

The increasing influence of atmospheric moisture transport on hydrometeorological extremes in the Euromediterranean region with global warming

Corresponding Author: Professor Luis Gimeno

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Gimeno,

Your manuscript titled "The increasing influence of atmospheric moisture transport on hydrometeorological extremes in the Euromediterranean region with global warming" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. Specifically, we ask you to:

1. Significantly enhance your manuscript in terms of presentation of results and writing style.
2. Enhance your arguments by separating moisture transport into circulation and moisture components, comparing results with other models, and analyzing the relative importance of circulation versus moisture changes.
3. Explain your methods thoroughly and provide specific details about the precipitation generation mechanisms during summer and winter.

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a

list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Dr Alireza Bahadori
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

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3. Introduction, line 100. Same comment for 'advanced statistical methods.'

4. Conclusions, second paragraph. This paragraph needs to provide some numbers for the changes.

4. Conclusions. I think there are two additional points that should be made here. First, the study uses a single model and it would be very useful to see if the overall results are similar in other models. Second, there's no analysis of the relative importance of circulation versus moisture changes (noted as important in the intro, line 86), which would help us better understand why these changes are occurring. I don't think noting these needed areas of future work detracts from the current study and it would help put these specific results in a broader context.

Reviewer #2 (Remarks to the Author):

please find my review attached

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Version 1:

Decision Letter:

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Dear Professor Gimeno,

Your revised manuscript titled "The increasing influence of atmospheric moisture transport on hydrometeorological extremes in the Euromediterranean region with global warming" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have reasonably addressed my initial comments and I am pleased to recommend the manuscript be accepted.

Reviewer #2 (Remarks to the Author):

The authors have made a substantial effort in addressing my comments, I'd like to commend them on this. While I don't agree with their view on the relevance of moisture transport from different origins in the case of draught events, I can see the value of their investigation. The only remaining point I feel very strong about: please indicate in all figures very clearly that the results come from a dynamical downscaling of ERA5 and CESM simulations using WRF. This should be made explicit in all relevant figure captions. So write for example WRF-ERA5 and WRF-CESM.

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Review of “The increasing influence of atmospheric moisture transport on hydrometeorological extremes in the Euro Mediterranean region with global warming” by Gimeno-Sotelo et al.

I read this paper about the relevance of large-scale moisture transport on hydrometeorological extremes in the Euromediterranean region with a lot of interest and I think that the general ideas and tools used are sound. The results, although difficult to grasp due to the presentation and writing, are new, relevant and interesting. However, I have fundamental problems with the writing which is not as carefully carried out as the research itself. I therefore recommend rejecting the paper and ask for a fundamental reframing and rewriting of the manuscript before resubmission. Also, I would advise the authors to think about submitting this paper to a journal with a format that allows for the necessary space to carefully discuss the relatively involved methodology and the quite complex results. In my opinion the letter format seems unsuitable for this kind of manuscript.

I list here my major concerns and add a few more detailed examples of my struggles with the writing below.

Major points:

- A. Imprecise writing: in many instances, the writing lacks precision and process-based interpretation. For example, in the introduction the moisture transport and precipitation generation mechanisms are not discussed separately. Also, the discussion of precipitation generation mechanisms remains very superficial and lacks depth. Why focus on atmospheric rivers, when over Europe frontal systems and cyclones are usually seen as the main precipitation generation mechanisms in winter and deep convection in summer (Rüdisühli et al. 2020)? Of course, very often atmospheric rivers (mainly as a transport feature) are associated with the frontal systems that generate the precipitation. But at this stage, the paper lacks a clear motivation for focusing on atmospheric rivers alone. Moisture transport can happen outside atmospheric rivers along low-level jets, or in cyclones with convergence of moisture from many sources. Also, the motivation for focusing on the Euro Mediterranean region is not clear. I think there are plenty of reasons for looking at this region, for example the complex picture of change in winter precipitation extremes with many coastal regions and Northern Africa mainly experiencing a decrease and the continental regions as well as the regions with orography experiencing a strong increase.
- B. Lack of process-based interpretation (role of convection, effect of resolution) and missing links to existing literature on the evaluation of kilometer scale simulations of precipitation (Ban et al. 2021) and precipitation triggering mechanisms in Europe in summer vs. winter (Giorgi et al. 2016; Rüdisühli et al. 2020)
- C. I doubt that combining the results on changes in precipitation and droughts is judicious. As recent papers on processes associated with heat waves and draughts suggest, the mechanisms behind these events are complex and due to a combination of processes at play (Schumacher et al. 2019; Röthlisberger and Papritz, 2023; Herrmann et al. 2024). This paper doesn't take this

complexity into account by simply looking at evaporation deficits at the moisture source and lack of strong moisture transport upstream.

Minor points:

1. L. 16: Why does it concern? Why is it important? Maybe rather point out the remaining uncertainties in future extreme precipitation predictions and the fact that the link with changes in circulation patterns is under researched.
2. L. 23-24: Already in the abstract I stumble over the lack of motivation for looking at atmospheric rivers
3. L. 97: The knowledge gap is not explicitly mentioned
4. L. 54-65: separate the discussion on the moisture transport mechanisms and the precipitation generation mechanisms, these are two different things. Also be very clear on your focus on the winter season (and remote sources) and shortly mention the existing literature on summer extreme precipitation and the role of deep convection.
5. L. 84: this is a repetition, combine with the second paragraph.
6. L. 89: what are other mechanisms?
7. L. 93: I think the motivation for the region of interest should come much earlier.
8. L. 125: The focus on the cold season should be shifted to the introduction together with a short but thorough review of the precipitation generation mechanisms.
9. L. 128: mention that this is meant for present day and in comparison to the ERA5 reanalysis
10. L. 132-138: I have difficulties following and understanding this. Where geographically do you mean exactly when you write "upwind of the dominant westerly and southerly flows from the Atlantic Ocean and the Mediterranean Sea".
11. L. 137-138: is it really worth noting that the extremes are lower along the French Atlantic coast? If yes, why is it so?
12. L. 140 and Fig. 1: EC, MC are not formally introduced (L. 165) and could be referred to in the text as well to make Fig. 1 a bit easier to access.
13. L. 148: widespread increase in the importance of moisture transport on extreme precipitation -> except in the Sahara and in general I find it quite patchy at least in the MC.
14. L. 151: why in contrast? In contrast to what? IVT at max P is also quite ok well reproduced by CESM2.
15. There is no discussion whatsoever on the influence of resolution and I don't quite understand if Fig. 1 shows CESM2 simulations. For me it is quite confusing to have CESM2 in Fig. 1 but reading that there was a dynamical downscaling done with WRF in the methods. So on which data and simulation resolution is Fig. 1 based?
16. L. 169-170: are these differences between changes in precipitation and changes in IVT at max precip really robust. With a bit of goodwill, I see more similarities than differences: decrease over the Pyrenees, on the east of the Appenine, on the east of Greece -> basically in the north-east of mountain ranges in Europe and in the Sahara there is a decrease or a weaker increase in precipitation extremes and in IVT at max precip.
17. L. 356-357: mention the role of convection in summer also in the conclusion.

18. L. 366-367: this comes a bit as a surprise, can you argue more why a dissociation between atmospheric rivers and extratropical cyclones is expected in a warmer climate?

References

Ban, N., Caillaud, C., Coppola, E. et al., 2021, The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation. *Clim. Dyn.*, 57, 275-302, <https://doi.org/10.1007/s00382-021-05708-w>.

Giorgi, F., Torma, C., Coppola, E. et al., 2016, Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. *Nat. Geosci.* 9, 584-589, <https://doi.org/10.1038/ngeo2761>.

Hermann, M., Wernli, H. & Röthlisberger, M., 2024, Drastic increase in the magnitude of very rare summer-mean vapor pressure deficit extremes. *Nat. Commun.*, 15, 7022, <https://doi.org/10.1038/s41467-024-51305-w>.

Röthlisberger, M., Papritz, L., 2023, Quantifying the physical processes leading to atmospheric hot extremes at a global scale. *Nat. Geosci.* 16, 210-216, <https://doi.org/10.1038/s41561-023-01126-1>.

Rüdisühli, S., Sprenger, M., Leutwyler, D., Schär, C., and Wernli, H., 2020, Attribution of precipitation to cyclones and fronts over Europe in a kilometer-scale regional climate simulation, *Weather Clim. Dynam.*, 1, 675-699, <https://doi.org/10.5194/wcd-1-675-2020>.

Schumacher, D.L., Keune, J., van Heerwaarden, C.C. et al., 2019, Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nat. Geosci.* 12, 712-717, <https://doi.org/10.1038/s41561-019-0431-6>.

RESPONSE TO REVIEWERS' COMMENTS

We would like to express our gratitude to the two reviewers for all their helpful comments. They offered extremely valuable perspectives on our work and effective suggestions for improvements. We reply to each comment in a point-by-point fashion.

IMPORTANT NOTE: All changes made throughout the manuscript are identified in blue color.

Reviewer #1 (Remarks to the Author):

This study examines the role of moisture transport in changes to winter precipitation maxima for the Euromediterranean region under a high emissions scenario, finding substantial changes by the end of the century under a high emissions scenario. The methodology appears sound, the analysis is reasonably described, and the results are useful. I was hoping for a separation of the moisture transport into circulation and moisture components but I think the analysis stands on its own without that. I have only a few minor editorial comments.

1. Abstract. The emissions scenario that is used for the study needs to be noted here. (Not critiquing the choice but it is a key piece of information for the abstract.)

We agree with the reviewer and have added that information to the abstract.

2. Abstract, line 21. The phrase 'deeply examine' is quite vague. I'd suggest explaining what you mean or just using 'examine.'

We agree with the reviewer. We have chosen to just use "examine".

3. Introduction, line 100. Same comment for 'advanced statistical methods.'

We agree. We have removed the word "advanced" to avoid the vague sentence.

4. Conclusions, second paragraph. This paragraph needs to provide some numbers for the changes.

Done. We have provided some numbers regarding the changes:

"For extreme precipitation, the influence of moisture transport is expected to be greater than that observed in the present in the mid-century period, with an increase of about 25% in the dependence in winter and about 10% in summer (a less relevant season in terms of moisture transport due to the higher importance of convective processes). However, for the end of the century, the importance of moisture transport in extreme precipitation is expected to decrease, finding a negligible increase (less than 5%) or

even a slight decrease (of about 5%) with respect to the present period, in winter and summer, respectively. (...) ”

4. Conclusions. I think there are two additional points that should be made here. First, the study uses a single model and it would be very useful to see if the overall results are similar in other models. Second, there's no analysis of the relative importance of circulation versus moisture changes (noted as important in the intro, line 86), which would help us better understand why these changes are occurring. I don't think noting these needed areas of future work detracts from the current study and it would help put these specific results in a broader context.

It is evident that using multiple models would enhance the robustness of the results. However, this is not a viable option given the methodology employed. The Lagrangian analysis that supports the result on the influence of moisture transport deficit on droughts requires extremely high simulation requirements. The use of a single model across the three time periods (historical, mid-century and end-century) necessitated the use of the majority of the simulation capacity of FINISTERRAE II, a high-performance supercomputer belonging to the Supercomputing Center of Galicia, for a period of two years. In our original paper published in *Nature Communications*, which was also based on this simulation, we first conducted an analysis covering five-year periods. At the request of the editor of *Nature Communications*, we expanded this to encompass three 30-year periods, resulting in a delay of over a year before the paper could be revised. The final paper also included references to CESM capacity and a comparison of basic variables with an ensemble of models. It is noteworthy that this is the only high-resolution Lagrangian simulation with a CMIP6 model available for 30-year periods at present. No other research group has undertaken a similar endeavour yet, due to the considerable computational demands involved.

The separation of thermodynamic (humidity) and dynamic (circulation) effects for the Lagrangian analysis on which the drought analysis is based is also a challenging task, as the technique is based on particle moisture tracking and the computation of moisture changes for each particle. This procedure makes it difficult to separate the effects because moisture changes are computed along the trajectories of the particles (i.e., both effects are included in the computation).

We think that these two comments, as suggested by the reviewer, could be included as possible future work in the modified version, commenting on the need for them and highlighting their great complexity. This information has been added in the conclusions section of the revised version of the manuscript, as follows:

“These findings stress the importance of considering projected changes in moisture transport from oceanic areas in future climates to explain the changes in extreme precipitation and drought. In order to improve the physical understanding of these projections, a future challenge would be to analyse the relative importance of the changes in thermodynamic effects (moisture changes) versus dynamic ones (circulation changes). It should be noted, however, that this is a challenge in Lagrangian analysis, as it would mean separating each of these effects when calculating the moisture changes of air particles along their trajectories. The use of different climate models from the one on which this study is based (CESM2) would also be another challenge that would enhance

the robustness of the obtained results, but whose high simulation requirements would be an extremely demanding task for future research.”

Reviewer #2 (Remarks to the Author):

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I read this paper about the relevance of large-scale moisture transport on hydrometeorological extremes in the Euromediterranean region with a lot of interest and I think that the general ideas and tools used are sound. The results, although difficult to grasp due to the presentation and writing, are new, relevant and interesting. However, I have fundamental problems with the writing which is not as carefully carried out as the research itself. I therefore recommend rejecting the paper and ask for a fundamental reframing and rewriting of the manuscript before resubmission. Also, I would advise the authors to think about submitting this paper to a journal with a format that allows for the necessary space to carefully discuss the relatively involved methodology and the quite complex results. In my opinion the letter format seems unsuitable for this kind of manuscript.

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We agree with the reviewer that the paper would be enhanced by a brief expansion of the introduction on precipitation systems in the Mediterranean and a separate wording on the mechanisms of precipitation and moisture transport affecting the region. This has been incorporated into the revised version of the paper, with a length adapted to the size of the manuscript, to the general environmental audience of the journal and without distorting the overall message of the paper, which is the changes in the relationship between moisture transport and hydrometeorological extremes.

We also agree with the reviewer that there are multiple meteorological structures other than atmospheric rivers responsible for extreme precipitation in the region, not only at the synoptic scale but also at the mesoscale (mesoscale convective systems and severe storms). We also agree that there are other moisture transport mechanisms than atmospheric rivers (see for example the review paper in *Annual Reviews of Environment and Resources*, Gimeno et al., 2016). This is true and we do not dispute it, but our paper is based on the influence of moisture transport on extreme precipitation in the Euro-Mediterranean region, and atmospheric rivers are the main moisture transport mechanism affecting that region (Gimeno et al., 2016). The other major moisture transport mechanisms, such as low-level jets, are much less important for precipitation in the Mediterranean region (Gimeno et al., 2016) and the other meteorological systems responsible for extreme precipitation either do not involve major moisture transport, such as storm cells, or those that do, such as extratropical cyclones or associated cold fronts, are mostly accompanied by atmospheric rivers when there is notable moisture transport (Gimeno et al., 2021).

- Gimeno, L. et al. (2016) Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events." *Annual Review of Environment and Resources* 41.1 117-141.
- Gimeno, L., Algarra, I., Eiras-Barca, J., Ramos, A. M., & Nieto, R. (2021). Atmospheric river, a term encompassing different meteorological patterns. *Wiley Interdisciplinary Reviews: Water*, 8(6), e1558. <https://doi.org/10.1002/wat2.1558>

Following the recommendations put forth by the reviewer, we have augmented the rationale behind selecting the Euro-Mediterranean region for this analysis.

The three following paragraphs of the Introduction section of the revised manuscript incorporate many of the changes that were made in order to account for this reviewer's comment:

“Behind extreme precipitation and meteorological drought and their changes under climate change, there are a number of diverse and complex mechanisms (O’Gorman, 2015; Ault, 2020; Hermann et al., 2024), but both hydrometeorological extremes have in common the fact that excesses or deficits in moisture transport to the region are frequent (Gimeno et al., 2012; Liu et al., 2020). In the most basic approximation, precipitation scales with the moisture content and an indicator of atmospheric instability (Emori and Brown, 2005). It is not possible to determine from the amount of water vapour in an air column at a given time how much of this is involved in precipitation. The water vapour in the column is changing, and it is therefore essential to ascertain the quantity of water

vapour transported from surrounding areas that converges in the column, since the available humidity at a given time and place is usually not sufficient to generate precipitation (*Trenberth et al., 2003*). It is therefore evident that moisture transport plays a significant role in the occurrence of precipitation when convergence occurs (*Mo et al., 2021*), which can occur in association with a multitude of meteorological processes, being in extratropics those related with highly complex baroclinic developments such as fronts and extratropical cyclones the most relevant ones (*Catto and Pfahl, 2013; Pfahl and Wernli, 2012*), with or without orographic effects (*Houze Jr, 2012*). This role of moisture transport on precipitation is particularly evident during the winter season, particularly in the case of remote moisture sources. Conversely, this role is less pronounced in the case of extreme summer precipitation, where deep convection plays a significant role (*Stevens, 2005*).

Furthermore, a number of moisture transport mechanisms are responsible for mean and extreme precipitation. These range from synoptic structures, such as tropical or extratropical cyclones, to planetary structures, including monsoonal circulations, atmospheric rivers (ARs) and low-level jets (LLJs) (*Gimeno et al., 2016*). In quantitative terms, the global transport of moisture is dominated mainly by these two last meteorological phenomena (*Gimeno et al., 2016*). In extratropical areas, ARs are the dominant mechanism, while in subtropical and tropical regions, LLJs are the dominant one. The two mechanisms are responsible for a significant portion of the meridional transport of moisture in the atmosphere, so it is estimated that the transport of moisture from ARs alone accounts for over 90% of the total flow of water vapour towards the poles at extratropical latitudes (*Zhu & Newell, 1998*). It is therefore not surprising that the control of extreme precipitation and meteorological drought by moisture transport is not spatially or seasonally homogeneous; the main influence is recorded in regions dominated by the main mechanisms of moisture transport, such as atmospheric rivers, low-level jets or tropical cyclones (*Gimeno et al., 2016*), indicating that in some regions, moisture transport strongly controls extreme precipitation and meteorological drought (*Gimeno-Sotelo and Gimeno, 2023, Gimeno-Sotelo et al., 2024b*).

One of the regions where the relationships between moisture transport and precipitation excesses and deficits are most pronounced is the Euromediterranean area. It is affected by the strongest moisture transport mechanisms that affect both average and, above all, extreme precipitation: the atmospheric rivers (ARs) on the European Atlantic coast (*Lavers and Villarini, 2013*). Therefore, it is not surprising that around the Mediterranean, there are large continental regions where both extreme daily precipitation and meteorological droughts are strongly affected by anomalously high or low moisture transport. In particular, the influence of moisture transport on extreme daily precipitation bears the signature of the AR track (*Gimeno-Sotelo and Gimeno, 2023, Konstali et al., 2024*). Moreover, meteorological droughts are highly likely to occur in the region in

response to deficits in moisture transport from the Atlantic Ocean or the Mediterranean Sea (*Gimeno-Sotelo et al., 2024b*). These major moisture transport mechanisms are projected to change significantly with global warming (*Payne et al., 2020*), which could dramatically alter the frequency and severity of extreme precipitation and meteorological drought in the Euromediterranean region. These hypothetical modifications in moisture transport could have dramatic consequences given the limited water resources of the region (*García-Ruiz et al., 2011*) and the frequent occurrence of droughts (*Cook et al., 2016*) and extreme precipitation events (*Mastrantonas et al., 2021*) there. There are strong additional reasons for choosing this region to study changes in the relationship between moisture transport and hydrometeorological extremes, such as its complex orography, with the Alps as a region of considerable precipitation and with increased summer precipitation with climate change (*Giorgi et al., 2016*), the very different meteorological systems responsible for precipitation in summer (mainly convective in a synoptic context of high-pressure precipitation) compared to winter and autumn (mainly precipitation due to cyclones and cold fronts) (*Rüdisühli et al., 2020*), and the complex picture of changes in winter precipitation extremes, with many coastal regions and northern Africa mainly experiencing a decrease and continental regions as well as regions with orography experiencing a strong increase (*Zittis et al., 2021; Lionello and Scarascia, 2020*)."

The corresponding changes have been explained carefully in response to the minor specific comments below.

B. Lack of process-based interpretation (role of convection, effect of resolution) and missing links to existing literature on the evaluation of kilometer scale simulations of precipitation (*Ban et al. 2021*) and precipitation triggering mechanisms in Europe in summer vs. winter (*Giorgi et al. 2016; Rüdisühli et al. 2020*)

We agree with the reviewer on the need to comment on the effect of resolution or the convection for the representation of extremes in the hydrological cycle, in particular precipitation and emphasise the enormous computational efforts made in this study for downscaling reanalysis and climate model data.

In our paper, we have used high-resolution data obtained using the Weather Research and Forecasting (WRF) model, forced with reanalysis data and CESM2 data, in line with *Zscheischler et al. (2021)*. In their paper, they concluded that reanalysis data are not suitable enough for representing extreme precipitation (in combination with extreme winds) in regions with high orography, such as the Alps region. This is a very similar framework to ours, where we study the relationship between moisture transport and extreme precipitation, and have also used the WRF model, forced with reanalysis and CESM2 data in order to better represent complex topography and small-scale convective processes.

In any case, the spatial resolution of our dynamic downscaling with WRF is 20 km and convection is parameterised (not resolved), differently from other studies using km-scale

simulations in which convection is resolved (e.g. *Ban et al., 2021* or *Rüdisühli et al., 2020*). Even for a terrain with such complex orography as the Alps, the work of *Ban et al. (2021)* found that the improved representativeness of precipitation intensity and frequency of km-scale models resolving convection compared to coarse resolution models with parameterised convection is particularly important for extreme summer precipitation and more important for the sub-daily range than for the daily one. On the one hand, the scope of our work focuses more on extreme winter precipitation and the role of moisture transport from remote sources. On the other hand, remarkable computational difficulties would be involved in running such a large domain and large periods as the ones used in our study at such a high resolution to resolve convection (*Kendon et al., 2021*). For both reasons, the used resolution and the fact that convection is parameterised with well-established schemes were the most appropriate choices.

Our results regarding extreme precipitation are consistent with those obtained in *Rüdisühli et al. (2020)*. Using outputs of a COSMO (Consortium for Small-scale Modeling) model simulation with 2.2 km grid spacing and resolved deep convection, they found winter maxima of heavy precipitation over the western Iberian Peninsula, mostly associated to cold fronts, usually related to high moisture transport, and summer maxima over regions with high topography (essentially the Alps and the Pyrenees), mostly associated to convective processes in a high-pressure context with very low moisture transport.

Additionally, it is important to point out that our study is mostly focused on future climate projections. There is not strong evidence that the enhanced representation of convective cloud processes in models resolving convection results in more assured estimates of future extreme precipitation compared to models with parameterised convection (*Fosser et al., 2020, 2024*). Indeed, when future changes are predominantly influenced by simple thermodynamic factors (namely, an increase in humidity), models resolving convection frequently project comparable changes to models with parameterised convection (*Ban et al., 2020*).

To account for the reviewer's comment, we have added two paragraphs to the Methods section (Data employed subsection), complementing the information already present there that referred to the necessity of downscaling the data:

“A problem in the study of hydrometeorological extremes in the present and future climates is the low resolution of the reanalyses and models used, which do not reproduce well the orography and some physical processes, such as small-scale convective processes, which are very influential in the occurrence of extreme precipitation. It is therefore very useful to dynamically downscale reanalyses and models to improve their representativeness (*Iles et al., 2020; Zscheischler et al., 2021*).

This article is based on dynamically downscaled data from the ERA5 reanalysis (*Hersbach et al., 2020*) and the Community Earth System Model Version 2 (CESM2; *Danabasoglu, 2020*) climate model, obtained by applying the Weather Research and Forecast (WRF-ARW) Eulerian mesoscale model, Version 3.8.1 (*Skamarock et al., 2008*). (...)

In this study, we use data at a spatial resolution of 20 km and a daily (and monthly) frequency to study the projected changes in the influence of moisture transport on extreme precipitation (and droughts) in the Euromediterranean region. (...)

The dynamic downscaling with WRF on which the data used in this study is based uses parameterised convection (not resolved), differently from other studies using km-scale simulations in which convection is resolved (e.g. *Ban et al, 2021* or *Rüdisühli et al, 2020*). Even for a terrain with such complex orography as the Alps, the work of *Ban et al. (2021)* found that the improved representativeness of precipitation intensity and frequency of km-scale models resolving convection compared to coarse resolution models with parameterised convection is particularly important for extreme summer precipitation and more important for the sub-daily range than for the daily one. On the one hand, the scope of our work focuses more on extreme winter precipitation and the role of moisture transport from remote sources. On the other hand, remarkable computational difficulties would be involved in running such a large domain and large periods as the ones used in our study at such a high resolution to resolve convection (*Kendon et al., 2021*). For both reasons, the used resolution and the fact that convection is parameterised with well-established schemes were the most appropriate choices.

Additionally, it is important to point out that our study is mostly focused on future climate projections. There is not strong evidence that the enhanced representation of convective cloud processes in models resolving convection results in more assured estimates of future extreme precipitation compared to models with parameterised convection (*Fosser et al., 2020, 2024*). Indeed, when future changes are predominantly influenced by simple thermodynamic factors (namely, an increase in humidity), models resolving convection frequently project comparable changes to models with parameterised convection (*Ban et al., 2020*)."

We have also added some discussion in this direction in the results section:

"It is important to take into account that in this study we use dynamically downscaled data at a 20 km resolution from the CESM2 model (with parameterised convection). However, our results regarding extreme precipitation align with those obtained in *Rüdisühli et al. (2020)*, in which outputs of a COSMO (Consortium for Small-scale Modeling) model simulation with 2.2 km grid spacing and resolved deep convection are used. In accordance with our Figures 1 and S3, *Rüdisühli et al. (2020)* found winter maxima of heavy precipitation over the western Iberian Peninsula, mostly associated to cold fronts, usually related to high moisture transport, and summer maxima over regions with high topography (essentially the Alps and the Pyrenees), mostly associated to convective processes in a high-pressure context with very low moisture transport."

Moreover, as explained in the previous point of the reviewer's response, we have added to the Introduction a brief description of the main systems that produce precipitation and extreme precipitation in the region.

Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., ... & Zander, M. J. (2021). The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation. *Climate Dynamics*, 57, 275-302.

Ban, N., Rajczak, J., Schmidli, J., and Schär, C. (2020) Analysis of Alpine precipitation extremes using generalized extreme value theory in convection-resolving climate simulations, *Climate Dynamics*, 55, 61–75, <https://doi.org/10.1007/s00382-018-4339-4>.

Fosser, G., Gaetani, M., Kendon, E. J., Adinolfi, M., Ban, N., Belušić, D., ... & Tölle, M. H. (2024). Convection-permitting climate models offer more certain extreme rainfall projections. *npj climate and atmospheric science*, 7(1), 51.

Fosser, G., Kendon, E. J., Stephenson, D., & Tucker, S. (2020). Convection-permitting models offer promise of more certain extreme rainfall projections. *Geophysical Research Letters*, 47(13), e2020GL088151.

Kendon, E. J., Prein, A. F., Senior, C. A., and Stirling, A.: Challenges and outlook for convection-permitting climate modelling, *Phil. Trans. R. Soc. A.*, 379, 20190547, <https://doi.org/10.1098/rsta.2019.0547>, 2021b

Rüdisühli, S., Sprenger, M., Leutwyler, D., Schär, C., and Wernli, H., (2020)., Attribution of precipitation to cyclones and fronts over Europe in a kilometer-scale regional climate simulation, *Weather Clim. Dynam.*, 1, 675–699, <https://doi.org/10.5194/wcd-1-675-2020>.

Zscheischler, J., Naveau, P., Martius, O., Engelke, S., and Raible, C. C.: (2021) Evaluating the dependence structure of compound precipitation and wind speed extremes, *Earth Syst. Dynam.*, 12, 1–16, <https://doi.org/10.5194/esd-12-1-2021>.

C. I doubt that combining the results on changes in precipitation and droughts is judicious. As recent papers on processes associated with heat waves and draughts suggest, the mechanisms behind these events are complex and due to a combination of processes at play (Schumacher et al. 2019; Röthlisberger and Papritz, 2023; Herrmann et al. 2024). This paper doesn't take this complexity into account by simply looking at evaporation deficits at the moisture source and lack of strong moisture transport upstream.

We do not disagree with the reviewer's opinion that the mechanisms leading to extreme precipitation and drought are complex and more diverse than excess or deficit moisture transport, but what is beyond doubt is that both hydrometeorological extremes share a strong dependence on moisture transport, as demonstrated in this and many previous papers (see Gimeno et al., 2016, as an example among many others cited in this manuscript). As the scope of the paper is the role of excess or deficit of moisture transport on both hydrometeorological extremes, and as this effect changes with climate change, it is quite reasonable to combine both extremes in a single paper.

Jimeno, L. et al. (2016) Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events." *Annual Review of Environment and Resources* 41.1 117-141.

In any case, we have added a sentence to remind that this is only one driver in the complex structure of drivers affecting both extreme precipitation and drought (please note that we have not included all the references suggested by the reviewer because some of them are related to temperature extremes or heatwaves, and this phenomenon is not the subject of our study):

“Behind extreme precipitation and meteorological drought and their changes under climate change, there are a number of diverse and complex mechanisms (O’Gorman, 2015; Ault, 2020; Hermann et al., 2024), but both hydrometeorological extremes have in common the fact that excesses or deficits in moisture transport to the region are frequent (Jimeno et al., 2012; Liu et al., 2020).”

O’Gorman, P. A. (2015). Precipitation extremes under climate change. *Current climate change reports* 1, 2, 49-59. <https://doi.org/10.1007/s40641-015-0009-3>.

Ault, T. (2020) On the essentials of drought in a changing climate. *Science*. 368, 256-260. DOI:10.1126/science.aaz5492

Hermann, M., Wernli, H. & Röthlisberger, M. (2024)., Drastic increase in the magnitude of very rare summer-mean vapor pressure deficit extremes. *Nat. Commun.*, 15, 7022, <https://doi.org/10.1038/s41467-024-51305-w>.

Jimeno, L., Stohl A., Trigo R.M., Domínguez F., Yoshimura K., Yu L., Drumond A., Durán-Quesada A.M., Nieto R. (2012) Oceanic and Terrestrial Sources of Continental Precipitation, *Reviews of Geophysics*, 50, RG4003, doi:10.1029/2012RG000389

Liu, B, Tan, X, Gan, TY, et al. (2020) Global atmospheric moisture transport associated with precipitation extremes: Mechanisms and climate change impacts. *WIREs Water*. 7:e1412. <https://doi.org/10.1002/wat2.1412>.

Minor points:

1. L. 16: Why does it concern? Why is it important? Maybe rather point out the remaining uncertainties in future extreme precipitation predictions and the fact that the link with changes in circulation patterns is under researched.

As explained in the response to the major comment, atmospheric rivers are the main moisture transport mechanism affecting the region and play a notable role in extreme precipitation there, so we consider that mentioning it in the abstract is highly relevant. We agree with the reviewer that mentioning the uncertainties in extreme precipitation

projections may be interesting, but we have not been able to include that information because of the abstract word limit of this journal.

2. L. 23-24: Already in the abstract I stumble over the lack of motivation for looking at atmospheric rivers

As explained before, atmospheric rivers are the major moisture transport mechanism affecting the region. We have changed the sentence to make it clear (“Atmospheric rivers, the main moisture transport mechanism affecting the region, play a notable role in extreme precipitation there.”).

3. L. 97: The knowledge gap is not explicitly mentioned

We agree with the reviewer. The sentence now reads as follows:

“Given the priority of solving the knowledge gap of unravelling the projected changes in the influence of moisture transport on extreme precipitation and meteorological droughts in the Euromediterranean region, here, we investigate these relationships in a scenario of high greenhouse gas emissions.”

4. L. 54-65: separate the discussion on the moisture transport mechanisms and the precipitation generation mechanisms, these are two different things. Also be very clear on your focus on the winter season (and remote sources) and shortly mention the existing literature on summer extreme precipitation and the role of deep convection.

We have split the paragraph into two, one on precipitation mechanisms and the other on moisture transport mechanisms, always with the aim of introducing the link between moisture transport and precipitation. We have also added a sentence at the end of the first of these two paragraphs to indicate that the role of moisture transport is more evident in winter, the focus of our study. The paragraphs now read as follows:

“Behind extreme precipitation and meteorological drought and their changes under climate change, there are a number of diverse and complex mechanisms (*O’Gorman, 2015, Ault, 2020, Hermann 2023*), but both hydrometeorological extremes have in common the fact that excesses or deficits in moisture transport to the region are frequent (*Gimeno et al., 2012; Liu et al., 2020*). In the most basic approximation, precipitation scales with the moisture content and an indicator of atmospheric instability (*Emori and Brown, 2005*). It is not possible to determine from the amount of water vapour in an air column at a given time how much of this is involved in precipitation. The water vapour in the column is changing, and it is therefore essential to ascertain the quantity of water vapour transported from surrounding areas that converges in the column, since the available humidity at a given time and place is usually not sufficient to generate precipitation (*Trenberth et al., 2003*). It is therefore evident that moisture transport plays a significant role in the occurrence of precipitation when convergence occurs (*Mo et al., 2021*), which can occur in association with a multitude of meteorological processes, being in extratropics those related with highly complex baroclinic developments such as fronts and extratropical cyclones the most relevant ones (*Catto and Pfahl, 2013; Pfahl and Wernli, 2012*), with or without orographic effects (*Houze Jr, 2012*). This role of moisture transport on precipitation is particularly evident during the winter season, particularly in the case of remote moisture sources. Conversely, this role is less pronounced in the case

of extreme summer precipitation, where deep convection plays a significant role (Stevens, 2005).

Furthermore, a number of moisture transport mechanisms are responsible for mean and extreme precipitation. These range from synoptic structures, such as tropical or extratropical cyclones, to planetary structures, including monsoonal circulations, atmospheric rivers (ARs) and low-level jets (LLJs) (Gimeno *et al.*, 2016). In quantitative terms, the global transport of moisture is dominated mainly by these two last meteorological phenomena (Gimeno *et al.*, 2016). In extratropical areas, ARs are the dominant mechanism, while in subtropical and tropical regions, LLJs are the dominant one. The two mechanisms are responsible for a significant portion of the meridional transport of moisture in the atmosphere, so it is estimated that the transport of moisture from ARs alone accounts for over 90% of the total flow of water vapour towards the poles at extratropical latitudes (Zhu & Newell, 1998). It is therefore not surprising that the control of extreme precipitation and meteorological drought by moisture transport is not spatially or seasonally homogeneous; the main influence is recorded in regions dominated by the main mechanisms of moisture transport, such as atmospheric rivers, low-level jets or tropical cyclones (Gimeno *et al.*, 2016), indicating that in some regions, moisture transport strongly controls extreme precipitation and meteorological drought (Gimeno-Sotelo and Gimeno, 2023, Gimeno-Sotelo *et al.*, 2024b).”

Mo, R., So, R., Brugman, M. M., Mooney, C., Liu, A. Q., Jakob, M., ... & Vingarzan, R. (2021). Column relative humidity and primary condensation rate as two useful supplements to atmospheric river analysis. *Water Resources Research*, 57(11), e2021WR029678.

Catto, J. L., & Pfahl, S. (2013). The importance of fronts for extreme precipitation. *Journal of Geophysical Research: Atmospheres*, 118(19), 10-791. <https://doi.org/10.1002/jgrd.50852>

Houze Jr, R. A. (2012). Orographic effects on precipitating clouds. *Reviews of Geophysics*, 50(1). <https://doi.org/10.1029/2011RG000365>

Pfahl, S., & Wernli, H. (2012). Quantifying the relevance of cyclones for precipitation extremes. *Journal of Climate*, 25(19), 6770-6780. <https://doi.org/10.1175/JCLI-D-11-00705.1>

Stevens, B. (2005). Atmospheric moist convection. *Annu. Rev. Earth Planet. Sci.*, 33(1), 605-643.

Gimeno, L., Dominguez, F., Nieto, R., Trigo, R., Drumond, A., Reason, C.J., Taschetto, A.S., Ramos, A.M., Kumar, R. and Marengo, J., (2016). Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events. *Annual Review of Environment and Resources*, 41, pp.117-141.

Gimeno-Sotelo, L., & Gimeno, L. (2023). Where does the link between atmospheric moisture transport and extreme precipitation matter?. *Weather and Climate Extremes*, 39, 100536. <https://doi.org/10.1016/j.wace.2022.100536>

Gimeno-Sotelo, L., Sorí, R., Nieto, R., Vicente-Serrano, S. M., & Gimeno, L. (2024b). Unravelling the origin of the atmospheric moisture deficit that leads to droughts. *Nature Water*, 1-12, <https://doi.org/10.1038/s44221-023-00192-4>.

5. L. 84: this is a repetition, combine with the second paragraph.

We agree with the reviewer. It has been done accordingly.

6. L. 89: what are other mechanisms?

Moisture transport plays a significant role in the occurrence of precipitation when convergence occurs (*Mo et al., 2021*), which can occur in association with a multitude of meteorological processes, being in extratropics those related with highly complex baroclinic developments such as fronts and extratropical cyclones the most relevant ones (*Catto and Pfahl, 2013; Pfahl and Wernli, 2012*), with or without orographic effects (*Houze Jr, 2012*). This role of moisture transport on precipitation is particularly evident during the winter season, particularly in the case of remote moisture sources. Conversely, this role is less pronounced in the case of extreme summer precipitation, where deep convection plays a significant role (*Stevens, 2005*).

Mo, R., So, R., Brugman, M. M., Mooney, C., Liu, A. Q., Jakob, M., ... & Vingarzan, R. (2021). Column relative humidity and primary condensation rate as two useful supplements to atmospheric river analysis. *Water Resources Research*, 57(11), e2021WR029678.

Catto, J. L., & Pfahl, S. (2013). The importance of fronts for extreme precipitation. *Journal of Geophysical Research: Atmospheres*, 118(19), 10-791. <https://doi.org/10.1002/jgrd.50852>

Houze Jr, R. A. (2012). Orographic effects on precipitating clouds. *Reviews of Geophysics*, 50(1). <https://doi.org/10.1029/2011RG000365>

Pfahl, S., & Wernli, H. (2012). Quantifying the relevance of cyclones for precipitation extremes. *Journal of Climate*, 25(19), 6770-6780. <https://doi.org/10.1175/JCLI-D-11-00705.1>

Stevens, B. (2005). Atmospheric moist convection. *Annu. Rev. Earth Planet. Sci.*, 33(1), 605-643.

As the paragraphs have been combined in order to account for Comment 5, this information has been added to the paragraph where precipitation mechanisms are explained.

7. L. 93: I think the motivation for the region of interest should come much earlier.

We have added additional reasons for the choice of region as suggested by the reviewer, but we prefer to leave the text on the choice of region once we have introduced the main topic of the study, the role of moisture transport in the occurrence of extreme precipitation and drought, and the possibility of changes with climate change. The additional reasons have been added to the text as follows: “There are strong additional reasons for choosing this region to study changes in the relationship between moisture transport and hydrometeorological extremes, such as its complex orography, with the Alps as a region of considerable precipitation and with increased summer precipitation with climate change (*Giorgi et al., 2016*), the very different meteorological systems responsible for precipitation in summer (mainly convective in a synoptic context of high-pressure precipitation) compared to winter and autumn (mainly precipitation due to cyclones and cold fronts) (*Rüdisühli et al., 2020*), and the complex picture of changes in winter precipitation extremes, with many coastal regions and northern Africa mainly experiencing a decrease and continental regions as well as regions with orography experiencing a strong increase (*Zittis et al., 2021; Lionello and Scarascia, 2020*).”

Giorgi, F., Torma, C., Coppola, E. et al., (2016)., Enhanced summer convective rainfall at Alpine high elevations in response to climate warming. *Nat. Geosci.*, 9, 584–589, <https://doi.org/10.1038/ngeo2761>.

Rüdisühli, S., Sprenger, M., Leutwyler, D., Schär, C., and Wernli, H., (2020)., Attribution of precipitation to cyclones and fronts over Europe in a kilometer-scale regional climate simulation, *Weather Clim. Dynam.*, 1, 675–699, <https://doi.org/10.5194/wcd-1-675-2020>.

Zittis, G., Bruggeman, A., and J. Lelieveld (2021) Revisiting future extreme precipitation trends in the Mediterranean. *Weather and Climate Extremes*, Volume 34, 10038,. <https://doi.org/10.1016/j.wace.2021.100380>.

Lionello, P., & Scarascia, L. (2020). The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast. *Regional Environmental Change*, 20(1), 31.

8. L. 125: The focus on the cold season should be shifted to the introduction together with a short but thorough review of the precipitation generation mechanisms.

In fact, the study focuses on the cold season for extreme precipitation, but not for drought, where no seasonal distinction is made, so it is necessary to keep the sentence about the main focus on winter in the results section on extreme precipitation, but we have added a sentence in the Introduction commenting on the most important role of moisture transport from remote sources for winter precipitation and the role of deep convection for summer precipitation (see Response to Comment 4).

We have also added a short text in the Introduction on the relative importance of different meteorological systems for precipitation in the Mediterranean (see Response to Comment 4).

However, we have also added a clarification in the sentence of the results section referring the focus on the cold season: “Since the influence of moisture transport on extreme precipitation is much greater in winter than in summer in the Euromediterranean area (Gimeno-Sotelo and Gimeno, 2023), the main focus of our **extreme precipitation analysis** is on the cold season (January-March), with a brief reference to the summer season (July-September).”

9. L. 128: mention that this is meant for present day and in comparison to the ERA5 reanalysis

Done. Those sentences now read as follows: “For the historical period (1985-2014), the spatial pattern of extreme precipitation is satisfactorily reproduced by the dynamically downscaled CESM2 data with respect to the dynamically downscaled ERA5 reanalysis data in the same period (Fig. 1a, b). This is also true for the associated IVT (Fig. 1e, f) and the percentage of days of extreme precipitation coinciding with atmospheric rivers (Fig. 1i, j).”

10. L. 132-138: I have difficulties following and understanding this. Where geographically do you mean exactly when you write “upwind of the dominant westerly and southerly flows from the Atlantic Ocean and the Mediterranean Sea”.

The westerly flow from the Atlantic Ocean is obvious in terms of the general atmospheric circulation. However, there are unusual structures similar to ARs in the Mediterranean (Med-ARs; see *Lorente-Plazas et al., 2020*), transporting moisture from northern Africa to the Western Mediterranean. Nevertheless, those structures are so unusual that we think that referring to them may be misleading. Therefore, that sentence now reads as follows: “upwind of the dominant westerly flow from the Atlantic Ocean”. Moreover, that reference has been removed from the manuscript.

Lorente-Plazas, R., Montavez, J. P., Ramos, A. M., Jerez, S., Trigo, R. M., & Jimenez-Guerrero, P. (2020). Unusual atmospheric-river-like structures coming from Africa induce extreme precipitation over the western Mediterranean Sea. *Journal of Geophysical Research: Atmospheres*, 125(2), e2019JD031280.

11. L. 137-138: is it really worth noting that the extremes are lower along the French Atlantic coast? If yes, why is it so?

The French Atlantic coast is an example of a region where the concurrence between atmospheric rivers and extreme precipitation is high, but where the values of extreme precipitation are not so high (due to its low orography). We think it is worth noting this example as an illustration of the role of orographic forcing in extreme precipitation generation and its role in modulating the precipitation associated to meteorological systems such as fronts or extratropical cyclones (Houze Jr, 2012). We have added that clarification to the revised manuscript: “For example, atmospheric rivers are responsible for most of the extreme precipitation days recorded on both the French Atlantic coast and the western Iberian Peninsula, but extreme precipitation values are lower in the former case, highlighting the role of orographic forcing in extreme precipitation generation and its role in modulating the precipitation associated to meteorological systems such as fronts or extratropical cyclones (Houze Jr, 2012).”

Houze Jr, R. A. (2012). Orographic effects on precipitating clouds. *Reviews of Geophysics*, 50(1). <https://doi.org/10.1029/2011RG000365>

12. L. 140 and Fig. 1: EC, MC are not formally introduced (L. 165) and could be referred to in the text as well to make Fig. 1 a bit easier to access.

Done. The sentence now reads as follows: “A general increase of 40% and 80% is recorded in the northern part of the region in the mid-century period (2036-2065) and end-century period (2071-2100), respectively.”

13. L. 148: widespread increase in the importance of moisture transport on extreme precipitation -> except in the Sahara and in general I find it quite patchy at least in the MC.

Yes, we agree with the reviewer, but, in general terms, there is an increase in the importance of moisture transport on extreme precipitation. We do not consider that referring to the Sahara is relevant in terms of the general behaviour of the Euro-mediterranean region.

14. L. 151: why in contrast? In contrast to what? IVT at max P is also quite ok well reproduced by CESM2.

We agree. We have replaced “In contrast,” with “Moreover,”.

15. There is no discussion whatsoever on the influence of resolution and I don't quite understand if Fig. 1 shows CESM2 simulations. For me it is quite confusing to have CESM2 in Fig. 1 but reading that there was a dynamical downscaling done with WRF in the methods. So on which data and simulation resolution is Fig. 1 based?

As explained in the Methods section, “This article is based on dynamically downscaled data from the ERA5 reanalysis (Hersbach et al, 2020) and the Community Earth System Model Version 2 (CESM2; Danabasoglu, 2020) climate model, obtained by applying the Weather Research and Forecast (WRF-ARW) Eulerian mesoscale model, Version 3.8.1 (Skamarock et al., 2008).”. Thus, all the results obtained in this article (including Fig.1) are based on dynamically downscaled data from the CESM2 model and the ERA5 reanalysis. The spatial resolution, as mentioned in the Methods section, is 20 km, for all the results obtained in the article (“In this study, we use data at a spatial resolution of 20

km and a daily (and monthly) frequency to study the projected changes in the influence of moisture transport on extreme precipitation (and droughts) in the Euromediterranean region.”).

With respect to Fig. 1, we have added that information in the description of the results related to that figure: “For the historical period (1985-2014), the spatial pattern of extreme precipitation is satisfactorily reproduced by the **dynamically downscaled CESM2 data** with respect to the **dynamically downscaled ERA5 reanalysis data** in the same period (Fig. 1a, b). This is also true for the associated IVT (Fig. 1e, f) and the percentage of days of extreme precipitation coinciding with atmospheric rivers (Fig. 1i, j).”.

We have also added some discussion to Fig. 1 in terms of model resolution and the role of convection (resolved or parameterised):

“It is important to take into account that in this study we use dynamically downscaled data at a 20 km resolution from the CESM2 model (with parameterised convection). However, our results regarding extreme precipitation align with those obtained in *Rüdisühli et al. (2020)*, in which outputs of a COSMO (Consortium for Small-scale Modeling) model simulation with 2.2 km grid spacing and resolved deep convection are used. In accordance with our Figures 1 and S3, *Rüdisühli et al. (2020)* found winter maxima of heavy precipitation over the western Iberian Peninsula, mostly associated to cold fronts, usually related to high moisture transport, and summer maxima over regions with high topography (essentially the Alps and the Pyrenees), mostly associated to convective processes in a high-pressure context with very low moisture transport.”

Rüdisühli, S., Sprenger, M., Leutwyler, D., Schär, C., and Wernli, H., (2020)., Attribution of precipitation to cyclones and fronts over Europe in a kilometer-scale regional climate simulation, *Weather Clim. Dynam.*, 1, 675–699, <https://doi.org/10.5194/wcd-1-675-2020>.

16. L. 169-170: are these differences between changes in precipitation and changes in IVT at max precip really robust. With a bit of goodwill, I see more similarities than differences: decrease over the Pyrenees, on the east of the Appenine, on the east of Greece -> basically in the north-east of mountain ranges in Europe and in the Sahara there is a decrease or a weaker increase in precipitation extremes and in IVT at max precip.

The spatial pattern may be similar in terms of increases/decreases but not in terms of magnitude (see, e.g., the Iberian Peninsula, with stronger increases in IVT at maximum precipitation than in maximum precipitation). See also the northern Africa region, with increases in IVT at maximum precipitation, and where maximum precipitation will remain relatively stable. However, we have slightly modified that sentence: “Therefore, the pattern of change in extreme precipitation is different from that of the change in the role of the IVT associated with extreme precipitation.”

17. L. 356-357: mention the role of convection in summer also in the conclusion.

Done. It has been indicated that summer is “a less relevant season in terms of moisture transport due to the higher importance of convective processes”.

18. L. 366-367: this comes a bit as a surprise, can you argue more why a dissociation between atmospheric rivers and extratropical cyclones is expected in a warmer climate?

In a recent paper published in 2023, *Wang et al.* identified a decoupling between Arctic warming and the occurrence of extratropical cyclones. The decoupling can be attributed to two factors. Firstly, there is a discrepancy in the migration patterns towards the pole with warming, with extratropical cyclones exhibiting a faster migration than ARs. This implies that ARs will tend to move further away from the centres of extratropical cyclones in the future. This was demonstrated in the numerical simulations conducted by *Wang et al. (2023)* in their paper. A second, more conceptual reason is that in a warmer climate with higher humidity (approximately 7% per Celsius degree), it would be possible to obtain high IVT values and associated ARs with moderate winds, without the need for large wind values associated with extratropical cyclones. This confirms the dominant role of thermodynamic over dynamical effects on ARs. The greater importance of the thermodynamic component over the dynamical one in ARs in a warmer climate has been described by *Zhang et al. (2024)*. We have rewritten that paragraph in the revised manuscript to try to explain it better:

“The decoupling can be attributed to two factors. Firstly, there is a discrepancy in the migration patterns towards the pole with warming, with extratropical cyclones exhibiting a faster migration than ARs. This implies that ARs will tend to move further away from the centres of extratropical cyclones in the future. This was demonstrated in the numerical simulations conducted by *Wang et al. (2023)*. A second, more conceptual reason is that in a warmer climate with higher humidity (approximately 7% per Celsius degree), it would be possible to obtain high IVT values and associated ARs with moderate winds, without the need for large wind values associated with extratropical cyclones. This confirms the dominant role of thermodynamic over dynamical effects on ARs in a warmer climate (*Zhang et al., 2024*).”

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RESPONSE TO REVIEWER'S COMMENTS

We thank both reviewers for their positive comments. The response to their reviews is found in blue colour.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have reasonably addressed my initial comments and I am pleased to recommend the manuscript be accepted.

Thank you very much for the positive review.

Reviewer #2 (Remarks to the Author):

The authors have made a substantial effort in addressing my comments, I'd like to commend them on this. While I don't agree with their view on the relevance of moisture transport from different origins in the case of draught events, I can see the value of their investigation. The only remaining point I feel very strong about: please indicate in all figures very clearly that the results come from a dynamical downscaling of ERA5 and CESM simulations using WRF. This should be made explicit in all relevant figure captions. So write for example WRF-ERA5 and WRF-CESM.

Thank you very much for your comment. As suggested, we have indicated in all figures and captions that the results come from a dynamical downscaling of ERA5 and CESM2 simulations using WRF by writing "WRF-ERA5" and "WRF-CESM2" where appropriate.