Reviewer 1:

Thank you for the opportunity to respond to your excellent comments. By addressing them, we believe the manuscript has improved in the communication of its results as well as it's overall readability. We have endeavored to address each of the reviewers' comments in an itemized fashion so as to streamline the editorial process. Please see below:

Comment 1:

ERA5 has difficulties representing complex terrain and convective precipitation over the Front Range region and provides comparison with PRISM in Appendix A.1. However, several important issues remain insufficiently addressed.

Figure A2 indicates substantial spatial discrepancies between ERA5 and PRISM precipitation. It is unclear how these biases may propagate into the WAM2layers backtracking results. Have the authors considered any sensitivity tests (e.g., weighting or bias-correcting precipitation using PRISM) to assess the robustness of the diagnosed moisture sources?

In addition, since WAM2layers is driven by ERA5 evaporation fields, potential biases in ERA5 evapotranspiration over mountainous regions in the western US, where ERA5 is known to exhibit wet biases, may systematically influence the estimated land-surface recycling contributions. At minimum, this limitation should be discussed more explicitly.

Response:

Thank you for your comment. The main objective of this paper is to provide a preliminary look into the extremely wet May-July season of 2023 and create a foundation for quantifying the evaporative origins of Front Range precipitation. While conducting this work we considered sensitivity testing of ERA5 precipitation to further ensure our meteorological input data was as accurate as possible. This is why we provided the comparison with PRISM. However, to fully diagnose the robustness of utilizing ERA5 data as input for moisture source analyses within the WAM2layers would require rerunning the WAM2layers with perturbed or alternative evapotranspiration forcing. This is a substantial undertaking and would require a dedicated effort, though it is certainly an important project for future WAM2-layers model-development work.

In regards to ERA5's wet evapotranspiration bias in the mountainous western US, this is an important point to address. In reviewing the literature, we could not find specific biases in evapotranspiration products in ERA5 for the mountainous Western US. Existing ERA5 evapotranspiration evaluations report reasonable skill in energy partitioning, but these papers are global and/or have limited coverage in high-elevation western US sites. (Martens et al. (2020); Muñoz-Sabater et al. (2021)).

That being said, we now include a discussion of how this bias and other biases in ERA5 are unclear with respect to how they affect the results of our study, and emphasize that WAM2layers output may inherit the effects of these biases. We decided to rewrite text in section 2.3, starting immediately after line 173. New text is bolded in this excerpt:

"ERA5 is the most current version of ECMWF's global climate reanalysis data product and performs well against precipitation observations in North America (Crossett et al., 2020; Beck et al., 2019; Tarek et al., 2020) **and global ERA5 evapotranspiration evaluations report reasonable skill in energy partitioning (Martens et al., 2020; Muñoz-Sabater et al., 2021). ERA5 has been known to exhibit other various biases in their precipitation or other meteorological variables (Lavers et al., 2022; Akinsanola et al., 2024). However, as mentioned in Lundquist et al. (2019), apparent mountain biases could be inherent in the observation equipment as well.**

Furthermore, ERA5 precipitation datasets do not directly assimilate in-situ precipitation observations into its precipitation product and known to have trouble representing convective precipitation (Hersbach et al., 2020), **a preliminary comparison** of ERA5 precipitation to the Parameter-elevation Regressions on Independent Slopes Model (PRISM) monthly precipitation totals is included in Appendix section A.1. The PRISM monthly precipitation dataset was a natural choice for comparison due to its gridded nature, incorporation of in-situ precipitation observations, and ability to resolve complex terrain (Daly et al., 2021). We find that although there are substantial differences in the amount and spatial distribution of precipitation in eastern Colorado, ERA5 can correctly capture May-July of 2023 as a very anomalously wet season compared to average, making it well suited for identifying major source regions of Colorado's Front Range precipitation. **Overall, the results of this study are not immune to the biases exhibited in the original ERA5 input data. Although outside the scope of this project, future work should investigate how biases in input meteorological data directly affects moisture source identification with the WAM2layers.**"

We also inserted all new text in Appendix A, starting on line 628:

"Keys et al. 2014, found that when running the WAM2layers with two different meteorological input datasets (MERRA-2 and ERA-Interim) results in differences in tracked evaporation results. However, core moisture sources remain spatially similar. We decided that ERA5 and PRISM precipitation datasets were capturing general precipitation patterns well enough when considering the focuses of this study. This analysis is intended to serve as a preliminary investigation into the major moisture sources of Colorado's Front Range in May-July of 2023 and the past twenty-three years, rather than a precise quantification. For that purpose, we believe that ERA5 is well suited for the goals of the research presented."

References:

Akinsanola, A. A., Jung, C., Wang, J., & Kotamarthi, V. R. (2024). Evaluation of precipitation across the contiguous United States, Alaska, and Puerto Rico in multi-decadal convection-permitting simulations. Scientific Reports, 14, 1238. https://doi.org/10.1038/s41598-024-51714-3.

Keys, P. W., Barnes, E. A., Van Der Ent, R. J., and Gordon, L. J.: Variability of moisture recycling using a precipitationshed framework, Hydrol. Earth Syst. Sci., 18, 3937–3950, https://doi.org/10.5194/hess-18-3937-2014, 2014.

Lavers, D. A., Simmons, A., Vamborg, F., & Rodwell, M. J. (2022). An evaluation of ERA5 precipitation for climate monitoring. Quarterly Journal of the Royal Meteorological Society, 148(748), 3152–3165. https://doi.org/10.1002/qj.4351
Lundquist, J., Hughes, M., Gutmann, E., & Kapnick, S. (2019). Our skill in modeling mountain rain and snow is bypassing the skill of our observational networks. Bulletin of the American Meteorological Society, 100(12), 2473–2490. https://doi.org/10.1175/BAMS-D-18-0001.1
Martens, B., Schumacher, D. L., Wouters, H., Muñoz-Sabater, J., Verhoest, N. E. C., & Miralles, D. G. (2020). Evaluating the land-surface energy partitioning in ERA5. Geoscientific Model Development, 13(9), 4159–4181. https://doi.org/10.5194/gmd-13-4159-2020
Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., & Thépaut, J.-N. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Figure A3

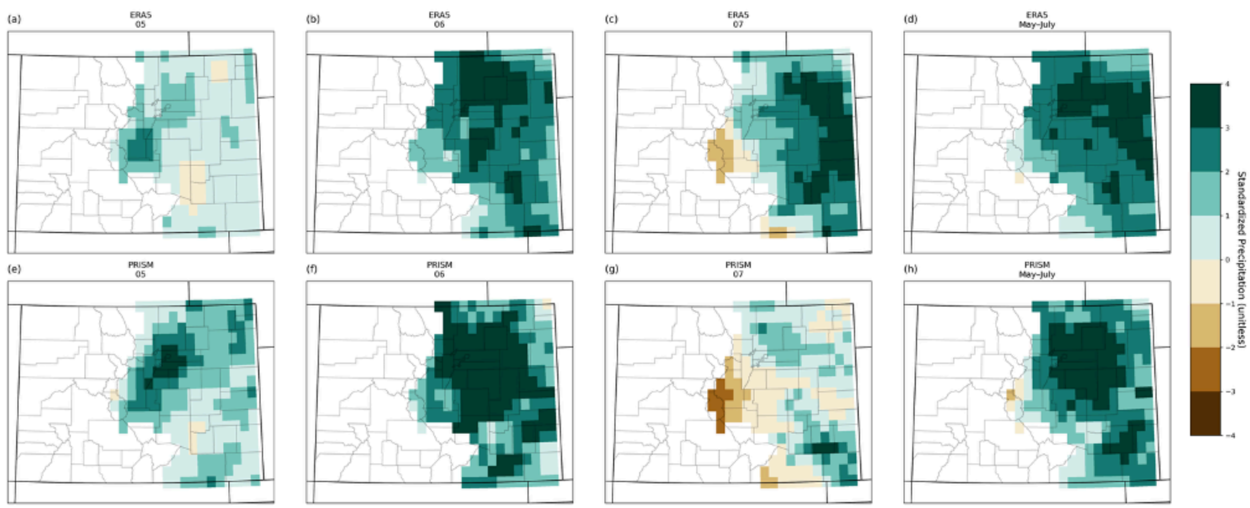


Figure A3 Caption: Standardized anomalous monthly precipitation in eastern Colorado during May-July of 2023. These maps indicate how many standard deviations 2023 was from the 2000-2022 average relative to their respective datasets. Maps across the top row (a-d) reflect standardized anomalous precipitation from ERA5 whereas the bottom row (e-h) show estimates from the regridded PRISM data. Precipitation data is masked to only show precipitation totals over the five sink regions used in this full study.

Comment 2:

I think the manuscript requires significant restructuring. Currently, the Appendix contains a very large number of figures, many of which are either not referenced in the main text or are only briefly mentioned without sufficient accompanying discussion or interpretation. Several figures appear disconnected from the core paper.

In my opinion, materials that are not central to the primary conclusions should instead be moved to a Supplementary Information file rather than remaining in the Appendix of the main manuscript. Even for supplementary materials, the figures should still be explicitly cited, interpreted, and connected to the scientific arguments presented in the paper.

For example, Line 87 states that the Appendix contains results from other regions, but these results are not accompanied by additional analysis or discussion explaining their relevance to the study objectives.

Response:

We thank the reviewer for their comment and suggestion. Appendix B figures have been moved to the Supplementary file since the other sink region analyses are not pivotal to the main conclusions in this study. Similarly, we have moved Figure A4 (the map of Colorado's alternate climate divisions) to the SI, since Figure 2 already shows the Front Range region's location. As there's no accompanying text for the other Alternate Climate Divisions, keeping Figure A4 in the Appendix would be redundant, and it fits more naturally in the SI.

We agree that supplementary figures should be cited and connected to scientific arguments in the paper. Thus we have added a new discussion section that briefly explains the additional analysis, introduces the figures, and explains our rationale of broadening the dissemination of scarce moisture recycling information. Below is the new subsection within the discussion starting on line 538.

4.1 Scarcity of moisture recycling information in arid Western US

> "While this analysis has been focused on the sources of extreme precipitation for the Northern Front Range region in 2023, extreme precipitation was experienced across eastern Colorado in 2023. Thus, we conducted additional analyses for four other eastern Colorado regions, including: the Eastern Plains, High Mountain Valley, Pikes Peak, San Luis Valley, and Arkansas Basin. In general terms, these regions experienced extreme, if not record-breaking, precipitation during the summer of 2023. In Supplemental figures B1-B24, we detail region-specific precipitation analysis, including an investigation into region-specific modes of variability and spatial clustering of source regions.
>
> We note that while these other regions are all located in eastern Colorado, they span a wide range of ecological regions, including grasslands, high altitude forests, mountains, shrublands, and arid deserts (Chapman et al., 2006). Extreme precipitation will affect these locations in a wide variety of ways, and a comprehensive analysis falls outside the scope of this work. Nonetheless, we include these figures in the Supplementary Materials to support broader dissemination of regional moisture recycling information to academic and practitioner communities."

References:

Chapman, S.S., Griffith, G.E., Omernik, J.M., Price, A.B., Freeouf, J., and Schrupp, D.L., 2006, Ecoregions of Colorado (color poster with map, descriptive text, summary tables, and photographs): Reston, Virginia, U.S. Geological Survey (map scale 1:1,200,000s).

Comment 3:

The paper currently contains unnecessary descriptive text. For example, the Introduction does not need subdivision into two separate subsections. In most manuscripts, the final paragraph of the Introduction already serves to state the study objectives. In the Results section, several introductory sentences (e.g., Lines 230–232) are not necessary and could instead be incorporated directly into subsection titles.

Response:

Thank you for pointing this out. Indeed, the Introduction's last paragraph does not need to reside in a subsection of its own. The subsection title, "1.2 Study Goals" has been removed and the text within that subsection remains unchanged as the final paragraph in the Introduction.

We also agree that lines 230-232 can be removed and incorporated into subsection titles. Where necessary, we have incorporated these lines into the subsection titles as follows:

- The title for Section 3.1 remains unchanged as, "Moisture Sources of May, June, and July 2023 Precipitation"
- The title for Section 3.2 has been altered from "Comparing 2023 to previous decades" to "Comparing 2023 to Average Moisture Sources of the Past 23 Years"
- The title for Section 3.3 has been altered from, "Clustering of Interannual Evaporation Patterns" to "K-Means Clustering: Comparing 2023 to Individual Moisture Sources of the Past 23 Years"
- The title for section 3.4 has been altered from, "Dominant Variability Patterns" to "EOF Decomposition: Contextualizing 2023 Among Dominant Variability Patterns"

Comment 4:

The statistical robustness of the EOF decomposition and k-means clustering analysis is somewhat concerning given the relatively limited sample size (24 seasons). With such a small sample size, it is difficult to assess whether the identified EOF modes and clusters are statistically stable and physically meaningful. At present, the EOF discussion feels largely descriptive rather than mechanistically interpretable. It should provide stronger justification for the EOF and clustering methodology, discussion of robustness and sensitivity, and clearer physical interpretation of the dominant modes and clusters.

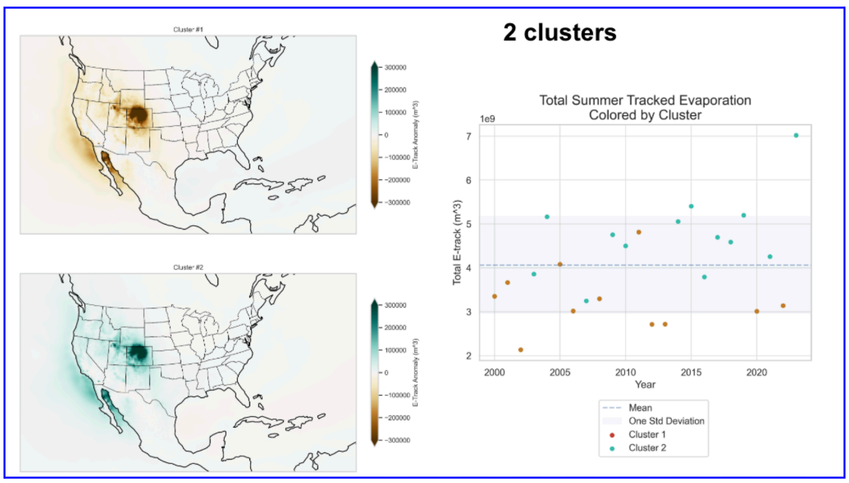
Response

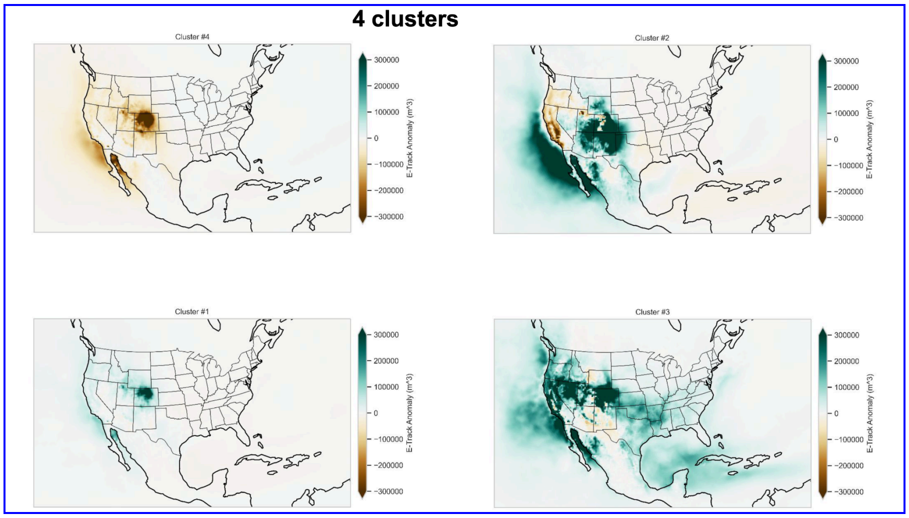
Thank you for raising this important point about the robustness of our results due to a sample size of 24. We agree that a sample size of 24 seasons is modest, but we would like to emphasize that we view the EOF decomposition and k-means clustering as complementary, exploratory analyses that provide additional context for the 2023 season, while the central claims of the paper are addressed in Sections 3.1 and 3.2. That being said, we have revised the text to state this more explicitly.

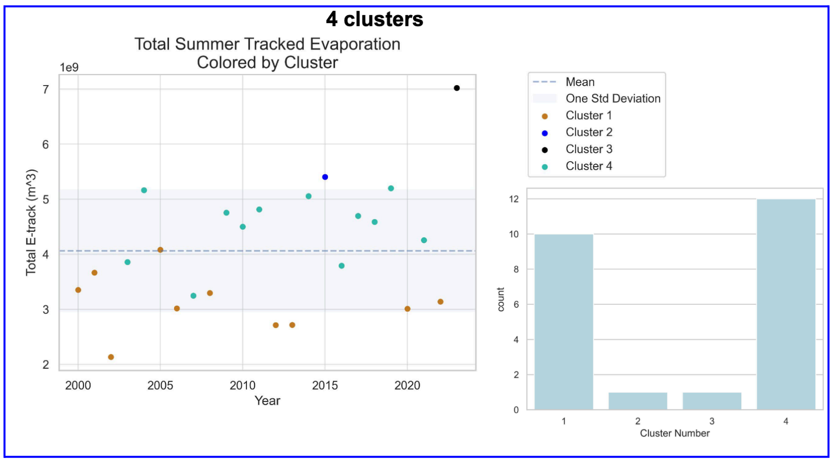
Regarding the robustness and confidence in these analyses, despite the modest sample size, we find that the two distinct methods agree and compliment one another. For example, Clusters 1 and 2 (Figure 7) closely resemble the spatial pattern of EOF1 (Figure 9). This agreement across methods increases our confidence that these signals are meaningfully captured, even with 24 samples. We include these analyses primarily to add context to the 2023 season and to motivate future questions about the relationship between moisture sources and Front Range precipitation, rather than to draw conclusions on previous moisture source behavior.

We also tested the sensitivity of the clustering analysis by varying the number of clusters. Results using 2 and 4 clusters yield similar findings to our main analysis, indicating that the core results are robust to this choice. For the reviewer's reference, we have included these results here, though we believe at this level of detail that these extra figures are not necessary in the main text, as it is already discussed beginning on line 369. As follows:

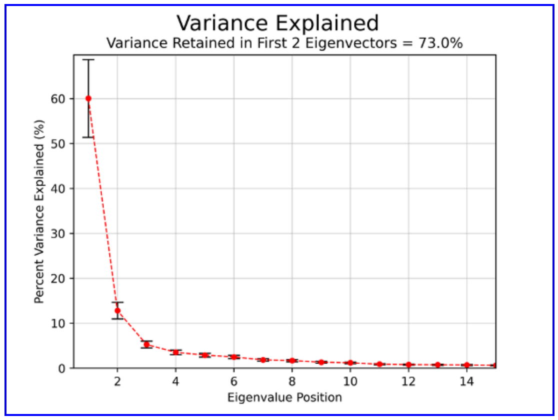
> “This analysis was also conducted for k values of 4 and 2 to ensure that the main characteristics of clusters did not change dramatically when choosing a different k value. We found very similar clusters when using a k value of 4, with nearly identical clusters to those found here with an added cluster of one MJJ season, May-July of 2015. When using a k value of 2, the MJJ season was sorted into clusters that resembled the wet and dry clusters shown in Figure 7 with May-July of 2023 being sorted into the cluster with a composite of positive tracked evaporation anomalies around Colorado. The characteristics between clusters found in this section did not change dramatically when altering the number of k values.”







Concerning the EOF analysis' robustness, we do not believe our sample size undermines the validity of EOF 1 and 2. We apply the North et al. (1982) rule of thumb, shown in Figure 8, where eigenvalues are considered statistically distinguishable when their sampling-error bars do not overlap. The error bars for eigenvalues 1 and 2 are well separated from each other and from the remaining modes, indicating these two modes are statistically distinct. Beginning at eigenvalue 3, however, the error bars overlap substantially and become indistinguishable from one another. We therefore do not claim individual physical significance for EOF3 and beyond. Below we have attached Figure 8 for reference.



With the reviewer's comments in mind, we have revised the manuscript to state this limitation more explicitly and to clarify that our physical interpretation is restricted to the first two modes, which satisfy North's separation criterion. We also note that additional years of data would likely shift these modes, albeit modestly, due to similar findings in EOF analyses found in Keys et al. (2014). As such, we have softened our language accordingly to reflect this as a current best estimate rather than a fixed characterization.

We have added new text beginning on line 401 as follows,

> "Error bars for eigenvalues one and two are well separated from each other and from the remaining modes, indicating these two modes are statistically distinct. Beginning at eigenvalue three, however, the error bars overlap substantially and become indistinguishable from one another, so we cannot claim individual physical significance for EOF3 and beyond."

In addition, we incorporated additional text into Section 4 (Discussion) line 536 as follows,

> "Given the scarcity of comparative literature and a relatively modest sample of twenty-four seasons, these results should be interpreted as an exploratory framework for understanding potential modes of variability rather than a definitive characterization."

Comment 5:

Overall writing style resembles a project report rather than a scientific manuscript. For example, the manuscript repeatedly refers to "the project," which should be avoided in formal scientific writing. In addition, the paper presents a large amount of figures and analysis but does not always clearly discuss the key scientific findings and implications. I encourage the authors to place greater emphasis on synthesizing the primary scientific insights rather than exhaustively documenting all analyses.

Response:

Thank you for pointing this out. We agree that the manuscript's text and style should better align with a scientific manuscript. We have changed any mention of "project" in the text to "study" or "manuscript" to improve the overall writing style. Additionally, to synthesize the main results of this study further, we moved Figures 6 and 8, along with the text exclusively related to these figures, into the Appendix. We believe this strikes a good balance between providing sufficient detail on the choices made in these analyses and maintaining a clear, concise flow in the main text.

Comment 6:

Line 83: Remove “which partially funded this project.” Such acknowledgements are more appropriately included in the Acknowledgements section rather than here.

Response:

We agree with the reviewer here, and removed line 83. We did not decide to expand upon this in the acknowledgements because the Colorado Water Conservation Board has already been acknowledged in the Financial support section that states, “We would like to acknowledge the Colorado Water Conservation Board for providing the funds to complete this publication.”

Comment 7:

Line 140: Please provide a clearer justification for conducting the analysis at monthly timescales. Extreme precipitation events are often strongly associated with higher-frequency variability (e.g., daily scales), and the implications of temporal aggregation should therefore be discussed more carefully.

Response:

Thank you for your comment. Line 140 was originally written as follows:

> “For our purposes, we decided to aggregate daily tracked evaporation to the monthly scale for further confidence in our results at the monthly scale instead of the daily timeframe.”

Now, with revision, this text states:

> “We then aggregated the daily tracked evaporation to the monthly scale. While extremes are often at much shorter timescales (e.g., days), our emphasis was on regional-scale, and seasonally-aggregated moisture sources. Moreover, aggregating to the monthly scale enabled our work to be consistent with other monthly analyses, such as ranking of monthly extremes in Figure 1.”

Comment 8:

Line 167: Consider replacing “For this project” with “For this work” or “For this study.” Similar wording should be corrected throughout the manuscript.

Response:

We fully agree with the reviewer here, and we have replaced line 167’s “For this project” with “For this study”.

Comment 9:

Figure 3 caption: The caption states that maps defining the regions are provided elsewhere. Please explicitly cite the corresponding supplementary or appendix figure number (e.g., Figure A5) within the caption or main text.

Response:

Thank you for this comment, we have updated Figure 3’s caption to the following:

> “A map defining each of these regions has been provided earlier in this text as Figure 2 in Section 2.2.”

As opposed to the original text,

> “A map defining each of these regions is provided in the supplementary.”

For more context, we have decided to move Figure A5 into the main text, as Reviewer 2 noted its importance to the overall paper. Moisture contributions from specific regions are central to the conclusions of this paper, and the definition of these regions should therefore be included in the Methods.

Comment 10:

Line 463: Typo error, "Finaly" to "Finally".

Response:

Indeed, we have corrected this typo on line 463.

Comment 11:

Line 563: The phrase "Due to project time-constraints" is not appropriate for scientific writing. I also think this kind of wording should generally be avoided in scientific manuscripts. Consider rephrasing more objectively, for example, "In this study, we only focus on …"

Response:

Thank you for highlighting this, we have re-written the text, "Due to project time-constraints" to "In this study, we only focus on…".