the moisture supply respectively has been halved (54 to 28 mm/month) and increased with roughly a factor 4 (4 to 17 mm/month). Another major difference between present winter and summer is the west-loss term, which was implemented based on the findings in section 4.1. The amount of precipitation over the Rhine catchment which is originating from over the west boundary, is found to be higher during summers than during winters (resp. 22 and 14 mm/month).

During future winters the moisture supply from the different source-regions is not changing with more than 1 mm/month relative to its present value. However, the supply from over the west-boundary is larger (5 mm/month increase). For future summers the changes are stronger, as moisture supply from over the North-Atlantic ocean and West-Europe drop with respectively 10 and 7 mm/month (Figure 4.3). These drops in moisture supply correspond with the absolute decrease of precipitation over the Rhine catchment as shown in 3.1. Since the changes in the magnitude of *ECPR* are likely to be caused partly by consecutive drops in precipitation, analysing a contribution which is independent of the precipitation change, would give more insight in possible shifts in supply areas. Therefore the relative contribution of moisture sources is discussed in the next section.

4.3 Relative contribution of ECPR

4.3.1 Spatial distribution of ECPR

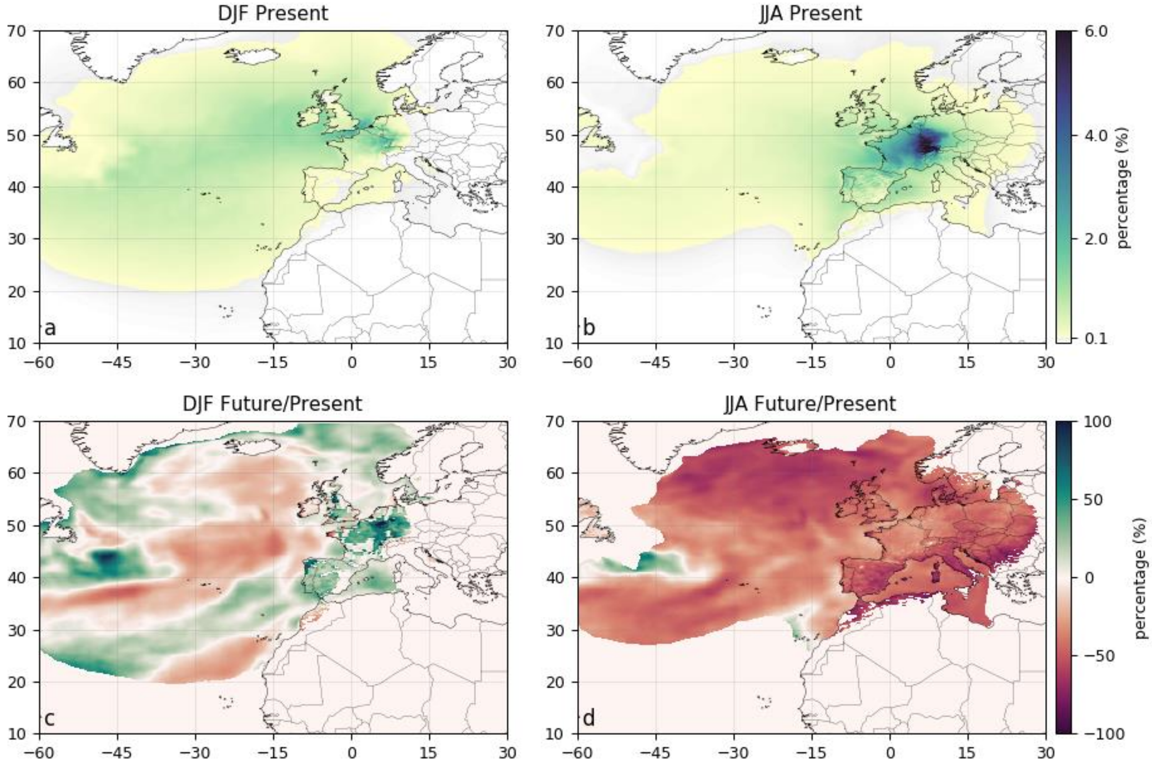

Figure 4.4: ECPR for present climate divided by the total precipitation over the Rhine catchment during the corresponding period of tracking, for both winter (a) and summer (b). Besides, the relative changes in ECPR between future and present are shown for winter (c) and summer (d). The relative differences are independent of the precipitation differences between present and future. All units are in percentages. Note that only the areas which contribute more than 0.1% during present climate are shown.

The seasonal differences in the spatial distribution of *ECPR* on a relative scale are very similar to the differences on an absolute scale, as discussed in section 4.2.1. Therefore, the change to the future is what draws the attention. Relative to present winter, the main change is that in future winter the small area at the warm Gulf stream (40°N, 45°W) together with the Rhine catchment itself, is found to supply more moisture for precipitation over the Rhine catchment (50% increase). Apart from the increase around (40°N, 45°W), the Atlantic ocean predominantly supplies less moisture in the future: a large area with an average decrease of 25% is visible in Figure 4.4c. For future summers, only the area around the warm Gulf stream increases in contribution (40%). For the rest of the domain, considerably less evaporation is contributed to precipitation over the Rhine catchment. Since West-Europe is responsible for on average 2–6% of the total precipitation over the Rhine catchment (Figure 4.4b), the decrease of 25-50% the moisture supply in the future will have a large impact on an absolute scale.

The changes over the Atlantic ocean for both future winters and summers can be directly related to the change in evaporation pattern towards the future, as found in section 3.3. For future winters the pattern as visible in Figure 4.4c correlates very well with the evaporation pattern as visible in Figure 3.4c (section 3.3). However, this does not hold for future summers, as the decrease in *ECPR* is mainly caused by relatively increased moisture advection over the western boundary of the study area (section 4.1).

4.3.2 SCPR per source-region

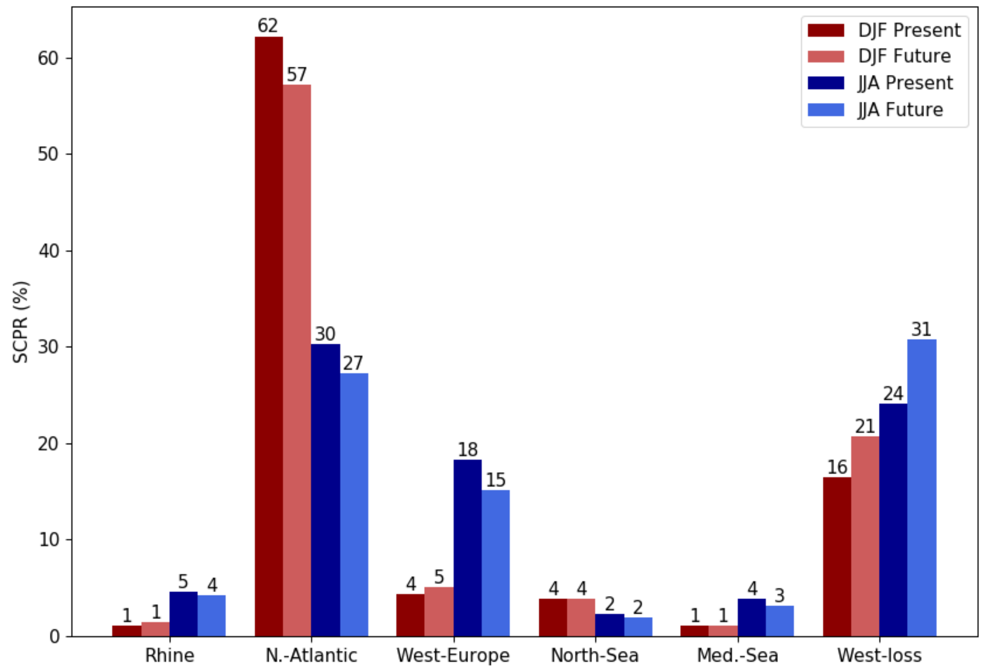

Figure 4.5: Contribution of different source-regions to the precipitation over the Rhine catchment (SCPR). The contributions are relative to the total precipitation over the Rhine catchment in the corresponding period. Units are in %.

The Source Contribution to Precipitation over the Rhine catchment *(SCPR)* indicates what percentage of the total precipitation is supplied by a specific source-region. Since all major source-regions have been selected and analysed, the sum of the relative contributions per season and per time period, should add up to nearly 100 percent. However, it is found that this is not the case, as precipitation originates partly from outside the study area. Therefore, the west-loss contribution is implemented to put the other contributions into perspective (Figure 4.5).

When comparing the relative contributions of the *SCPR* per source-region, a similar distribution as for the absolute moisture supply is visible (section 4.2.2). Winter precipitation over the Rhine catchment during present climate is strongly dependent on the moisture supply from the North-Atlantic ocean (62%) and only slightly dependent on moisture supply from the other source-regions (10%). On the other hand, for summer precipitation the relative contribution from the North-Atlantic is only 30% while the contribution of evaporation over land (West-Europe and the Rhine catchment) is higher (23%). Especially the strong increase of the *RER* for the Rhine catchment is interesting, although on an absolute scale, the contribution is still low (4 mm/month). The 23% which originates from evaporation over Europe, matches the calculations of Van der Ent (2014), who found a regional recycling for Europe of 27%. Moisture advection from over the west border (North-America), is found to be 16 and 24% for respectively winter and summer. Van der Ent (2014) indirectly confirms this high value as he found that evaporation over the eastern part of North-America for 30% is precipitated over land on an annual average. Since the westerlies dominate, it is very likely that this 30% is precipitated over Europe. However, since North-America is not included in the study area, it is only justified to state that the order of magnitude of the west-loss is realistic as such that the west-loss term is not likely to be caused by a modelling error.

Sodemann and Zubler (2010) calculated the moisture sources of precipitation over the Alps, which are partly located in our study area. They found that between 1995 and 2002 precipitation originated on an annual scale for 39.6% from the North-Atlantic ocean, for 20.8% over Europe, for 16.6% from the North and Baltic sea and for 23.3% from the Mediterranean Sea. Besides, moisture supply from the North-Atlantic ocean was found to be higher than the annual value during winter, while for Europe this is true during summer. However, moisture supply from the Mediterranean Sea was found to be high as precipitation over the southern part of the Alps (not part of the Rhine catchment) is relying strongly on moisture advection from the Mediterranean Sea (Figure 8 in Sodemann and Zubler, 2010). The fact that the moisture supply of especially the North-Atlantic ocean and Europe as found by Sodemann and Zubler (2010), are on the same order of magnitude as our findings, confirms our findings.

Relative to the future, the changes for both winter and summer are in the order of a few percents. The North-Atlantic ocean is found to supply 5 and 3 percent less for respectively winter and summer. West-Europe provides slightly more moisture in future winters (1%) but its contribution decreases for future summers (3%).

5. Moisture sources for the dry summer of 2018

During the summer of 2018 a severe drought was present over a large part of the Rhine catchment. Based on the Royal Dutch Meteorological Institute this was (in)directly caused by a high pressure system, located over southern Scandinavia (KNMI, 2019). In this chapter it is further investigated what possible causes are for the decrease in precipitation. Similar as for the analyses of EC-Earth present and future climate, first the components of the atmospheric water balance for ERA5 data are shown and discussed. Next, *ECPR* is assessed by showing spatial patterns and by quantitatively analysing the contribution of the pre-defined source-regions. The summer of 2018 is used as a single relevant case. The results of the moisture tracking are put into perspective by comparing them with the results of tracking under EC-Earth present and future climate conditions.

5.1 Components of the atmospheric water balance

5.1.1 Precipitation

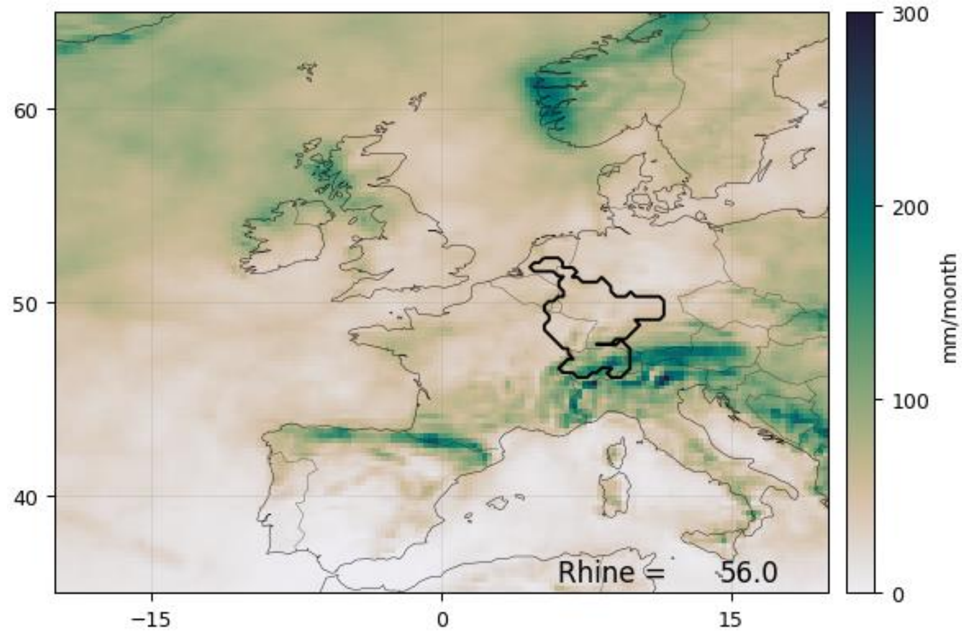

Figure 5.1: Precipitation over West-Europe for the summer of 2018. Note that the units are in millimeter per month. The black line denotes the boundary of the Rhine catchment.

Table 5.1: Precipitation values for summers during present and future climate and 2018.

Period	*EC-Earth present summer*	*EC-Earth future summer*	*ERA5 2018 summer*
Precipitation (mm/month)	92	66	56

It is observed that during the summer of 2018, the precipitation over the Alps, the southern part of the Rhine catchment, is on average 150 mm/month. This is in contrast with the amount of moisture that precipitates over the flat countries of the Rhine catchment (North-eastern France, West-Germany and the Netherlands), which is in the order of 25 mm/month. Averaged over the entire Rhine catchment, the total amount of precipitation is 56 mm/month (Figure 5.1). In present summer, precipitation is on average 92 mm/month while in future summer this is only 66 mm/month (Table 5.1). The fact that precipitation during 2018 is only 56 mm/month underlines the extremeness of the summer drought during 2018, as it was found in 3.1 that the future summer precipitation decrease already was very large.

5.1.2 Wind

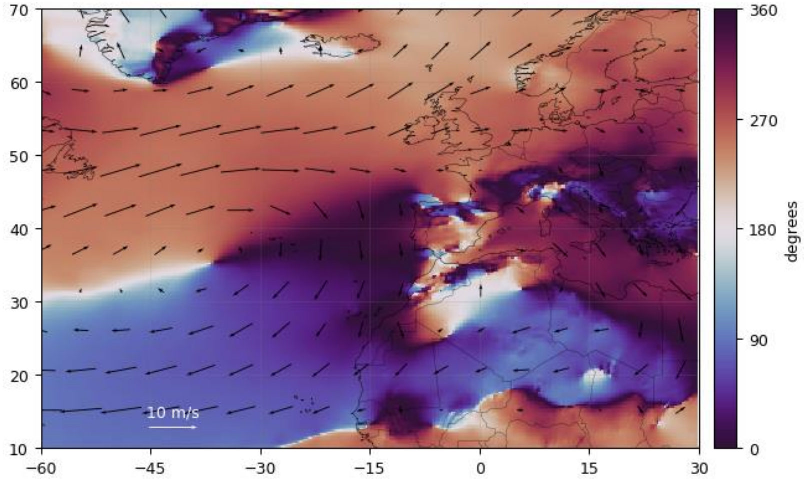

Figure 5.2: Wind direction in degrees for the summer of 2018 at 850 hPa. The quivers indicate wind direction as well as the magnitude of the velocity. Note that the colour bar is cyclic which results in one colour for northerly winds.

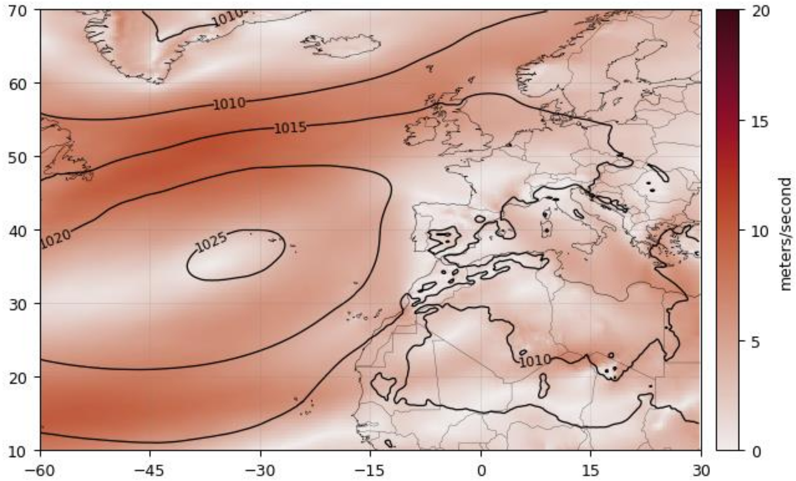

Figure 5.3: Wind speed for the summer of 2018 at 850 hPa together with contour lines of mean sea level pressure (hPa). The units are in meters per second.

The wind is found to flow westerly in the northern part and easterly in the bottom part of the study area. Before the coast of Spain and Morocco a northerly flow is present. The westerly wind flows towards Europe cover a large part of the North-Atlantic ocean and therefore the latter is likely to be a major source region for precipitation over the Rhine catchment. However, due to the northerly flow field at (40°N, 15°W), and the south-westerly flow before the coast of Great-Britain, large parts of the North-Atlantic ocean are not supplying moisture to West-Europe. Winds from the African continent are of minor importance due to their low wind speeds and the easterly orientation (Figure 5.2).

Apart from the winds above the subtropical high, the typical wind velocity over the Atlantic ocean is 10 m/s. Over land, the magnitude is considerably lower: the average wind velocity over Africa and Europe is below 5 m/s. The higher wind speed over the North-Atlantic (55°N, 40°W), matches with the stronger pressure gradient at the same location (Figure 5.3a). The low wind speed over Europe, which is the result of small pressure gradients, could limit the amount of moisture transport out of

Europe. This might result in an enhanced contribution of local evaporation to precipitation over the Rhine catchment.

5.1.3 Evaporation

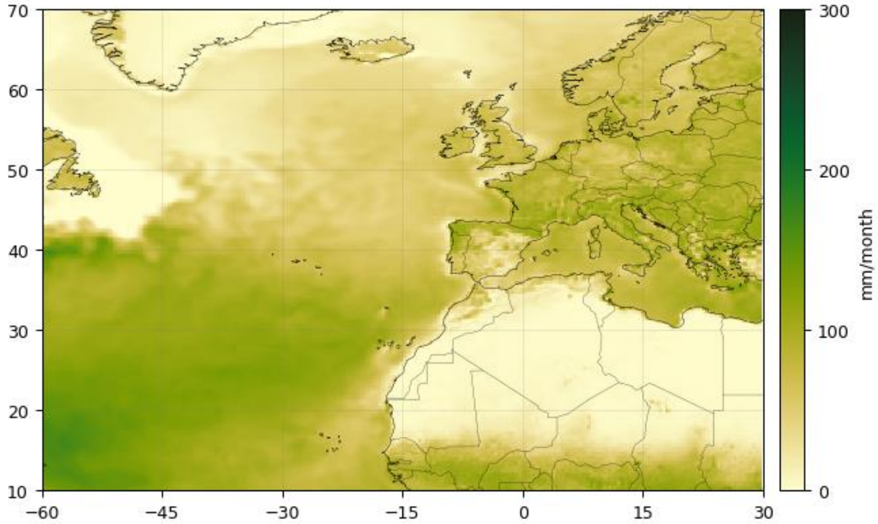

Figure 5.4: Evaporation pattern over the study area during the 2018 summer. Units are in millimeter per month.

Apart from Spain, evaporation over Europe amounts on average 100 mm/month. Over the North-Atlantic ocean evaporation rates up to 150 mm/month (below 40°N) are observed as well as values of 50 mm/month (above 40°N) (Figure 5.4).

5.2 Origin of precipitation over the Rhine catchment

5.2.1 Absolute contribution

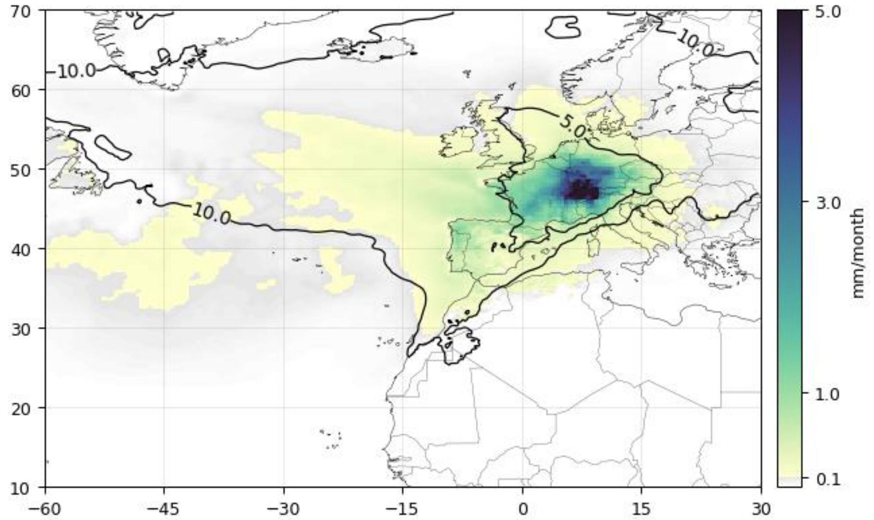

Figure 5.5: Absolute amount of ECPR (> 0.1) for the summer of 2018. Units are in millimeter per month. Besides, time contours are shown (days), which indicate the time interval between the moment of evaporation and the moment of precipitation over the Rhine catchment.

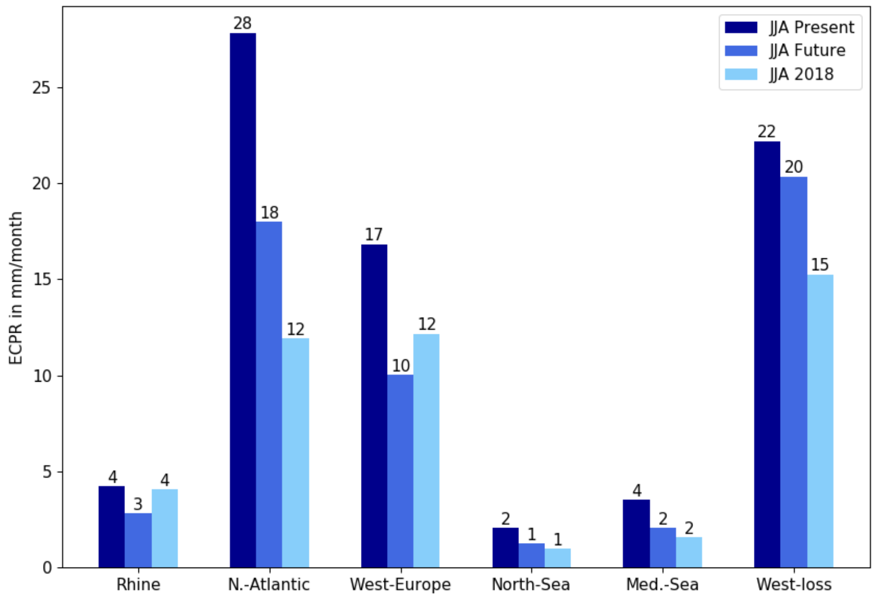

Figure 5.6: ECPR of different source-regions for the summer in present and future climate and 2018. Units are in mm/month.

Precipitation over the Rhine catchment is in general supplied by Europe and the North-Atlantic ocean. During the 2018 summer, peak *ECPR* values of 5 mm/month are observed over the Rhine catchment and values up to 0.5 mm/month over the North-Atlantic ocean. Despite the higher peak values of *ECPR* over Europe, the North-Atlantic ocean is an important supplier due to its large surface area. The time contours indicate that the origin of *ECPR* is predominantly westward, although low *ECPR* is observed due to low evaporation rates over the North-Atlantic ocean (section 5.1.3). The strong increase in travel time on the south-east side of the domain indicates that there is not a direct supply from these regions towards the Rhine catchment. However, there is a direct connection between North-East Europe and the Rhine catchment, although the travel time is relatively high due to low wind speeds as found in section 5.1.2 (Figure 5.5).

In line with the findings in the previous section, it is shown in Figure 5.6 that precipitation over the Rhine catchment originates mainly from the North-Atlantic ocean and Europe. *ECPR* from the North-Atlantic ocean is as high as *ECPR* from West-Europe, since both supply 12 mm/month. The Rhine, North-Sea and Mediterranean-Sea together supply only 7 mm/month of *ECPR*. The magnitude of *ECPR* supplied by the different source-regions variates strongly between summers in present and future climate and the summer of 2018. During the summer in 2018, the moisture supply from the North-Atlantic ocean is 16 and 6 mm/month less than in respectively present and future summers. Over West-Europe a drop in *ECPR* during the summer of 2018 is observed compared to present climate. However, relative to future climate, *ECPR* from West-Europe in 2018 is 2 mm/month higher in summer. Finally, a high moisture transport from the west of the study area is observed in all summers (Figure 5.6). As it was found by Van der Ent (2014) that especially during summers the *ECPR* from North-America can be significant, it is possible that this contribution is even higher than the contribution of West-Europe itself. However, due to the domain limitation, it is not possible to check to which extent *ECPR* originates from North-America.

5.2.2 Relative contribution

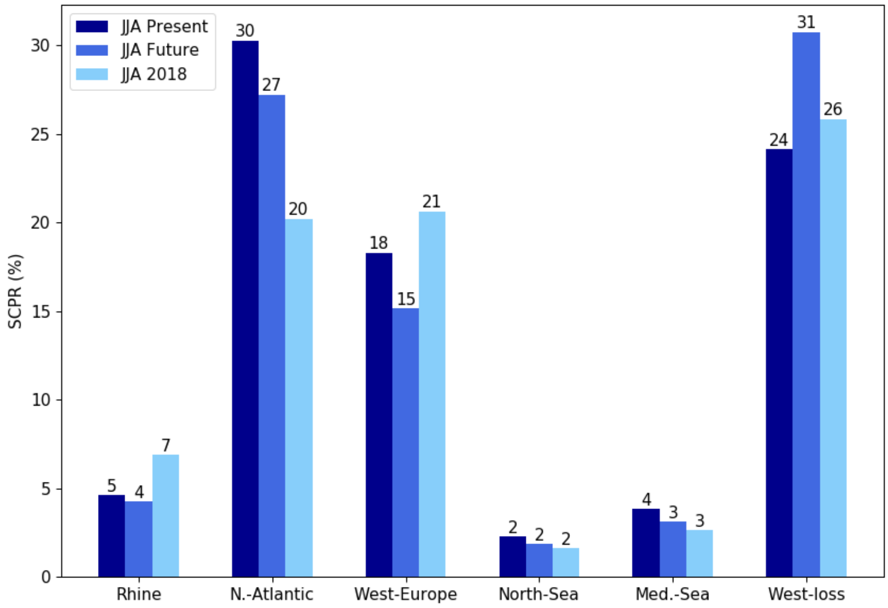

Figure 5.7: SCPR of different source-regions for the summer in present and future climate and 2018. Units are percentages. A value of 20% implies that the region supplies 20% of the total precipitation.

As precipitation was found to be very low in the summer of 2018, it is not surprising that the moisture supply from source-regions dropped consequently. However, if the moisture supply is investigated independent of the amount precipitation, relative differences between the contributions of the source-regions under different climate conditions can be found. The Source Contribution to Precipitation over the Rhine catchment (*SCPR)* is used to assess this.

It is shown that for the North-Atlantic ocean, the moisture supply drops with 7 percent in 2018, relative to the future climate. For West-Europe, another major supplier, an increase is observed: 21 percent of the precipitation over the Rhine catchment is supplied by evaporation over West-Europe in the 2018 summer. This is 6% more than during a future summer. The Regional Evaporative Recycling (*RER)* surprisingly increased up to 7% in 2018, while the supply of the North and Mediterranean Sea maintained its order of magnitude. The low *SCPR* over the North-Atlantic ocean during 2018 is partly caused by a disruption in the wind flow. The northerly flow field around the subtropical high (40°N, 15°W) and the south-westerly flow before the coast of Great-Britain are observed to be larger in the 2018 summer (section 5.1.2) than under present or future climate conditions (section 3.2.1). As a result the moisture supply towards Europe is limited and the *SCPR* of that source-region drops. *SCPR* over West-Europe and the *RER* over the Rhine catchment are found to be high which is related to the low wind-speeds over Europe as found in section 5.1.2. Due to these low wind-speeds, less evaporation over Europe was lost by advection which explains the relatively high *SCPR*.

6. Conclusions, limitations and recommendations

6.1 Conclusions

Precipitation over the Rhine catchment amounts 86 mm/month during winter and 92 mm/month during summer in the present climate. Whereas during winter a slight increase in precipitation relative to the future climate is found, during future summer the amount of precipitation decreases drastically from 92 to 66 mm/month. Wind is found to be flowing predominantly westerly and therefore large parts of the North-Atlantic ocean are expected to provide evaporation to precipitation over the Rhine catchment. During winter, the flow field of the westerlies extents some degrees more south than during summer, resulting in a larger potential supply area for precipitation over the Rhine catchment. However, in future winters this effects diminishes slightly, as the westerly flow field becomes smaller due to widening of the Hadley circulation. The wind speed is found to be higher over the North-Atlantic ocean during winters (~15 m/s) than during summers (~7 m/s). Regarding future conditions, especially in the upper part of the study area (between 50 and 60˚N), wind velocities are increasing with 2-3 m/s in both seasons. However, in future summer a drop in velocity is found over south-western Europe. As wind speed partly determines the magnitude of evaporation over the North-Atlantic ocean, consequently during winter higher evaporation values are found (150 to 300 mm/month) than during summer (75 to 150 mm/month). On the other hand, over Europe evaporation is almost zero in winter, where in summer the evaporation is around 100 mm/month. In future climate, evaporation is dropping in value over the North-Atlantic ocean, most significantly in winter. Additionally, in summer, evaporation is found to decrease also over South-Europe.

After backtracking precipitation over the Rhine catchment, *ECPR* is found to originate for ~25% west from the study-area, indicating possible moisture advection from North-America. Within the study area, *ECPR* is transported predominantly from the North-Atlantic ocean and West-Europe. In present winter, on an absolute scale the contribution from the North-Atlantic ocean is an order of magnitude larger than the contribution of the other source-regions (respectively 54 and 1-4 mm/month). In present summer, *ECPR* from the North-Atlantic ocean is halved (28 mm/month) and West-Europe has become a major supplier as well (17 mm/month). The regional contribution of the Rhine catchment is found to be low in both winter and summer (1 and 4 mm/month respectively), which is related to the small size of the catchment. In future winter the North-Atlantic ocean is found to supply 5% less of the total precipitation over the Rhine catchment. The relative contribution of the other source-regions (*SCPR)* does not differ more than 1% with present winters, indicating that the importance of the source-regions stays the same during future winter. For future summer, *SCPR* changes with a similar order of magnitude. The major suppliers (North-Atlantic ocean and West-Europe), show a decrease of 3% in *SCPR* relative to present summers. However, on an absolute scale the changes are large as both the North-Atlantic ocean and West-Europe supply significantly less *ECPR* in future summer (respectively 10 and 7 mm/month decrease). Finally, atmospheric moisture that is tracked at the west border is high in both present and future climate, but especially in future summer as 31 percent of the total precipitation over the Rhine catchment originates west from that border.

During the summer of 2018, precipitation over the Rhine catchment is even lower than during future climate summers, indicating that June, July and August of 2018 were exceptionally dry. The 10 mm/month drop is mainly caused by less precipitation over the Netherlands and Germany. The wind flow towards Europe is found to be predominantly westward. The wind speed is strong over the North-Atlantic ocean (10 m/s) but weak over Europe (2 m/s). Evaporation over the northern part of the North-Atlantic ocean is low (50 mm/month), while this increases towards the subtropical high (>100 mm/month). Over Europe, evaporation amounts 100 mm/month.

ECPR originates mainly from Europe and the North-Atlantic ocean. However, the supply from the North-Atlantic ocean during 2018 (12 mm/month), is much lower than during present and future summers

(28 and 18 mm/month respectively). Despite its small surface area, West-Europe has become equally important, as it also contributes 12 mm/month to precipitation over the Rhine catchment during the 2018 summer. The minor source-regions supply amounts similar to a future summer, although moisture supply from the Rhine catchment itself is slightly higher. *ECPR* that is tracked at the west border is 5 mm/month lower during 2018, however it is still higher (15 mm/month) than the individual contribution of the North-Atlantic ocean and West-Europe (12 mm/month). The *SCPR,* which is independent of the total amount of precipitation, is found to drop for the North-Atlantic ocean. This is the result of a low evaporation rate and a disturbed westerly flow field over the North-Atlantic ocean, limiting the moisture supply towards Europe. *SCPR* for Europe itself is high, caused by low moisture transport out of Europe.

6.2 Limitations

Since a model has been used for both moisture tracking and the analyses, unavoidable simplifications have been made. The major simplification that could affect the magnitude of moisture advection is the use of only two vertical layers. Although Van der Ent (2014) found that the WAM-2layers model yields nearly identical results as a highly advanced online multiple layer model, it is still a large deviation from reality.

For this study, data from EC-Earth was used. Hazeleger et al. (2012) compared EC-Earth data with observations, reanalysis data and other coupled atmosphere–ocean-sea ice models. Specific limitations of EC-Earth should be considered as it might explain some of the trends in the data which were observed in this study. The major limitation of the EC-Earth simulations is the fact that it is found to underestimate the surface temperatures (Hazeleger et al., 2012). For our study domain the underestimation in EC-Earth data is between 0 and 2 degrees over West-Europe and between 1 and 3 degrees over the North-Atlantic ocean (Hazeleger et al., 2012). Especially over sea, colder surfaces lead to lower evaporation rates by decreasing the exchange coefficient and the humidity contrast between the sea surface and the air above it (Laîné et al., 2014). Therefore, evaporation in this study is likely to be underestimated. To find out to which extent the underestimation of evaporation influenced our findings, this study should be repeated with other data.

The study has focused on quantifying *ECPR* over the entire study area. Despite the fact that the study area was extended to the coast of North-America, it was found that *ECPR* originated even west from the study area. As this contribution was on average 25%, a large part of the precipitation over the Rhine catchment was not tracked and therefore not analysed.

6.3 Implications & recommendations

Predicted increases in both the air temperature and sea surface temperature (IPCC, 2014) are very likely to affect the evaporation over the North-Atlantic ocean. As it is found that the North-Atlantic ocean is an important supplier of *ECPR*, enhanced global warming will affect the magnitude of precipitation over the Rhine catchment. Besides, the expected decrease of soil moisture content over Europe is going to affect the *regional recycling of evaporation* and consequently the amount of precipitation. However, the largest uncertainty in future precipitation is based on the global atmospheric circulation pattern, which is hard to predict (Bony et al., 2015). A shift of a few degrees in wind-direction close to the subtropical high can cause a large drop in moisture advection towards Europe. The drought during the summer of 2018 is only one example, caused by an anomaly in wind direction. Further research should therefore among others focus on the understanding of the behaviour of the westerlies under future climate conditions.

During the study, the *ECPR* pattern has not been compared with all the possible explanatory variables. It was chosen to investigate pressure, wind direction, wind speed and evaporation, as these were part of the water balance. However, variables such as relative humidity and sea surface temperature and their change towards the future, which (in)directly affect the magnitude of evaporation could be investigated as well. For the analyses of the summer of 2018, ERA5 data of its summer was compared with summers under EC-Earth present and future climate. In order to assess the return period of such a dry summer, it could be compared with single summers under present and future climate conditions.

The study has been performed with the use of EC-Earth data. Investigating the atmospheric moisture sources with other Global Climate Model or re-analyses data could give insight in possible shortcomings of EC-Earth data and (in)validate our findings.

Finally, this study can be repeated with a larger domain to quantify the importance of moisture supply from North-America.

7. References

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