

High-resolution geomechanical modeling reveals accelerating infrastructure risks from permafrost degradation in Northern Alaska

Corresponding Author: Dr Ziyi Wang

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Dr Wang,

Your manuscript titled "High-Resolution Geomechanical Modeling Reveals Accelerating Infrastructure Risks from Permafrost Degradation in Northern Alaska" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

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* Compellingly and thoroughly illustrate the physics-constrained geomechanical models for infrastructure risks assessment due to permafrost degradation.

*Transparently report the methodological validation, model's generalizability, and associated uncertainties.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look

forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Nandita Basu, PhD
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If a community resource is unavailable, data can be submitted to generalist repositories such as <https://figshare.com/> or <http://datadryad.org/> Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Overview and general recommendation:

This manuscript presents a comprehensive and methodologically rigorous assessment of infrastructure risks due to permafrost degradation across northern Alaska. By coupling a physics-based ground thermal model with geomechanics-informed projections of thaw settlement and long-term bearing capacity, the authors develop a high-resolution (30 m) modeling framework capable of quantifying the nonlinear and accelerating hazards that Arctic communities may face throughout the 21st century. The study provides valuable insight into the accelerating nature of thaw settlement and bearing capacity loss across both local and regional scales. The identification of a tipping point in the 2060s and the use of long-term strength for analysis are particularly novel. I think the manuscript will make a valuable and citable contribution and should be published. However, several issues should be addressed before the manuscript can be accepted. I recommend major revisions before publication.

Major comments:

The main innovation of this manuscript lies in the development of a new framework that integrates physics-constrained geotechnical models with a process-based ground thermal model to assess 21st-century changes in thaw settlement and the bearing capacity of civil infrastructure foundations at a 30-meter spatial resolution. A particularly notable aspect is the consideration of additional loads, and the use of long-term strength to quantify foundation bearing capacity in permafrost regions. However, the validation of the methodology needs to be strengthened. Currently, validation is only performed for undisturbed ground without additional loads from civil infrastructure. Is it possible to validate the impact of additional loads as well?

In addition, the study is limited to northern Alaska. Expanding the analysis to cover the entire state of Alaska would significantly increase its broader relevance and impact.

Specific comments:

- (1) Figure 1b and 1c: Would it be possible to show both the observations and simulations together for better comparison? Also, would it be more appropriate to use centimeters as the unit?
- (2) Page 4 Line 86: Is this referring to InSAR measurements? Please specify the data source and measurement method more clearly.
- (3) Page 5-6 Line 106-109: The content overlaps with the description in Figure 1 and can be integrated into the description in Figure 1.
- (4) Page 11 Line 225: It is necessary to provide a comparison of the differences in four community driving factors as a comparison on a local scale. Using only a regional scale graph (e.g., Supplementary Figs. 2 and 3) is insufficient.
- (5) Page 18, Lines 345 and 357: The concept of a "tipping point" is introduced somewhat abruptly. Please provide a clear definition of what is meant by "tipping point" in the context of this study. Additionally, please elaborate on why the identified threshold qualifies as a critical tipping point—specifically, what physical, geotechnical, or system-level changes occur beyond this threshold that justify its classification as a tipping point?
- (7) Page 19 Line 375: The threshold bearing capacity used to classify infrastructure as "at risk" are reasonable but somewhat arbitrary. Please provide a short justification or sensitivity discussion for these choices.
- (8) Method: The framework that integrates physics-constrained geotechnical models needs more detailed description and illustration.

Reviewer #2 (Remarks to the Author):

Wang et al. present a high-resolution (30 m) community-scale model to project geohazards and their implications for civil infrastructure on the Alaskan Arctic Coastal Plain (ACP) throughout the 21st century. Using this model, they provide spatiotemporal patterns of thaw subsidence, derive thaw settlement rates for the ACP with and without accounting for the loading effect of infrastructure, and quantify the projected loss of bearing capacity. In addition, they introduce a risk index to assess which types of civil infrastructure (e.g., buildings, roads, pipelines) are most at risk due to these geohazards (thaw settlement and loss of bearing capacity).

While there are models that quantify thaw settlement and loss of bearing capacity as a consequence of permafrost degradation (e.g., Streletskiy et al., 2023, DOI: 10.1088/1748-9326/acab18), to the best of my knowledge – and acknowledging that this is not my primary field – no study has applied a community-level model at such high spatial resolution. This approach not only provides communities with valuable information for decision-making, but also advances the state of the art by accounting for the loading effect of infrastructure on thaw settlement – an important factor, as additional stress from infrastructure accelerates settlement.

Overall, I find the study innovative and valuable. At the same time, certain sections of the manuscript could benefit from further clarification and additional contextual information. Providing these details would make the work more accessible to readers from different disciplinary backgrounds, including those without a strong engineering perspective, and thereby

broaden its impact.

Some more detailed comments, questions and suggestions concerning (i) use of consistent wording and terminology, (ii) figure improvements, and (iii) further clarifications can be found below.-

L 29-31: "Degrading permafrost also alters the physical and mechanical properties of frozen soil and leads to reduced long-term strength and lower bearing capacity" Here you already introduce long-term strength and bearing capacity. For better flow, I recommend introducing these in the third paragraph in which you describe the bearing capacity in detail.

L 31: "irreversible damages" Could you name some examples for these ?

L 40: "excess melt water" "excess ice melt water" or simply "this melt water" as you are already specifying it at the beginning of the sentence.

L 42: "excess melt" excess ice melt

L 52: "lifespan" Defined in how many years?

L 86: "hindcast-modeled" Please clarify in this paragraph that you are using your model for these hindcast simulations.

"Hindcast model" reads a bit too vague and conceals the vital information that this is done to validate the accuracy of your model.

L 86: "published data" Please add references.

L 89: "by 2015" If you are referring to a total subsidence of 8-15 cm from 2003 to 2015, you don't necessarily have to mention "by 2015" again. It is already clearly described.

L 91: "2000" Is there a reason you don't provide the total subsidence here for 1992-2000?

Figure 1: For b) and c) there is a mix up of symbols. In the text you mention measured total subsidence of 8-15 cm for Barrow, but label it S_e , which you describe as "simulated thaw subsidence (S_e)" in the text and Table 1 Suppl.

I suggest to define another symbol for "measured total subsidence" or state clearly when you are talking about modeled and measured total subsidence/ subsidence rates. The same goes for the rate.

Figure 1, caption: "Maps of simulated thaw subsidence under RCP8.5 for 2003-2015 (top) and 1992-2000 (bottom)" I suggest showing the hindcasted thaw subsidence (1a) in cm/yr, as you are comparing two heterogeneous time spans: Barrow shows 9 cm in 12 yrs (top) and 3 cm in 8 yrs.

L 108: "thaw subsidence" simulated thaw subsidence, see comment Figure 1. Staying consistent with your wording improves reader comprehension.

L 109: "Fig. 1c" The Figures 1a-c show parameters in m, but in the text you refer to them in cm. I would suggest to harmonize this.

L 115: "simulations under" [...] simulations with our model under [...]

L 172: "As the rate of permafrost table decline increases" suggestion: "As the permafrost table declines at an increasing rate [...]"

L 181-183: "Ice-rich permafrost typically has high short-term strength but gradually weakens over time under a constant loading, a phenomenon known as creep. As such, long-term creep failure is the primary mechanism of foundation failure in permafrost regions" This explanation would be helpful in the introduction. You could consider moving it.

L 185: "ultimate bearing capacity below 200 kPa" As a non-engineer, I am curious what this value implies. What type of infrastructure is especially at risk, if the bearing capacity falls below 200kPa? Buildings and bridges for sure, but what about power lines, roads? It would be nice to have a sort of reference here.

L 186: "low-latitude" "low-latitude" seems a bit misleading here. The ACP stretches approx. from 69 to 71 N. Maybe you could refer to it as the "southern part/border of the ACP" or "further south"?

L 192: "low-latitude" see comment above

L 210-212: "Previous projections for the North Slope Borough indicate that the mean bearing capacity of a pile foundation ranges from 1500 to 2500 kPa by 2040/26. Our projections align with this range under both RCP8.5 and RCP4.5 by the 2040s." Previous projections with different models? Could you say a bit more about this? Do you mean decreases to "values from 1500 to 2500 kPa"?

L 217-219: "Utqiagvik shows the lowest thaw settlement rate among the four communities, with mean thaw settlement reaching 0.13 m by the 2050s and 0.5 m by the 2090s (Fig. 5a)." Here you say "rate" - usually implying a measurement over time. But reading on and looking at figure 5, I assume you mean total/cumulative thaw settlement, compared to 2020?

L 220: "Point Lay exhibits the highest rate of thaw settlement, reaching 0.19 m by the 2050s and 2.7 m by the 2090s" see comment above: please clarify the value.

L 229: "(Supplementary Figs. 2 and 3)," Fig. 2 shows permafrost characteristics simulated for 2050 and 2090, which are active layer thickness, ground temperature and talik thickness. I strongly suggest to stay consistent when referring to these variables and not using the "deepening permafrost table" as an interchangeable term. Please also briefly explain their connection.

L 239: "Thaw settlement" Total thaw settlement

L 253-254: "The coastlines of Utqiagvik and Wainwright show increasing thaw settlement. In Point Lay, settlement intensifies along both the coastline and the Kokolik River delta." This is vital information. Is this discussed ?

L 264-266: "This increased thaw settlement by mid-century is primarily driven by the rapid thickening of the active layer near the coastlines and near the river deltas. By the 2090s, widespread talik development is projected across all four coastal communities." This is hard to see on the supplement figures with the current diverging color scheme and unharmonized color scale, see comments in Fig. 2 and 3 of the supplement.

L 267-270: "Extensive talik formation is expected in the northeastern part of Utqiagvik, where thermokarst lakes are present. Talik also develops extensively in northeastern Wainwright, along the Kokolik River delta in Point Lay, and in the

northwestern and southeastern coastal areas of Barter Island near Kaktovik." see comment above about visualization of these parameters

L 271: "heat storage effect of surface water and the presence of saline ground material" I think this statement would benefit from 1-2 brief explanatory sentences.

L 277: "with a" "translating to a" "representing a"?

L 314: "In Utqiagvik, higher bearing capacity is concentrated near the coastline. A similar spatial pattern is observed in Wainwright, where bearing capacity remains higher near the coastline and lower in inland areas by the 2050s" This is interesting, as Fig. 6 shows that these coastlines are experiencing higher thaw settlement values. Do you discuss this later?

L 328: "Similarly, higher bearing capacity is concentrated in the northeastern region of Barter Island in Kaktovik due to the relatively high θ_s " I suggest adding an additional figure to the supplement where you show the volumetric fraction of soil particles on a community level.

L 331: "rapid rise in mean annual ground temperatures" Point Lay is not visible on the regional maps in Fig. 2 Suppl. Further, I suggest implementing the proposed changes concerning the color scale and scheme to make this rapid rise more visible.

L 331: "2090s" refer to Fig. 2 in Suppl.

L 341: "21st century infrastructure risks under permafrost degradation" In this section I am missing information about the I_{risk} on the community level. Looking back to the spatial heterogeneities of thaw settlement in e.g. Wainwright or Point Lay, it would be interesting to see, whether these translate to spatial heterogeneities in the I_{risk} index. Would you be able to provide community level "hot spot" maps for the I_{risk} ?

L 349: "0.2 m settlement threshold" this thaw settlement threshold should be mentioned in the methods section. alongside the bearing capacity threshold you set.

"moderate stress conditions" meaning 15 and 30 kPa, respectively?

L 405: "previous studies" Please add references

"excess melt water" excess ice melt water

L 411-413: "Finally, our framework presents high-resolution 30-m hazard maps, substantially finer than the coarser-scale outputs (e.g., 1 km or 10 km grids)" Exactly! Show your I_{risk} on the community scale.

L 413: "previous studies" please add references

L 416: "hazards" geohazards - I suggest you stay consistent.

L 421: "permafrost dynamics" Or permafrost conditions/ characteristics, assuming you are referring to ground temperatures, talik and ALT thickness here? I suggest you stay consistent with your wording.

L 422-424: "Second, the time-dependent consolidation behavior of thawing soils and the time required to reach ultimate settlement are not considered in the current framework." That is interesting. Could you please say 1-2 sentences about what this entails?

L 425: "foundation types and dimensions" Could you say a few words about this? You look at pile foundations - which are other very typical foundation types and how do they compare in terms of bearing capacity and thaw settlement?

L 425-427: "Finally, in terms of subsurface features, the current framework does not model the development of cryopegs or account for the role of cryopegs in permafrost stability." I see that you explain some of these uncertainties, incl. the cryopegs, in your supplementary material. If you don't want to include it here - though in my opinion important - refer to it please.

L 432: "thaw settlement" cumulative, compared to 2020?

L 434: "underestimation of thaw settlement." I recommend underlining this with the value from your results.

L 450: "provides" provides

L 453: "200 cm" 200 cm below the ground surface

L 453: "The soil properties were derived using machine learning algorithms trained on global soil profiles." Could you please clarify if you applied these machine learning algorithms or SoilGrids? Further, it would be nice to have 1-2 sentences explaining the ML algorithm. And did you use the same ML algorithm for both properties?

L 454: "depth-weighted average" meaning shallow ground depths have more or less weight? Do you have reference for this?

L 457: "We used the ground ice map of northern Alaska in our assessment. The ground ice map illustrates the distribution of excess ground ice volume within the upper five meters of permafrost. Supplementary Fig. 2c shows the ground ice distribution across the Arctic Coastal Plain." This reads a bit misleading. The reference and Fig. 2 c Suppl. point to a massive ice map, based on ground ice, not a ground ice map itself. This is important as ground ice content can be far beyond 30% in this region, see e.g. <https://www.sciencedirect.com/science/article/pii/S0165232X12001644>? via=ihub#bi0005

The paragraph would benefit from a clarification, that you are showing a massive ice map - which is a kind of ground ice. I suggest to not use these two terms interchangeably, see e.g. <https://www.permafrost.org/publication/glossary-of-permafrost-and-related-ground-ice-terms/>.

It could also help to give an example. I assume by massive ice you are mostly referring to ice wedges?

Please also add the unit (here and) in the figure, volumetric fractions?

L 461-474: "permafrost temperature dynamics", "permafrost conditions", "permafrost dynamics", "permafrost conditions"

In this paragraph you use i) permafrost temperature dynamics, ii) permafrost conditions, and iii) permafrost dynamics to describe the permafrost characteristics (talik thickness, ALT thickness and ground temperature) shown in Fig. 2 Suppl. I would suggest to stay consistent with your wording for better reading comprehension, e.g. permafrost characteristics

L 478: "excess melt water" water from melting excess ice

L 489, 490: "excess melt water" excess ice melt water

L 505: "bulk density and specific gravity (based on soil types)" Could you provide or reference a table, in which one could look up these values per soil type shown in Fig 1. Suppl.?

L 509: "We" I suggest starting this paragraph with a title, e.g. "Assessment of permafrost compressibility properties"

L 509: "experimentally determined relationships to calculate C_c and e_{th} " Please add a reference for these.

L 523: "fall within typical ranges observed for ice-rich permafrost." Please provide some studies for reference here.

L 538: "higher-latitude" see comment above on "low-latitude". Maybe you could describe its as "northern" coastal regions or coastal regions between Utqiagvik and Kaktovik

L 553-554: "using specific gravity and foundation depth" are they defined somewhere?

L 569: "North Slope Science Initiative" reference?

L 571: "predefined threshold values." Please provide these values.

L 578-583: "To represent road-induced loading conditions, we select vertical stress values of 10, 30, and 50 kPa. These stress values capture the range from conservative far-field stress to localized peak stress typically observed under roadways. For pipelines, vertical stress values of 5, 15, and 25 kPa are used to reflect common pipeline-induced loading conditions. For buildings, infrastructure at high risk is determined based on the loss of bearing capacity exceeding a threshold value ($\theta_b \cdot c$) of 35%, 50%, and 65%." Looking at the Fig. 9, it becomes apparent that 10 & 50 kPa, 5 & 25 kPa, and 35 & 65% are the lower and upper bounds for your simulations. Please rewrite this paragraph to make this more clear. It is also important to mention here that the loss of bearing capacity is in comparison to the 2020s state. Further, there is an equation missing for the I_{risk} index.

L 585-586: "Design safety factors are the factors used in foundation designs; a higher factor represents a more conservative design applied in construction." This explanation might cut it too short. What does a "more conservative design" mean in this context? It remains unclear to me.

Supplementary Information

L 12: "covered with" characterized by

L 18: "degradation. These communities are Utqiagvik, Wainwright, Point Lay, and Kaktovik." add reference, e.g. Liew et al. 2022 10.3390/jmse10030422

L 34: "Excess ice content" Massive ice

L 40: "Supplementary Fig. 2" I would advise against using diverging colour bars in Fig. 2 (a,e, h) and Fig.3. (c,e) They introduce an artificial midpoint, confusing the reader and making it harder to interpret. In these cases, I suggest using sequential color bars - they are way more intuitive when showing strictly positive variables such as thickness, concentrations, intensities, etc.

Also, please normalize the min and max values of the color bars (d-i) for the reader to be able to compare the temperature and thickness (ALT+ talik) changes between 2050 and 2090.

Further, it seems that Point Lay is not visible on the maps. You could consider shifting the extent to the west to show the community.

L 42: "Only massive ice content is 43 considered in excess ice." please adapt the subfigure title accordingly

L 53: "Supplementary Fig. 3" I would advise against using diverging colour bars in Fig. 2 (a,e, h) and Fig.3. (c,e) They introduce an artificial midpoint, confusing the reader and making it harder to interpret. In these cases, I suggest using sequential color bars - they are way more intuitive when showing strictly positive variables such as thickness, concentrations, intensities, etc.

L 66: "Supplementary Fig. 4" Please harmonize the color scale (uniform min and max values across all time steps) for better comparability.

Again, I would advise against using divergent color bars. See comment in Fig. 2 and 3 Suppl.

L 88: "Supplementary Fig. 6" The flow chart could benefit from some restructuring. In its current version, it looks like "Extract raster maps" is done parallel to retrieving areas where the bearing capacity and thaw settlement reach a certain threshold. The same goes for the next steps.

Maybe you could make it clearer that these are subsequent steps. It might also be nice to include the threshold values or at least specify them in the text.

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Version 1:

Decision Letter:

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Dear Dr Wang,

Your manuscript titled "High-Resolution Geomechanical Modeling Reveals Accelerating Infrastructure Risks from Permafrost Degradation in Northern Alaska" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised (particularly from Reviewer 2). We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Nandita Basu, PhD
Consulting Editor, Communications Earth & Environment
Associate Editor, Communications Sustainability
Nature Portfolio

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Please refer to our data policies at <http://www.nature.com/authors/policies/availability.html>.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have addressed all of my previous concerns. I only have a minor suggestion: label the y-axes of all figures with full words (such as thaw subsidence for Fig. 1b) instead of abbreviations (such as Se for Fig. 1) to improve readability.

Reviewer #2 (Remarks to the Author):

Wang et al. have addressed the suggestions of both reviewers and improved the manuscript by providing additional information and clarifications, thus enhancing its accessibility to readers from different backgrounds compared to the initial submission.

The authors also added a section on the validation of the modeling framework which was based on comparing the model output with InSAR measurements derived from Liu et al.. In its current form, however, I see one considerable issue. The manuscript states that the model framework was validated using only one location south of Prudhoe Bay, at a pipeline access road connecting the Dalton Highway and the TAPS. While this location is certainly urban-disturbed, I argue that it may not adequately represent the infrastructure load typical of communities with a denser network of buildings and roads. Further, only the simulated thaw settlement rates were validated, not the thaw subsidence rates. Does Liu et al. also provide measurements for thaw subsidence?

I was also wondering, about the size of the validation study region (Fig. 10). The scale bar is missing, but I assume the width is less than 1 km? What was the spatial resolution of the validation InSAR dataset, 10-15 m? At this resolution, could some pixels smooth over road embankments or include undisturbed tundra, potentially leading to an underestimation of the thaw settlement rates?

If feasible, I suggest extending the validation of the model with (InSAR) measurements from representative community locations, and also include a validation of thaw subsidence, to support the robustness of the model framework. Otherwise, a thorough discussion of these limitations would be important.

I am still somewhat uncertain about your use of the terms thaw subsidence and thaw settlement. In your introduction you state that "thaw settlement consists of volume reduction from both excess ice melt water drainage AND stress-induced pore

water drainage" (stress from infrastructure), while thaw subsidence only describes ground surface changes "due to the drainage of excess ice melt water". While you follow this definition in comparing subsidence ($\Delta q = 0 \text{ kPa}$) and settlement ($\Delta q = 100 \text{ kPa}$) in Figure 2, you later refer to thaw settlement only (e.g. Figure 3). I would suggest to check your entire manuscript again if you used them consistently.

Further in-line comments are provided below:

In line comments:

Line 33-35: "Widespread loss of function of residential buildings, roads, and utility lines due to degrading permafrost-induced thermokarst and thaw subsidence has been documented in Point Lay, Alaska 11." Is there a reason why you don't also reference Liew et al. 2022 (doi: <https://doi.org/10.3390/jmse10030422>) here? The surveys on civil infrastructure damages were in the same communities as in your study.

L 116, Fig. 1 b, c: - according to the S_{obs} range, the values lie within 5-13 cm per year for Barrow? Is this correct or is there a mismatch between the y axis labels and the actual data?

Line 498: "permafrost conditions": "permafrost characteristics"

Line 515: "excess melt water": excess ice melt water

Line 552: "mean annual thaw settlement rate ($\dot{S}$)" in line 557 further down, you say "median" values. Could you please clarify which one it is?

Line 557: " $\Delta q = 0$ and 100 ": $\Delta q = 0$ and $\Delta q = 100$

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Version 2:

Decision Letter:

<*** REMEMBER TO ATTACH REVISIONS CHECKLIST (WORD)***>

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Dear Dr Wang,

Your manuscript titled "High-Resolution Geomechanical Modeling Reveals Accelerating Infrastructure Risks from Permafrost Degradation in Northern Alaska" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Nandita Basu, PhD
Consulting Editor, Communications Earth & Environment
Associate Editor, Communications Sustainability
Nature Portfolio

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

The authors have addressed all my previous concerns and included a statement on the limitation of the model focusing on infrastructure loading from pipelines and roads over full community layouts.

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**High-Resolution Geomechanical Modeling Reveals Accelerating Infrastructure Risks from
Permafrost Degradation in Northern Alaska**

Dear Editor and Reviewers:

We thank the editor and reviewers for the review report. We sincerely appreciate your time and constructive comments and suggestions to improve this manuscript. A revised manuscript with tracked changes and a clean version without tracked changes are submitted. Replies to the comments are presented as follows.

Reviewer #1:

General comment

This manuscript presents a comprehensive and methodologically rigorous assessment of infrastructure risks due to permafrost degradation across northern Alaska. By coupling a physics-based ground thermal model with geomechanics-informed projections of thaw settlement and long-term bearing capacity, the authors develop a high-resolution (30 m) modeling framework capable of quantifying the nonlinear and accelerating hazards that Arctic communities may face throughout the 21st century. The study provides valuable insight into the accelerating nature of thaw settlement and bearing capacity loss across both local and regional scales. The identification of a tipping point in the 2060s and the use of long-term strength for analysis are particularly novel. I think the manuscript will make a valuable and citable contribution and should be published.

However, several issues should be addressed before the manuscript can be accepted. I recommend major revisions before publication.

Response: We thank the reviewer for recognizing our research on the geomechanical modeling of degrading permafrost-induced infrastructure risk. We also appreciate the constructive feedback from the reviewer. Below, we outline how we addressed these concerns.

Major comments

The main innovation of this manuscript lies in the development of a new framework that integrates physics-constrained geotechnical models with a process-based ground thermal model to assess 21st-century changes in thaw settlement and the bearing capacity of civil infrastructure foundations at a 30-meter spatial resolution. A particularly notable aspect is the consideration of additional loads, and the use of long-term strength to quantify foundation bearing capacity in permafrost regions. However, the validation of the methodology needs to be strengthened. Currently, validation is only performed for undisturbed ground without additional loads from civil infrastructure. Is it possible to validate the impact of additional loads as well?

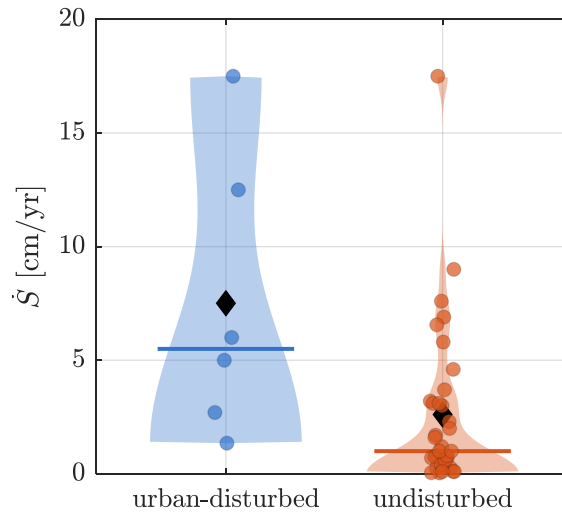
In addition, the study is limited to northern Alaska. Expanding the analysis to cover the entire state of Alaska would significantly increase its broader relevance and impact.

Response: We thank the reviewer for pointing out the significance of a more thorough validation of the model considering additional loads from civil infrastructure. Please find below how we addressed your comments:

1. Evidence of higher thaw subsidence rate under urban-disturbed regions.

We reanalyzed published data on observed permafrost thaw subsidence rates ($\dot{S}_{obs}$) from low-lying regions in Alaska, Arctic Canada, and Russia (Creel et al. 2024) to compare rates

between urban-disturbed and undisturbed regions (Supplementary Fig. 15). An increase in the thaw subsidence rate is evident in urban-disturbed regions, with a mean $\dot{S}_{obs}$ of 7.51 cm/yr compared with a mean $\dot{S}_{obs}$ of 2.61 cm/yr in undisturbed regions. The median $\dot{S}_{obs}$ for urban-disturbed regions is 5.5 cm/yr, compared with a median $\dot{S}_{obs}$ of 1.0 cm/yr in undisturbed regions. This increased thaw subsidence rate may be attributed to the additional loading from civil infrastructure in urban-disturbed permafrost regions. The additional load further decreases the void ratio of the thawing soil, leading to an increasing settlement rate.



Supplementary Fig. 15 Comparison of observations for urban-disturbed vs undisturbed thaw subsidence rate. The black dots represent mean value. The horizontal lines denote median value. The collected data are adapted from Creel et al. (2024) under a Creative Commons license (CC BY 4.0).

The above discussion on the evidence of higher thaw subsidence rates in urban-disturbed regions has been added to Section 5 of the **Supplementary Information** and referenced in the **main text** (lines 510-511).

2. Validation of the proposed thaw settlement model considering infrastructure loading effect.

We validate our modeling framework that considers the infrastructure loading effect by hindcasting thaw settlement and comparing the mean annual thaw settlement rate ($\bar{\dot{S}}$) with InSAR observations in an urban-disturbed region on the Alaska Arctic Coastal Plain about 14 km south of Deadhorse (Liu et al. 2015). The soil compressibility properties are calculated using equations (7) and (8). The simulations are performed for the period 2006-2010 under the RCP8.5 climate forcing scenario.

The simulated median $\bar{\dot{S}}$ values within the study region are 0.28 and 2.3 cm/yr for $\Delta q = 0$ and 100 kPa, respectively. The InSAR observations of $\dot{S}_{obs}$ (2.7 ± 0.7 cm/yr for 2006-2010) (Liu et al. 2015) are shown as a shaded gray region (Fig. 10). The hindcast simulations from our model that considers the infrastructure loading effect closely align with the InSAR observations in the urban-disturbed region. In contrast, simulations that do not consider this loading effect underestimate $\bar{\dot{S}}$. These results validate the proposed framework that accounts for the loading effect of civil infrastructure.

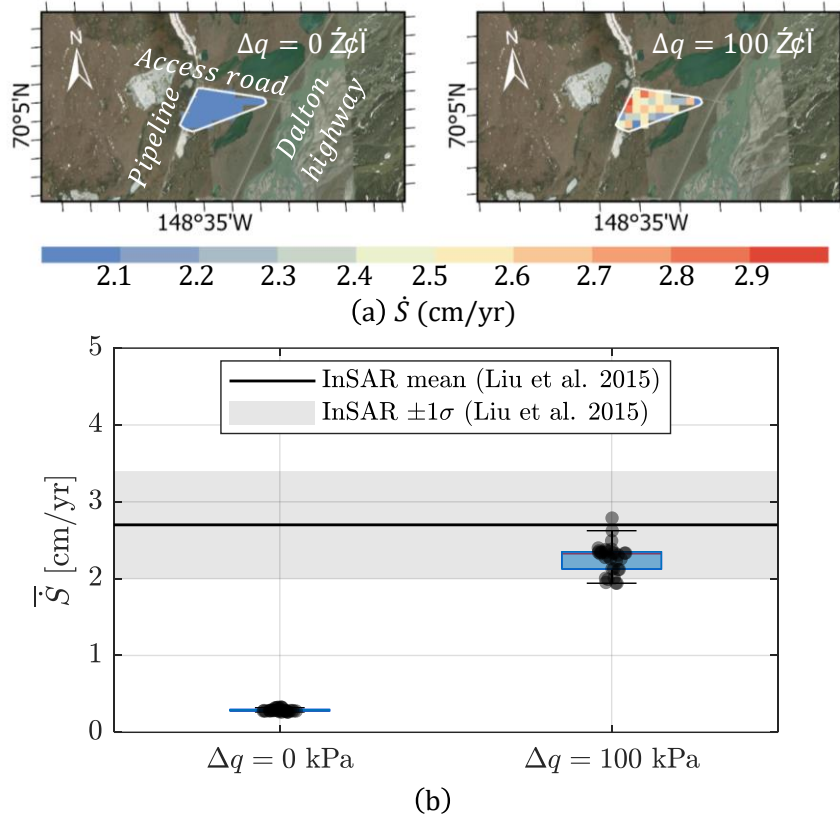


Fig. 10 Validation of the thaw settlement framework considering infrastructure loading. a, Spatial patterns of simulated mean annual thaw settlement rate ($\bar{S}$) for $\Delta q = 0$ and 100 kPa under RCP8.5 during 2006-2010 (study region outlined in white). A vertical stress of 100 kPa approximates the combined loading from the pipeline, access road, and the Dalton Highway. **b,** Box plots of $\bar{S}$ under the two loading conditions within the study region. The shaded region denotes InSAR observed thaw settlement rates for 2006-2010 (Liu et al. 2015). Each point along the box plot represents an individual pixel within the study region.

We have added the above discussion on the validation of the thaw settlement model considering the infrastructure loading effect to the **Methods** section of the main text (**lines 549-572**), highlighted in blue in the tracked-changes version.

3. Model generality

We thank the reviewer for their comment regarding expanding the analysis to the entire Alaska. We agree that statewide coverage would broaden relevance. However, our aim in this paper is to demonstrate a general, physics-constrained framework at high spatial resolution (30 m) for Northern Alaska communities. This framework can be applied to other regions and generalized to various permafrost conditions. In this framework, the thaw settlement model accounts for the compressibility of thawing ice-rich soils (Wang et al. 2025), and the bearing capacity model relies on creep behavior and temperature-dependent long-term strength (Wang et al. 2026). These are physical processes that apply to all permafrost conditions and are not site-specific. Please refer to our response to your final comments for a detailed description of the framework. Extending the framework to other regions of Alaska or the pan-Arctic is feasible but requires region-specific calibration of the model parameters rather than new theoretical development.

Please see the added text based on the above discussion in the **Discussion section of the main text (lines 440–445)**, highlighted in blue in the tracked-changes version of the manuscript.

[References]

- [1] Liu, L., Schaefer, K. M., Chen, A. C., Gusmeroli, A., Zebker, H. A. & Zhang, T. Remote sensing measurements of thermokarst subsidence using InSAR. *J. Geophys. Res. Earth Surf.* **120**, 1935–1948 (2015); <https://doi.org/10.1002/2015JF003599>.
- [2] Wang, Z., Xiao, M., Bray, M., Nicolsky, D. & Ji, X. Creep deformation and long-term strength of ice-rich permafrost in Northern Alaska. *J. Geotech. Geoenviron. Eng.* **152**, 04025161 (2026); <https://doi.org/10.1061/JGGEFK.GTENG-13324>.

[3] Wang, Z. & Xiao, M. Large strain thaw consolidation model for ice-rich fine-grained permafrost considering adsorptive and capillary unfrozen water and secondary compression. *Cold Reg. Sci. Technol.* **2025**, 104714 (2025b); <https://doi.org/10.1016/j.coldregions.2025.104714>.

Specific comments

(1) Figure 1b and 1c: Would it be possible to show both the observations and simulations together for better comparison? Also, would it be more appropriate to use centimeters as the unit?

Response: Thank you for this comment. Figures 1b and 1c have been revised to show the observations ($\dot{S}_{obs}$; shaded gray regions) and simulations ($\dot{S}_e$) together for better comparison. The unit scale has been changed from meters to centimeters. In addition, Figure 1a now presents the mean annual thaw subsidence rate ($\bar{\dot{S}}_e$, cm/yr) rather than thaw subsidence (S_e), as the simulations were conducted over different time periods in the two regions. Figure 1c shows box plots at two-year intervals to maintain consistency with Figure 1b and keep the figure clear.

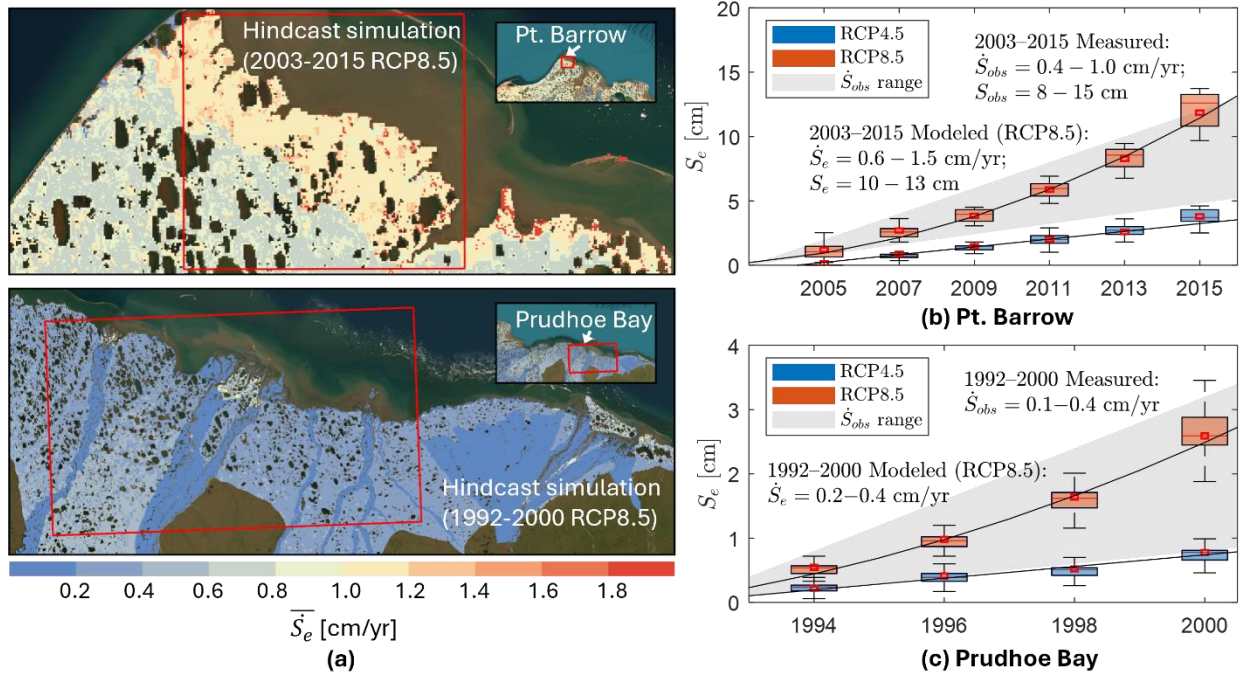


Fig. 1 Spatial patterns and temporal trends of hindcast-modeled thaw subsidence. a, Maps of simulated mean annual thaw subsidence rate ($\bar{S}_e$) under RCP8.5 for 2003-2015 (top) and 1992-2000 (bottom). *Inserted* maps highlight the study regions near Pt. Barrow and Prudhoe Bay used for model comparison. **The study regions are marked by red boxes.**

Subsidence is estimated based on permafrost table changes and excess ice content (equation (2)). **b, c,** Box plots of simulated thaw subsidence in two-year intervals near Point Barrow from 2005 to 2015 and near Prudhoe Bay from 1992 to 2000. Box plots show the median (center line), mean (square), interquartile range (25th to 75th percentile, box), and whiskers extending to 1.5 times the interquartile range. Polynomial regression is applied to fit the mean values. Only positive pixel values are considered. The model simulates thaw subsidence under conditions where additional vertical stress $\Delta q = 0$ kPa, representing undisturbed ground without civil infrastructure to match the conditions under which in-situ measurements and InSAR observations were taken.

Please see the revised figure in lines 113-127, highlighted in blue in the manuscript with tracked changes.

(2) Page 4 Line 86: Is this referring to InSAR measurements? Please specify the data source and measurement method more clearly.

Response: Thank you for your comments. This paragraph has been revised as follows:

“We hindcast thaw subsidence rates ($\dot{S}_e$) with our modeling framework and compare $\dot{S}_e$ against in-situ measurements³⁴ and InSAR observations³⁵ from two regions: near Point Barrow and Prudhoe Bay (Fig. 1). In-situ measurements near Point Barrow indicate observed thaw subsidence rates ($\dot{S}_{obs}$) ranging from 0.4 cm to 1.0 cm per year between 2003 and 2015, with a total subsidence (S_{obs}) of 8 cm to 15 cm³⁴. In Prudhoe Bay, InSAR observations recorded thaw subsidence rates ranging from 0.1 cm to 0.4 cm per year from 1992 to 2000³⁵.”

Please see the revised texts in **lines 91-96**, highlighted in blue in the manuscript with tracked changes.

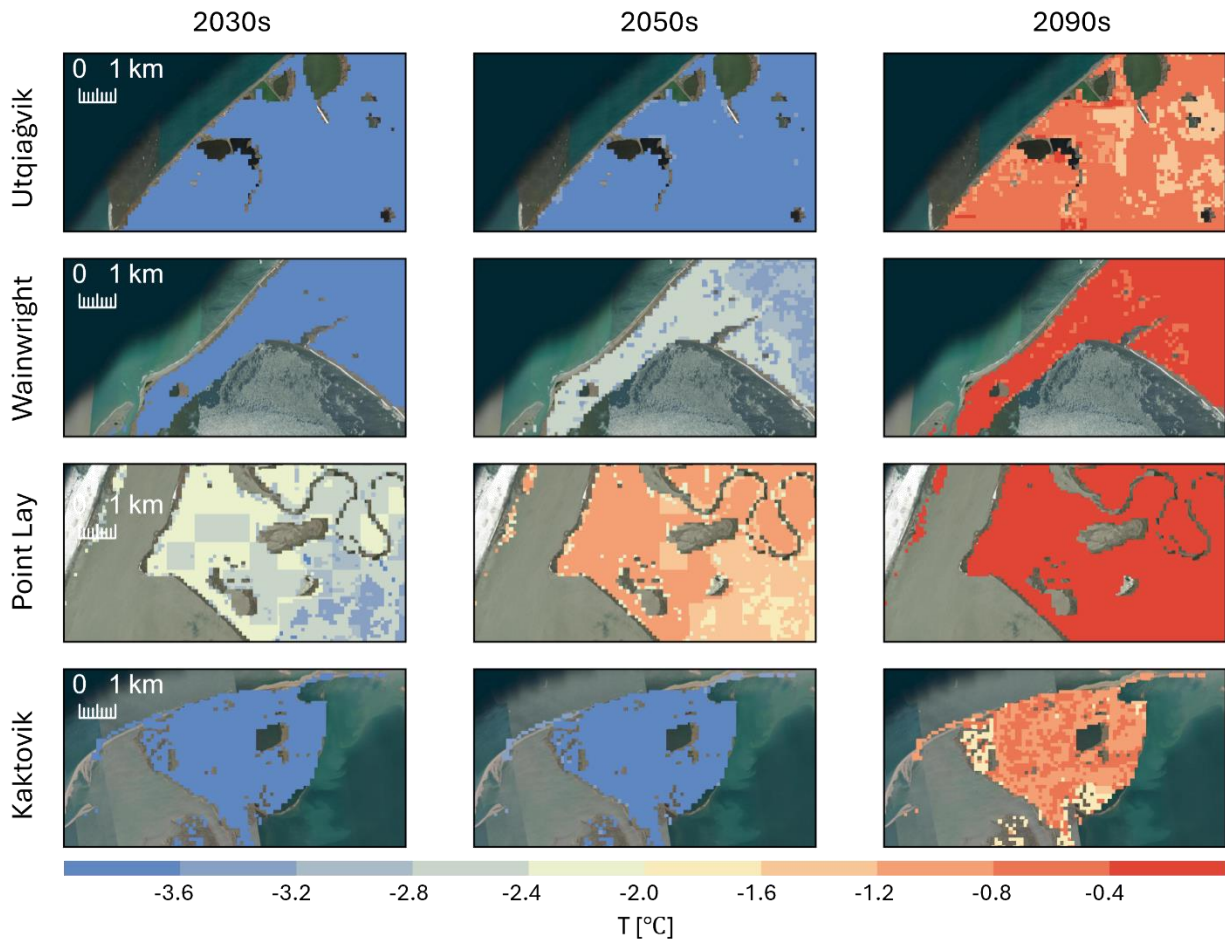
(3) Page 5-6 Line 106-109: The content overlaps with the description in Figure 1 and can be integrated into the description in Figure 1.

Response: Thank you for this comment. This sentence has been incorporated into the caption of Figure 1. Please see the revised Figure 1 caption provided in response to Specific Comment 1 above.

(4) Page 11 Line 225: It is necessary to provide a comparison of the differences in four community driving factors as a comparison on a local scale. Using only a regional scale graph (e.g., Supplementary Figs. 2 and 3) is insufficient.

Response: Thank you for this comment. We have provided local-scale driving factors, including active layer thickness (**Supplementary Fig. 3**), talik thickness (**Supplementary Fig. 4**), soil properties (i.e., thawed void ratio, compressibility index, and volumetric soil particle fraction) (**Supplementary Fig. 5**), and ground temperature (**Supplementary Fig. 6**)—to support our argument in the main text. Please see the local-scale ground temperature figure below. To keep

our response concise, please refer to the response to **Reviewer 2's comments on L253, L328**, or to the **Supplementary Information** for the other figures.



Supplementary Fig. 6 Spatial patterns of projected 21st century ground temperature in four coastal communities in northern Alaska. Projected ground temperature for the next decade (2030s), mid-century (2050s), and end-of-century (2090s) in: Utqiagvik (first row), Wainwright (second row), Point Lay (third row), and Kaktovik (fourth row). Ground temperature is calculated under RCP8.5 climate forcing.

(5) Page 18, Lines 345 and 357: The concept of a "tipping point" is introduced somewhat abruptly. Please provide a clear definition of what is meant by "tipping point" in the context of this study. Additionally, please elaborate on why the identified threshold qualifies as a critical tipping point—

specifically, what physical, geotechnical, or system-level changes occur beyond this threshold that justify its classification as a tipping point?

Response: We appreciate the opportunity to clarify the terminology. Quoting Lenton et al. (2019)’s description of climate tipping points: “In climate science, a tipping point is a critical threshold that, when crossed, leads to large, accelerating, and often irreversible changes in the climate system.” A tipping point is, therefore, formally a state threshold beyond which the system reorganizes, often abruptly (Armstrong McKay et al. 2022).

In our study, we define a time window that reflects the accelerating infrastructure risk that places most civil infrastructure at risk in northern Alaska. The underlying triggers are likewise state-based thresholds, i.e., (i) cumulative thaw settlement $\geq$ thaw settlement threshold (S^*) and/or (ii) bearing capacity reduction $\geq$ bearing capacity reduction threshold (θ_{bc}^*). However, different types of infrastructure cross these state thresholds in different years due to spatial variability in soils, excess ice, and ground thermal regimes. The regional response emerges as a concentrated time interval during which many infrastructures first exceed their thresholds. Therefore, we rephrased the previous term “tipping point” as the “transition window,” which is more accurate in the context of this work. Here, the “transition” marks a change from low to high rates of growth in the at-risk fraction, and from a minority at risk to a state in which most of the infrastructure ($\geq 50\%$) is classified as at risk.

Consequently, we define the “transition window (2060s-2080s)” as the period during which the infrastructure at-risk fraction (I_{risk}) exhibits its highest decadal rate of increase and rises to $\geq 50\%$ under various loading conditions and design safety factors.

The revised term and its definition have been shown in **line 19, line 354, line 366, and line 459**, highlighted in blue in the manuscript with tracked changes.

For the physical and geotechnical rationale of this transition, three processes contribute to the sharp increase in the at-risk infrastructure fraction (I_{risk}) during the 2060s-2080s:

1. Thermal and settlement accumulation: The long-term effects of climate warming drive a continuous increase in ground temperature, active layer thickness, and talik development. Within the 2060s-2080s timeframe, the cumulative thaw settlement or loss of bearing capacity of most infrastructure first crosses the threshold values, marking the sharp increase in the at-risk fraction.
2. Nonlinear permafrost table response: The decline of permafrost table due to increasing air temperature is highly nonlinear. Assuming the soil properties are homogeneous and independent of temperature, the active layer thickness can be estimated using the Stefan relation, which relates it to the square root of the thawing index. However, as air temperature continues to rise, the annual freezing index can no longer offset the annual thawing index. Subsequent summers then begin from a warmer baseline (Farquharson et al. 2022). The combined thickness (ALT and TT) integrates the net annual heat surplus and produces an accelerating trajectory of thaw settlement. This acceleration results in most infrastructure crossing the threshold during the 2060s-2080s.
3. Strength degradation with temperature: The decrease in the long-term strength of permafrost with increasing temperature is highly nonlinear (Wang et al. 2026). As subfreezing temperatures rise toward the melting point, a large amount of unfrozen water appears. The creep rate of frozen soil increases sharply with temperature (Glen's flow law), resulting in a drastic decrease in bearing capacity. Consequently, most infrastructure crosses the threshold during the 2060s-2080s.

We also modified the in-text explanation of the occurrence of “transition window”:

The original texts **lines 357-360**: “The tipping point around the 2060s results from the long-term effects of climate change on permafrost. By the 2060s, large areas exhibit increased thaw settlement and a decline in bearing capacity beyond critical thresholds. Geohazards exceeding these thresholds place most infrastructure on the Arctic Coastal Plain at high risk and mark the tipping point.”

The modified texts **lines 366-370**: “The transition window (2060s-2080s) results from (1) long-term climate warming that drives a continuous increase in thaw settlement and bearing capacity loss, causing most infrastructure to cross the risk threshold; (2) accelerating thaw settlement due to the nonlinear response of the active layer and talik thickness to climate warming (Farquharson et al. 2022); and (3) accelerating bearing capacity loss due to increasing creep rates as the ground temperature gets warmer (Wang et al. 2026).”

References

- [1] Lenton, T. M. et al. Climate tipping points—too risky to bet against. *Nature* 575, 592–595 (2019). <https://doi.org/10.1038/d41586-019-03595-0>.
- [2] Armstrong McKay, D. I. et al. Exceeding 1.5 °C global warming could trigger multiple climate tipping points. *Science* 377, eabn7950 (2022). <https://doi.org/10.1126/science.abn7950>.
- [3] Farquharson, L. M., Romanovsky, V. E., Kholodov, A. & Nicolsky, D. Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. *Nat. Geosci.* **15**, 475–481 (2022). <https://doi.org/10.1038/s41561-022-00952-z>.
- [3] Wang, Z., Xiao, M., Bray, M., Nicolsky, D. & Ji, X. Creep deformation and long-term strength of ice-rich permafrost in Northern Alaska. *J. Geotech. Geoenviron. Eng.* **152**, 04025161 (2026); <https://doi.org/10.1061/JGGEFK.GTENG-13324>.

(6) Page 19 Line 375: The threshold bearing capacity used to classify infrastructure as “at risk” are reasonable but somewhat arbitrary. Please provide a short justification or sensitivity discussion for these choices.

Response: Thank you for your comments. We address your comments as follows:

Quoting Andersland and Ladanyi (2003): “In unfrozen soils, the value of the design factor of safety of 2 or 3 is usually adopted, which is also applicable to short-term failure of footings in frozen soils. According to Vialov (1959) and Tsytovich (1975), when the long-term bearing capacity corresponding to the service life of the structure is divided by a factor of safety equal to 1.5, failure will not occur.”

Therefore, we selected three design factors of safety—1.6, 2.0, and 3.0—in this study to represent the general design criteria for civil infrastructure in cold regions engineering. Accordingly, these three design factors of safety correspond to bearing capacity reductions of 35%, 50%, and 60%, assuming that infrastructure failure occurs when the factor of safety drops below 1. We added a detailed description regarding the relationship between the factor of safety and bearing capacity reduction (**lines 642-649**). We modified the figure captions as follows:

The original texts **lines 375-377**: “The threshold bearing capacity reduction (θ_{bc}^*) values correspond to design safety factors of 1.6, 2.0, and 3.0, respectively, assuming infrastructure damage occurs when the bearing capacity falls below a safety factor of 1.”

The revised texts **lines 386-388**: “The threshold bearing capacity reduction (θ_{bc}^*) values correspond to design safety factors of 1.6, 2.0, and 3.0, respectively, assuming infrastructure damage occurs when the bearing capacity falls below a safety factor of 1. The selected design

safety factors reflect general design criteria where design safety factors range from 1.5 to 3.0 in cold regions engineering (Andersland and Ladanyi 2003).”

(7) Method: The framework that integrates physics-constrained geotechnical models needs more detailed description and illustration.

Response: Thank you for your comments. We provided a more detailed description and illustration of the geotechnical models as follows:

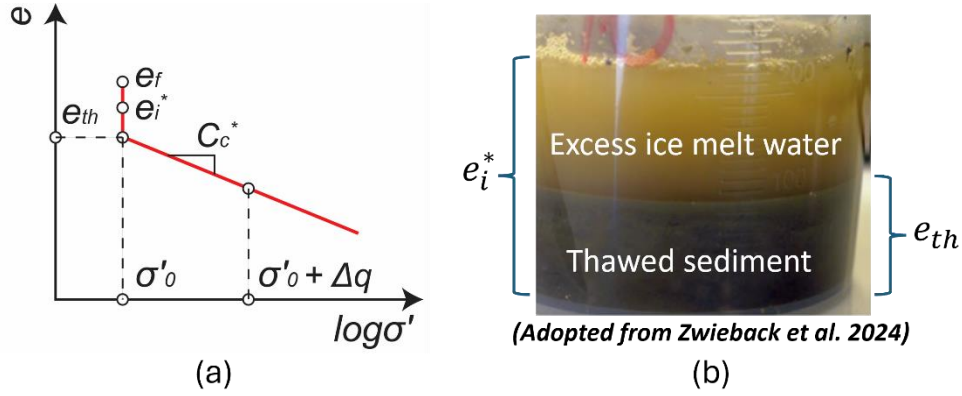
The geotechnical model used in this study simulates thaw settlement by considering three physical processes—the decrease in void ratio that occurs when melting water of excess ice drains, the phase changes, and vertical stress increases. Supplementary Fig. 16a illustrates the compressibility behavior of thawing ice-rich permafrost, and Supplementary Fig. 16b shows thawed permafrost with excess ice melt water (above) and thawed sediment (below). The initial frozen void ratio (e_f) of the permafrost first decreases to the initial thawed void ratio (e_i^*) due to the phase change. Then, the excess ice melt water drains out, causing the void ratio to decrease further to the thawed void ratio (e_{th}). The relationship between the decrease of void ratio from e_f to e_{th} and the volumetric excess ice content is shown in equation (S1).

$$\frac{e_f - e_{th}}{1 + e_f} = \theta_{excess,ice} \quad (S1)$$

Therefore, thaw subsidence induced by drainage of excess ice melt water can be calculated as

$$S_e = \Delta Z_{ALT+TT} \frac{e_f - e_{th}}{1 + e_f} = \Delta Z_{ALT+TT} \theta_{excess,ice} \quad (S2)$$

Starting from thawed sediment after the drainage of excess ice melt water, the increase in effective stress (σ') in the soil leads to a further decrease in the void ratio, following a linear relationship between void ratio and $\log \sigma'$ (Wang et al. 2025). This volume change depends on the magnitude of the increase in vertical stress (Δq), and the associated settlement is expressed by equation (3) in the main text.

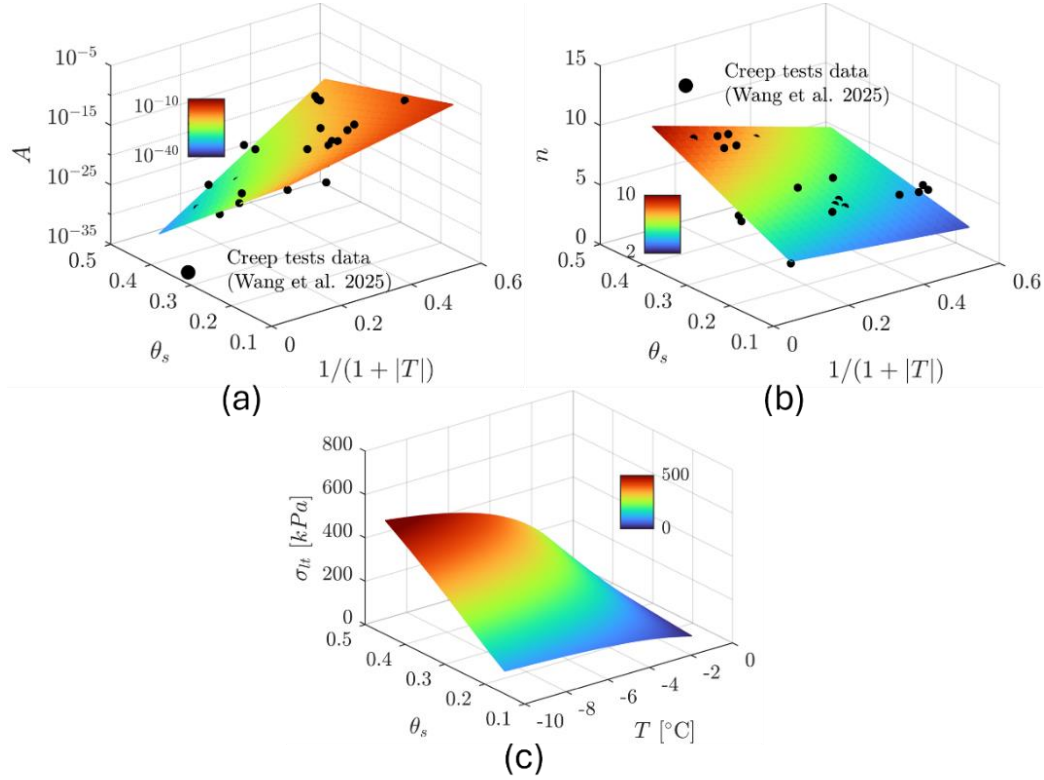


Supplementary Fig. 16 Behavior of thawing ice-rich permafrost. **a**, Constitutive relationship between void ratio and effective stress. **b**, thawed sediment and excess ice melt water. Panel (b) adapted from Zwieback et al. (2024) under a Creative Commons license (CC BY 4.0).

The bearing capacity was calculated based on the creep rate of the permafrost because creep failure is the most common failure mode in cold regions engineering (Andersland and Ladanyi 2003). Creep of permafrost is a physical process in which permafrost undergoes slow deformation under persistent stress (e.g., civil infrastructure loading). The creep rate in this study is calculated using a modified Glen's flow law embedded with empirically derived relationships based on laboratory data (Supplementary Fig. 17a,b). The modified Glen's flow law, which considers the interactive effects of the volumetric soil particle fraction and temperature, is expressed as follows (Wang et al. 2026).

$$\dot{\epsilon} = \exp(-14.1 - 154.1\theta_s + \frac{186.9}{1 + |T|}\theta_s) \sigma^{1.4+20.1\theta_s - \frac{19.6}{1+|T|}\theta_s} \quad (S3)$$

Eq. (S3) was developed based on retrieved permafrost samples from the Arctic Coastal Plain, with θ_s ranging between 0.15 and 0.45 (Wang et al. 2026). The model can be applied across the study region because the calibrated ranges cover the θ_s variations on the Arctic Coastal Plain (see Supplementary Fig. 7c). The bearing capacity of the foundation should, therefore, be calculated based on the long-term strength. Long-term strength is the stress within which the creep deformation-induced strain remains below the failure strain during the service life of the civil infrastructure. Substitute Eq. S3 into Eq. 9 in the main text, the variation of long-term strength (σ_{lt}) with θ_s and T can be calculated and shown in Supplementary Fig. 17c.



Supplementary Fig. 17 Creep behavior and long-term strength of ice-rich permafrost. a,b, Variations of Glen's flow law parameters with volumetric soil particle fraction and temperature. **c,** Variations of long-term strength with volumetric soil particle fraction and temperature. Creep test data and regression are adopted from Wang et al. (2026).

A new section called “**6 Physics-constrained geotechnical model**” have been added in the Supplements **lines 216-255**, based the above description and illustration of the physics-constrained geotechnical model.

The following texts has been added to the “Method” section in the main text:

“See Section 6 of the Supplementary Information for the detailed description and illustration of the physics-constrained geotechnical model for simulating thaw settlement and bearing capacity.”

Please see added texts in the **lines 583-585**, highlighted in blue in the manuscript with tracked changes.

[References]

- [1] Zwieback, S. et al. Excess ground ice profiles in continuous permafrost mapped from InSAR subsidence. *Water Resour. Res.* 60, e2023WR035331 (2024). <https://doi.org/10.1029/2023WR035331>.
- [2] Wang, Z., Xiao, M., Bray, M., Nicolsky, D. & Ji, X. Creep deformation and long-term strength of ice-rich permafrost in Northern Alaska. *J. Geotech. Geoenviron. Eng.* 152, 04025161 (2026); <https://doi.org/10.1061/JGGEFK.GTENG-13324>.
- [3] Wang, Z. & Xiao, M. Large strain thaw consolidation model for ice-rich fine-grained permafrost considering adsorptive and capillary unfrozen water and secondary compression. *Cold Reg. Sci. Technol.* 2025, 104714 (2025); <https://doi.org/10.1016/j.coldregions.2025.104714>.

Reviewer #2:

General comment

Wang et al. present a high-resolution (30 m) community-scale model to project geohazards and their implications for civil infrastructure on the Alaskan Arctic Coastal Plain (ACP) throughout the 21st century. Using this model, they provide spatiotemporal patterns of thaw subsidence, derive thaw settlement rates for the ACP with and without accounting for the loading effect of infrastructure, and quantify the projected loss of bearing capacity. In addition, they introduce a risk index to assess which types of civil infrastructure (e.g., buildings, roads, pipelines) are most at risk due to these geohazards (thaw settlement and loss of bearing capacity).

While there are models that quantify thaw settlement and loss of bearing capacity as a consequence of permafrost degradation (e.g., Streletskiy et al., 2023, DOI: 10.1088/1748-9326/acab18), to the best of my knowledge – and acknowledging that this is not my primary field – no study has applied a community-level model at such high spatial resolution. This approach not only provides communities with valuable information for decision-making, but also advances the state of the art by accounting for the loading effect of infrastructure on thaw settlement – an important factor, as additional stress from infrastructure accelerates settlement.

Overall, I find the study innovative and valuable. At the same time, certain sections of the manuscript could benefit from further clarification and additional contextual information. Providing these details would make the work more accessible to readers from different disciplinary backgrounds, including those without a strong engineering perspective, and thereby broaden its impact.

Some more detailed comments, questions and suggestions concerning (i) use of consistent wording and terminology, (ii) figure improvements, and (iii) further clarifications can be found below.

Response: We appreciate the reviewer's constructive summary and detailed suggestions. Please find below how we have incorporated your suggestions and comments.

Specific comments

L29-31: “Degrading permafrost also alters the physical and mechanical properties of frozen soil and leads to reduced long-term strength and lower bearing capacity” Here you already introduce long-term strength and bearing capacity. For better flow, I recommend introducing these in the third paragraph in which you describe the bearing capacity in detail.

Response: We thank the reviewer for this suggestion. This sentence has been moved to the beginning of the third paragraph, with minor revisions to improve the flow:

“Degrading permafrost alters the physical and mechanical properties of frozen soil and leads to reduced bearing capacity.”

The revised text has been moved to **lines 51-52**, highlighted in blue in the manuscript with tracked changes.

L 31: “irreversible damages” Could you name some examples for these?

Response: Thank you for this comment. The following examples are added:

“For example, cracking along the Alaska Highway due to thaw subsidence has been frequently observed in Yukon, Canada (Calmels et al. 2015). Widespread loss of function of

residential buildings, roads, and utility lines due to degrading permafrost-induced thermokarst and thaw subsidence has been documented in Point Lay, Alaska (Jones et al. 2025).”

The added texts are shown in **lines 31-34**, highlighted in blue in the manuscript with tracked changes.

[References]

[1] Jones, B. M. et al. Climate change and infrastructure development drive ice-rich permafrost thaw in Point Lay (Kali), Alaska. *Environ. Res. Ecol.* **4**, 035003 (2025).

[2] Calmels, F. et al. *Vulnerability of the North Alaska Highway to Permafrost Thaw: A Field Guide and Data Synthesis* (ed. Halladay, P.) (Yukon Research Center, 2015).

L 40: “excess melt water” "excess ice melt water" or simply "this melt water" as you are already specifying it at the beginning of the sentence.

Response: Changed to “excess ice melt water.”

Please see the changed term in **line 41**, highlighted in blue in the manuscript with tracked changes.

L 42: “excess melt” excess ice melt

Response: Changed to “excess ice melt water.”

Please see the changed term in **line 43**, highlighted in blue in the manuscript with tracked changes.

L 52: “lifespan” Defined in how many years?

Response: The lifespan is the design service life of an infrastructure, e.g., 50 years (Andersland and Ladanyi 2003). Here we added an example of 50 years into the origin texts:

“Long-term strength is defined as the maximum stress a soil can sustain without reaching a non-attenuating creep over the lifespan (e.g., a 50-year service life; Andersland and Ladanyi, 2003) of engineering structure.”

Please see the revised texts in **lines 56-58**, highlighted in blue in the manuscript with tracked changes.

L 86: “hindcast-modeled” Please clarify in this paragraph that you are using your model for these hindcast simulations. "Hindcast model" reads a bit too vague and conceals the vital information that this is done to validate the accuracy of your model.

Response: Changed to “We hindcast thaw subsidence rates ($\dot{S}_e$) with our modeling framework and compare $\dot{S}_e$ against in-situ measurements (Streletskiy et al. 2017) and InSAR observations (Liu et al. 2010) from two regions: near Point Barrow and Prudhoe Bay (Fig. 1).”

Please see the revised texts in **lines 91-93**, highlighted in blue in the manuscript with tracked changes.

L 86: “published data” Please add references.

Response: References have been added as shown in above texts.

L 89: “by 2015” If you are referring to a total subsidence of 8-15 cm from 2003 to 2015, you don't necessarily have to mention "by 2015" again. It is already clearly described.

Response: Thank you for this comment. We have deleted “by 2015” from the original sentence.

L 91: “2000” Is there a reason you don't provide the total subsidence here for 1992-2000?

Response: Thank you for pointing this out. Liu et al. (2010) report only annual thaw subsidence rates for 1992–2000, without cumulative totals. To avoid introducing unverified assumptions, we report rates only.

Figure 1: For b) and c) there is a mix up of symbols. In the text you mention measured total subsidence of 8-15 cm for Barrow, but label it S_e , which you describe as "simulated thaw subsidence (S_e)" in the text and Table 1 Suppl.

I suggest to define another symbol for "measured total subsidence" or state clearly when you are talking about modeled and measured total subsidence/subsidence rates. The same goes for the rate.

Response: Thank you for this comment. We have defined another symbol S_{obs} for the measured total subsidence and $\dot{S}_{obs}$ for the measured total subsidence rate in Figs. 1b and c.

Figure 1, caption: “Maps of simulated thaw subsidence under RCP8.5 for 2003-2015 (top) and 1992-2000 (bottom)” I suggest showing the hindcasted thaw subsidence (1a) in cm/yr, as you are comparing two heterogeneous time spans: Barrow shows 9 cm in 12 yrs (top) and 3 cm in 8 yrs.

Response: Thank you for this comment. We have modified Fig. 1a by showing mean annual thaw subsidence rate $\bar{S}_e$ (cm/yr). The regional map has zoomed in to a finer scale. Figures 1b and 1c have been revised to show the observations ($\dot{S}_{obs}$; shaded gray regions) and simulations ($\dot{S}_e$) together for better comparison. Figure 1c shows box plots at two-year intervals to maintain consistency with Figure 1b and keep the figure clear. The revised Fig. 1 is shown below:

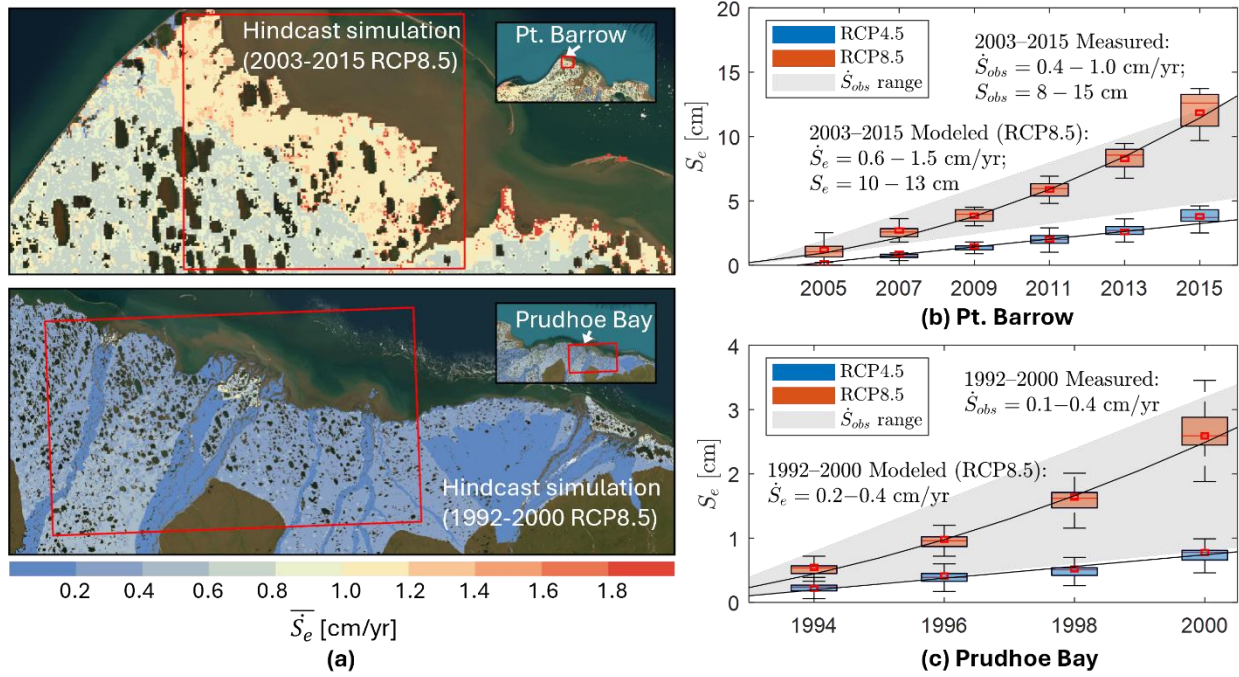


Fig. 1 Spatial patterns and temporal trends of hindcast-modeled thaw subsidence. a, Maps of simulated mean annual thaw subsidence rate ($\bar{S}_e$) under RCP8.5 for 2003-2015 (top) and 1992-2000 (bottom). *Inserted* maps highlight the study regions near Pt. Barrow and Prudhoe Bay used for model comparison. *The study regions are marked by red boxes.*

Subsidence is estimated based on permafrost table changes and excess ice content (equation (2)). **b, c,** Box plots of simulated thaw subsidence in two-year intervals near Point Barrow from 2005 to 2015 and near Prudhoe Bay from 1992 to 2000. Box plots show the median (center line), mean (square), interquartile range (25th to 75th percentile, box), and whiskers extending to 1.5 times the interquartile range. Polynomial regression is applied to fit the mean values. Only positive pixel values are considered. The model simulates thaw subsidence under conditions where additional vertical stress $\Delta q = 0$ kPa, representing undisturbed ground without civil infrastructure to match the conditions under which in-situ measurements and InSAR observations were taken.

Please see the revised figure in lines 113-127, highlighted in blue in the manuscript with tracked changes.

L 108: “thaw subsidence” simulated thaw subsidence, see comment Figure 1. Staying consistent with your wording improves reader comprehension.

Response: We thank the reviewer for the suggestion. “thaw subsidence” has been changed to “simulated thaw subsidence.”

L 109: “Fig. 1c” The Figures 1a-c show parameters in m, but in the text you refer to them in cm. I would suggest to harmonize this.

Response: We revised Figure 1a–c, the caption, and the corresponding text to use centimeters (cm) consistently.

L 115: “simulations under” [...] simulations with our model under [...]

Response: The original text has been revised as:

“Hindcast simulations with our model under RCP8.5 closely align with in-situ measurements and InSAR observations.”

Please see the revised texts in **line 103**, highlighted in blue in the manuscript with tracked changes.

L 172: “As the rate of permafrost table decline increases” suggestion: "As the permafrost table declines at an increasing rate [...]"

Response: The original text has been revised as:

“This compression-induced thaw strain accelerates ground deformation as the permafrost table declines at an increasing rate over time.”

Please see the revised texts in **lines 167-169**, highlighted in blue in the manuscript with tracked changes.

L 181-183: “Ice-rich permafrost typically has high short-term strength but gradually weakens over time under a constant loading, a phenomenon known as creep. As such, long-term creep failure is the primary mechanism of foundation failure in permafrost regions” This explanation would be helpful in the introduction. You could consider moving it.

Response: Thank you for your comments. This explanation has been moved to the third paragraph of the introduction.

Please see the moved texts in **lines 53-56**, highlighted in blue in the manuscript with tracked changes.

L 185: “ultimate bearing capacity below 200 kPa” As a non-engineer, I am curious what this value implies. What type of infrastructure is especially at risk, if the bearing capacity falls below 200kPa? Buildings and bridges for sure, but what about power lines, roads? It would be nice to have a sort of reference here.

Response: We appreciate the reviewer for this comment. In our manuscript, 200 kPa is reported only to indicate the upper bound of modeled bearing capacity across the Arctic Coastal Plain by the 2090s—it is not used as a design threshold nor to infer infrastructure-specific risk. Our risk assessment is performed separately in “21st century infrastructure risks under permafrost degradation,” where we quantify risk via bearing capacity reduction, rather than by comparing to an absolute value such as 200 kPa.

L 186: “low-latitude” "low-latitude" seems a bit misleading here. The ACP stretches approx. from 69 to 71 N. Maybe you could refer to it as the "southern part/border of the ACP" or "further south"?

Response: Thank you for this comment. The term “low-latitude areas” has been revised as “southern border of the Arctic Coastal Plain” The revised sentence is shown as:

“A significant portion of the region near Point Lay and the southern border of the Arctic Coastal Plain experiences a complete loss of bearing capacity due to mean annual ground temperatures rising above 0°C.”

Please see the revised texts in **lines 189-191**, highlighted in blue in the manuscript with tracked changes.

L 192: “low-latitude” see comment above

Response: Thank you for this comment. The term “low-latitude areas” has been revised as “southern border of the Arctic Coastal Plain.”

L 210-212: “Previous projections for the North Slope Borough indicate that the mean bearing capacity of a pile foundation ranges from 1500 to 2500 kPa by 2040²⁶. Our projections align with this range under both RCP8.5 and RCP4.5 by the 2040s.” Previous projections with different models? Could you say a bit more about this? Do you mean decreases to "values from 1500 to 2500 kPa"?

Response: We thank the reviewer for this comment. Here, the mentioned previous projection used an empirical model that related soil type and ice content to bearing capacity (Streletskiy et al. 2012). Therefore, it used a different model. We intend to compare our modeling results with the previous projections. Here, the range from 1500 to 2500 kPa represents the spatial variation in bearing capacity across the Arctic Coastal Plain. We have revised this sentence to clarify the reference to the previous projections that used a different model, as follows:

“Previous projections using a different model for the North Slope Borough indicate that the mean bearing capacity of pile foundations ranges from 1500 to 2500 kPa by 2040.”

Please see the revised texts in **lines 213-215**, highlighted in blue in the manuscript with tracked changes.

L 217-219: “Utqiagvik shows the lowest thaw settlement rate among the four communities, with mean thaw settlement reaching 0.13 m by the 2050s and 0.5 m by the 2090s (Fig. 5a).” Here you say "rate" - usually implying a measurement over time. But reading on and looking at figure 5, I assume you mean total/cumulative thaw settlement, compared to 2020?

Response: We thank the reviewer for this careful reading. The term “thaw settlement rate” has been revised to “cumulative thaw settlement”.

Please see the revised texts in **line 222**, highlighted in blue in the manuscript with tracked changes.

L 220: “Point Lay exhibits the highest rate of thaw settlement, reaching 0.19 m by the 2050s and 2.7 m by the 2090s” see comment above: please clarify the value.

Response: The term “rate of thaw settlement” has been changed to “cumulative thaw settlement.”

Please see the revised texts in **line 225**, highlighted in blue in the manuscript with tracked changes.

L 229: “(Supplementary Figs. 2 and 3),” Fig. 2 shows permafrost characteristics simulated for 2050 and 2090, which are active layer thickness, ground temperature and talik thickness. I strongly

suggest to stay consistent when referring to these variables and not using the "deepening permafrost table" as an interchangeable term. Please also briefly explain their connection.

Response: Thank you for catching this unclear phrasing. We revised the term “deepening permafrost table” to the “permafrost table decline”. Specifically, when no talik is present, depth to the permafrost table is the active layer thickness. Once a Sub-aerial talik forms, the depth to the permafrost table equals to the summation of active layer thickness and talik thickness.

Please see the revised term in **line 232**, highlighted in blue in the manuscript with tracked changes.

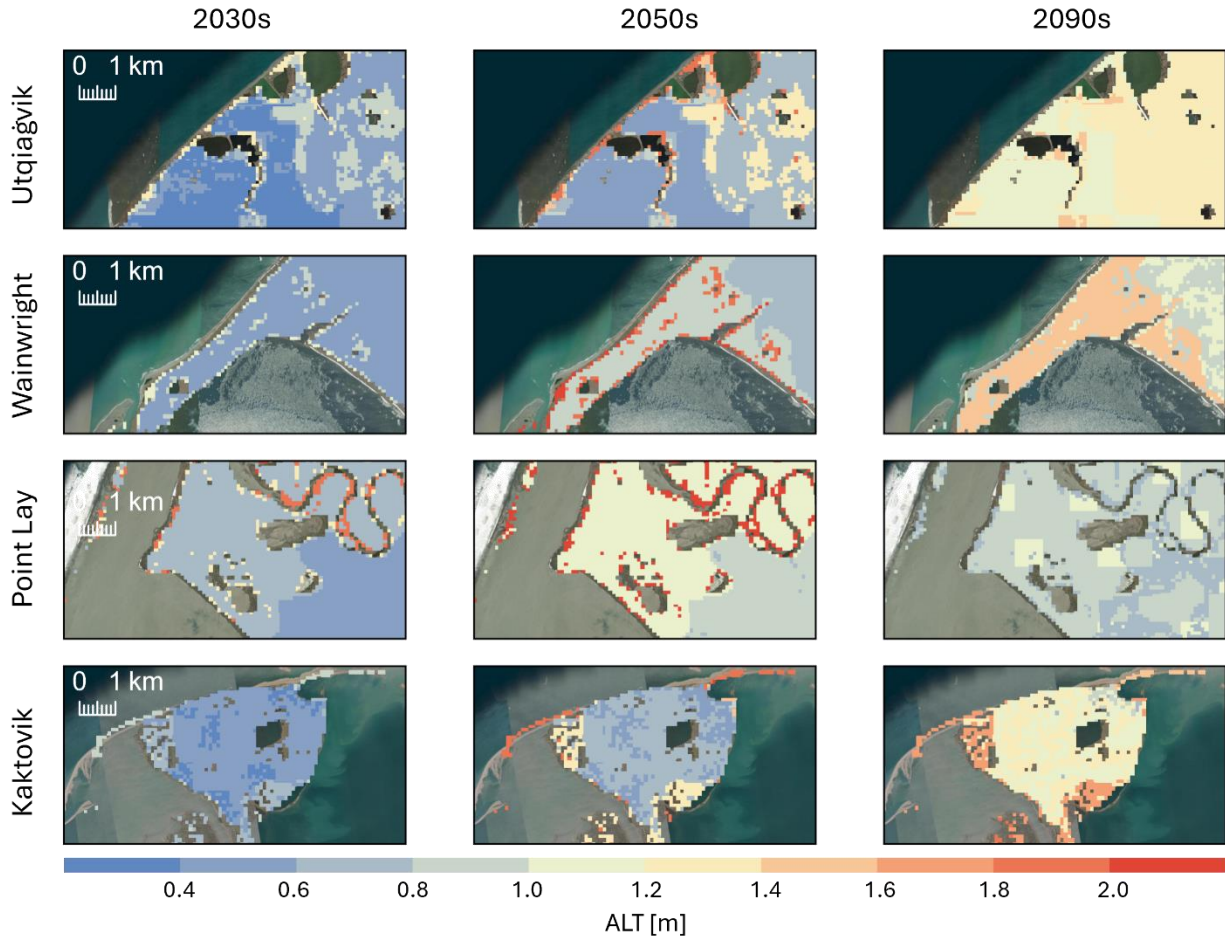
L 239: “Thaw settlement” Total thaw settlement

Response: We revised the term “Thaw settlement” to “Total thaw settlement.”

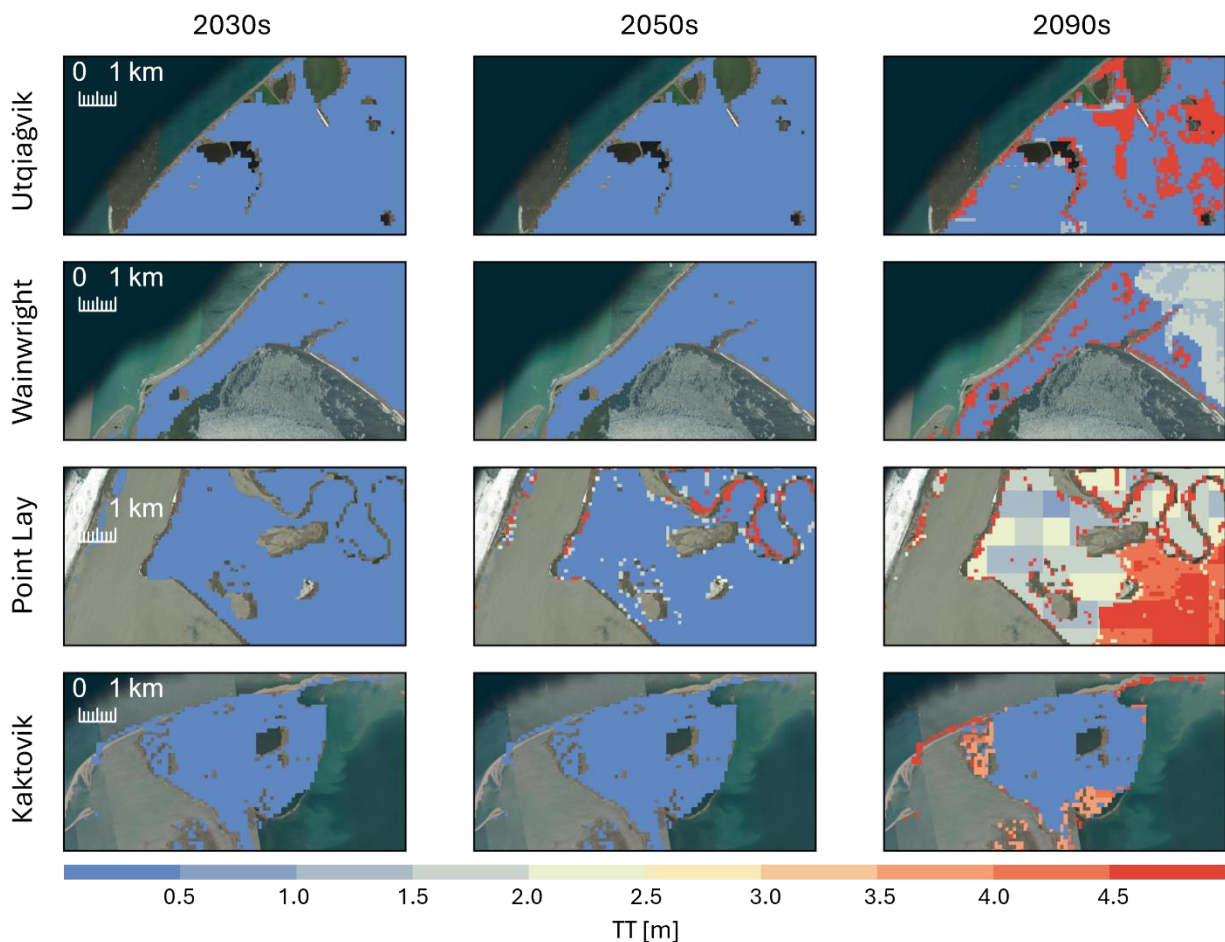
Please see the revised term in **line 243**, highlighted in blue in the manuscript with tracked changes.

L 253-254: “The coastlines of Utqiagvik and Wainwright show increasing thaw settlement. In Point Lay, settlement intensifies along both the coastline and the Kokolik River delta.” This is vital information. Is this discussed?

Response: We have discussed the driving factors behind the modeled thaw settlement increase in those regions in the following paragraph in the main text (**lines 268-278**). This increased thaw settlement by mid-century is primarily driven by the rapid thickening of the active layer and the development of taliks near the coastlines and river deltas. Please refer to **Supplementary Figs. 3 and 4** for details on the local-scale ALT and TT thicknesses as shown below:



Supplementary Fig. 3 Spatial patterns of projected 21st century active layer thickness in four coastal communities in northern Alaska. Projected active layer thickness for the next decade (2030s), mid-century (2050s), and end-of-century (2090s) in: Utqiagvik (first row), Wainwright (second row), Point Lay (third row), and Kaktovik (fourth row). Active layer thickness is calculated under RCP8.5 climate forcing.



Supplementary Fig. 4 Spatial patterns of projected 21st century talik thickness in four coastal communities in northern Alaska. Projected talik thickness for the next decade (2030s), mid-century (2050s), and end-of-century (2090s) in: Utqiagvik (first row), Wainwright (second row), Point Lay (third row), and Kaktovik (fourth row). Talik thickness is calculated under RCP8.5 climate forcing.

L 264-266: “This increased thaw settlement by mid-century is primarily driven by the rapid thickening of the active layer near the coastlines and near the river deltas. By the 2090s, widespread talik development is projected across all four coastal communities.” This is hard to see on the supplement figures with the current diverging color scheme and unharmonized color scale, see comments in Fig. 2 and 3 of the supplement.

Response: Thank you. We have provided local-scale active layer thickness and talik thickness across all four communities at different timeframes in the Supplementary Information to support this section (**Supplementary Figs. 3 and 4**). The previous regional-scale Supplementary Figs. 2 and 3 have also been revised based on your comments. Please see the revised regional-scale ALT and TT in response to the comments for the **Supplementary Figures for L40, L53, and L66** below.

L 267-270: “Extensive talik formation is expected in the northeastern part of Utqiagvik, where thermokarst lakes are present. Talik also develops extensively in northeastern Wainwright, along the Kokolik River delta in Point Lay, and in the northwestern and southeastern coastal areas of Barter Island near Kaktovik.” see comment above about visualization of these parameters

Response: Please see the previously provided local-scale talik and active layer thicknesses for the four communities.

L 271: “heat storage effect of surface water and the presence of saline ground material” I think this statement would benefit from 1-2 brief explanatory sentences.

Response: Surface water store summer heat and, during winter freeze-up, release latent heat that delays and limits winter refreeze. Consequently, the depth of potential thaw may gradually exceed the depth of potential freeze in those regions, leaving a perennially thawed layer (talik) (Farquharson et al. 2022). The presence of saline ground material depresses the freezing point and maintains higher unfrozen water content. This sentence has been revised as:

“Talik formation in these regions is attributed to the heat storage effect of surface water and the presence of saline ground material. Surface water can act as an insulator and delay winter

freeze of the subsoil. Consequently, the depth of potential thaw may gradually exceed the depth of potential freeze, resulting in the development of a talik.”

Please see the added texts in **lines 276-278**, highlighted in blue in the manuscript with tracked changes.

L 277: “with a” "translating to a"/ "representing a"?

Response: Thank you for this comment. We revised the phrase “with a” to “translating to a.”

Please see the revised phrase in **line 284**, highlighted in blue in the manuscript with tracked changes.

L 314: “In Utqiagvik, higher bearing capacity is concentrated near the coastline. A similar spatial pattern is observed in Wainwright, where bearing capacity remains higher near the coastline and lower in inland areas by the 2050s” This is interesting, as Fig. 6 shows that these coastlines are experiencing higher thaw settlement values. Do you discuss this later?

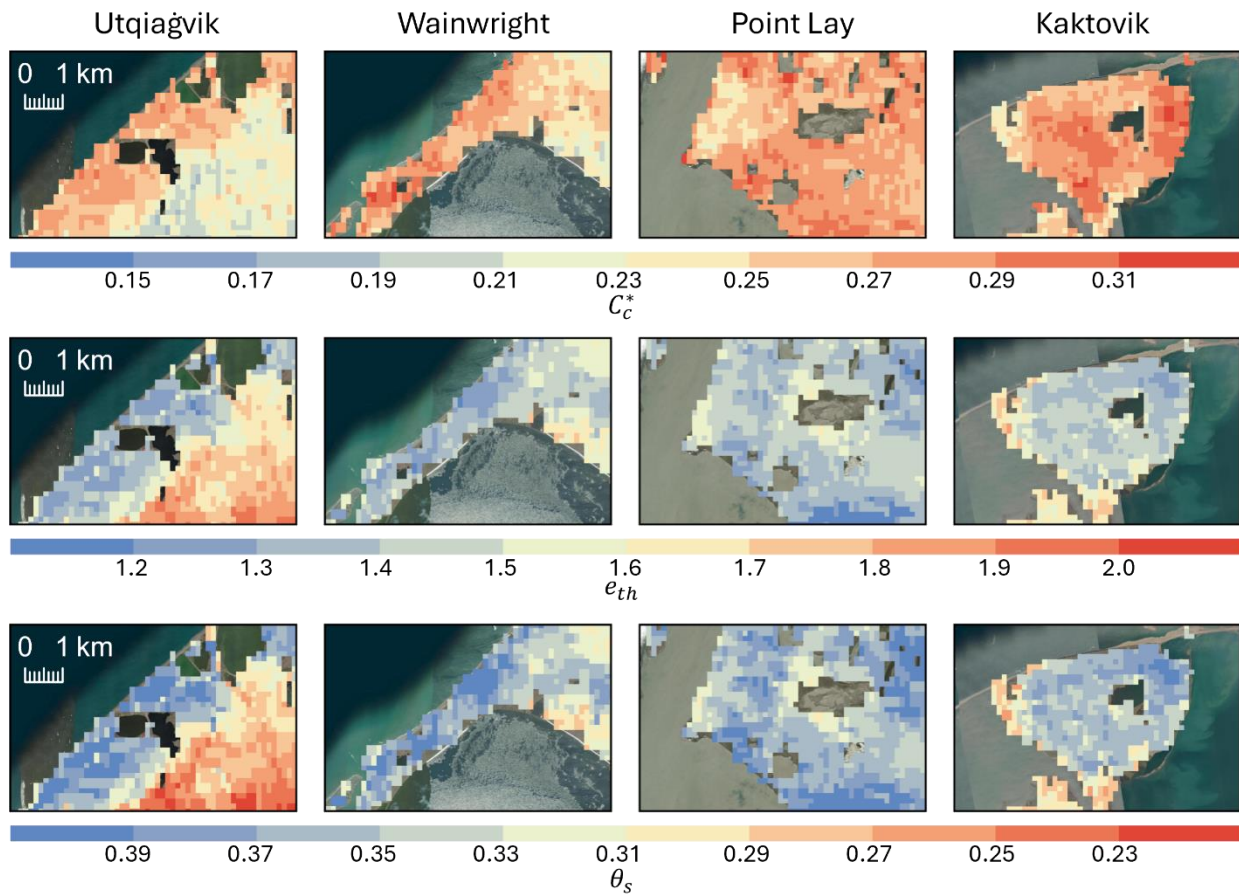
Response: We thank the reviewer for the comment. In Fig. 6, the higher thaw settlement is mainly concentrated along the coastlines and river channels. However, in Fig. 7, the higher bearing capacity actually covers the entire coastal regions of Utqiagvik and Wainwright. To improve clarity, this sentence has been revised as follows:

“Higher bearing capacity covers the coastal region of Utqiagvik. A similar spatial pattern is observed in Wainwright, where bearing capacity remains higher in the coastal region by the 2050s.”

Please see the revised phrase in **lines 320-322**, highlighted in blue in the manuscript with tracked changes.

L 328: “Similarly, higher bearing capacity is concentrated in the northeastern region of Barter Island in Kaktovik due to the relatively high θ_s ” I suggest adding an additional figure to the supplement where you show the volumetric fraction of soil particles on a community level.

Response: Thank you for your suggestions. Please see the added Supplementary Fig. 5, which presents the local-scale volumetric soil particle fraction, to support our argument.



Supplementary Fig. 5 Spatial patterns of soil properties in four coastal communities in northern Alaska. Shown are the soil compressibility index, thawed void ratio, and volumetric soil particle fraction for Utqiagvik (first column), Wainwright (second column), Point Lay (third column), and Kaktovik (fourth column).

Please see added Supplementary Fig. 5 in the **Supplementary Information** and reference in the main text in **line 233** and **line 338**.

L 331: “rapid rise in mean annual ground temperatures” Point Lay is not visible on the regional maps in Fig. 2 Suppl. Further, I suggest implementing the proposed changes concerning the color scale and scheme to make this rapid rise more visible.

Response: Please see the revised regional-scale ground temperature map in response to the comment regarding **Supplementary Fig. 2** for **L40** below.

L 331: “2090s” refer to Fig. 2 in Suppl.

Response: Thank you. We have referred to the local-scale ground temperature map (Supplementary Fig. 6) and soil properties map (Supplementary Fig. 5) in the Supplementary Information here.

Please see added reference in **line 338**, highlighted in blue in the tracked changes manuscript.

L 341: “21st century infrastructure risks under permafrost degradation” In this section I am missing information about the I_{risk} on the community level. Looking back to the spatial heterogeneities of thaw settlement in e.g. Wainwright or Point Lay, it would be interesting to see, whether these translate to spatial heterogeneities in the I_{risk} index. Would you be able to provide community level "hot spot" maps for the I_{risk} ?

Response: We thank the reviewer regarding the lack of detailed information in the original manuscript to quantify I_{risk} . We addressed your comments as follows:

I_{risk} is defined as the areas (for buildings) or lengths (for roads and pipelines) of civil infrastructure characterized as at-risk divided by the total areas or lengths of the civil infrastructure.

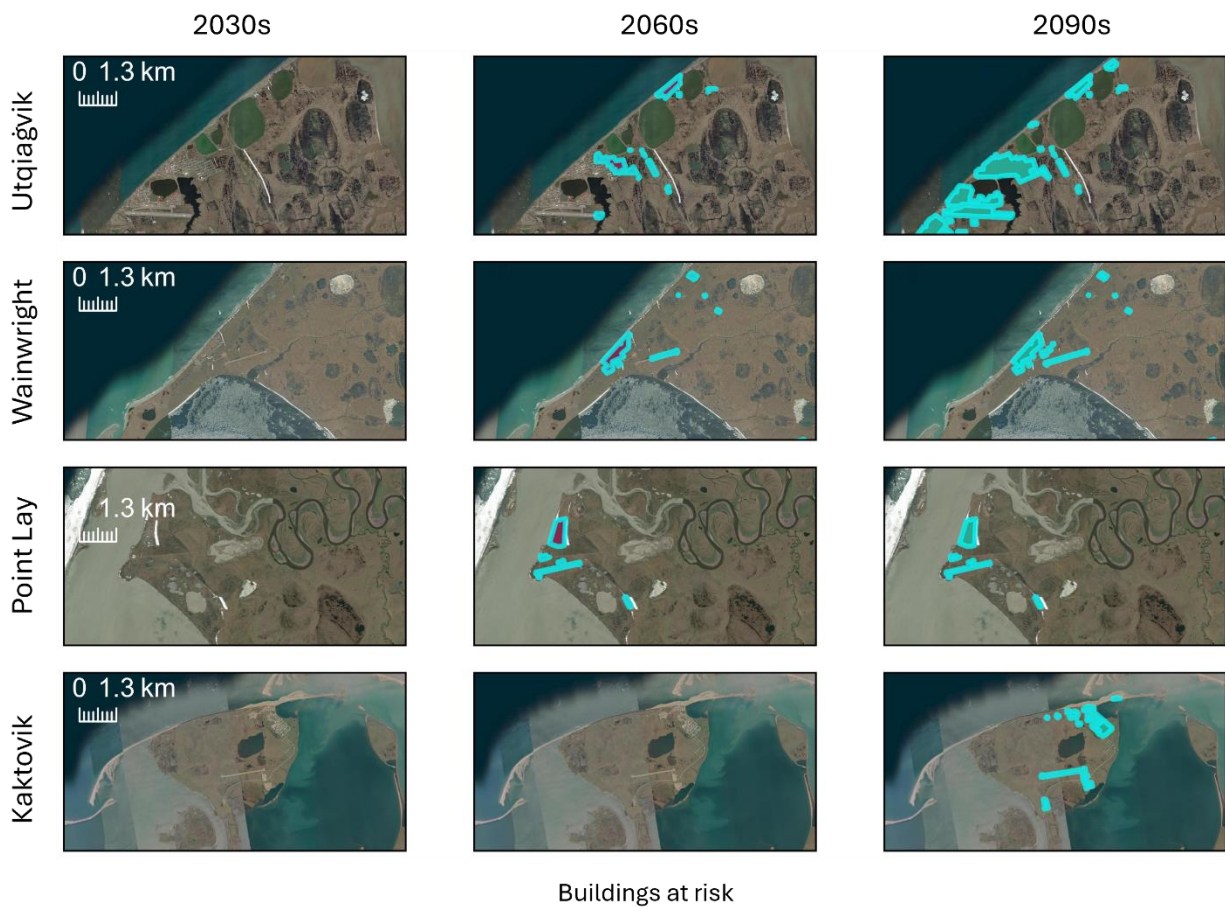
The mathematical expression for I_{risk} is defined as:

$$I_{risk} = \frac{\sum_{i=1}^N m_i R_i}{\sum_{i=1}^N m_i} \quad (17)$$

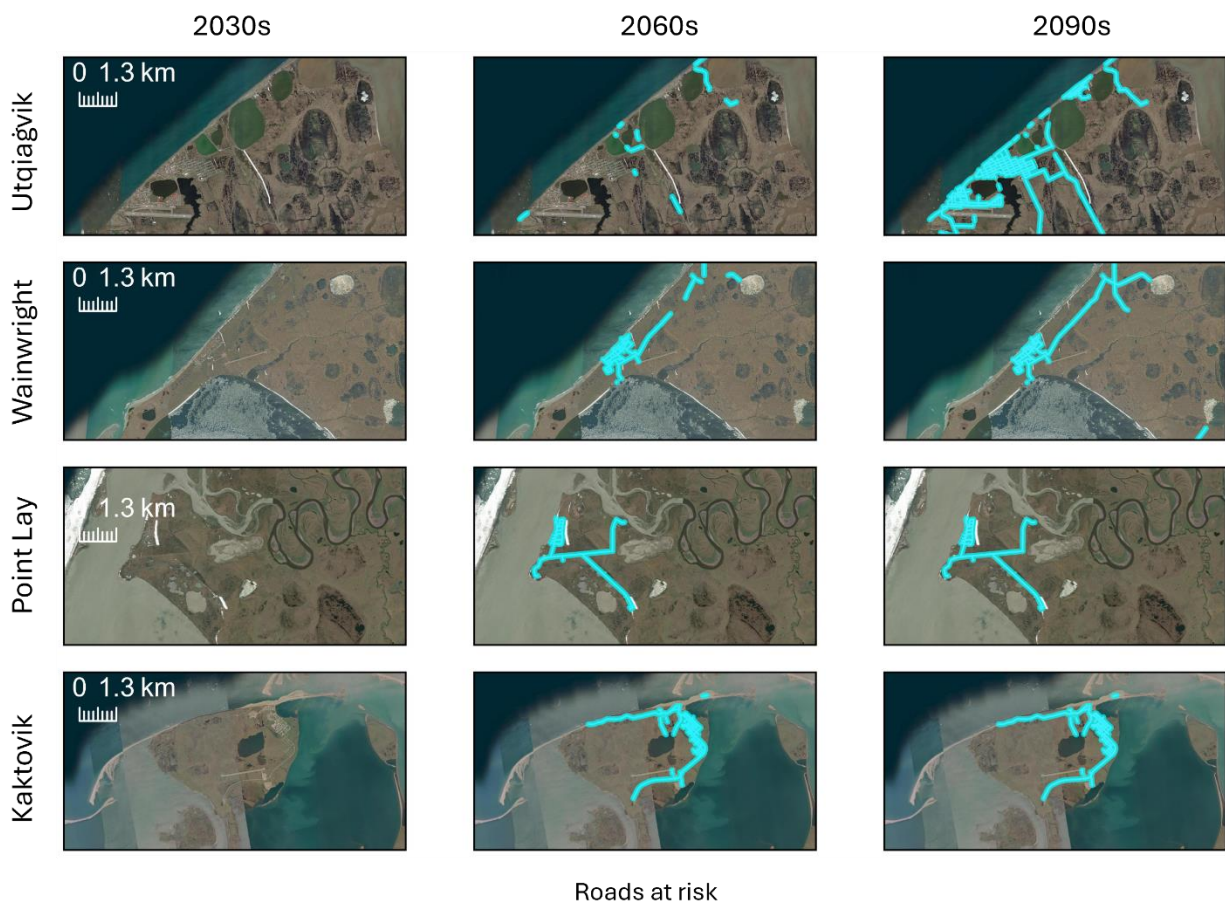
where i denotes a single infrastructure element, m_i represents area for buildings and length for roads or pipelines, N is the total number of infrastructure elements, and R represents whether the infrastructure element is characterized as “at-risk” or not, determined based on whether the bearing capacity reduction or thaw settlement exceed the threshold value or not.

$$R_i = \begin{cases} 1, & \text{element } i \text{ is classified "at risk"} \\ 0, & \text{otherwise} \end{cases} \quad (18)$$

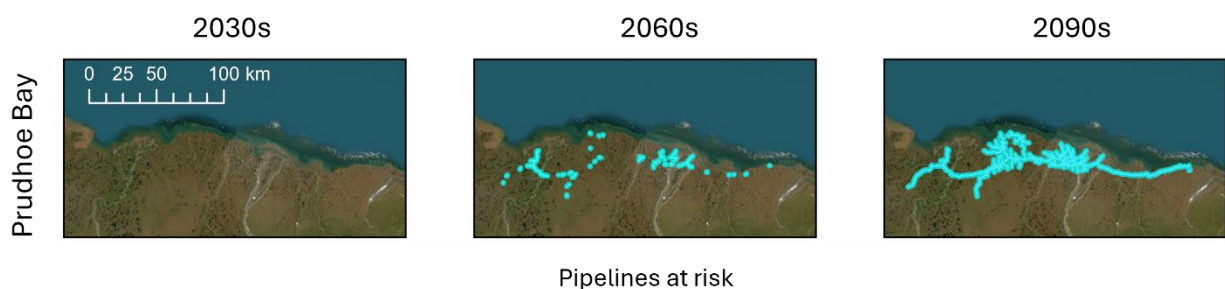
Because I_{risk} is a scalar rather than a vector for each infrastructure element, it cannot be shown spatially but only varies with time. However, we can show the spatiotemporal distribution of the R_i vector for each infrastructure element (see Supplementary Figs. 11-13 below).



Supplementary Fig. 11 Spatial distribution of projected buildings at risk. Projected buildings at risk for the 2030s, 2060s, and 2090s are shown for Utqiagvik (first row), Wainwright (second row), Point Lay (third row), and Kaktovik (fourth row). The buildings at risk are determined under RCP 8.5 climate forcing.



Supplementary Fig. 12 Spatial distribution of projected roads at risk. Projected roads at risk for the 2030s, 2060s, and 2090s are shown for Utqiagvik (first row), Wainwright (second row), Point Lay (third row), and Kaktovik (fourth row). The roads at risk are determined under RCP 8.5 climate forcing.



Supplementary Fig. 13 Spatial distribution of projected pipelines at risk near Prudhoe Bay. The pipeline at risk is projected for the 2030s, 2060s, and 2090s under the RCP 8.5 climate forcing scenario.

Please see the added texts in **lines 651-658**, highlighted in blue in the manuscript with tracked changes and added figures in the **Supplementary Information**.

L 349: “0.2 m settlement threshold” this thaw settlement threshold should be mentioned in the methods section. alongside the bearing capacity threshold you set.

“moderate stress conditions” meaning 15 and 30 kPa, respectively?

Response: Thank you for this comment. The following writing has been added in the methods section:

“Roads and pipelines at risk are determined based on the thaw settlement exceeding a threshold value (S^*) of 0.2 m.”

Please see the added texts in **lines 637-638**, highlighted in blue in the manuscript with tracked changes.

“Moderate stress conditions” represents 30 kPa for road and 15 kPa for pipeline, respectively. We have revised the previous sentence as:

“Forty-five percent of roads and 52% of pipelines are projected to exceed the 0.2 m settlement threshold under 30 and 15 kPa conditions, respectively.”

Please see the revised texts in **lines 357-359**, highlighted in blue in the manuscript with tracked changes.

L 405: “previous studies” Please add references

“excess melt water” excess ice melt water

Response: References have been added to the original text, and the term “excess melt water” has been changed to “excess ice meltwater.” The revised sentence is shown below:

“This infrastructure loading effect is often overlooked in previous studies (Nelson et al. 2002; Streletskiy et al. 2012; Hong et al. 2014; Hjort et al. 2022), where thaw settlement is typically estimated based solely on the drainage of excess ice melt water.”

Please see the revised texts in **lines 416-417**, highlighted in blue in the manuscript with tracked changes.

L 411-413: “Finally, our framework presents high-resolution 30-m hazard maps, substantially finer than the coarser-scale outputs (e.g., 1 km or 10 km grids)” Exactly! Show your I_{risk} on the community scale.

Response: We appreciate the reviewer’s constructive suggestions regarding the infrastructure-at-risk map. Please refer to our response to the previous comments to see the added R_i map at the community scale.

L 413: “previous studies” please add references

Response: please see below the revised sentence with added references:

“Finally, our framework presents high-resolution 30-m hazard maps, substantially finer than the coarser-scale outputs (e.g., 1 km or 10 km grids) in previous studies (Hjort et al. 2018; Streletskiy et al. 2023).”

Please see the added reference in **line 424**, highlighted in blue in the manuscript with tracked changes.

L 416: “hazards” geohazards - I suggest you stay consistent.

Response: The term “hazards” has been changed to “geohazards.”

Please see the revised texts in **line 428**, highlighted in blue in the manuscript with tracked changes.

L 421: “permafrost dynamics” Or permafrost conditions/ characteristics, assuming you are referring to ground temperatures, talik and ALT thickness here? I suggest you stay consistent with your wording.

Response: The term “permafrost dynamics” has been changed to “permafrost characteristics.”

Please see the revised texts in **lines 432-433**, highlighted in blue in the manuscript with tracked changes.

L 422-424: “Second, the time-dependent consolidation behavior of thawing soils and the time required to reach ultimate settlement are not considered in the current framework.” That is interesting. Could you please say 1-2 sentences about what this entails?

Response: We thank the reviewer for this comment. Time-dependent thaw consolidation means the ground does not settle all at once after thaw; instead, settlement accumulates as melt water slowly drains and the soil skeleton adjusts. The pace depends mainly on how easily water can flow in the pores (i.e., hydraulic conductivity) and how far it must travel (Wang et al. 2025); our framework reports the final settlement only and does not simulate this gradual dissipation of water with time.

Please see the added texts in **section 4 of the Supplementary Information**.

[References]

[1] Wang, Z. & Xiao, M. Large strain thaw consolidation model for ice-rich fine-grained permafrost considering adsorptive and capillary unfrozen water and secondary compression. *Cold Reg. Sci. Technol.* **2025**, 104714 (2025); <https://doi.org/10.1016/j.coldregions.2025.104714>.

L 425: “foundation types and dimensions” Could you say a few words about this? You look at pile foundations - which are other very typical foundation types and how do they compare in terms of bearing capacity and thaw settlement?

Response: Thank you for your comments. Deep circular footing (pile foundation) and shallow strip footing are two widely used civil infrastructure foundations in cold regions engineering (Andersland and Ladanyi et al. 2003). In the supplementary information, we explicitly compare deep circular footings and shallow strip footings in Supplementary Fig. 14. The results indicate that bearing capacity differences between the two foundation types are negligible below 2000 kPa. Since 2000 kPa is considered high for most civil infrastructure, using the standard pile foundation for regional-scale analysis is reasonable.

L 425-427: “Finally, in terms of subsurface features, the current framework does not model the development of cryopegs or account for the role of cryopegs in permafrost stability.” I see that you explain some of these uncertainties, incl. the cryopegs, in your supplementary material. If you don't want to include it here - though in my opinion important - refer to it please.

Response: We thank the reviewer for the suggestion. Considering the word limit and the need for conciseness in the manuscript, we have added a reference in the main text directing readers to the detailed discussion on model uncertainty. The original text has been revised as follows:

“Finally, in terms of subsurface features, the current framework does not model the development of cryopegs⁴⁵ or account for the role of cryopegs in permafrost stability (see Section 4 of the Supplementary Information).”

Please see the revised texts in **lines 438**, highlighted in blue in the manuscript with tracked changes.

L 432: “thaw settlement” cumulative, compared to 2020?

Response: We have revised the original texts as follows:

“In the four coastal communities, thaw settlement relative to the 2020s is projected to reach 0.15-0.3 m by the 2050s and 0.5-2.7 m by the 2090s under RCP8.5.”

Please see the revised texts in **lines 449-450**, highlighted in blue in the manuscript with tracked changes.

L 434: “underestimation of thaw settlement.” I recommend underlining this with the value from your results.

Response: We have revised this sentence as follows:

“Omitting the effect of infrastructure-induced stress leads to an underestimation of thaw settlement (e.g., the mean thaw settlement across the Arctic Coastal Plain increases from 0.42 m to 1.1 m by the 2090s under the RCP8.5 scenario, considering a vertical stress of 100 kPa).”

Please see the revised texts in **lines 452-453**, highlighted in blue in the manuscript with tracked changes.

L 450: “provids” provides

Response: We have corrected “provids” to “provides.”

Please see the revised texts in **line 469**, highlighted in blue.

L 453: “200 cm” 200 cm below the ground surface

Response: We have revised this sentence as follows:

“The estimated soil properties were provided for seven standard depths from the ground surface to 200 cm below the ground surface.”

Please see the revised texts in **lines 472**, highlighted in blue.

L 453: “The soil properties were derived using machine learning algorithms trained on global soil profiles.” Could you please clarify if you applied these machine learning algorithms or SoilGrids? Further, it would be nice to have 1-2 sentences explaining the ML algorithm. And did you use the same ML algorithm for both properties?

Response: Thank you for the suggestion. We did not train new ML model; we used the published SoilGrids250 m product from ISRIC. SoilGrids predicts soil properties with an ensemble of tree-based models (random forest, gradient boosting, and multinomial logistic regression) trained on 150,000 soil profiles and 158 remotes sensing-based soil covariates (Hengl et al. 2016). We used the same SoilGrids outputs for both soil bulk density and clay content, i.e., the algorithm is the same.

Added texts: “SoilGrids predicts soil properties with an ensemble of tree-based models (random forest, gradient boosting, and multinomial logistic regression) trained on 150,000 soil profiles and 158 remotes sensing-based soil covariates.”

Please see the added texts in **lines 474-476**, highlighted in blue.

L 454: “depth-weighted average” meaning shallow ground depths have more or less weight? Do you have reference for this?

Response: Thank you for asking. By “depth-weighted average,” we mean a thickness-weighted mean over a target depth. Practically, for a soil property $x(z)$ over 0-Z m, we use

$$\bar{x}_{0-z} = \frac{\sum_k x_k \Delta z_k}{\sum_k \Delta z_k} \quad (S1)$$

where k represents different layers. So, the shallower layers only have “more weight” if they occupy more of the depth; we do not add extra emphasis to shallow depths beyond their thickness. This is the standard approach used with SoilGrids depths (e.g., 0–5 m, 5–15 m, *etc.*) and is recommended in the SoilGrids documentation and related guidelines (Hengl et al. 2016).

We have added reference to the original texts.

L 457: “We used the ground ice map of northern Alaska in our assessment. The ground ice map illustrates the distribution of excess ground ice volume within the upper five meters of permafrost. Supplementary Fig. 2c shows the ground ice distribution across the Arctic Coastal Plain.” This reads a bit misleading. The reference and Fig. 2 c Suppl. point to a massive ice map, based on ground ice, not a ground ice map itself. This is important as ground ice content can be far beyond 30% in this region, see e.g.

<https://www.sciencedirect.com/science/article/pii/S0165232X12001644?via=ihub#bi0005>

The paragraph would benefit from a clarification, that you are showing a massive ice map - which is a kind of ground ice. I suggest to not use these two terms interchangeably, see e.g. <https://www.permafrost.org/publication/glossary-of-permafrost-and-related-ground-ice-terms/> .

It could also help to give an example. i assume by massive ice your are mostly referring to ice wedges?

Please also add the unit (here and) in the figure, volumetric fractions?

Response: We appreciate the reviewer’s careful reading. We agree that ground ice and excess ice should not be used interchangeably, and the volumetric ice content can reach up to 80% in the Alaska Arctic Coastal Plain (Wang et al. 2026). Regarding the relationship between excess ice and massive ice, according to the definition, excess ice refers to the volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen condition. Massive ice is described as large bodies of ground ice that typically have an ice content of at least 250%. Therefore, massive ice is generally considered a form of excess ground ice (van Everdingen 1998). We have revised the sentence as follows:

“We used the excess ice map of northern Alaska in our assessment. The excess ice map considers the distribution of volumetric massive ice content within the upper five meters of permafrost. Supplementary Fig. 2c shows the massive ice distribution across the Arctic Coastal Plain. Our analysis uses the upper value of each classified range of ice content.”

Please see the revised texts in **lines 480-483**, highlighted in blue.

Regarding the ice content, our previous Supplementary Fig. 2 used a diverging color map that did not clearly show the range. The upper value of the ice content is actually 80% in the massive ice map we used. This value is clarified in the revised **Supplementary Fig. 2** in response to **L40**.

L 461-474: “permafrost temperature dynamics”, “permafrost conditions”, “permafrost dynamics”, “permafrost conditions”

In this paragraph you use i) permafrost temperature dynamics, ii) permafrost conditions, and iii) permafrost dynamics to describe the permafrost characteristics (talik thickness, ALT thickness and ground temperature) shown in Fig. 2 Suppl.

I would suggest to stay consistent with your wording for better reading comprehension, e.g. permafrost characteristics

Response: Thank you for your suggestion. We have revised these terms to “permafrost characteristics.” We have also checked the manuscript to ensure terminology consistency.

L 478: “excess melt water” water from melting excess ice

Response: Thank you for your suggestion. This sentence has been revised as:

“When permafrost warms and thaws, water from melting excess ice first drains out without the compression of the soil skeleton.”

Please see the added texts in **line 501**, highlighted in blue.

L 489, 490: “excess melt water” excess ice melt water

Response: Thank you for this comment. The term “excess melt water” has been revised as “excess ice melt water.”

Please see the added texts in **line 513**, highlighted in blue.

L 505: “bulk density and specific gravity (based on soil types)” Could you provide or reference a table, in which one could look up these values per soil type shown in Fig 1. Suppl.?

Response: Thank you for this comment. The bulk density map is shown in Supplementary Fig. 2a. The specific gravity of soil grains (G_s) was estimated based on the soil types. We have added

Supplementary Table 1 to show the specific gravity of the soil grains for each soil type (adapted from Andersland and Ladanyi 2003) on the Alaska Arctic Coastal Plain. The fluvial peat, silt, and gravel represent a mixed soil type. We calculate the mean specific gravity assuming the mixture is composed of 30% fluvial peat, 40% silt, and 30% gravel.

Supplementary Table 1 Specific gravity of soil grains on the Alaska Arctic Coastal Plain (adapted from Andersland and Ladanyi 2003).

Soil type	Marine silt	Marine silty sand	Aeolian silt	Aeolian silty sand	Fluvial peat, silt, and gravel
G_s	2.3	2.6	2.4	2.65	2.1

Please see the revised texts in **lines 528-529** in the main text and added texts and table in the Supplementary Information.

L 509: “We” I suggest starting this paragraph with a title, e.g. "Assessment of permafrost compressibility properties"

Response: Thank you for the suggestion. We have added the title “Assessment of Permafrost Compressibility Properties” at the beginning of this paragraph.

L 509: “experimentally determined relationships to calculate C_c^* and e_{th} ” Please add a reference for these.

Response: Thank you for the comment. We have added references (Dumais and Konrad 2019; Dumais and Konrad 2024) regarding the empirical relationships used to calculate C_c^* and e_{th} .

L 523: “fall within typical ranges observed for ice-rich permafrost.” Please provide some studies for reference here.

Response: Thank you for the suggestion. We have added references here. This sentence has been revised as follows:

“These values fall within typical ranges observed for ice-rich permafrost (Smith 1972; Dumais and Konrad 2024; Mohammadi and Hayley 2024)”

Please see the revised texts in **line 548**, highlighted in blue.

[References]

Smith, L. B. *Thaw consolidation tests on remoulded clays* MSc thesis, Univ. of Alberta, Edmonton (1972).

L 538: “higher-latitude” see comment above on “low-latitude”. Maybe you could describe its as “northern” coastal regions or coastal regions between Utqiagvik and Kaktovik

Response: Thank you for the suggestion. We have revised the “high-latitude coastal regions” to “coastal regions between Utqiagvik and Kaktovik”.

Please see the revised texts in **lines 591-592**, highlighted in blue.

L 553-554: “using specific gravity and foundation depth” are they defined somewhere?

Response: We appreciate the reviewer for catching this typing error. We used bulk density and foundation depth (H) to estimate the ground overburden pressure at the foundation level. The mathematical expression for p_0 is

$$p_0 = [\rho_b + (1 - \theta_s)\rho_i]gH \quad (S4)$$

where ρ_i is the ice density and g is the acceleration due to gravity.

Please see the added texts in **lines 608-610**, highlighted in blue.

L 569: “North Slope Science Initiative” reference?

Response: We have added reference to the dataset for infrastructure. This sentence has been revised as:

“Infrastructure data are obtained from the North Slope Science Initiative (Alaska Center for Conservation Science 2023).”

Please see the added reference in **lines 624**, highlighted in blue.

[Reference]

Alaska Center for Conservation Science (ACCS). *North Slope Infrastructure (V13): Roads, Pipelines and Developed Areas*. (2023). North Slope Science Catalog (updated 22 Mar 2023). Accessed 13 Oct 2025.

L 571: “predefined threshold values.” Please provide these values.

Response: Thank you for this comment. We have explicitly stated the threshold values for both thaw settlement and bearing capacity reduction:

“Roads and pipelines at risk are determined based on the thaw settlement exceeding a threshold value (S^*) of 0.2 m⁴⁰.”

“For buildings, infrastructure at risk is determined based on the loss of bearing capacity exceeding threshold values (θ_{bc}^*) of 35%, 50%, and 65%.”

Please see the added texts in **lines 637-639**, highlighted in blue.

L 578-583: “To represent road-induced loading conditions, we select vertical stress values of 10, 30, and 50 kPa. These stress values capture the range from conservative far-field stress to localized peak stress typically observed under roadways. For pipelines, vertical stress values of 5, 15, and 25 kPa are used to reflect common pipeline-induced loading conditions. For buildings, infrastructure at high risk is determined based on the loss of bearing capacity exceeding a threshold value (θ_{bc}^*) of 35%, 50%, and 65%.” Looking at the Fig. 9, it becomes apparent that 10 & 50 kPa, 5 & 25 kPa, and 35 & 65% are the lower and upper bounds for your simulations. Please rewrite this paragraph to make this more clear. It is also important to mention here that the loss of bearing capacity is in comparison to the 2020s state.

Further, there is an equation missing for the I_{risk} index.

Response: We thank the reviewer for this comment. We revised this paragraph to 1) clarify that the listed values define lower/middle/upper threshold, 2) state explicitly that bearing capacity reduction is measured relative to the 2020s baseline. We also provided mathematical expression for I_{risk} in the subsequent paragraph. For detailed explanation of I_{risk} , please refer to our response to your previous comment above. The revised paragraph now reads:

“To represent road-induced loading conditions, we select vertical stress values of 10, 30, and 50 kPa. These stress values represent the lower, middle, and upper bounds, ranging from conservative far-field stress to localized peak stress typically observed under roadways. For pipelines, vertical stress values of 5, 15, and 25 kPa are used to reflect common pipeline-induced loading conditions. For buildings, infrastructure at risk is determined based on the loss of bearing capacity exceeding threshold values (θ_{bc}^*) of 35%, 50%, and 65%. The loss of bearing capacity is calculated with respect to the 2020s baseline.”

Please see the revised texts in **lines 633-640**, highlighted in blue.

L 585-586: “Design safety factors are the factors used in foundation designs; a higher factor represents a more conservative design applied in construction.” This explanation might cut it too short. What does a "more conservative design" mean in this context? It remains unclear to me.

Response: We thank the reviewer’s comment. In geotechnical design, the factor of safety (FS) is defined as the ratio of the ultimate bearing capacity that a foundation can sustain (q_{ult}) to the actual service or allowable bearing capacity (q_{all}) (Eq. 16).

$$FS = \frac{q_{ult}}{q_{all}} \quad (16)$$

For an infrastructure element, the allowable bearing capacity can be assumed to remain constant depending on its service function. Therefore, the percentage reduction in q_{ult} is the same as that in FS . Design safety factors are the factors used in foundation designs. A higher design factor of safety means that stronger foundations are required to achieve a higher q_{ult} at the design state, entailing a more conservative design.

Please see the added texts in **lines 642-649**, highlighted in blue.

Supplementary Information

L 12: “covered with” characterized by

Response: We changed the term “covered with” to “characterized by.”

Please see the added texts in **line 12**, highlighted in blue.

L 18: “degradation. These communities are Utqiagvik, Wainwright, Point Lay, and Kaktovik.”

add reference, e.g. Liew et al. 2022 10.3390/jmse10030422

Response: Thank you for this suggestion and providing the close-related reference. We have added the provided reference here.

L 34: “Excess ice content” Massive ice

Response: We thank the reviewer for this comment. Regarding the relationship between excess ice and massive ice, according to the definition, excess ice refers to the volume of ice in the ground that exceeds the total pore volume the ground would have under natural unfrozen condition. Massive ice is described as large bodies of ground ice that typically have an ice content of at least 250%. Therefore, massive ice is generally considered a form of excess ground ice (van Everdingen 1998). We have kept the term “excess ice content” here, since in the following sentence we explicitly state that only the massive ice content is considered, i.e., “We only considered massive ice content and used the upper value of each range.”

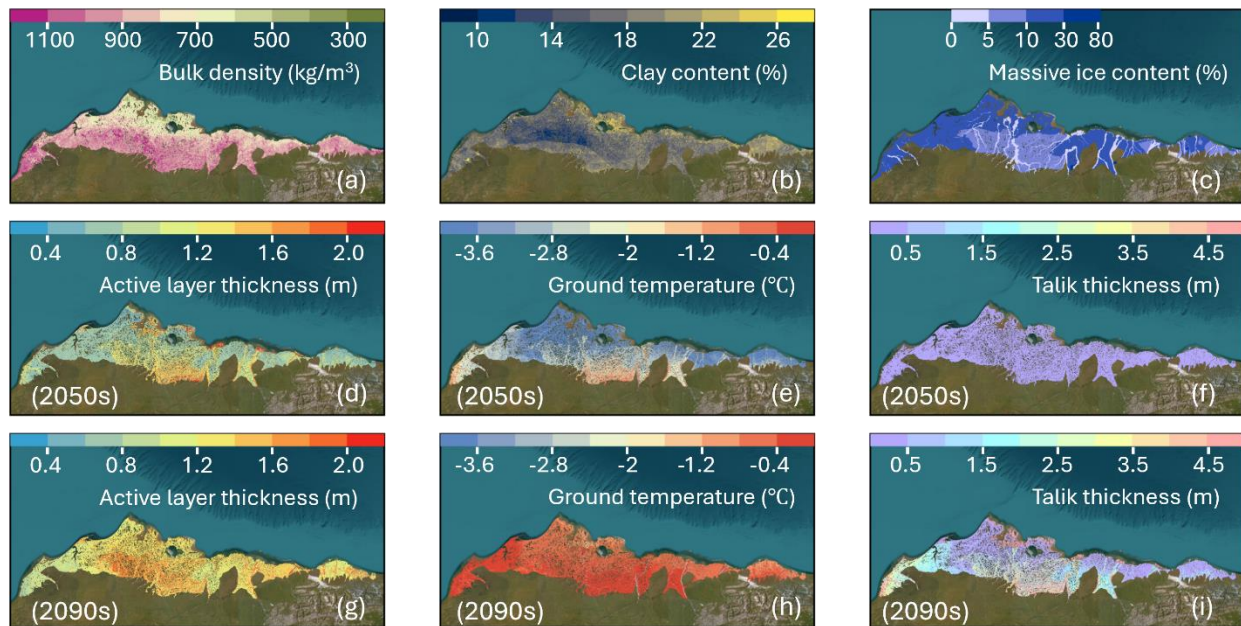
Please see the sentence in **lines 35-36** in the Supplementary Information.

L 40: “Supplementary Fig. 2” I would advise against using diverging colour bars in Fig. 2 (a,e, h) and Fig.3. (c,e) They introduce an artificial midpoint, confusing the reader and making it harder to interpret. In these cases, I suggest using sequential color bars - they are way more intuitive when showing strictly positive variables such as thickness, concentrations, intensities, etc.

Also, please normalize the min and max values of the color bars (d-i) for the reader to be able to compare the temperature and thickness (ALT+ talik) changes between 2050 and 2090.

Further, it seems that Point Lay is not visible on the maps. You could consider shifting the extent to the west to show the community.

Response: Thank you for the detailed suggestions. The revised fig is shown below:



Supplementary Fig. 2 Soil properties and permafrost characteristics. a-b, Maps of bulk density and clay content derived from SoilGrids (Hengl et al. 2017). The bulk density refers to dry bulk density. c, Map of volumetric excess ice distribution (modified from Jorgenson et al. 2014). Only massive ice content is considered in excess ice. Our analysis uses the upper value of each classified range. d-i, Permafrost characteristics at 30-m resolution simulated by the GIPL2.0 model for the 2050s and 2090s using RCP8.5 climate forcing scenario.

Please see the revised figure in **Supplementary Information**.

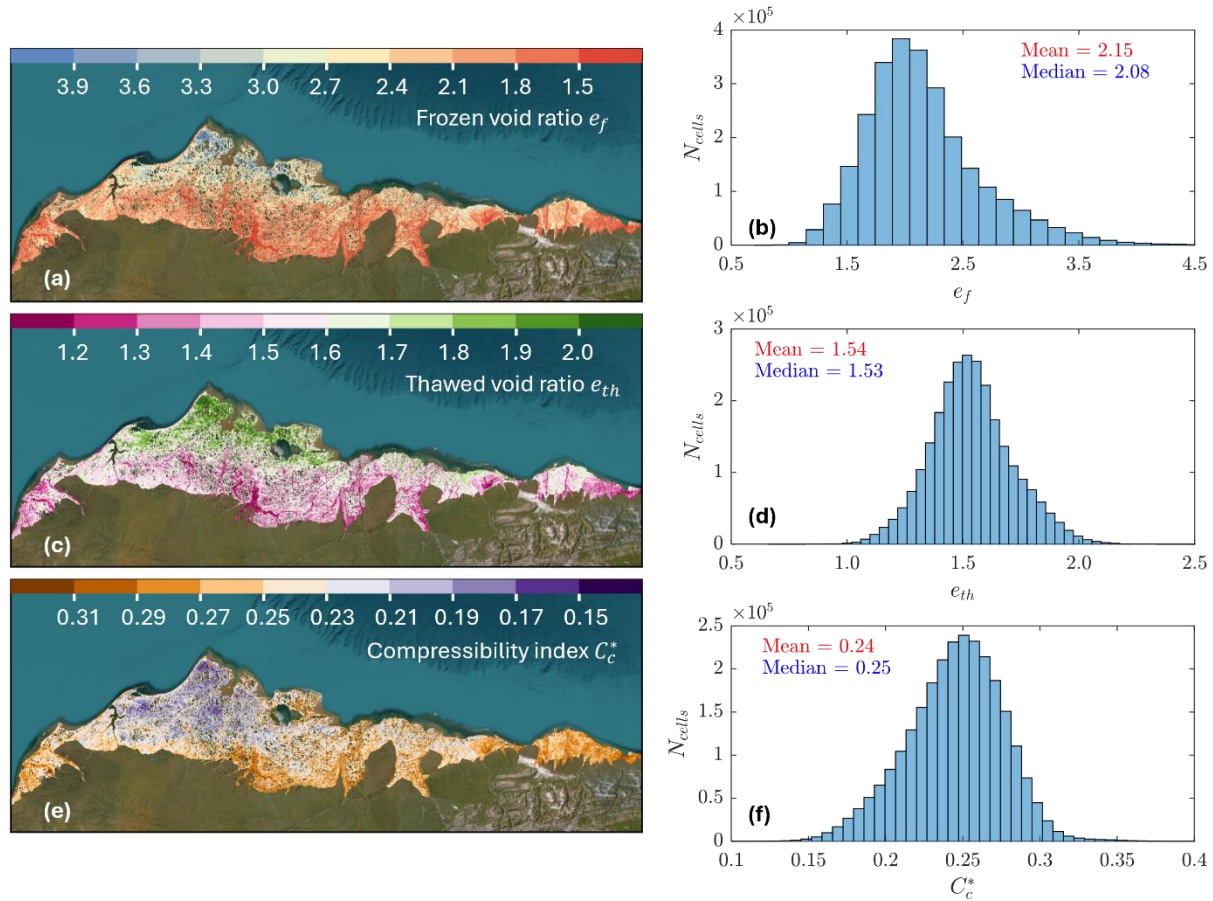
L 42: “Only massive ice content is 43 considered in excess ice.” please adapt the subfigure title accordingly

Response: Thank you. We modified the subfigure title from “excess ice content” to “massive ice content.”

L 53: “Supplementary Fig. 3” I would advise against using diverging colour bars in Fig. 2 (a,e, h) and Fig.3. (c,e) They introduce an artificial midpoint, confusing the reader and making it harder to

interpret. In these cases, I suggest using sequential color bars - they are way more intuitive when showing strictly positive variables such as thickness, concentrations, intensities, etc.

Response: Thank you. The revised fig is shown below. Because new figures are added, the previous supplementary Fig. 3 now becomes supplementary Fig. 7.



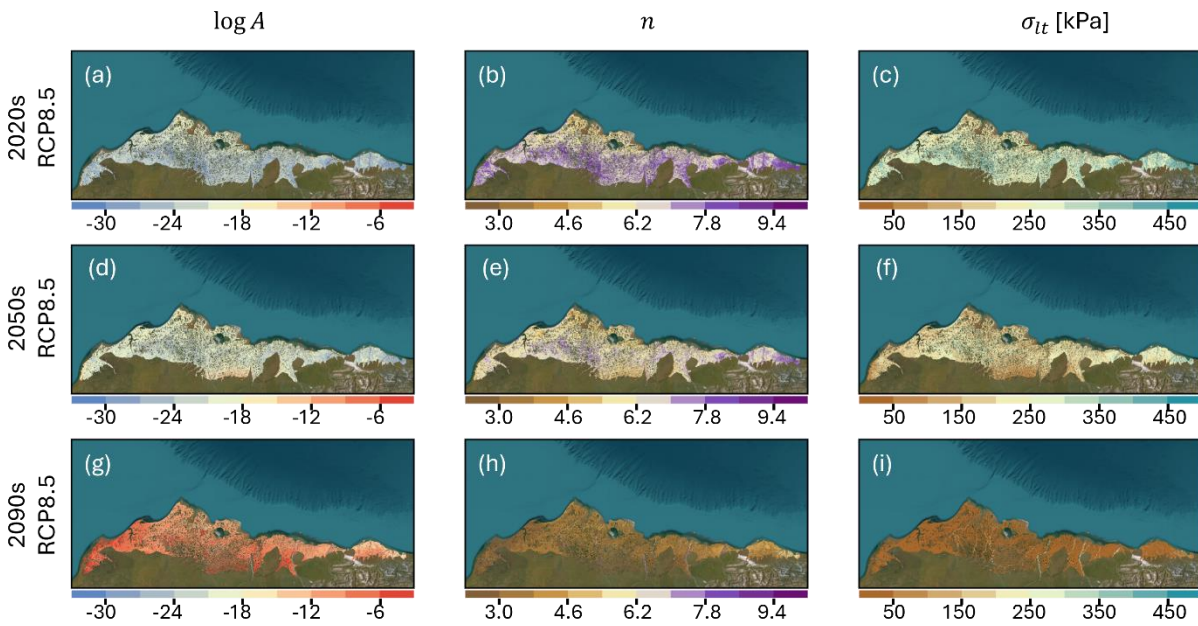
Supplementary Fig. 7 Permafrost compressibility properties on the Arctic Coastal Plain. a, b, Spatial distribution of frozen void ratio and its data distribution. **c, d,** Thawed void ratio estimated from the frozen void ratio using an empirical equation derived from experimental data (Dumais and Konrad 2019). **e, f,** Spatial distribution of the permafrost compressibility index and its data distribution.

Please see the revised figure in **Supplementary Information**.

L 66: “Supplementary Fig. 4” Pleas harmonize the color scale (uniform min and max values across all time steps) for better comparability.

Again, I would advise against using divergent color bars. See comment in Fig. 2 and 3 Suppl.

Response: Thank you. The revised fig is shown below. Because new figures are added, the previous supplementary Fig. 4 now becomes supplementary Fig. 8.



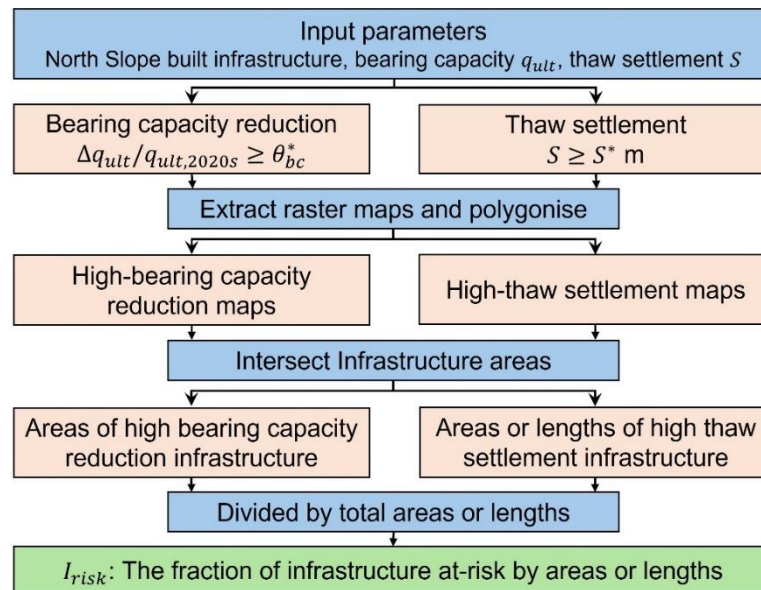
Supplementary Fig. 8 Spatiotemporal distributions of creep parameters of Glen's flow law and long-term strength of permafrost on the Arctic Coastal Plain. a-c, Projections for the 2020s. **d-f,** Projections for the 2050s. **g-i,** Projections for the 2090s. Permafrost dynamics are simulated under RCP8.5 climate forcing. Grid cells with mean annual ground temperatures above 0°C are excluded.

Please see the revised figure in **Supplementary Information**.

L 88: “Supplementary Fig. 6” The flow chart could benefit from some restructuring. In its current version, it looks like "Extract raster maps" is done parallel to retrieving areas where the bearing capacity and thaw settlement reach a certain threshold. The same goes for the next steps.

Maybe you could make it clearer that these are subsequent steps. It might also be nice to include the threshold values or at least specify them in the text.

Response: Thank you for this comment. We have revised the flow chart of infrastructure risk assessment by clearly showing the step-by-step geoprocessing as shown below. The threshold values are specified in the main text.



Supplementary Fig. 10 Flow chart of infrastructure risk assessment. Geospatial data on projected bearing capacity and thaw settlement is used as input to identify at-risk areas of civil infrastructure. Each step is performed in the ArcGIS Pro software (ESRI 2024).

Please see the revised figure in **Supplementary Information**.

**High-Resolution Geomechanical Modeling Reveals Accelerating Infrastructure Risks from
Permafrost Degradation in Northern Alaska**

Dear Editor and Reviewers:

We thank the editor and reviewers for the review report. We appreciate the time spent synthesizing the comments and providing constructive suggestions for improvement. A revised manuscript with tracked changes (all revisions highlighted in blue), along with a clean version, has been submitted. Our detailed responses to the comments are presented below.

Reviewer #1:

The authors have addressed all of my previous concerns. I only have a minor suggestion: label the y-axis of all figures with full words (such as thaw subsidence for Fig. 1b) instead of abbreviations (such as S_e for Fig. 1) to improve readability.

Response: Thank you for your comments and suggestions for improvement of this manuscript. We have labeled all figures with full words instead of abbreviations.

Reviewer #2:

Wang et al. have addressed the suggestions of both reviewers and improved the manuscript by providing additional information and clarifications, thus enhancing its accessibility to readers from different backgrounds compared to the initial submission.

The authors also added a section on the validation of the modeling framework which was based on comparing the model output with InSAR measurements derived from Liu et al. In its current form, however, I see one considerable issue. The manuscript states that the model framework was validated using only one location south of Prudhoe Bay, at a pipeline access road connecting the Dalton Highway and the TAPS. While this location is certainly urban-disturbed, I argue that it may not adequately represent the infrastructure load typical of communities with a denser network of buildings and roads.

Further, only the simulated thaw settlement rates were validated, not the thaw subsidence rates. Does Liu et al. also provide measurements for thaw subsidence?

I was also wondering, about the size of the validation study region (Fig. 10). The scale bar is missing, but I assume the width is less than 1 km? what was the spatial resolution of the validation InSAR dataset, 10-15 m? At this resolution, could some pixels smooth over road embankments or include undisturbed tundra, potentially leading to an underestimation of the thaw settlement rates?

If feasible, I suggest extending the validation of the model with (InSAR) measurements from representative community to support the robustness of the model framework. Otherwise, a thorough discussion of these limitations would be important.

Response: Thank you for comments and suggestions for improvement of this manuscript. We addressed your concerns as follows:

(1) Representativeness of the validation site for infrastructure loading

We appreciate the reviewer's concern about the representativeness of the selected validation site. However, our goal in this validation step is to test the model response to vertical loads on permafrost, rather than to reproduce the full community layouts. The chosen location south of

Prudhoe Bay includes two of the most common civil infrastructure types on the North Slope—roads and pipeline—which exert vertical stress on the ground and are known to induce pronounced thaw settlement. In this sense, the site captures the key mechanical process we seek to validate: the additional thaw settlement caused by infrastructure loading.

We agree that the footprint of infrastructure at this site differs from those in communities dominated by residential buildings, and we now acknowledge this limitation. However, the validity of the thaw settlement framework itself depends on its ability to reproduce deformation under an additional vertical stress, not on whether the validation site lies within a town or not.

(2) Validation of thaw subsidence without additional vertical stress

The purpose of the newly added validation section is specifically to test the model response to additional infrastructure loading, i.e., thaw settlement under $\Delta q > 0$. For this reason, we focused on an urban-disturbed area with roads and pipelines that impose additional vertical stress on the ground. Validation of thaw subsidence in the absence of additional vertical loading on the tundra is already provided earlier in the manuscript (Fig. 1), where we compare modeled thaw subsidence with both in-situ (Streletskiy et al. 2017) and InSAR measurements (Liu et al. 2010). Thus, the two validation steps are complementary: Fig. 1 validates thaw subsidence without added load, and the new section (Fig. 10) validates thaw settlement under infrastructure loading.

(3) Inclusion of pixels near, but not directly on the road and pipeline

The InSAR deformation product used for validation has a ground spatial resolution of 15 m (Liu et al. 2015). We have also added a scale bar to Fig. 10. We agree that some validation pixels are not centered exactly on the road or pipeline but also include adjacent tundra. Because vertical stress from the infrastructure decays laterally away from the load (as described by elastic stress distribution solutions), these pixels are expected to experience lower ground stress and therefore

smaller thaw settlement than pixels located directly beneath the infrastructure. We now clarify this in the revised manuscript and note that the inclusion of pixels near, but not directly on the road and pipeline may lead to underestimation of local thaw settlement.

Importantly, Liu et al. (2015) reported a mean deformation rate of 2.7 ± 0.7 cm/yr for 2006-2010 using the identical study region. Our validation window is chosen to be consistent with the validation sites so that our modeled thaw settlement is compared against the same spatial average as the InSAR data.

(4) Discussions of the limitations of the validation strategy

At present, to the best of our knowledge, the south of Prudhoe Bay site is the only location where spatially long-term InSAR-derived vertical deformation rates are available in North Slope and civil infrastructures are clearly characterized. As discussed above, this site is therefore the only one that presently allows a quantitative validation of thaw settlement under additional vertical stress. In response, we have added the following discussions to clearly acknowledge the limitations of this validation approach:

In the **lines 550-554**, we added: “The validation site contains roads and pipelines rather than the residential buildings that dominate our four study communities and therefore does not capture full community layouts. However, the site represents a typical infrastructure loading area and captures the key mechanical process we seek to validate—thaw settlement under additional vertical stress from infrastructure.”

In the **lines 558-560**, we added: “To ensure consistency with the spatially averaged InSAR measurements (Liu et al. 2015), the comparison is carried out over the similar spatial polygon. Some pixels near, but not directly over the infrastructure likely experience lower ground stress and smaller thaw settlement.”

I am still somewhat uncertain about your use of the terms thaw subsidence and thaw settlement. In your introduction you state that “thaw settlement consists of volume reduction from both excess ice melt water drainage and stress-induced pore water drainage” (stress from infrastructure), while thaw subsidence only describes ground surface changes “due to the drainage of excess ice melt water”. While you follow this definition in comparing subsidence ($\Delta q = 0$ kPa) and settlement ($\Delta q = 100$ kPa) in Figure 2, you later refer to thaw settlement only (e.g. Figure 3). I would suggest to check your entire manuscript if you used them consistently.

Response: Thank you for pointing this out. We have reviewed the entire manuscript to ensure consistency based on our definitions. Specifically, we have labeled all figures with full terms rather than abbreviations. The captions for Figs. 2, 3, and 10 and the corresponding paragraphs have been revised to clarify terminology and adhere to our definitions.

In-line comments:

Lines 33-35: “Widespread loss of function of residential buildings, and utility lines due to degrading permafrost-induced thermokarst and thaw subsidence has been documented in Point Lay, Alaska.” Is there a reason why you don’t also reference Liew et al. 2022 (doi: <https://doi.org/10.3390/jmse10030422>) here? The surveys on civil infrastructure damages were in the same communities as in your study.

Response: We agree with the reviewer’s suggestion. We have revised this sentence in lines 32-35 as follows:

“For example, widespread loss of function in residential buildings, roads, and utility lines due to degrading permafrost-induced thermokarst and thaw subsidence has been documented in four coastal communities—Utqiagvik, Wainwright, Point Lay, and Kaktovik—in northern Alaska (Jones et al. 2025; Liew et al. 2022).”

L116, Fig. 1 b,c: - according to the S_{obs} range, the values lie within 5-13 cm per year for Barrow? Is this correct or is there a mismatch between the y axis labels and the actual data?

Response: The shaded S_{obs} region was plotted using the measured thaw subsidence rate, i.e., 0.4 cm/yr for the lower bound and 1.0 cm/yr for the upper bound. By 2015, the values range from 4.8 to 12 cm (Fig. 1b). The measured thaw subsidence does not fall within the range implied by the measured subsidence rates because the reported rate is not a mean annual value. We report the exact values provided in the literature.

Line 498: “permafrost conditions”: “permafrost characteristics.”

Response: We have revised “permafrost conditions” to “permafrost characteristics” in **line 493**.

Line 515: “excess melt water”: excess ice melt water.

Response: We have revised “excess melt water” to “excess ice melt water” in **line 510**.

Line 552: “mean annual thaw settlement rate ($\bar{S}$)” in line 557 further down, you say “median” values. Could you please clarify which one it is?

Response: Thank you for this comment. The “mean annual” is the average over time. The “median” here refers to the median value of $\bar{S}$ for all pixel cells within the selected polygon, as each pixel cells has its own $\bar{S}$ value. We revised this sentence as follows for clarification:

Lines 560-562: “For all pixels within the study region, the simulated median $\bar{S}_e$ and $\bar{S}$ values are 0.28 and 2.3 cm/yr for $\Delta q = 0$ and $\Delta q = 100$ kPa, respectively.”

Line 557: “ $\Delta q = 0$ and 100”: “ $\Delta q = 0$ and $\Delta q = 100$.”

Response: We have revised “ $\Delta q = 0$ and 100” to “ $\Delta q = 0$ and $\Delta q = 100$ ” in **lines 561-562**.

**High-resolution geomechanical modeling reveals accelerating infrastructure risks from
permafrost degradation in Northern Alaska**

Dear Editor:

We thank the editor and reviewers for their review reports. We appreciate the time spent synthesizing the comments. All reviewer comments were addressed in the prior version, and no additional comments were raised in this round. We thoroughly checked the manuscript to ensure it meets the formatting requirements listed in the Editorial Requests Table.

Reviewer #2:

The authors have addressed all my previous concerns and included a statement on the limitation of the model focusing on infrastructure loading from pipelines and roads over full community layouts.

Response: Thank you for your comments and suggestions for improvement of this manuscript.