We appreciate the time that the reviewer put into this paper. Below, we provide detailed explanations of how we plan to revise the manuscript. The reviewer's comments are in *blue italics*, our responses are in black, and relevant text from the manuscript, whether newly added or edited, is **bold**. We are grateful for the reviewer's insightful feedback.

This paper builds on previous work by the same research team (Chen et al., Remote Sensing of Environment, 2020), which utilized satellite radar interferometry (InSAR) to estimate frozen ground properties. The current study extends that work by focusing on total soil water storage within the entire active layer column, an important hydrological property that remains poorly constrained across vast permafrost regions.

Major comments:
The previous work by Chen et al. (2020) established a link between seasonal subsidence and active layer water storage. The primary advancements in this latest work include presenting water storage as a key result, incorporating InSAR data from an additional satellite frame to extend the study area, and identifying InSAR errors caused by DEM defects. While these contributions are valuable, the paper in its current form does not sufficiently emphasize the fundamental novelty of the methodology. The stacking approach and the scaling of seasonal subsidence by density difference to derive total water content remain the same as the previous work. If these methods are not fundamentally new, I recommend shortening the related methodological section and referring readers to Chen et al. (2020) for more details.

Response: Following the reviewer's comment, we rewrote the last paragraph of the introduction to better illustrate the new contribution made in this paper compared to the Chen et al., (2020) proof of concept paper: **"Chen et al. (2020) found that the amplitude of the seasonal thaw subsidence is proportional to the amount of water stored in the saturated active layer at the end of a thaw season. This is consistent with findings from recent studies that InSAR-derived seasonal subsidence rates reflect spatial soil moisture patterns (Chen et al., 2022, 2023; Widhalm et al., 2024). In this paper, we further established a conceptual model that relates InSAR seasonal thaw subsidence observations to soil water storage in the saturated active layer. Our goal is to advance InSAR techniques for the high-resolution mapping of water storage above-permafrost. To demonstrate this, we mapped soil water stored in the saturated active layer using ALOS PALSAR data over a much larger area in the Arctic Foothills than used in Chen et al. (2020). We validated the InSAR results using in-situ soil measurements collected at more than 200 remote sites within ~ 100 km of the Toolik Field Station as well as optical imagery and land cover maps. Our results show that InSAR soil water storage estimates derived from two separate satellite frames are consistent with in-situ observations under different vegetation covers. An important new contribution of this work is on uncertainty quantification. We determine the primary error sources in Toolik ALOS PALSAR Line-Of-Sight (LOS) measurements, and we discuss how errors in InSAR LOW measurements can be linearly related to errors in soil water storage estimates".**

We summarized our InSAR processing strategy and cited Chen et al. (2020) in the original draft. However, one reviewer noted earlier: "*although the authors clearly indicated that the same procedure proposed by Chen et al. 2020 is used, they should provide more information/details regarding the InSAR procedure/strategy*". This is why we expanded Section 2.2 to better describe the InSAR processing method, which makes the paper self-contained and easier to follow. The uncertainty propagation analysis is covered in Section 2.2 following Equation (4), and InSAR major error sources are discussed in Section 2.3. The results on the uncertainty analysis are presented in Section 3.2 and Section 3.3.

The paper highlights DEM error issues that cause noticeable artifacts in individual interferograms at fine, local scales. While these issues are worth noting, the authors did not correct these errors in their InSAR processing. Moreover, it appears that these errors do not affect the final water storage estimates after stacking multiple interferograms (e.g., Figure 5c).

Response: The reviewer is correct, the DEM coregistration errors only affect areas of high slope angle, and we did not individually correct each pixel for potential coregistration errors (as described fully below). An important contribution of this work is to quantify the uncertainty in the active layer soil water storage estimates from major InSAR measurement error sources (Section 2.3). This is an important step forward to enable accurate interpretation of InSAR observations over permafrost terrain, and scalability and uncertainty quantification are important in new remote sensing water storage retrieval algorithm development.

In Section 2.3, we conducted quantitative assessment of DEM coregistration errors, and discussed the results in Section 3.3 as follows: We predicted the phase errors due to DEM mis-alignment (Figure 12) based on Equation (6)-(7), and compared them to the phase observations from multiple interferograms (Figure 11). We evaluated the estimated InSAR phase errors due to DEM-misalignment in magnitude and spatial distribution (Figure 13). We show that this error increases with InSAR perpendicular baselines (Figure 14; blue dots), a key feature of DEM-related InSAR phase errors rather than other geophysical processes such as solifluction. We note that these DEM artifacts are not just visible in individual interferograms, but they are present in the InSAR thaw subsidence map (Figure 5a), mostly at pixels with large slope angles (Figure 13).

It is difficult to fully correct the pixel misregistration issues. In this study, we removed the topographic phase during interferogram formation using the Arctic DEM v3.0 data (Porter et al., 2018), which are widely used in the Arctic community because of its pan-arctic coverage and high quality (Tozer et al., 2019). We used the same image co-registration routine as the standard InSAR processing software such as GMTSAR and ISCE (Co-author J. Chen is on the GMTSAR developer team). The 2-D cross correlation method for image alignment can achieve ~ 0.1-pixel accuracy in the best-case scenario. However, the accuracy can be worse than 1 pixel because SAR images and DEM data were acquired from sensors with different spatial resolutions, imaging geometries, and uncertainties. Because the pixel offset between SAR and DEM images is not a constant, a manual adjustment would have to be performed at each individual pixel, which is not practically feasible. Based on the fact that these pixel misregistration artifacts are mostly observed in a small subset of pixels with relatively large slope angles (Figure 13), we conclude InSAR is a feasible technique for regional active layer water storage mapping over our study site. Future work may focus on the development of a misalignment correction algorithm.

For the HESS readership, I suggest strengthening and elaborating more on the hydrological significance of this method and results. For instance, what are the advantages and limitations of estimating soil water content using this method? What new insights are gained from the estimated water storage in the context of permafrost hydrology?

Response: This paper uses space geodetic observations to map water stored near the earth's surface. We stated in the abstract: "**The hydrology of thawing permafrost affects the fate of the vast amount of permafrost carbon due to its controls on waterlogging, redox status, and transport. However, regional mapping of soil water storage in the soil layer that experiences annual freeze-thaw cycles above permafrost, known as the active layer, remains a formidable challenge over remote arctic regions**". We further justified the scientific rationale of the work in the first paragraph of introduction. Existing InSAR permafrost studies tended to associate the magnitude of the InSAR-observed thaw subsidence with the active layer thickness. However, our recent work (Chen et al., 2020) shows that the amplitude of the maximum seasonal thaw subsidence is proportional to the amount of soil water that experiences the active layer freeze-thaw cycle (not necessarily the active layer thickness). This means that satellite remote sensing of surface deformation is a potential strategy for mapping water storage in the active layer with broad coverage and relatively high spatial resolution. In this paper, we further developed a conceptual model (Figure 2) that relates InSAR seasonal thaw subsidence observations to soil water storage in the saturated active layer (Section 2.1). The resulting InSAR active layer water storage map will be an interest to many people who work in the field of permafrost hydrology research, including but not limited to the remote sensing scientists.

An important assumption we employ is that the observed InSAR deformation is associated with the active layer freeze-thaw processes. At the end of Section 2.1, we discussed various hydrological and geophysical processes that may lead to deformation in permafrost environment: "**We emphasize that many geophysical processes can lead to surface deformation in permafrost terrain detectable by InSAR (Zwieback et al., 2024b). For example, slope creep processes may produce long-term downward deformation trends in regions with large slope angles (Dini et al., 2019). Post-glacial rebound and tectonic motions typically vary at 100-km or larger spatial scales and can be considered as nearly spatially uniform over our study area (Liu et al., 2010; Stephenson et al., 2022). Given that InSAR measures relative deformation with respect to a local reference point, InSAR is only sensitive to spatially varied surface deformation over the study area. Hydrological loading and unloading can produce millimeter-level surface deformation signals (Liu et al., 2010), which is much smaller than centimeter-level freeze-thaw deformation. Furthermore, peat accumulation and erosion processes (Jones et al., 2017) can cause changes in surface scattering properties, which decorrelate radar phase measurements (Zebker and Villasenor, 1992). As a result, it is difficult to capture these processes using InSAR. In Section 2.2, we discuss how to extract long-term and seasonal deformation signals from InSAR observations. The magnitude and characteristics of deformation signals, combined with in-situ observations (Section 2.4), can be used to determine the primary geophysical processes that contribute to the observed deformation patterns**".

The rigor of this work could be further improved by providing a quantification of the uncertainties associated with the water storage estimates and discussing the limitations of the method (again, in the context of permafrost hydrology). For example, the simple scaling does not account for unfrozen water, excess ice, or vertical moisture migration; the stacking-based InSAR processing might not be applicable in cases of significant inter-annual variations and linear secular trends; other InSAR errors such as tropospheric delay or phase artifacts due to soil moisture changes are not explicitly accounted, etc.

Response: As noted in our response above, we discussed various geophysical processes that may lead to deformation in permafrost environment, and our method is based on the assumption that the active layer freeze-thaw process is the primary geophysical process that contributes to the the observed deformation. Given the characteristics of the observed deformation signals (Figure B3) and in-situ validation results, this assumption is valid over the Toolik area. As shown in Figure 2, water in the unsaturated zone (tension water) can expand to fill the empty pore space during freezing without contributing to surface deformation. In Section 2.1, we further emphasize that the InSAR method is not sensitive to water in the active layer that does not experience the annual freeze-thaw cycle (e.g., the runoff term Q in Equation 2). Because InSAR measures the total deformation over all depths, it is not sensitive to vertical moisture migration.

In terms of secular trends, in Section 2.2 we state that: "**We first solved for the long-term LOS deformation trend at a pixel of interest based on a stacking approach. That is, averaging all interferograms that contain minimal seasonal deformation signals (e.g., a July-to-July pair) and relatively large long-term signals (e.g., span multiple freeze-thaw cycles)**". We note that stacking methods have been used to solve for the linear deformation trend over multiple periods of time, and the results are comparable to the SBAS InSAR time series method (Staniewicz et al., 2020). At the end of Section 3.1, we further discussed the limitation of the stacking method: **"Due to the limited ALOS PALSAR temporal sampling rate, the investigation of inter-annual variability of InSAR thaw subsidence patterns is outside the scope of this work. Future work can focus on studying how the signal magnitude of seasonal thaw subsidence changes over multiple years using Sentinel-1 data collected with 6-12 day revisit cycles (Zwieback and Meyer, 2021; Zwieback et al., 2024)".**

In terms of other InSAR errors, in Section 2.3 we discussed the major error sources including tropospheric noise. We included key references on InSAR tropospheric noise studies (Zebker et al., 1997; Emardson et al., 2003) to support our assumption that residual tropospheric noise level in individual interferograms is ~ 2 cm (after long-wavelength tropospheric noise was removed during the planar ramp removal process). We typically expect large tropospheric noise in hot and humid environments. Due to a cool and dry tundra climate over the Toolik area, we do not expect the tropospheric noise level to be substantially higher than the values reported in Emardson's 2003 South California study. We note that a thaw subsidence pattern similar to the final stacking solution was identified from all individual interferograms that span a common season, and the differences (a measure of noise terms) are on the order of centimeters. This is also consistent with the assumption that residual tropospheric noise level in individual interferograms is ~ 2 cm. Stacking reduces the impact of random noise by $\sqrt{N}$, where N is the number of independent SAR acquisitions. As a result, the turbulent random noise level can be reduced to less than 1 cm after stacking four interferograms formed from four SAR acquisitions. The change in soil moisture can lead to closure phase errors, which is typically much smaller than the tropospheric noise term in Equation (5).

Reference:

Staniewicz, S., Chen, J., Lee, H., Olson, J., Savvaidis, A., Reedy, R., Breton, C, Rathje, E., and Hennings, P. (2020). InSAR reveals complex surface deformation patterns over an 80,000 km2 oil-producing region in the Permian Basin. Geophysical Research Letters, 47, e2020GL090151. https://doi.org/10.1029/2020GL090151.

Minor comments:

Section 1:

Some papers published in recent years have made similar attempts to estimate soil water content above permafrost using InSAR. Consider citing some of them and highlighting your contributions.

- *Chen, J., Wu, T., Liu, L., Gong, W., Zwieback, S., Zou, D., Zhu, X., Hu, G., Du, E., Wu, X., Li, R., and Yang S. (2022), Increased water content in the active layer revealed by regional-scale InSAR and independent component analysis on the central Qinghai-Tibet Plateau, Geophysical Research Letters, 49, e2021GL097586, https://doi.org/10.1029/2021GL097586.*
- *Chen, R. H., Michaelides, R. J., Zhao, Y., Huang, L., Wig, E., Sullivan, T. D., Parsekian, A. D., Zebker, H. A., Moghaddam, M., and Schaefer, K. M. (2023), Permafrost Dynamics Observatory (PDO): 2. Joint Retrieval of Permafrost Active Layer Thickness and Soil Moisture From L-Band InSAR and P-Band PolSAR, Earth and Space Science, 10, e2022EA002453, https://doi.org/https://doi.org/10.1029/2022EA002453*
- *Widhalm et al. InSAR-derived seasonal subsidence reflects spatial soil moisture patterns in Arctic lowland permafrost regions, https://egusphere.copernicus.org/preprints/2024/egusphere-2024-2356 (Paper accepted for publication in The Cryosphere, title to be changed)*

And two recent review papers for your reference.

- *Zwieback, S., Liu, L., Rouyet, L., Short, N., and Strozzi, T. (2024), Advances in InSAR Analysis of Permafrost Terrain, Permafrost and Periglacial Processes, https://doi.org/10.1002/ppp.2248.*
- *Streletskiy, D., Maslakov, A., Grosse, G., Shiklomanov, N., Farquharson, L., Zwieback, S., Iwahana, I., Bartsch, A., Liu, L., Strozzi, T., Lee, H., and Debolskiy, M. (2025), Thawing*

permafrost is subsiding in the Northern Hemisphere–review and perspectives, Environmental Research Letters, 20, 013006, https://doi.org/10.1088/1748-9326/ada2ff.

Response: Thank you for these references, we now have them cited appropriately in our manuscript. As noted in our response to the major comments, we rewrote the introduction to better illustrate the new contribution made in this paper beyond that in Chen et al., (2020). We also discussed the assumptions and limitations of the method in Section 2.1. We cited recent work noted here in the revised paper.

Section 2:

(Also relevant to section 3.2) Consider using alternative DEM such as the Copernicus GLO-30 Digital Elevation Model or the latest release of ArcticDEM (v4.1) to quantify and even reduce DEM errors.

Response: We used both Kuparuk River River watershed DEM and Arctic DEM in the original InSAR analysis, and the resulting interferograms have comparable quality. We recently reprocessed the ALOS PALSAR interferograms using the updated ArcticDEM, and we found that these artifacts due to SAR-DEM misregistration remain present. We emphasize that the DEM data and ALOS data were collected by different sensors with different spatial resolutions and image geometries. Uncertainties can be further introduced by the filtering techniques applied during image processing. Therefore, it is difficult to fully correct the pixel misregistration issues using the standard InSAR processing software alone. An important contribution of our work is to provide a method for estimating this error at different pixel locations. This enables accurate interpretation of InSAR phase signatures (e.g. the patterns shown in Figure 11 from several real interferograms are DEM artifacts rather than real deformation signals).

Line 153: could you specify the masking thresholds?

Response: We updated the figure caption of Figure B2 and state that the mask **"excludes any pixels with amplitude dispersion < 0.25 and phase coherence < 0.2 (e.g., water bodies and the area affected by the 2007 Anatuvuk River fire)."** We now add this information in the main text as well.

Line 163-179: much of its content doesn't fit within the InSAR processing section and could be relocated.

Response: Equation (4) relates the observed seasonal LOS deformation due to the active layer thaw to the amount of water stored in the saturated active layer. We decided to keep Equation (4) and the relevant discussion in Section 2.2, because this equation is built upon Equation (1) and Equation (3), and it shows that 1 cm errors in InSAR LOS deformation measurements can lead to 14 cm error in z_{water} estimates. This naturally leads to Section 2.3, which covers error sources in InSAR LOS deformation measurements.

Section 3:

Figure 5: panel b DEM colorbar's annotations are flipped; please also cite the source of the land cover map in the caption.

Response: Thank you, we corrected the colorbar and added relevant citations in the figure caption.

Figure 6 caption: What is meant by '4% vector length'?

Response: We edited the last sentence of the figure caption as **"... The normalized Z_{water} curve was then smoothed using a box car filter with a window size equal to 4% of the number of radar pixels along the transect."**

Table 1: only need to keep one significant digit after the decimal points, to be consistent with the description in the main text.

Response: We updated Table 1 as suggested.

I understand the challenges of directly comparing remote sensing estimates with in-situ measurements. I recommend including scatter plots comparing these in the supplementary materials.

Response: As we stated in Section 2.4, a pixel in an InSAR-derived deformation map is ~ 100-by-100 meter, while field measurements were collected at sites with size ~ 900 cm^2 (30-by-30 cm plots). The soil layer thickness and the depth to water table measurements can vary substantially within one InSAR pixel at multiple soil pits. This is why the exact point-to-point comparison is not feasible. Instead, we designed a statistical comparison approach to compare the distribution of Z_{water} as inferred by InSAR and field observations under different vegetation covers (Figure 8).

While we devoted substantial amount of effort to collect over 200 soil samples (from these samples, porosity can be measures, we were not able to collect at least three soil samples (one from acrotelm, one from cateletem, and one from mineral soils) at every soil pit due to time constraints and the remote nature of the site. This makes it impossible to generate the scatter plots as suggested by the reviewer.

Line 308: PALSAR is misspelled.

Response: We have corrected this typo.

Figure 9: add vertical and horizonal scales for the DEM profile and add a distance scale to panel (c) Add distance scales to Figures 10d, 11a, 12a.

Response: We updated Figures 9, 10, 11, and 12 as suggested.

Line 428: Since section 3.3 primarily presents and discusses simulations of errors due to 1-2 pixel misregistration in individual interferograms, it is unclear how your approach provides a valuable way to identify and characterize pixel misregistration errors in the final LOS deformation estimates.

Response: In Section 3.3, we showed that the observed phase patterns (Figure 11) closely resemble the patterns of the simulated DEM errors (δ in Equation 6) due to 1-2 pixel misregistration to east (Figure 12a and Figure 12c). This allows us to conclude that the observed InSAR phase patterns are likely due to DEM errors rather than true deformation signals. We note that the LOS phase error due to DEM-SAR image misregistration is controlled by the amount of pixel misregistration, the local slope, and the InSAR perpendicular baseline. We estimated the InSAR LOS phase error due to 1 pixel misregistration for a perpendicular baseline of 5104 meters in Figure 13. Given that the pixel misregistration error is typically on the order of sub-pixels and the perpendicular baselines in most ALOS interferograms are less than 5104 meters, we reach an important conclusion that InSAR is a feasible technique for regional active layer water storage mapping for a majority of pixels over our study site.

We clarified these points at the end of Section 3.3: "**Nonetheless, our approach provides a method to estimate spatial characteristics and upper bound of InSAR phase errors due to DEM-SAR pixel misregistration in individual interferograms**".