## Response to RC2

This study aims to improve the spatial resolution of FT detection products without sacrificing accuracy, using passive microwave-based FT data from AMSR-E/2 TB through the DFA. Downscaling indicators, such as MODIS-based LST and ATI, are used to integrate soil moisture information. The downscaled FT records were validated with in-situ soil temperatures, assessing accuracy changes post-downscaling. Trend analyses of the high-resolution FT records capture detailed dynamics, meeting the growing spatial and temporal resolution needs of GCOS for FT monitoring. This study provides valuable FT data for enhancing cryospheric and ecological research, offering an important resource for future studies. The study is well written and the methods used are rigorous. I recommend a minor revision to address some of my comments.

**Reply:**

Thank you for your thorough and encouraging evaluation of our work. In line with your recommendation for a minor revision, we have carefully reviewed the manuscript and implemented the following improvements:

**#1** In the study it categorizes up to 17 land cover types, each representing a distinct vegetation type. However, I believe relying solely on satellite images to build FT products may oversimplify the process. It would be beneficial to incorporate the biogeochemical mechanisms specific to each vegetation type (e.g., forest, savanna, grassland) when determining FT. Could you provide further clarification on how these mechanisms are integrated into the analysis?

**Reply:**

Thank you very much for your valuable comments.

We fully agree with your point that freeze-thaw (FT) processes differ significantly among various vegetation types due to their distinct biogeochemical mechanisms. The near-surface soil FT process involves dynamic changes in soil and vegetation moisture states, which lead to significant variations in soil dielectric properties. Specifically, when surface temperatures drop below freezing, the liquid water in the soil gradually freezes into ice; conversely, as temperatures rise above freezing, the ice melts back into liquid water. Due to the substantial difference in dielectric constants between liquid water and ice, this moisture state transition causes pronounced changes in dielectric properties, a phenomenon that is particularly complex across different vegetation types.

Passive microwave remote sensing technology effectively captures these changes in soil dielectric properties. Therefore, this study introduces the quasi-emissivity (Qe) index in FT discrimination based on passive microwave observations, defined as the ratio of 18.7 GHz horizontally polarized TB ($TB_{18.7H}$) to 36.5 GHz vertically polarized TB ($TB_{36.5V}$). Qe comprehensively characterizes the dielectric property changes occurring throughout the FT process, reflecting dynamic changes in soil and vegetation moisture states. Consequently, this indicator can indirectly capture the biophysical status of vegetation and soil conditions, thus considering the distinct biogeochemical mechanisms specific to different vegetation types during the FT process.

While our current approach does not explicitly quantify these mechanisms for each vegetation type, the satellite-derived Qe index integrates these effects by capturing the combined changes in soil and vegetation dielectric properties. We appreciate your suggestion and may consider incorporating vegetation-specific parameters and biogeochemical data in future studies to better characterize the distinct mechanisms of different vegetation types during the FT process.

We have expanded the description of our approach using quasi-emissivity to capture dynamic changes in soil and vegetation moisture states. This clarification has been added to Section 3.1 of the revised manuscript.

**Changes in manuscript:**

Lines 202–216 in Section 3.1:

"The DFA is a surface FT discrimination method developed using AMSR-E and AMSR2 data, demonstrating high accuracy compared to existing FT products. Near-surface FT variations are closely associated with soil temperature and moisture, which are reflected by the TB at 36.5 GHz in vertical polarization ($TB_{36.5V}$) and the Quasi-emissivity (Qe).

Qe is defined as the ratio of the TB at 18.7 GHz in horizontal polarization ($TB_{18.7H}$) to $TB_{36.5V}$. This ratio serves as an indicator of soil moisture, as microwave emission at these frequencies is highly sensitive to changes in water content. The near-surface soil FT process involves dynamic changes in soil and vegetation moisture states, which lead to significant variations in soil dielectric properties. Due to the substantial difference in dielectric constants between liquid water and ice, these phase transitions cause pronounced dielectric changes, a phenomenon further complicated by the distinct biogeochemical mechanisms of different vegetation types. The Qe index introduced in this study comprehensively characterizes the combined dielectric effects of both soil and vegetation during the FT process. Thus, Qe not only reflects soil moisture variations, but also indirectly captures the biophysical status of vegetation and soil conditions, enabling consideration of the unique biogeochemical processes associated with various vegetation types during the FT process.

Therefore, $TB_{36.5V}$ and Qe were selected as key parameters for FT discrimination (Zhao et al., 2011).

The DFA is further parameterized to separately detect FT status during ascending and descending orbits (Wang et al., 2019b), as expressed by the following equations:"

**#2** While the validation provides an overall accuracy metric, it may not be sufficient to establish robustness. I suggest conducting validation separately within different landscapes where FT characteristics vary significantly. Additionally, comparing results against site-level observations would strengthen the validation process. Including more statistical measures would further enhance the robustness of the findings.

**Reply:**

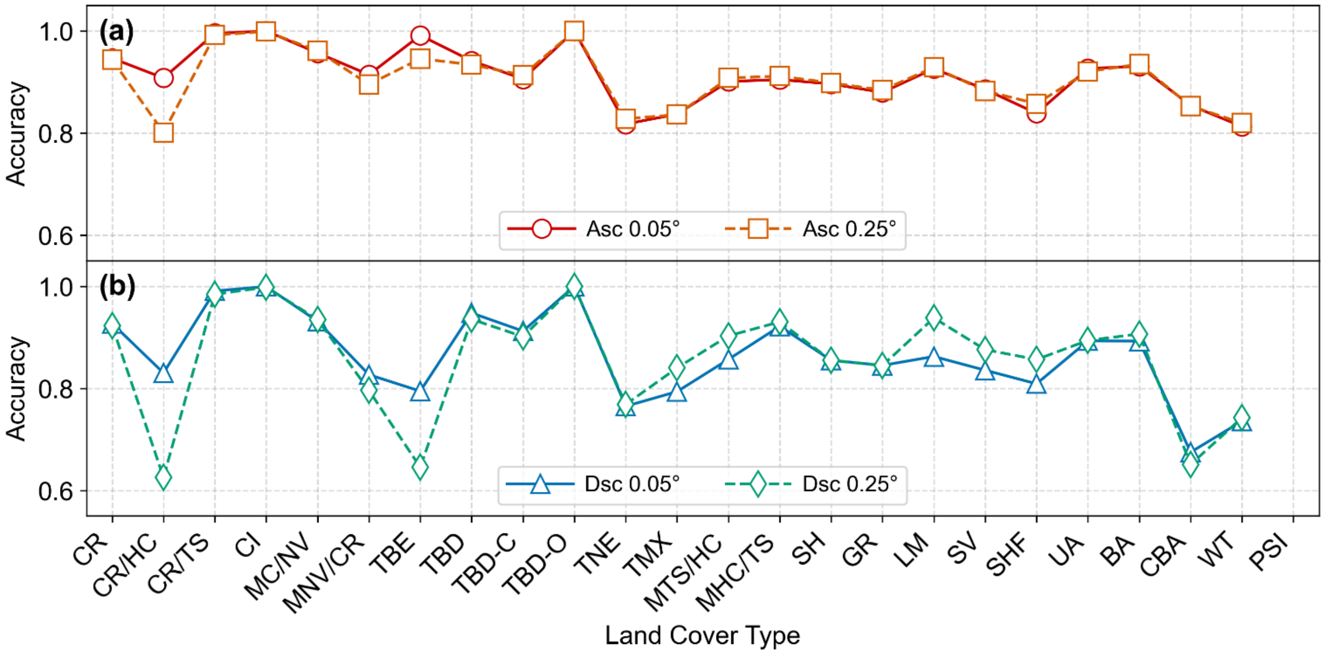
Thank you for your valuable comments.

Regarding the overall accuracy metric and other statistical measures, since our FT product is a binary classification (frozen/thawed) rather than continuous decimal values, traditional regression metrics such as R2 and RMSE cannot be applied. Therefore, we adopted classification accuracy as the primary metric for validation of our downscaled FT dataset.

Regarding comparing results against site-level observations, we conducted comprehensive validation against in situ soil temperature data from 44 global ground observation networks, covering over 1,000 stations. We carefully selected ground measurements temporally matched to satellite observations to compare the classified frozen/thawed states. The results demonstrate that the downscaled products maintain accuracy comparable to the original coarse-resolution products, with overall accuracies exceeding 83% across multiple networks. Detailed statistics and scatter plots are presented in Section 3.4 (Figure 6 and Table 3) of the manuscript.

In response to the suggestion of conducting validation separately within different landscapes, we have added a statistical accuracy table grouped by land cover types derived from the ESA CCI Land Cover 2010 dataset provided by ISMN sites (see Table 4 of the revised manuscript and Response Fig. 1). This table details the classification accuracies of both 0.25° and 0.05° resolution datasets across different land cover types, effectively capturing product performance variations under diverse physiographic conditions. This content will be incorporated into Section 4.2 to further enhance the robustness of the validation.

We sincerely appreciate your constructive comments, which have helped strengthen the scientific rigor of our study.




**Response Figure 1. Line plots of classification accuracy for the 0.25° and 0.05° FT products across different land cover types: (a) ascending passes; (b) descending passes. The x-axis abbreviations are explained in Response Table 1.**

**Response Table 1 ESA CCI land cover classification framework.**

| Code | ESA CCI Land Cover Classes | | Code | ESA CCI Land Cover Classes | |
|---|---|---|---|---|---|
| | Abbreviated name | Full name | | Abbreviated name | Full name |
| 10 | CR | Cropland, rainfed | 100 | MTS/HC | Mosaic tree and shrub (>50%) / herbaceous cover (<50%) |
| 11 | CR/HC | Cropland, rainfed / Herbaceous cover | 110 | MHC/TS | Mosaic herbaceous cover (>50%) / tree and shrub (<50%) |
| 12 | CR/TS | Cropland, rainfed / Tree or shrub cover | 120 | SH | Shrubland |
| 20 | CI | Cropland, irrigated or post-flooding | 130 | GR | Grassland |
| 30 | MC/NV | Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) | 140 | LM | Lichens and mosses |
| 40 | MNV/CR | Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) | 150 | SV | Sparse vegetation (tree, shrub, herbaceous cover) (<15%) |
| 50 | TBE | Tree cover, broadleaved, evergreen, Closed to open (>15%) | 180 | SHF | Shrub or herbaceous cover, flooded, fresh/saline/brakish water |
| 60 | TBD | Tree cover, broadleaved, deciduous, | 190 | UA | Urban areas |

| | | | | | |
|---|---|---|---|---|---|
| | | Closed to open (>15%) | | | |
| 61 | TBD-C | Tree cover, broadleaved, deciduous, Closed (>40%) | 200 | BA | Bare areas |
| 62 | TBD-O | Tree cover, broadleaved, deciduous, Open (15-40%) | 201 | CBA | Consolidated bare areas |
| 70 | TNE | Tree cover, needleleaved, evergreen, closed to open (>15%) | 210 | WT | Water |
| 90 | TMX | Tree cover, mixed leaf type (broadleaved and needleleaved) | 220 | PSI | Permanent snow and ice |

**Changes in manuscript:**

Lines 412-415 in Section 4.2:

In addition, Table 4 summarizes the classification accuracies of both products across various land cover types for both ascending and descending passes. The land cover types are defined by the ESA CCI Land Cover 2010 classification values provided by the ISMN sites, enabling a more comprehensive assessment of performance under different physiographic conditions.

Lines 430-432, Table 4 in Section 4.2:

**Table 4 Validation results for the coarse- and high-resolution FT products across various land cover types. Land cover types are sourced from the ESA CCI Land Cover 2010 classification values provided within the ISMN site dataset.**

| **No** | **Land cover type** | **Ascend** | | | **Descend** | | |
|---|---|---|---|---|---|---|---|
| | | Num | Accuracy (0.05°) | Accuracy (0.25°) | Num | Accuracy (0.05°) | Accuracy (0.25°) |
| 1 | Cropland, rainfed | 275,743 | 94.66% | 94.37% | 277,149 | 92.71% | 92.26% |
| 2 | Cropland, rainfed / Herbaceous cover | 10,129 | 90.79% | 80.11% | 10,157 | 83.01% | 62.56% |
| 3 | Cropland, rainfed / Tree or shrub cover | 12,127 | 99.54% | 99.20% | 11,336 | 99.07% | 98.42% |
| 4 | Cropland, irrigated or post-flooding | 5,162 | 99.99% | 99.91% | 5,217 | 99.93% | 99.81% |
| 5 | Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) | 4,896 | 95.70% | 96.12% | 5,439 | 93.14% | 93.47% |
| 6 | Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) | 25,702 | 91.44% | 89.54% | 27,613 | 82.67% | 79.58% |
| 7 | Tree cover, broadleaved, | 7,466 | 99.14% | 94.58% | 12,210 | 79.45% | 64.53% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | evergreen, Closed to open (>15%) | | | | | | |
| 8 | Tree cover, broadleaved, deciduous, Closed to open (>15%) | 12,658 | 94.14% | 93.40% | 12,094 | 94.76% | 93.53% |
| 9 | Tree cover, broadleaved, deciduous, Closed (>40%) | 15,445 | 90.60% | 91.34% | 14,557 | 91.21% | 90.13% |
| 10 | Tree cover, broadleaved, deciduous, Open (15-40%) | 198 | 100.00% | 100.00% | 198 | 100.00% | 100.00% |
| 11 | Tree cover, needleleaved, evergreen, closed to open (>15%) | 898,729 | 81.77% | 82.81% | 996,959 | 76.49% | 76.84% |
| 12 | Tree cover, mixed leaf type (broadleaved and needleleaved) | 10,529 | 83.71% | 83.61% | 12,351 | 79.36% | 84.00% |
| 13 | Mosaic tree and shrub (>50%) / herbaceous cover (<50%) | 22,384 | 90.10% | 90.79% | 24,002 | 85.67% | 90.28% |
| 14 | Mosaic herbaceous cover (>50%) / tree and shrub (<50%) | 5,159 | 90.48% | 91.17% | 4,955 | 92.15% | 93.02% |
| 15 | Shrubland | 217,565 | 89.63% | 89.83% | 236,376 | 85.49% | 85.47% |
| 16 | Grassland | 596,806 | 87.98% | 88.41% | 626,309 | 84.49% | 84.47% |
| 17 | Lichens and mosses | 2,711 | 92.62% | 92.88% | 3,153 | 86.24% | 93.78% |
| 18 | Sparse vegetation (tree, shrub, herbaceous cover) (<15%) | 25,240 | 88.56% | 88.26% | 28,065 | 83.54% | 87.57% |
| 19 | Shrub or herbaceous cover, flooded, fresh/saline/brakish water | 16,913 | 83.87% | 85.76% | 19,753 | 80.89% | 85.64% |
| 20 | Urban areas | 41,406 | 92.64% | 92.07% | 37,230 | 89.29% | 89.39% |
| 21 | Bare areas | 2,955 | 93.10% | 93.49% | 3,178 | 89.26% | 90.64% |
| 22 | Consolidated bare areas | 642 | 85.41% | 85.31% | 665 | 67.48% | 65.08% |
| 23 | Water | 5,213 | 81.31% | 81.96% | 6,120 | 73.57% | 74.23% |
| 24 | Permanent snow and ice | 0 | / | / | 0 | / | / |