Active and Passive Microwave Signatures of Diurnal Soil Freeze-Thaw Transitions on the Tibetan Plateau

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Abstract—Active and passive microwave characteristics of diurnal soil freeze-thaw transitions and their relationships are crucial for developing retrieval algorithms of the soil liquid water content (θliq) and freeze/thaw state, which, however, have been less explored. This study investigates these microwave characteristics and relationships via analysis of ground-based measurements of brightness temperature (TB) and backscattering coefficients (σ0) in combination with simulations performed with the Tor Vergata discrete radiative transfer model. Both an L-band (1.4 GHz) radiometer ELBARA-III and a wide-band (1–10 GHz) scatterometer are installed in a seasonally frozen Tibetan meadow ecosystem to measure diurnal variations of TB and copolarized σ0 at both hh (σ0hh) and vv (σ0vv) polarizations. Analysis of measurements collected between December 2017 and March 2018 shows that 1) diurnal cycles are observed in both TB and σ0 due to the change in surface θliq caused by diurnal soil freeze-thaw transitions; 2) a negatively linear relationship is found between ε and σ0 regardless of frequency, polarization combinations, and observation angles; 3) slopes (β) of linearly fit equations between ε and σ0 decrease with increasing observation angles of ELBARA-III, while the ones between ε and σ0 increase with increasing observation angles; and 4) correlations between ε and σ0 increase with decreasing microwave frequency of σ0 measurements and ELBARA-III observation angles, and magnitudes of diurnal σ0 cycles also increase with decreasing microwave frequency. Moreover, the calibrated Tor Vergata model shows capability to reproduce both diurnal ε and σ0 variations as well as to quantify their relationships at different frequencies and observation angles.

Index Terms—Active and passive, frozen soil, L-band microwave radiometry, sentinel, soil moisture active passive (SMAP), soil moisture and ocean salinity (SMOS), wide-band microwave scatterometer.

I. INTRODUCTION

A CCURATE information on soil moisture and diurnal freeze-thaw transitions plays an important role in quantifying water and heat exchanges in cold regions such as the Tibetan Plateau [1]. Microwave remote sensing is recognized as one of the best ways to monitor soil moisture and freeze/thaw state at the regional or global scale due to its high sensitivity to soil permittivity and all-weather sensing ability [2], [3]. Over the past few decades, numerous efforts have been devoted to developing large-scale soil moisture and freeze/thaw state products from spaceborne passive and active microwave sensors, such as the Special Sensor Microwave Imager (SSMI) [4]–[7], Advanced Microwave Scanning Radiometer-Earth (AMSR-E) [8], [9], Advanced Scatterometer (ASCAT) [10], Soil Moisture and Ocean Salinity (SMOS) [3], [11], and Sentinel-1A/B [12]. However, most of these research was conducted separately based on either passive or active microwave sensors.

A joint use of active and passive microwave measurements for retrieving soil moisture and freeze/thaw state has gained increasing research interest, especially after the launch of National Aeronautics and Space Administration (NASA)'s Aquarius [13], [14] and Soil Moisture Active Passive (SMAP) [15], [16] satellites. Spaceborne active microwave sensors [e.g., synthetic aperture radar (SAR)] generally have the advantage of sensing land surface at fine spatial resolution (e.g., ~1 km or finer) but are highly susceptible to interlinked scattering of vegetation and the underlying rough ground. On the other hand, spaceborne passive microwave sensors (i.e., radiometer) have a better sensitivity to soil permittivity but suffer from coarse spatial resolution (e.g., dozens of kilometers) as constrained by the antenna size. Therefore, a joint use of active and passive microwave sensors provides the potential to combine their relative advantages for improving spatial resolution and accuracy of soil moisture products. The SMAP mission that simultaneously collected radar and radiometer measurements at the L-band with the spatial resolution of 3 and 40 km was dedicated to integrating...
both sensors to produce an intermediate resolution (9 km) and accuracy of global soil moisture product [15], [17]. Although the SMAP radar stopped working on July 2015, progress has been made to use other alternative radar measurements such as the C-band Sentinel-1A/B for generating the intermediate resolution product [18]. The downscaling algorithm implemented by the SMAP mission is mainly based on a quasi-linear relationship between emissivity ($\epsilon$) and backscatter ($\sigma^0$) measurements that is captured by a slope parameter ($\beta$). While this linear relationship has widely been tested for the L/L- and L/C-band combinations of radiometer and radar measurements [14], [18], [19], little is known about other cases such as the L/S- and L/X-band combinations. In addition, the above-mentioned works mainly focused on thawed soil conditions, and whether the linear relationship still exists in the frozen soil conditions is unknown.

In addition to the downscaling subject, the synergy of active and passive microwave sensors has also been explored in other ways that are beyond the spatial resolution issue. For instance, a triangle-like shape was found in the $\sigma^0$ versus $\epsilon$ plane based on both measurements and theoretical simulations [20], whereby three vertices represent the active and passive microwave characteristics of dry surface, wet surface, and vegetation volume scattering, respectively. Collie and Xu [21] developed a normalized residual scattering coefficient based on a similar concept. To overcome the difficulty in applying the discrete scattering model at the satellite scale, Dente et al. [22] used both C-band AMSR-E radiometer and ASCAT scatterometer measurements to constrain the complex model for obtaining an optimal parameter dataset. Similar work was recently done by Wang et al. [23] and Bai et al. [24] to simultaneously simulate both $\sigma^0$ and $\epsilon$ as well as retrieve soil moisture based on L-band active and passive microwave measurements collected by the Aquarius and SMAP, respectively. These studies have shown the potential to obtain an identical parameter dataset for reproducing both active and passive microwave measurements at the same frequency based on a unified model, while its validity for different frequency measurements has not been tested. In addition, the performance of the discrete scattering model in simulating both $\sigma^0$ and $\epsilon$ has not been investigated for the frozen soil conditions as well.

In the context of SMAP mission, a series of field campaigns have been conducted with airborne radiometers and radars/scatterometers to collect active and passive measurements over various land and climate conditions, such as the SMAPEx [25], SMAPVEX12 [26], scanning L-band active passive experiment (SLAPEx) [27], and SMAPVEX15 [28] carried out in Australia, Canada, and USA, respectively. More recently, a similar flight campaign with configuration of variable incidence angles was performed in the northern part of China to validate a new concept of Terrestrial Water Resources Satellite (TWRS) [29]. However, only the SLAPEx was devoted to the frozen soil conditions, where more than half of land surface is covered by permafrost and seasonal frost during winters in the Northern Hemisphere [30]. It is thus imperative to investigate the active and passive microwave characteristics of frozen ground. As a pioneer, Wegmüller [31] investigated the impact of soil freezing and thawing on microwave signatures based on a ground-based radiometer-scatterometer system (i.e., RASAM) working at frequency ranging from 3 to 11 GHz. In comparison to the spaceborne or airborne system, the ground-based system is able to monitor the diurnal soil freezing and thawing transitions at much higher temporal resolution. It should be noted that different models were adopted by Wegmüller [31] to interpret active and passive microwave measurements separately, which hamper the joint usage of complementary information behind both sensors.

Therefore, we investigate in this study the active and passive microwave characteristics of diurnal soil freezing and thawing transitions and their relationships at different frequencies via combined analysis of ground-based measurements and simulations performed with a unified discrete scattering model. An L-band (1.4 GHz) radiometer (i.e., ELBARA-III) and a wide-band scatterometer working at frequency between 1 and 10 GHz have been installed in a seasonally frozen Tibetan meadow ecosystem to measure diurnal variations of brightness temperature ($T_B$) and copolarized $\sigma^0$. The discrete scattering model developed at the Tor Vergata University of Rome (hereafter “Tor Vergata model”) [32] that has been widely validated in the Tibetan meadow ecosystem [22], [23] is implemented to simulate both $\epsilon$ and $\sigma^0$ measurements and quantify their relationships.

This article is organized as follows. The ground-based radiometer and scatterometer measurements are described in Section II. Section III introduces the Tor Vergata model and its optimization method. Detailed analyses on $T_B$ and $\sigma^0$ measurements as well as their relationships are presented in Section IV. Section V investigates the performance of the calibrated Tor Vergata model in simulating both $\epsilon$ and $\sigma^0$. Brief findings are concluded in Section VI.

## II. MAQU FIELD SITE AND MEASUREMENTS

The ground-based L-band ELBARA-III radiometer and a wide-band scatterometer were installed in a seasonally frozen alpine meadow ecosystem (33.92 °N, 102.16 °E) located in the Maqu County over the northeast Tibetan Plateau [33]–[35]. The elevation of the Maqu site is about 3450 m, and the soil type is sandy loam with an average of 49.7% sand content, 2.2% clay content, and a bulk density of 1 g cm$^{-3}$ near the soil surface (i.e., 0–10 cm). In January 2016, the ELBARA-III radiometer was deployed on a 4.8-m tower (Fig. 1) to measure the $T_B$ of ground at 1.4 GHz every 30 min, and the observation angles range between 40$^\circ$ and 70$^\circ$ relative to nadir in steps of 5$^\circ$. A two-point calibration strategy that uses an active cold source (ACS) and a resistive source (RS) as internal reference noise sources is adopted to obtain the $T_B$ from raw data of ELBARA-III measurements. Noise temperature of the ACS is derived from cold sky measurements performed once per day at an angle of 155$^\circ$, and noise temperature of the RS is kept constant as the internal temperature of instrument using a 50-Ω resistor. The accuracy of the calibrated $T_B$ measurements is better than 1 K [36]. Concurrent micrometeorological measurements, e.g., air temperature, solar
radiations, precipitation, and surface heat fluxes, were also performed (Fig. 1). In August 2016, a vertically dense soil moisture and soil temperature (SMST) profile measurement was performed with the Decagon 5TM capacitance probes every 15 min installed at following depths below the surface: 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, and 100 cm. The accuracy of the 5TM probe in measuring the liquid water content ($\theta_{\text{liq}}$) under frozen soil conditions was confirmed in our previous work [37] via comparisons with $\theta_{\text{liq}}$ simulations made by a land surface model. It was shown that there is still the presence of $\theta_{\text{liq}}$ in the frozen soil due to the absorptive and capillary forces exerted by soil particles. Until now, the above instruments are still operational in the Maqu site, and detailed information about those measurements can be found in Zheng et al. [35] and Su et al. [38].

In August 2017, the wide-band scatterometer was mounted on the same tower (Fig. 1) to measure the backscatter of ground over 1–10 GHz hourly (before December 2017) or every 30 min (after December 2017). The scatterometer consists mainly of a two-port vector network analyzer (VNA, PNA-L 5232A, Keysight), two dual polarization broadband horn antennas (BBHX9120LF, Schwarzbeck), and four phase-stable coaxial cables (Succoflex SF104PEA, Huber & Suhner) to connect the antennas with the VNA. The antenna boresight angle was fixed at a 55° angle of incidence, and a computer program was designed to perform the scatterometer’s measurements automatically. Recently, the copolarized backscattering coefficients ($\sigma^0$) at S- (2.5–3.0 GHz), C- (4.5–5.0 GHz), and X-bands (9.0–10.0 GHz) were derived by Hofste et al. [33] from the scatterometer measured amplitude and phase of radar return for the period between August 2017 and August 2018.

Since the uncertainty is greatest at the L-band due to the low angular resolution issue and pulse deformation effect, the $\sigma^0$ of the L-band was not derived. A detailed description of the scatterometer measurements and estimation of $\sigma^0$ is outlined in [33]. Specifically, the $\sigma^0$ was estimated by the narrow-beam approximation in combination with mapping the function $G^2/R^4$ over the ground to account for the impact of wide antenna radiation patterns ($G$), whereby $R$ is the distance between the ground surface and the antennas. The incidence angles ($\theta$) of different bands and polarizations were considered as the incidence angle at the surface point where $G^2/R^4$ has its peak value. This results in $\theta = 49°$ for the S-band at vv polarization and 44° for hh polarization, $\theta = 51°$ for the C-band at both vv and hh polarizations, and $\theta = 53°$ for the X-band at vv polarization and 54° for hh polarization. A rectangular metal plate and two metal dihedral reflectors were used as the reference targets to calibrate the scatterometer, and the frequency averaging technique was adopted to mitigate the fading effect. The uncertainty in the derived $\sigma^0$ was estimated to vary from ±1.3 to ±2.7 dB for different frequencies and polarizations due to the impacts of fading, calibration, and system stability. The scatterometer stopped working during the period from October 23 to December 14, 2017 due to a power supply failure.

In this study, a cold period between December 15, 2017 and March 15, 2018 is selected for the analysis, whereby concurrent measurements of multangular L-band $T_B$, S-, C-, and X-band copolarized $\sigma^0$ at different incidence angles, profile SMST, and micrometeorological variables are available. All the data are processed to a time interval of 30 min. It should be noted that there is a 10-min offset between each ELBARA-III and scatterometer measurements.
III. METHODS

A. Discrete Radiative Transfer Model

The active and passive versions of the Tor Vergata model [32], [39], [40] are adopted in this study to simultaneously simulate the copolarized \(\sigma^0\) and emissivity \(e\) of diurnal soil freeze-thaw transitions. The Tor Vergata model was developed based on the microwave radiative transfer theory and adopts a discrete approach, which has been extensively calibrated/validated for its application to the Maqu grassland site [22]–[24], [34].

As in [22], the soil profile is assumed as a homogeneous infinite half-space with a rough interface, and the overlying grass at the Maqu site is represented as an ensemble of discrete dielectric disks. The electromagnetic properties (e.g., absorption and scattering coefficients) of the discrete disks are calculated by employing the Rayleigh–Gans approximation and physical optics approximation in [41] for frequency below and above 5 GHz, respectively. Leaf coverage is needed to compute the electromagnetic properties of grass, which is represented by the leaf area index (LAI). The contributions from individual disks are integrated by applying the matrix doubling algorithm in [41] to obtain the transmission and bistatic scattering coefficients of vegetation canopy. The bistatic scattering coefficient of soil is estimated by adopting the integral equation method (IEM) in [42], whereby the needed soil permittivity \(e_s\) is obtained via using the four-phase dielectric mixing model as described in [34] (see also Section III-B). Litter is further considered as an extra thin layer as in [22], which is treated as a dielectric mixture of air, water, and litter. The matrix doubling algorithm is further adopted to combine the scattering contributions from vegetation and soil-litter medium to obtain the total bistatic scattering coefficients of vegetation-soil system in all directions. The \(\sigma^0\) is equal to the bistatic scattering coefficients in the backward direction where the zenith and azimuth angles of the scattered signal are opposite to those of the incident signal. The reflectivity \(r_{\alpha}\) is obtained by integrating the bistatic scattering coefficients over the upper hemisphere, and the emissivity is then computed by applying Kirchoff’s energy conservation law, i.e., \(e = 1 - r_{\alpha}\). The uniqueness of the Tor Vergata model is that it is able to simulate the \(\sigma^0\) and \(e\) at multiple frequencies and incidence angles using an identical microwave radiative transfer model based on the same set of vegetation and soil parameters. Detailed descriptions of the Tor Vergata model are referred to [22] and [32].

B. Soil Effective Temperature and Permittivity

Soil effective temperature \(T_{\text{eff}}\) is needed to convert the simulated \(e\) to \(T_B\) \((T_B = e \times T_{\text{eff}})\), which can be estimated based on the SMST profile measurements (Section II) as [43]

\[
T_{\text{eff}} = \frac{1}{\pi} \int_{0}^{\infty} T(z) a(z) \exp \left[ - \int_{0}^{z} a(z') dz' \right] dz \tag{1}
\]

\[
a(z) = \frac{4\pi}{\lambda} \frac{\varepsilon_s'(z)}{2\sqrt{\varepsilon_s''(z)}} \tag{2}
\]

where \(T(z)\) and \(a(z)\) are the soil temperature and soil attenuation coefficient at depth \(z\), respectively, \(\lambda\) is the wavelength, and \(\varepsilon_s'\) and \(\varepsilon_s''\) are the real and imaginary parts of soil permittivity.

In this study, the soil permittivity \(\varepsilon_s(e_s = \varepsilon_s' + i \cdot \varepsilon_s'')\) is estimated by the four-phase dielectric mixing model in [44], [45] that has been validated by Zheng et al. [46] for its application to both frozen and unfrozen soil conditions in the Maqu site

\[
\varepsilon_s''(\theta) = (\theta - \theta_{\text{th}})\varepsilon_{\text{air}}^n + \theta_{\text{th}}\varepsilon_{\text{ice}}^n + (\theta - \theta_{\text{th}})\varepsilon_{\text{matrix}}^n (1 - \theta_{\text{th}})\varepsilon^0 \tag{3}
\]

where the exponent \(n\) is set equal to 0.5, \(\theta\) is the volumetric total soil water content, \(\theta_{\text{th}}\) is the volumetric liquid soil water content, \(\theta_{\text{th}}\) is the porosity, and \(\varepsilon\) represents the permittivity with subscripts air, w, ice, and matrix referred to air, water, ice, and soil matrix. Readers are referred to [46] for a detailed description on the four-phase dielectric mixing model.

C. Parameter Optimization

As in [22], the most sensitive parameters of the Tor Vergata model will be optimized by tuning the parameter values to reach an optimal match between the measured and simulated \(\sigma^0\) and \(T_B\). The Tor Vergata simulated \(e\) is converted to \(T_B\) by multiplying the \(T_{\text{eff}}\), i.e., \(T_B = e \times T_{\text{eff}}\). The following cost function is used to minimize the differences between the Tor Vergata simulations and \textit{in situ} measurements:

\[
J = \frac{\text{MAE}(\sigma_{\text{hh}}^0)}{\Delta \sigma_{\text{hh},\text{obs}}} + \frac{\text{MAE}(\sigma_{\text{vv}}^0)}{\Delta \sigma_{\text{vv},\text{obs}}} + \frac{\text{MAE}(T_B^H)}{\Delta T_B^H,\text{obs}} + \frac{\text{MAE}(T_B^V)}{\Delta T_B^V,\text{obs}} \tag{4}
\]

where MAE is the mean absolute error between the Tor Vergata simulations and \textit{in situ} measurements, \(\Delta\) represents the standard deviation of scatterometer or ELBARA-III measurements, \(T_B^H\) and \(T_B^V\) are the brightness temperature at horizontal and vertical polarizations, and \(\sigma_{\text{hh}}^0\) and \(\sigma_{\text{vv}}^0\) are the copolarized backscattering coefficients at hh and vv polarization combinations.

IV. MEASURED MICROWAVE SIGNATURES OF SOIL FREEZE-THAW TRANSITIONS

A. Long-Term Analysis

Fig. 2(a) and (b) shows the time series of scatterometer measured copolarized \(\sigma^0\) at the S-, C-, and X-bands with a time interval of 30 min for the hh and vv polarizations, respectively. The measured precipitation and surface albedo derived from the measured up- and downward shortwave radiations are also shown in Fig. 2(a) and (b) to indicate the snowfall and presence of snowpack, respectively. Fig. 2(c) shows the ELBARA-III measured \(T_B^H\) and \(T_B^V\) at the incidence angles of 40° and 55° relative to the nadir together with the derived surface albedo. Data gaps noted for the \(T_B\) measurements, e.g., between February 2 and 8, 2018, are mainly caused by power supply failures. In support of analysis, Fig. 2(d) and (e) further shows the profile SMST measurements at soil depths of 2.5, 5, 10, 25, 70, and 100 cm, and the \(T_{\text{eff}}\) estimated by using (1) based on the profile SMST measurements is shown in Fig. 2(e) as well.

The upper soil layers are generally frozen before the beginning of February, e.g., the soil temperatures \(T_s\) above the
Fig. 2. Time series of *in situ* measurements with a time interval of 30 min from December 15, 2017 to March 15, 2018. (a) Scatterometer measured $\sigma^0$ at the S-, C-, and X-bands for hh and (b) vv polarizations. (c) ELBARA-III measured $TB$ at observation angles of 40$^\circ$ and 55$^\circ$ for both polarizations. (d) $\theta_{liq}$ and (e) $Ts$ at soil depths of 2.5, 5, 10, 25, 70, and 100 cm. The precipitation is shown in (a), surface albedo is shown in (b) and (c), and $T_{eff}$ is shown in (e) as well.
Diurnal variations can be also observed for both copolarized $\sigma^0$ and $T_B$ measurements. Specifically, the magnitudes of diurnal $\theta_{liq}$ cycles generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column. Interestingly, similar diurnal variations can be also observed for both copolarized $\sigma^0$ and $T_B$ measurements. Generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column. Interestingly, similar diurnal variations can be also observed for both copolarized $\sigma^0$ and $T_B$ measurements. Specifically, the magnitudes of diurnal $\theta_{liq}$ cycles generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column.

B. Diurnal Variations

Two short periods excluding the presence of snowfall and snowpack are further selected to investigate the microwave characteristics of diurnal soil freezing and thawing transitions. The microwave characteristics of diurnal soil freezing and thawing transitions can be observed in the measured $\theta_{liq}$ for soil layers above 25 cm due to the diurnal soil freezing and thawing transitions caused by the changes of $T_s$. The magnitudes of diurnal $\theta_{liq}$ cycles generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column. Interestingly, similar diurnal variations can be also observed for both copolarized $\sigma^0$ and $T_B$ measurements. Specifically, the magnitudes of diurnal $\sigma^0$ cycles generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column. Interestingly, similar diurnal variations can be also observed for both copolarized $\sigma^0$ and $T_B$ measurements. Generally follow the diurnal $T_s$ variations, both of which decrease with increasing soil depth due to the damping effect of the soil column.

**References**

[47], [48].

The surface soil starts thawing at the beginning of February with the increase of $T_s$, and much larger magnitudes of diurnal $\theta_{liq}$ cycles can be noted for the measurements taken at 2.5 cm due to stronger soil freezing and thawing variations as seen in the near-surface layer. As a result, much larger magnitudes of diurnal cycles can be also found in both copolarized $\sigma^0$ and $T_B$ measurements. The snowfall and presence of snowpack are more frequent since the end of January, and the freezing and thawing of both snowpack and surface soil leads to the larger magnitudes of diurnal $\sigma^0$ and $T_B$ variations. It can be noted that the values of $\sigma^0$ measured at both X- and C-bands are comparable to each other due to the fact that the presence of snowmelt and increase of $\theta_{liq}$ largely decrease their penetration capacities.
Fig. 3. Diurnal variations of (a) and (c) $\sigma^0$ measurements at the S-, C-, and X-bands for hh and vv polarizations and (b) and (d) L-band $T_B$ measurements and emissivity at observation angles of 40° and 55° for horizontal and vertical polarizations in (a) and (b) freezing (December 15–20) and (c) and (d) thawing (February 21–26) periods. The $\theta_{liq}$ measurements at a soil depth of 2.5 cm are shown in (a) and (c), and $T_{eff}$ is shown in (b) and (d) as well.

Fig. 4 shows the angular dependency of averaged $T_B$ measurements at both polarizations for the selected freezing and thawing periods. The angular characteristics clearly reveal the typical Fresnel behavior for both periods, whereby the $T_B$ measurements monotonically decrease with the increase in the incidence angle, and the $T_B$ measurements show a “Brewster-like” maximum at about 55°–60°.

C. Relationships Between Active and Passive Measurements

Fig. 5 shows the relationships between L-band $e$ at observation angles ranging from 40° to 55° and C-band copolarized $\sigma^0$ measurements at an observation angle of 51° (see Section II) for the selected freezing and thawing periods. Both linearly fit equations and correlation coefficients ($R^2$) are also shown in the figure. Negatively linear relationships are found between the L-band $e$ and C-band $\sigma^0$ regardless of observation angles and polarization combinations for both periods. The negative linear relationships also hold for both daytime (7–18 h) and nighttime (19–6 h) measurements (figures not shown). Such a relationship was widely reported and implemented as the theoretical basis for downscaling coarse resolution L-band SMAP $T_B$ measurements with the high resolution C-band Sentinel $\sigma^0$ measurements [18], [29], [50], [51]. Interestingly, both slopes ($\beta$) and intercepts of linearly fit equations between L-band $e^H$ and C-band $\sigma^0$ generally decrease with the increase in ELBARA-III incidence angles in both periods, while those of linearly fit equations between $e^V$ and $\sigma^0$ increase with increasing incidence angles. As the observation angles increase, the $R^2$ values generally show decreasing trends for both polarizations and periods. It can be noted that the $R^2$ values are larger in the freezing period for different observation angles and polarizations in comparison to those in the thawing period.

Table I further provides the $R^2$ values and slopes of linearly fit equations between L-band $e$ at observation angles ranging from 40° to 55° and copolarized $\sigma^0$ measurements of S- and X-bands for the selected freezing and thawing periods. Similar to the C-band, the negatively linear relationships also exist between the L-band $e$ and $\sigma^0$ of both S- and X-bands except the $e^H$ and $\sigma^0$ in the freezing period. The slopes of linearly fit equations between L-band $e^V$ and $\sigma^0$ of both S- and X-bands increase with the increase of ELBARA-III
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Fig. 5. Relationships between (a) and (c) L-band $e^H$ at multiple observation angles and C-band $\sigma^0_{hh}$ and (b) and (d) L-band $e^V$ at multiple observation angles and C-band $\sigma^0_{vv}$ for the selected (a) and (b) freezing and (c) and (d) thawing periods.

TABLE I

<table>
<thead>
<tr>
<th>Incidence Angle of ELBRA-II</th>
<th>Freezing Period</th>
<th>Thawing Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-band</td>
<td>X-band</td>
</tr>
<tr>
<td></td>
<td>$e^H$ and $\sigma^0_{hh}$</td>
<td>$e^V$ and $\sigma^0_{vv}$</td>
</tr>
<tr>
<td></td>
<td>Slope $R^2$</td>
<td>Slope $R^2$</td>
</tr>
<tr>
<td>40°</td>
<td>-0.015, 0.118</td>
<td>-0.022, 0.609</td>
</tr>
<tr>
<td>45°</td>
<td>-0.014, 0.104</td>
<td>-0.023, 0.672</td>
</tr>
<tr>
<td>50°</td>
<td>-0.014, 0.099</td>
<td>-0.027, 0.742</td>
</tr>
<tr>
<td>55°</td>
<td>-0.014, 0.099</td>
<td>-0.031, 0.760</td>
</tr>
</tbody>
</table>

observation angles, especially in the freezing period, while the corresponding $R^2$ values decrease with increasing observation angles. For the linear relationships between L-band $e^H$ and $\sigma^0_{hh}$ of both S- and X-bands, the slopes decrease with increasing observation angles in the thawing period as the C-band, while the $R^2$ values in the freezing period are very small. In addition, it can be noted that the $R^2$ values generally increase with the increase in the wavelength as shown in Fig. 5 and Table I.

V. SIMULATION OF DIURNAL SOIL FREEZE-THAW PROCESSES

A. Design of Model Calibration and Validation

The Tor Vergata model described in Section III-A is adopted to simulate the diurnal variations of $\sigma^0$ and $e$ at different frequencies and observation angles as well as to quantify their relationships for the selected freezing and thawing periods. Specifically, the L-band $e$ at an observation angle of 40° and C-band $\sigma^0$ at an observation angle of 51° that approximately represent the configurations of L-band SMAP $T_B$ and C-band Sentinel $\sigma^0$ measurements are investigated.

Several soil and vegetation parameters are needed to run the Tor Vergata model, including soil permittivity ($\varepsilon_s$), moisture contents of leaf and litter layers, LAI, leaf dimensions (i.e., radius and thickness), litter biomass, and height standard deviation ($s$) and autocorrelation length ($l$) of surface roughness. The $\varepsilon_s$ is estimated using the four-phase dielectric mixing model ([3]) with in situ $\theta_{liq}$ and $T_e$ measurements of 2.5 cm as well as laboratory measurements of soil properties (i.e., bulk density, sand and clay contents). The LAI
is obtained from the MODIS product (MCD15A3H) with values ranging from 0.22 to 0.30 for the study period between December 2017 and March 2018. As in [23], the values for leaf dimensions are taken from [22], and the values of remaining more sensitive parameters are further calibrated in this study using both ELBARA-III and scatterometer measurements. Specifically, the ELBARA-III measured $T_B^H$ and $T_B^V$ at an observation angle of 40° and scatterometer measured $\sigma_0^H$ and $\sigma_0^V$ at the C-band in the freezing period (December 15–20, 2017) are used to calibrate the Tor Vergata model with the method described in Section III-C. In addition, the calibrated Tor Vergata model is further validated using both ELBARA-III and scatterometer measurements in the thawing period (February 21–26, 2018), which is then used to quantify the relationships between L-band $e$ of 40° and C-band $\sigma_0$ of 51° for both freezing and thawing periods.

### B. Model Simulations

Table II lists the values of needed parameters for the Tor Vergata model obtained by the model calibration and derived from [22]. The optimized values obtained in this study are comparable to those reported in [22] except that the lower value of leaf moisture content and zero value of litter biomass are obtained. As also shown in [52], the impact of the litter layer can be ignored for the selected freezing and thawing periods at the Maqu site. The lower leaf moisture content can be expected since the work of [22] focused on the warm and rainy season.

Fig. 6(a) and (c) shows the diurnal variations of scatterometer measured $\sigma_0$ and simulations produced by the calibrated Tor Vergata model at the C-band for both hh and vv polarizations in the freezing and thawing periods, respectively. The corresponding error statistics, i.e., bias, root mean squared error (RMSE), and unbiased RMSE (ubRMSE), computed between the scatterometer measurements and simulations are given in Table III. The calibrated Tor Vergata model generally captures well the diurnal variations of $\sigma_0$ measurements for

### Table II

<table>
<thead>
<tr>
<th>Table II</th>
<th>LIST OF INPUT PARAMETERS FOR THE TOR VERGATA MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Soil Moisture, In-situ measurements taken at 2.5cm</td>
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<tr>
<td></td>
<td>Soil properties, Laboratory measurements</td>
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<td></td>
<td>Autocorrelation length function, Exponential function</td>
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<td></td>
<td>Height standard deviation, 0.4 cm</td>
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<td></td>
<td>Correlation length, 7 cm</td>
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<td></td>
<td>Litter biomass, 0 g cm²</td>
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<tr>
<td></td>
<td>Litter moisture content, 0</td>
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<td></td>
<td>Plant moisture content, 0.4 g cm</td>
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<td></td>
<td>LAI, MODIS product</td>
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<tr>
<td></td>
<td>Disc radius, 1.4 cm</td>
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<tr>
<td></td>
<td>Disc thickness, 0.02 cm</td>
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<td></td>
<td>Disc angular distribution, Random</td>
</tr>
<tr>
<td>Leaves</td>
<td>Disc radius, 1.4 cm</td>
</tr>
<tr>
<td></td>
<td>Disc thickness, 0.02 cm</td>
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<tr>
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<td>Disc angular distribution, Random</td>
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</table>
TABLE III

<table>
<thead>
<tr>
<th>Periods</th>
<th>$\sigma_{\text{in}}$ (dB)</th>
<th>Bias</th>
<th>RMSE</th>
<th>ubRMSE</th>
<th>$\sigma_{\text{out}}$ (dB)</th>
<th>Bias</th>
<th>RMSE</th>
<th>ubRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezing Period</td>
<td>-0.18</td>
<td>0.34</td>
<td>0.29</td>
<td>0.27</td>
<td>0.51</td>
<td>0.43</td>
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<tr>
<td>Thawing Period</td>
<td>-0.32</td>
<td>0.64</td>
<td>0.55</td>
<td>0.36</td>
<td>1.04</td>
<td>0.98</td>
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Fig. 7. Relationships between measured and simulated (a) and (c) L-band $e_H$ at an observation angle of 40° and C-band $\sigma_{\text{in}}^0$ at an observation angle of 51° and (b) and (d) L-band $e_V$ and C-band $\sigma_{\text{in}}^0$ for the selected (a) and (b) freezing and (c) and (d) thawing periods.

both hh and vv polarizations in both periods, leading to bias and RMSE values of less than 0.35 and 1.05 dB, respectively, which is well within the measurement uncertainty. The $\sigma^0$ simulations at the hh polarization are better than the vv polarization for both periods, and the simulations in the freezing period outperform the thawing period. A time lag is observed between the peaks of measured and simulated $\sigma^0$ especially in the freezing period, which can be explained by the fact that the input of $\theta_{\text{liq}}$ taken at 2.5 cm cannot capture well the earlier thawing of the upper soil layer.

Fig. 6(b) and (d) shows further the ELBARA-III measured $T_B$ and Tor Vergata simulations at the observation angle of 40° in the freezing and thawing periods, respectively. The corresponding error statistics computed between the ELBARA-III measurements and simulations are provided in Table IV. The calibrated Tor Vergata model is also able to simulate well the diurnal variations of $T_B$ measurements except that larger overestimations can be noted for the $T_B^V$ simulations in the freezing period. In addition, the magnitude of diurnal $T_B^H$ cycles is slightly underestimated. This can be related to the dielectric discontinuities from air to bulk soil caused by inhomogeneous distribution of moisture in the soil volume that was not considered in the Tor Vergata model [53].

The $T_B$ simulations at the horizontal polarization are generally better than the vertical polarization for both periods. Smaller bias and RMSE values are obtained for the thawing period in comparison to the freezing period. In summary, the calibrated Tor Vergata model is able to reproduce well both the diurnal variations of C-band $\sigma^0$ and L-band $T_B$ measurements for both polarizations in both periods with the same set of vegetation and soil parameters.

Fig. 7 shows the relationships between L-band $e$ at an observation angle of 40° and C-band copolarized $\sigma^0$ measurements and simulations produced by the calibrated Tor Vergata model for the selected freezing and thawing periods. Both linearly fit equations and correlation coefficients ($R^2$) are shown in the figure as well. The negatively linear relationships noted between the L-band $e$ and C-band $\sigma^0$ measurements can be also reproduced by the Tor Vergata simulations with larger $R^2$ values and lower scatter among data points. In general, the Tor Vergata simulations tend to produce lower values of slope and intercept for linearly fit equations between L-band $e_H$ and C-band $\sigma_{\text{in}}^0$, while larger values are found for linear relationships between $e_V$ and $\sigma_{\text{in}}^0$ for both periods. It can be also noted that both slopes and intercepts of linearly fit equations between $e$ and $\sigma^0$ simulations in the freezing period are comparable to
those of the thawing period, while large differences are found between the relationships of $e$ and $\sigma^0$ measurements. This indicates that the actual conditions are more complex than the model approximations. In addition, the impacts of fading, calibration, and system stability caused by the temperate effect would bring uncertainties to the scatterometer measurements that may lead to the spread of observation points shown in Fig. 7. Nevertheless, the calibrated Tor Vergata model shows the potential to quantify the relationships between $e$ and $\sigma^0$ at different frequencies and observation angles in both freezing and thawing periods.

VI. CONCLUSION

This study investigates the active and passive microwave characteristics of diurnal soil freezing and thawing transitions via combined analysis of ground-based measurements and simulations performed with a discrete radiative transfer model. A dataset of concurrent L-band (1.4 GHz) ELBARA-III radiometry, S- (2.5–3.0 GHz), C- (4.5–5.0 GHz), and X-band (9.0–10.0 GHz) scatterometer, profile SMST and micrometeorological measurements performed in a seasonally frozen Tibetan meadow ecosystem is selected for the analysis. The dataset is collected during a cold period from December 15, 2017 to March 15, 2018. The Tor Vergata discrete radiative transfer model allowing us to simultaneously simulate the copolarized $\sigma^0$ and $e$ at multiple frequencies and observation angles based on the same set of vegetation and soil parameters is calibrated/validated using the ground-based measurements. The calibrated model is then used to quantify the relationship between L-band $e$ at an observation angle of 40° and C-band copolarized $\sigma^0$ at an observation angle of 51°.

Analyses of ground-based measurements in the cold period show that 1) diurnal cycles are clearly observed in both copolarized $\sigma^0$ and $T_B$ measurements due to the change of surface $\theta_{liq}$ caused by diurnal soil freezing and thawing transitions; 2) the magnitudes of diurnal $\sigma^0$ cycles increase with decreasing microwave frequency while the corresponding absolute $\sigma^0$ values show a contrary trend; and 3) the snowfall and presence of snowpack increase both copolarized $\sigma^0$ and $T_B$ values. Two short continuous observation periods, i.e., a freezing period (from December 15 to 20, 2017) and a thawing period (from February 21 to 26, 2018), are further selected to investigate the diurnal microwave characteristics and the relationship between active and passive measurements. It is demonstrated that 1) the $\sigma^0$ increases with the increase of $\theta_{liq}$ between 8 and 17 h due to soil thawing and then decreases from 17 to 8 h caused by refreezing of $\theta_{liq}$, while the $T_B$ shows a contrary trend with change of $\theta_{liq}$; 2) the diurnal $T_B$ cycles are dominated by the $e$ variations caused by freezing and thawing of the surface layer; 3) negatively linear relationships are found between the L-band $e$ and copolarized $\sigma^0$ of S-, C- and X-bands regardless of observation angles and polarization combinations; 4) slopes ($\beta$) of linearly fit equations between $e^v$ and $\sigma^0_{vh}$ decrease with the increase of ELBARA-III observation angles, while those of linear equations between $e^v$ and $\sigma^0_{vv}$ show contrary trend; and 5) the $R^2$ values between $e$ and $\sigma^0$ increase with decreasing microwave frequency of $\sigma^0$ measurements and ELBARA-III observation angles.

The calibrated Tor Vergata model is shown to be able to reproduce well both the diurnal variations of C-band $\sigma^0$ and L-band $T_B$ measurements for both polarizations in both freezing and thawing periods with the same inputs. For instance, the bias and RMSE values of the $\sigma^0$ simulations are less than 0.35 and 1.05 dB for both hh and vv polarizations in both periods. In addition, both $\sigma^0$ simulations of hh polarization and $T_B$ simulations of horizontal polarization are better than those of vv and vertical polarizations. Moreover, the negatively linear relationships noted between the L-band $e$ and C-band $\sigma^0$ measurements can be also reproduced by the calibrated model with larger $R^2$ values and lower scatter among data points.

This study confirms that the negatively linear relationships widely reported for L-band $e$ and C-band $\sigma^0$ under thawed soil conditions can also be observed in the frozen soil conditions, and such a relationship also exists between L-band $e$ and $\sigma^0$ of both S- and X-bands. In addition, this study further demonstrates the suitability of adopting an identical microwave radiative transfer model (e.g., Tor Vergata model) to quantify above-mentioned relationships at different frequencies and observation angles. These findings are crucial for developing retrieval and downscale algorithms based on both active and passive microwave measurements to obtain high resolution $\theta_{liq}$ products under both frozen and thawed soil conditions.

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Experimental Research, which are comprehensive remote sensing experiments Telemetry Experimental Research and the Heihe Watershed Allied Telemetry Experimental Research, which are comprehensive remote sensing experiments conducted sequentially in recent years with over 350 participants in China. His research interests include land data assimilation, the application of remote sensing and geography information system in hydrology and cryosphere science, and integrated watershed modeling.

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