Response to Reviewer #1 Comments

Comment 1:

The authors present a unique and important new dataset of Earth thermoelastic vertical displacement at 15000 GPS stations globally. This is an important source of GPS signal, especially at annual and semi-annual periods, and yet there is no operational or even non-operational widely available product for users to apply to GPS bedrock time series in order to reduce noise and signal. The methods look solid and robust in the main. The work builds on previous work published with some methodological advances. The dataset and quality control is well described. I expect this will be a widely used dataset, although note there is no statement on if the dataset will be kept up to date - something that will terminate its usefulness as GPS time series get longer. Likewise, the decision to commence in 2000 may cut off the greatest value. During the sparsely observed (by GPS) 1990-2000 period the effects of signals like this will be even greater in some studies due to asymmetry of the global network. it also leaves users wondering what to do with older data.

Response 1:

Thank you very much for your positive comments and helpful suggestions. We agree that version control and long-term maintenance are important for a reusable GNSS correction dataset. In the revised manuscript, we have clarified in the Data availability section that the TED dataset is released as a versioned product. Future revisions or extensions, if any, will be archived as updated Zenodo releases, with the version number, release date, and a brief description of changes provided for each release. Users are also encouraged to cite the specific dataset version used in their analysis.

Regarding the starting year of 2000, we agree that earlier GNSS observations could be valuable for some long-term geophysical studies. The limitation is not the ability of the thermoelastic model to generate TED estimates before 2000, but rather the quality and consistency of the available GNSS coordinate time series during the early period. Before 2000, the global GNSS network was much sparser, and many stations had shorter records, less homogeneous processing strategies, and larger uncertainties, which may affect the evaluation of the correction performance and the consistency of large-scale statistical analyses.

For the current release (Version 2), we focus on the 2000–2023 period, which provides a balance between global station coverage, coordinate time-series quality, input-data consistency, and correction performance. The thermoelastic model itself can be extended to earlier periods where sufficient GNSS observations and input datasets are available. Future releases may include pre-2000 TED estimates after further evaluation of the consistency and reliability of the corresponding GNSS time series.

Comment 2:

First, as with all previous studies of global thermoelastic deformation, the authors mishandle areas of the planet that are permanently and seasonally ice- or snow-covered. Take Antarctica for example. The permanent ice cover there insulates the sub-ice region from experiencing any annual thermal effects. This presumably affects the deformation of sites located next to the ice sheet or on rock outcrops through the ice sheet. This will include Greenland, and the many small glacier regions globally. As such, I suspect the modelling is unreliable in these regions and should be removed from the dataset until the model is revised. To investigate this, I looked at two Antarctic sites CRDI and MAW1, which are adjacent to the Antarctic Ice Sheet, on small (~100x100m outcropping bedrock). The modelled series (see in the PDF) show significant annual signal and, in the case of CRDI, an apparent offset in 2010. My initial reaction is that these are likely not robust signals. However, maybe the thermal effect is of such small scale that even 100mx100m outcrops are enough to experience these thermal deformations (although presumably the very cold ice to the side of the sites also regulates the bedrock temperature considerably). I suspect the CRDI offset is not caught by the QC as there are few sites in Antarctica. But I also presume this is driven by an ERA5 temperature artefact. Also, there does not appear to be any data in the SoilsGrid paper under the permanent ice, so it is not clear how these regions are modelled anyhow.

Seasonal snow cover is more complex. This would be available in ERA5 I guess, in addition to temperature. Again, snow will insulate the soil/bedrock from air temperatures.

Response 2:

Thank you very much for this important and helpful comment. We agree that permanent ice cover, glaciers, ice shelves, and seasonal snow can strongly modify the near-surface thermal boundary condition and therefore affect the reliability of thermoelastic modelling. The current global model relies on ERA5 soil-temperature forcing over land and SoilGrids-based shallow subsurface properties, which are difficult to represent reliably beneath permanent ice or in glacier-covered regions. Therefore, in the revised manuscript and dataset screening, we have excluded stations located in Antarctica, Greenland, permanent ice-covered or glacier-covered regions, ice shelves, and their surrounding buffer zones from the released dataset and the subsequent statistical analyses (Figure 2; https://doi.org/10.5281/zenodo.21069958 (Lu et al., 2026a)). The Antarctic stations mentioned by the reviewer, CRDI and MAW1, are therefore no longer included in the main release or used in the revised analysis.

Seasonal snow cover is more complex. We agree that snow insulation can attenuate and delay the thermal signal reaching the soil or bedrock. However, we did not systematically remove all seasonally snow-covered stations, because this would exclude many otherwise useful GNSS stations in northern Europe, Canada, the northern United States, northern Japan, and mountainous regions. Instead, we clarified that the thermal insulation effect of seasonal snow cover is treated as a source of uncertainty and discussed as a limitation of the current product. We also note in the Discussion and conclusions that larger uncertainties may occur at stations affected by strong seasonal snow cover, frozen ground, large soil-moisture variations, or poorly documented local site conditions.

Section 2.1, we added the following description of the station screening:

<u>“Because the present model depends on soil-temperature forcing over land and shallow subsurface properties, we further exclude stations located in Antarctica,</u>

Greenland, permanent ice-covered or glacier-covered regions, ice shelves, and their surrounding buffer zones. These sites are not included in the released dataset or the subsequent statistical analyses because their surface and near-surface thermal boundary conditions, as well as their shallow subsurface properties, are difficult to represent reliably using the current global input datasets. Stations affected by seasonal snow cover are not systematically removed, since doing so would exclude many otherwise useful GNSS stations in northern Europe, Canada, the northern United States, northern Japan, and mountainous regions. Instead, the thermal insulation effect of seasonal snow cover is treated as a source of uncertainty and discussed as a limitation of the current product."

Section 5, we added the following limitation:

"The model also uses static shallow subsurface properties and does not explicitly include time-varying soil moisture, snow insulation, freeze–thaw processes, or permanent ice conditions. Larger uncertainties may therefore occur at stations affected by strong seasonal snow cover, frozen ground, large soil-moisture variations, complex coastal or lake-side environments, or poorly documented local site conditions. Future updates could improve the treatment of snow, soil moisture, and frozen ground, and may consider sub-daily products or other model extensions after further validation with appropriate GNSS solutions and improved input datasets."

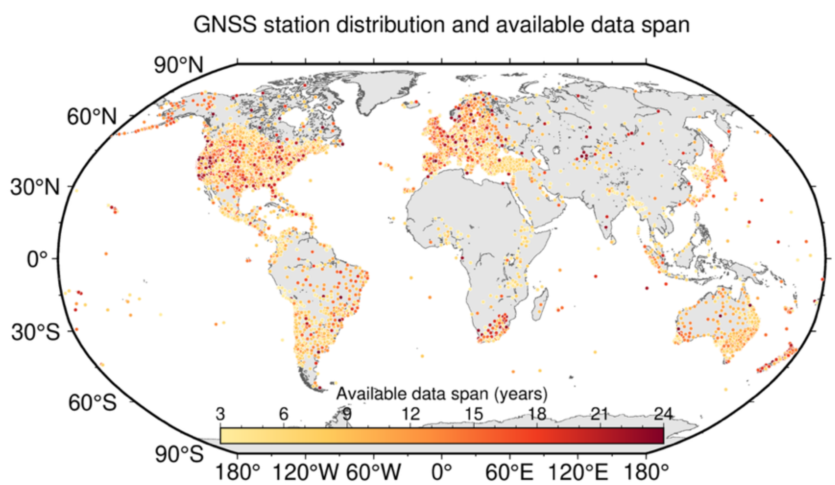

Figure 2 Spatial distribution and temporal coverage of GNSS stations.

Comment 3: Second, I was not sure how ocean and lake areas are considered and what resolution any mask has. There are many coastal GPS sites and presumably this will matter.

Response 3:

Thank you for this helpful comment. We agree that the treatment of ocean and lake areas is important for coastal and lake-side GNSS stations. In the revised manuscript, we clarified how these areas are handled in both the temperature forcing and the subsurface parameterization. ERA5 soil-temperature fields are used on the 0.25° × 0.25° regular latitude–longitude grid, and only valid land grid cells with soil-temperature values are used for stations close to coastlines or large lakes. Ocean and lake grid cells are excluded from the upper-boundary forcing. For the layered subsurface properties, we use SoilGrids 2.0, which provides global land soil-property maps at 250 m spatial resolution. Ocean and lake areas are not assigned valid SoilGrids values; therefore, only valid land soil-property values are used to construct the layered subsurface column.

We have added the following clarification in Section 2.2:

"ERA5 soil-temperature fields are used on the 0.25° × 0.25° regular latitude–longitude grid. For stations close to coastlines or large lakes, only valid land grid cells with soil-temperature values are used; ocean and lake grid cells are excluded from the upper-boundary forcing."

We have also added the following clarification in Section 2.3:

"In this study, we use SoilGrids 2.0, which provides global land soil-property maps at 250 m spatial resolution. Ocean and lake areas are not assigned valid SoilGrids values; therefore, for stations close to coastlines or large lakes, only valid land soil-property values are used to construct the layered subsurface column."

Comment 4: Third, the data itself has no version control. I would expect there will be revisions and hence the dataset should be versioned. The data instructions are not clear that the trend component is not to be trusted.

Response 4:

Thank you very much for this helpful suggestion. We agree that version control is necessary for a reusable GNSS correction product. In the revised manuscript, we have clarified in the Data availability section that the TED dataset is distributed as a versioned release. Future revisions or extensions, if any, will be archived as updated Zenodo releases, with the version number, release date, and a brief description of changes provided for each release. Users are also asked to cite the Zenodo DOI together with the specific dataset version used in their analysis.

We also agree that the trend component needs clearer guidance. In the revised manuscript, we clarified that the TED series are intended mainly for correcting seasonal and nonseasonal thermoelastic variability in GNSS height time series. We also added a caution that linear trends fitted to the TED series should be interpreted with caution because they may be affected by uncertainties in the long-term behaviour of the temperature forcing and model inputs.

Section 4, Data availability

"The TED dataset is distributed as a versioned release. Future revisions or extensions, if any, will be archived as updated Zenodo releases, with the version number, release date, and a brief description of changes provided for each release. Users should cite the Zenodo DOI together with the specific dataset version used in their analysis. The TED series are intended mainly for correcting seasonal and nonseasonal thermoelastic variability in GNSS height time series. Linear trends fitted to the TED series should be interpreted with caution, because they may be affected by uncertainties in the long-term behaviour of the temperature forcing and model inputs."

Comment 5: Finally, it is a shame that the authors only released the vertical components. It would have been interesting to see the horizontals. Also, it would be useful in some cases to consider subdaily corrections for thermal expansion, and hence, the 6h series would have been useful, not just the daily ones. Maybe that will be a focus of future work, including validating the subdaily signals.

Response 5:

Thank you very much for this helpful suggestion. We agree that horizontal and sub-daily thermoelastic displacement products would be useful for some GNSS applications. However, the current FEM_{FL} model used in this study is a one-dimensional vertically layered model and estimates vertical thermoelastic displacement only. It does not provide reliable horizontal displacement estimates, and therefore horizontal components are not included in the present release.

Regarding temporal resolution, although the model is driven by hourly ERA5 soil-temperature forcing, the technical evaluation and GNSS-based assessment in this study are based on daily GNSS coordinate time series. Therefore, the current release provides daily vertical TED time series that can be directly aligned with daily GNSS height time series. We have clarified this scope in the revised manuscript. We also agree that sub-daily thermoelastic corrections may be useful, and sub-daily TED products may be considered in future releases after further validation with sub-daily GNSS solutions.

Section 4, we added the following clarification:

"This release provides daily vertical TED time series for direct use with daily GNSS height time series. Horizontal components are not included because the one-dimensional FEM_{FL} model used here estimates vertical thermoelastic displacement only. Although the model is driven by hourly ERA5 soil-temperature forcing, sub-daily TED series are not released in this version because the technical evaluation and GNSS-based assessment are based on daily GNSS coordinate time series. Sub-daily TED products may be considered in future releases after further validation with sub-daily GNSS solutions."

Section 5, Conclusion and discussion:

"Future updates could improve the treatment of snow, soil moisture, and frozen ground, and may consider sub-daily products or other model extensions after further validation with appropriate GNSS solutions and improved input datasets."

Minor comments

Comment 6: L15 I am not sure the current TED is reproducible. That would require code and workflows.

Response 6: We have revised the wording in the Abstract to avoid implying full reproducibility of the product from code and workflows. The Abstract now states that a globally consistent station-level TED product has not been widely available.
Revised text:
"However, a globally consistent station-level TED product has not been widely available."

Comment 7: L24 add how many stations had independent site characterisations.

Response 7: Thank you for this suggestion. We have revised the Abstract to include the number of stations with documented foundation-depth information.
Revised text:
“For the 2,612 stations with documented foundation-depth information, site-information-constrained solutions agree closely with SoilGrids-based solutions, with annual-amplitude differences mostly about 0.01–0.03 mm and annual-phase differences generally within 1–3°.”

Comment 8: L32 the authors merge the effect of TED into the combined effect with loading products. The authors should stick to just the TED effect here in the abstract. it is no more than +-10% at most sites. That is ok.

Response 8: Thank you for this helpful comment. We agree that the effect of TED should be separated from the combined effect of non-tidal loading products in the Abstract. In the revised manuscript, we have removed the statement based on the combined correction and now report only the TED-only correction result.
Revised text:
“When applied alone to GNSS height time series, TED produces positive WRMS reductions at about 79% of the assessed stations, with most improvements within 3–5% and the largest WRMS reductions reaching about 10%.”

Comment 9: L49 obscure *other* subtle

Response 9: Revised.

Comment 10: L66 this is an important point. you could say a little more. there is no CM movement in this case, even if there is CF and CE movement.

Response 10: Thank you for this important clarification. We agree that thermoelastic deformation does not imply a true motion of the Earth-system centre of mass. The effect discussed here is an apparent signal in GNSS-derived geocenter estimates, caused by thermoelastic station displacement and its projection into estimated geocenter parameters. We have revised the text to make clear that unmodelled thermoelastic station motion may affect GNSS-derived geocenter estimates, but should not be interpreted as true motion of the centre of mass.
Revised text:
“For example, Wei et al. (2025) showed that unmodelled thermoelastic displacement at GNSS stations could project into annual signal of the Z component in GNSS-derived geocenter estimates. This signal should be interpreted as an apparent geocenter variation associated with station displacement and network geometry, rather than true motion of the Earth-system centre of mass. Accounting for thermoelastic station motion may

therefore reduce this apparent annual signal and improve the consistency of GNSS-derived geocenter estimates across independent solutions."

Comment 11: L103 this is where I would like to see versioning

Response 11: Thank you for this suggestion. We have added a statement on dataset versioning where the dataset release is first introduced. The revised text clarifies that the TED dataset is released as a versioned product and that station information and data-description files are provided to facilitate consistent use and future updates. More detailed information on versioning, future revisions, and citation of specific dataset versions is provided in the Data availability section.
Revised text:
"The dataset is released as a versioned product, with station information and data-description files provided to facilitate consistent use and future updates."

Comment 12: L114 in this section it would be good to say what is not modelled. Buildings and monuments above ground, such as pillars. These may cause significant effects, and the authors could cite such works.

Response 12: Thank you for this helpful suggestion. We agree that the above-ground monument and building-related thermal expansion can be important at individual GNSS stations and should be clearly distinguished from the subsurface thermoelastic deformation modelled in this study. In the revised manuscript, we added a clarification in Section 2.4 to state that the released TED product represents subsurface thermoelastic deformation only. It does not include thermal expansion of above-ground structures, such as concrete pillars, steel masts, rooftop monuments, buildings, or antenna-support structures. We also added relevant references to previous studies on monument-related thermal effects.
Revised text:
"The released TED product represents subsurface thermoelastic deformation only. It does not include thermal expansion of above-ground structures, such as concrete pillars, steel masts, rooftop monuments, buildings, or antenna-support structures. These monument-related effects can be important at individual stations and have been reported in previous studies (e.g., Romagnoli et al., 2003; Yan et al., 2009, 2010; Lu et al., 2026b). They are not included in this release because globally complete information on monument height, material, geometry, anchoring condition, and local thermal environment is not available for most GNSS stations. The TED series should therefore be interpreted as a subsurface thermoelastic correction, rather than a complete correction for all temperature-related site effects."

Comment 13: L149 gives the horizontal resolution of ERA5 forcing.

Response 13: Thank you for this suggestion. We have revised the sentence to explicitly state the horizontal grid of the ERA5 soil-temperature forcing used in this study.
Revised text:
"ERA5 soil-temperature fields are used on the 0.25° × 0.25° regular latitude–longitude grid."

Comment 14: L189 give the horizontal resolution of the FEM.

Response 14: Thank you for this comment. We have clarified that the FEMFL model used in this study is a one-dimensional vertically layered model run independently at each GNSS station, rather than a model with a horizontal finite-element mesh. Therefore, the model itself does not have a horizontal resolution. The spatial sampling of the TED product is determined by the GNSS station locations, while the input fields retain their native horizontal resolutions, namely 0.25° × 0.25° for ERA5 soil temperature and 250 m for SoilGrids.

Comment 15: L230-233 I didn't understand this sufficiently well to be able to reproduce it. Why not just take daily averages?

Response 15: Thank you for this comment. We agree that the previous description was not sufficiently clear. We have revised the text to explain how the final daily TED series is constructed from the four 6-hour realizations. Specifically, each realization is decomposed into annual, semiannual, and residual components. The annual and semiannual components are averaged using amplitude–phase vectors to treat the cyclic nature of phase consistently and preserve the mean magnitude and timing of the seasonal signal, while the residual component is averaged from the four 6-hour samples within each day. This clarification explains why the final product is not obtained simply by selecting a single UTC epoch and makes the procedure easier to reproduce.
Revised text:
"Daily GNSS coordinate solutions are usually reported as daily estimates, whereas near-surface temperature and the resulting thermoelastic response depend strongly on local solar time. If temperature forcing is sampled at only one fixed epoch, stations at different longitudes correspond to different local times, and part of the diurnal temperature signal may be aliased into longer-period components. To reduce this effect, FEM_{FL} is driven by ERA5 soil-temperature forcing sampled at 00:00, 06:00, 12:00, and 18:00 UTC, producing four TED realizations for each station. Each realization is decomposed into annual, semiannual, and residual components. The annual and semiannual components are averaged using amplitude–phase vectors to treat the cyclic nature of phase consistently and to preserve the mean magnitude and timing of the seasonal signal. The residual component is averaged from the four 6-hour samples within each day. The final daily TED series is obtained by adding the vector-averaged harmonic component and the daily averaged residual component, producing a correction series compatible with daily GNSS height time series."

Comment 16: L367 this paragraph, please explicitly cite the panels of Fig 6 as relevant

Response 16: Revised

Comment 17: Fig 6 caption. explain all panels explicitly

Response 17: Revised

Comment 18: L388 'weak' downplays it without showing us the trends. Delete weak and let the reader decide that. change long-term to trend-like.

Response 18: Thank you for this comment. We agree that the word "weak" could downplay the trend-like signal without sufficient supporting evidence, and that "long-term" may imply a more reliable geophysical trend than intended. In the revised manuscript, we have removed this trend-related discussion to avoid over-interpreting the fitted linear component. The TED product is now presented mainly in terms of seasonal and nonseasonal thermoelastic variability, and the corresponding trend-related wording, including "weak" and "long-term", has been deleted.

Comment 19: Section 3,3 As also noted for the abstract, the merging of the TED product with surface loading products, some with much larger importance, is not satisfactory. Please commence with the TED effect on WRMS. You could reasonably remove first the other signals from the series.

Response 19: Thank you for this important comment. We agree that the contribution of TED should be separated from the combined effect of non-tidal loading products. In the revised manuscript, we reorganized Section 3.3 so that it now starts with the TED-only WRMS assessment. The WRMS change is evaluated by applying only the TED correction to the GNSS height time series, without removing NTAL, NTOL, or HYDL. We have also removed the previous emphasis on the combined correction from the Abstract and avoided attributing the improvement from loading products to TED.
Revised text in the Abstract:
"When applied alone to GNSS height time series, TED produces positive WRMS reductions at about 79% of the assessed stations, with most improvements within 3–5% and the largest WRMS reductions reaching about 10%."
Revised text in Section 3.3:
"The effect of TED on GNSS height time series is first examined by applying the TED correction alone, without removing NTAL, NTOL, or HYDL (Fig. 11). Positive WRMS reductions are found at about 79% of the assessed stations, indicating that removing TED reduces the scatter of the GNSS height series at most sites. The improvement is generally modest, mostly within 3–5%, and locally reaches about 5–10%. Some stations show

negative WRMS reductions, locally around −2% to −5%, indicating that the TED-only correction does not improve every GNSS height series.”

Comment 20: Figure 14 labels the y-axis as %. Note the different colour scale for NTAL and HYDL

Response 20: Revised

Comment 21: L646 new para at 'in practical'. Give TED only results not the merged results with NTAL etc.

Response 21: Thank you for this comment. We agree that the practical correction result should focus on the TED-only effect rather than the combined effect with non-tidal loading products. In the revised manuscript, we removed the discussion of merged WRMS results from NTAL, NTOL, HYDL, and TED. Section 3.3 now reports the standalone contribution of TED to GNSS height time series. The loading products are mentioned elsewhere only for order-of-magnitude comparison and for illustrating the relative timing and amplitude of the different displacement components.

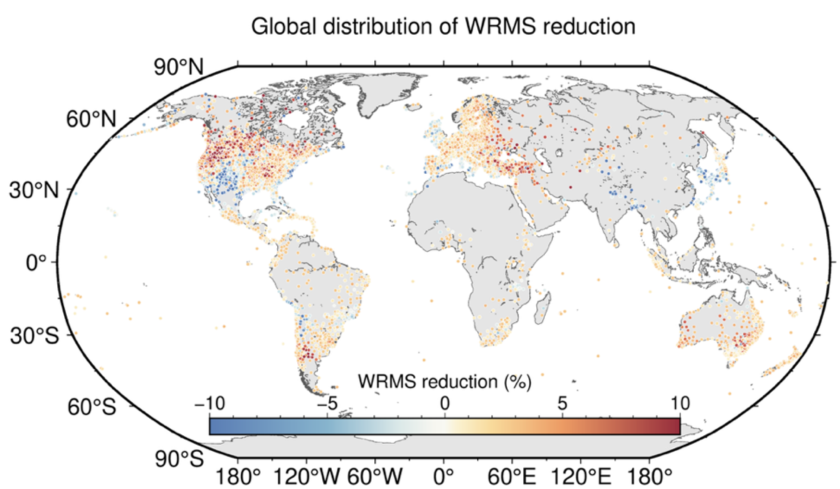

Figure 11 Global distribution of WRMS changes after applying the TED-only correction to GNSS height time series. Positive values indicate reduced WRMS after removing TED, while negative values indicate increased WRMS.

Comment 22: L657 add also above-ground pillars.

Response 22: Revised. We have explicitly included above-ground structures, such as concrete pillars, steel masts, rooftop monuments, buildings, and antenna-support structures, in the revised description of the effects not included in the released TED product.