QLB-NET
A Dense Soil Moisture and Freeze–Thaw Monitoring Network in the Qinghai Lake Basin on the Qinghai–Tibetan Plateau

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ABSTRACT: Soil moisture (SM) and soil freeze–thaw (FT) are two relatively active surface parameters that are significant to the sustainable development of the water–land–air–plant–human nexus. Over time, regional or global SM and FT datasets with different spatial resolutions have been developed. In response to the requirements of multiscale product validation and multisource uncertainty tracking, a soil moisture and soil temperature (ST) monitoring network in the Qinghai Lake Basin (QLB-NET) was established in September 2019. The QLB-NET is characterized by densely distributed in situ sites (82 sites) measuring SM and ST at 5-, 10-, and 30-cm depths, with 60 sites in a large-scale network covering an area of 36 km × 40 km and 22 sites evenly distributed across two small-scale 1 km × 1 km networks. Quantitative analyses of the in situ measurements show that the QLB-NET can provide stable and reliable ground truth for SM and FT over coarse grid scales, e.g., 36 km × 36 km, 25 km × 25 km, and 0.25° × 0.25°. When statistics are correspondingly performed over 50 out of 54, 25 out of 29, and 25 out of 28 sites, the results are described as follows: 1) the standard deviation of the mean SM varies between 0.0127 and 0.0196 m$^3$ m$^{-3}$, with the corresponding difference between the upper and lower quartiles being less than 0.02 m$^3$ m$^{-3}$; 2) the ground freeze–thaw state can be correctly identified with high probabilities ranging from 85.3% to 100% on two freeze–thaw transitional dates. The QLB-NET observed datasets are distributed online and will be continuously updated through cooperation with the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn), facilitating product validation and uncertainty tracking, spatiotemporal analysis of SM change and FT transition, optimization of the SM and FT retrieving algorithms and scaling methods, and development of the mountainous microwave radiative transfer model.

SIGNIFICANCE STATEMENT: This study aims to introduce the newly constructed QLB-NET in detail, including the site deployment strategy, the installation and maintenance, the sensor calibration, and the characteristics and quality of the in situ SM and ST measurements. Quantitative analyses of the in situ measurements show that the QLB-NET can provide stable and reliable ground truth for SM and FT over coarse grid scales, e.g., the SMAP 36 km × 36 km grid. The high-quality QLB-NET measurements will facilitate research of product validation and uncertainty tracking, spatiotemporal analysis of SM change and FT transition, optimization of the SM and FT retrieving algorithms and scaling methods, and development of the mountainous microwave radiative transfer model.

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As essential variables in land–atmosphere feedbacks at weather and climatic time scales, soil moisture (SM) and soil freeze–thaw (FT) are two relatively active surface parameters that are interrelated and interinfluenced (Entekhabi et al. 2004). Moreover, SM and FT are significant to the sustainable development of the regional and global water–land–air–plant–human nexus (X. Li et al. 2018, 2021). In the context of global warming, these two parameters are essential for studying hydrothermal changes in the cryosphere (Yao et al. 2019). Their temporal and spatial dynamics can effectively reflect climate changes and substantially impact ecosystem health (Homans 2007). The Global Climate Observation System (GCOS) program explicitly includes SM and FT as two Essential Climate Variables (ECV; https://gcos.wmo.int/en/essential-climate-variables).

The microwave remote sensing technique is one of the best ways to monitor regional/global SM and FT due to long-term, large-scale, and high-revisit observations, as well as the sensitivity to liquid water content and the capacity to penetrate clouds, rain, and vegetation. Several operational SM and FT products retrieved from observations of different microwave sensors have been successively released, such as the global SM and FT products from AMSR-E/2 (Njoku et al. 2003; Owe et al. 2008; Fujii et al. 2009; Du et al. 2017; Zhao et al. 2011; Hu et al. 2023, 2019), SMAP (O’Neill et al. 2021; Derksen et al. 2017), SMOS (Wigneron et al. 2021; Rautiainen et al. 2016; Kerr et al. 2012; Bai et al. 2022), and FY-3 (Kang et al. 2021), as well as global long-term SM products (Dorigo et al. 2017) from the Climate Change Initiative (CCI) project and FT product (Kim et al. 2017) from NASA’s Earth System Data Record (ESDR) program, which are based on over 40 years of archived and emerging microwave remote sensing observations. In addition, by combining remote sensing data and land surface model simulations, the land data assimilation system (LDAS) has joined the mainstream of SM acquisition, such as SM products from ERA5-Land (Hersbach et al. 2020), GLDAS (Rodell et al. 2004), and GLEAM (Martens et al. 2017). Following a temperature-to-FT threshold (Chai et al. 2014; Kim et al. 2019; Wang et al. 2020), soil temperature (ST) estimated from LDAS provides another possible method for soil FT acquisition.

Generally, these remotely sensed or LDAS-based SM and FT products all have a coarse spatial resolution of tens of kilometers. It remains a challenge to clarify the exact accuracies of different SM or FT products (Liu et al. 2021; Wang et al. 2020), especially under complex environmental conditions, which is not conducive to the further improvement of product quality and restricts their applications in related research areas. However, despite the inevitability of representativeness errors (F. Chen et al. 2017; Colliander et al. 2022), direct validation against ground measurements is still a meaningful way to evaluate the
accuracy of satellite-retrieved or model-derived geophysical products, e.g., SM (Bindlish et al. 2018) and FT (Kraatz et al. 2018). Following this consideration, the International Soil Moisture Network (ISMN; https://ismn.earth/en/; Dorigo et al. 2021) was initiated to pool in situ SM networks worldwide in cooperation with the Global Soil Moisture Data Bank (Robock et al. 2000). In China, several in situ SM and ST monitoring networks have been established since the 2000s, including networks located in the Genhe watershed in Heilongjiang Province and the Saihanba area in Hebei Province (Jiang et al. 2020) and networks deployed in the Shandian River basin and Xiaoluan River basin during the Soil Moisture Experiment in the Luan River (SMELR; Zhao et al. 2020).

In particular, it is important to provide in situ SM and ST measurements over the Qinghai–Tibetan Plateau (QTP; Yao et al. 2019), which serves as the Water Tower of Asia and provides essential ecosystem services to China and other Asian countries (Chen et al. 2021). The QTP, characterized by complex and unique biological and climatic conditions with complicated topography, has experienced significant climate change over the past 30 years, directly impacting its surrounding climate and environment through atmospheric and hydrological processes (Yao et al. 2019; Wang et al. 2022), e.g., an overall warming and moistening trend and different situations of permafrost degradation. In situ monitoring of SM and ST under different topography, microclimatic environment, and spatial heterogeneity conditions on the QTP will contribute to understanding the soil hydrothermal changes and the resulting increase in carbon emissions, as well as the mechanisms of plateau vegetation adaptation to future climatic and anthropogenic changes; it will also offer variables for developing the Earth system model to well describe the water–land–air–plant–human nexus (X. Li et al. 2018, 2021).

Over the past two decades, efforts have been dedicated explicitly to constructing observation networks to provide pixel-scale “true” values of SM and ST in the QTP, as summarized in Table 1. Su et al. (2011) developed the Tibetan Plateau Observatory (Tibet-Obs) in the QTP for collecting SM and ST, including the Ngari network (24 sites) in a cold arid environment with most sites in desert/sparse grassland; the Maqu network (20 sites) in a cold, humid environment with land-cover type dominated by grassland; and the Naqu network (11 sites) in a cold, semiarid environment covered by grassland. The Tibet-Obs status and a 10-yr (2009–19) dataset were introduced by P. Zhang et al. (2021). Yang et al. (2013) constructed a multiscale SM and ST Monitoring Network in Naqu in the central QTP (CTP-SMTMN) through three field campaigns during the summers of 2010 and 2012. It consists of 56 sites that measure SM and ST at three spatial scales (termed “large network,” “medium network,” and “small network” with spatial extents of 1.0°, 0.3°, and 0.1°, respectively) at depths of 0–5, 10, 20, and 40 cm. The large network has 38 sites deployed along a cross transect. The medium network is nested in the large network and consists of 22 sites, distributed as uniformly as possible with the consideration of logistics. The small network is further nested in the medium grid and consists of nine sites. Later, in 2015, a new Pali network in the semiarid area of the southern TP was constructed, with 21 sites deployed (Y. Chen et al. 2017). During the Heihe Watershed Allied Telemetry Experimental Research (HiWATER; Li et al. 2013), an SM&ST network (WATER-NET; Jin et al. 2014), which is affiliated with the Heihe Integrated Observatory Network (S. Liu et al. 2018, 2023), was deployed in the Babao River Basin in the northeastern QTP, with 40 sites spread across four 25 km × 25 km grids (average of 10 sites per grid). The land-cover type is uniform (grassland) within the extent of WATER-NET. These in situ networks have not only served much SM and FT direct validation work in the QTP (Chen et al. 2013; Li et al. 2015; C. Li et al. 2018; Zeng et al. 2015; Y. Chen et al. 2017; Ma et al. 2017; Liu et al. 2019) but also supported the development of indirect validation methods (Liu et al. 2021; Li et al. 2022). However, compared with more than 70 networks in the ISMN, mainly in the United States.
and Europe, only nine networks in China are included in the ISMN. Among them, four networks, i.e., Naqu of CTP-SMTMN and Ngari, Maqu, and Naqu of Tibet-Obs, are on the QTP, which is insufficient. In addition, nearly all the six networks on the QTP mentioned above were constructed before the launch of the newest L-band SMAP instrument; the site distributions within each network were designed according to the grid extent of AMSR2 (0.25° × 0.25°) or SMOS (25 km × 25 km). According to Table 1, when using them to validate SMAP products at a spatial resolution of 36 km × 36 km, the maximum site density is no more than 20 per SMAP grid. For the three networks of Tibet-Obs, the maximum site density per SMAP grid is even smaller than 10, which is very limited and cannot meet the need for comprehensive evaluations of the SM or FT products at the subregional scales of the QTP under a variety of hydrothermal and microclimatic conditions. Moreover, it is also challenging for scaling research to obtain pixel-scale “true” values using relatively limited sites in a coarse-resolution grid.

In response to the above challenges and requirements, a dense soil moisture and temperature monitoring network was constructed within the Qinghai Lake Basin in QTP (hereafter abbreviated to QLB-NET). In this paper, we overviewed the newly constructed QLB-NET, Table 1. Comparisons between QLB-NET and other in situ networks in the QTP. The values under a table header marked with an asterisk (*) represent the statistics over a SMAP 36-km EASE-Grid 2.0 grid.

<table>
<thead>
<tr>
<th>Network</th>
<th>Dataset</th>
<th>Extent (lat, lon)</th>
<th>Total site number</th>
<th>Maximum site density*</th>
<th>Measured depth (cm)</th>
<th>Measured interval (min)</th>
<th>Constructed year</th>
<th>Min/max DEM* (m)</th>
<th>TCI*</th>
<th>Main land cover**</th>
<th>Climate*</th>
<th>Permafrost thermal stability*</th>
<th>SOC density** (kg m⁻²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLB-NET</td>
<td>Tianjun</td>
<td>37.24°–37.58°N, 98.97°–99.32°E</td>
<td>82</td>
<td>54</td>
<td>5, 10, 30</td>
<td>30</td>
<td>2019</td>
<td>3,322/4,333</td>
<td>291</td>
<td>G: 90.9%</td>
<td>C: 7.6%</td>
<td>Plateau temperate semiarid zone</td>
<td>85.4%</td>
<td>14.6% (T: 7.1%, U: 7.5%)</td>
</tr>
<tr>
<td>WATER-NET</td>
<td>Heihe</td>
<td>37.85°–38.26°N, 100.14°–101.08°E</td>
<td>40</td>
<td>20</td>
<td>4, 10, 20</td>
<td>5</td>
<td>2012</td>
<td>2,533/5,013</td>
<td>687</td>
<td>G: 67.0%</td>
<td>C: 17.5%</td>
<td>Plateau temperate semiarid zone</td>
<td>55.2%</td>
<td>44.8% (T: 21.1%, U: 16%)</td>
</tr>
<tr>
<td>CTP-SMTMN</td>
<td>Naqu</td>
<td>31.03°–31.95°N, 91.68°–92.46°E</td>
<td>56</td>
<td>20</td>
<td>0–5, 10, 20, 40</td>
<td>30</td>
<td>2012</td>
<td>4,485/5,172</td>
<td>196</td>
<td>G: 91.1%</td>
<td>H: 5.0%</td>
<td>Plateau subcold semihumid zone</td>
<td>98.4%</td>
<td>1.6% (U: 1.6%)</td>
</tr>
<tr>
<td></td>
<td>Pali</td>
<td>27.70°–28.16°N, 89.07°–89.29°E</td>
<td>21</td>
<td>10</td>
<td>5, 10, 20, 40</td>
<td>30</td>
<td>2015</td>
<td>3,328/6,644</td>
<td>879</td>
<td>G: 52.7%</td>
<td>F: 11.4%</td>
<td>Plateau temperate semiarid zone</td>
<td>91.4%</td>
<td>8.6% (T: 3.9%, U: 2.9%)</td>
</tr>
<tr>
<td>Tibet-Obs</td>
<td>Ngari</td>
<td>32.42°–33.45°N, 79.62°–80.17°E</td>
<td>24</td>
<td>8</td>
<td>5, 10, 20</td>
<td>15</td>
<td>2008</td>
<td>4,204/6,046</td>
<td>520</td>
<td>G: 57.1%</td>
<td>B: 15.2%</td>
<td>Plateau temperate arid zone</td>
<td>85.3%</td>
<td>14.7% (T: 3.5%, U: 6.6%)</td>
</tr>
<tr>
<td></td>
<td>Maqu</td>
<td>33.62°–34.02°N, 101.72°–102.60°E</td>
<td>20</td>
<td>8</td>
<td>5, 10, 20</td>
<td>15</td>
<td>2008</td>
<td>3,217/4,473</td>
<td>358</td>
<td>G: 96.9%</td>
<td>C: 1.1%</td>
<td>Plateau subcold semihumid zone</td>
<td>99.4%</td>
<td>0.6% (T: 0.2%, U: 0.4%)</td>
</tr>
<tr>
<td></td>
<td>Naqu</td>
<td>31.23°–31.38°N, 90.78°–92.11°E</td>
<td>11</td>
<td>7</td>
<td>5, 10, 20, 40, 60, 80</td>
<td>15</td>
<td>2008</td>
<td>4,417/5,253</td>
<td>240</td>
<td>G: 93.3%</td>
<td>W: 1.3%</td>
<td>Plateau subcold semihumid zone</td>
<td>99.6%</td>
<td>0.4% (T: 0.1%, U: 0.3%)</td>
</tr>
</tbody>
</table>

* Data obtained from X. Zhang et al. (2021) with B for bare areas, C for rainfed cropland, F for evergreen forest, G for grassland, and H for herbaceous cover.
* Data obtained from Zheng et al. (2013).
* Data obtained from Ran et al. (2021) with S for seasonal frozen ground, P for permafrost including unstable (U), transitional (T), semistable, stable, and very stable types.
* Data obtained from Liu et al. (2022) for 0–200-cm soil
introduced the network configuration, analyzed the characteristics and quality of the in
situ SM and ST measurements, and conducted preliminary applications of in situ SM and
ST measurements to evaluate several SM and FT products.

Overview of the QLB-NET

**Scientific objectives.** The QLB-NET is committed to serving at least four aspects of research
needs by providing stable and reliable ground truth through densely distributed in situ sites:

1) to support comprehensive validations of coarse-resolution SM and FT products on QTP
   by collaborating with the existing SM&ST networks;
2) to support the improvement of the SM retrieval and FT discrimination algorithms to
   enhance the accuracies of the microwave SM/FT products;
3) to support studies on the spatiotemporal characteristics of SM change and FT transition,
   as well as their driving mechanisms in alpine meadows on QTP; and
4) to support the development and optimization of scaling methods, e.g., upscaling and
downscaling, and development of indirect validation methods, such as three-cornered
hat (TCH), triple collocation (TC), and categorical triple collocation (CTC).

**Experimental area.** Qinghai Lake, located in the northeastern QTP, is an important
water conservation area and water vapor circulation channel in western China. It is also
an important water body to maintain the ecological security of the QTP and a natural
barrier to prevent the spread of desertification in western China to the east. To sup-
port water-cycle-related research in Qinghai Lake Basin, the QLB-NET is deployed in
Tianjun, about 70 km northwest of Qinghai Lake. In addition, as listed in Table 1, since
all the six existing networks on the QTP were constructed before the launch of the newest
L-band SMAP instrument and were designed for the grid extent of AMSR2 (0.25° × 0.25°) or
SMOS (25 km × 25 km), the in situ measurements from limited sites within a SMAP
grid (36 km × 36 km) are characterized with high uncertainties when validating the
coarse-resolution SMAP products. The dense site density per SMAP grid in the QLB-NET
can effectively fill this gap and meet the need for comprehensive evaluations of the SM
or FT products. Figure 1 shows the location of the QLB-NET on QTP, along with the loca-
tions of WATER-NET, CTP-SMTMN (Naqu and Pali), and Tibet-Obs (Ngari, Maqu, Naqu),
using a background of daily averaged soil moisture derived from SMAP during 2020.
The QLB-NET has an area of approximately 36 km × 40 km, covering the footprint of the
−3-dB beamwidth of the SMAP antenna. Moreover, a distance of 70 km between QLB-NET
and Qinghai Lake can ensure that the QLB-NET is out of the −10-dB footprint of SMAP
and other microwave sensors. Therefore, Qinghai Lake does not influence the satellite
microwave observations over the QLB-NET extent.

The QLB-NET is within a plateau temperate semiarid zone with an annual average pre-
cipitation of approximately 418 mm, a quarter of which occurs during the growing season
from May to September. As shown in Fig. 1b, the QLB-NET land surface is typically covered
by alpine grasslands (~90.9%) with few croplands (~7.6%) (X. Zhang et al. 2021). Other
land-cover types include bare soil, waterbodies, urban areas, and wetlands, covering an
area of no more than 1.5%. In addition, approximately 15% of the QLB-NET in the northern
section (Fig. 1b) is a transitional/unstable permafrost area (Ran et al. 2021) where a sig-
nificant freeze–thaw-disturbed topography can be observed. Based on the measurements
collected from 109 undisturbed ring-knife soil samples, the soil texture in this area is
dominated by silt and sand with comparable magnitudes of approximately 22% and 70%
on average, respectively, while the clay content consistently maintains a low value of less
than 8%. Soil texture components show notable spatial variability (approximately 13% and 20% for mass percent of silt and sand, respectively). Another typical feature is that the soil organic carbon (SOC) content is generally high in the topsoil (average 10% in mass) and gradually decreases with soil depth (approximately 3% at a depth of 30 cm). Soils with

Fig. 1. (a) The location of the QLB-NET in the QTP with a background of daily averaged soil moisture derived from SMAP during 2020, (b) distributions of the sites and two small-scale networks (NET1 and NET2) in the large-scale network with the permafrost thermal stability overlaid on the land cover, (c) the site distributions in the small-scale network NET1, and (d) the site distributions in the small-scale network NET2.
high SOC contents have high porosity and water retention capacity, which corresponds to a high microwave dielectric constant and will definitely lead to a significant difference in the observations of microwave sensors. The soil texture and SOC variabilities also lead to substantial SM heterogeneity in horizontal and vertical extensions, significantly affecting the surface energy budget and ecological/hydrological processes.

The elevation within the QLB-NET ranges from 3,249 to 4,335 m: significant relief in the northern section, a rugged area with rolling hills in the middle section, and a relatively flat surface in the southern section. Compared with other in situ networks on the QTP, the QLB-NET is characterized by a moderately undulating terrain with a topography complexity index (TCI, defined as the DEM standard deviation within a specific area) of 291 m and a different situation of permafrost degradation, as shown in Table 1. The moderately undulating terrain in the QLB-NET, along with Maqu (TCI = 358 m) and Ngari (TCI = 520 m), can fill the gap between highly undulating (e.g., Pali and Heihe) and flat (e.g., Naqu) terrain to facilitate the development of an accurate radiation transfer model for mountainous areas. In addition, according to the permafrost thermal stability in Table 1, Naqu, Pali, and Maqu are all in seasonally frozen soil areas, while approximately 15% of QLB-NET and Ngari are permafrost. Notably, all permafrost areas of the QLB-NET are under transitional/unstable conditions, which differs from Ngari (approximately 10% out of 15%). The different situations of permafrost degradation in QLB-NET and Ngari may be due to their different climates, with QLB-NET being in a plateau temperate semiarid zone and Ngari being in a plateau temperate arid zone. Moreover, the difference between the permafrost degradation situations of QLB-NET and Ngari is also an explanation for the different SOC densities in QLB-NET (17.46 kg m$^{-2}$) and Ngari (6.68 kg m$^{-2}$) (F. Liu et al. 2018), as listed in Table 1.

**Network configuration**

**Site deployment at two scales.** The QLB-NET was mainly accomplished during the autumn of 2019. Figures 1b–d show the deployment of the network. SM and ST, as well as bulk electric conductivity (EC), are directly measured. The QLB-NET is characterized by the most intensively distributed sites at two spatial scales, i.e., one large-scale network (Fig. 1b) and two small-scale networks (Figs. 1c,d) with spatial extents of 36 km × 40 km and 1 km × 1 km, respectively. There are a total of 82 sites: 60 sites in the large-scale network started operating in September 2019, and 22 sites in the two small-scale networks started operating in September 2020.

The QLB-NET is designed to match the spatial resolutions of different SM and FT products derived from microwave sensors or LDAS by providing spatially dense in situ measurements. The large-scale network covers an EASE-Grid 2.0 SMAP grid of 36 km × 36 km with 54 sites deployed. Moreover, there are distributed densely sites within the grids of AMSR2 (0.25° × 0.25°), SMOS (25 km × 25 km), and ERA5 (0.1° × 0.1). The site distributions (Fig. 1b) in the large-scale network are designed using kriging optimization methods under the consideration of logistics. Details of the kriging optimization methods can be found in Jin et al. (2014) and Ge et al. (2015). The two small-scale networks are nested in the large-scale network, consisting of 11 sites for each, with sites distributed as uniformly as possible. They are designed to serve scaling-related research work by providing ground true values at the scale of 1 km × 1 km. Most sites are deployed on grasslands, the dominant land cover, two are deployed on dry riverbeds, and one is deployed on a wetland.

**Installation and maintenance.** At each site, SM, ST, and EC profiles are measured by Campbell CS655 sensors manufactured by Campbell (United States, [www.campbells.com](http://www.campbells.com)) at three different depths. One sensor is horizontally inserted into 5-cm topsoil to measure...
the underground SM and ST at a 5-cm depth. This depth is comparable to that penetrated by ongoing and upcoming passive microwave sensors. The other two sensors are horizontally inserted at 10- and 30-cm depths, respectively (Fig. 2), serving research such as root-zone SM analysis. The data are recorded every 30 min, and each record reflects the average SM and ST over the past half hour. The power is supplied by a high-density battery, which can support the measurement for more than 3 years. The datalogger, also deployed below the ground surface, is inside a waterproof container to avoid soil water intrusion damage to the measuring system. Moreover, to avoid possible subsequent vandalism or livestock destruction, after the device is deployed, the soil and turf will be backfilled to maximize the restoration of the original land surface, as shown in Fig. 2b. A shielded cable connected to the datalogger is deployed in shallow soil to facilitate data acquisition. Such a device design and deployment scheme was successful, and only two dataloggers were damaged by soil water intrusion due to bolt breakage during the past 3 years (i.e., 2019–22).

We manually collect data and check the status of each site once a year at the beginning of September (before the soil starts freezing) since most of the area is not covered by wireless communication signals. Damaged devices identified during each year’s network inspection will be replaced to ensure that the sites remain densely distributed during the operational period of the QLB-NET. All the newly deployed sensors will be calibrated to ensure the data’s reliability. Under careful and continuous maintenance, the QLB-NET is expected to be operated for more than 10 years and can continuously provide long-term and high-quality in situ measurements.

**Sensor calibration.** The Campbell CS655 sensor measures SM and ST with accuracies of ±0.03 m³ m⁻³ and ±0.1°C, respectively. Notably, a soil-specific calibration is necessary to guarantee the measurement accuracy of SM; this is particularly important for our experimental area, where high SOC contents in the topsoil, generally indicating a high content of soil organic matter, may violate the built-in relationship between soil permittivity and SM (Mironov et al. 2019).

To calibrate the sensor, we took 109 undisturbed ring-knife soil samples at a 10-cm depth from different sites in September 2019 and July 2020 to obtain the true SM values from
the mass difference between the fresh and corresponding dried soil samples. Then, a conversion relationship, as shown in Fig. 3, can be established between the ring-knife-measured SM and the probe-measured SM. The CS655 measured SM values are highly correlated with the ring-knife measured SM values with a determined coefficient of $R^2 = 0.873$. Moreover, the ring-knife measured SM is slightly larger than the CS655 measured SM values with a slope of 1.072 and a positive bias of approximately 9%. For calibration, the three-depth SM values collected by the Campbell CS655 sensors from the 60 sites in the large-scale network and 22 sites in the two small-scale networks are all multiplied by the regressed coefficient of 1.072.

**Characteristics of the in situ SM and ST measurements**

**Typical seasonal dynamics and significant spatial variations in the in situ measurements.**

Figure 4 shows the seasonal variations in daily mean SM and ST and their standard deviation (STD) observed over the 60 sites at three depths (5, 10, and 30 cm) during September 2019 and August 2021. Generally, the SM ranges of the three depths during a frozen season (from November to March) are very similar but much different during an unfrozen season (from April to October). In the unfrozen season, the SM values generally vary from the highest and the most fluctuating at the top layer (5 cm) to the lowest and the most stable at the bottom layer (30 cm), mainly due to the significant influences of precipitation, air temperature, and vegetation coverage on the SM variations. In addition, the SM varies between 0.10 and 0.50 m$^3$ m$^{-3}$ in unfrozen seasons, with sizable STDs up to 0.1 m$^3$ m$^{-3}$. In contrast, the SM varies between 0.05 and 0.1 m$^3$ m$^{-3}$ in frozen seasons, with an average STD of approximately 0.02 m$^3$ m$^{-3}$. The wide SM range indicates a large temporal variability, while the comparably higher STD implies significant spatial variations. This temporal variability corresponds to a high seasonal dynamic, confirming that the in situ measurements from QLB-NET are perfect for validating SM products under a coarse spatial resolution. In contrast, the spatial variations, especially during the unfrozen seasons, indicate strong spatial heterogeneity, which is useful for comparing, optimizing, and generalizing scaling methods. Similarly, the ST at the top layer of 5 cm has the most significant variation range, with comparably higher values during the unfrozen season and lower values during the frozen season. The corresponding STDs are relatively small, with a maximum value of approximately 3°C and a mean value of approximately 0.07°C. This finding implies that the ST values across the 60 sites do not fluctuate much.

Figure 5 shows the seasonal variations in observed daily mean SM and ST over the small-scale NET1 and NET2 at 5-, 10-, and 30-cm depths during September 2020 and August 2021. It can be observed that the SM over a 1 km $\times$ 1 km grid is relatively homogeneous with a smaller STD than that over the QLB-NET, especially in the 5-cm depth. The very small STDs of ST also indicate that there is little difference in ST over the small-scale networks. Comparison between the mean SMs from small-scale NET1 and NET2 shows that,
during the unfrozen season, the mean SM from NET1 is relatively higher than from NET2, while the STs from the two small-scale networks are comparable.

Figure 6 shows the variations in the daily mean SM and ST of four sites on the typical alpine grasslands, i.e., grass on the south slope of a hillside (site 25), grass on a river floodplain (site 28), wetland meadow (site 47), and alpine swamp meadow (site 59). It indicates that the SMs on different land covers have different dynamic characteristics. Specifically, during the growing seasons, the SM values on grasslands generally have lower peak values of approximately 0.4 m$^3$ m$^{-3}$ (as shown for sites 25 and 28) with a broader variation range due to rainfall and evapotranspiration compared with the SM values on meadows, which present higher peak values of approximately 0.6 m$^3$ m$^{-3}$ and narrower variation ranges (as shown for sites 47 and 59). In addition, sharp declines in SM and ST during autumn imply quick soil freezing processes, while the fluctuating increases in SM during spring and the corresponding short platform at approximately 0°C in the ST curve jointly indicate a continuous freeze-to-thaw transition period and a slow thawing process. This phenomenon is more pronounced in meadows than in grasslands.

**Stability and reliability of the statistics over the dense monitoring network.** Different results can be obtained when statistics are performed for different samples, which will
undoubtedly increase the validation uncertainty when using it as a reference ground truth. As mentioned above, one advantage of the QLB-NET is its denser distribution of the sites within a coarse satellite grid compared with other in situ networks (e.g., 54 sites within a 36 km × 36 km grid, 29 sites within a 25 km × 25 km grid, and 28 sites within a 0.25° × 0.25°), which will significantly improve the stability and reliability of the ground truth. Here, the mean SM (MSM) variations with the number of sites randomly selected from the corresponding grid scale for averaging are investigated; the probability variations in correctly identifying frozen/thawed ground are also examined.

For the validation purpose of SM products, the uncertainty of the in situ SM should be sufficiently small. Taking the daily average at a 5-cm depth as an example, Fig. 7 is plotted based on statistics from the results of a 3,000-member bootstrapping method on 1 July and 31 August 2020. It shows variations in the statistics over different sites at three grid scales and variations in the corresponding STD of the mean SM below. Figure 7 shows that the range between the upper and lower quartiles narrows, and the corresponding STD of MSM decreases as the number of sites used for averaging increases. For example, the difference between the upper and lower quartiles of the MSM over the 36 km × 36 km SMAP grid on 1 July 2020, changes from approximately 0.12 m³ m⁻³ (1 site randomly selected) to approximately 0.02 m³ m⁻³ (50 sites randomly selected). Moreover, the corresponding STD of MSM decreases from approximately 0.0978 to 0.0135 m³ m⁻³ as the number of sites increases from 1 to 50. It is the same for the other five cases shown in Fig. 7, which indicates that enough available in situ sites can substantially improve and ensure the stability and reliability of the statistics. By taking one further step forward, we repeated the above statistical process on each day during the growing season of 2020 from 1 May to 30 September to find a statistically significant minimum number of sites that can ensure the STD of the mean SM to be no more than 0.025 m³ m⁻³ at the three grid scales of 36 km × 36 km, 25 km × 25 km and 0.25° × 0.25° (Fig. 1b). The results show that it generally requires more sites for grids of 36 km × 36 km and
25 km × 25 km than 0.25° × 0.25°, and the mean minimum required number of sites for the three grid scales are respectively around 24, 23, and 16. The significant difference between the statistically minimum required number of sites over grids of 25 km × 25 km and 0.25° × 0.25° should be attributed to their different coverages, as shown in Fig. 1b.

The classification accuracies of most FT products during transitional seasons (i.e., when the soil temperature is approximately zero) are relatively low. For the purpose of validating FT products, it is critical to determine the true ground state of freeze or thaw, especially during transitional seasons. However, obtaining the true ground state is challenging in the case of a limited number of in situ sites. The ground states on 29 October 2020 and 30 March 2021, which are within transitional seasons, are investigated here to demonstrate this issue. Based on a 3,000-member bootstrapping method applied to the 5-cm ST, Fig. 8 shows the probability that the ground will be classified as frozen or thawed when a different number of sites participates in the calculation. It is very clear that classification uncertainty exists. There is a higher possibility of identifying the ground state as “thawed” when fewer sites are included. However, as the number of sites increases, we can obtain a more definitive answer that the ground is in a frozen state. This phenomenon exists on both transitional days across all three grid scales. However, for all cases in Fig. 8, by exploiting densely distributed in situ sites, the QLB-NET can provide users with a stable and reliable true ground state at a very high probability. Similarly, the minimum number of sites that can ensure a probability of correctly classifying the frozen or thawed ground to be higher than 90% for each day at the three grid scales is also analyzed by running the above procedure on each day during four freeze–thaw transitional seasons, i.e., 1–30 April in 2020 and 2021, as well as 15 October–15 November in 2019 and 2022. The results show that the minimum site requirement varies a lot from day to day.
when selecting the probability of 90% as a benchmark. Specifically, when the minimum number of sites is no less than 23, 21, and 19 for the three grid scales of 36 km × 36 km, 25 km × 25 km, and 0.25° × 0.25°, respectively, 85% days of the four transitional seasons will have a classification accuracy higher than 90%. If 90% of the days are desired, the minimum number of sites should be 32, 27, and 25 for the three grid scales. It is worth noting that the above statistically significant minimum number of sites is only suitable to the transitional seasons defined in this work.

Generally speaking, since the available sites in the QLB-NET are much denser than the minimum requirements, as demonstrated above, we are confident that the QLB-NET can provide stable and reliable in situ measurements for the SM and FT product validation.

**Preliminary applications of in situ SM and ST measurements**

The SM&FT datasets for validation. Here, we use five SM datasets for preliminary analyses and applications of the in situ SM measurements. The latest Version 8 Level 3 SMAP radiometer SM dataset (SMAPdca) (O’Neill et al. 2021), with a spatial resolution of 36 km × 36 km under the Equal-Area Scalable Earth Grid 2.0 (EASE-Grid 2.0) projection, is a remote-sensed product derived from the L-band (1.4 GHz) brightness temperature (TB) from descending

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![Fig. 7. Distribution of the mean SM, along with the STD of the mean SM, on 1 Jul and 31 Aug 2020 at grid scales of (a),(b) 36 km × 36 km, (c),(d) 25 km × 25 km and (e),(f) 0.25° × 0.25° obtained by applying a 3,000-member bootstrapping method to a different number of sites.](image-url)
and ascending half-orbit satellite passes [approximately 0600 and 1800 local solar time (LST), respectively] using a double-channel algorithm (DCA; [https://nsidc.org/]). The official SM product derived from the AMSR2 sensor provided by JAXA is also used (AMSRjaxa; Fujii et al. 2009). The AMSRjaxa SM has a spatial resolution of 0.1° × 0.1° and is available at [https://gportal.jaxa.jp]. The ERA5 (Hersbach et al. 2020) is a reanalysis dataset ([https://cds.climate.copernicus.eu]) generated by the Copernicus Climate Change Service (C3S). It provides four depths of SM datasets and covers a period from January 1981 to near–real time. The hourly SM dataset from the first layer (0–7 cm) with a 0.1° × 0.1° spatial resolution is used. The other two SM datasets ([https://data.tpdc.ac.cn/]) are derived using a multichannel collaborative algorithm (MCCA) respectively based on the SMAP and AMSR2 observed TBs (Zhao et al. 2021; Hu et al. 2023), cited as SMAPmcca and AMSRmcca hereafter. The SMAPmcca owns a spatial resolution of 9 km × 9 km under the same EASE-Grid 2.0 projection, while the AMSRmcca owns the exact spatial resolution with ERA5 SM. The latter three SM datasets are resampled to the SMAP’s spatial resolution of 36 km × 36 km.

In addition, the operational SMAP FT and ESDR FT are also utilized for preliminary analyses and applications of the in situ ST measurements. The latest Version 3 Level 3 SMAP FT product of 0600 LST descending half-orbit passes, with an Earth-fixed global 36-km EASE-Grid 2.0 projection (Xu et al. 2020), is used in this work ([https://nsidc.org/]).
The baseline algorithm of SMAP FT is the normalized polarization ratio algorithm (NPR) (Derksen et al. 2017), which utilizes vertically and horizontally polarized brightness temperatures to examine the time series NPR evolution relative to signatures acquired during seasonal reference frozen and thawed states. The latest Version 5 ESDR FT product is a part of the NSIDC DAAC Making Earth System Data Records for Use in Research Environments (MeaSUREs) data collection, with an Earth-fixed global 25 km EASE-Grid projection. It consists of two parts, the SMMR–SSM/I–SSMIS record spanning 42 years from 1979 to 2020 and the AMSR-E/AMSR2 record from June 2002 to December 2017. The determination of soil FT state is based on the modified seasonal threshold algorithm (MSTA; Kim et al. 2017). The ESDR FT product (https://nsidc.org/), obtained from SSMIS F17 Tb during its 0620 LST overpass, is utilized here. Similarly, the ESDR FT is resampled to the SMAP’s spatial resolution of 36 km × 36 km.

**Evaluations of SM products.** Figure 9 shows an example of evaluating the SMAPdca, SMAPmcca, AMSRjaxa, AMSRmcca, and ERA5 SM products during the unfrozen season between April and October with the corresponding statistics listed in Table 2. Note that all 54 sites in the 36 km × 36 km grid are utilized to obtain the averaged grid reference value. We can observe that the time series variation in SMAPdca and SMAPmcca behaves similarly to the QLB-NET SM with a correlation coefficient (R) of 0.641 and 0.759 and root-mean-square error (RMSE) of 0.065 and 0.058 m³ m⁻³ for the morning orbit. Much higher R (0.903/0.848) and relatively lower RMSE (0.027/0.032 m³ m⁻³) between SMAPdca/SMAPmcca and QLB-NET SM can be observed for the afternoon orbit. It is worth noting
that SMAPmcca generally has more available observations than SMAPdca (morning orbit: 196 versus 168; afternoon: 198 versus 182). Moreover, both SMAPdca and SMAPmcca perform better than AMSRjaxa and AMSRmcca for morning and afternoon orbits. The AMSRmcca has an $R$ of 0.423/0.434 and RMSE of 0.088/0.085 m$^3$m$^{-3}$ with the QLB-NET SM for the morning/afternoon orbit. The positive Bias (0.038/0.064 m$^3$m$^{-3}$) for morning or afternoon orbit indicates that the AMSRmcca behaves slightly overestimated. However, the AMSRjaxa SM performs even worse, with a significant underestimation during the unfrozen seasons. The relatively worse performances of AMSRjaxa and AMSRmcca may be attributed to the lower sensitivity of the higher frequencies of AMSR2 (e.g., 6.925/10.65/18.7 GHz) to SM than SMAP (1.4 GHz). The ERA5 SM has an apparent underestimation during the unfrozen seasons, with an $R$ of 0.499 and an RMSE of 0.131 m$^3$m$^{-3}$ for morning orbit and an $R$ of 0.545 and an RMSE of 0.133 m$^3$m$^{-3}$ for afternoon orbit. The results presented in Fig. 9 and Table 2 can help us better understand other factors impacting the quality of the SM datasets.

**Evaluations of FT products.** Here, the classification accuracies for frozen soil and thawed soil and the overall classification accuracy calculated based on the QLB-NET FT dataset are presented in Fig. 10. For the morning orbit, the frozen soil classification accuracy of SMAP FT (95.9%) is much higher than that of ESDR FT (72.8%). In comparison, the thawed soil classification accuracy of SMAP FT (87.0%) is lower than that of ESDR FT (95.7%). The opposite is true for the afternoon orbit, i.e., higher classification accuracies of ESDR FT for frozen soil (89.5% versus 79.4%) and SMAP FT for thawed soil (96.7% versus 92.7%). This trend is similar to that found by Li et al. (2022), who carried out validation work for SMAP and ESDR FT products over China using soil temperature measurements from 355 sparse meteorological stations and six dense in situ networks.

Since it remains a challenge to correctly identify the soil freeze–thaw status with a high probability during a rapid freeze–thaw transition period (e.g., temperature above zero in the daytime and below zero in the nighttime), we take one further step forward to examine the monthly classification accuracies of SMAP and ESDR FT products regarding the QLB-NET FT from 3 September 2019 to 31 December 2020. The results are presented in Fig. 11. Unsurprisingly, both SMAP and ESDR have relatively lower classification accuracies during the frozen/thawed transition seasons, i.e., March, April, October, and November, compared with the highest frozen/thawed soil classification accuracies (nearly 100%) during the frozen/thawed season in winter/summer. As an area facing a higher potential of permafrost degradation than CTP-SMTMN and Tibet-Obs (see Table 1), the active layer depth within QLB-NET will potentially increase, and the soil freeze–thaw transition will occur more frequently. As it is of great significance and an urgent requirement to improve the classification accuracy of FT products in transition seasons, it will be a good choice to carry out this kind of research based on the QLB-NET in future work.

### Table 2. Performance metrics of the SMAPdca, SMAPmcca, AMSRjaxa, AMSRmcca, and ERA5 SM products during the unfrozen seasons from 3 Sep 2019 to 3 Aug 2021 within the QLB-NET. $N$ represents the number of available data participating in the statistic.

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Fig. 10. The classification accuracies for frozen soil (blue), thawed soil (orange), and the overall classification accuracy (gray) are calculated based on the QLB-NET FT dataset. AM and PM represent the morning and afternoon orbits of SMAP/ESDR, respectively.

Fig. 11. The monthly classification accuracies of (a),(c) SMAP and (b),(d) ESDR FT products regarding the QLB-NET ST-derived FT dataset from 3 Sep 2019 to 31 Dec 2020. $T_{\text{in situ}}/T$ represents the percentage of thawed soil classified by both SMAP/ESDR and QLB-NET. $F_{\text{in situ}}/T_{\text{in situ}}$, $T/F_{\text{in situ}}$, and $T/T_{\text{in situ}}$ have the same relationship. The percentage at the bottom of each bar is the total classification accuracy, i.e., the sum of percentages of $T/T_{\text{in situ}}$ and $F/F_{\text{in situ}}$. 
Conclusions

The dense soil moisture and temperature monitoring network in the Qinghai Lake Basin (QLB-NET) has been successfully established. We have completed major procedures, including network design, sensor installation, data collection, calibration, and archive. The network consists of 82 sites that measure SM and ST at three depths of 5, 10, and 30 cm. The large-scale network was deployed with 60 sites in the 36 km × 40 km experimental area, completely covering the coarse grids of SMAP (36 km × 36 km), SMOS/ESDR (25 km × 25 km), AMSR2 (0.25° × 0.25°), ERA5 (0.1° × 0.1°), and so on. There are two small-scale observation networks, which consist of 11 sites in a 1 km × 1 km area. All data were quality-controlled by checking the SM and ST time series to remove suspected or incorrect data. The metadata includes site information of geographic position, elevation, slope, aspect, land cover, soil texture, SOC content, start time, etc.

The seasonal dynamics and spatial variations in the QLB-NET SM and ST measurements were analyzed, and the quality of the QLB-NET measured SM and ST-derived FT datasets were carefully examined based on a 3,000-member bootstrapping method. Preliminary applications of the QLB-NET SM and ST-derived FT measurements are also conducted in this paper. The results show that QLB-NET can provide stable and reliable ground truth at grid scales of 36 km × 36 km, 25 km × 25 km, and 0.25° × 0.25° when statistics are correspondingly performed over 50 out of 54, 25 out of 29, and 25 out of 28 sites: 1) the STDs of the mean SM measurements vary between 0.0127 and 0.0196 m³ m⁻³, with the corresponding difference between the upper and lower quartiles of the mean SM less than 0.02 m³ m⁻³; 2) the ground freeze–thaw state can be correctly identified with high probabilities ranging from 85.3% to 100% on two freeze–thaw transitional dates. These results further illustrate the high qualities of the spatially dense QLB-NET observations, i.e., SM and ST, that can be used as reliable reference true values for product validations and uncertainty analyses. The QLB-NET is well qualified and could be a candidate core validation site for satellite SM and FT production.

The QLB-NET adds new value to the existing in situ SM and FT observations in the QTP. Specifically, 1) it provides reliable ground truth through densely distributed in situ sites at one large-scale network and two small-scale networks to benefit scaling-related research and comprehensive validation work; 2) it fills the gap between highly undulating and flat terrain with its moderate undulating terrain to facilitate the development of accurate radiation transfer models for mountainous areas; 3) it helps to improve the accuracies of SM products, such as AMSRjaxa, AMSRmcca, SMAPdca, and SMAPmcca SM, by optimizing model parameters using in situ measurements; 4) as an area facing a higher potential of permafrost degradation accomplished with possibly increasing active layer depth and soil freeze–thaw transition frequency, QLB-NET will play an essential role in improving the classification accuracy of FT products in transition seasons; and 5) it is a representative area within the QTP for studying interconnection and interaction between changes in soil carbon/vegetation phenology and soil hydrothermal conditions (e.g., FT and SM) under the background of climate change. Overall, the QLB-NET has great potential to support studies as mentioned above in the QTP independently or by collaborating with the existing SM&ST networks. The possible applications of the QLB-NET measurements include comprehensive validations of coarse-resolution SM and FT products, studies on the characteristics of soil moisture change and its driving mechanism in alpine meadows, optimization of the SM and FT retrieving algorithms and scaling methods, development of indirect validation methods, such as TCH, TC, and CTC, and improvement of the mountainous microwave radiative transfer model.
To encourage the general use of the QLB-NET measurements by a range of communities, we are cooperating with the National Tibetan Plateau Data Center (TPDC; http://data.tpdc.ac.cn; Pan et al. 2021) to publish the observed data. Since the QLB-NET runs over a long-term basis, hopefully for more than 10 years under careful maintenance, damaged devices will be replaced during each year’s network inspection to ensure that the sites remain densely distributed all the time. Moreover, the continuously observed data will be updated online annually to facilitate related research.

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Data availability statement. The operational SM datasets used in this article are openly available at https://doi.org/10.5067/OMHV5RGFX380 (SMAPdca SM), https://doi.org/10.11888/Terre.tpdc.300486 (SMAPmcca SM), https://gportal.jaxa.jp (AMSRjaxa SM), https://doi.org/10.11888/Terre.tpdc.272907 (AMSRmcca SM) and https://doi.org/10.24381/cds.e2161bac (ERA5 SM). The SMAP FT and ESDR FT are respectively available at https://doi.org/10.5067/ZJOKL452HRLD and https://doi.org/10.5067/LJ6SLXJB2CQ. Due to confidentiality agreements, the QLB-NET observations will be made available online in 2024 at the TPDC (https://data.tpdc.ac.cn). Details of the ground data and how to request access are now available from Dr. Ziwei Xu (xuzw@bnu.edu.cn).
References


