Review #1

Dear authors,

It is an interesting study to read, and the description of the data is detailed and well-explained. In my opinion, the article could benefit from a more explicit or separate description of the methods and more elaboration on the limitations or challenges of the study. Below are my comments.

Dear Reviewer,

Thank you for the detailed comments. Your comments have been addressed and incorporated into a new draft of the manuscript. Please see below for the description of the changes with respect to each comment.

Sincerely,

Stephanie Bringeland (corresponding author), on behalf of co-authors.

Specific comments:

Parts of the methodology were described in the Results and Discussion section. For example, in line 205, 206 and line 257-262. Having this placed in a separate methods section might make it easier to grasp what was done in which way and why. I recommend considering a separate methods section in addition to the description of the data.

For clarification, a section ("2.4 Time Series Analysis Methods") was added to summarize processing steps involved in the analysis. This text was originally included in the Results and Discussion section.

I am missing the limitations and challenges in your chosen approach. For example, in line 105-108, you share about the advantage of CGS compared to mascon solutions. However, it was not mentioned how this (does not) show in your results, nor how it influences your outcome. It would be interesting to have these included. Could you elaborate more on these?

L109-110, 123-125: A description of the persistent spatial leakage present in the CGS solution, despite the application of user-defined regions was added. Also, a note was added to acknowledge the lack of ground truth data with which to determine the most 'accurate' GRACE-derived solution.

Section 2.1 describes how is dealt with the gaps in the GRACE/GRACE-FO data records in between the two missions for the JPL mascon data. How was this handled with the CGS method? This was not clear to me. Also, figure 3 shows a gap in the data, but figure 4 has a linear interpolation for the TWSA.

Figure 2(b): Please add a scale, north arrow and legend in the sub-figure.

These elements have been added to Figure 2(b).

Line 187-190: NAO is mentioned to be included in the analysis, but the only mention of it is in section 2.4. Is it included in the analysis? If so, where? If not, consider removing this part.

Text added (L341) to emphasize the lack of correlation between NAO and water storage components in the SSRB.

Line 202: The HGS TWSA values are compared to GRACE-derived values. In figure 3, it also shows a difference between the two GRACE-derived values (JPL and CGS). Could you specify which of the two it is compared to, or if it is to a combination of both, how this is done?

it is not clear what this is referring to as we cannot find an instance where the GRACE-derived value is not explicitly stated.

Figure 7 is interesting and nice. It would be clearer if the different subfigures had a title or something else clearly indicating which data they are showing (e.g., HGS TWSA, HGS surface water).

The subfigures have been labelled for clarity.

Line 287: Using word precipitation for the sum of rainfall + snowmelt might be slightly confusing for the reader. Was there a clear reason to define it as such? If not, perhaps the writers could consider using a different phrasing, such as “water input”.

The wording has been changed to ‘liquid water flux’, which is defined in the text, for clarity.

Line 290 and Line 295 mention two different numbers: 90% confidence bounds and 95% confidence intervals. Which one is the correct one? Or if both are, could you clarify this in more detail to avoid confusion?

Both should read 95%. This has been corrected in the text (L297).

Review #2

Overall, the research is interesting and uses sophisticated modelling and data derivation techniques. However, the manuscript is a little confusing because more information needs included in the background to understand the research justification, all the methods, results, and discussion are mixed together, and the research uses only modelled data as comparison (e.g. no in situ data for validation). Therefore, I am recommending major revisions, which includes the addition of a several paragraphs in the introduction, a "Study Area Section", an "Analysis" section in the methods, and a "limitations" section before the conclusion, in addition to other recommendations, which you can see below.

Dear Reviewer,

Thank you for the detailed feedback. Your comments have been addressed and incorporated into an improved draft of the manuscript. Please see below for the description of the changes with respect to each comment.

Sincerely,

Stephanie Bringeland (corresponding author), on behalf of co-authors.

Line 39: An additional paragraph is needed here to explain water storage variability. This should explain the conceptual background of the variables used in the study (e.g. surface water, soil moisture, groundwater, etc.) and how they interact and how research shows they are likely to change under climate change conditions. *Note – this is different than paragraph 1, which basically introduces climate change. This second paragraph needs to justify why this research is important and highlight the knowledge gap. Explain to your reader why it is important to study water storage variability and what research has previously been conducted on it and how your research is filling that gap. Then end with an objective sentence that highlights the importance of your research goal.

A paragraph has been added to address this gap (L42-51):

"This study considers four integrated components of terrestrial water storage, namely surface water (e.g., rivers, lakes, and streams), soil moisture (i.e., water content in the unsaturated zone), groundwater (i.e., water content in the fully saturated zone), and snowpack. Increasingly it is recognized that there is significant interaction between these components, and considering the exchange between components is critical for comprehensive representation of a terrestrial water system (Barthel and Banzhaf, 2016). Isotopic mass balance methods and deterministic modelling have been used to confirm and quantify interactions between terrestrial water storage components (Barthel et al., 2008; Hwang et al., 2018, 2023) which become even more important to consider in the context of climate change, as impacts to individual components, such as reduced snowpack, can have cascading effects on terrestrial water storage in a given region (Hayashi and Farrow, 2014). This study facilitates a comprehensive assessment of terrestrial water storage in the Canadian Prairies by combining integrated model-based and independent satellite gravimetry-based estimates of terrestrial water storage changes."

Another new paragraph: There also needs to be some research and justification for the time-variable frequency. Explain in this paragraph: Why is it important to study the intra- and multi-year cyclicity of these variables? What does that tell us? What has previous research shown in terms of hydrologic cycling? What does research say regarding how climate change might impact these cycles? What is the knowledge gap? Why is your research studying these time-variable frequencies novel? (e.g. this should be in the paper – not simply an explanation for me, the reviewer).

A new paragraph has been added (L52-63) to include a more thorough justification for time-variable frequency analysis:

"Terrestrial water storage in the Canadian Prairies is impacted by large-scale meteorological and atmospheric anomalies (e.g., the El Niño Southern Oscillation (ENSO)) through temperature and precipitation anomalies that impact evapotranspiration and infiltration rates (Garnett and Khandekar, 2015; Knox and Lawford, 1990; Shabbar et al., 2011). Many global-scale pressure and temperature anomalies fluctuate with multi-year cyclicity that is not necessarily resolvable at short time scales. In addition, climate change is impacting the behaviour of these large-scale meteorological patterns, including the increased frequency of multi-year ENSO events (Lu et al., 2025). Thus, examining the time-variable frequency content of terrestrial water storage alongside indices representing global atmospheric and oceanic anomalies allows for the assessment of drivers of water storage change in the Canadian Prairies, which can lead to better predictive capacity for water management purposes. While relationships between these indices and individual components of terrestrial water storage (e.g., streamflow) have been assessed (Asong et al., 2018; Garnett and Khandekar, 2015; Knox and Lawford, 1990; Shabbar et al., 2011; Shabbar and Bonsal, 2004; Shabbar and Skinner, 2004), this study provides a more comprehensive evaluation linking large-scale atmospheric fluctuations with all components of terrestrial water storage in the Canadian Prairies."

Line 50: Figure 1: I would recommend moving the study area map to a new section called "Study Area", which goes after "introduction", roughly on line 83. In this new section, please detail the extent, hydrological and climatological averages, the forest/land use type, the population centers, the river systems, the name of the provinces, the mountain ranges, elevations, temperature and precipitation changes with elevation and latitude, and anything else relevant for the reader. Currently, the map includes cities, roadways, rivers, and provincial borders – but you don't explain those to the reader and anyone unfamiliar with the location cannot geolocate the study.

A larger-scale map has been added to Figure 1 to show the SSRB in the North American context to help the reader geolocate the study, including labels for provinces and states. In addition, a paragraph has been added to include more details about the study area (L117-134):

"The headwaters of the South Saskatchewan River originate on the eastern slopes of the Rocky Mountain foothills which form the western boundary of the SSRB. Snowmelt from the Rocky Mountains accounts for much of the surface water flow in the SSRB, including approximately 80% of the streamflow of the Bow River, which in turn makes up around 43% of the annual flow of the South Saskatchewan River (Ghoreishi et al., 2021). The Bow, Oldman, and Red Deer Rivers all originate in the Rocky Mountain foothills, while the South Saskatchewan River begins at the confluence of the Bow and Oldman Rivers between Lethbridge and Medicine Hat, and is eventually joined by the Red Deer River near the Alberta/Saskatchewan border. The western portion of the SSRB falls within the Montane Cordillera ecozone, where annual precipitation ranges from 500 to 800 mm annually (Natural Resources Canada, 2006; Wilken et al., 1996). This portion of the SSRB contains significant temperate and sub-polar needleleaf forest which transitions into shrubland in the eastern direction. Temperatures in the SSRB vary with altitude but generally range from -30°C to +30°C annually. The central and eastern portions of the SSRB lie within the Prairie ecozone, which is part of the Great Plains of North America. Farmland covers over 90% of this ecozone (Wilken et al., 1996), and annual precipitation ranges from 200 to 600 mm (Natural Resources Canada, 2006). The Prairie Ecozone is characterized by the presence of topographical depressions formed during the last glacial maximum which are referred to as prairie potholes and lead to poor surface water connectivity (Spence and Woo, 2003; Vanderhoof et al., 2016). The SSRB is economically tied to water availability as it is a centre for agricultural and industrial activities which rely on water supply (Sauchyn et al., 2020). The Bow, Oldman, and South Saskatchewan Rivers have reached their allocation limits, such that no new allocations of water are permitted (Pentney and Ohrn, 2008). Thus, the changing demand for water must be managed with consideration for how water supply is impacted by annual, interannual, and long-term trends."

Line 66: You did a great job explaining studies that have used GRACE. I recommend adding 1-3 sentences at line 66 justifying why GRACE is appropriate for your study.

A sentence has been added to justify the use of GRACE/GRACE-FO (L75-78):

"At the scale of the SSRB, GRACE/GRACE-FO can sufficiently (< 2 cm equivalent water height (EWH) error (Vishwakarma et al., 2018)) resolve TWSA changes and is independent of hydrological models used herein, making it a useful tool for comparison and validation."

Line 70: You need a paragraph or several sentences explaining the HydroGeoSphere model, previous research that has implemented it, and why it is the most effective model to answer your research question.

Several sentences have been added to properly introduce and justify the use of the HydroGeoSphere model (L79-85):

"This study employs a HydroGeoSphere (HGS; Aquanty, 2024)) fully integrated groundwater – surface water (GW-SW) model. HGS simulates surface and subsurface flow using a modified form of the Richards' equation for 3D variably saturated flow, the 2D diffusion wave equation for depth-integrated surface flow, and the 1D Manning's equation for open channel flow. HGS has been used extensively in Canadian hydrological analyses, including in the Athabasca River Basin north of the SSRB (Hwang et al., 2023) and the Northern Great Plains (Frey et al., 2021). In a region with complex and variable hydrological dynamics including the prairie pothole region, the fully integrated HGS model is well suited to represent all components of terrestrial water storage (Barthel et al., 2008; Barthel and Banzhaf, 2016)."

Section 2.1: This is a lot of detail about how GRACE works. Please provide a paragraph at the beginning of the section explaining the variables that you extracted from it, the spatial resolution, the temporal resolution, and the time/dates of the data.

Methods: The methods should have four sections: Study Area, Data, and Modelling, Analysis. Currently, you have the modelling mixed in with the methods, which is a little confusing. I am recommending that you separate the Data (e.g. GRACE, oceanic indices) from the Models (CLSM, HGS) and add a new section called "Analysis", which includes an explanation of the least-squares regression, trend analysis, and time-variable frequency analysis (e.g. continuous wavelet transformation and power spectral density), and anything else currently mixed in with the results.

Line 122: Once again, it is unclear what variables were extracted/modelled form the HydroGeoSphere model. Please provide a paragraph up front explaining the variables that you extracted from it, the spatial resolution, the temporal resolution, and the time/dates of the data.

I think you should also include a table of the variables extracted from each model, the original data sources, the acronyms, and the resolutions. It would make the data sources easier to visualize. (For example, the cm equiv. water height, surface water anomaly, etc.)

Line 285: You need to add an explanation to the new “Analysis” section on how you calculated the variables to remove seasonal effects.

A table was added (Table 1, L139) at the beginning of a new section (“2 Description of Data and Models”) which summarizes the data or model source, processing centre, variable(s) with units, spatial resolution, spatial extent, temporal resolution, and appropriate references for all data and models used in the analysis. This table separates measurement-derived data and model-derived data to improve clarity for the reader.

In addition, some changes have been made to sections 2.1 GRACE/GRACE-FO, 2.2 HydroGeoSphere, and 2.3 Catchment Land Surface Model to clarify the variables used and the processing steps applied for the study.

A new section (3 Time Series Analysis Methods) has been added to describe the signal decomposition, continuous wavelet transform, and Lomb-Scargle power spectral density estimates. These descriptions have been removed from the Results section for clarity and to avoid redundancy.

Precipitation equals snowmelt plus rainfall is a little confusing – this also needs to go in the methods.

The wording has been clarified – ‘precipitation’ has been changed to ‘liquid water flux’ where appropriate to avoid confusion.

I’m a little concerned that this study only compared modelled output. There are no in situ surface, snow, or groundwater data to validate the outputs. Although the models generally had similar outputs (e.g. Figure 3), what is to say that all of the models weren’t wrong? I think you need to justify this based on literature in a “model limitations” section before the conclusion. Also, I think it would be relevant to include literature that has found similar outputs to yours from in situ data that used validation to underscore the accuracy of the model outputs.

A new section (4 Limitations) has been added to emphasize the limitations of the study (L392-401):

“While in-situ data was used to calibrate and validate the HydroGeoSphere model used in the study (see Figure 2), the conclusions of this study rely mainly on model-based data and satellite observations. While many studies consider historical (Martz et al., 2007; Newton and Taube, 2023; Zare et al., 2022) or projected (Islam and Gan, 2014; Shrestha et al., 2021; Tanzeeba and Gan, 2012) hydrological trends in the SSRB, it is challenging to compare results directly, as the spatial and temporal extent of trend analysis differs. In addition, data from GRACE/GRACE-FO has no true ‘ground truth’ comparison, so error can only be estimated theoretically. While the data from GRACE/GRACE-FO is processed to remove non-TWSA effects (e.g., glacial isostatic adjustment, atmospheric noise), any error in the models used to correct for these effects is propagated into the final estimate of TWSA. The results and conclusions of the study should therefore be interpreted within the context of the limitations described.”

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