

Replies to reviewer #1

“Benchmarking convection-permitting climate simulations for hydrological applications: A comparative study of WRF-SAAG and observation-based products”

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We thank the reviewer for his/her time, revision and suggestions to our paper. We provide responses to each individual point below, and how we will address the main comments of the reviewer. For clarity, comments are given in black italics, and our responses are given in plain blue text.

General Comment:

The manuscript offers an evaluation of daily total precipitation, maximum daily temperature, and minimum daily temperature variables simulated by the WRF-SAAG convective-permitting numerical model for hydrological applications. It compares these outputs with meteorological station measurements and simulations from the CR2MET and RF-MET products in the conterminous Chile. Furthermore, these variables are used as input data in a conceptual hydrological model (HBV-like) in order to assess the performance of the simulated daily streamflow against observed series in pristine catchments with low glacier cover.

*The work addresses a fundamental topic in mountain regions, which is the use of numerical models to supplement the lack of meteorological measurements, especially for precipitation. However, the article has certain structural deficiencies that require manuscript **major revisions**:*

1. The title and the body of the text do not specify which hydrological applications are being addressed to (e.g., flood risk, rain-on-snow events, water supply projections, among others - see a non-exhaustive list in Table 1 of Dominguez et al., 2024). The associated temporal scale and hydrological processes are also not defined.

We agree that the original submission lacked the specification of target hydrological applications. In the revised version, we will specify that the proposed framework is applied for simulating diverse hydrological signatures, oriented to mean flow, and extremes, including floods and droughts, through the analysis of hydrological signatures across continental Chile.

Table 1: Hydrologic signatures.

Signature name	Signature description
Q/P	Runoff coefficient.
Q_{mean}	Mean daily discharge (mm/d)
Q_{JJA}	Mean daily discharge of winter days (JJA) (mm/d)
Q_{DJF}	Mean daily discharge of summer days (DJF) (mm/d)
Q_{95}	95% flow quantile (high flow) (mm/day)

Q_5	5% flow quantile (low flow) (mm/d)
<i>low_q_freq</i>	Frequency of low-flow days (< 0.2 times the mean daily flow) (days/year)
<i>high_q_freq</i>	Frequency of high-flow days (> 9 times the median daily flow) (days/year)
<i>low_q_dur</i>	Average duration of low-flow events (number of consecutive days < 0.2 times the mean daily flow) (d)
<i>high_q_dur</i>	Average duration of high-flow events (number of consecutive days > 9 times the median daily flow) (days)
$Q_{50\%}$	Day of year when 50% of the flow volume
<i>baseflow_index</i>	Baseflow index (ratio of mean daily baseflow to mean daily discharge, hydrograph separation performed using digital filter) (-)
<i>slope_fdc</i>	Slope of the flow duration curve (between the log-transformed 33rd and 66th streamflow percentiles)
<i>stream_elas</i>	Streamflow precipitation elasticity (sensitivity of streamflow to changes in precipitation at the annual time scale) (-)

Additionally, we have clarified that the evaluation of precipitation, air temperature and simulated discharge is conducted at the daily time scale, which is consistent with the temporal resolution of the streamflow records used, and serve as a basis for the dominant processes analyzed.

Finally, we have modified the title to reflect the specific applications and study domain:

“Benchmarking convection-permitting climate simulations for hydrometeorological characterizations: A comparative study of WRF-SAAG and observation-based products in Chile”

2. In line with the previous point, if by hydrological application the authors mean "hydrological models", thus: Which models are they? at what scales? representing which physical processes?

We have modified the text to specify that (i) only one hydrological model (TUW) is used, (ii) WRF-SAAG and hydrological model simulations are evaluated at the daily time scale, and (iii) average flow conditions, high flow and low flow events, as well as other hydrological signatures such as streamflow precipitation elasticity and the baseflow index, are the target hydrological processes.

3. The scientific advancement is not made clear. This is also reflected in the poorly developed Conclusions section. What new facets does this work offer? What are the hydrological novelties? Where does this leave us?

This work is motivated by the recent publication of the hourly precipitation and temperature simulations for South America (Dominguez et al., 2024), which provide new meteorological

input data for application-relevant research across the continent. One of the areas of interest for the WRF-SAAG community is the evaluation of convection-permitting model output for the characterization of extreme hydrometeorological events through process-based hydrological modeling. This study contributes to this objective by (1) presenting an assessment of WRF-SAAG daily outputs along a hydroclimatically diverse Andean subdomain, which shows comparable performance for replicating hydrometeorological extremes when contrasted against two widely used regional observation-based products – CR2MET (Boisier et al., 2018) and RF-MEP (Baez-Villanueva et al., 2020); and (2) mapping differences between WRF-SAAF, CR2MET and RF-MEP across different hydroclimates. Additionally, this paper expands on previous assessments of WRF precipitation outputs using in-situ observations (e.g., Ikeda et al., 2010; Mendoza et al., 2015) and offline hydrological modeling applications (e.g., Mendoza et al., 2016) conducted in other mountainous regions of the world. The results presented in this paper have shed light on the potential of WRF-SAAG for characterizing diverse hydrological signatures, oriented to mean, and extreme flow| and future avenues of research. Importantly, the work presented here has laid the foundation for using kilometer scale model data to study future hydrological changes in the Andes and interpret them based on the performance of such models under current climate conditions. This is essential for increasing resilience to climate change in Andean countries.

We will explicitly emphasize these messages in the revised Introduction and Conclusions sections to highlight the scientific contribution and hydrological relevance of the study.

4. There is an aporia (a logical contradiction) in the methodology that the authors themselves present. If, according to the manuscript under review, the WRF-SAAG model was not designed to simulate singular events but rather hydroclimatic features in South America (lines 111, 214, and 402), why does the article evaluate the performance of the simulations against daily events of precipitation, maximum temperature, and minimum temperature?

While the WRF-SAAG simulations were not designed as a reanalysis dataset (i.e., they do not include data assimilation or spectral nudging), they are nonetheless capable of reproducing historic weather patterns, particularly when these events are influenced by large-scale atmospheric forcing. Therefore, evaluating WRF-SAAG at the daily scale allows us to assess its general skill in representing historical weather variability and the spatial and temporal characteristics of key hydroclimatic variables, even though the system was not designed to reproduce every singular event precisely. However, given the spatial scale of the WRF simulations, they explicitly resolve convective precipitation, even when it is not fully measured by the sparse observations, especially in high-elevation zones.

To clarify this point, we will revise the Introduction, Methods, and Discussion sections to explicitly state that the daily-scale evaluation is designed to assess the overall performance of WRF-SAAG in representing historical hydroclimatic variability, rather than to reconstruct individual events exactly, where specific schemes may better reproduce mesoscale events, as previously revised by other authors (e.g., Huang et al., 2024; Lagos-Zúñiga et al., 2024).

5. Following the same line of reasoning, according to Dominguez et al. (2024), the WRF-SAAG runs use a reanalysis product (ERA5) as their initial and boundary conditions, which by definition represents the best snapshot of weather conditions at a specific place and time (Kalnay et al., 1996). Furthermore, Dominguez et al. (2024 - see Fig. 4) present an evaluation of singular events (peak precipitation hour), comparing simulations (Nov. 2018 to Mar. 2019) with station measurements, GPM-IMERG, and ERA5.

We acknowledge that WRF-SAAG uses ERA5 reanalysis data as its initial and boundary conditions, which constrains the simulation to realistic large-scale atmospheric states. While Dominguez et al. (2024) demonstrated the model's capacity to reproduce specific weather events for a particular period, our study has a broader objective: to evaluate WRF-SAAG's overall skill in representing daily hydroclimatic variability across South America. Because the model is forced by ERA5, it can reproduce many large-scale weather events, although smaller-scale or convective processes may be displaced or not captured. This distinction will be clarified in the Introduction, Methods, and Discussion sections, where we have noted the influence of ERA5 boundary conditions, and we explicitly discuss that the evaluation focuses on large-scale features and may not capture all small-scale events.

Specific Comment:

Title

It should reflect which hydrological application the authors aim to address, ideally indicating the process and its temporal scale. I recommend incorporating the study area (i.e., continental Chile).

We have modified the title following the reviewer's recommendation:

“Benchmarking convection-permitting climate simulations for hydrometeorological characterizations: A comparative study of WRF-SAAG and observation-based products in Chile”

Abstract

L6. State explicitly that you will evaluate daily maximum and minimum temperature. This should be made clear in the abstract.

We have been explicit in the abstract that the minimum and maximum daily temperatures are evaluated:

“In this paper, we evaluate the quality of WRF-SAAG daily precipitation and daily maximum and minimum temperature simulations”

L18. If you are going to use a hydrological model, please declare this in the sentence where you reference the methodology used.

The sentence referenced in Line 18 has been revised to explicitly state that a hydrological model is used as part of the methodology. The updated sentence has clarified the role of the hydrological model within the study framework, ensuring transparency from the outset.

Introduction

L37. You use the expression "Satellite-based products," which, for example, is not the case for CR2MET or RF-MET. Change to "Gridded products."

We appreciate the reviewer's sentiment. However, the sentence in L37 specifically refers to products derived from satellite observations and, therefore, the term "satellite-based products" is appropriate in that context. The introduction follows a logical structure that first discusses different sources of meteorological data, and the cited text (L37) intentionally refers to satellite-derived datasets to highlight their limitations in complex terrain and high-elevation regions, which is a relevant background for motivating the use of alternative products. Note that CR2MET nor RF-MEP are mentioned in that paragraph, since those products are obtained by combining reanalysis output, topographic descriptors and ground observations.

To avoid any ambiguity, we will revise the paragraph to make a clearer distinction between satellite-based products and gridded blended datasets such as CR2MET and RF-MEP in the following sentences.

L62/63. The sentence should conclude with at least one citation.

We have added the references Prein et al. (2023) and Lundquist et al. (2019) associated with the lines:

"As a result, high-resolution atmospheric models can perform similarly (e.g., Prein et al., 2023) or even outperform (e.g., Lundquist et al., 2019) gridded observational products in capturing total precipitation over complex terrain. Additionally, these models offer a physically consistent and spatially continuous representation of precipitation, making them a viable alternative for hydrological modeling applications."

L72. The authors state that there is "little" information on the performance of the CR2MET and RF-MET products; however, in L78 (in the same paragraph), they provide some numbers and cite an article that has already evaluated their performance. There is a logical contradiction in the writing of this paragraph.

We appreciate this suggestion, and we have edited the manuscript to avoid this interpretation. With "limited information", we aimed to state that no systematic assessments of CR2MET and RF-MEP daily precipitation have been conducted using ground measurements as the observational reference. We have reworded the text in that section to clarify this point:

"While these observation-based datasets have been widely used for different applications (e.g., Hernandez et al., 2022; Murillo et al., 2022 in the case of CR2MET, and Chen et al., 2022; Al-Saeedi et al., 2024 in the case of RF-MEP), no systematic assessments of CR2MET

and RF-MEP daily precipitation have been conducted using ground measurements as the observational reference”.

Further, the study cited in L78 (Baez-Villanueva et al., 2021) **did not evaluate the products against station observations**; instead, it presented a simple comparison of annual precipitation amounts retrieved from different products across macro-regions, with the aim to assess the impact of the choice of forcing dataset on the regionalization of hydrological model parameters.

Study domain

Fig. 1. Where does the precipitation for the catchments used to calculate the runoff coefficient come from? A gridded product? Which one?

In the current version of the preprint, the precipitation used to calculate the runoff coefficient was obtained from the gridded dataset CR2MET v2. However, for the revised version of the manuscript, we will recalculate the runoff coefficient using the three available precipitation products to provide a more robust and comparative assessment. In addition, we will include other hydrological signatures to complement the evaluation of hydrological modeling performance.

L140. Same comment.

The precipitation dataset is CR2MET (v2.5). Please see our previous response.

Methods - General Comments

If both CR2MET and RF-MET were constructed using station measurements, does it make sense to compare their performance at those same locations? I agree that the reported errors can be used as a reference for the performance of WRF-SAAG, but many lines of text are wasted on the analysis of these two products. It would be more fruitful to calculate the difference between the grids (WRF-SAAG vs. CR2MET and RF-MET) to visualize substantial differences. Furthermore, the introduction emphasizes the lack of measurements in high-mountain areas, which further highlights the importance of performing this grid-to-grid comparison; otherwise, the potential of WRF-SAAG remains very limited.

We have decided to keep the assessment of CR2MET and RF-MEP against station observations for two reasons: (1) the results demonstrate that, despite the precipitation products combine reanalysis data and ground observations, they were not designed to match station measurements perfectly; and (2) the reported errors are valuable for the hydrometeorology community since this is the first assessment against in-situ observations at the daily time scale.

Additionally, we appreciate and agree with the reviewer’s recommendation regarding a grid to grid comparison. Therefore, we will include figures with differences between products for different temporal aggregations, with the aim to identify areas with scarce or null available observations.

*The hydrological application referred to by the authors in the title is hydrological modeling. Even so, this is very general and therefore weak. Models are subject to multiple sources of uncertainty, and parameter calibration can, in turn, **yield correct results for the wrong reasons**, especially when the only facet being evaluated is the catchment streamflow (Beven, 2006; Kirchner, 2006).*

***If the authors decide to incorporate the broad area of hydrological models as their application in a revised version, they should define the working scales, processes, and model types from the beginning** (this must be reflected in the methodology). Using a numerical model for the sole purpose of running it does not reveal new advancements in hydrology. For example, does it make sense to apply a temperature-index model, like the TUWmodel, in the Near-North and Far-North macrozones where sublimation can account for more than 70% of the seasonal snowpack (e.g., Ayala et al., 2023)?*

We appreciate the reviewer's feedback, and we agree that the hydrological modeling application originally presented can be substantially strengthened. In the revised manuscript, we will address this point by expanding the hydrological evaluation (i) by comparing a broader set of hydrological signatures to assess model behavior across different temporal and process-based dimensions, and (ii) by including an analysis of additional model outputs, such as evapotranspiration (ET) and soil moisture. Additionally, we will explicitly declare the TUWmodel limitations, especially in arid regions where turbulent fluxes are not represented by conceptual rainfall-runoff models. One of the specific goals of this research is to test the applicability of WRF-SAAG simulations for hydrological applications starting with simple models as it hasn't been tested yet in continental Chile. To highlight the specific goals, we will explicitly state them in the introduction to settle the readers' expectations.

Methods - Regarding the Subsections

Section 4.1 should be entitled "Evaluation of daily precipitation and maximum and minimum temperatures."

We thank the reviewer for this suggestion. The title of Section 4.1 has been modified to: "Evaluation of daily precipitation and maximum and minimum temperatures".

In the introduction, the authors emphasize that in mountain areas (e.g., Chile), most stations are located at low altitudes and are scarce, which leverages the use of high-resolution dynamic models (e.g., WRF-SAAG) to capture total precipitation patterns along mountain ranges like the Andes. However, in the proposed methodology, they evaluate the performance of WRF-SAAG using station measurements, the majority of which are located below 3000 m a.s.l. and with a low-density network in the Cordillera.

We acknowledge the limitations associated with the sparse and low-altitude distribution of meteorological stations in mountainous regions such as the Andes. However, the evaluation of WRF-SAAG and the other gridded products was conducted using the maximum number of available quality-controlled stations, which represents the best observational information currently accessible for continental Chile.

To complement the station-based evaluation and provide additional insights into the representation of those fields in ungauged regions, the revised manuscript will incorporate a direct comparison of the spatial fields from the three meteorological products (CR2MET, RF-MEP and WRF-SAAG). This gridded intercomparison highlights the main differences among products across elevation gradients and complex terrain, particularly in the Andes.

Perhaps it would be more interesting, given that CR2MET and RF-MET are built with station measurements, to conduct an analysis of the differences (quarterly?) between grids so that the reader can visualize latitudinal and altitudinal discrepancies. In which quarter are the differences smaller (larger)? Why?

We agree that a comparison between the gridded products would provide valuable insights, particularly because CR2MET and RF-MEP are derived from station observations while WRF-SAAG originates from a dynamical model. As noted in the previous response, the revised manuscript will include a direct intercomparison of the gridded fields from the three meteorological products to highlight latitudinal and altitudinal differences across Chile. Different temporal aggregations have also been evaluated to identify the main differences among the products.

In Figure 1.d, the authors show the reference runoff coefficient for each catchment. After clarifying the source of the precipitation, what values does this coefficient yield when using precipitation simulated by WRF-SAAG? CR2MET? RF-MET? How do the time series and the climatological value for each catchment compare? Given the hydroclimatic regime of each catchment, what values would be logical to expect? Are the absolute values of total precipitation reasonable?

In the revised version of the manuscript, we will calculate the runoff coefficient – together with other hydrological signatures — using data from the three available products: WRF-SAAG, CR2MET, and RF-MET. This has allowed us to evaluate the consistency among datasets and to quantify how the choice of precipitation and temperature product affects the estimation of runoff and other hydrological signatures.

After the general comments, if you still wish to incorporate the hydrological model, the following lines should be taken into account,

- *In section 4.2, the hydrological model is poorly presented. TUWmodel is one of the many versions of the original HBV. First, present and cite HBV, then TUWmodel.*

The manuscript has been revised to first present the original HBV model, including appropriate citations, before introducing TUWmodel as a specific version.

- *What daily temperature value do you use as input data for the model? Minimum and maximum? Daily mean? Up to this section, you have stated that you are evaluating the daily maximum and minimum temperatures.*

For the hydrological model, the daily mean temperature, calculated as the average of the daily minimum and maximum temperatures, is used as input. The manuscript has

been revised to explicitly state this in Section 4.2 to ensure consistency with the previously described evaluation of daily minimum and maximum temperatures.

- *Figure 6.c. Except for the river in the Southern macrozone, the model is incapable of simulating the observed annual cycle of the rivers. Is this because WRF-SAAG does not capture the seasonality of precipitation? Could it be that the model does not adequately simulate the dominant physical processes?*

To provide more insights on the mismatch between simulated and observed runoff seasonalities, we will include additional figures of annual cycles of precipitation and temperature in the revised version of the manuscript.

Final suggestion

After these comments are addressed, I look forward to revisiting the Methods, Results, Discussion, and a richer, more substantive Conclusions section.

We thank the reviewer for the constructive feedback and valuable suggestions. All points raised will be address in the revised manuscript, including clarifications in the Methods, Results, and Discussion sections, as well as an expanded and more substantive Conclusions section.

References:

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