Reviewer 1

R: We thank the reviewer for the suggestions/comments/feedback that helped us improve our manuscript and for tacking time to read and review our paper. Below you will find a point by point response to each concern/request raised throughout the review process.

The paper provides an interesting and unique contribution showing atmospheric rivers as drivers of high flows in the lower Rhine catchment. It thus enriches our understanding of hydrometeorological flooding drivers at the catchment level for this global region. By utilizing a long and comprehensive meteorological record, the authors show how indeed ARs have led to important damages in the region. It also provides interesting insights these events are preceded up to 7 days by intense moisture transport from the tropical North Atlantic basin typically precede ARs. The comments I have are minor which concern mainly methodological clarifications as well as suggestions to provide more insights of the repercussions of their findings. If a new version of the manuscript successfully address these issues I would recommend the article for publication. Please find here below my specific observations:

• Line 78: "i) analyze from a hydrological point of view" This sounds rather broad and ambitious; this line should be refined to specify what 'hydrological' actually means in the context of this publication

R: The text has been modified accordingly.

• Line 81: "iii) link the flood peaks with 80 the occurrence of AR". It does not look very scientifically sound to try to find a link between these two aspects. This suggest that the objective is already anticipating the results. This objective should be changed to something along the lines of 'explore how the occurrence of ARs explains flood peaks' or similar

R: Thank you for this comment. We have modified the paragraph according to reviewer's suggestion.

• 95-102: This paragraph should be enriched with references. It sounds as if data has been already processed and the authors are already presenting their results

R: Following the reviewer's suggestion we have added more reference for this paragraph and extended with more information.

• Line 98: "winter or spring floods, which are triggered by warm air intrusions with corresponding snow melt in flatlands and low mountain ranges and summer floods, which are fed by large-scale 100 heavy rain or long-lasting repeated precipitation episodes (in connection with late snowmelt / glacier runoff in the Alps)" Please improve the fluidity of this sentence or try to split it two. At present it is not very clear

R: The paragraph has been modified and improved in the revised version of the manuscript.

• Line 112: This paragraph would be enriched by a short 1-2 sentence conclusion about the general hydrological trends of these tributaries.

R: We have added the required in formation in the revised version of the manuscript.

• Line 114: How is this station representative for the catchment? What about the impact of upstream water infrastructure (dams, reservoirs, levees, and others which may mitigate floods)? Wouldn't readings at this specific part of the catchment give a misleading interpretation if the catchment is heavily intervened? Is hydraulic and infrastructure intervention indeed important here?. I think that this is very relevant when you compare events of 1925 vs the 1990s. I suppose that a number of hydraulic interventions have been made in the river in a period of ~60 years. Probably these interventions and the fact that you are just looking at river gauge readings are leading us to underestimate the connection between ARs and flood peaks. Even if the role of hydraulic infrastructure is not deemed as relevant in this part of the catchment, it would be useful to clarify these aspects throughout the text.

R: In the revised version of the manuscript we have added a paragraph regarding the importance of Köln gauging station as well as the influence of river training on the flood magnification in the Lower Rhine. Although Rhine River has been intensively modified, most of the river training was don in the upper Rhine, especially on the Swiss side of the river. There are numerous studies showing that the modification on the catchment area have a relatively small influence on the flood peak in the Lower Rhine.

• Line 144: reference? What is the general proportion of floods happening during winter vs summer? Are winter ones more or less frequent (generally speaking although these trends, naturally, are not constant)?

R: We have added a new figure (Figure S1) with the occurrence rate of annual maxima over the period 1817 – 2019. The annual maxima, @Köln gauging station occurs mainly during the winter months. This information has been added in the revised version of the manuscript. More than 80% of the annual maxima of daily streamflow at Köln gauging station occur during the extended winter months (November – March).

• Line 214 and in general throughout the text: The manuscript would be highly enriched if somehow these monetary losses are translated to current usd/eur values; not asking the authors to perform a complex econometric calculation but it would be useful to put these economic losses in perspective. For example, the 1925 event seemed to have caused losses of 100 Million DM vs 50 Million DM in 1993 vs 500M is 1995. How do they compare each other nowadays in current USD/EUR?. Similarly, the text would be enriched if the authors provide a table (or figure) comparing the impacts that these events have had on human lives, displaced people, monetary losses, infrastructure damages (even a qualitative description), and others. This would provide a useful information to understand the truly impacts of ARs in this key global catchment.

R: We agree with this comment and we have tried to change the currency of monetary losses in Euro. We were able to make mostly just a rough approximation, because we do not have data regarding the inflation rate for 1925/26 for example.

• Line 333, Conclusions:

o In general I think that either here or in previous sections there should be a short discussion describing the general trends of ARs-caused high flows over these 2-century time period. With the data you already have, it would be very useful to have a perspective on whether ARs-caused floods in the Rhine have been more recurrent? Or more intense? Both? None? While I understand that a full and comprehensive trend type of analyses might be out of the scope of this study, the manuscript will be highly enriched if even few sentences are added exploring this issue.

R: We fully agree with this comment and we have changes substantially the conclusion part. We have added also some discussion in the section to make it more readable.

o The conclusions should also highlight the socio-economic impacts that these events have caused.

R: As stated before the conclusions part has been modified substantially and we have tried to take into account all reviewer's suggestions/comments.

Reviewer 2

We thank the reviewer for the suggestions/comments/feedback that helped us improve our manuscript and for tacking time to read and review our paper. Below you will find a point by point response to each concern/request raised throughout the review process.

Review: Rivers in the sky, flooding on the ground

This paper investigates the relationship between atmospheric rivers and extreme flooding in the lower Rhine basin. So far, studies mostly investigated this relation between extreme rainfall (or flooding) and ARs for coastal regions. Therefore, the objectives to analyze the connection between ARS and floods occurring more inland is relevant and interesting, and fits the scope of HESS. The study describes the hydrometeorological situation of the three most extreme flood events over the lower Rhine basin in the last 180 years, and the connection with atmospheric rivers. In addition, composites of the large-scale circulation and IVT describing atmospheric rivers are analyzed for the 10 most extreme flood events. Although the analyses answer the research objectives, in my view there is much more potential and knowledge to gain from the dataset and method then is done so far in the manuscript. In fact, the section on the composites of the 10 largest flood events is very short, and has much more potential. I will give a few suggestions on additional questions/ experiments, and leave it up to the author/editor if these analyses are needed in this manuscript or can be potentially used as research questions for further studies. In addition, I have some major comments and unclarified on the paper below, which should be addressed before publishing. Furthermore, the writing of the manuscript can be improved, being consistent in tense, English language, and use of units throughout the manuscript. Please find my minor comments at the end of this document.

Additional questions arising from the manuscript:

How are the trends in flooding and ARs over the dataset? The dataset spans quite a substantial time (1836-2015) and in the method section it is indicated that floods probably would happen more frequently (Line 101-110), so it would be nice to explore this further using this dataset. You can also assess if Atmospheric Rivers are going to be more frequent and intense over the lower Rhine catchment as you refer to that is the case over the North Atlantic (line 370)

R: In the revised version of the manuscript we have included some text and a new figure (Figure S14) showing the trends in the annual maxim at Köln gauging station. Regarding the ARs we not aware of any observational study that has shown a robust and prominent trend in ARs in the historical record. Nevertheless, we have tried to compute the number of days when an AR occurs over the lower Rhine and add this information in the manuscript (see last paragraph of section 3.4).

ARs are projected to increase in the future but analysis of the historical trend, if observable, is challenging given the limited length of ground truth for ARs and complication from multi-decadal natural variability. Regarding the future projections, we can just rely on already published studies, because an in-depth analysis regarding this topic is beyond the scope of the current study.

As Atmospheric Rivers are associated with the Warm Conveyor Belt of extratropical cyclones, besides holding a lot of moisture, temperatures are often warmer than normal within these ARs. The effect of temperature on snow melt in the Alps or lower Rhine basin could positively influence discharge peaks. This aspect remains underexposed in this study. For example in the case of high temperature inducing snow melt could be related.

R: We fully agree with this comment. Most of the flooding for our selected events were related to a sharp increase in the temperature which led to snowmelt. We have added more information/ discussion regarding this issues in the revised version of the manuscript.

> I miss the explanation of the mechanism how Atmospheric Rivers result in extreme rainfall (for coastal areas; when an AR reaches a topographical barrier air parcels are lifted and adiabatically cooled, resulting in clouds and precipitation). For the lower Rhine this lifting mechanism is probably related to the Ardennes area? I am wondering if these mountains trigger enough uplift to result in precipitation or that the amounts of moisture during the three investigated cases is so high that only little uplift is needed.

R: The extreme flooding events at Köln and in the lower Rhine area are mainly related to extreme flooding of the Moselle river. This is one of the main reason for which we focused our manuscript also on the streamflow and precipitation data at Trier station (situated ion the main course of Moselle river). The catchment area of Moselle river includes the western side of the Vosges Mountains (elevation ~ 1,424 m) and the southern part of the Eifel range. We have added this information and more physical explanation regarding the extreme rainfall and ARs over our analyzed region, in the revised version of the manuscript.

> You have selected the 3/10 most extreme flood events in the lower river Rhine area and linked those to Atmospheric Rivers. In a dataset of 180 years, more flood events could be selected and their link with Atmospheric Rivers can be investigated. With that, the robustness of the link between ARs and extreme rainfall and flooding over the lower Rhine basin can be analyzed and put into perspective.

R: We agree with this comment, but our aim was to focus on the most extreme floods in the lower Rhine. For the current study we will keep just this 10 flood events, but in the future we want to make another study in which we want to include more floods events and also analyzed the floods and their triggers in the upper Rhine area.

Major comments:

The title is illustrative, although does not exactly reflect the novelty of this research with the focus on the link between large-scale circulation (ARs) and floods **inland**.

R: We agree with this comment. We have modified the title of our manuscript as follows: "Rivers in the sky, flooding on the ground: the role of atmospheric rivers for the inland flooding in central Europe"

Atmospheric studies such as Helen Dacre (2015) argue that atmospheric rivers are a result of constant local recycling of water along the cold front of an extratropical cyclone. This suggests that precipitation related to ARs originates more locally rather than from sub-tropical regions as is indicated in line 68, 74, 336 etc. Please discuss or revise.

R: The text has been modified accordingly. We appreciate the pointer to the Dacre (2015) study, but would like to note that the role of local versus remote moisture sources in ARs likely varies from region to region and from cases to cases. It's not universally true that "precipitation related to ARs originates more locally rather than from sub-tropical regions". We have tried to modify the text in such a way not to put extensive focus on the tropical source for the moisture transport.

In the introduction ARs and the relation with different teleconnections is mentioned, but I don't see that coming back in the rest of the paper. Have you checked NAO indices for the events you studied? This could be interesting, as you often refer to a low south of Greenland (Iceland) and a high over the coast of North Africa (Azores), which gives indication for a positive NAO resulting in strong flows to northwestern Europe. It would be interesting to invest the index of NAO for the selected flood events.

R: A discussion regarding NAO has been added in the revised version of the manuscript (see Section 3.5). For the period 1950 – 2019, when we have access to daily NAO values, NAO was in a positive case for the flood events of 1970, 1988 and 1993. For the flood event of 1995, NAO was altering between positive and negative values the week preceding the flood event. One of the most extreme case was for the December 1993 flood, when NAO was in positive phase from 16. October until 22 December 1993.

Although your showing IVT in the figures, I miss the embedding in the text. The case studies could have more focus on this IVT values and how anomalous they are, as to my knowledge values in IVT of 800 kg/m/s are quite exceptional. It would be nice to put this a bit more in perspective.

R: We fully agree with this comment and we have modified the text accordingly in the revised version of the manuscript, in such a way to integrate the IVT values better throughout the text.

The lag between AR/extreme precipitation is interesting and could deserve some more attention throughout the manuscript. Of course this mainly depends on local timing and location, indicating the importance of local processes (to be added on line 40) although it depends on the size of your catchment. Both in the conclusion as in the abstract I miss quantification of the results. Can you give some numbers to align your statements? For example indicate how anomalous the selected events were in terms of discharge and IVT related to the AR. I think an important conclusion from this research is that in these extreme events, large-scale circulation are rather similar but local conditions leading to the flood not. This is an interesting conclusion which could be highlighted more, and could be strengthened if it was further quantified in the conclusion and abstract as well.

R: Following the reviewer's comment/suggestion we will modify the text in such a way to add more information regarding the magnitude of the selected events and how anomalous they are in a long term perspective. We will change the text through the entire manuscript to add the required information where is needed.

Minor comments:

Line 8: The role of the large scale atmospheric circulation

Line 13: sentence: The influence of ... In my view atmospheric rivers are part of the large-scale circulation, the .. is done via the prevailing large-scale atmospheric circulation.. sounds very odd to me

Line 34: that coping with floods is not **trivial**

Line 40: I would argue that for flood forecasting and the time of occurrence, location and magnitude scales from mesoscale to local scale are important. Especially knowledge on local orography is needed to get the location of the flooding right

Line 42: Same sentence as last sentence of previous paragraph.. combine?

Line 49: This sentence is not clear. What do you mean with regional and local climates?

Line 115: Rhein --> Rhine

Line 118: what is the time resolution of the reanalysis data?
Line 119: I am confused that a re-analysis dataset has ensemble members, could you explain that?
Line 121: has several improvements > vague statement, either name improvements or leave out
Line 133: divided by gravity (g).
Lines around 133: What is the vertical resolution of your wind and specific humidity data?
Line 152: Where do you show the EOBS gridded precipitation dataset? Not clear how and if this comes back in your results. Although it would be good to analyze a gridded precipitation field over the lower Rhine basin instead of a point observation at Trier.
Line 161: .. in the large parts of the Rhine catchment..
Line 164: od -> of
Line 167: Can you quantify the total amount of precipitation over the lower Rhine basin area instead of showing the gridpoint values in the appendix. That would give more quantification to the results.
Line 169: This sounds like a positive North Atlantic Oscillation. Would be good to check the index for the selected events.
Lines around 170: Miss numbers of IVT in 1925 case, that would give indication of the 'severity' of AR. Can you give some IVT values here to give some indication as you do for the hydrometeorological situation of 1993 (line 229). In general it would be good to embed the values of IVT a bit more within the text as I think they are quite exceptional, can you compare with climatology? Or average value of ARs at this latitude (as the value of IVT is latitude dependent)
Line 180: specific humidity or moisture
Line 183 etc: Why do you talk about wind and moisture separately here? You can refer to IVT and Figure 3 and in my opinion there is no need in showing figure 4 as it gives the same information as Figure 3.
Line 223: too should be to
Line 228: Again, could you give precipitation values averaged over the basin? And compare that to climatology?
Line 238: Where is statement based on? Add reference
Line 268: become > became. Keep tenses consistent throughout the result section.
Line 268: Where is Berus meteorological station located? Indicate in map
Line 298: driver > driven
Line 319: plum should be plume?
Line 321: by a south-westerly wind (Figure 11) > you are showing IVT vectors and no wind vectors in Figure 11 so wrong reference
Line 322: By visual inspection.. etc. Are you referring to the individual ARs per event or the composites here? If you refer to the composites I would not expect to see individual ARs as the composite gives an average and the ARS are therefore smoothed and you can expect IVT with widths bigger than 1000 km wide.
Line 336: Sentence 2 in the conclusion is not a conclusion of your work, but new information: I would move it to the introduction
Line 346: what is meant by westerly, southwesterly and north-westerly large-scale circulation types? Do you mean prevailing winds? Please clarify.
Line 358-363: This sentence is an explanation why more storms (ARs) occur in winter and should be moved to the methodology section to explain why this study focuses on wintertime.
Line 363: .. is done .. this sentence is not very easy to read
Line 379: I guess this research is about the UK? Maybe good to add that in the sentence to be more specific

R: All the minor comments/suggestions have been taken into account and addressed individually in the revised version of the manuscript.

Table & Figures
I see in Table 1 that the magnitude of the flood of 1995 is as high as the one in 1920, so why was the case of 1995 described and not the one from 1920? Or is it because these stream flows are from Koln while you based your analysis on the ones from Trier? This should be stated more clearly in the text, as it is not clear from the methods.

R: The choice of 1925/26, 1993 and 1995 is mainly due to data availability (precipitation at Trier gauging station, daily precipitation over Germany - REGNIE database). We have added this information in the revised version of the manuscript.

Also streamflow in Trier station is mentioned in Figure 4 and similar figures, while I understand from the Composite events section that you base your analysis on flood peaks measured at Koln (should be Cologne) gauging station. This is confusing.

R: We will modify the text in such a way to make more clear why we used both flood peaks at Trier and Köln. In general, the floods peaks at Köln are preceded by a few days by flood peaks at Trier gauging station. Most of the flood event at Köln and in the lower Rhine are triggered by flood peaks on the Moselle River (where Trier gauging station is situated). That's why we show both time series.

Missing units in Figure 3, 4 and all similar figures

R: The units have been added for all the figures in the manuscript in a proper manner.

In my opinion the figures with daily specific humidity and wind at 900 hPa do not add enough additional information to be shown in the main manuscript.

R: These figures have been removed from the revised version of the manuscript.

Figure 2: alone should be along

R: Modified as suggested.

Figure 2b and all subsequent figures. Is it needed to show daily streamflow from all these locations and for the whole year? If so, those locations should also be located in Figure 1 or mentioned in the methods section. In my opinion the a figures with discharge at Trier and Cologne give enough information and I would rather show the spatial distribution of precipitation as an addition.

R: We agree with the reviewer, but the main message by using all gauging station on Rhine catchment area is to show that the flood peaks at Köln gauging station are mainly influenced by the flood waves of the Moselle river and to a much lesser extend by the streamflow in the middle and upper Rhine basin.

Figure 12: Not sure what the colors present here? Are these the colours for the 10 different extreme events? I cannot imagine that the orange AR just south of Greenland at Lag0 leaded to a flooding in the Alps, can you comment? This figure needs more explanation in the caption and also a color scale.

R: In Figure 12 there is a representation of all ARs recorded, over the whole North Atlantic basin, prior to the floods. Some of the ARs do not reach the European continent and are not related to our analysis, but is was very hard to exclude them from the figure. It is a rather challenging technical problem due to the data format. Nevertheless, we have tried to exclude all the ARs which are not related to our floods from the figure in the revised version of the manuscript.

Some figures in the additional material miss units and the data sources should be clarified in more detail, are these gridded observation data, re-analysis?

R: All figures have been modified/improved following all the comments/suggestions from all 3 reviewers.

References

Dacre, H.F., Clark, P.A., Martinez-Alvarado, O., Stringer, M.A. and Lavers, D.A., 2015. How do atmospheric rivers form?. *Bulletin of the American Meteorological Society*, *96*(8), pp.1243-1255.

I just wanted to refer to this article which just appeared in Journal of Hydrometeorology which also makes the connection between Atmospheric Rivers and floodings, but then for western Norway:

Hegdahl, T.J., Engeland, K., Müller, M. and Sillmann, J., 2020. An event-based approach to explore selected present and future Atmospheric River induced floods in western Norway. *Journal of Hydrometeorology*, (2020). https://journals.ametsoc.org/doi/10.1175/JHM-D-19-0071.1

R: Thank you for the references. We were not aware of the Hegdahl et al. (2020) paper. We have integrated the paper in the introduction part.

Reviewer 3

R: We thank the reviewer for the suggestions/comments/feedback that helped us improve our manuscript and for tacking time to read and review our paper. Below you will find a point by point response to each concern/request raised throughout the review process.

Rivers in the Sky, flooding on the ground
Reviewer 3 Report Round 1

This article analyzes the role played by atmospheric rivers in some of the most important flood events in the lower part of the Rhine River basin. Overall, the paper is well written, and the inclusion of the perspective of the hydrological extremes –floods– rather than the simple extreme precipitation is always an added value. The authors find most of the more important flood events over the region were preceded by an AR event, and this is an interesting result that could be valuable for the region. The quality of the figures is acceptable, but it could be improved. I suggest the authors improve some of them if that is not very problematic.
I believe that the title is a bit pretentious. It is a very catching title that would be probably the best choice for a review paper or a paper intended to get conclusions on a global scale. This manuscript is focused on a very particular region of Inland Europe, and I think that this should be reflected in the title somehow. I would perfectly understand if the authors would like to keep the "Rivers in the sky, flooding on the ground" –I would have done the same–, but I suggest that this title should be extended with a citation to the region of interest somehow.

R: We agree with this comment. We have modified the title of our manuscript as follows: "Rivers in the sky, flooding on the ground: the role of atmospheric rivers for the inland flooding in central Europe"

I have already read the comments made by the other reviewers, and I mostly agree with them. Reviewer 2 suggests to extend the 10-events composites. I will not put that condition as necessary to give my full recommendation to publish, but I think that it could be a good improvement for the paper if the authors are willing to do it.

R: Although we fully agree with this comment/suggestion, our aim was to focus on the most extreme floods in the lower Rhine. For the current study we will keep just this 10 flood events, but in the future we want to make another study in which we want to include more floods events and also analyzed the floods and their triggers in the upper Rhine area. If we extend the current study to more flood events, it means changing almost substantially the structure and the outcome. We want to regard this study as a starting point for more in-depth studies regarding extreme inland flooding and their large scale driver, with a special emphasis on ARs.

Also, this colleague suggests the authors include a discussion about Helen Dacre's (and others) perspective of the importance of local convergence of moisture in ARs development. He/She is right, but I would like the authors to take into account –when they discuss this point– that there is also a huge bunch of articles of all kinds pointing out to the essential role played by the large scale advection of tropical and subtropical moisture. I do not think that the authors should take sides with any of those perspectives –actually, I believe that both mechanisms are necessary, and the relative importance between them changes among the events–, but both may be included in the discussion.

R: We agree with both reviewers comments. Thus, we have tried to change the text in the revised manuscript to be able to properly discuss and integrate the aforementioned comments/concerns. Some parts of the revised version of the manuscript have been substantially modified and new information has been added.

I will not suggest major changes, however, some of my comments (particularly those regarding the very likely explosive nature of some of the involved cyclones and also those regarding the role played by NAO) will take some time from the authors to be replied. I would like to read and discuss the answers in an eventual second round of the review process.

R: We have tried our best to improve the revised manuscript tacking into account the reviewer's suggestions/comment.

Minor Comments

L.43 I suggest the authors consistently arrange the citations by chronological order. It is not only fairer for our colleagues, but also the result is more elegant. For example, in this case, I would start from Lavers and finish by DeFlorio or Guan and Waliser.

R: The references have been modified accordingly.

L.54 Please, leave a blanck space between "50" and "km".

R: Modified as suggested.

L.57 The beneficial aspects of ARs are not restricted to arid/semiarid areas at all. Most ARs are beneficial even in mid-latitudes.

This idea is well discussed in Ralph (2019), and I think that should be included somehow in the text. Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., ... & Smallcomb, C. (2019). A scale to characterize the strength and impacts of atmospheric rivers. Bulletin of the American Meteorological Society, 100(2), 269-289.

R: Modified as suggested.

L.65 There are some other important analyses relating ARs and extreme precipitation and floods in Europe that the authors did not take into account. (e.g. Eiras-Barca et al.; 2016, 2017).

R: We have integrated the aforementioned references in the revised version of the manuscript.

L.87 I think that section 2 must be included in the methods section. However, this is just my opinion and I let this decision to the authors.

R: We agree with this suggestion and we moved section 2 in the data and methods section.

L.116 If the authors had SLP, why did they start the vertical integration at the level of 1000 hPa instead of SLP, which would the most correct option?

R: We start the vertical integration at 1000 hPa due to the limitation for the wind and specific humidity data. The SLP data is used to look at the large scale circulation. For the vertical integration we are actually using the surface pressure.

L.130-134 I don't see the need to describe with words what the equations are already saying.

R: Modified as suggested.

L.135 The algorithm (and database) developed by Guan at UCLA is one of the most commonly used in our field, and I am not going to call it into question. However, did the author consider the possibility that the detection thresholds could have substantially changed in these almost 200 years that they are considering in the analysis?

R: We appreciate this interesting question. Fundamentally, this relates to the question whether the definition of ARs should change as the climate changes, and we think it could be argued either way. In the current study, we chose to use a fixed AR definition – similar approaches have been used for studying AR changes between the current and future climates (e.g., Espinoza et al. 2018; Massoud et al. 2019) and have proved useful. This is also consistent with the study of other types of extremes. For example, a hurricane a century ago is still a hurricane today.

L.136 Please, replace the asterisks by ·

R: Modified as suggested.

L.152 How well is performing EOBS over Germany? Some analyses pointed out the fact that EOBS may not be the best option over continental Europe...

R: The new EOBS version (v21.e) is rather robust over Germany, mainly because in the E-OBS database the highest number of station are the German ones. The E-OBS data was included in the supplementary figures mostly to show that the precipitation was not located over Germany, but it was stretching From France towards Germany in a rather narrow band. In the revised version of the manuscript we have included also the REGNIE dataset, which is a German product of daily precipitation with a 1km x 1km spatial resolution and which is restricted only to country level.

L.164 Please, leave a blank space between 27 and mm. Take this into account throughout the rest of the article.

R: Modified as suggested.

L.320 The presence of both the high pressure over the Iberian and the low-pressure north of the British isles will be both almost mandatory requirements for a strong AR to landfall in the region of interest. However, I am not sure that the plots in Figure 11 are really catching the importance of the low-pressure system, which is essentially the one that is carrying the warm conveyor belt and the AR in its pre-frontal region. Particularly, I would be interested to know how many of those 10 systems were explosive cyclogenesis. There is a recent article (Eiras-Barca et al., 2018) analyzing the important correlation between explosive cyclogenesis and strong ARs over Europe, and it would be interesting to know how many of those 10 systems leading to the 10 highest flood peeks were explosive cyclones. Additionally, I think that there is room here for a brief discussion about the role played by the NAO in all this. I suggest the authors include a brief discussion on the matter.

R: Following the reviewer's suggestion/comment we have actually checked if some of the extreme floods analyzed in our study (e.g. 1988, 1993 and 1995) are also associated with explosive cyclones. We have used the database kindly provided by Jorge Eiras-Barca (https://esd.copernicus.org/articles/9/91/2018/esd-9-91-2018.html). For the aforementioned 3 extreme flood events no explosive cyclones have been recorded during the flood peaks or prior to them.
For the whole analyzed period (1836 – 2019) it has been shown that the NCEP-20C reanalysis dataset as well as ERA-20C data are not optimal datasets for extratropical cyclones and windstorms analysis (Befort et al., 2016) (https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/asl.694). In their study Befort et al. (2016) have show that the use of the long-term reanalysis dataset (NCEP- 20C and ERA-20C) is hampering a reliable analysis of real long-term trends of cyclone and windstorm activity. In a similar study Wang et al. (2013) (https://link.springer.com/article/10.1007/s00382-012-1450-9) have shown that the use of NCEP – 20C ensemble-mean is found to be unsuitable for accurately determining cyclone statistics. Thus, we cannot make a proper analysis regarding explosive cyclones and extreme flood events over Lower Rhine over the whole length of our dataset. Nevertheless, we have added a new section regarding the role played by the NAO in the occurrence of the flood events in the Lower Rhine (see Section 3.5)

Figure 1 Is not clear what "euro_dem" is.

R: The text has been modified following the reviewer's suggestion.

Figures 3,4,6,7,9,10,11 Please include the units in the color bars or the arrows.

R: The units have been added for all the figures in the revised manuscript in a proper manner.

Rivers in the sky, flooding on the ground: the role of atmospheric rivers for the inland flooding in central Europe

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Abstract. The role of large-scale atmospheric circulation and atmospheric rivers (ARs) in producing extreme flooding and heavy rainfall events in the lower part of Rhine River catchment area is examined in this study. Analysis of the largest 10 floods in the lower Rhine, between 1817–2015, show that all these extreme flood peaks have been preceded up to 7 days in advance by intense moisture transport from the tropical North Atlantic basin, in the form of narrow bands, also known as atmospheric rivers. Most of the ARs associated with these flood events are embedded in the trailing fronts of the extratropical cyclones. The typical large-scale atmospheric circulation leading to heavy rainfall and flooding in the lower Rhine is characterized by a low pressure center south of Greenland which migrates towards Europe and a stable high pressure center over the northern part of Africa and southern part of Europe and projects on the positive North Atlantic Oscillation phase. The days preceding the flood peaks, lower (upper) level convergence (divergence) is observed over the analyzed region, which indicates strong vertical motions and heavy rainfall. Vertically integrated water vapor transport (IVT) exceeds 600 $kg \cdot m^{-1} \cdot s^{-1}$ for the largest floods, marking these as very strong ARs. The results presented in this study offer new insights regarding the importance of moisture transport as driver of extreme flooding in the lower part of Rhine River catchment area and we show for the first time that ARs are an useful tool for the identification of potential damaging floods inland Europe.

1 Introduction

The intensity and frequency of precipitation extremes and floods have increased over the last decades in many parts of the world (Blöschl et al. 2015; Stadtherr et al. 2016). As a result, an increase in the flood hazard and its associated damages has become a major concern both for society and economy. In terms of economic losses, floods are the most widespread hazard at European level (Barredo 2009; Paprotny et al. 2018). Throughout the last decades Europe has been affected by numerous heavy rainfall events corroborated with damaging floods. Among the most costliest and damaging floods, at European level, we have: the 1993 and 1995 winter floods in France, Germany, Netherlands and Belgium (Chbab 1995; Fink et al. 1996; Engel 1997; Disse and Engel 2001); the 2000, 2007 and 2014 floods in U.K. (Kelman 2001; Posthumus et al. 2009; Muchan et al. 2015; Stevens et al. 2016); the 2002 and 2013 damaging floods in the Elbe river catchment area (Ulbrich et al. 2003a; Ulbrich et al. 2003b; Ionita et al. 2015a); the 2005 floods in the eastern part of Europe (Barredo 2007; Ionita 2015b) and the 2010 floods in central part of Europe (Bissolli et al. 2011), among others. These recent floods, recorded in different parts of the European continent, have shown that coping with floods is not trivial and for a better management and improvement of flood predictions it is necessary to improve our understanding of the underlying mechanisms of these extreme events. Taking into account the fact that climate change is expected to lead to an intensification of the hydrological cycle and in particular the hydrological extremes (O'Gorman and Schneider 2009; Allan et al. 2014) it is imperative to properly understand the relationship between heavy rainfall events and floods and the prevailing large-scale atmospheric circulation on scales from planetary to mesoscale, in order to be able to provide skillful forecasts of upcoming floods in terms of time of occurrence, location and magnitude.

Flood risk management decisions and flood forecasting depends strongly on our understanding of the large scale drivers of hydrological variability (Lavers et al. 2014; DeFlorio et al. 2019; Guan and Waliser 2019). The timing, magnitude and duration of floods and heavy rainfall events depends on the hydroclimatic variability on different time scales ranging from hourly, daily, seasonal to interannual. This variability is connected to the large scale moisture transport on the entire atmospheric column, which in turn is controlled by different large scale teleconnection patterns such as the North Atlantic Oscillation (NAO), the Pacific North American Oscillation (PNA) and El Niño-Southern Oscillation (ENSO) (Guan et al. 2013; Paltan et al. 2017). Studies of ARs impacting the coastal European region found significant relationship between winter ARs and NAO (Lavers and Villarini 2013b). In the southern part of Europe ARs are concurrent with a positive NAO phase, whereas over the northern part of Europe, ARs are concurrent with a negative phase of NAO. Apart from these pre-defined large-scale teleconnection patterns, regional and local climates also modulate the water vapor transport, in the form of transient, narrow and elongated corridors, also known as atmospheric rivers (ARs) (Zhu and Newell 1994; Guan and Waliser 2019a; Ralph et al. 2018; Shields et al., 2018). ARs are responsible for ~90% of the poleward vertically integrated water vapor transport outside of the tropics and at any time there are at least 3 to 5 ARs around the globe (Zhu and Newell 1998; Guan and Waliser 2015). Their horizontal dimensions can be up to several thousands km long with an average width of ~ 500 km (Ralph et al. 2004b; Ralph and Dettinger 2011). The moisture associated with ARs can be visible in the free troposphere as well as in the boundary level (Ralph et al. 2004a; Neiman et al. 2008), and their structure results from either local convergence along the cold front of extratropical cyclones (Dacre et al. 2015) or from transport from lower latitudes (Zhu and Newell 1998).

Different studies have linked the occurrence of ARs to extreme rainfall and flooding in different parts of the world, extending from arid/semi-arid areas to the polar regions (Ralph et al. 2019). For example, in California, ARs contribute to 30 – 50% of the river flow (Dettinger 2011) and they supply on average ~30% of the total precipitation in the west coast of U.S and Europe (Lavers and Villarini 2013a). On the other hand, heavy floods in California and Washington states have been linked to ARs occurrence (Ralph et al. 2006; Neiman et al. 2011), and similar results were later found in other west-coast areas. In a recent study, Little et al. (2019) have shown that ARs are a major contributor to extreme snowfall and ablation in the Southern Alps of New Zeeland. At European level ARs have been found to significantly influence heavy rainfall events over the Iberian Peninsula (Ramos et al. 2015; Eiras-Barca et al. 2016; Brands et al. 2017; Eiras-Barca et al. 2018), U.K. (Lavers et al. 2011; Lavers and Villarini 2015), Norway (Benedict et al. 2019; Hegdahl et al. 2020) and France (Lu et al. 2013). Lavers et al. (2011) have shown that U.K. extreme floods and precipitation are mainly driven by ARs, while Lu et al. (2013) related the extreme floods in the western part of France in January 1995 with tropical moisture exports in the form of ARs.

All the aforementioned studies, at European level, were conducted over coastal regions, where ARs make landfall, thus contributing substantially to extreme rainfall events and floods over these regions. Nevertheless, for the European mainland there are limited studies which show a direct link between ARs occurrence and heavy rainfall events and flooding. For example, Paltan et al. (2017) have shown that 50% of the Rhine river floods can be related to ARs, but their study took into account all floods peaks which are exceeded 10% of the time, over the period 1979 - 2010. In this study, we want to explore the relationship between the 10 highest flood peaks (in terms of their magnitude) in the lower part of Rhine river catchment area and intense water vapor transport and the large-scale atmospheric circulation over the last 180 years, including the lead/lag relationship between the timing of flood peaks and the occurrence of AR conditions which has not been the focus of previous studies on AR-related flooding.

The objectives of this study are to (i) analyze from a hydrological point of view (e.g. daily hydrographs and flood magnitude) three of the most damaging winter floods (1925/26, 1993 and 1995) in the lower part of Rhine River catchment area; (ii) analyze the large-scale circulation preceding these extreme flood events; (iii) explore if/how the occurrence of ARs explains extreme flood peaks and (iv) use a cohesive long-term data sets (e.g. reanalysis products) to analyze the common drivers of 10 of the highest flood peaks (in terms of magnitude) recorded at Köln gauging station, situated in the lower Rhine.

The outline of the study is as follows. The basic features of the Rhine River catchment area are described in Section 2, while the data and methods are described in Section 3. The hydrometeorological situation in relationship with the most damaging floods is given in Section 4. The discussion and the main conclusions of the paper are presented in Section 5.

2 Study region and data

2.1 Catchment area

Rhine River ranks the 9th among the Eurasian rivers, having a total length of ~1250 km, a drainage area of ~185260 km^2 and an average streamflow of 2300 m^3/s. The catchment area of Rhine River covers 9 countries (Germany, Austria, Switzerland, Belgium, Luxembourg, Lichtenstein, Italy, France and the Netherlands) (Figure 1), while the river itself provides services for inland waterway transportation, drinking water, power generation, agriculture, tourism and urban sanitation (Uehlinger et al. 2009). The Rhine is Europe's most important inland waterway, transporting almost 200 million tons per year (approximately two-thirds of the European inland waterway volume) (Meißner et al. 2017).

Rhine River catchment area comprises different sub-basins (e.g. the Alpine Rhine, the High Rhine, the Upper Rhine, the Middle Rhine and the Lower Rhine), influenced by different meteorological conditions. As such, the Rhine river has a complex runoff regime, with a summer maximum on the Alpine, High and Upper Rhine, and a winter maximum on the Middle and Lower Rhine, influenced by tributaries Main and Moselle (Belz 2010; Pfeiffer and Ionita 2017). Extreme floods events in the Rhine region can be divided in two classes according to their hydrometeorological causes i) winter/spring floods, triggered by warm air intrusions and snow melt, occurring mostly in the flatlands (e.g. Lower Rhine) and ii) summer floods, triggered by heavy rainfall and low snow melt in the Alpine region. Documentary and historical records, since 1000AD, do not list a single flood event which occurred simultaneously in all sub-basins of the Rhine river (Disse and Engle, 2001).

The major tributaries of Rhine river, on the German side are: Neckar, Main and Moselle. All the tributaries are characterized by a pluvial regime, with the mean runoff reaching the highest values in the winter months and the minimum in August- September. Throughout the 20th century, flood peaks show an upward trend in the Alpine and pre-Alpine Rhine basin (Belz et al. 2007). In the Middle and Lower Rhine, extreme floods due to enhanced rainfall sometimes combined with snowmelt, have increased in intensity, especially during the winter months, in the second part of the 20th century (Belz et al. 2007). The increasing trend in the flood peaks, in the Middle and Lower Rhine basin, is largely due to the contribution from the Moselle River where flood waves with peaks up to 4200 m^3/s can occur in winter months (annual mean average discharge at Cochem gauging station = 313 m^3/s). Min (2006) has shown that the basin-averaged precipitation for the Moselle basin shows a significant increase since 1980, accompanied by a tendency towards more frequent intense precipitation events (e.g. exceeding 10mm/day) in the winter half-year (November–April). The overall increase in the winter precipitation in the catchments of the lower Rhine tributaries, has caused an increase of ~10% of the mean discharge at Lobith gauging station during the 20th century.

Flooding along the Rhine River basin is a natural phenomenon. Nevertheless, flood risk, especially in the Upper Rhine has been highly increased by river training. The Upper Rhine was subjected to heavy river training from the beginning of the 19th century until 1977. As a result of this river training, the flood risk downstream has considerably increased due to a shortening of the river course, a reduction of potential floodplains by constructing dikes directly on the summer river bed, increased velocity of waves and the overlapping with flood waves from the tributaries. For Köln gauging station, Pinter et al. (2006) have shown that river engineering had an insignificant effect on the flood magnification throughout the 20th century. The main driver of the flood magnification at Köln gauging station has been found to be an increase in the precipitation over the Rhine basin. A small contribution to the flood magnification in the lower Rhine comes also from land use and industrialization of the German agriculture.

2.2 Data

The main variable analyzed in this study is the daily streamflow data at Köln gauging station situated in the lower part of the Rhine catchment area (Figure 1). Köln gauging station is one of the most important gauges along the Rhine; at this point starts one of the most populated area over Rhine basin - North Rhine-Westphalia, respectively. In addition, before Köln gauging station there is a confluence point for three of the main tributaries of the lower Rhine: Lahn, Moselle and Sieg. We choose this gauging station for the current analysis due to the availability of daily streamflow data (1817 – 2019), the importance of the Lower Rhine both from an economical and societal point of view and because the river training effects are not so significant in this part of Rhine's catchment area. The daily streamflow data was provided by the German Hydrological Institute (www.bfg.de).

For the large-scale atmospheric circulation, we have used the daily sea level pressure (SLP), zonal and meridional wind, geopotential height at 500mb level, potential vorticity, air temperature at 850mb level, specific humidity and surface pressure from the 20th Century Reanalysis data V3 (Slivinski et al. 2019). The 20th Century Reanalysis data V3 uses a state-of-the-art data assimilation system and surface pressure observations, it has 64 vertical levels and 80 ensemble members. The output of this reanalysis product is a 4D global atmospheric dataset spanning the period 1836 to 2015. The resolution of the data set is ~1° x 1° (Slivinski et al. 2019).

The vertically integrated water vapor transport (IVT) (Peixoto and Oort 1992) is calculated through zonal wind (u), meridional wind (v) and specific humidity (q), from the 20th Century Reanalysis v3 data set. IVT vectors for latitude (ϕ) and longitude (λ) are defined as follows:

$$\vec{Q}(\lambda,\phi,t) = Q_\lambda \vec{i} + Q_\phi \vec{j}$$

Where zonal (Q_λ) and meridional (Q_Φ) components of Q are given by:

$$Q_\lambda = -\int_{1000}^{300} qu \frac{dp}{g}$$

$$Q_\phi = -\int_{1000}^{300} qv \frac{dp}{g}$$

where *u* is the zonal wind component, *v* is the meridional wind component, *q* is the specific humidity and *g* is the gravity. The ARs are identified using the vertically integrated water vapor transport (IVT) between the 1000 and 300 hPa levels. The methodology used in this study to define an AR is based on the global detection algorithm of Guan and Waliser (2015). We consider an AR if the IVT exceeds an intensity threshold (e.g. the local 85th percentile), if it has a minimum value of 100 $kg \cdot m^{-1} \cdot s^{-1}$ and a length of at least 2000 km, among other considerations detailed in Guan and Waliser (2015). Performance of this AR detection algorithm has been validated against dropsonde observations over the north-eastern Pacific (Guan et al. 2017), and results based on this global algorithm were found to agree well with algorithms independently developed for three specific regions (Guan and Waliser 2015).

To identify the flood events, we extracted, from the daily streamflow time series at Köln gauging station, the top ten daily streamflow values over the period 1817 – 2019 . We have compared our flood events with the ones from the information platform of the German Hydrological Institute (http://undine.bafg.de/rhein/rheingebiet.html). We have restricted our analysis just over the winter months (November – March), due to the fact that summer floods tend to be produced by different mechanisms (e.g. convective precipitation). In the lower Rhine, more than 80% of the flooding events occur during the period November – March (Figure S1). For the top 10 winter flood events over the lower Rhine River basin (Table 1), we have extracted also daily precipitation and daily mean air temperature at Trier weather station, which is situated on the main course of Moselle River, one of the most important tributaries of Rhine River. We choose Trier station due to its length (1907 – 2019) and due to the fact that most of the floods on the lower basin of Rhine river are mainly influenced by the input from the Moselle river (Figure 1). The daily precipitation and daily mean air temperature data were extracted from the ftp server of the German Weather Service (ftp://opendata.dwd.de/climate_environment/CDC/).

To analyze the spatial distribution of the daily precipitation amount during the days prior the flood peaks we have used two gridded datasets: daily precipitation data from the EOBS-v20e data set (Cornes et al. 2018), with a spatial resolution of 0.25° x 0.25° and the REGNIE daily precipitation dataset (Rauthe et al. 2013) with a spatial resolution of 1km x 1km. The E-OBS data set cover the whole European region, while the REGNIE dataset is restricted to Germany.

3 Results

3.1 Hydrometeorological situation - 1925/26

The last week of November 1925 was characterized by heavy snowfall in the western part of Germany and the lower areas of the Rhine River basin (Soldan 1927). After a short period of dry and cold days, at the beginning of the second week of December it began to thaw, until mid-December. In parts of the Rhine area, heavy snowfall corroborated with extremely low temperatures were recorded over the period 12 – 18th of December 1925 (Figure

S2 and Figure S3). After this period of heavy snowfall and low temperatures, warm and humid air masses penetrated from the south-west on the 26th of December. The warm and humid air slid onto the cold air between the mountain areas of the Rhine region and caused extremely high rainfall in large parts of the Rhine catchment area between 27th until 29th of December 1925 (Figure S4). From the 27th until 31st of December heavy rainfall affected large parts of the Moselle's catchment area and the lower part of Rhine River basin. The highest rainfall amount, at Trier station, was recorded on the 27th of December (27mm) (Figure 2a). The cumulated rainfall amount over the period 27 – 31 December was 92.5mm. Overall, in December 1925 the total rainfall amount over the lower part of Rhine Rivers basin was on average almost double compared to the climatological mean (Figure S5a). These extreme rainfall events in the last week of December 1925, were driven by a dipole-like structure in the SLP filed with a deep low pressure system (960 hPa) centered south of Greenland and a high pressure system (1025 hPa) centered over the northern part of Africa (Figure 3a). This dipole-like structure started to develop on the 25th of December and persisted until the 31st of December, slightly shifting its centers (Figure 3). This circulation structure led to a pronounced south-westerly air flow over France and western part of Germany, associated with a narrow band of atmospheric moisture extending from the U.S coast up to central part of Europe. The narrow band of moisture was particular active on the 27th, 28th, 29th and 30th of December (Figure 3c, 3d, 3e and 3f), leading to heavy rainfall over northern part of France and western part of Germany (Figure S4). As this band of moisture ascended in the warm sector of the extra-tropical cyclone and was forced to rise over the mountain areas in the Moselle catchment area (southern Vosges Mountains in France, and Hunsrück and Eifel Mountains in Germany), heavy rainfall was forced and thus the high flood peaks some days later in the lower part of Rhine River basin. At Trier gauging station, the flood peak reached its third highest value (3600 m^3/s) on the 31st of December 1925. During the days with extreme rainfall and flood peaks at Trier station (27 – 30.12.1925, Figure S4) the maximum of the water vapor flux within the plume exceeded 700 $kg \cdot s^{-1} \cdot m^{-1}$ (Figure 3, Table 2), while at day -1 and day 0 of the flood peak at Köln gauging station the vapor flux weakened to ~400 $kg \cdot s^{-1} \cdot m^{-1}$. The arrival of the ARs towards the western part of Europe coincides with a sharp increase in the temperature over the western part of Europe (Figure S6), strong advection of moisture and heavy rainfall towards our analyzed region.

Looking more into detail into the dynamic fields of IWV during the days with heavy rainfall events, one can identify a distant source of moisture. During the days of rainfall events, recorded at Trier station, a long and narrow band of IWV is transported from the sub-tropical latitudes, passing the North Atlantic Ocean and reaching the western part of Europe (Figure 4). This narrow band of moisture is transported by a southwestern wind, at 900 hPa level, above 20m/s (Figure S7 – left column). This combination of wind and IWV, concentrated in such narrow bands suggests the presence of an AR, in agreement with the results obtained by using the AR tracking algorithm of Guan and Waliser (2015) (Figure 3).

The synoptic evolution of the tropopause level flow is analyzed using the dynamical tropopause on the 330K isentropic level (Figure 4). Previous studies (Browning et al. 1997; Froidevaux and Martius 2016) have shown that flooding end extreme rainfall are linked with upper-level troughs associated with the presence of elongated intrusions of air, the so-called potential vorticity (PV) streamers. Southern intrusion of air with high PV in the lower stratosphere or higher troposphere are corroborated with lowering of the dynamical tropopause, intense vertical motions, cyclogenesis and heavy rainfall (Krichak et al. 2014; Rimbu et al. 2020). The days prior to the flood peak, featuring extreme rainfall at Trier gauging station, are associated with high PV values (PV >2PVU) over the analyzed region (Figure 4). The axis of the IWV field follows the nonlinear behavior of the PV and the maximum of the IWV is situated in the overturning of the 2PVU contour line (Figure 4). The shape of the 2PVU contour lines indicates the presence of an anticyclonic Rossby wave breaking (Payne and Magnusdottir 2014). AR activity is also linked with the breaking of the midlatitude Rossby waves (RWB), which can be either cyclonic or anticyclonic (Payne and Magnusdottir 2014). In this respect, we have found that all the ARs that have passed the western part of Europe, prior to the flood peak were associated with an anticyclonic Rossby wave breaking (ARWB) (Table 2), which is in agreement with the study of Zavadoff and Kirtman (2020) who have shown that ARs over the western part of Europe are linked mostly with ARWB, and in broad consistency with (Hu et al. 2017) who found most of the AR landfalls along the northern coast of western US were associated with ARWB.

In order to further analyze the dynamical drivers of extreme flood events we computed the divergence field for the upper (300 hPa) and lower (900 hPa) levels wind speed. The wind speed and its associated divergence/convergence at the 900 (300) hPa level are shown in Figure S7. The upper and lower level analysis (Figure S7 – right column) indicates the presence of an upper level jet branch, shifted southwards and stretching from the central North Atlantic basin until the central part of Europe and an area with upper level divergence over our analyzed region (contour lines in Figure S7), which is an indicator of deep convection (Hoskins et al. 1978; Krichak et al. 2014). In addition, at lower levels, we can observe an intense low-level jet is present with a similar orientation as the upper level jet (Figure S7 – left column) over the analyzed region. The upper level divergence and lower level convergence over our analyzed region, are an indication of strong vertical motions and heavy rainfall (Hoskins et al. 1978). The days characterized by rainfall episodes (e.g. 27 – 31.12.1925 – Figure 2a) are all associated with a southward shift of the polar front, convergence over the catchment area (dashed lines in Figure S7) and enhanced moisture transport in narrow band stretching from the tropical Atlantic until our analyzed region (Figure 4).

From a hydrological perspective, the thaw that started in the second week of December 1925 brought the first flood peaks in the Rhine River and its tributaries (especially the Neckar and Mosel), which peaked in the middle of the month (Figure 2b). The subsequent frost period reduced the water flow, before the renewed thaw caused rising peaks again in the third week of December. Over this period of time, most of the Rhine River tributaries (e.g. the Aare, Murg, Kinzig, Neckar, Lahn) and especially the Moselle brought relatively large volumes of water to the Rhine (Soldan 1927). This caused the flood peaks in the Middle and Lower Rhine to rise abruptly. The subsequent brief cold snap caused the water levels to drop again from 23rd of December, before the abrupt weather change on 26th of December, which led to the outstanding flood event. The rapid ascent of the Rhine began on the 27th of December. On the Upper Rhine, the flood peak of the Ill river merged with that of the Rhine on the 30th of December (Soldan 1927). The water of the Moselle reached the Rhine on early January 1. Dike breaks occurred above Köln and at Neuss. In the Prussian Rhine province, more than 28000 houses and 2500 businesses were flooded, and more than 13500 apartments had to be cleared. The most severely damaged cities were Köln and Koblenz with 72000 and 14000 people affected, respectively. Agricultural damage was also significant as 74000 hectares of land were under water. Arable crops and crop stocks were destroyed and gravel and sand were deposited on the cultivated areas. The damage to hydraulic engineering systems on the Rhine, Mosel and Ruhr was put at ~284000 €. The damage to the traffic facilities outside the rivers was rather small given the size of the flood. The total damage was estimated to ~75 million € for the Prussian Rhine region (Soldan 1927).

3.2 Hydrometeorological situation - 1993

November 1993 and the first week of December 1993 were characterized by relatively reduced amounts of rainfall over Rhine River catchment area (Bornefeld 1994). Between 8th to 24th of December, the general weather situation was characterized by several Atlantic low pressure systems (heavy storm with hurricane gusts on December 9) and a stable high pressure system in front of the North African continent, which led to frequent rainfall, sometimes heavy rain over the northern part of France and western part of Germany (Deutscher Wetterdienst 1994). The maximum amount of precipitation, at Trier station, was recorded on the 20th of December 1993 (33.3mm) (Figure 5a). Overall, in the period from 8th to 20th of December 1993, in the catchment areas of Neckar, Nahe and Mosel, as well as in large parts of the central Upper Rhine and central Middle Rhine, more than double of the long-term December precipitation, was recorded (Figure S5a and S8). The extratropical cyclones in the North Atlantic persisted several days pushing a narrow band of moisture towards central Europe (Figure 6). High rates of IVT (up to 800 kg m^{-1} s^{-1}) were recorded from the 18th until 21st of December (Figure 6b, 6c and 6d). Over lower Rhine, the maximum of the IVT reached values up to ~620 kg·s^{-1}·m^{-1} (Table 2). At the same time, warm, humid air entered the Rhine area, which led to an extraordinary increase in temperature (Figure 5a). After a rainless 18th of December, the 19th and 20th of December were characterized by heavy rainfall events over most of Rhine's River catchment area (Figure 5a). The days characterized by heavy rainfall over our analyzed region (Figure S8) are associated with a narrow band of IWV (Figure 4), stretching from the sub-tropical North Atlantic basin until the central part of Europe, strong winds directed towards the western part of Europe and lower (upper) level converge (divergence) (Figure S10). This large-scale pattern is favorable of strong vertical motions and heavy rainfall over our analyzed region. As in the case of the 1925/26 flood peak, the axis of the IWV follows the path of the 2PVU contour line (Figure 7) and exceeds 20mm for all the days with heavy rainfall at Trier station (Figure 5). For the 1993 flood peaks, the days prior to the flood were associated with anticyclonic RWB (Table 2) which led to sharp meridional gradients of PV over Europe (Figure 7). Positive upper level PV anomalies affect the structure of the atmosphere below them (Schlemmer et al. 2010), such that cold air and reduced static stability are found below the positive PV anomalies (Figure S9). The PV streamer observed over the period 18 – 21.12.1993 (black contour line Figure 7) was associated with warm air advection towards the western part of Europe (Figure S9) and cold air advection over the eastern part of Europe, which led to snow melt and heavy rainfall over the lower Rhine catchment area (Figure 5 and S9).

The precipitation in the first half of December 1993 caused the soil to become saturated with water, so that the subsequent rain had an immediate drainage effect (Soldan 1927). However, a noteworthy flood wave only developed in the Rhine from the inflow of the Neckar, which led to a significant flood and reached its peak water level on December 22 at the Rockenau level (Engel et al. 1994). The highest flow at the Kaub level dates to December 23rd. An extraordinarily flood peak developed in the Moselle, and the highest daily streamflow of the century was recorded at the Cochem gauging station on the 22nd of December (4020 m^3/s). This flood peak in the Moselle merged with the Rhine on December 23, leading to one of the largest known flood waves of the Rhine downstream of Koblenz (Figure 5b). The combined flood peak passed through Andernach on 23rd of December 1993 and reached Köln gauging station on 24th of December (10600 m^3/s) (Figure 5b), where the flood protection wall of the old town was flooded for about 70 hours, and Rees and Emmerich cities on the following day.

The Christmas flood in the Rhine area caused several human losses and required evacuations in many cities. In Baden-Württemberg (Neckar area), Rhineland-Palatinate and North Rhine-Westphalia high building damage occurred. In Koblenz, almost a quarter of the built-up area of the city was flooded, while 10000 inhabitants and ~ 4000 houses were directly affected by the flood. In North Rhine-Westphalia, the number of damaged households was considerable, especially in Königswinter, Bonn and especially in Köln. In Köln, over 4500 households had a direct flood damage and another 9000 households suffered damage from increased groundwater. The damage to the federal shipping routes was estimated to be ~9,8 million €. Due to the flooding, the shipping had to be completely stopped on Neckar and Saar for 9 days, on the Mosel 12 days and on the Rhine from Koblenz to the Dutch border for 7 days. The lost transport revenues were estimated at over 38 million €. A total of approximately 1,4 billion € was damaged in the whole Rhine regions affected by this flood event (Münchener Rückversicherungs-Gesellschaft 1999).

3.3 Hydrometeorological situation - 1995

After local heavy rain in the higher low mountain regions at the end of December 1994, several periods of precipitation in January 1995 brought heavy rainfall to the entire Rhine region (Engel 1999). The cold spell in the first week of January 1995 (Figure 8a) led to snow fall in the middle part of Rhine River. In the Alpine region there were almost 100 cm of snow recorded at the end of the first week of January 1995. In the second week of January 1995, a north-westerly flow led to daily showers on top of the accumulated snow (Engel 1999). Thus, the rainfall corroborated with the snow melt, due the temperature increase, led to small flood peaks along the Rhine and its tributaries (Figure 8b). The situation became exceptional starting with the 22nd of January 1995. The rainfall episodes began on the evening of the 21st of January and last ~30 hours. The total precipitation recorded in January 1995 (168 mm), overaged over the German part of the Rhine basin, is the highest one recorded over the period 1881 – 2019 for the month of January (Figure S5b). The extreme rainfall episode was triggered by a frontal system which deepened into a low pressure system over the western part of Europe. On the 22nd of January 1995, Trier meteorological station recorded the highest daily precipitation amount (49.6mm) over the last 70 years for the month of January. This event led to an increase in the water levels of Moselle river to a flood peak of 2880 m^3/s at Trier station and 3410 m^3/s at Cochem gauging station, on the 23rd of January 1995 (Figure 8b). On the 25th of January 1995, another exceptional rainfall event was recorded, with values up to 55mm in 24 hours over large area in the Moselle and Rhine catchment areas (Figure S11). This event was triggered by an AR event, with a magnitude of ~600 $kg \cdot s^{-1} \cdot m^{-1}$ (Figure 9b) and a westerly flow of the large-scale atmospheric circulation characterized by a deep low pressure system over Scandinavia and a high pressure system over northern part of Africa. Between 26th to 29th of January 1995, small frontal waves driven by the low pressure system south of Greenland (Figure 9c-f) led to more rainfall episodes (Figure 8a) over Moselle's catchment area and large parts of Rhine River catchment area (Figure S11). These frontal systems were corroborated with ARs stretching from the sub-tropical North Atlantic basin and bringing moisture to the western part of Europe (Figure 9e and 9f). The prevailing large-scale atmospheric circulation, during the days characterized by enhanced rainfall over large area of Rhine's catchment area (Figure S11), featured narrow bands of moisture transport from the sub-tropical North Atlantic basin towards the western part of Europe (Figure 10) and enhanced lower level convergence over central part of Europe (Figure S13). The upper level large-scale atmospheric circulation was characterized by divergence over Rhine's catchment area, ascending motions and heavy rainfall (Figure S13). As in the case of the 1925/26 and 1993 flood peaks, the axis of the IWV follows the path of the 2PVU contour line (Figure 10) and exceeds 20mm for all the days with heavy rainfall at Trier station (Figure 10). For the 1995 flood peaks, the days prior to the flood were associated with anticyclonic RWB (Table 3) which led to sharp meridional gradients of PV over Europe (Figure 10) and the advection of warm air advection towards the western part of Europe (Figure S12) and cold air over the eastern part of Europe. The combination of warm aid advection and intense ARs, lead to snow melt and heavy rainfall over the Rhine catchment area and central part of Germany (Figure S11).

As a result of the repeated rainfall episodes, the catchment area in the Middle and Lower Rhine as well as the tributaries Main, Nahe, Mosel and Sieg saw a steep increase in daily streamflow (Engel 1999). The water inflow from the Main and Nahe rivers resulted in a significant increase in the flood wave at the Mainz and Kaub gauges, where the Christmas flooding from 1993 was exceeded. On 30th of January 1995, after the flooding of the Moselle began, the flood peaks of the Rhine reached 10700 m^3/s at Köln gauging station (the second highest daily streamflow recorded over a period of 200 years). Due to the flood inflow of the Sieg, the flood peak at Köln gauging station was further increased, reaching with a water level 6 cm higher than during the Christmas flood in 1993 (Engel 1999). At the Rees gauging station the peak of the flood wave was 11300 m^3/s and was above the Christmas flood in 1993 (10600 m^3/s) and only just below the highest known flood peak in January 1926 (11.700 m^3/s). Overall, the extreme floods of January 1995 were mainly triggered by long lasting rainfall episodes driven by frontal systems from the North Atlantic basin, a high frequency of AR events and intense moisture transport from the sub-tropical North Atlantic basin until the western part of Europe, as well as a southward shift of the polar front and upper (lower) level divergence (convergence) over the analyzed region.

The 1995 floods had huge consequences both for society and economy in Germany and the Netherlands. In numerous cities and towns on the Rhine and the tributaries, streets and houses were flooded, power outages and damage to the infrastructure occurred and 5 people were killed (Münchener Rückversicherungs-Gesellschaft 1999). The total monetary damage in the German Rhine catchment area estimated to be ~398 million €. Due to the exceeding of the highest navigable water levels, shipping had to be temporarily suspended on individual sections of the and the monetary losses for the shipping related companies was ~ 36 million €. For the Köln city alone, the damage was around 47 million € (half as much as in the 1993 Christmas flood) and 4000 people were directly affected by the floods. In the Netherlands, at least 4 people were killed and ~250000 people had to be evacuated because of dike breaches and extensive flooding of polders and large parts of cities were submerged between 30 January and 1 February 1995 – from the Limburg region south of Nijmegen and from Zeeland, around Rotterdam, Europe's largest port (Münchener Rückversicherungs-Gesellschaft 1999).

3.4 Composite events

The crucial role that ARs have in preceding extreme flooding in the lower part of Rhine river catchment area is highlighted also by analyzing the IVT, SLP and the AR origin with different time lags (0 – 7 days) for the 10 highest flood peaks measured at Köln gauging station. The occurrence date and the magnitude of each flood peak are shown in Table 1. The composite of all flood peaks shows that all of them are preceded up to 7 days by a plume of moisture, in the shape of an AR, accompanied by a deep low pressure center over the British Isles and a high pressure center over the Iberian Peninsula (Figure 11). The maximum of the IVT, averaged over the 10 floods peaks, reaches values of up to 500 $kg \cdot s^{-1} \cdot m^{-1}$. The ARs associated with heavy winter floods in the lower part of the Rhine River basin have an elongated shape, thus confirming the AR geometrical criterion of being at least 2000 km long and less than 1000 km wide (Ralph et al. 2004; Neiman et al. 2008).

Snapshots of the evolution of the AR axis, indicating the development and propagation of the AR prior to the occurrence date of the top 10 flood peaks, over the last 180 years, are shown in Figure 12. The evolution of ARs for the different snapshots demonstrate further the importance of moisture transport from the North Atlantic Ocean in producing damaging floods in the lower part of Rhine river basin. In all cases the moisture transport is directed towards the north-western part of France penetrating until the western part of Germany. The axis of the ARs is strongly influenced by the dipole-like structure in the SLP field, with a migrating deep low over the central part of the North Atlantic and a high pressure system over the northern part of Africa and Iberian Peninsula. For all the 10 analyzed cases there was at least one AR preceding the flood peak with a lag varying between 2 to 7 days. The maximum of the IVT, over the catchment area of Rhine, is reached 4 up to 6 days prior each flood peak (Table 2).

In a long term perspective, there is a significant positive trend in the AR occurrence rate (~0.9 days /decade) over the analyzed region (S14a) corroborated with a positive, but not significant, trend in the precipitation averaged over the catchment area of Rhine River over the winter months (November – March) (Figure 14b). The highest magnitude of ARs reaching up to the lower Rhine was recorded from 1990s onwards. The increase in the number of ARs reaching up to the lower Rhine and the positive trend in precipitation does not necessary mean an increase in the annual maxima of the daily streamflow at Köln gauging station over the period 1836 – 2015 (Figure S14c). The lack of change in the amplitude of the annual maxima at Köln gauging station might be influenced also by the lack of snow cover, which is a pre-requisite for extreme flood peaks, like in the case of the years 1925/26, 1993 and 1995. At country level, snow days have decreased uniformly at a rate of 0.5 days/year in the recent past (Kreyling 2011), this trend being projected to continue to a point where significant parts of Germany will no longer regularly experience snow cover.

3.5 NAO and Circulation types

Over the analyzed region, the floods events of 1970, 1988, 1993 and 1995 were all preceded by days with a positive NAO index (not shown). In the case of the 1993 flood event, the daily NAO index was characterized by positive values for almost two consecutive months (26.10.1993 – 22.12.1993). For the whole analyzed period (1836 -2019), just monthly data are available for the NAO index. A visual inspection of the NAO index during the month of each flood event, indicates that in 9 out of the 10 extreme floods events, NAO was in a positive phase. The only exception is the flood peak from 31.03.1845 (March NAO = -0.54). The values of the NAO index for each flood peak are shown in Table 3. Overall, extreme flood peaks, in the lower Rhine region seem to be preceded by a positive phase of the NAO. A positive phase of NAO is, in general, associated with an increased chance of higher rainfall in northwest Europe and lower rainfall in southern Europe. The long lasting positive

NAO prior to most of the flood peaks, might be one of the main driver behind the high magnitude of the ARs. Zavadoff and Kirtman (2020) have shown that long lasting phases of NAO have a more significant influence of the ARs distribution when compared with short-lived NAO phases.

Looking more into detail at country level, the influence of NAO on the hydroclimate of Germany was found to be very complex (Riaz et al. 2017). The relationship between winter NAO and precipitation was found to be rather week in the southern part of Germany, but statistically significant in the northern part. Riaz et al. (2017) have shown that the precipitation over Germany is mainly influenced by the position of the Icelandic Low, independent of the strength and position of the Azores High. Thus by using the state of the art definition of the NAO, namely the difference in the sea level pressure between Iceland an Azores, one cannot capture the real influence of NAO on the central European climate. A way to tackle this issue is to look at synoptic scale circulation types (e.g. Großwetterlage, (Hess and Brezowsky 1952)). When looking at particular circulation types (e.g. Großwetterlage) the extreme flood peaks from 1881 onwards are all preceded mainly by days featuring either Cyclonic west wind (WZ) or Southern west wind (WS) circulation types. Both types represent zonal circulation types (westerly flow), associated with extreme precipitation and floods over Germany (Petrow et al. 2009). For example, the 1993 and 1995 flood events were preceded by days featuring just the WZ circulation type (Table 3). Caspary (1995) has shown that over the period 1926 – 1996, nearly all flood events in the Upper Danube River basin have been caused by WZ circulation type. In their study, Petrow et al. (2009) have found that 62% of the maximum discharges in the basins situated in the western part of Germany are triggered by the circulation patterns: WZ, WS, SWZ and NWZ. In this study we have found that the WZ circulation type was present, in the days prior to the flood peaks, in 7 out of 8 of analyzed extreme flood events over the period 1881 – 2019 (Table 2). For the 1993 and 1995 flood events, only the WZ circulation type was present the days prior to the flood peak. Overall, the occurrence of these CTs (WZ and WS) seem to be a pre-requisite for extreme flood events in central part of Europe (Caspary 1995; Petrow et al. 2009).

4. Discussion and Conclusions

The variability of European precipitation, in winter, is strongly affected by enhanced moisture transport from the sub-tropical North Atlantic basin (Lu et al. 2013; Lavers and Villarini 2015). Overall, ARs are responsible for ~20 - 30% of all recorded precipitation in regions situated in the western part of Europe (mainly France and Iberian Peninsula) (Gimeno et al. 2016). While ARs are essential ingredients in producing heavy rainfall events and flooding over the coastal areas of the European continent (e.g. Portugal, Spain, France, Norway) little is known about their influence on the precipitation and flood events inland Europe (Gimeno et al. 2016). Although there have been numerous studies linking ARs with floods and heavy precipitation, over large parts of the world (Neiman et al., 2008; Lavers et al. 2011; Dettinger 2011; Lavers and Villarini 2013b; Marengo et al. 2016; Paltan et al. 2017; Vázquez et al. 2017, Benedict et al. 2019; Guan and Waliser 2019b; among others) this is the first study in which ARs are linked with specific events of extreme flooding inland Europe, more specific over the lower part of Rhine catchment area, which is one of the biggest rivers in Europe. The lower part of Rhine catchment area is dominated by winter floods, which are often caused by westerly, southwesterly and north-westerly large-scale circulation types (Beurton and Thieken 2009).

In this study we have shown that extreme floods, in winter, occur predominantly during mild and wet episodes associated with a southwards shift of the polar front and frontal systems moving from the North Atlantic basin towards Europe, corroborated with intense moisture transport from the sub-tropical North Atlantic basin until the western part of Europe. From a hydrological point of view (e.g. flood peak magnitude), the 1925/26 flood was the worst flood of the 20th century at Köln gauging station. However, the total volume of water was much higher for the 1993flood than in 1925/1926 (Engel et al. 1999). The Rhine transported ~ 60% more water during the 1993 flood compared to the 1925/26 flood event. The total damage caused by the Rhine flood in 1993 was estimated at ~1.4 billion euros, however, the damage caused by the Christmas floods in 1995 was only about half as great as in 1993, due the prevention measures implemented by the Rhine River countries after the 1993 flood event and due to earlier flood warnings.

Although the mechanism behind each individual extreme flood is rather different, heavy snowfall, a sharp increase in the mean air temperature followed by thawing and/or just extreme rainfall events, for the analyzed cases there is one thing in common: the heavy snowfall and/or rainfall are driven by intense moisture transport from the Atlantic basin, towards northern part of France and western part of Germany, in narrow and long bands, which in contact with high mountain regions over the Moselle catchment area and parts of Rhine catchment area lead to extreme flooding. The precipitation anomalies associated with extreme flood peaks are not just local, but they occur on a larger spatial scale (Figure S8 and S11). The spatial structure of the precipitation reflects the mean direction with which the IVT and thus the ARs are moving towards Europe. The typical large-scale synoptic circulation leading to heavy rainfall events and extreme flooding, in the lower part of Rhine's catchment area, is characterized by an atmospheric circulation pattern characterized by a deep and mobile low pressure center south of Greenland, which migrates towards the northern part of Europe, and a high pressure system over the northern part of Africa and southern part of Europe. The dipole-like structure in the SLP field leads to a south-westerly flow over France and western Germany. As the plume of moisture ascends in the warm sector of the extra-tropical cyclone and it is forced to rise over the Vosges Mountains in France, and Hunsrück and Eifel Mountains in Germany, it precipitates out, thus producing extreme rainfall in a relatively narrow band and extreme flooding some days later.

The strong pole to equator temperature gradient, in winter, results in an enhanced baroclinic zone and storm tracks affecting the western part of Europe. The extratropical cyclones, associated with the extreme flooding events over western part of Europe, including the lower catchment area of Rhine river, grow in these baroclinic zones which also contain the ARs that make landfall over the European land mass (Lavers and Villarini 2013b). The influence of ARs on the Rhine River flood events is done via the prevailing large-scale atmospheric circulation and most of the ARs associated with these flood events are embedded in the trailing fronts of the extratropical cyclones. The evolution of the atmospheric circulation during the days prior the floods are limited mainly to changes in the amplitude of the sea level pressure. The low pressure systems develop a stronger anomaly than its positive counterpart. The dipole SLP pattern observed during the days prior to the flood peaks, is reminiscent of the positive phase of NAO and it guides the IVT is a narrow band through France and the British Chanel to the western part of Germany. This was also confirmed by looking at the daily and monthly values of the NAO index during the days prior to the floods events or the monthly NAO index during the month of the flood. In 9 out of the 10 extreme floods events, the monthly NAO was in a positive phase. The influence of

NAO on the flooding events over our analyzed region is made via the influence on the frequency and direction of the extratropical cyclones. The phase of NAO has a strong impact on the extratropical cyclones frequency, affecting both the location and the orientation of the cyclone tracks, extreme cyclones occurring more (less) frequently during strong positive (negative) NAO phases (Pinto et al. 2009).

The higher amplitude of the low pressure systems indicate the importance of the extratropical cyclones in directing the storm tracks towards the central part of Europe. The synoptic situation, in a PV framework, for the days characterized by heavy rainfall, exhibits meridional elongated PV anomalies, associated with anticyclonic Rossby wave breaking. ARs activity over western Europe is linked with mid-latitude Rossby wave breaking and strong PV anomalies (Zavadoff and Kirtman 2020). The flood peaks of 1925/26, 1993 and 1995 share in common the passage of sharp meridional PV gradient associated with anticyclonic RWB. These PV transitions at the tropopause level are accompanied, in all analyzed cases, by the advection of warm and humid air over Rhine catchment area and cold air intrusions over the eastern part of Europe. PV streamers and anticyclonic Rossby wave breaking have been associated also with extreme precipitation and flooding over the Alpine region (Martius et al. 2006; Froidevaux and Martius 2016; Rimbu et al. 2020).

One of the most interesting finding of this study is the fact that the extreme floods are preceded, especially 4-5 days in advance (Figure 12), by intense moisture transport from the sub-tropical Atlantic, in the form of ARs. The time lag between the AR occurrence and flood peak is related to the fact that multiple factors (e.g. duration of precipitation, time travel from the tributaries to Köln gauging station, snowpack, soil moisture) are influencing the magnitude of the flood wave. Thus, this time lag between the ARs occurrence and the flood peak, in the lower part of the catchment area of Rhine river, can be used as a potential predictor for the upcoming floods in the lower part of Rhine catchment area. Overall, the North Atlantic ARs are projected to increase both in magnitude and frequency, implying a greater risk of extreme rainfall and flooding (Lavers et al. 2013c), thus more studies are needed to test if also smaller flood peak are associated with intense moisture transport and their potential predictability.

This study adds new understanding of the meteorological processes leading to the occurrence of extreme rainfall events and flooding in the central part of Europe. Identifying ARs as a potential contributor to floods in the lower part of Rhine River catchment area, thus inland Europe, indicates the need for further studies to better understand the drivers of hydrometeorological extremes over different parts of Europe, thus allowing for a better assessment of flood risk.

Acknowledgements. This study was promoted by Helmholtz funding through the Polar Regions and Coasts in the Changing Earth System (PACES) program of the AWI. Funding by the AWI Strategy Fund Project - PalEX and by the Helmholtz Climate Initiative - REKLIM are gratefully acknowledged.

Author contributions. MI designed the study and wrote the paper. VN and BG helped with the writing of the paper and interpret the results.

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

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Table 1. Date of occurrence and magnitude of the ten flood events recorded at Köln gauging station used in this study.

Date	Magnitude
31.03.1845	9.800 m^3/s
5.02.1850	9.710 m^3/s
29.11.1882	10.200 m^3/s
16.01.1920	10.700 m^3/s
1.01.1926	10.900 m^3/s
2.01.1948	9.890 m^3/s
25.02.1970	9.690 m^3/s
29.03.1988	9.550 m^3/s
24.12.1993	10.600 m^3/s
30.01.1995	10.700 m^3/s

Table 2. Daily values of the magnitude of the IWT for the days prior to each flood peak (Table 1) averaged over the box 4°-12°E; 47°-56°N. The shaded grey boxes represent the days when the highest magnitude over was recorded. The climatology of computed over the period 1961 – 1990.

	1845	**1850**	**1882**	**1920**	**1926**	**1948**	**1970**	**1988**	**1993**	**1995**
Lag 7	246.25	241.38	142.59	175.70	150.39	226.45	63.53	89.05	245.60	222.54
Lag 6	90.24	62.06	289.43	329.78	232.27	**359.86**	88.23	146.34	**281.42**	**324.16**
Lag 5	139.43	35.05	**396.43**	**481.75**	344.47	**468.97**	**227.72**	**207.93**	**618.99**	**331.26**
Lag 4	**228.80**	**225.81**	**340.10**	**454.43**	287.79	**229.94**	**221.48**	**269.74**	**419.36**	**153.40**
Lag 3	**399.21**	**336.96**	**314.03**	**439.36**	**484.90**	90.53	**301.12**	**203.16**	194.42	**350.20**
Lag 2	**235.00**	**293.96**	148.03	209.42	**713.26**	48.72	169.46	151.01	194.19	290.37
Lag 1	112.78	161.67	60.79	116.66	**378.41**	153.66	91.09	87.51	169.60	133.06
Lag 0	154.05	143.08	32.79	252.85	150.32	343.95	46.33	140.85	56.34	109.88
Climatology	**80.02**	**64.98**	**118.27**	**92.88**	**106.13**	**106.13**	**64.98**	**80.02**	**106.13**	**92.88**

Table 3. Monthly values of the NAO index (second column), days with anticyclonic Rossby wave breaking (ARWB, third column) and the type of circulation patterns(GWL, fourth column) active during the days prior to each of the 10 extreme flood peaks at Koln gauging station.

	Monthly NAO	ARWB	GWL
31.03.1845	-0.54	22 – 24.03.1845 28 – 29 .03.1845	
5.02.1850	4.13	31.01 – 2.02.1850 5 - 02.1850	
29.11.1882	2.01	23 – 26.11.1882 28 – 29.11.1882	23 – 25.11.1882 -» WZ 26 – 29.11.1882 -» NWZ
16.01.1920	2.84	10 – 15.01.1920	10 – 14.01 -» WZ 15 – 16.01 -» WA
1.01.1926	0.29	27 – 31.12.1925	18 – 30.12 -»WS 31.12 – 1.01 -»WZ
2.01.1948	0	25 – 28.12.1947	26 – 30.12 -» WS 31.12 – 2.01 -» WZ
25.02.1970	1.10	19 – 23.02.1970	18 – 20.02 -» WZ 21 – 24.02 -» WW
29.03.1988	0.78	23 – 27.03.1988	21 – 28.03 -» WS
24.12.1993	2.17	18 – 24.12.1993	8 – 24.12 -» WZ
30.01.1995	2.70	26 – 30.01.1995	22 – 30.01 -» WZ

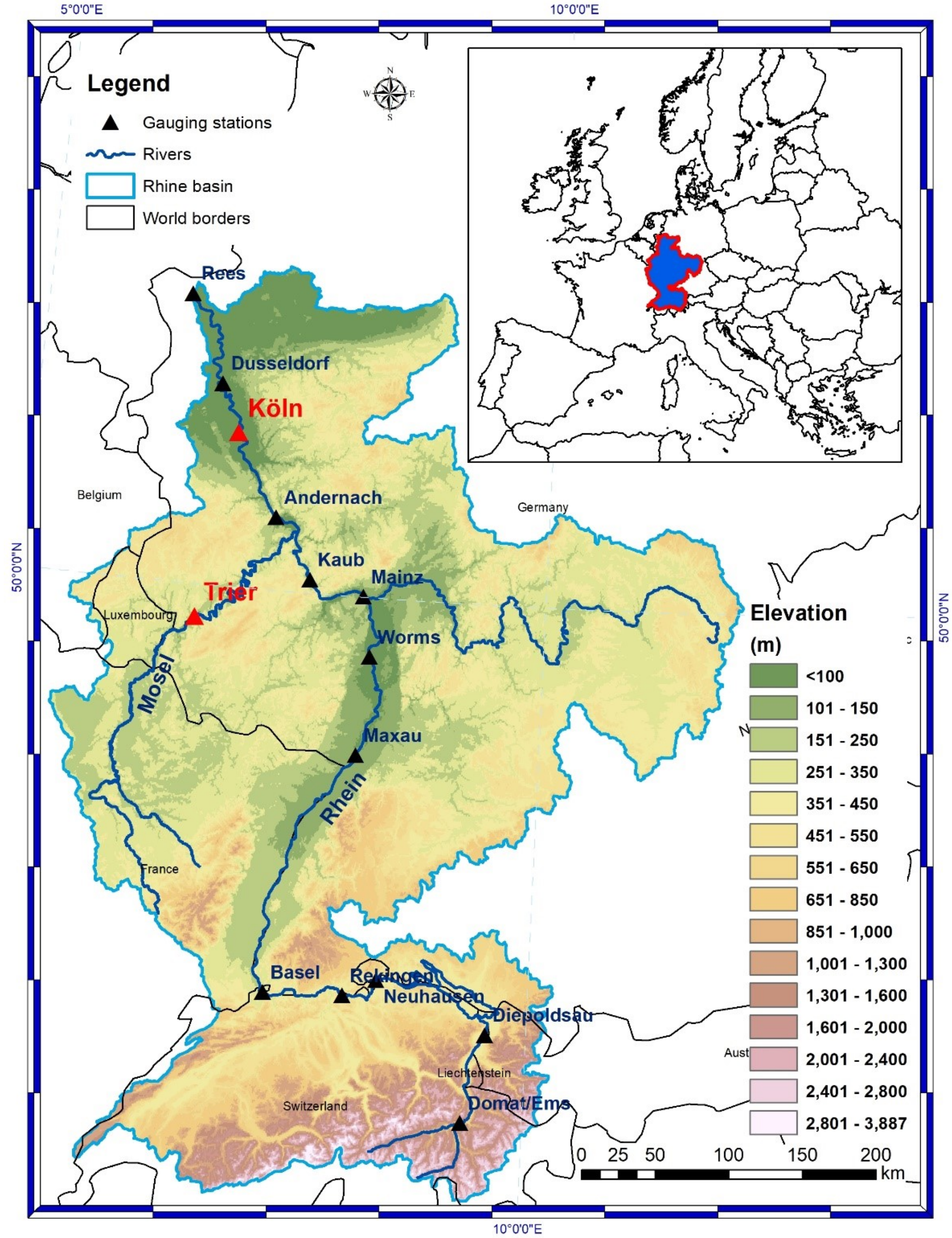
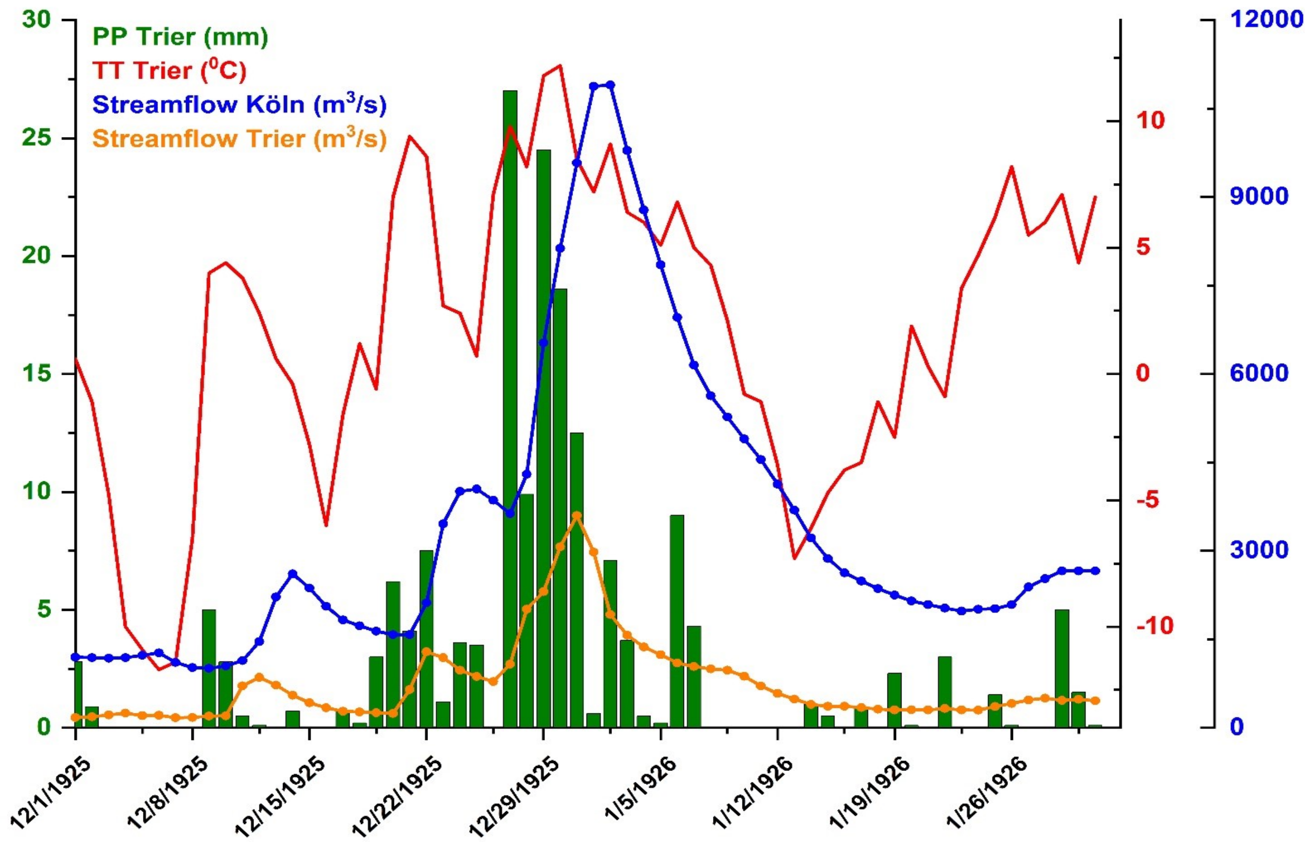


Figure 1. Rhine River catchment area (black contour) and the location of Trier meteorological station and Köln gauging station. The digital elevation model data was extracted from the WorldClim 2 dataset (Fick and Hijmans 2017).

a)



b)

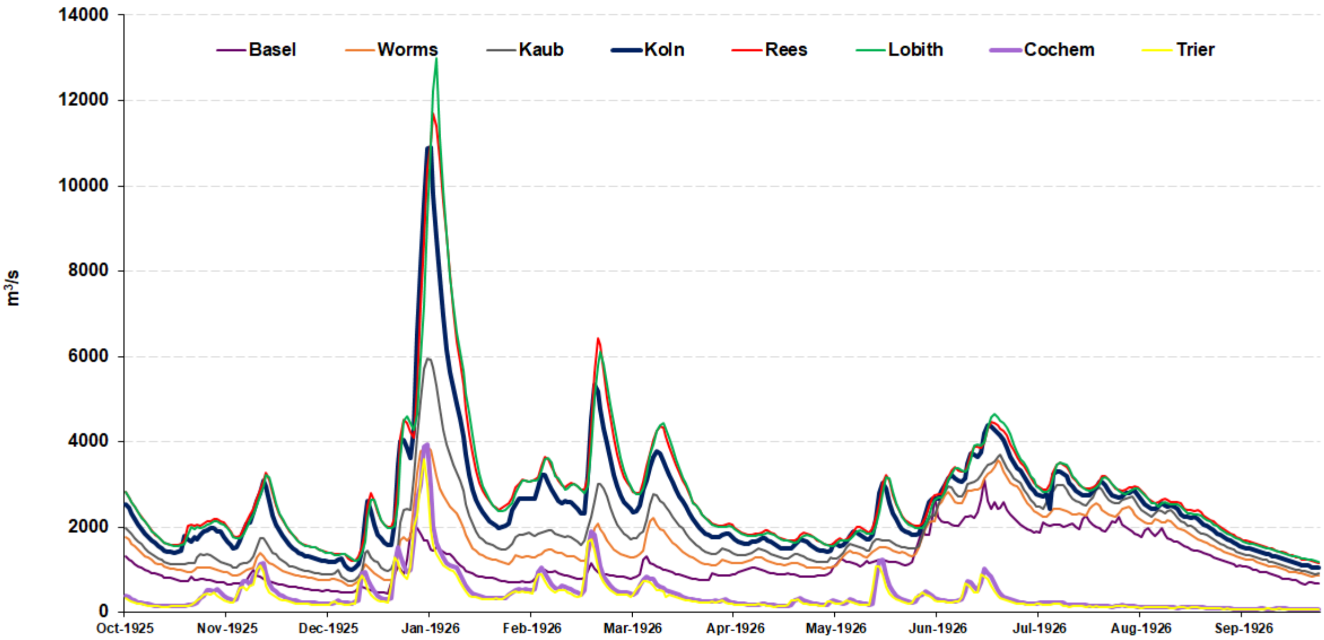


Figure 2. a) Daily precipitation (green bars) at Trier meteorological station, daily mean temperature (red line), daily streamflow at Köln gauging station (blue line) and daily streamflow at Trier gauging station (orange line) for the period 1.12.1925 – 31.1.1926 and b) Daily streamflow at different gauging station along Rhine River (Basel, Worms, Kaub, Köln, Rees, Lobith) and Moselle River (Trier and Cochem) for the period 1.10.1925 – 30.09.1926.

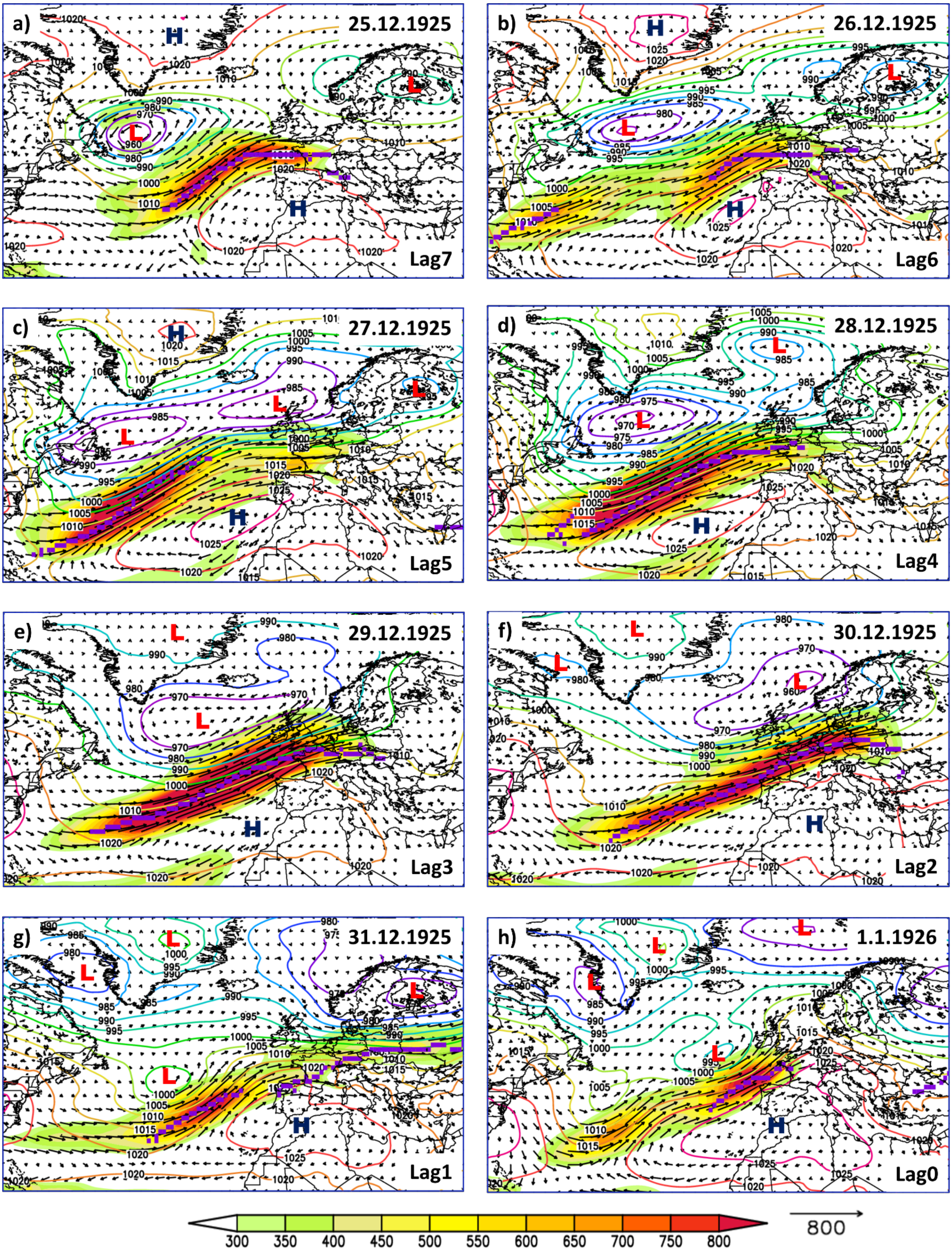


Figure 3. Daily sea level pressure (SLP, colored contour lines), magnitude of the integrated water vapor transport (IVT, shaded colors), direction of the integrated water vapor transport (vectors) and location of the AR axis (magenta line) for different time lags (0 – 7 days) for the 1925/26 flood event. Units: SLP (hPa) and IVT ($kg \cdot s^{-1} \cdot m^{-1}$).

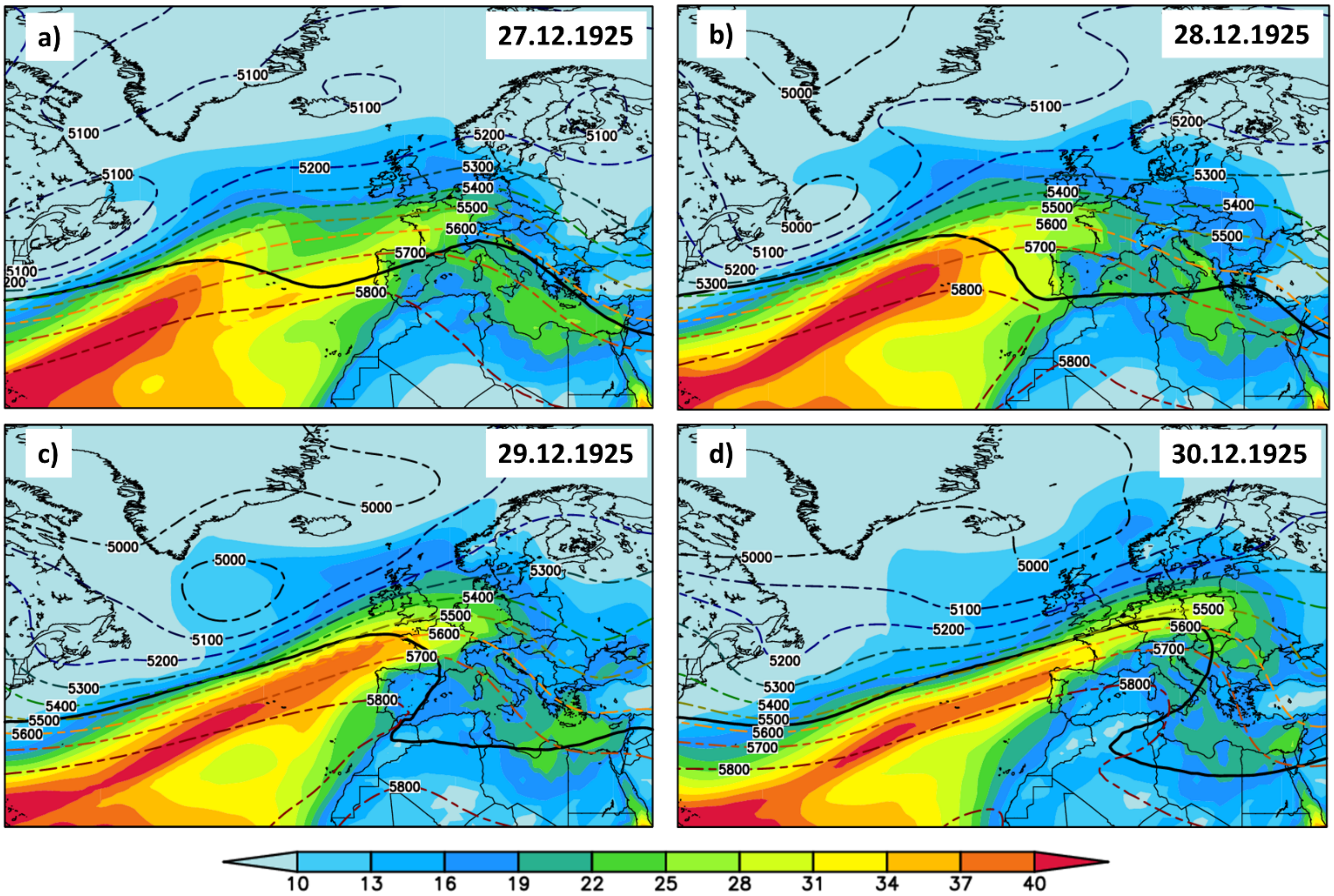
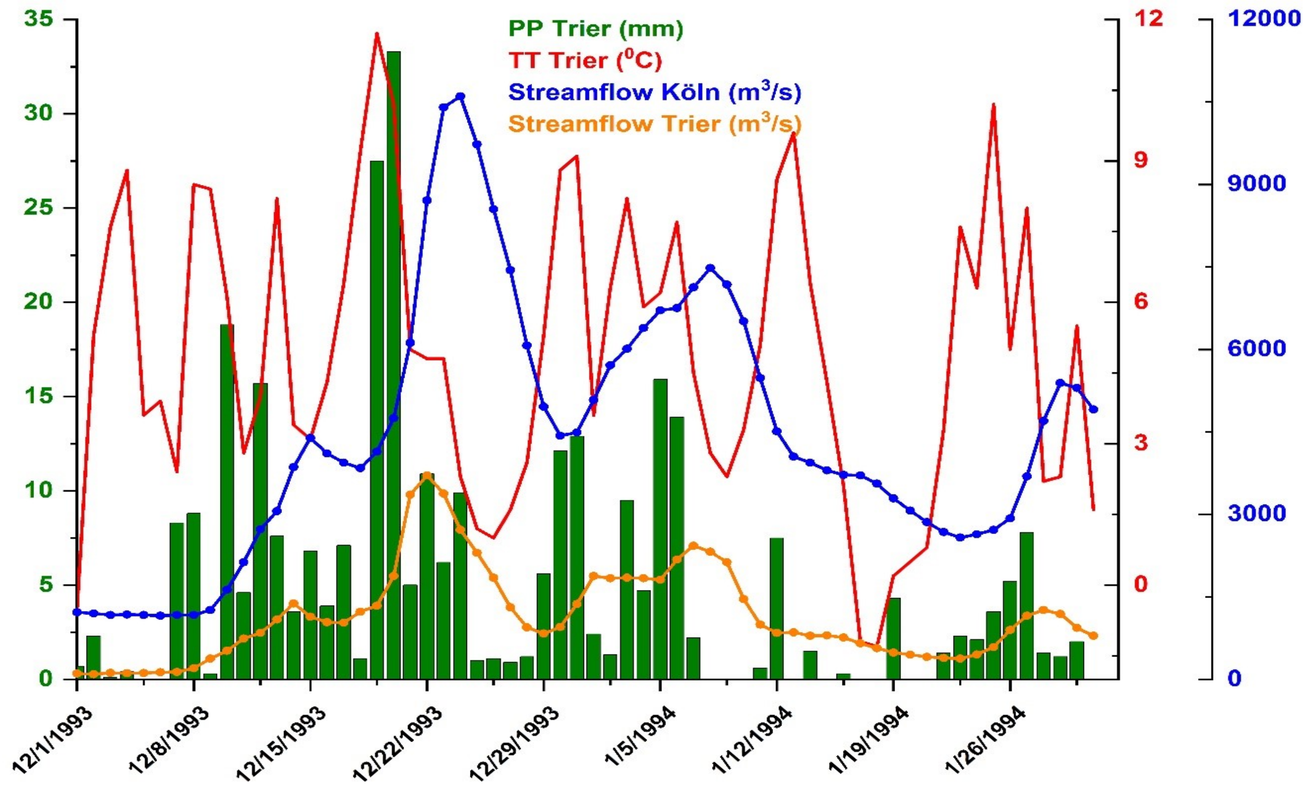


Figure 4. Daily integrated water vapor (IWV, shaded colors) and daily geopotential height at 500 hPa (Z500, contour lines) for a) 27.12.1925; b) 28.12.1925; c) 29.12.1925 and d) 30.12.1925. The thick black line in a) – d) indicates the 2PVU contour at 330K. Units: IWV (kg m^{-2}) and Z500 (m).

a)



b)

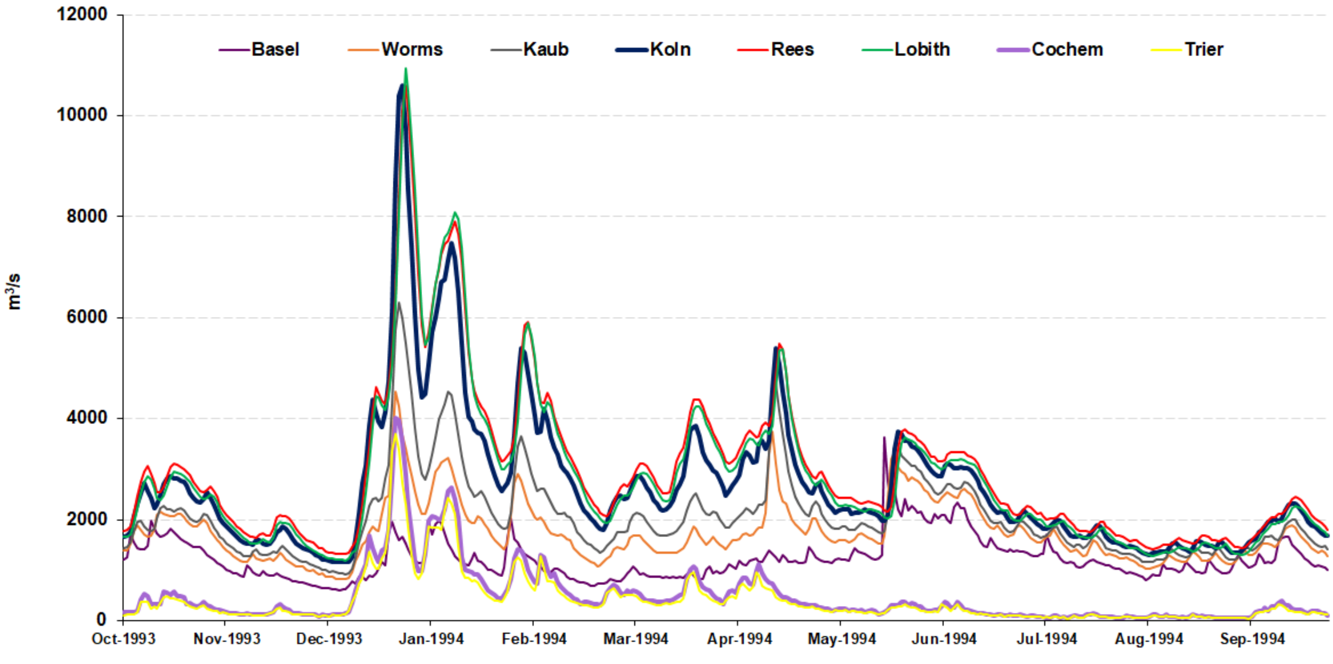


Figure 5. a) Daily precipitation (green bars) at Trier meteorological station, daily mean temperature (red line), daily streamflow at Köln gauging station (blue line) and daily streamflow at Trier gauging station (orange line) for the period 1.12.1993 – 31.1.1993 and b) Daily streamflow at different gauging station along Rhine River (Basel, Worms, Kaub, Köln, Rees, Lobith) and Moselle River (Trier and Cochem) for the period 1.10.1993 – 30.09.1994.

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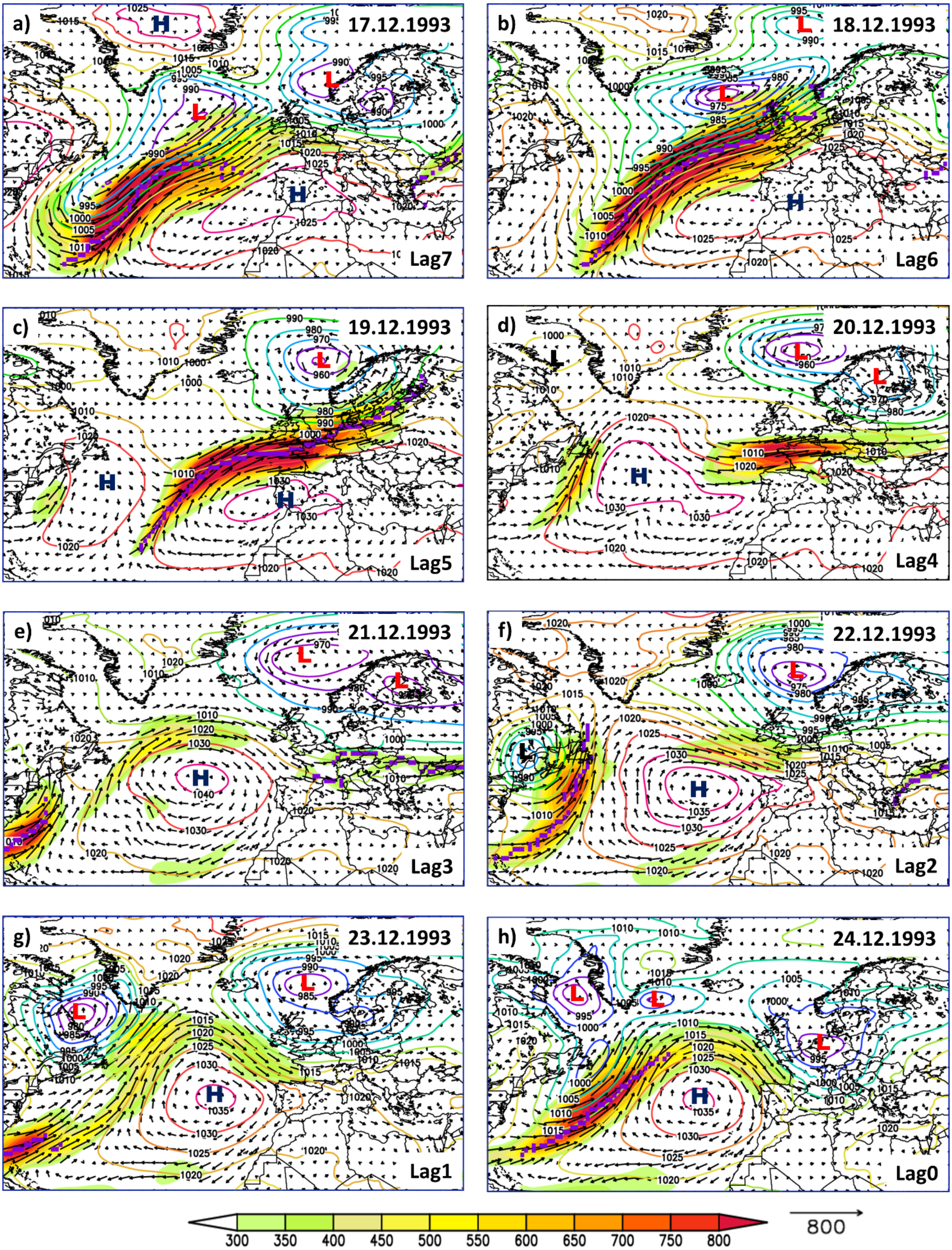


Figure 6. Daily sea level pressure (SLP, colored contour lines), magnitude of the integrated water vapor transport (IVT, shaded colors), direction of the integrated water vapor transport (vectors) and location of the AR axis (magenta line) for different time lags (0 – 7 days) for the 1993 flood event. Units: SLP (hPa) and IVT ($kg \cdot s^{-1} \cdot m^{-1}$).

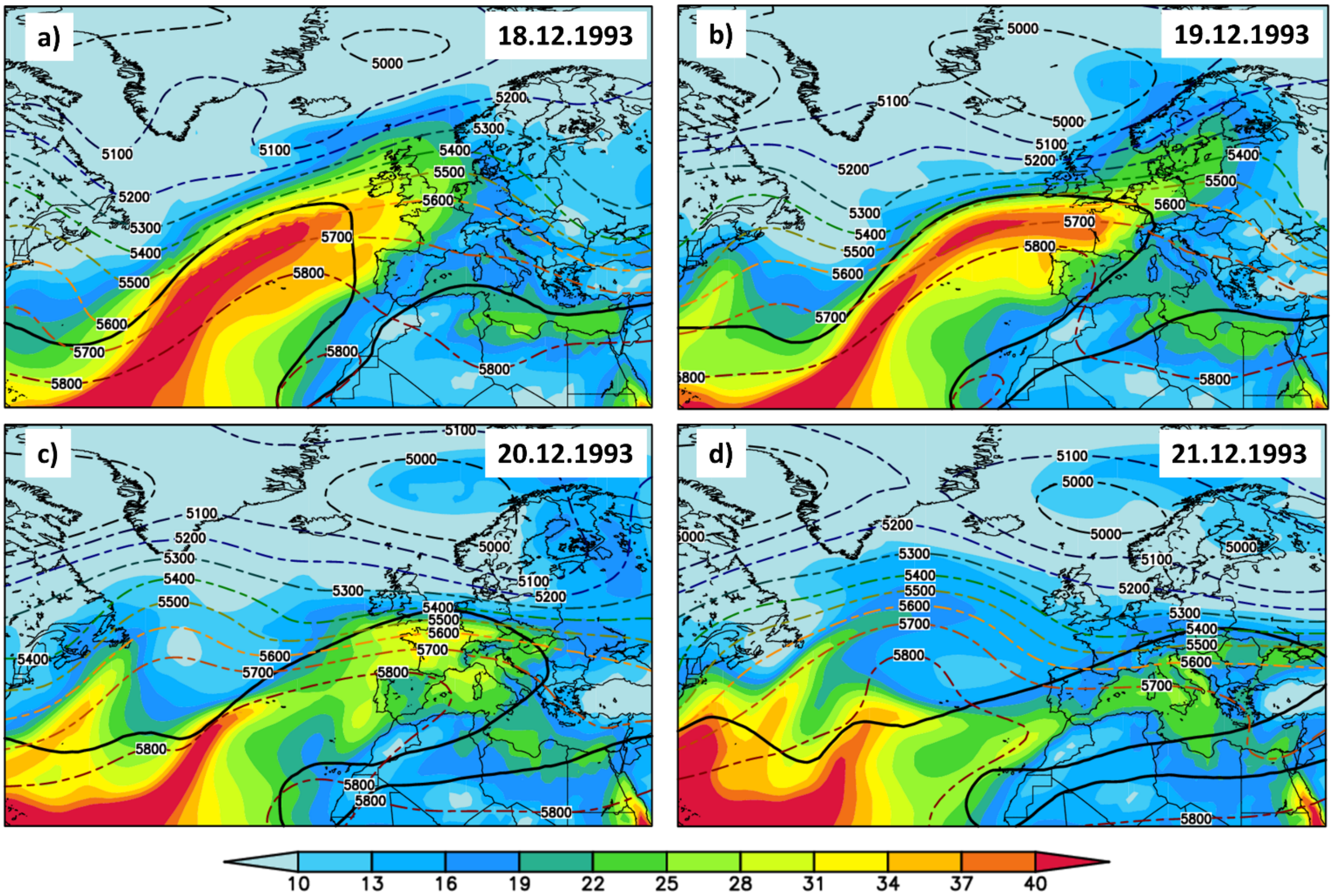
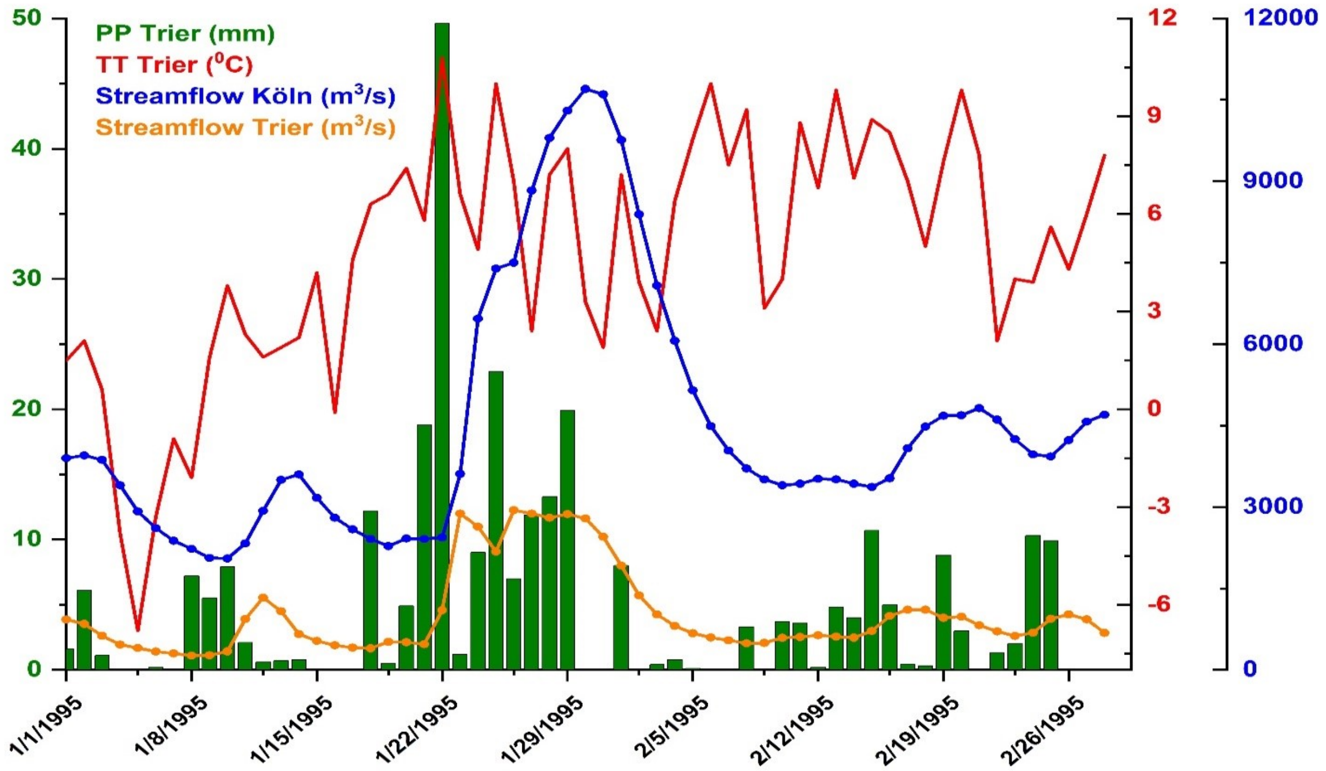


Figure 7. Daily integrated water vapor (IWV, shaded colors) and daily geopotential height at 500 hPa (Z500, contour lines) for a) 18.12.1993; b) 19.12.1993; c) 20.12.1993 and d) 21.12.1993. The thick black line in a) – d) indicates the 2PVU contour at 330K. Units: IWV (kg m^{-2}) and Z500 (m).

a)



b)

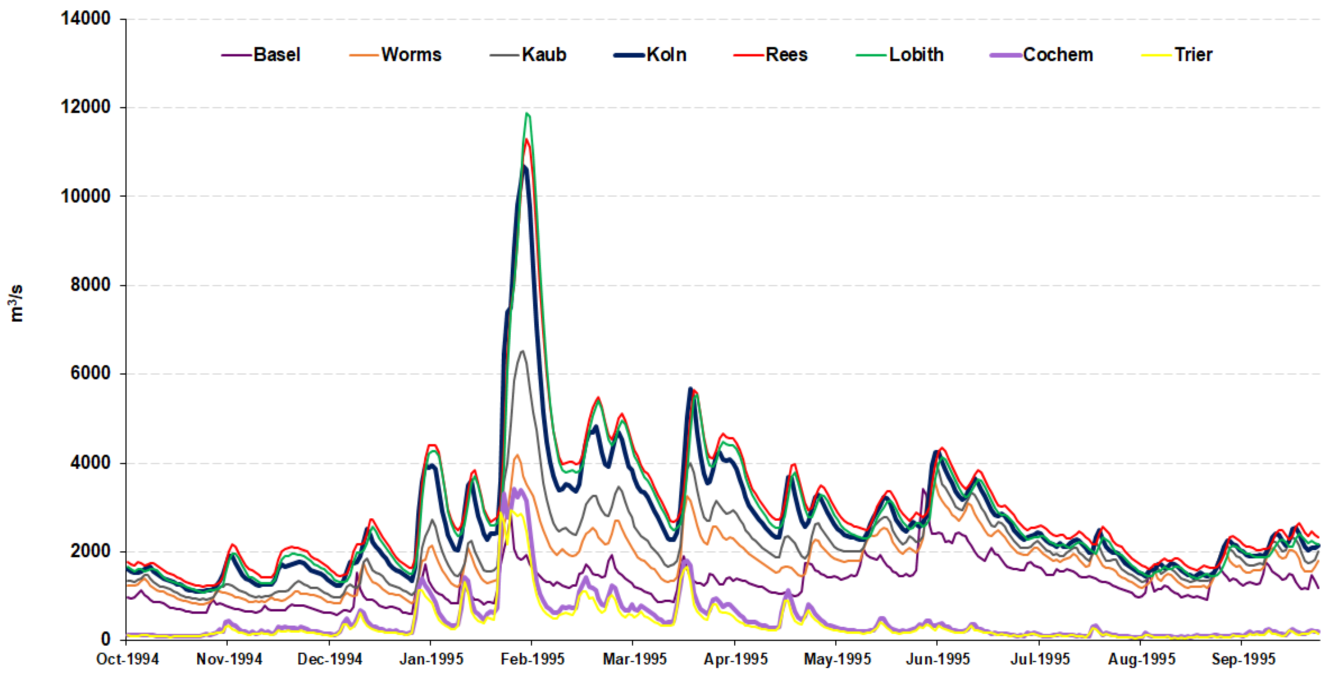


Figure 8. a) Daily precipitation (green bars) at Trier meteorological station, daily mean temperature (red line), daily streamflow at Köln gauging station (blue line) and daily streamflow at Trier gauging station (orange line) for the period 1.1.1995 – 28.2.1995 and b) Daily streamflow at different gauging station along Rhine River (Basel, Worms, Kaub, Köln, Rees, Lobith) and Moselle River (Trier and Cochem) for the period 1.10.1994 – 30.09.1995.

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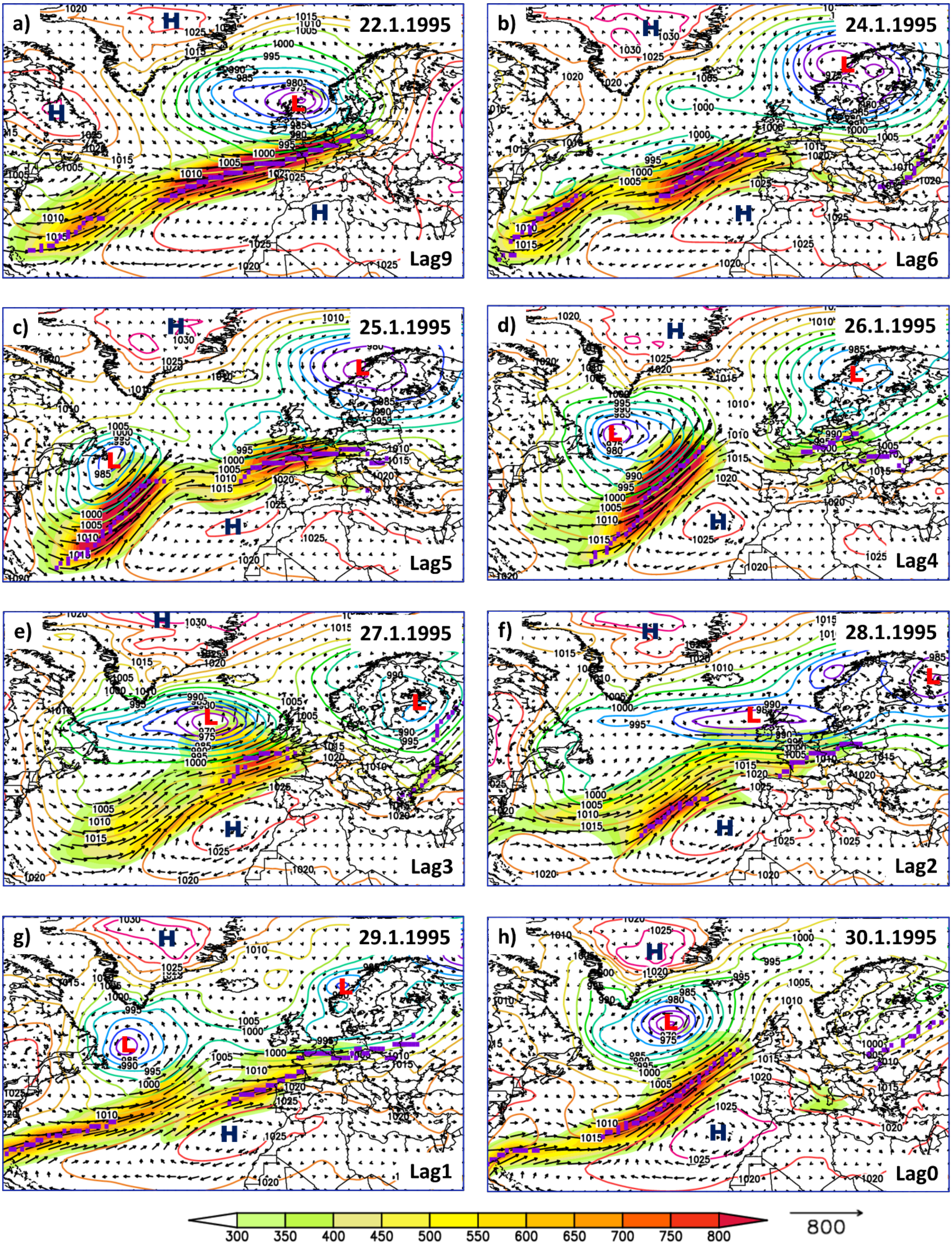

Figure 9. Daily sea level pressure (SLP, colored contour lines), magnitude of the integrated water vapor transport (IVT, shaded colors), direction of the integrated water vapor transport (vectors) and location of the AR axis (magenta line) for different time lags (0 – 7 days) for the 1995 flood event. Units: SLP (hPa) and IVT ($kg \cdot s^{-1} \cdot m^{-1}$).

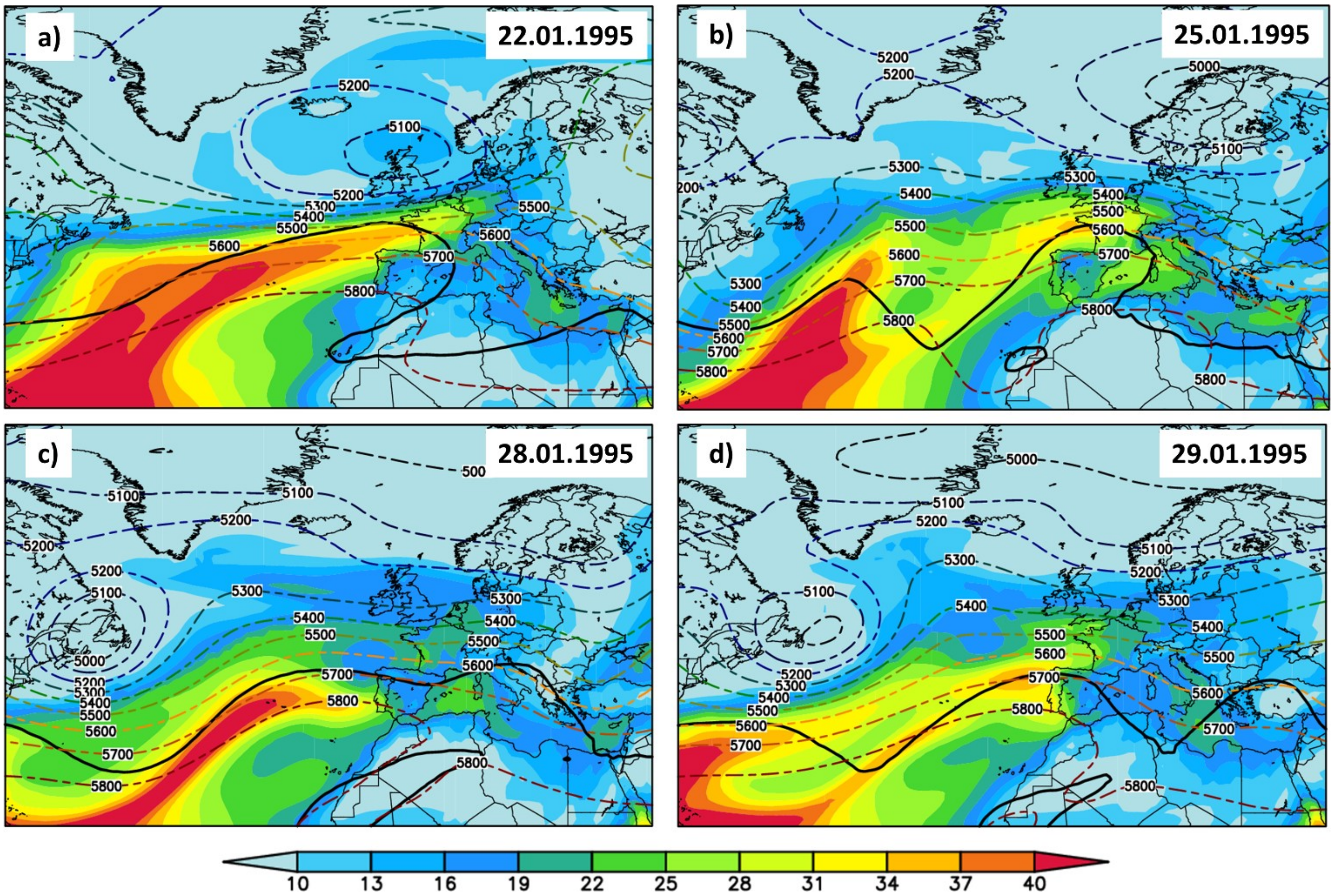

Figure 10. Daily integrated water vapor (IWV, shaded colors) and daily geopotential height at 500 hPa (Z500, contour lines) for a) 22.01.1995; b) 25.01.1995; c) 28.01.1995 and d) 29.01.1995. The thick black line in a) – d) indicates the 2PVU contour at 330K. Units: IWV (kg m^{-2}) and Z500 (m).

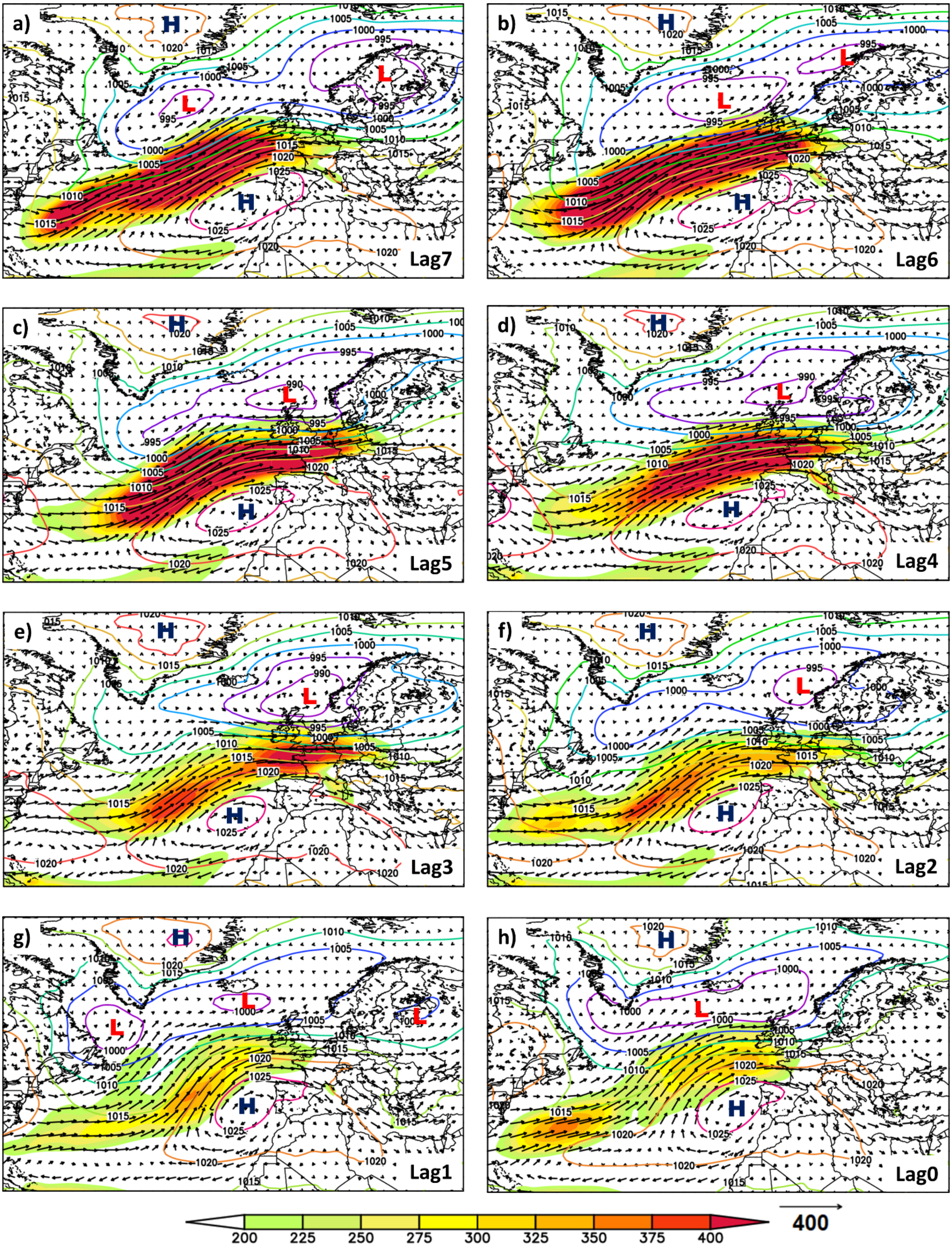

Figure 11. Composite of the mean sea level pressure (SLP, colored contour lines), magnitude of the integrated water vapor transport (IVT, shaded colors) and the direction of the integrated water vapor transport (vectors) for different time lags (0 – 7 days) for the 10 highest flood peaks recorded at Köln gauging station (see Table 1). Units: SLP (hPa) and IVT (kg·s^{-1}·m^{-1}).

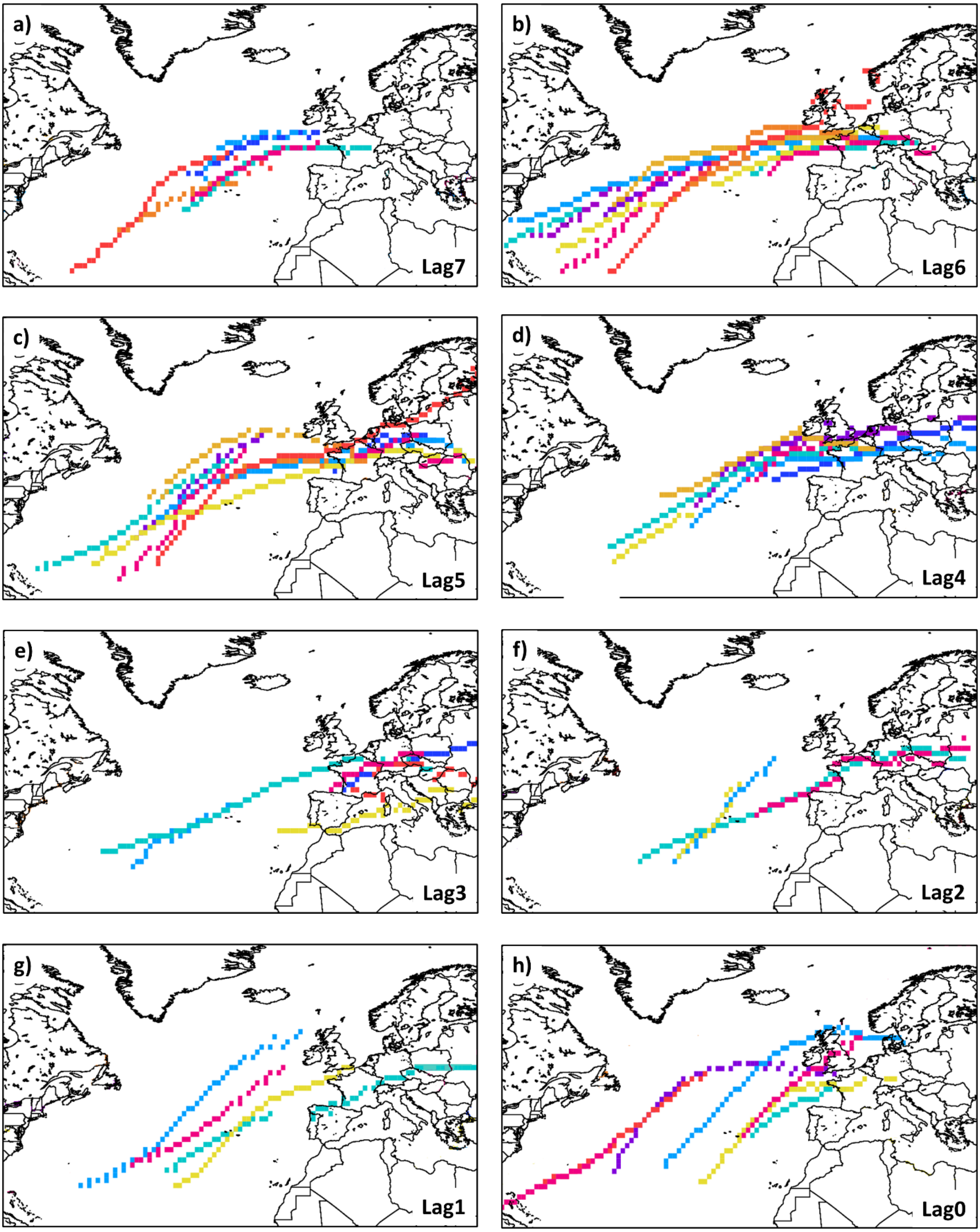

Figure 12. The AR axis location for the top 10 winter floods with different time lags (0 – 7 days). Each color is assigned to a flood peak.

Supplementary file

Rivers in the sky, flooding on the ground: the role of atmospheric rivers for the inland flooding in central Europe

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[4] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

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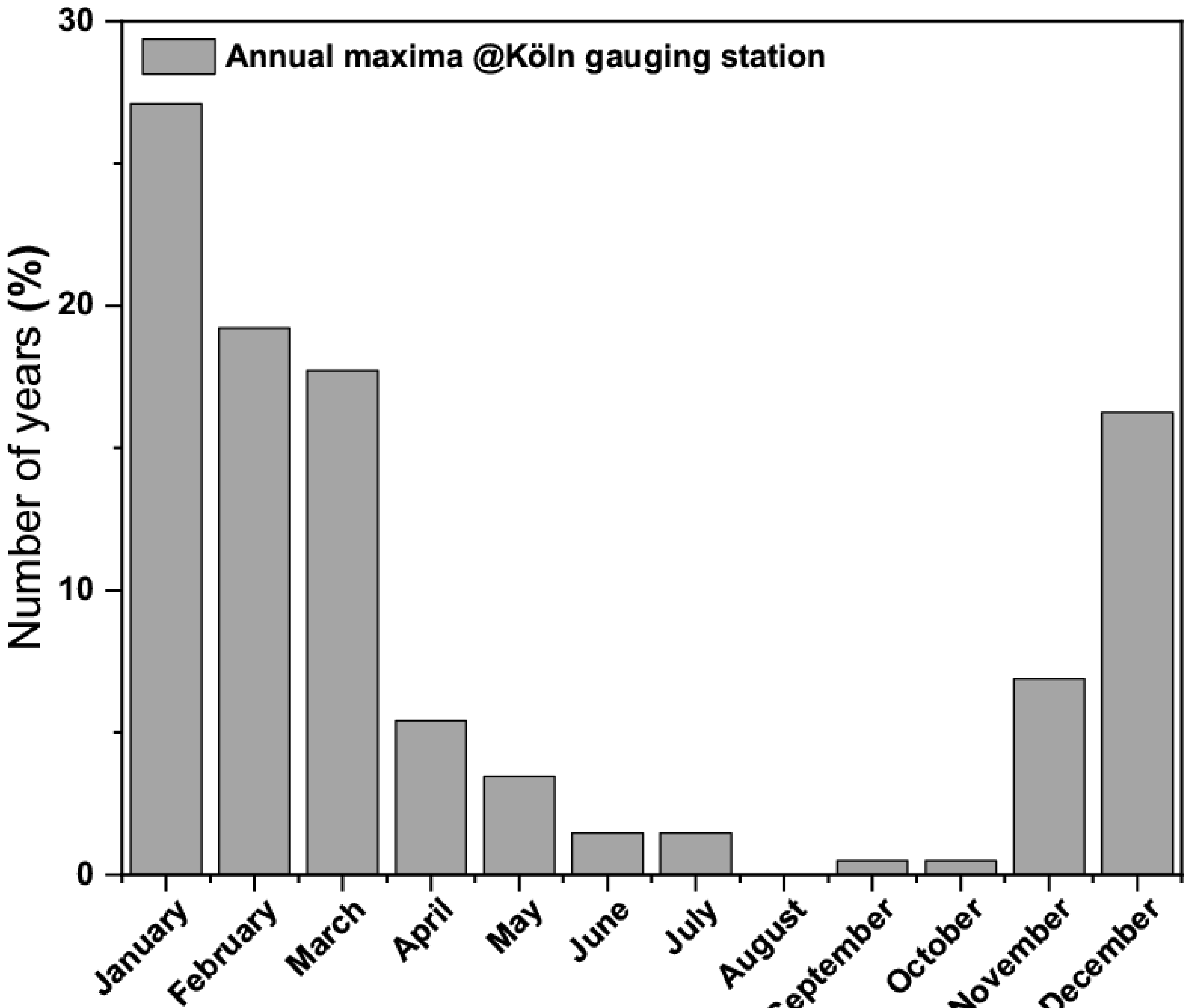


Figure S1. Monthly distribution of annual peak daily flows (% of number of years over the period 1817 – 2019) at Köln gauging station.

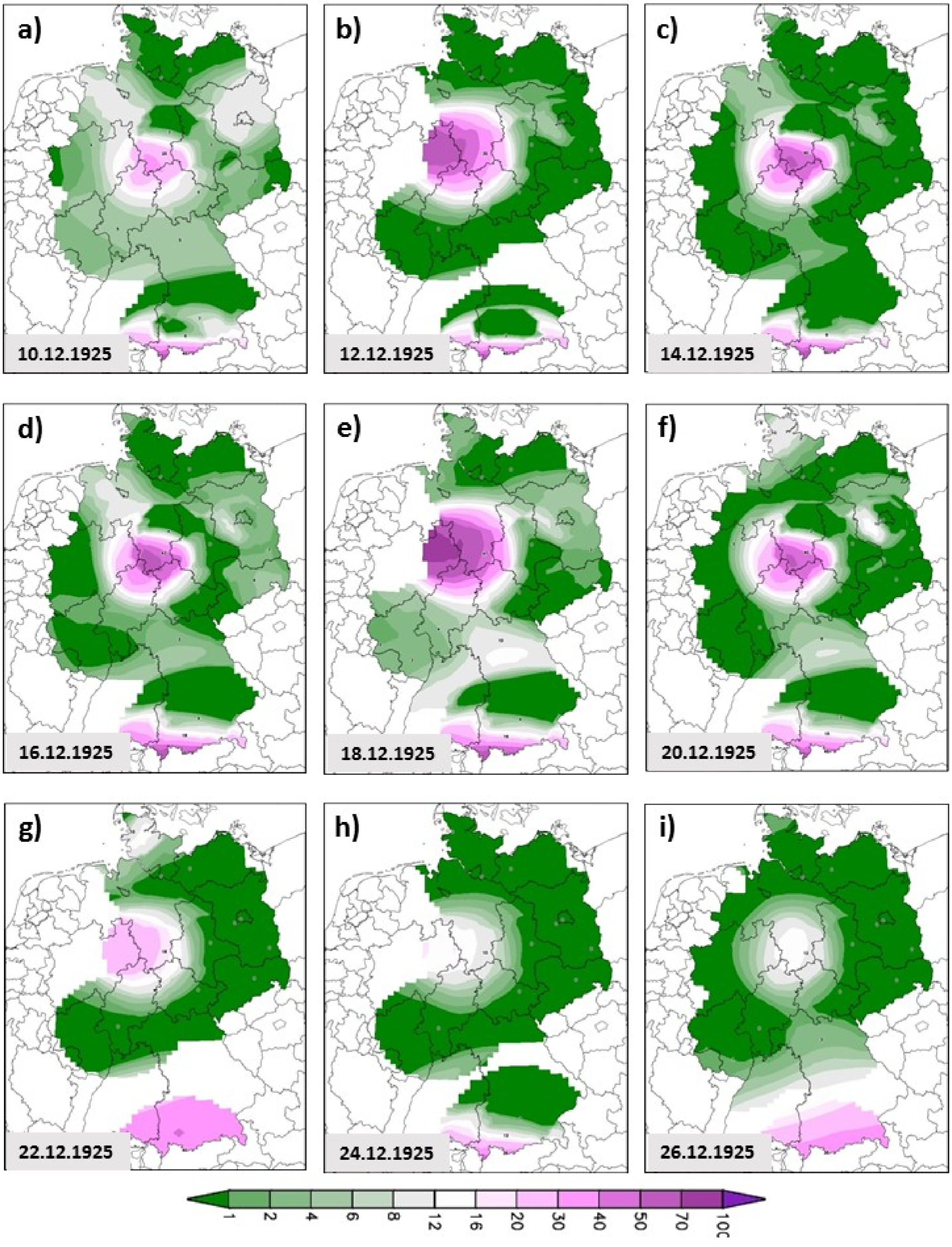


Figure S2. Daily snow depth (cm) for December 1925: a) December 10; b) December 12; c) December 14; d) December 16; e) December 18; f) December 20; g) December 22; h) December 24 and i) December 26. Data source: www.wetterzentrale.de

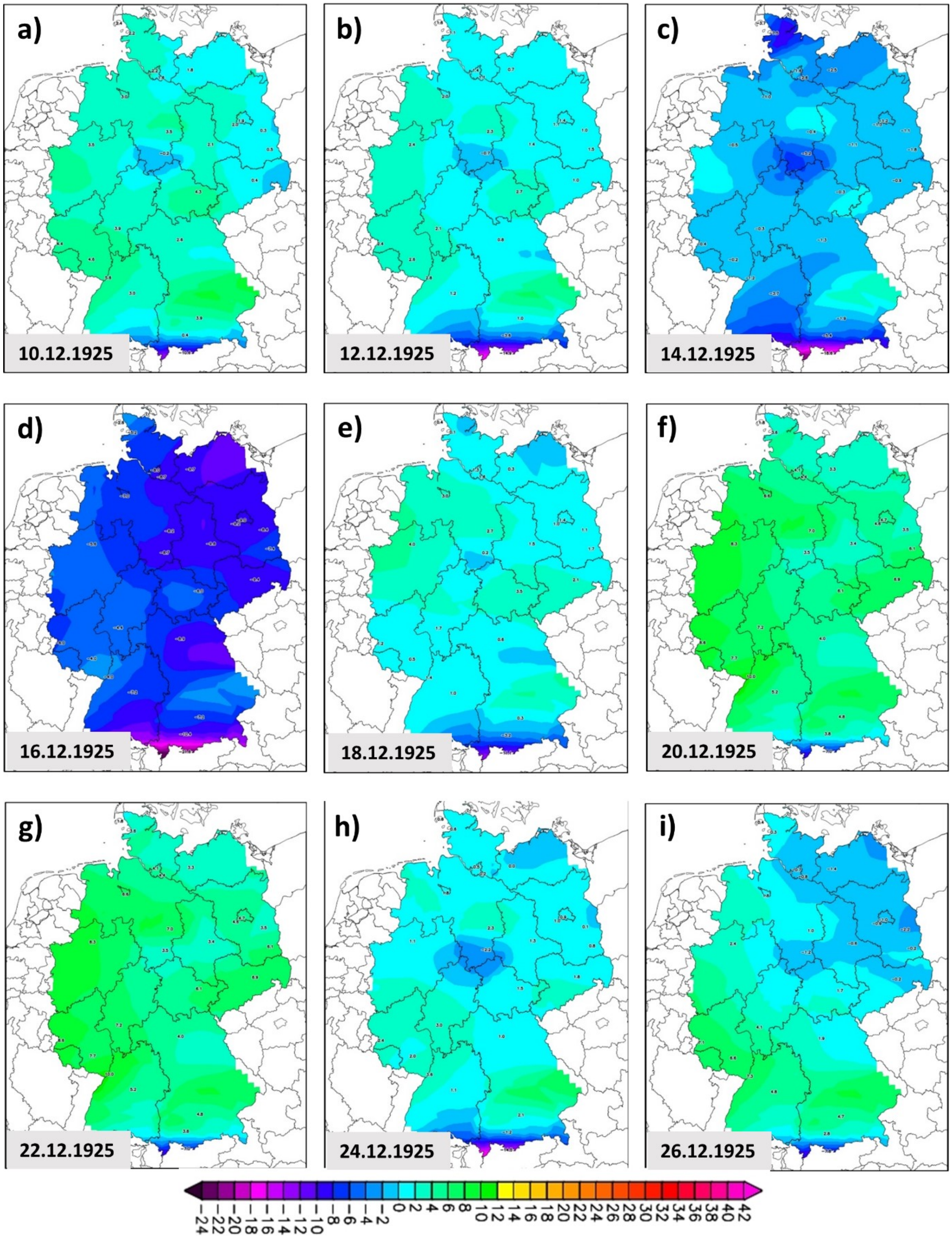


Figure S3. Daily mean temperature (°C) for December 1925: a) December 10; b) December 12; c) December 14; d) December 16; e) December 18; f) December 20; g) December 22; h) December 24 and i) December 26. Data source: www.wetterzentrale.de

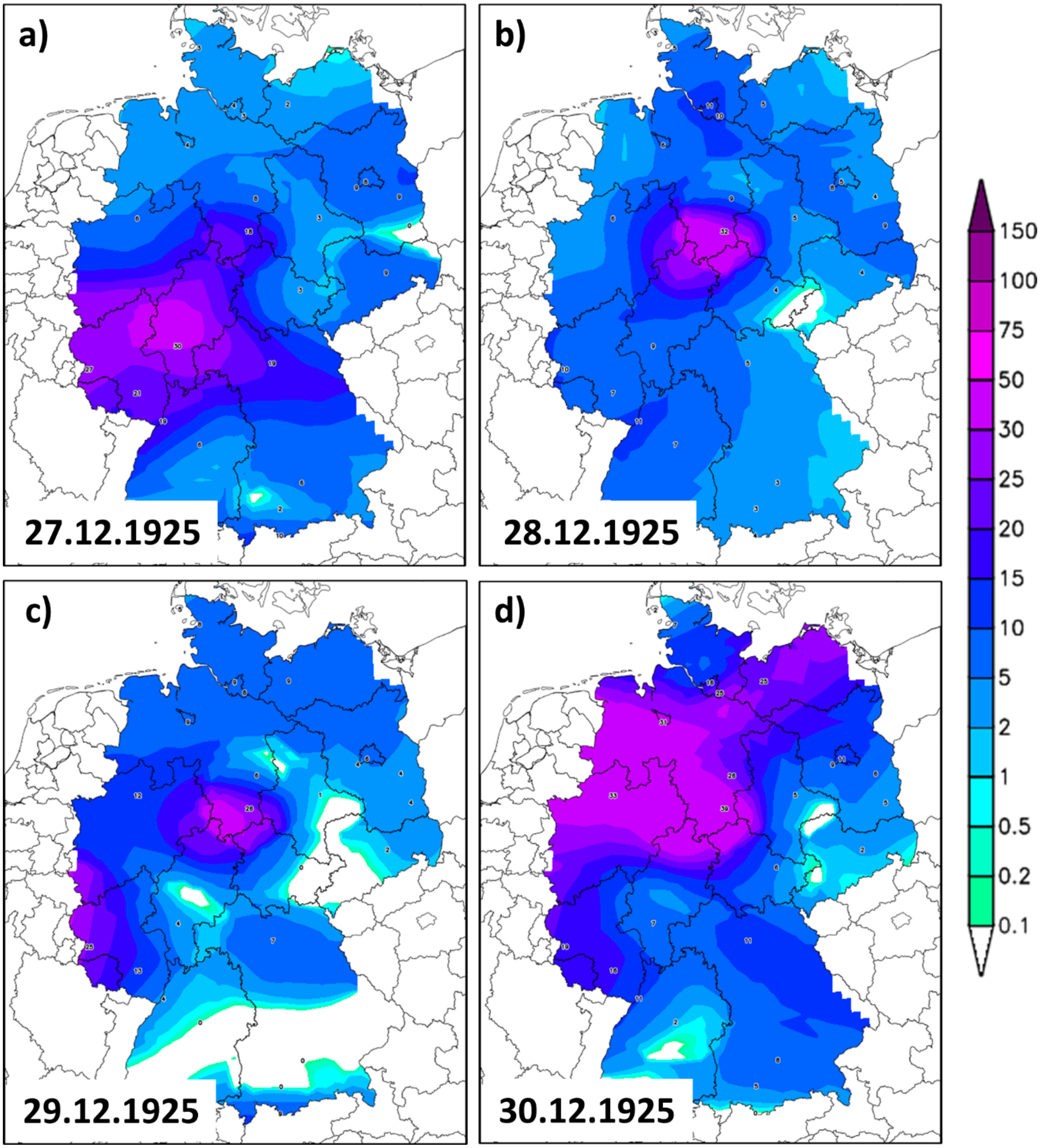
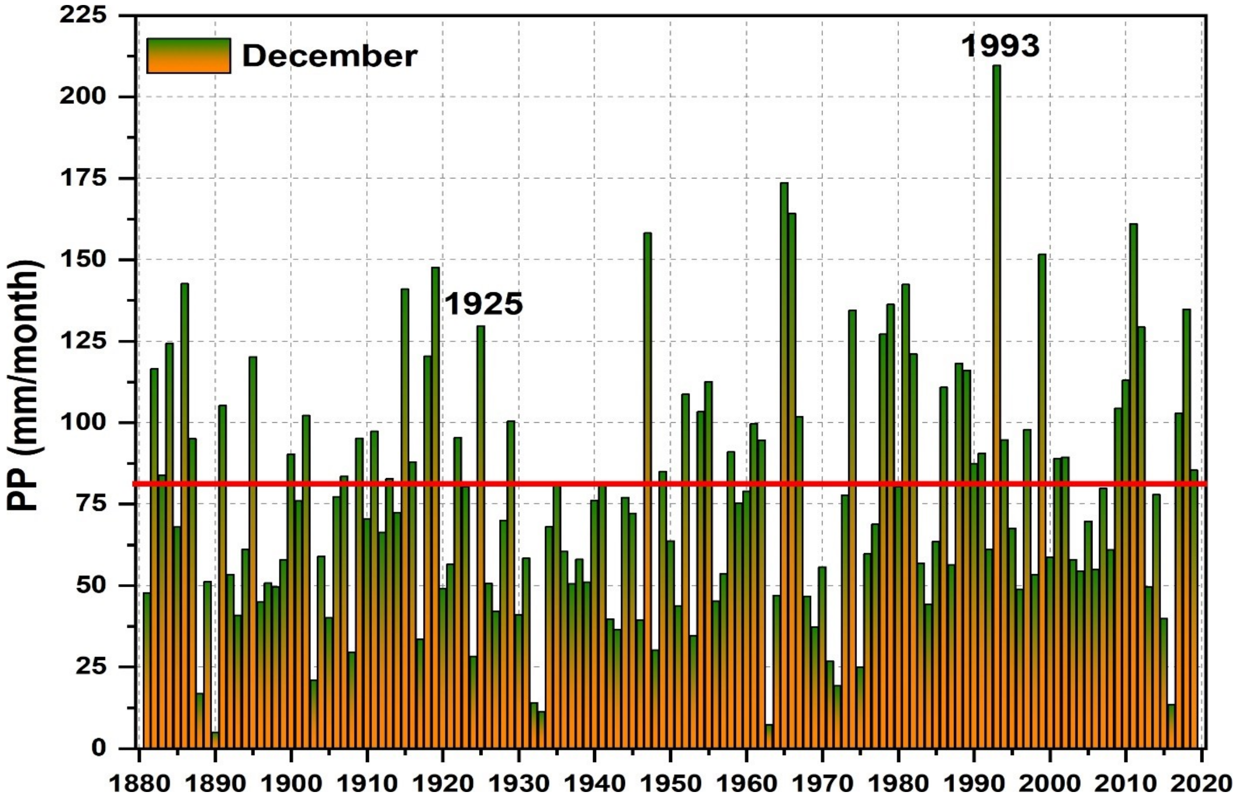


Figure S4. Daily precipitation amount for December 1925: a) December 27; b) December 28; c) December 29 and d) December 30. Units of measure: PP (mm/day). Data source: www.wetterzentrale.de

a)



b)

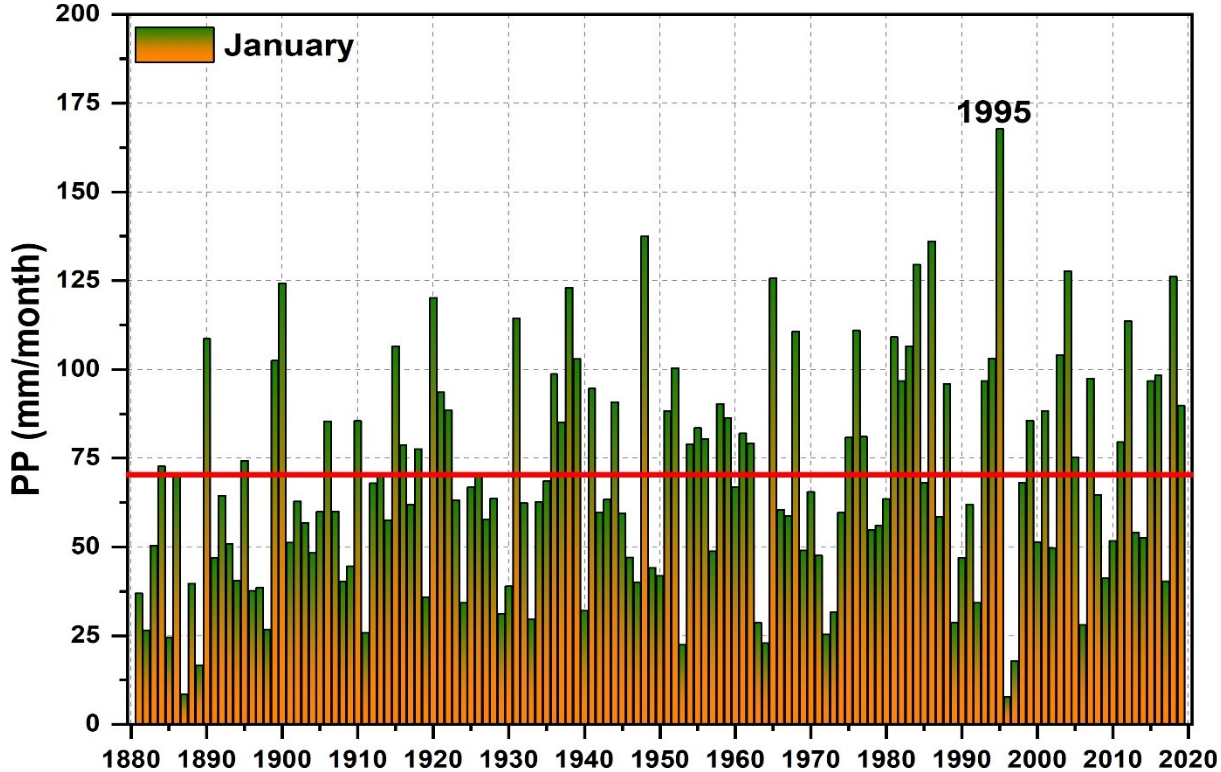


Figure S5. Monthly precipitation total, over the period 1881 -2019, for: a) December and b) January. The red line in a) and b) represents the climatology over the period 1971 – 2000. Data source: www.dwd.de

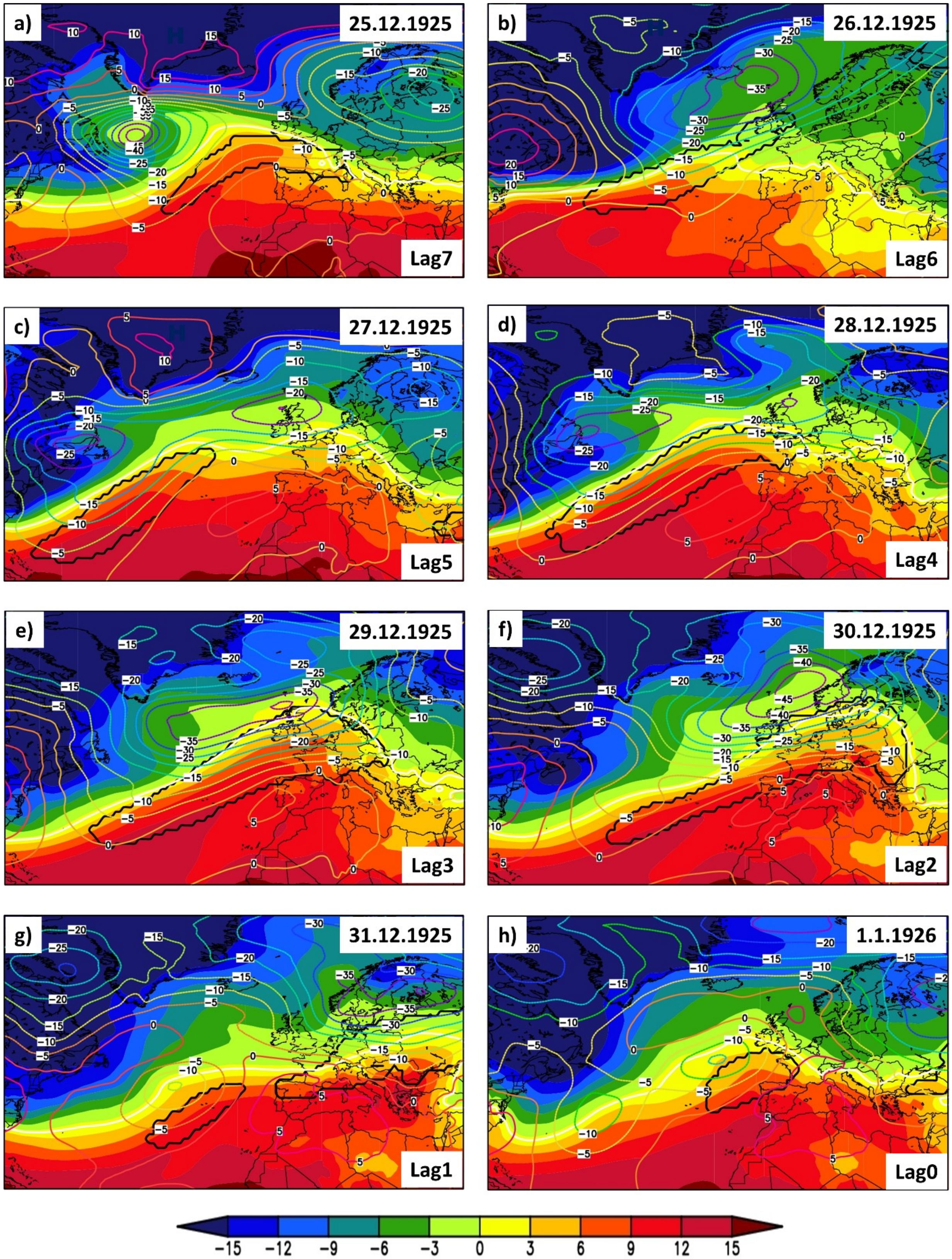


Figure S6. Daily anomalies of the mean sea level pressure (SLP, colored contour lines), daily mean temperature at 850mb level (TT850, shaded colors) and relative area covered by ARs (black contour line) during the days before the 1925/26 flood peak with different time lags (0 – 7 days). Units: SLP (hPa) and TT850 (°C).

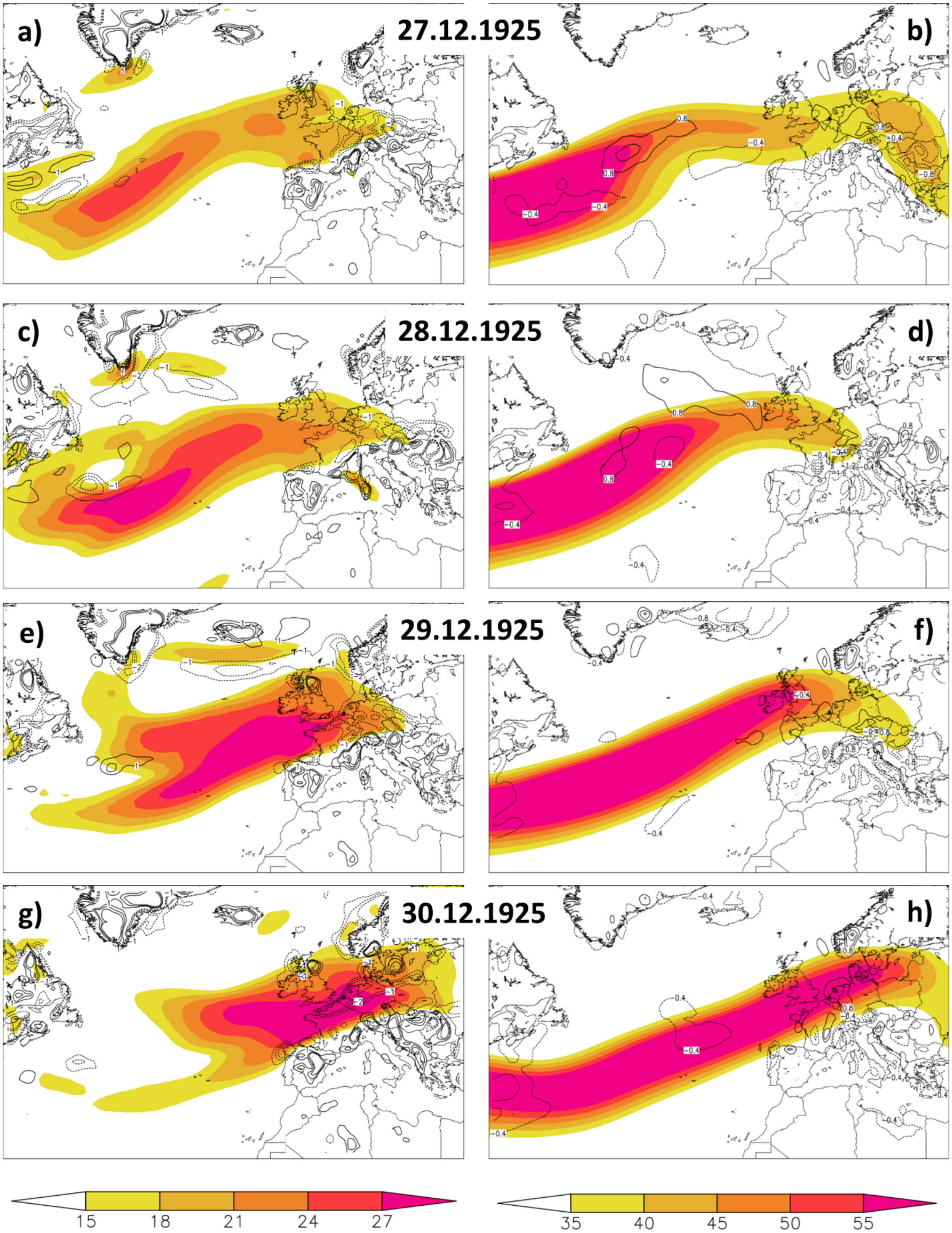


Figure S7. Daily zonal wind at 300 hPa level (shaded colors) and divergence/convergence (contour lines) for a) 27.12.1925; b) 28.12.1925; c) 29.12.1925 and d) 30.12.1925.

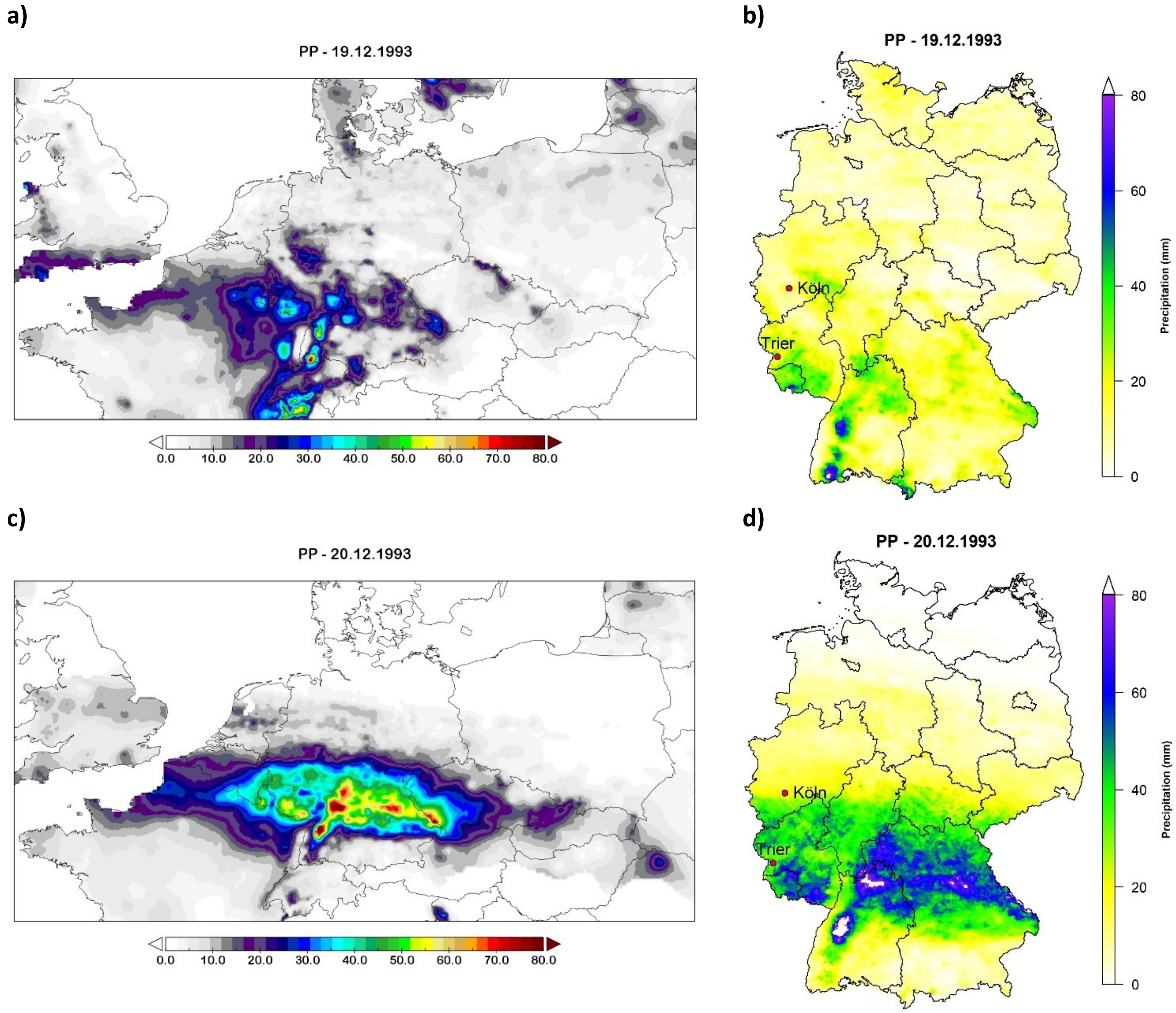


Figure S8. Daily precipitation amount based on the E-OBS data set (left column) and on the REGNIE data set (right column) for: a) and b) 19.12.1993; and c) and d) 20.12.1993. Units of measure: PP (mm).

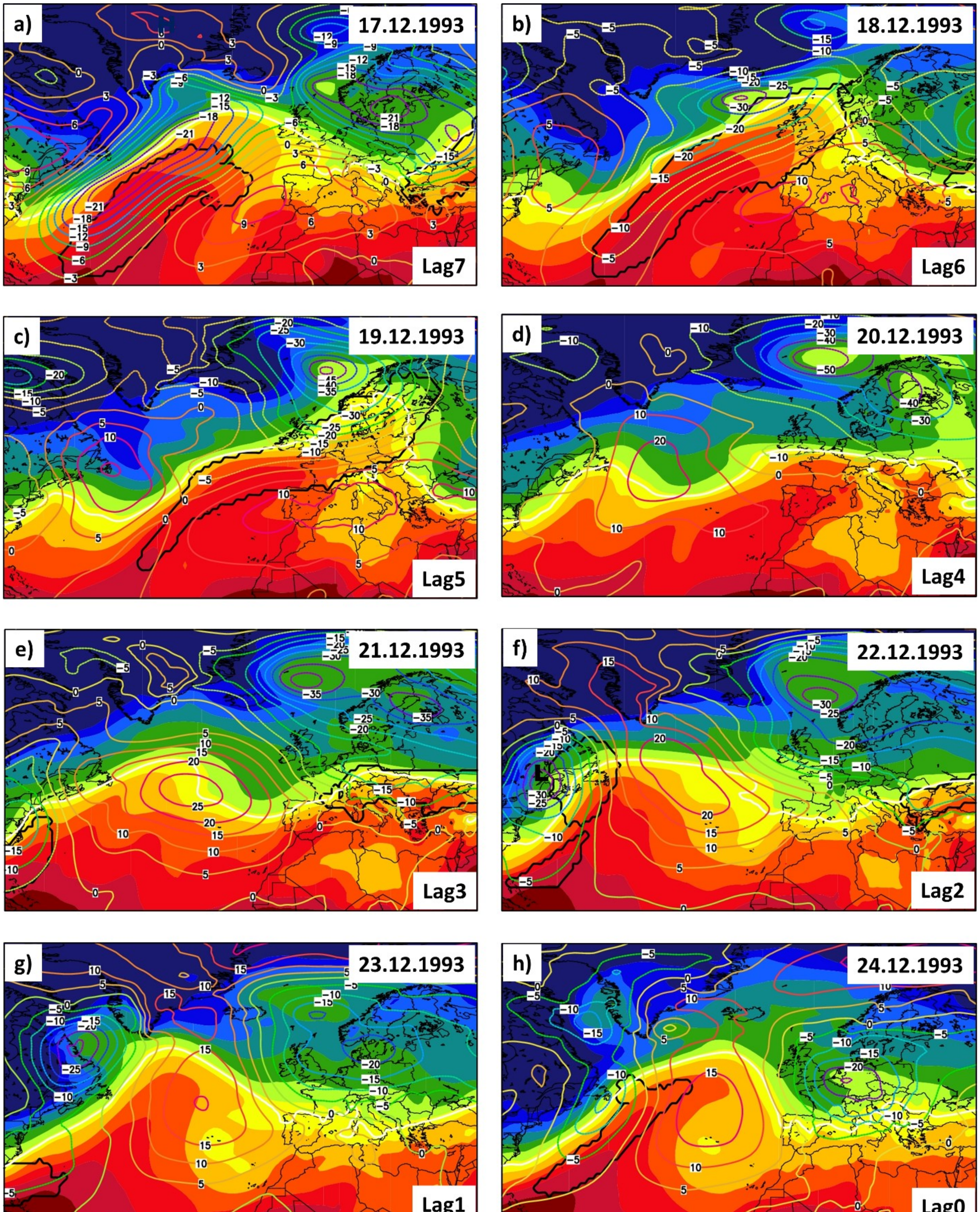


Figure S9. Daily anomalies of the mean sea level pressure (SLP, colored contour lines), daily mean temperature at 850mb level (TT850, shaded colors) and relative area covered by ARs (black contour line) during the days before the 1993 flood peak with different time lags (0 – 7 days). Units: SLP (hPa) and TT850 (°C).

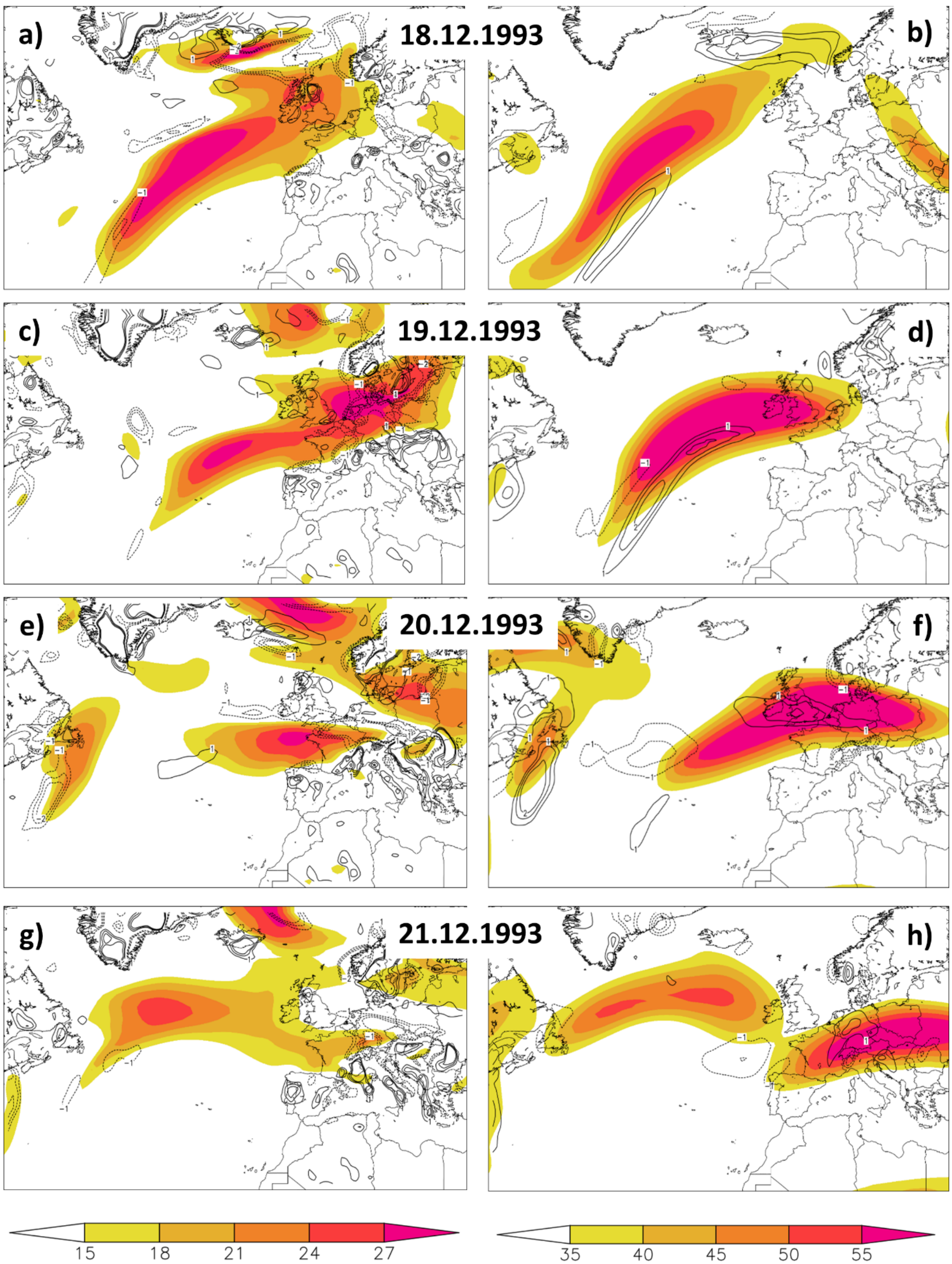


Figure S10. Daily zonal wind at 300 hPa level (shaded colors) and divergence/convergence (contour lines) for a) 19.12.1993 and b) 20.12.1993

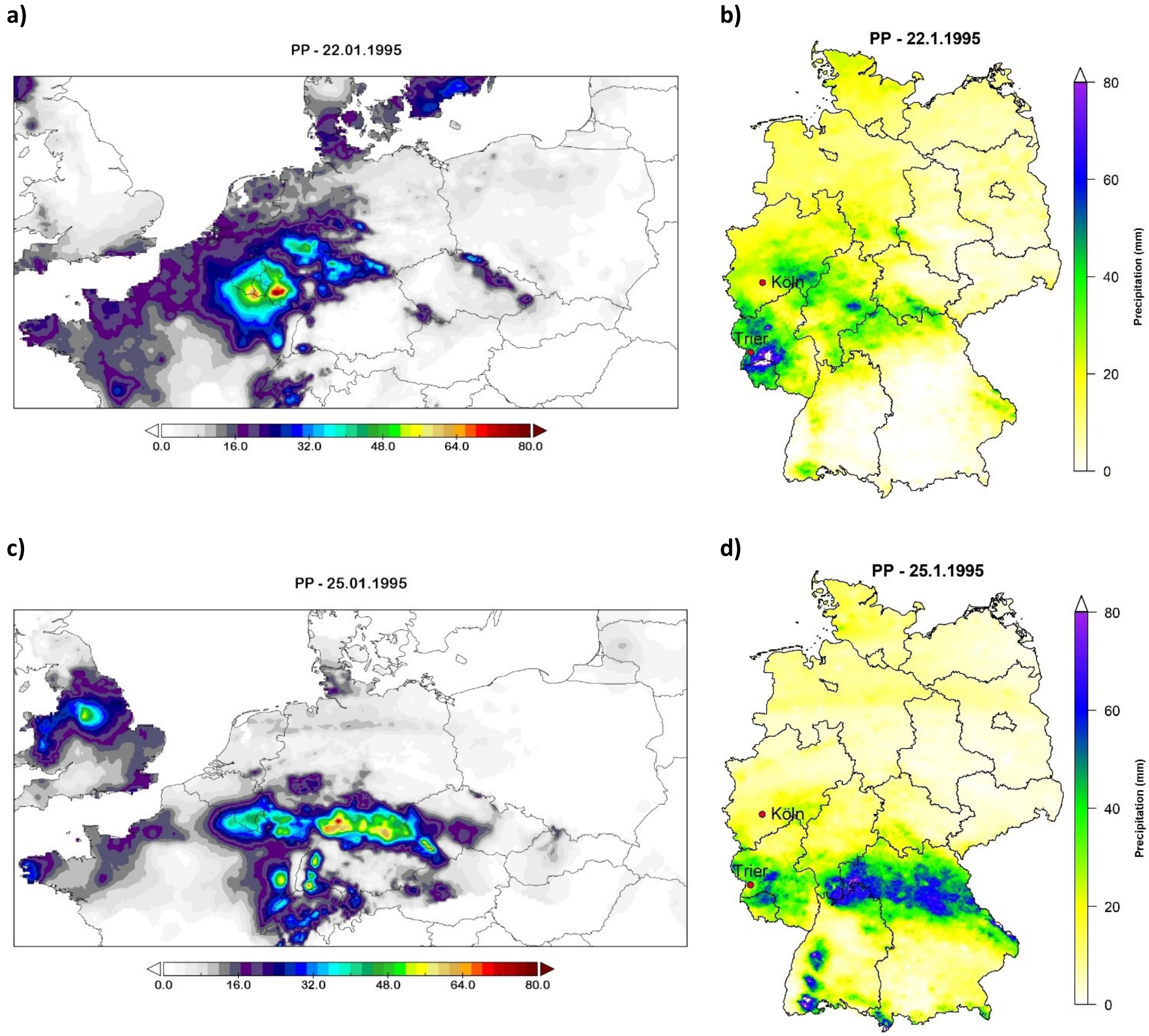


Figure S11. Daily precipitation amount based on the E-OBS data set (left column) and on the REGNIE data set (right column) for: a) and b) 22.1.1995; and c) und d) 25.1.1995. Units of measure: PP (mm).

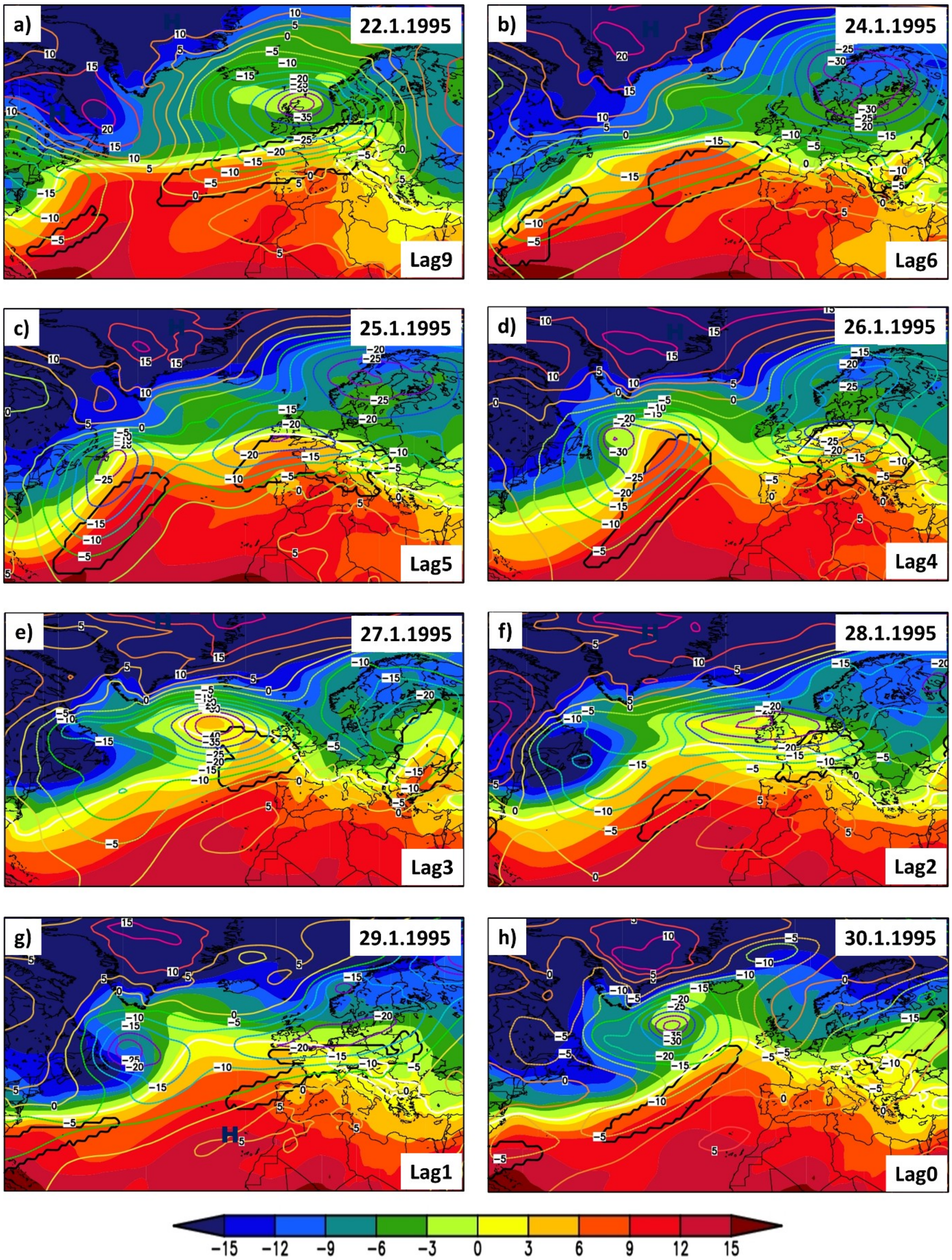


Figure S12. Daily anomalies of the mean sea level pressure (SLP, colored contour lines), daily mean temperature at 850mb level (TT850, shaded colors) and relative area covered by ARs (black contour line) during the days before the 1995 flood peak with different time lags (0 – 7 days). Units: SLP (hPa) and TT850 (°C).

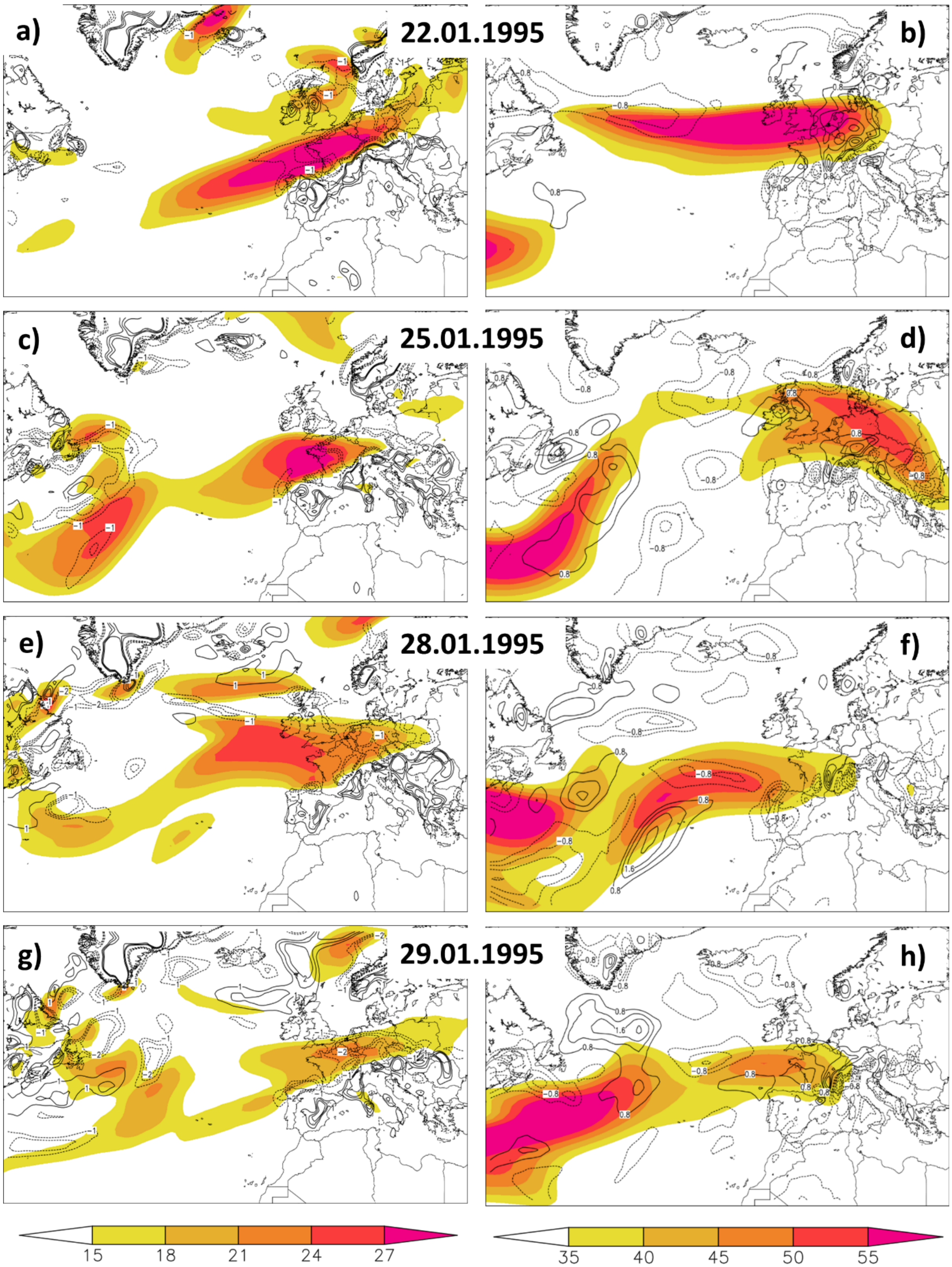


Figure S13. Daily zonal wind at 300 hPa level (shaded colors) and divergence/convergence (contour lines) for a) 22.1.1995; b) 25.1.1995; c) 28.1.1995 and d) 29.1.1995.

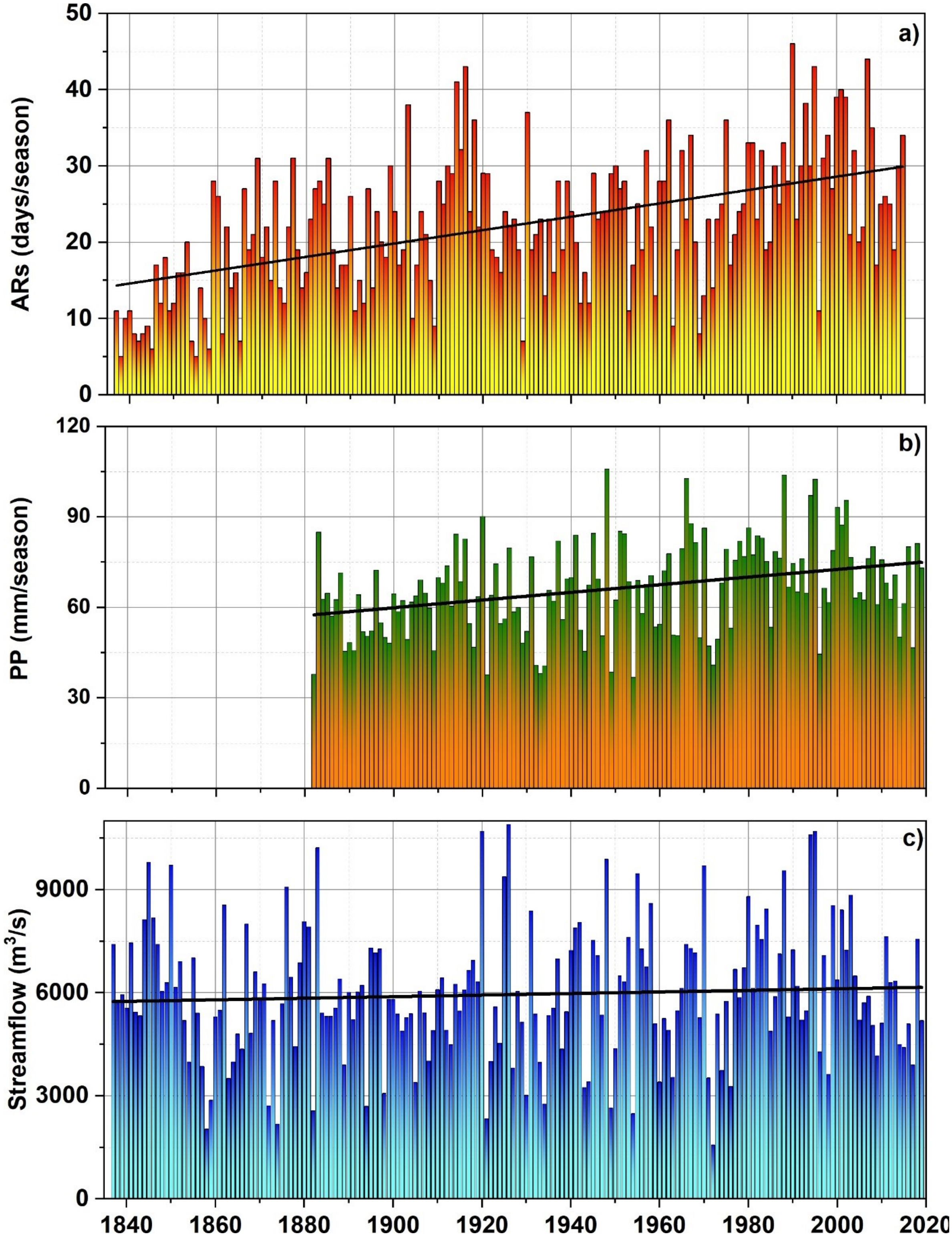


Figure S14. a) Number of days/season with ARs over the region 4° - 12°E; 47 – 56°N, for the period 1836 – 2015; b) Seasonal precipitation averaged over the German side of Rhine catchment area for the period 1881 – 2019 and c) Daily maximum streamflow at Köln gauging station over the period 1836 – 2019. For a), b) and c) we used only the period November – March for the analysis.