

Analysis of Soil Hydraulic and Thermal Properties for Land Surface Modelling over the Tibetan Plateau

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Abstract

Soil information (e.g. soil texture and porosity) from existing soil datasets over the Tibetan Plateau (TP) is claimed to be inadequate and even inaccurate for determining soil hydraulic properties (SHP) and soil thermal properties (STP), hampering the understanding of the land surface process. As the soil varies across three dominant climate zones (i.e. arid, semi-arid, and ~~semi-humid~~_{sub-humid}) over the TP, the associated SHP & STP is expected to vary correspondingly. To obtain an explicit insight into the soil hydro-thermal ~~consistency for land surface modelling properties~~ over the TP, *in situ* and laboratory measurements of over ~~40-30~~ soil property profiles were obtained across the climate zones. Results show that porosity and SHP & STP differ across the climate zones and strongly depend on soil texture. In particular, it is proposed that gravel impact on porosity and SHP & STP are both considered in the arid zone and in deep layers of the semi-arid zone. Parameterization schemes for porosity, SHP ~~and~~ STP are investigated and compared with measurements taken. ~~This reveals that the porosity determined by the bulk density scheme is the most applicable for the TP.~~ To determine the SHP, including soil water retention curves and hydraulic conductivities, the pedotransfer functions (PTFs) developed by Cosby et al. (1984) (for the Clapp-Hornberger model) and the continuous Wösten et al. (1999) (for the van Genuchten-Mualem model) are recommended. The STP parameterization scheme proposed by Farouki (1981) based on the mode of De Vries (1963) performed better across the TP than other schemes. Using the parameterization schemes mentioned above, the uncertainties of five existing regional and global soil datasets and their derived SHP/STP over the TP are quantified through comparison with *in situ* and laboratory measurements. The measured soil ~~physical property~~ properties dataset is available at <http://doi.org/10.4121/uuid:61db65b1-b2aa-4ada-b41e-61ef70e57e4a> <https://data.4tu.nl/repository/uuid:c712717c-6ac0-47ff-9d58-97f88082ddc0>.

Keywords: Soil hydraulic and thermal properties; the Tibetan Plateau; Pedotransfer functions; Soil Maps; Land Surface Model.

1. Introduction

As the highest plateau in the world ~~with a very large area~~, the Tibetan Plateau (TP) exerts a ~~huge significant~~ influence on the Earth's climate system ~~and plays a prominent role in the evolution of the Asian monsoon system~~ (Yao et al., 2012; Qiu, 2008; Ma et al., 2017; Kang et al., 2010). Studying this influence can advance our understanding of climate change (Ma et al., 2017). Soil Moisture (hereafter as SM) - one of the lower boundary conditions of the atmosphere - is a crucial land surface state (Koster et al., 2004) and therefore of high interest ~~to investigate the. It modulates~~ land-atmosphere interactions, ~~and reflects-reflecting~~ the trend and the variability of feedback between the water cycle and climate over the TP (Su et al., 2013; Su et al., 2011). ~~Accurate SM information is claimed as a necessity for improving precipitation and hydrology forecasts~~ (Drusch, 2007; Dirmeyer, 2000; Robinson et al., 2008) ~~especially on the TP where it undergoes evident climate change~~ (Ma et al., 2017; Douville et al., 2001; Yang et al., 2014; Yang et al., 2011). Consistent spatial-temporal SM data can be obtained by using land surface models (LSMs) assimilating *in situ* and satellite observations. In these models, the specification of soil hydraulic properties (SHP) (i.e. soil water retention curve, hydraulic conductivities) and soil thermal properties (STP) (i.e. thermal conductivities and heat capacity) is considered more decisive for SM simulation than atmospheric forcing and land surface characteristics ~~are~~ (Shellito et al., 2016; Livneh et al., 2015; Kishné et al., 2017; Gutmann and Small, 2005). ~~because~~ SHP ~~and STP~~ govern the partitioning of SM between infiltration and evaporation flux and ~~STP regulate~~ water heat transport processes (Zeng et al., 2009a; Zeng et al., 2009b; Garcia Gonzalez et al., 2012).

In situ measurements of basic soil properties and SHP & STP are crucial for the physical consistency of soil properties for soil moisture and heat flux simulation by LSMs. LSMs frequently use the Clapp and Hornberger (1978) model and the Van Genuchten (1980)-Mualem (1976) model for SHP, and the Farouki (1981) and Johansen (1975) schemes for STP. Since direct measurements of SHP & STP are always too time, labor and cost consuming, pedotransfer functions (PTFs) (Bouma, 1989; Van Looy et al., 2017) using basic soil property information have been developed to estimate parameters in the above SHP & STP schemes. Examples are the Cosby et al. (1984) PTF (e.g. based on sand fraction) for the CH scheme estimate in Noah and Community Land Model (Chen and Dudhia, 2001; Oleson et al., 2008), and the soil class PTF (e.g. based on soil texture types) for the VG scheme (Balsamo et al., 2009) in the Hydrology-Tiled European Centre for Medium-Range Weather Forecasts (ECMWF) Scheme for Surface Exchanges over Land (H-TESEL). However, these aforementioned PTFs sometimes cannot predict well the SHP & STP, especially when soils contain organic matter or gravels (particle diameter ≥ 2 mm), because gravels and organic matter have different hydraulic and thermal properties than other fine mineral soils, and this suggests a necessity to obtain comprehensive soil properties information (e.g. not only soil texture and porosity information, but also soil organic content and gravel fraction). Furthermore, studies using information on state variables (e.g. near-surface soil moisture or brightness temperature) can retrieve effective SHP & STP directly or indirectly through PTFs and LSMs (Ines and Mohanty, 2008a; Han et al., 2014; Dimitrov et al., 2014; Dimitrov et al., 2015; Yang et al., 2016). Nevertheless, most of such retrievals only focus on the basic surface soil properties and SHP, based on the assumption of a homogenous soil column. If the system is highly heterogeneous (e.g. along the vertical profile), retrieval may be problematic (Ines and Mohanty, 2008b), and *in situ* measurements of soil property profiles can shed light on the soil property retrieval of the vertical profile.

Many global and local efforts have been made to compile and develop soil databases, but uncertainties in soil datasets might also cause bias in predicting SHP & STP, and hence introduce uncertainties in representing the land surface states by LSMs. It has been reported that the overestimations of ECMWF SM analyses in the central TP could be partly attributed to the unrepresentative soil information from the FAO Digital Soil Map (2003) as used in the H-TESEL (Su et al., 2013). Currently, there is only soil texture information and few soil organic content profiles available over the TP when extracted from the published global *in situ* soil profiles (Batjes et al., 2017). The profiles of other vital soil properties, such as dry bulk density (BD) and porosity, are not provided (e.g. no *in situ* BD or porosity profiles available). Moreover, there is no comprehensive *in situ* measurements of basic soil properties, SHP and, particularly for STP for land surface modelling over the TP.

(Su et al., 2013) In this study, we implemented the *in situ* and laboratory measurements of soil physical property profiles across the three climate zones of the TP and compiled the Tibet-Obs soil properties dataset. Based on the dataset, the variations in basic soil properties and SHP & STP across the three climate zones were investigated. Applications of the Tibet-Obs dataset were demonstrated through two cases: ~~based on the in situ and laboratory~~

measurements of soil physical property profiles, the variations in basic soil properties and SHP & STP across the three climate zones of the TP are investigated. 1) discussed The appropriate parameterization schemes of porosity and SHP & STP are discussed for their applicability over the TP for land surface modelling over the TP; 2) evaluated. Furthermore, the uncertainties of the five existing regional and global soil datasets and their derived SHP & STP over the TP are quantified against the *in situ* and laboratory measurements. In Section 2 of this paper, the field campaign and laboratory experiments are introduced described as well as the parameterization schemes for porosity and SHP & STP estimates. The specification of Tibet-Obs dataset with data availability are documented in Section 3. Results on the application of this dataset are presented in Section 4. soil basic property profiles and SHP & STP profiles over the TP are discussed in Section 3. The evaluation of existing soil datasets is also presented. The availability of the measured soil property dataset is documented in Section 4. Conclusions are presented in Section 5. This paper is expected to contribute to land surface modelling and hydro-climatology communities for their studies of the third pole environment, also to soil community in terms of filling geographic gaps of the published existing global soil databases.

Basic soil properties such as soil texture and porosity determine the SHP and STP, and show spatial variation over the TP due to the varying formation factors (e.g. climate & parent material). The TP could be categorized into three dominant climatic zones: an arid zone, a semi-arid zone and a semi-humid zone, according to the Food and Agriculture Organisation (FAO) Aridity Index Map (Zeng et al., 2016). The Tibetan Plateau Observatory of plateau scale soil moisture (SM) and soil temperature (ST) (Tibet Obs) (Su et al., 2011) are distributed throughout these climatic zones: the Ngari network in the arid zone, where sandy soils mixed with gravel are distributed widely; the Naqu network in the semi-arid zone, where loamy sand with organic matter and gravels dominate; the Maqu network in the semi-humid zone, where fine minerals with large silt proportions prevail. Of these, the Naqu network is collocated with the multi-scale SMST monitoring network on the central Tibetan Plateau (CTP-SMTMN) (Yang et al., 2013). *In situ* measurement of soil basic properties and SHP & STP across these networks is crucial for understanding the soil physical consistency of LSMs, and thereby, understanding the land-atmosphere interactions over the TP.

LSMs frequently used are the Clapp and Hornberger (1978) model (i.e. CH scheme) and the Van Genuchten (1980)-Mualem (1976) model (i.e. VG scheme) for SHP, and the Farouki (1981) and Johansen (1975) schemes for STP. Pedotransfer functions (PTFs) (Bouma, 1989) using basic soil property information are developed to estimate parameters in the above SHP/STP schemes. For example, the Noah and Community Land Model (Chen and Dudhia, 2001; Oleson et al., 2008) used the Cosby et al. (1984) PTF for the CH scheme. The Hydrology Tiled European Centre for Medium-Range Weather Forecasts (ECMWF) Scheme for Surface Exchanges over Land (H-TESSEL) used the soil-class PTF (e.g. based on soil texture types) for the VG scheme (Balsamo et al., 2009).

Global and local efforts have been made to compile and develop soil databases, such as the FAO-UNESCO Soil Map of the World (2007) (hereafter as FAO-UNESCO), the Harmonized World Soil Database (hereafter as HWSD) (FAO/IASA/ISRIC/ISSCAS/IR, 2012), a Chinese data set of soil properties (Shangguan et al., 2012; Shangguan et al., 2013) and soil hydraulic parameters using PTFs (Dai et al., 2013) released by Beijing Normal University (hereafter as BNU), “SoilGrids1km” (Hengl et al., 2014) and the updated version of “SoilGrids250m” (Hengl, 2017) released by the International Soil Reference and Information Center (ISRIC)—World Soil Information (WoSIS) Institute, and the hydraulic parameters based on SoilGrids1km and Schaap et al. (2001) PTFs (hereafter as HPSS) (Montzka et al., 2017). The soil profiles collected *in situ* as metadata for developing the above datasets were accessible from ISRIC World Data Center for Soils (Batjes et al., 2017). Nevertheless, when the metadata were extracted over the TP, only soil texture fraction and soil organic content profiles were available. Profiles of other vital soil properties, such as bulk density (BD) and porosity, were not provided (e.g. no *in situ* BD or porosity profiles available). Furthermore, the basic soil properties from above-cited datasets were not necessarily consistent with each other. Uncertainties in soil datasets over the TP might cause bias in predicting SHP & STP, and hence introduce uncertainties in representing the land surface states by LSM. It has been reported that the overestimations of ECMWF SM analyses in the central TP could be partly attributed to the unrepresentative soil information from the FAO Digital Soil Map (2003) as used in H-TESSEL (Su et al., 2013).

Studies using information on state variables (e.g. near surface soil moisture or brightness temperature) can retrieve effective SHP & STP directly or indirectly through PTFs and LSMs (Ines and Mohanty, 2008a; Han et al., 2014; Dimitrov et al., 2014; Dimitrov et al., 2015; Yang et al., 2016). Nevertheless, most of such retrievals only focus on the basic surface soil properties and SHP, based on the assumption of a homogenous soil column. If the system is highly heterogeneous (e.g. along the vertical profile), retrieval may be problematic (Ines and Mohanty, 2008b). In this study, based on the *in situ* and laboratory measurements of soil physical property profiles, the variations in basic soil properties and SHP & STP across the three climate zones of the TP are investigated. The parameterization schemes of porosity and SHP & STP are discussed for their applicability over the TP for land surface modelling. Furthermore, the uncertainties of the five existing regional and global soil datasets and their derived SHP & STP over the TP are quantified against the *in situ* and laboratory measurements. In section 2 of this paper, the field campaign and laboratory experiments are introduced as well as the parameterization schemes for porosity and SHP & STP estimates. Results on the soil basic property profiles and SHP & STP profiles over the TP are discussed in Section 3. The evaluation of existing soil datasets is also presented. The availability of the measured soil property dataset is documented in Section 4. Conclusions are presented in Section 5.

2. Experimental Designs and Parameterization Schemes ~~Materials and methods~~

2.1 Experimental Designs

2.1.1 Field experiments

Soils show spatial variation over the TP due to the varying soil formation factors (e.g. climate & parent material). The TP can be categorized into three dominant climatic zones: an arid zone ($0.03 < \text{Aridity Index (AI)} < 0.2$), a semi-arid zone ($0.2 < \text{AI} < 0.5$) and a sub-humid zone ($0.5 < \text{AI} < 1.0$), according to the Food and Agriculture Organisation (FAO) Aridity Index Map (Fig. 1a) (Zeng et al., 2016). The Tibetan Plateau Observatory of plateau scale soil moisture (SM) and soil temperature (ST) (Tibet-Obs) (Su et al., 2011) are distributed throughout these climatic zones: 1) the Ngari network in the arid zone, located in the western part of the TP with the elevation ranging between 4200 and 6300 m above mean sea level (a.s.l.), where the annual mean temperature is 1.01°C and the annual mean precipitation amount is 66.4 mm, the land cover is a typical desert environment dominated by bare soil surrounded with sparse grass, and soils are prevailed by sandy soils mixed with gravel (Fig. 1b); 2) the Naqu network in the semi-arid zone, located in a flat terrain with rolling hills at an average elevation of 4500 m a.s.l., where the annual mean temperature is -0.6°C and the annual mean precipitation amount is 482 mm, the land cover is characterized as grasslands consisting of prairie grasses and mosses, and soils are dominated by loamy sand with organic matter and gravels (Fig. 1c); and 3) the Maqu network in the sub-humid zone, located at the north-eastern edge of the TP with elevations ranging between 3430 m and 3750 m, where the annual mean temperature is 1.8°C and the mean precipitation is 600 mm annually with more than 70% falling during the monsoon season (e.g. from June till September). The land cover is dominated by short grassland, and soils are dominated by fine minerals with large silt proportions (Fig. 1d). Of these, the Naqu network is collocated with the multi-scale SMST monitoring network on the central Tibetan Plateau (CTP-SMTMN) (Yang et al., 2013).

A field experiment was carried out across the TP in August 2016, taking soil core samples and measuring field saturated hydraulic conductivity (K_s) at various soil depths (Table 1 & Fig. 1). Soils were vertically sampled using sample rings and augers (Eijkelkamp Soil & Water Company) in the vicinity of existing SMST stations of the Tibet-Obs (Su et al. 2011). Table 1 lists the specific sampling approach: 1) the soil was sampled (c.a. 200 g) with a plastic bag used to measure gravel content, soil texture and soil organic content (SOC); 2) the soil was sampled with standard sample rings (5cm in height, 100 cm^3 in volume) for the determination of ~~bulk density~~ dry bulk density (BD), porosity and thermal conductivity (λ); 3) for deriving the Soil Water Retention Curve (SWRC), a dedicated small sample ring (1 cm in height, 20 cm^3 in volume) was used; 4) the *in situ* K_s was measured using the Aardvark permeameter (2840 operating instructions - Eijkelkamp), a fully automated constant-head borehole permeameter. The Reynolds and Elrick solution aided with soil texture-structure category information (Elrick, 1989) was chosen for calculating K_s .

Within the Maqu network, soil samples were collected at eight stations, located in areas to the east, west and southeast of the ELEBARA-III radiometer location as well as in the southwest corner of the Maqu network (Fig. 1a). The K_s was measured at three locations near the ELBARA station, and at one location (CST05-near) in the southwest corner. Within the Naqu network, soil samples were taken at eight sites along the southwest branch of the CTP-SMTMN network ~~by Yang et al. (2013)~~ (Fig. 1b), ~~and the~~ The K_s was measured at seven sites at BJ, Naqu_west, NQ01-04 and MS3608. Within the Ngari network, ~~we sampled~~ soils were sampled at 14 stations (Fig. 1c). Eight sites at Ali02, SQ03, SQ07, SQ10, SQ17, SQ18, SQ20 and SQ21 were chosen for K_s measurement. In total, 155 soils samples were taken and loaded into plastic bags, 101 samples were collected in standard rings and another 96 samples in small rings. Due to the remoteness and harsh environment on the TP, the locations chosen for soil sampling and fieldwork needed to take practical considerations into account, such as: 1) the location should be accessible by track, local road or national road; 2) the surrounding area should be flat enough to be representative of the local area.

2.1.2 Laboratory Experiments

Three categories of soil samples were handled. From the 155 samples (59 from Ngari, 45 from Naqu and 51 from Maqu) in plastic bags, the soils were first separated into ~~coarse gravels~~ and fine ~~components~~ minerals (size $< 2\text{ mm}$) by using a sieve of 2 mm diameter mesh and weighed separately to obtain gravimetric gravel fractions (GGF). ~~Based on fine minerals and the standard particle size classes of the United States Department of Agriculture (USDA), sand~~ Sand ($0.05\text{ mm} < \text{size} < 2\text{ mm}$), silt ($0.002\text{ mm} < \text{size} < 0.05\text{ mm}$) and clay ($\text{size} < 0.002\text{ mm}$) percentages, ~~as well~~

as and the mean particle diameter of the fine ~~component minerals~~ (FD) were determined ~~using with~~ the Malvern Mastersizer 2000 particle size analyzer (<http://www.malvern.com>), and the SOC was determined by the Total Organic Content analytical instrument of Multi N/C 3100 (<http://www.analytik-jena.de/>). For ~~the coarse components~~ gravels, a set of sieves with diameters of 2, 2.5, 4, 5, 7, 10, 16, 20, 25, 31.5, 40 and 50 mm were used to obtain their particle size distribution and the mean particle diameter of gravels (GD).

The 101 undisturbed soil samples (35 from Ngari, 21 from Naqu and 45 from Maqu) in standard sample rings were saturated and then dried in the oven (105°C) for 24 hours. The difference between wet and dry weight with known volume was used to calculate porosity and BD. The KD2Pro thermal property analyzer connected to an SH-1 sensor (Decagon Devices) was used to measure heat capacity C_s and thermal conductivity λ , while the soil was drying, providing drying C_s -SM and λ -SM curves.

The 96 samples in small rings were intended for use in the SWRC experiment ~~by~~ using the pressure cell method, but to complete this entire task was considered too time and labor consuming. Therefore, instead of utilizing all soil samples, only 30 out of 96 samples were used for E-east, E-west, E-southwest, CST05-near, NST30 and NST33 sites in the ~~we regarded 30 samples at E east, E west, E southwest, CST05 near, NST30 and NST33 sites in the~~ Maqu network ~~to be representative~~. As the structure of the samples at Naqu and Ngari networks was so ~~unconsolidated that the material did not remain enclosed within the rings, only 25 Soil samples with loose structures as in the Naqu and Ngari networks were found to easily seep out of the thin rings. Therefore, undisturbed samples packed-contained~~ in standard rings were used from ~~at~~ Naqu_north, SQ17, SQ18 and SQ21 sites ~~for measuring SWRC in the semi arid and arid regions~~.

The quality of the measured soil property dataset was evaluated based on quality indicators (e.g. observation date, level of trust, data quality rating and accuracy) from World Soil Information (WoSIS) institute (Ribeiro et al., 2015). These four indicators provide measures that allow investigators to recognize factors that may compromise the quality of certain data and hence their suitability for use (Ribeiro et al., 2015). The results show that the dataset is of trust level 'C', which means the highest level of the subjective measure inferred from soil expert knowledge. The entered data (level 'A') have been standardized (level 'B'), i.e. data numbers were correspondingly aligned with measured soil properties involved in the GlobalSoilMap specifications (GlobalSoilMap, 2009) and with the measurement method and unit (see above paragraphs in Sec. 2.2). Level "B" dataset was further harmonized ("C") to be sorted in the reference table (Ribeiro et al., 2015). For instance, tables for the profile data (see Table S6 in the Supplement) described a soil profile and its attributes (e.g. land cover, position), and its constituent layers with their respective soil properties. These collated raw data included error-checking for possible inconsistencies. Furthermore, the values of the measured soil properties and SHP & STP were compared to those available in the literature to cross-check if they were within a reasonable range.

The collected basic soil ~~property-properties~~ and SHP & STP datasets ~~over Tibet-Obs named the Tibet-Obs dataset were will be~~ further used to evaluate the existing soil datasets of the FAO-UNESCO Soil Map of the World (2007) (hereafter as FAO-UNESCO), the Harmonized World Soil Database (hereafter as HWSD) (FAO/IIASA/ISRIC/ISSCAS/JR, 2012), a Chinese data set of soil properties (Shangguan et al., 2012; Shangguan et al., 2013) and soil hydraulic parameters using PTFs (Dai et al., 2013) released by Beijing Normal University (hereafter as BNU), "SoilGrids1km" (Hengl et al., 2014) and the updated version of "SoilGrids250m" (Hengl, 2017) released by the International Soil Reference and Information Center (ISRIC) - WoSIS institute, and the hydraulic parameters based on SoilGrids1km and Schaap et al. (2001) PTFs (hereafter as HPSS) (Montzka et al., 2017) FAO-UNESCO (FAO/UNESCO, 2007), HWSD (FAO/IIASA/ISRIC/ISSCAS/JR, 2012), BNU (Shangguan et al., 2012; Shangguan et al., 2013), SoilGrid1km (Hengl et al., 2014), SoilGrid250km and HPSS (Montzka et al., 2017) over the TP. The ~~detailed information of description of the existing datasets used~~ is listed in Table S1 of the Supplement. All datasets were linearly interpolated to match the measured dataset at specific depths, to ensure the (inter) comparability.

2. ~~2-3~~ Parameterization Schemes

Many basic soil property dependent schemes have been proposed for porosity estimation. The Cosby et al. (1984)'s uni-variate PTF that uses ~~s~~ sand percentage (hereafter the Cosby-S scheme, see Eq. (A1) in the Appendix) has been widely used, and it is to note that there is a multi-variate PTF (Cosby et al. (1984)) that uses clay as well as sand

(Van Looy et al., 2017). Porosity can ~~also~~ be inversely related with soil dry bulk density (Hillel, 2003) and calculated from in situ BD (hereafter the BD scheme, see Eq. (A2)). In most cases, these schemes perform well. However, with SOC in soils, ~~the existence of SOC~~, soil porosity ~~and water retention capability both~~ tends to increase. Another factor affecting porosity is the gravel content. As gravel content increases, ~~these properties the porosity~~ tends to decrease. Chen et al. (2012) parameterized the impact of SOC and gravel content into a porosity estimation scheme (hereafter the SocVg scheme, see Eq. (A3-A6)). Zhang et al. (2011) proposed a mixing-coefficient model to ~~depict~~ calculate porosity of binary mixture made of a coarse (gravel) and a fine component over a range of gravel content (hereafter the BM scheme, see Eq. (A7-A10)).

In this study, as Fig. 2 shows, the Cosby-S, BD, SocVg and BM schemes were evaluated for their applicability over the three climate zones.

For the SHP estimate, we selected the Clapp and Hornberger (1978) (hereafter CH) and the Van Genuchten (1980) - Mualem (1976) (hereafter VG) schemes. Based on measured SWRCs, we used the scaling method (see Eq. (A15)) (Montzka et al., 2017) to ~~obtain-determine~~ the hydraulic parameters of saturated soil moisture (θ_s), soil water potential at air-entry (ϕ_s), and b -an empirical parameter related to the pore-size distribution of the soil matrix in the CH equation (see Eq. (A11-A12)), and parameters of θ_s , residual soil moisture θ_r , α - a parameter corresponding approximately to the inverse of the air-entry value, n -a shape parameter in the VG model (see Eq. (A13-A14)). ~~Tand-derive~~ the field capacity (FC) and the permanent wilting point (PWP) (regarded as the SM at about -33 kPa and -1500 kPa of ~~suction-matrix~~ pressure, respectively) were also derived as they are the main parameters for soil water budget. Furthermore, the selected PTFs (see Table A1 in the Appendix, Table A1) were used to estimate hydraulic parameters of SWRCs-CH and SWRCs-VG. Given that good θ_s estimate will improve SWRCs prediction, the optimal porosity scheme will be pre-selected for determining SWRCs-CH and SWRCs-VG. ~~combined with the optimal porosity scheme were used to estimate the SWRCs-CH and SWRCs-VG. Estimated SWRCs from PTFs. These two estimations (e.g. measured vs. PTFs), were further compared with the measurement determined SWRCs to indicate the uncertainty of using different PTFs, and suitable PTFs with the lowest bias were selected.~~

Saturated hydraulic conductivity, K_s , combined with SWRCs-CH or SWRCs-VG is used to calculate the unsaturated hydraulic conductivity (K) and diffusivity (D). The PTFs used for SWRCs-~~CH and SWRCs-VG~~ estimations also had ~~have corresponding~~ equations (see footnotes in Table A1, Appendix, Table A1) ~~for to predict estimating K_s , while~~ and most PTFs were developed based on fine minerals. To estimate the K_s of a mixture containing gravels, Peck and Watson (1979) used a heat-flow analogy correlating the K_s of the mixture with the K_s of both fine minerals and the volumetric gravel fraction (VGF) (hereafter the PTFs-VGF scheme, see Eq. (A16)). This PTFs-VGF scheme can be applied to soils with low gravel content (Zhang et al., 2011). It is noted that the PTFs-VGF scheme needs an input ($K_{sat,fs}$, see Appendix A.43) from the PTFs K_s estimation. Furthermore, Koltermann (1995) used the Kozeny–Carman equation to estimate the hydraulic conductivity for binary mixtures, and ~~a-the~~ suitable grain diameter estimation was also declared important (Kamann et al., 2007). To improve the performance of the Kozeny–Carman equation ~~for estimating the K_s of binary mixtures~~, Zhang et al. (2011) introduced the BM scheme for estimating porosity and a power-averaging method for calculating representative grain diameter (hereafter the BM-KC scheme, see Eq. (A17-A19)). In this study, the standard PTFs (see ~~Appendix, Table A1 in the Appendix~~), PTFs-VGF and BM-KC schemes were employed as shown in Fig. 2.

Several (semi-) empirical models have been developed to estimate the ~~STP~~ soil thermal conductivity λ . De Vries (1963) developed a Maxwell equation analogous physics based model to describe λ (see Eq. (A22)). This model can predict λ accurately, although this is complicated by the fact that at least five soil mineral components and their separate shape features need to be taken into account (Tarnawski and Wagner, 1992). Furthermore, the effect of vapor movement caused by the temperature gradient is also ~~considered-parameterized~~ in the De Vries (1963) model. It should be noted that the consideration of soil vapor flow is critical to accurately investigate the simultaneous transfer of moisture and heat, particularly in semi-arid and arid environments (Zeng et al., 2011b, a; Zeng and Su, 2013). Farouki (1981) proposed an alternative method and regarded liquid water as the continuous medium and soil minerals as uniform particles in the De Vries (1963) model. ~~Furthermore, tIn this model, the λ of soil minerals was estimated by using a geometric mean equation from the quartz content in soil minerals and the λ of quartz and other soil minerals (see Eq. (A23)).~~ The λ of vapor together with the shape ~~feature-factor~~ for air pore ~~was- were~~ calculated

in terms of water content and porosity ([see Eq. \(A24-A25\)](#)) (hereafter the *D63F scheme*). Tian et al. (2016) developed a simple and generalized De Vries-based model, which assumed that the λ and shape features of soil minerals were determined by soil texture (sand, clay and silt), and that the effect of vapor movement was negligible (hereafter the *T16 scheme*, [see Eq. \(A26-A29\)](#)). The empirical model proposed by Johansen (1975) used the Kersten (1949) number and λ in dry and saturated conditions to estimate λ (hereafter the *J75 scheme*, [see Eq. \(A30-A35\)](#)). In this study, as shown in Fig. 2, the D63F, T16 and J75 schemes were adopted. For each λ scheme, a comparison was made using parameters (i.e. the λ of soil minerals) with ([see Eq. \(A34\)](#)) and without ([see Eq. \(A23\)](#)) gravel ~~and~~/ SOC considerations. The De Vries (1963) model was used for calculating C_s ([see Eq. \(A20-A21\)](#)). The details of porosity and SHP & STP schemes are listed in the Appendix (A.1–5).

3. The Tibet-Obs dataset

3.1 Data availability

The soil physical dataset is available at the 4TU.ResearchData data center at <http://doi.org/10.4121/uuid:61db65b1-b2aa-4ada-b41e-61ef70e57e4a> <https://data.4tu.nl/repository/uuid:c712717c-6ac0-47ff-9d58-97f88082ddc0>. The data is stored in .XLSX files. A readme file describes the structure of the EXCEL, the measurement devices and contact information. The download linkages of existing soil property datasets used in this paper are included in .txt file. The location of sampling is stored in .kmz file. The raw data for each sampling site is also provided.

3—Results and Discussions

3.2 Basic analyses of the Tibet-Obs dataset

Soil texture

Figure 3 shows the mean of sand, clay and silt percentages, gravimetric gravel fraction (GGF), soil organic content (SOC), and the mean diameter of fine components and gravels (FD and GD) at profiles-different depths across the three climate zones over the TP. In Ngari network under the arid zone (Fig. 3a), the mean sand content was around 80% and exhibited with higher values at surface layers of 5 and 10 cm than at deep layers. Silt and gravel contents ranged between 10-20% and this-the percentages increased with depth. Clay content and SOC were 3% and 0.8%, respectively, and remained constant along the profile. The FD and GD ranged from 0.19-0.24 mm and 4-8 mm, respectively, and showed a tendency to increase from the top to a depth of 20 cm, but to decrease in the deeper layers. It can be concluded that soil texture in the arid zone consisted-consists of a high proportion of coarse sand accompanied by gravel, and that the gravel content increased-increases till 20 cm and then decreases slightly in the deeper the-layer.

In Naqu network under the semi-arid zone (Fig. 3b), the mean sand fraction ranged from 70-80% with a slight decrease with depth. The silt and clay contents ranged from-15-25% and 4-8%, respectively, and displayed-an increasing trend-increased with depth. The GGF at depths of 40 and 50 cm exceeded-exceeded 50% for soils at depths of 40 and 50 cm, while it was much lower for-at the shallow layers. Mean FD and GD ranged from-0.18-0.22 mm and 4-8 mm, respectively. GD at deep layers was larger than that at shallow layers. SOC approached 10% in the surface layers but quickly declined at deep layers. It can be summed up that soil texture in the semi-arid zone was-is dominated by a high percentage of sand mixed with a small proportion of gravels, but with high SOC in shallow layers, and mainly mixed with big gravels at deep layers.

In Maqu network under the semisub-humid zone (Fig. 3c), mean silt and clay contents were around 60% and 10%, respectively, with a smoothly decreasing trend along the profile. The mean sand fraction ranged from 28-40% and increased with depth. No gravel was found. Mean FD ranged from 0.024-0.036 mm, and fine soil mineral particles in deep layers (40 and 80 cm) were larger than in shallow layers (see Fig. 3c lower panel). Similar to the SOC profile distribution in the Naqu network, stratification occurred-with-the SOC was almost 20% in surface soil layers almost reaching 20%, and declining-declined at almost double the rate at each further depth almost 1/16 at 80 cm. Soil texture in the semi-humidsub-humid zone was-is characterized as being dominated by a high percentage of silt content with relatively large SOC in the shallow layers, and with mainly fine sand mixed in the deep layers.

Bulk densityDry bulk density & Porosity

In Ngari network under the arid zoneIn the arid zone (Fig. 4a), the BD varied slightly (between 1.55 and 1.65 g/cm³) with depth, showing a peak at 10 cm. The porosity of the surface layer was slightly higher than in deep layers, with a mean profile porosity of 0.33. The porosity at 20 cm was the lowest in the profile, which might be caused by this layer containing the greatest proportion of gravel as well as the greatest GD and FD (see Fig. 3a, upper and lower panels). In Naqu network under the semi-arid zone In the semi-arid zone (Fig. 4b), the BD increased continuously with depth, with a minimum of 1 g/cm³ in the top layer and a maximum of 2.1 g/cm³ in the bottom layer. The porosity peaked at around 0.6 in-at the top layer, while monotonously decreasing to 0.25 down-intoa the bottom layer. Combined with the soil texture analysis (see Fig. 3b), variations of BD and porosity in the profile were inferred relevant to the high SOC in the surface layer and the large gravel content in the bottom layer. In Maqu network under the semi-humidsub-humid zone (Fig. 4c), the BD ranged from 0.8 to 1.5 g/cm³ and increased with

depth, while porosity decreased with depth and ranged from 0.72 to 0.45. The ~~profile pattern stratification~~ of BD and porosity ~~in the profile~~ might be induced by SOC ~~laying layering in the surface and soil texture fraction variations in the deep layers~~ as Fig. 3c reveals. In summary, profiles of BD and porosity differ with soil texture variation over the three climate zones, and both the SOC and gravels affect the porosity. Overall porosity at shallow layers (5, 10 and 20 cm) ~~decreased-increases~~ from the arid to the semi-arid and to the ~~semi-humid~~sub-humid zones, while at deep layers (≥ 40 cm) it ~~showed-shows~~ an ~~increase~~ ~~decrease~~ from the semi-arid to the arid and then the ~~semi-humid~~sub-humid zones.

Soil water retention curve (SWRC) and S_s aturated hydraulic conductivity (K_s)

Figure 5 shows the pressure-cell measured SWRCs (markers in the figure) differed across the three climate zones. In Ngari network under the arid zone, soil water retention quickly reduced as the suction slightly increased (Fig. 5a). The same situation occurs for the deep layers in Naqu network under the semi-arid zone (Fig. 5b). In Maqu network under the sub-humid zone, soil water retention was high and gradually decreased as the suction increased (Fig. 5c). Figure 5 also shows the CH and VG models captured the retention characteristic of soil water (lines in the figure) well across the three climate zones. Determined parameters of $[\theta_s, b, \varphi_s]$ in the CH and $[\theta_r, \theta_s, \alpha, n]$ in the VG models based on measured SWRCs and the scaling method are listed in Table 2.

Saturated hydraulic conductivity (K_s)

In Ngari network under the arid zone (Fig. 5a6a), the magnitude of mean K_s was of the order of 10^{-5} (m/s). The K_s at a depth of 20 cm was lower than at other depths, which might be due to ~~this layer exhibiting least the lowest values~~ of porosity in this layer (see Fig. 4a). In Naqu network under the semi-arid zone (Fig. 5b6b), the mean K_s exhibited a variation of one order ~~two orders~~ of magnitude with depth, namely 10^{-6} (m/s) at depths of 10, 20 and 50 cm and 10^{-5} (m/s) at a depth of 40 cm. In Maqu network under the ~~semi-humid~~sub-humid zone (Fig. 5c6c), K_s also differed by one order ~~two orders~~ of magnitude: 10^{-6} (m/s) at depths of 5, 10, 20 and 80 cm and 10^{-7} (m/s) at a depth of 40 cm. It is to be noted that the K_s profiles of both the semi-arid and ~~semi-humid~~sub-humid zones ~~depict-presented~~ a lower K_s in shallow layers than in the deeper layer. This is mainly due to the negative correlation between saturated hydraulic conductivity and soil organic carbon in soils ~~where hydrophobic functional group might dominate with organic carbon composition and reduces soils wettability~~ (Nemes et al., 2005; Wang et al., 2009; Ellerbrock et al., 2005). As can be seen, K_s ~~varied-varies~~ with soil texture over the three climatic zones, and both SOC and gravels ~~had have~~ an effect. At a certain depth, where the soil basic properties ~~underwent-undergo~~ a transition (see Fig. 3), ~~a minimumthe~~ K_s reaches a minimum ~~always existed~~. The mean and the standard deviation of the soil properties of the profiles in the three climate zones are listed in the Supplement (Table S2-S4).

Gravel impact on porosity and K_s

Figures 6a7a&b show that ~~with a GGF < 0.3 in shallow layers,~~ porosity did not ~~tend to~~ change ~~with GGF increasing within 0.3 in shallow layers~~, while with a GGF > 0.4, porosity tended to decline ~~with increasing GGF~~, especially in deep layers. For example, porosities ~~for layers~~ with a GGF of 0.6 and 0.72 at 20 cm and 40 cm depths were lower than those with a GGF < 0.3 at 5 cm and 10 cm depths (Fig. 6a7a). With more gravels embedded in the matrix, the flow paths in the soil would become blocked and the porosity reduced (Zhang et al., 2011). However, the porosity did not always decrease as the GGF increased. Porosity ~~for the layer~~ with a GGF of 0.84 in the semi-arid zone was higher than porosities with a GGF ranging between 0.4 and 0.6 at 50 cm depth (Fig. 6b7b). Porosity ~~for the layer~~ with a GGF of 0.7 at 20 cm depth in the arid zone was also higher than that with a GGF of 0.6 at 40 cm depth (Fig. 6a7a). Porosity tended to increase as the GGF ~~continued to~~ increase, ~~because d. In fact,~~ when a GGF is relatively high (> 1 -porosity of gravels), connected pores can form among the gravels, and thus increase porosity (Zhang et al., 2011).

Figures 6e7c&d show a slight decrease in K_s at 10 cm ~~depth at with~~ a GGF < 0.62 and a slight increase in K_s at ~~depths of 20 cm and 40 cm~~ with a GGF > 0.8, which is consistent with the changes in porosity. The observations clearly show that gravels have a distinct impact on the porosity and K_s in the arid and semi-arid zones. It should be noted that, although the *in situ* K_s measurements were conducted at locations adjacent to the places where we took

soil samples, ~~the heterogeneity issue may still exist~~ heterogeneity may have had an effect on the values of soil properties and parameters throughout our sampling procedures, as with any soil field experimentation. Nevertheless, the current findings based on field experiments are in line with reported findings based on laboratory experiments (Zhang et al., 2011; Koltermann, 1995; Sakaki and Smits, 2015).

Heat capacity C_s and thermal conductivity λ

Figures ~~7a8a&b~~ ~~&c~~ show that ~~the heat capacity C_s went up and down with SM increasing for Ngari and Naqu networks under the arid and semi-arid zones. Some samples from these two networks are fine-grained soils well mixture with gravels. For these samples, it is not easy to vertically insert needles of KD2Pro device (see Sect. 2.2), instead, the needles were buried with soils in the surface of the sample as the alternative for the measurement. Additionally, the KD2 needles might experience a slight skew when they touched the hard gravel. All these might cause the fluctuation of C_s when SM increased, while the overall rising trend was still observed in Figure 8a&b. Figure 8c shows C_s almost steadily increased with SM for the Maqu network under the sub-humid zone. Samples from sub-humid zone are all fine-grained soils and make the needle of KD2 device insert easily and thus form a steady environment for the measurement. Figures 8a&b&c show that no distinct stratification layering at different depths existed for C_s profiles with SM varying cross over the three climate zones. The C_s ranged from 1 at oven dry state to 2.5 MJ m⁻³ K⁻¹ as the soil reached saturation over the arid zone, 0.5 to 3 MJ m⁻³ K⁻¹ over the semi-arid zone, and 0.5 to 2.4 MJ m⁻³ K⁻¹ over the semi-humid sub-humid zone as soils dried out.~~

Figures ~~7d8d~~ ~~&e~~ ~~&f~~ show ~~how~~ the relationship of λ -SM varied with depth ~~and depended on soil texture~~. For the arid zone (Fig. ~~7d8d~~), the λ -SM curves ~~are were~~ very similar at each depth due to the nearly homogenous sandy soils across the whole profile (see Fig. 3a). The mean λ ranged from 1.8 at saturation and -0.2 (W m⁻¹ K⁻¹) as the soils ~~reached oven-dry states dried out~~. In the semi-arid zone (Fig. ~~7e8e~~), the λ -SM curves were stratified, and soils with gravels in deep layers (see Fig. 3b) clearly had a higher λ (>2 W m⁻¹ K⁻¹) than in other layers and other climate zones. In the ~~semi-humid sub-humid~~ zone (Fig. ~~7f8f~~), the λ -SM curves also presented ~~layering variation with depth~~, though within a much narrower range than in the semi-arid zone. Such ~~layering variation~~ is mainly caused by the sand distribution along the profile, which increased slightly with depth (see Fig. 3c). The mean λ in the ~~semi-humid sub-humid~~ zone ranged from ~~0.21.6-1.60.2~~ (W m⁻¹ K⁻¹) as soils dried out. Furthermore, the surface layers in the semi-arid and ~~semi-humid sub-humid~~ zones ~~comprised a lower had lower~~ λ values (Figs. ~~7e8e~~ ~~&f~~) because of the SOC influence.

4. Applications of the Tibet-Obs dataset

4.1 Assessing parameterization schemes for LSMs

3.2 Porosity estimation

Using basic soil properties data of Tibet-Obs with ~~Four~~ four schemes, porosities were used to estimate porosity, and the results were compared with the measured values. Comparisons against measured porosities (see Table A2 in the Appendix) indicate that the BD scheme performs the best for estimating porosity in profiles across the three climate zones, as it is a bulk estimation scheme that takes both gravel and fine minerals into consideration. The Cosby-S scheme overestimates porosities over the arid zone and provides constant porosity values over the semi-arid and sub-humid zones. The SocVg scheme also overestimated porosity, because the assumed porosity of gravels with a theoretical minimum value (0.363) is higher than the observed maximum (0.31) (Wu and Wang, 2006). The BM scheme estimates porosity well for soils with more gravels especially in the deep layers over the arid and semi-arid zones. ~~Although the SocVg scheme considers gravel impact through volumetric SOC determination, it is assumed that the gravel has the same porosity as the minerals (e.g. as determined by the Cosby-S scheme). In the SocVg scheme, the porosity of gravels with a theoretical minimum value (0.363) is higher than the maximum (0.31) found by Wu and Wang (2006). Consequently, the SocVg scheme led to the overestimation of porosity here. Because it considers the degree of mixture between fine minerals and gravels, the BM scheme also performed well, especially in the deep layers. In the arid zone, most porosities estimated by the Cosby-S scheme were higher than the measured porosities, and varied across a smaller range (0.36–0.42) than the measurements (0.28–0.42) did (Fig. 8a-1). Nevertheless, the Cosby-S scheme simulated the soil porosity at the surface layer well (smaller bias and RMSE; see Appendix, Table A2). The porosity derived from the BD scheme is seen distributed along the 1:1 line with the measurements (Fig. 8a-2) with lower bias and lower RMSE (see Table A2). The SocVg scheme strongly overestimated porosities (Fig. 8a-3), while porosities derived from the BM scheme matched well with the measurements (Fig. 8a-4) and comprised the lowest RMSE (see Table A2). As can be seen, for the arid zone, the Cosby-S scheme did not capture the variation in porosity at all depths, because the sand fraction only differed slightly with depth. The BD scheme performed well estimating the porosity, as it is a bulk estimation scheme that takes both gravel and fine minerals into consideration. Although the SocVg scheme considers gravel impact through volumetric SOC determination, it is assumed that the gravel has the same porosity as the minerals (e.g. as determined by the Cosby-S scheme). In the SocVg scheme, the porosity of gravels with a theoretical minimum value (0.363) is higher than the maximum (0.31) found by Wu and Wang (2006). Consequently, the SocVg scheme led to the overestimation of porosity here. Because it considers the degree of mixture between fine minerals and gravels, the BM scheme also performed well, especially in the deep layers.~~

In the semi-arid zone, porosities estimated by the Cosby-S scheme were approximately constant (0.40) (see Fig. 8b-1), which is contrary to the measured porosities (see Fig. 4b). Porosities derived from the BD scheme agreed well with the measurements (see Fig. 8b-2) and had the lowest bias and RMSE at all depths (see Table A2). The SocVg scheme overestimated porosities (see Fig. 8b-3). The BM scheme underestimated porosities at depths of 5, 10 and 20 cm (Fig. 8b-4), but simulated them well at deep 40 and 50 cm layers (lower bias and RMSE in Table A2). In the semi-humid zone, the Cosby-S scheme failed to estimate porosities (see Fig. 8c-1). As in other climate zones, the BD scheme represented the measurements in the semi-humid zone well (see Fig. 8c-2) with low bias and low RMSE (see Table A8), indicating its predictive accuracy and applicability for all depths and all three climate zones. It should be noted that the SocVg scheme performed better at surface layers than at greater depth (see Fig. 8c-3). Taking all these results together, it indicates that the BD scheme delivered the greatest predictive accuracy for estimating porosity in profiles across the three climate zones.

3.3 Soil hydraulic properties

Pressure-cell determined SWRCs

SWRC and K_s estimations

across the three climate zones and strongly depended on soil texture. Consistent with soil stratification, the SWRCs also showed distinct layering. The CH and VG models captured the retention characteristic of soil water well across the three climate zones. Particularly for the arid and semi-arid regions, both the CH and VG models performed well,

with just a slight underestimation by the VG model. In the semi-humid area, the VG model was more consistent with measurements than the CH model for soil suction <300 kPa. On the other hand, the CH model was more accurate when suction increased, although both the CH and VG models overestimated SM at a suction >300 kPa. Estimated parameters of the CH and VG models are listed in Table .

Various Using basic soil properties data of Tibet-Obs with the selected PTFs (see Table A1) combined with the BD porosity scheme, parameters of SWRCs-CH and SWRCs-VG were used to estimated (see Table A3 in the Appendix) predict SM at the different suction levels (i.e. SWRCs-CH & SWRCs-VG) as adopted by the pressure-cell experiment. Figure 9 shows comparisons of The mean-estimated SWRCs from PTFs combined with the BD porosity scheme a long with their variation ranges in each profile were compared with to the pressure-cell determined SWRCs measurements at 5 cm (see Sect. 3.2). shown in Fig. 10, and their absolute biases are shown in Fig. 11.

Fig. 10a shows the The Saxton et al. (1986) PTFs overestimated the SWRCs-CH in the profiles in the arid zone (Ngari), while the PTFs given by Campbell and Shiozawa (1992) and Saxton and Rawls (2006) underestimated them (Fig. 10a), and the Cosby et al. (1984) PTFs (1&2) presented good SWRCs-CH predictions with smaller absolute biases compared to measurements (see Table A4 Fig. 11 in the Appendix). In the semi-arid zone (Naqu) (Fig. 10b), all PTFs underestimated the SWRCs-CH at surface layers 5 cm, while the Cosby et al. (1984) PTFs (1&2), Saxton et al. (1986) and Saxton and Rawls (2006) PTFs captured these them well at deep layers and had with lower biases in the profile compared to measurements (see Table A4 Fig. 11b). In the semi-humid sub-humid zone (Maqu) (Fig. 10c), the Cosby et al. (1984) PTFs (1) and Saxton et al. (1986) PTFs underestimated SWRCs-CH in the profile, while other PTFs predicted SWRCs-CH them well, especially the Cosby et al. (1984) PTFs (1&2) (i.e. both had lower biases, see Fig. 11c, with the PTFs (1) performing better at high suction). Therefore, the Cosby et al. (1984) PTFs (1) are considered most suitable for predicting SWRCs-CH over the three climate zones. It is noteworthy that in combination with the BD scheme, the Cosby PTFs (1) performed much better regarding the estimation of SWRC-CH, compared with the estimates by the Cosby PTFs (1) combined with the Cosby-S porosity scheme (see section 3.2). On the other hand, without the BD scheme, the Saxton and Rawls (2006) PTFs were found to be performing better over the semi-arid and semi-humid zones (see Table S5 in the Supplement Fig. S1-S2).

For the SWRCs-VG estimates, the Rosetta1-H3 and Rosetta3-H3 PTFs were developed based on the mixed database (Schaap et al., 2001). Fig. 10 (right panel) shows they underestimated SWRCs-VG in the profiles across the three climate zones, as did the Rawls and Brakensiek (1985) PTFs. The Weynants et al. (2009) Rosetta3-H3 PTFs also underestimated the SWRCs-VG in the semi-arid zone and the Class Wösten et al. (1999) PTFs overestimated (Fig. 10b), as did the Class Wösten et al. (1999) PTFs. The Vereecken et al. (1989) PTFs, which were developed based on a database where hydraulic properties were measured for every sample with the same measurement techniques (Vereecken et al., 2010), performed well when the m was set at 1. However, these PTFs were not performing well for $m=1-1/n$ in the VG model and overestimated SWRCs-VG heavily out of range in the semi-humid sub-humid zone (broken green line in Fig. 10c). The Continuous Wösten et al. (1999) PTFs were derived developed based on from the database of Hydraulic Properties of European Soils (HYPRES) and as such were more affiliated with the database of Vereecken et al. (1989). The Weynants et al. (2009) PTFs were also developed based on the Vereecken et al. (1989) database and included BD as the variable. These two PTFs predicted SWRCs-VG well for the three climate zones, with smaller biases, and the former performing better for the semi-arid zone (Fig. 10 & Fig. 11). Comparisons of the estimated SWRCs from PTFs to the measurements at 10, 20 and 40 cm were illustrated in Fig. S1 in the Supplement. Accordingly, Consequently, the Cosby et al. (1984) PTFs (1) and the Continuous Wösten et al. (1999) PTFs combined with the BD porosity scheme have demonstrated are suggested to be most applicable for predicting the SWRCs-CH and SWRCs-VG, respectively, across the three climate zones.

K_s estimation

Taking basic soil properties data of Tibet-Obs as the input, The the $-K_s$ was estimates-estimated by using obtained with the PTFs scheme (see footnotes in Table A1), the empirical PTFs-VGF scheme (see Eq. (A16) in the Appendix) PTFs scheme scaled by gravel content and the semi-physical BM-KC scheme (see Appendix, A.4) Eq. (A17-A19)) Comparing them were compared against the in situ observations measured K_s . Figure 12a 10a&bd show

the PTFs scheme had a lower bias for predicting $\text{Log}_{10} K_s$ than the PTFs-VGF and BM-KC schemes did for the arid zone (Ngari). In particular, the PTFs given by Cosby et al. (1984) (1&2) predicted good K_s well that can be used for in the CH model for estimating hydraulic conductivity (K), and as did the Rosetta1-H3 PTFs, Rosetta3-H3 PTFs and Rawls and Brakensiek (1985) did in for the VG model. The K_s derived from BM-KC scheme had lower RMSE with measurements at 40 cm depth, indicating the gravel impact on K_s .

Figure ~~12e10b~~ & ~~d-e~~ show that the BM-KC scheme predicted better K_s had a lower bias for $\text{Log}_{10} K_s$ at depths of 10, 20 and 40 cm in the semi-arid zone (Naqu) than most PTFs and PTFs-VGF did at depths of 10, 20 and 40 cm in the semi-arid zone. For K_s estimation-estimate used in the CH model, the Cosby et al. (1984) (1) PTFs performed best at shallow depths, while the PTFs-VGF of these PTFs were better at deep layers of 40 and 50 cm. For K_s estimation-the usage in the VG model, K_s derived from no distinct difference existed between PTFs and PTFs-VGF schemes were almost the same, indicating that the estimated K_s used in for the VG model is less affected by gravels. The Rosetta1-H3 PTFs predicted K_s better than other PTFs, with only slight overestimation. Figure ~~12e10c~~ & f show most of the PTFs underestimated K_s , while the selected PTFs (i.e. ~~Cosby~~ Cosby (1) & Rosetta1-H3) in the arid zone also predicted K_s close to the measurements performed relatively well in the semi-humid sub-humid zone (Maqu). To sum up, the PTFs resulting from Cosby et al. (1984) (1) and Rosetta1-H3 PTFs are appropriate for the estimation of estimating K_s , respectively used in for the CH and VG models, respectively, across the three climate zones. PTFs-VGF of the Saxton and Rawls (2006) scheme should be applied in deep layers in the semi-arid zone, where gravel is abundant in the soil.

3.4 Heat Capacity and soil thermal conductivities

In Figure 13a the C_s estimate by the De Vries (1963) model depicts a small bias ($< 0.1 \text{ MJ m}^{-3} \text{ K}^{-1}$) across the arid zone and in shallow layers across the semi-humid zone, but large bias across the semi-arid zone and in deep layers across the semi-humid zone. Considering the impact of SOC in the semi-arid and semi-humid zones, Fig. 13b indicates an improved C_s estimate for soils at top layers, but a worsening at other depths. Nevertheless, the original formulation of the De Vries (1963) model is used for estimating profile C_s (see Appendix A.5).

The D63F, T16 and J75 schemes combined with the BD porosity scheme were used to estimate the λ . For the arid and semi-arid regions, the estimation of λ considered two scenarios: with (Case 1) and without (Case 2) gravel impact. For the semi-humid region, both with (Case 1) and without (Case 2) SOC impact were considered. Figure 14 shows that the D63F model had a lower bias than other schemes in both cases across the three climate zones, indicating a greater ability to predict λ . The T16 scheme overestimated λ , which may be due to its ideal assumption that the λ of soil minerals is totally determined by sand, clay and silt particles. The J75 scheme generally underestimated the λ .

Figure 14 also shows that the D63F scheme improved the λ estimate at surface layers in the arid zone and at a depth of 50 cm when incorporating gravel impact parameterization (lower biases in Case 2). The improvement also occurred with the T16 scheme, while biases tended to be greater for the J75 scheme. In the semi-humid zone biases also became larger for all schemes when SOC impact parameterization was involved. Although parameterization of the SOC impact was demonstrated to improve the λ estimate in the top layer (SOC $> 12\%$) over the Eastern TP (Chen et al., 2012; Zheng et al., 2015), it should be noted that the Cosby S scheme was used instead of the BD scheme, in these studies for porosity estimate, as adopted in this paper (see Sec. 3.2). Comparison of the λ estimate using these two porosity schemes for the semi-humid zone show that the D63F scheme combined with the BD porosity scheme can predict λ well across the three climate zones. When the D63F scheme is combined with the Cosby S scheme, it also performs well (see Supplement Fig. S3).

C_s and λ estimations

Using basic soil properties data of Tibet-Obs, the C_s was estimated through the De Vries (1963) model. Comparing to C_s measured, this scheme performs well over the three climate zones. Furthermore, with the consideration of SOC impact, it improves the C_s estimates for soils at top layers in the semi-arid and sub-humid zones (see Table A5 in the Appendix).

Based on the Tibet-Obs basic soil properties data, the D63F, T16 and J75 schemes combined with the BD porosity scheme were used to estimate the λ . For the arid (Ngari) and semi-arid (Naqu) regions, the estimation of λ

considered two scenarios: with (Case 1) and without (Case 2) gravel impact. For the sub-humid region (Maqu), λ estimation with (Case 1) and without (Case 2) SOC impact were considered. Table 3 shows that the λ derived from D63F model had a lower bias in all cases compared to the measurement than other schemes across the three climate zones. The T16 scheme overestimated λ , which may be due to its ideal assumption that the λ of soil minerals is totally determined by sand, clay and silt particles. The J75 scheme generally underestimated the λ .

Table 3 also shows that the D63F scheme improved the λ estimate at surface layers in the arid zone and at a depth of 50 cm when incorporating gravel impact parameterization (lower biases in Case 2). The improvement also occurred with the T16 scheme, while biases tended to be greater for the J75 scheme. In the sub-humid zone, biases also became larger for all schemes when SOC impact parameterization was considered. Although parameterization of the SOC impact was demonstrated to improve the λ estimate in the top layer (SOC > 12%) over the Eastern TP (Chen et al., 2012; Zheng et al., 2015), it should be noted that, in these studies for porosity estimate, the Cosby-S scheme was used instead of the BD scheme as adopted in this paper (see Sec. 4.1). Comparisons in Figure 11 indicate that the D63F scheme combined with the BD porosity scheme can predict λ well across the three climate zones. It is to note that combining with the Cosby-S scheme, the D63F scheme also performs well (see Fig. S2 in the Supplement).

3.5.4.2 Evaluation of the existing soil datasets

The current existing global and regional soil datasets, including FAO-UNESCO (FAO/UNESCO, 2007), HWSD (FAO/IIASA/ISRIC/ISSCAS/JR, 2012), BNU (Shangguan et al., 2012; Shangguan et al., 2013), SoilGrid1km (Hengl et al., 2014), SoilGrid250km and HPSS (Montzka et al., 2017), were extracted for the TP and compared with the *in situ* and laboratory measurements of Tibet-Obs. collected in the field. The measured basic soil property dataset was named of Tibet-Obs.

Basic soil ~~property~~ properties

Figure 11 shows that all datasets underestimated both the sand fraction and BD in the arid and semi-arid regions, while overestimated them in the ~~semi-humid~~sub-humid region. For the silt fraction, the pattern was reversed. Almost all datasets overestimated the silt fraction in the arid and semi-arid regions (only FAO-UNESCO underestimated silt very slightly in the semi-arid region), and underestimated the silt fraction in the ~~semi-humid~~sub-humid region. All datasets overestimated the clay fraction throughout the three climate zones.

The estimates of SOC from all the datasets were within 1% range of the measurements across the arid and semi-arid zones, and within 10% across the ~~semi-humid~~sub-humid zone, apart from the FAO-UNESCO data, which underestimated the SOC heavily in this region. Most of the GGF estimates for the arid zone were within 10%, with the FAO-UNESCO data underestimating by 20%. For the semi-arid and ~~semi-humid~~sub-humid regions, all datasets consistently, ~~respectively~~, underestimated and overestimated the GGF, ~~respectively~~.

The BD scheme was used to derive porosity from the existing datasets. Figure 12a shows that the estimations of porosity were higher than the *in situ* measurement for the arid zone, with the SoilGrid1km and HWSD providing the closest approximations. In the semi-arid zone (Fig. 12b), all datasets underestimated porosity at the top layer, but overestimated it at other depths. It should be noted that SoilGrid1km and SoilGrid250m presented porosity almost as a constant figure in each profile, which is not representative for conditions in the field. The porosity estimations from FAO-UNESCO, HWSD and BNU did show profile variation, although much less than the *in situ* measurements did. In the ~~semi-humid~~sub-humid region (Fig. 12c), all datasets underestimated porosity in the surface layers 5, 10 and 20 cm, and either underestimated or overestimated porosity in the deep layers.

SWRC and K_s

As previous analysis of PTFs (see ~~section~~ Sect. 4.13.3) suggested, the Cosby et al. (1984) and continuous Wösten et al. (1999) PTFs were used with basic soil properties (i.e. only texture, BD and SOC) from the independent datasets (e.g. SoilGrids etc.) to estimate, respectively, SWRCs-CH and SWRCs-VG ~~models~~. Given the relatively homogenous soil profile derived from existing products (see Fig. 13), the averaged SWRCs derived from existing datasets over different depths along with its deviations in the profile were used for comparison with the laboratory measurements. Figure 13a shows all datasets overestimated SWRCs in the profile in the arid zone, in the order of FAO-UNESCO > BNU > HWSD > SoilGrid250m > (HPSS for VG model) > SoilGrid1km > Tibet-Obs. In the semi-arid zone (Fig. 13b), all datasets underestimated SWRCs at the surface layers of 5 and 10 cm, while

overestimated at deep layers. FAO-UNESCO captured the SWRCs-CH at surface layers well, and BNU presented the closest estimations for deep layers. Regarding SWRCs-VG, SoilGrid250m and HWSD, respectively, matched the measurements at surface and deep layers well. In the ~~semi-humid~~sub-humid zone (Fig. 47e13c), all datasets showed similar SWRCs-CH, slightly underestimating at low suction (< 100 kPa) but then becoming consistent with the measurements. The results for SWRCs-VG were quite diverse. The HWSD and HPSS showed consistent underestimation. The FAO-UNESCO and BNU closely matched the measurements in deep layers. The SoilGrid1km and SoilGrid250m were within the range of the measurements across the whole profile, although their mean values were larger at high suction range (> 300 kPa). Furthermore, it should be noted that the averaged profile SWRCs derived from Tibet-Obs tended to reflect SWRCs at deep layers over the three climate zones. Additionally, the SoilGrid1km-, HWSD- and SoilGrid1km-derived FC (0.37, 0.41, 0.51 $\text{cm}^3 \text{cm}^{-3}$) and PWP (0.16, 0.20, 0.27 cm^{-3}) were found close to the mean measured values over the three respective climate zones (see Table A6 in the Appendix).

~~Figure 18 shows all existing datasets overestimated FC and PWP in the arid and semi-arid zones, while underestimated them in the semi-humid zone, in comparison with the laboratory measurement. With the Tibet-Obs dataset as input to the applicable PTFs good FC and PWP were generated. The SoilGrid1km-, HWSD- and SoilGrid1km derived FC and PWP were close to the mean measured values over the three respective climate zones.~~

~~K_s~~

Using basic soil properties (i.e. only texture, BD and SOC) from the independent datasets (e.g. SoilGrids etc) with the Cosby et al. (1984) (1) and Rosetta1-H3 PTFs, Table 4~~Figure 19~~ shows mean predicted K_s (10^{-6} m/s) in the profile for all existing datasets across the three climate zones. They were of a smaller order than the field measurements in the arid and semi-arid zones but of a larger order than some of the field measurements in the ~~semi-humid~~sub-humid zone. The Tibet-Obs dataset as input in the applicable PTFs predicted K_s well. The existing datasets for estimating SWRCs: SoilGrid1km, HWSD, and SoilGrid1km, also performed well estimating K_s in the three climate zones, respectively.

~~Soil diffusivity (D) and conductivity (K)~~

SHP & STP in LSMs

Most of LSMs use Richards' equation for soil water flow modelling (see A.6 in the Appendix) with the hydraulic conductivity. While in some LSMs (e.g. Noah and H-TESSEL), soil diffusivity (D) is used. When the soil dries down, with the largest pores in the soil draining, the K and D are reduced many orders of magnitude from saturation to dryness (Bittelli et al., 2015). Lower K (higher D) will result in slower water transport, and thereby subsequently a higher SM derived from LSMs compared to soil moisture measurements, and vice versa.

LSMs use thermal diffusion equation for soil heat transport modelling (see A.6 in the Appendix). Soil heat capacity (C_s) and thermal conductivity (λ) are the important thermal parameters in the equation. Lower λ with higher C_s will lead to reduced soil heat fluxes, and thereby subsequently the higher soil temperature derived from LSMs compared to soil temperature measurements, and vice-versa. The curves of K , D , C_s and λ derived by using basic soil properties from the independent datasets (SoilGrids etc.) with recommended parameterization schemes were compared to the measurements (see Fig. A1- A3 in the Appendix) for quantifying the LSMs' uncertainty inherited from soil dataset. A special case is formed by the FAO-UNESCO dataset, which slightly overestimated VG- K at surface layers and heavily underestimated it at deep layers, while heavily overestimated VG- D at surface layers and slightly underestimated it at deep layers. These would lead to the overestimation of derived SM, as the ECMWF SM analyses do in this region (Su et al., 2013). The uncertainty from soil dataset also propagates to soil temperature estimation. The FAO-UNESCO dataset underestimated C_s -SM at surface layers, but overestimated λ -SM, while at other depths estimating C_s -SM well, but underestimating λ -SM. These would lead to the underestimation of the simulated soil temperature, which is also consistent with the findings of ECMWF soil temperature analyses (Su et al., 2013). When the soil desaturates, and the largest pores in the soil drain, the hydraulic conductivity (K) and diffusivity (D) are reduced many orders of magnitude from saturation to dryness (Bittelli et al., 2015). Lower K combined with higher D will lead to slower water transport, and thereby subsequently a higher SM derived from the land surface model, and vice versa.

(Best et al., 2011)

When the soil desaturates, and the largest pores in the soil drain, the hydraulic conductivity (K) and diffusivity (D) are reduced many orders of magnitude from saturation to dryness (Bittelli et al., 2015). Lower K combined with higher D will lead to slower water transport, and thereby subsequently a higher SM derived from the land surface model, and vice versa.

Figure 20 and Figure 21 show how K and D vary within climate zones. All datasets provide lower D and K derived from CH and VG models than the laboratory measurements did in the arid zone (Fig20a and Fig21a). Similar to in the SWRCs comparisons, SoilGrid1km and HPSS provided the closest approximation to those datasets in the order: SoilGrid250m > HWSD & BNU > FAO UNESCO (Fig20a and Fig21a). In the semi arid zone, all datasets generated CH D and CH K similar to those of the measurements at depths from 20 to 50 cm, while overestimating them at the surface layer (Fig. 20b). All datasets predicted VG D and VG K well at depths from 10 to 40 cm, while underestimating them for the deepest layer (Fig21b). A special case is formed by the FAO UNESCO dataset, which slightly overestimated VG K at surface layers and heavily underestimated it at deep layers, while heavily overestimating VG D at surface layers and slightly underestimating it at deep layers. This would lead to the overestimation of derived SM, as the ECMWF SM analyses do in this region (Su et al., 2013). In the semi humid zone, all datasets generated high CH D and CH K , and were close to the measurements at the greatest depth (Fig. 20c). The HPSS overestimated VG D and VG K . The SoilGrid1km and SoilGrid250m both underestimated VG K , while they could reproduce the VG D very well. The FAO UNESCO, HWSD and BNU derived VG K closely matched the measurements in the profile, while they slightly overestimated the VG D .

Heat capacity C_s and thermal conductivity λ

The soil heat transport process is mainly characterized by the soil heat capacity (C_s) and thermal conductivity (λ) (Hillel, 2003). Lower thermal conductivity with higher heat capacity will lead to slower heat transport, and thereby subsequently the higher soil temperature derived from the land surface model, and vice versa.

Figure 22a shows all datasets underestimated C_s SM and λ SM in the arid zone. The degree of undervaluation decreases in the following order: BNU & FAO UNESCO > SoilGrid250m > HWSD > SoilGrid1km > Tibet-Obs. In the semi arid zone (Fig. 22b), the HWSD predicted a C_s SM close to the measurements for the top layer. The other datasets underestimated C_s SM when soils became dry, while aligning well with the measurements when the soil became wet ($SM > 3 \text{ cm}^{-3} \cdot \text{cm}^{-3}$). A special case is formed by the FAO UNESCO dataset, which underestimated C_s SM at surface layers, but overestimated λ SM, while at other depths estimating C_s SM well, but underestimating λ SM. These results would lead to the underestimation of the derived soil temperature, and a soil temperature in a surface layer lower than in a deep layer, which is consistent with the findings of ECMWF soil temperature analyses (Su et al., 2013). All datasets generated λ SM close to the measurements at surface layers, with HWSD performing the best when soil became wet. In the semi-humid region (Fig. 22c), all datasets overestimated C_s SM, with the SoilGrid1km estimation matching the measurements best. All datasets overestimated λ SM at surface layers, while underestimating λ SM at deep layers, with SoilGrid1km derived λ SM being consistent with the mean of the Tibet-Obs dataset.

3.5. Conclusions

For this study an *in situ* measurement dataset of soil physical properties was set up across the arid (Ngari), semi-arid (Naqu) and semi-humid/sub-humid (Maqu) climate zones across the Tibetan Plateau. The dataset can fill geographical gaps of global profiles on the third pole region. Analyzing this *in situ* dataset has made clear how shows that soil texture, bulk density (BD), porosity, soil hydraulic properties (SHP, i.e. soil water retention curve, hydraulic conductivity) and thermal properties (STP, i.e. heat capacity and thermal conductivity) differ for each climate zone and vary within each profile. Soil physical properties present stratification in the semi-arid and semi-humid zones. Gravels were found affecting porosity and SHP & STP in the arid zone and in deep layers of the semi-arid zone. Soil texture in the Ngari network under the arid zone consists of a high proportion of coarse sand accompanied by gravel, and that the gravel content increases till 20 cm and then decreases slightly in the deeper layer. Dry bulk density (BD) and porosity vary with depths slightly. Soil texture in the Naqu network under the semi-arid zone is dominated by a high percentage of sand mixed with a small proportion of gravels, but with high SOC in shallow layers, and mainly mixed with big gravels at deep layers. The BD is with a minimum in the top layer and a maximum in the bottom layer, and the porosity presents the opposite. Soil texture in the Maqu network under the sub-humid zone, is dominated by a high percentage of silt content with relatively large SOC in the shallow layers, and with mainly fine sand mixed in the deep layers. The BD increases with depth and the porosity decreases. Depending on basic soil properties varying over three climate zones, soil hydraulic properties (SHP, i.e. soil water retention curve, hydraulic conductivity) and thermal properties (STP, i.e. heat capacity and thermal conductivity) differ for each climate zone and vary within each profile, (e.g. presenting layering in the semi-arid and sub-humid zones), and gravels were found affecting porosity and SHP & STP in the arid zone and in deep layers of the semi-arid zone.

Various schemes for estimating the porosity and SHP & STP over the TP were examined. The BD scheme has been demonstrated to be most suitable for estimating the porosity over the three climate zones. The Cosby et al. (1984) PTFs proved more applicable for SHP estimation by the Clapp and Hornberger (1978) (CH) model, and the continuous Wösten et al. (1999) PTFs for SHP estimation by the Van Genuchten (1980) - Mualem (1976) (VG) model. The original formulation of the De Vries (1963) model can be deployed successfully for estimating the heat capacity of a profile. Furthermore, the De Vries (1963) model combined with the Farouki (1981) scheme (D63F) and with the implementation of the BD porosity scheme proved superior for estimating thermal conductivity.

Referenced by the measurements, uncertainties of the existing soil basic property datasets and their derived SHP & STP were quantified across the TP. This information provided indicative signs is of significance on assessing the LSMs' uncertainty inherited from soil datasets, soil parameterization in LSMs, moreover, on screening the proper soil datasets for LSMs over the TP. On the other hand Furthermore, the existing soil property datasets were can be also used as the ancillary data for SM retrieval. For example, the composited datasets of FAO and HWSD were used in the Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) SM product generation. Therefore the information also became valuable for understanding uncertainties in satellite SM products inherited from soil maps. Based on the dataset comparison, this paper indicates that SoilGrid1km can reduce such uncertainty and is therefore recommended for use in the arid and semi-humid/sub-humid zones, while the combination of FAO-UNESCO at shallow layers and HWSD at deep layers is recommended for the semi-arid zone over the TP.

In summary, this paper provides a comprehensive *in situ* measured dataset of soil physical properties over the TP and presents the applicable schemes to use for porosity and SHP & STP estimation in the LSM across the TP. The dataset contributes, which is significantly for generating spatial-temporally consistent spatial-temporally soil moisture and temperature estimates by LSMs simulation and helps provide the references for soil basic properties and SHP/STP retrieval. Furthermore, the evaluation of the existing soil property datasets is crucial for quantifying the uncertainty arising from soil data used in the LSMs and in soil moisture retrieval from microwave remote sensing.

Author contributions: Yijian Zeng and Zhongbo Su conceptualized the experiment design; Hong Zhao designed the experiment with the help of Yijian Zeng; Hong Zhao conducted the field experiment and lab experiment,

summarizing/organizing data; the authors, including Shaoning Lv, were involved in the fieldwork; Hong Zhao wrote the paper. Yijian Zeng and Zhongbo Su commented and revised the paper.

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Table 1 Sampling approach for soil basic properties, SHP and STP over the Tibet-Obs

Sampling Approach	Soil Texture	Gravel Content	Soil Organic Content	Bulk Density Dry	Porosity	Thermal Conductivity	Soil Water Retention Curve	Hydraulic Conductivity	Sampling Depths		
									Maqu	Naqu	Ngari
Plastic bag	√	√	√						5cm	5cm	5cm
Standard sample rings				√	√	√			10cm 20cm	10cm 20cm	10cm 20cm

Small sample rings							√		40cm 80cm	40cm 50cm	40cm
Profile Auger								√	10cm 20cm 40cm 80cm	10cm 20cm 40cm 50cm	10cm 20cm 40cm

Table 2 Pressure-cell determined parameters of the CH and VG models for the three climate zones. The scaling method used for the determination is Eq. A15 in the Appendix.

Region	Depth (cm)	CH							VG			
		λ	ψ	θ_s	θ_{fc}	θ_{wp}	θ_r	θ_i	α	n	θ_{fc}	θ_{wp}
		-	cm	cm ³ ·cm ⁻³	cm ³ ·cm ⁻³	cm ³ ·cm ⁻³	cm ³ ·cm ⁻³	cm ³ ·cm ⁻³	cm ⁻¹	-	cm ³ ·cm ⁻³	cm ³ ·cm ⁻³
Ngari (arid)	5	0.185	4.346	0.304	0.209	0.103	0.028	0.250	0.021	1.393	0.223	0.086
	10	0.162	5.825	0.323	0.244	0.131	0.028	0.285	0.022	1.305	0.256	0.116
	20	0.160	2.023	0.270	0.173	0.094	0.028	0.201	0.020	1.340	0.182	0.082
	40	0.180	2.447	0.277	0.173	0.087	0.028	0.211	0.028	1.366	0.182	0.075
Naqu (semi- arid)	5	0.071	0.020	0.506	0.299	0.228	0.027	0.328	0.050	1.097	0.302	0.225
	10	0.100	11.211	0.433	0.389	0.265	0.037	0.439	0.039	1.151	0.397	0.254
	20	0.162	4.594	0.393	0.286	0.154	0.037	0.350	0.036	1.285	0.299	0.138
	40	0.129	1.639	0.392	0.266	0.162	0.037	0.301	0.020	1.265	0.277	0.144
	50	0.187	0.578	0.391	0.183	0.090	0.037	0.226	0.026	1.428	0.196	0.076
Maqu (semi- humid)	5	0.277	39.041	0.790	0.750	0.287	0.047	0.766	0.016	1.329	0.611	0.301
	10	0.253	39.165	0.724	0.695	0.288	0.047	0.600	0.011	1.268	0.576	0.296
	20	0.241	37.894	0.660	0.645	0.272	0.047	0.543	0.012	1.251	0.530	0.284
	40	0.199	33.131	0.535	0.534	0.250	0.047	0.472	0.013	1.225	0.454	0.254
-	80	0.268	36.610	0.558	0.556	0.206	0.047	0.493	0.014	1.314	0.488	0.208

Region	Depth (cm)	CH							VG			
		λ	ψ	θ_s	FC	PWP	θ_r	θ_i	α	n	FC	PWP
		-	cm	cm ³ cm ⁻³	cm ³ cm ⁻³	cm ³ cm ⁻³	cm ³ cm ⁻³	cm ³ cm ⁻³	cm ⁻¹	-	cm ³ cm ⁻³	cm ³ cm ⁻³
Ngari (arid)	5	0.19	4.35	0.30	0.21	0.10	0.03	0.25	0.02	1.39	0.22	0.09
	10	0.16	5.83	0.32	0.24	0.13	0.03	0.29	0.02	1.31	0.26	0.12
	20	0.16	2.02	0.27	0.17	0.09	0.03	0.20	0.02	1.34	0.18	0.08
	40	0.18	2.45	0.28	0.17	0.09	0.03	0.21	0.03	1.37	0.18	0.08
Naqu (semi-arid)	5	0.07	0.02	0.51	0.30	0.23	0.03	0.33	0.05	1.10	0.30	0.23
	10	0.10	11.21	0.43	0.39	0.27	0.04	0.44	0.04	1.15	0.40	0.25
	20	0.16	4.59	0.39	0.29	0.15	0.04	0.35	0.04	1.29	0.30	0.14

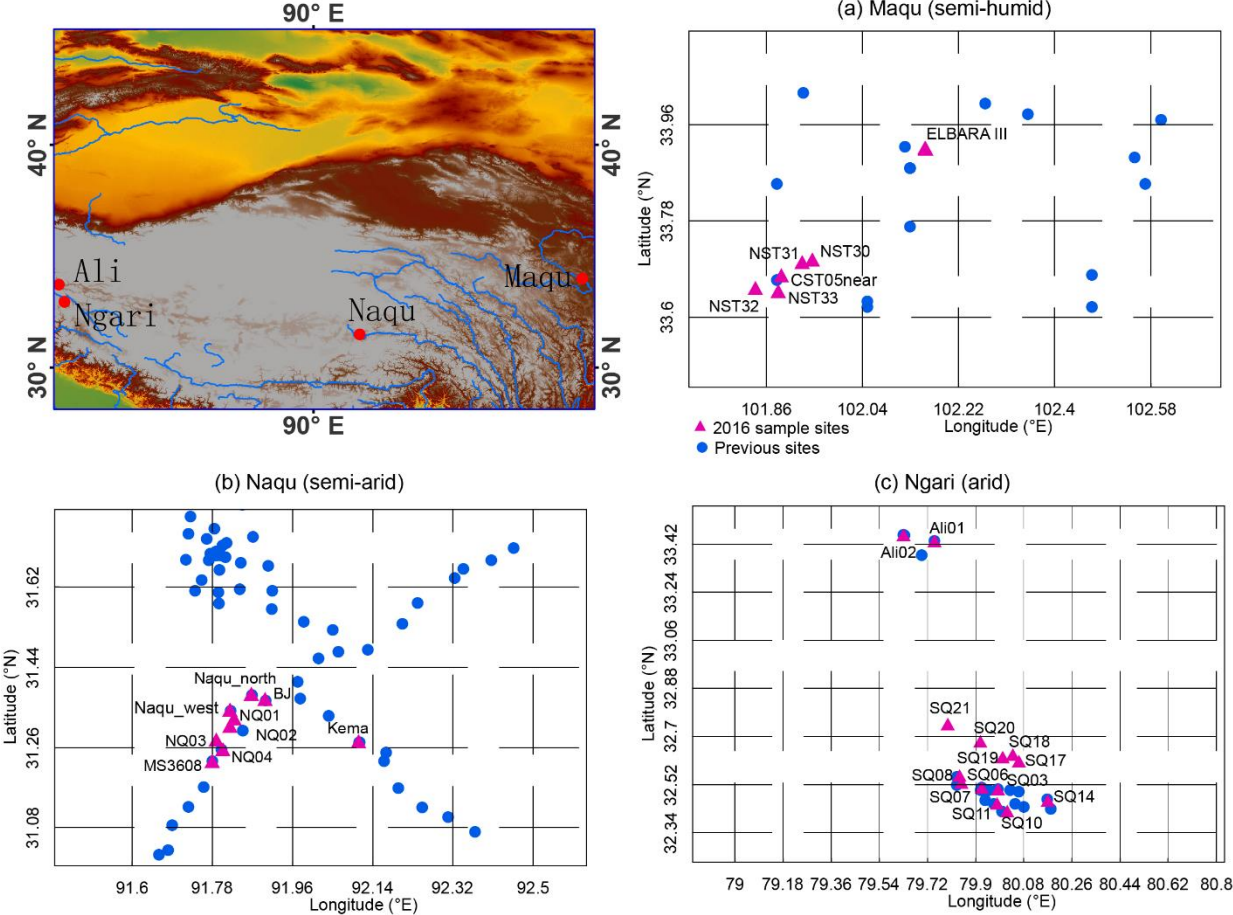
	40	0.13	1.64	0.39	0.27	0.16	0.04	0.30	0.02	1.27	0.28	0.14
	50	0.19	0.58	0.39	0.18	0.09	0.04	0.23	0.03	1.43	0.20	0.08
Maqu (sub-humid)	5	0.28	39.04	0.79	0.75	0.29	0.05	0.77	0.02	1.33	0.61	0.30
	10	0.25	39.17	0.72	0.70	0.29	0.05	0.60	0.01	1.27	0.58	0.30
	20	0.24	37.89	0.66	0.65	0.27	0.05	0.54	0.01	1.25	0.53	0.28
	40	0.20	33.13	0.54	0.53	0.25	0.05	0.47	0.01	1.23	0.45	0.25
	80	0.27	36.61	0.56	0.56	0.21	0.05	0.49	0.01	1.31	0.49	0.21

Table 3 Biases of λ estimates based on D63F, T16 and J75 schemes combined with the BD scheme in the profiles across the three climate zones and the measurements. Case 1 is the bias (listed in the upper part of the table) derived from schemes not considering gravel impact parameterization for the arid and semi-arid zone or SOC impact parameterization for the sub-humid zone. Case 2 is the bias (listed in the lower part of the table) with these parameterizations taken into consideration. The unit of listed value is $W\ m^{-1}\ K^{-1}$.

Schemes	Ngari (arid)				Naqu (semi-arid)					Maqu (sub-humid)				
	5 cm	10 cm	20 cm	40 cm	5 cm	10 cm	20 cm	40 cm	50 cm	5 cm	10 cm	20 cm	40 cm	80 cm
D63F	0.06	0.18	0.02	-0.01	0.09	-0.02	-0.03	0.01	0.20	0.01	-0.04	-0.06	-0.05	-0.08
T16	0.30	0.32	0.30	0.07	0.02	0.25	0.31	0.54	0.99	0.05	0.10	0.18	0.23	0.20
J75	0.26	-0.24	-0.42	-0.37	0.38	-0.21	-0.35	-0.35	-0.23	0.13	-0.20	-0.29	-0.32	-0.37
D63F	0.00	0.08	-0.13	-0.14	0.20	-0.11	-0.16	-0.26	-0.20	0.14	-0.19	-0.22	-0.13	-0.12
T16	0.26	0.25	0.18	-0.02	0.13	0.18	0.20	0.27	0.44	0.16	-0.16	-0.14	0.01	0.00
J75	0.29	-0.23	-0.43	-0.39	0.34	-0.28	-0.43	-0.53	-0.49	0.22	-0.31	-0.41	-0.41	-0.45

Table 4 Comparisons of mean derived K_s from the applicable PTFs for the CH and VG models based on various soil datasets, with the measurements. The unit of listed value is m/s.

Region		Measured	Tibet-Obs	FAO-UNESCO	HWSD	BNU	SoilGrid1km	SoilGrid250m	HPSS
Ngari (arid)	CH	2.53E-05	1.81E-05	7.16E-06	5.74E-06	4.92E-06	7.51E-06	7.29E-06	
	VG	2.53E-05	2.41E-05	6.09E-06	4.14E-06	4.26E-06	4.96E-06	6.95E-06	7.42E-06
Naqu (semi-arid)	CH	2.50E-05	1.49E-05	7.05E-06	7.98E-06	7.91E-06	6.34E-06	6.22E-06	
	VG	2.50E-05	2.38E-05	5.25E-06	5.39E-06	9.59E-06	5.84E-06	5.99E-06	6.65E-06
Maqu (sub-humid)	CH	4.21E-06	3.00E-06	7.05E-06	6.72E-06	3.91E-06	4.24E-06	3.97E-06	
	VG	4.21E-06	1.65E-05	5.25E-06	4.85E-06	3.07E-06	5.62E-06	3.15E-06	4.33E-06



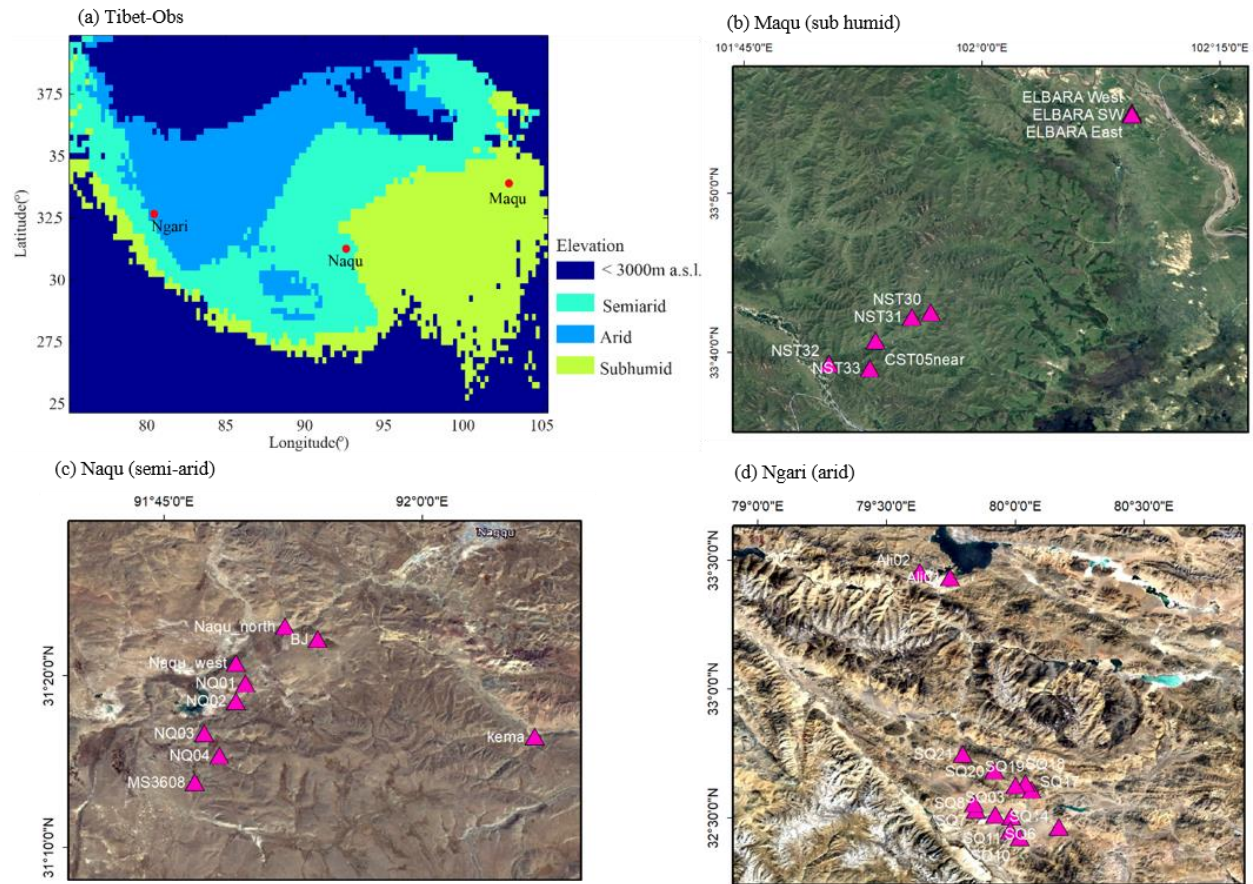


Figure 1 The Location of Tibet-Obs and the spatial distribution of soil sampling across three climate zones.
(a) Tibet-Obs networks are distributed under the three different climatic zones where the zones were
classified based on the FAO Aridity Index Map. The dark blue color represents the area around Tibetan
Plateau, with elevation lower than 3000 m above sea level (a.s.l.) (Zeng et al. 2016). (b), (c) and (d) are
samplings distribution in the Maqu network under the sub-humid zone, Naqu network under the semi-arid
zone and Ngari network under the arid zone respectively, in the kml image from Google Earth. It is to note
that the image acquisition times were in August, February and December respectively. The triangle in ginger
pink represents each sampling site.

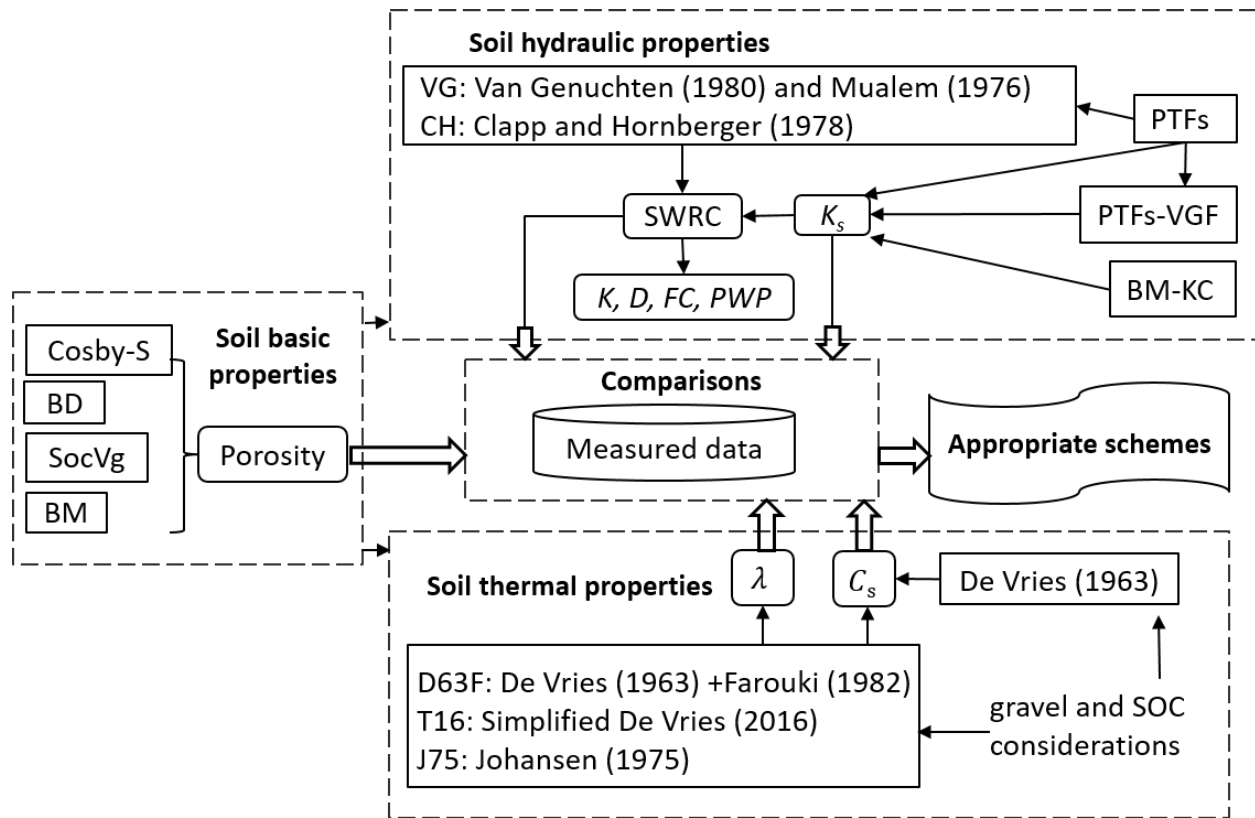
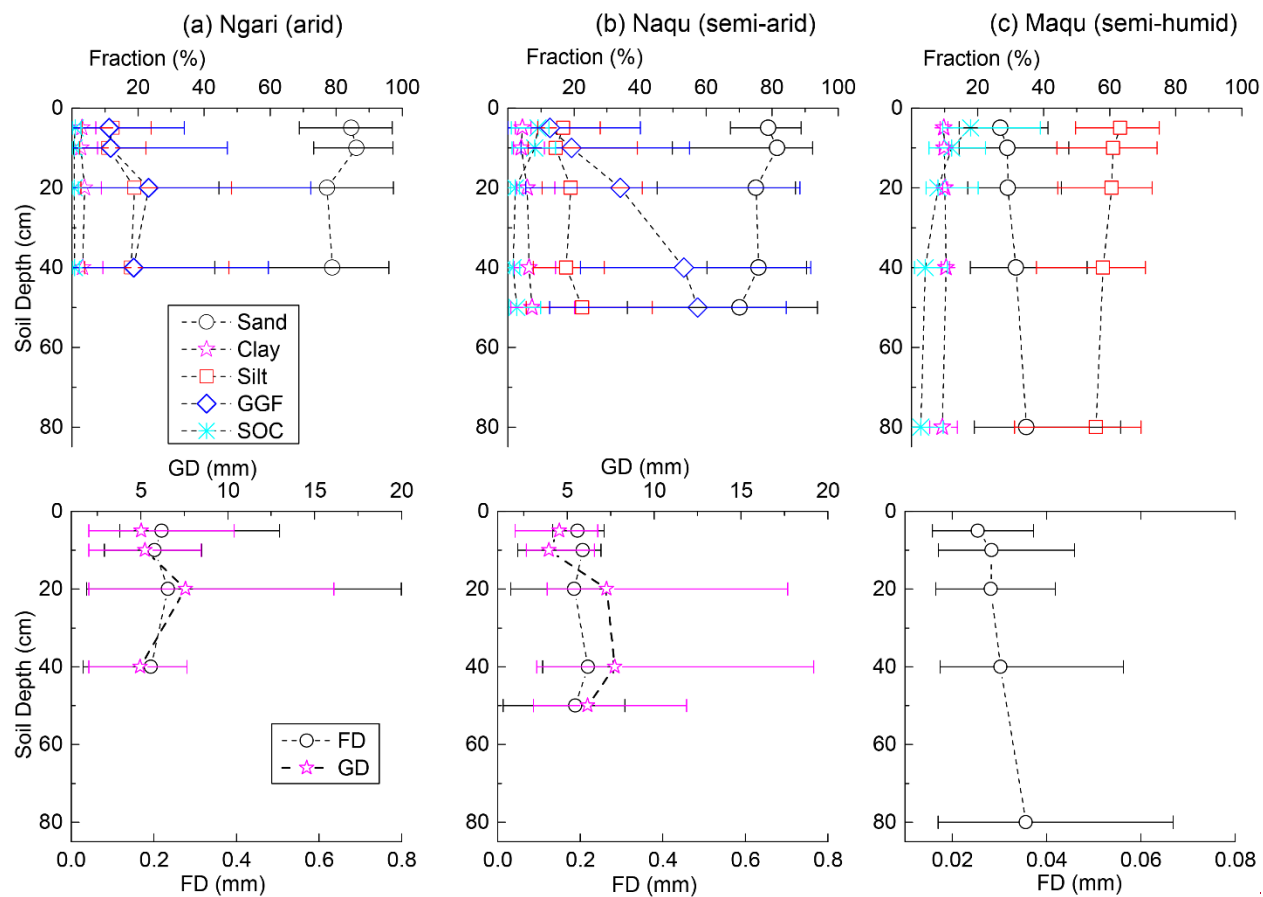


Figure 2 Flowchart depicting the implementation of different schemes of porosity and SHP/STP by using *in situ* basic soil properties data. Dashed boxes indicate various categories of parameterization schemes and the comparisons with *in situ* the measurements. Block arrows show the main data flow for comparisons. Single arrows represent the steps that occur internally for each part or connect various parts. Rectangles represent schemes. Rounded rectangles denote porosity and SHP/STP parameters. K and D represent hydraulic conductivity and diffusivity, respectively.



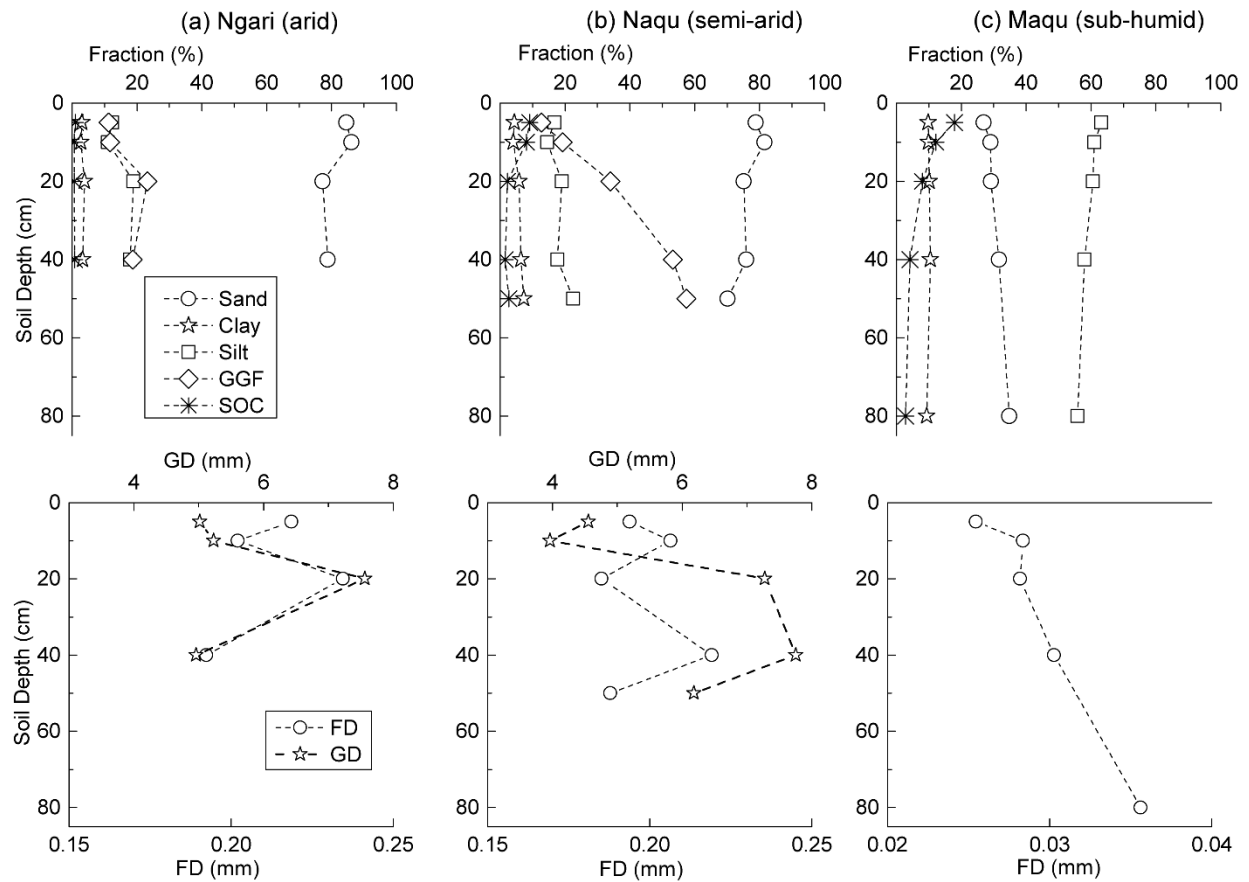


Figure 3 Profiles of mean soil basic properties at three climate zones. Top panel: Variations in Sand, Clay, Silt, GGF, and SOC at various depths. Bottom panel: Variations in GD and FD at different depths. GGF is the gravimetric gravel fraction. SOC is the soil organic matter content. FD is the mean particle diameter of fine minerals. GD is the mean particle diameter of gravels. **The bar represents the lowest and highest values in the profile.**

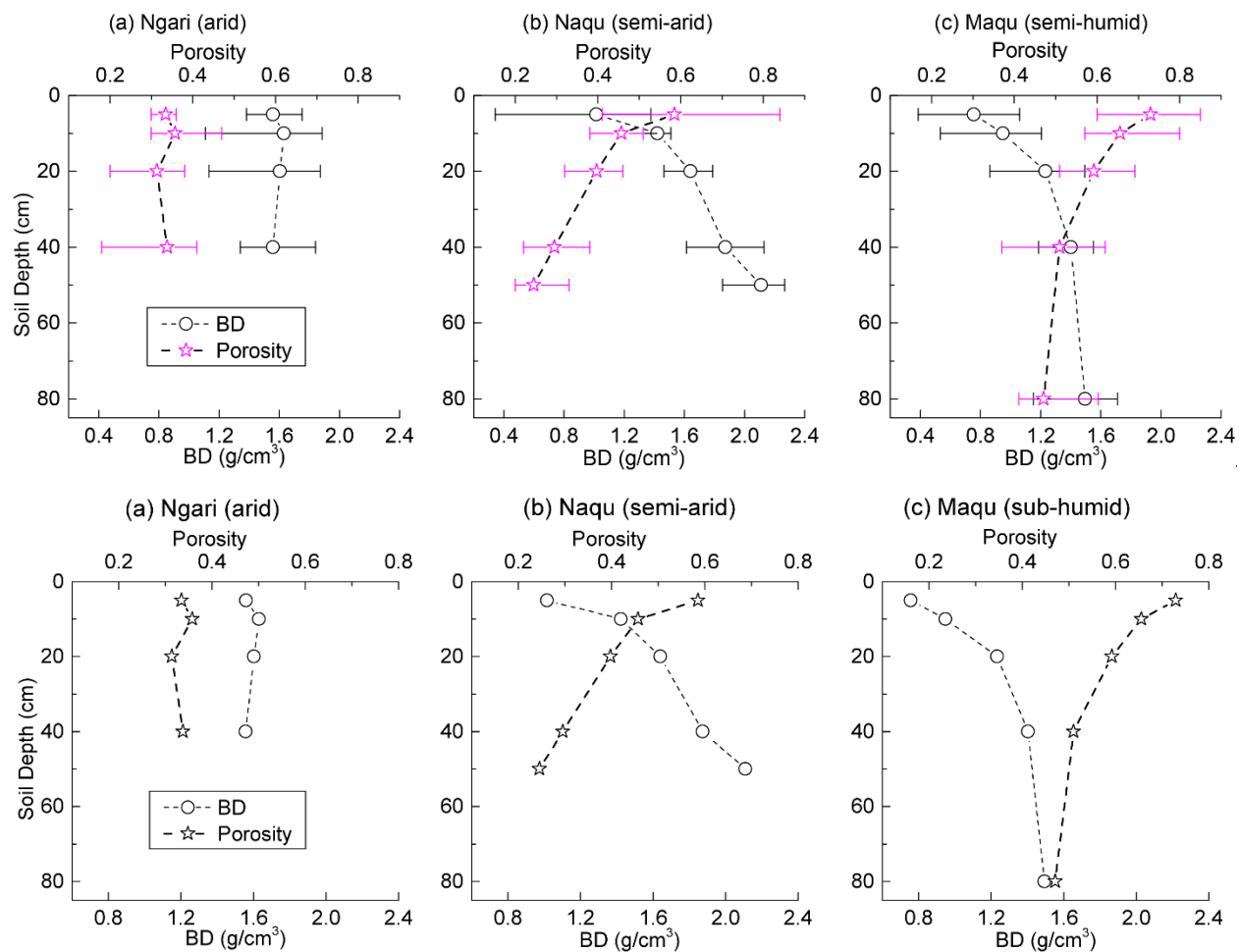


Figure 4 Profiles of bulk densitymean dry bulk density (BD) and porosity at three climate zones. The bar represents the lowest and highest values in the profile.

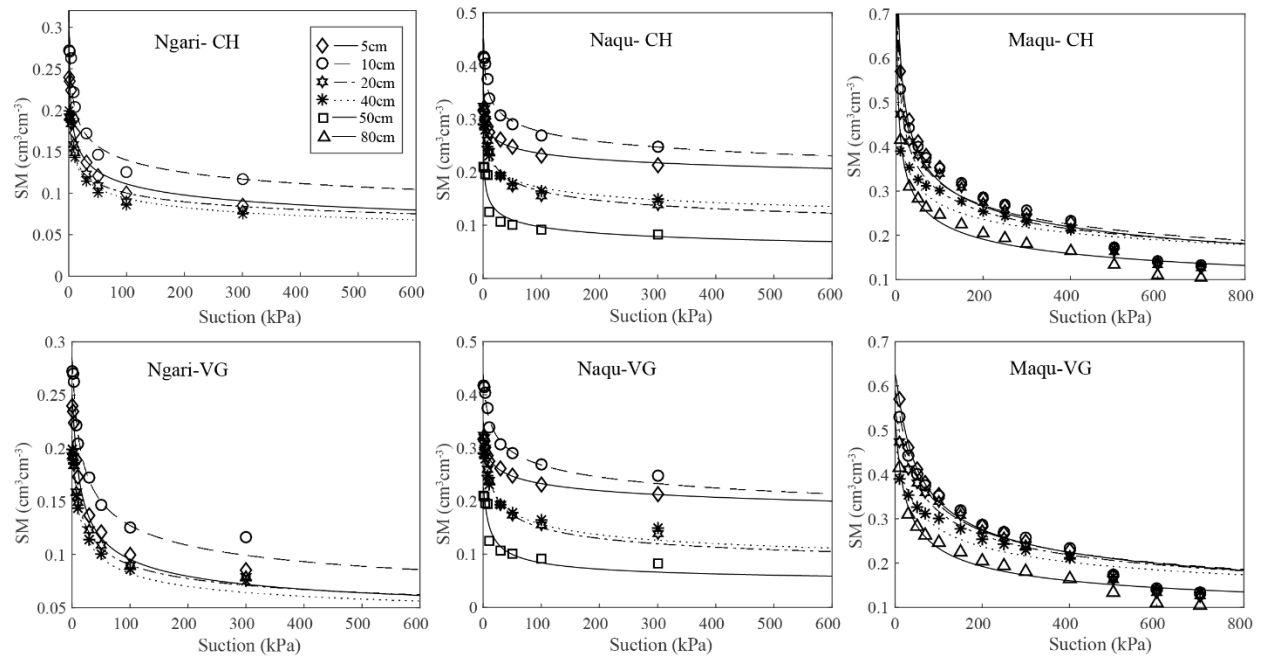
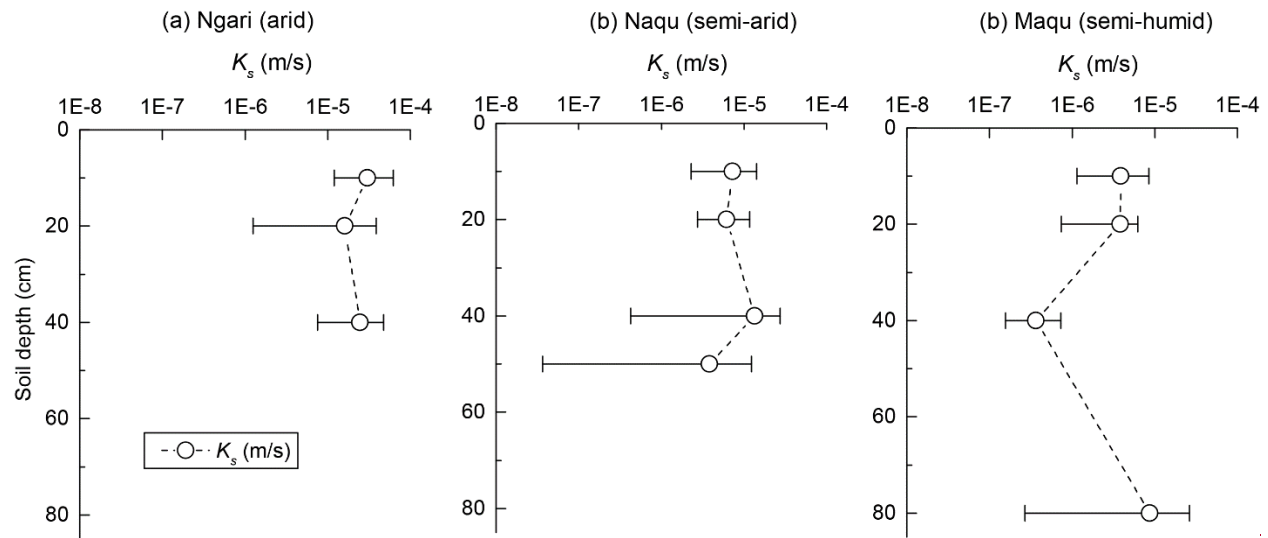


Figure 5 Average observational SWRCs and determined SWRCs-CH and SWRCs-VG from scaling method at different depths under the three climate zones: Ngari in the arid zone, Naqu in the semi-arid zone and Maqu in the sub-humid zone. Dots denote average observed soil moisture content at specific suction. Lines represent determined SWRCs-CH and SWRCs-VG.



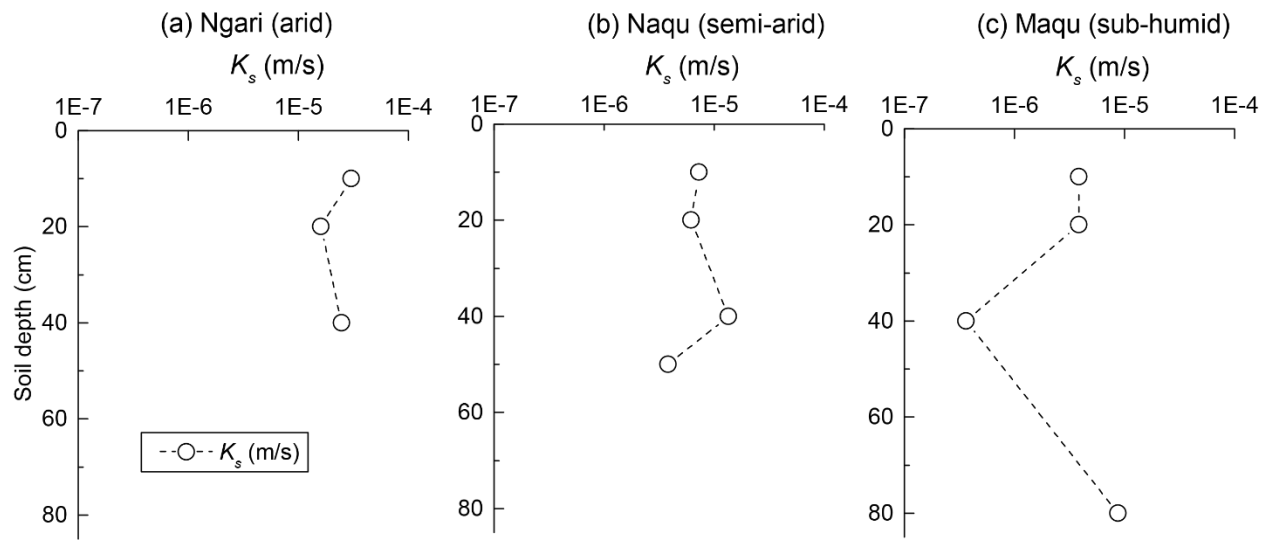


Figure 5-6 Profiles of mean saturated hydraulic conductivity (K_s) at three different climate zones. **The bar represents the lowest and highest values in the profile.**

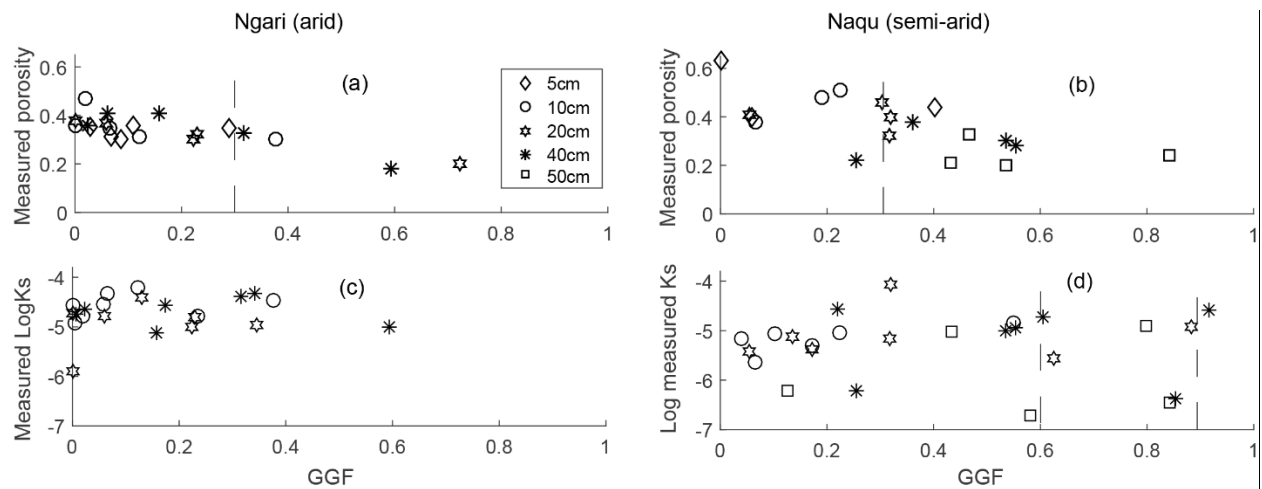


Figure 6-7 Scatter points of measured porosities (Top panel) and K_s (Bottom panel) with GGF varying at profile in the arid and semi-arid zones.

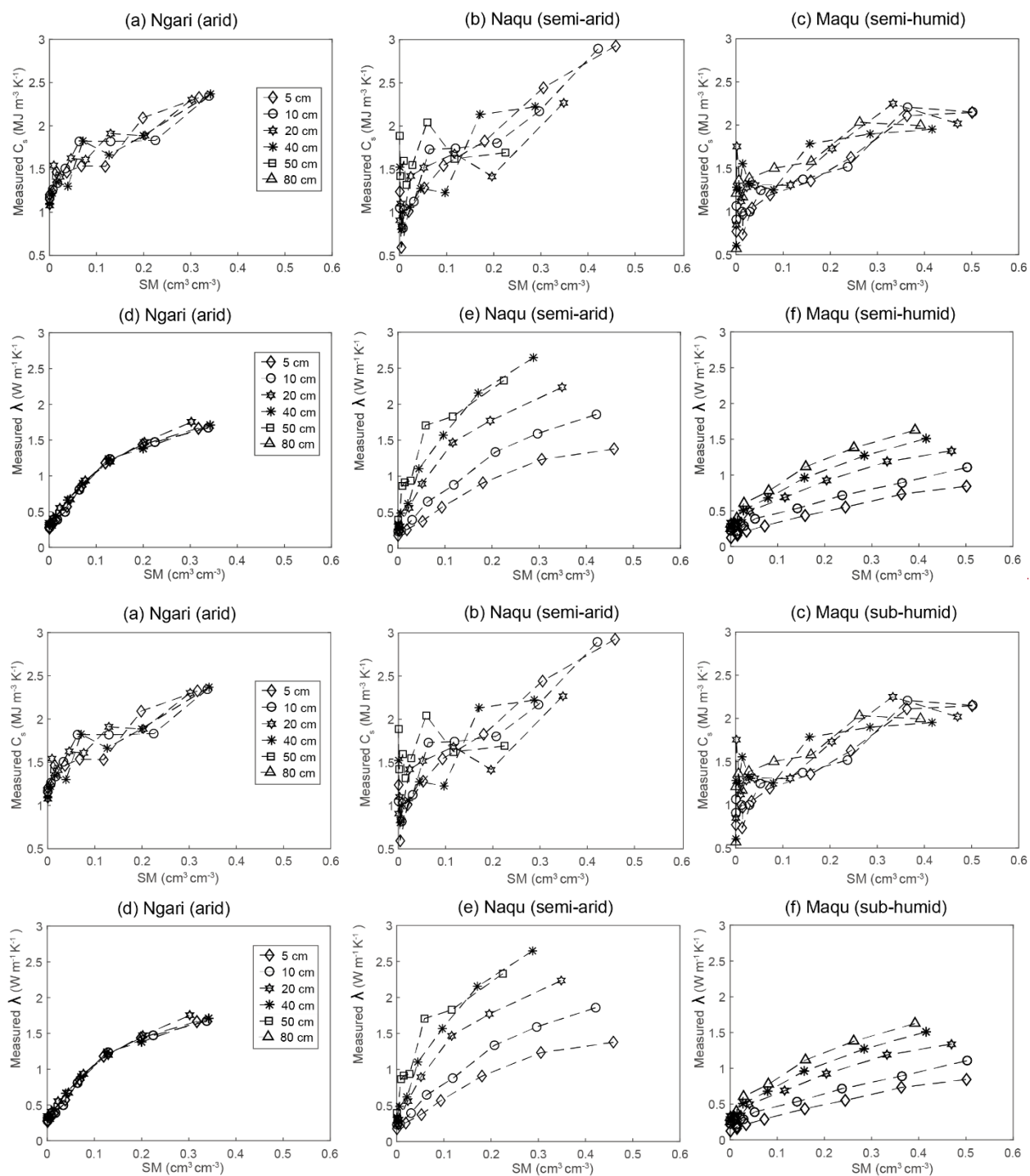


Figure 7-8 Profiles of Mean soil heat capacity (C_s) and thermal conductivities (λ) with varying water content (SM) **at different depths** in three climate zones.

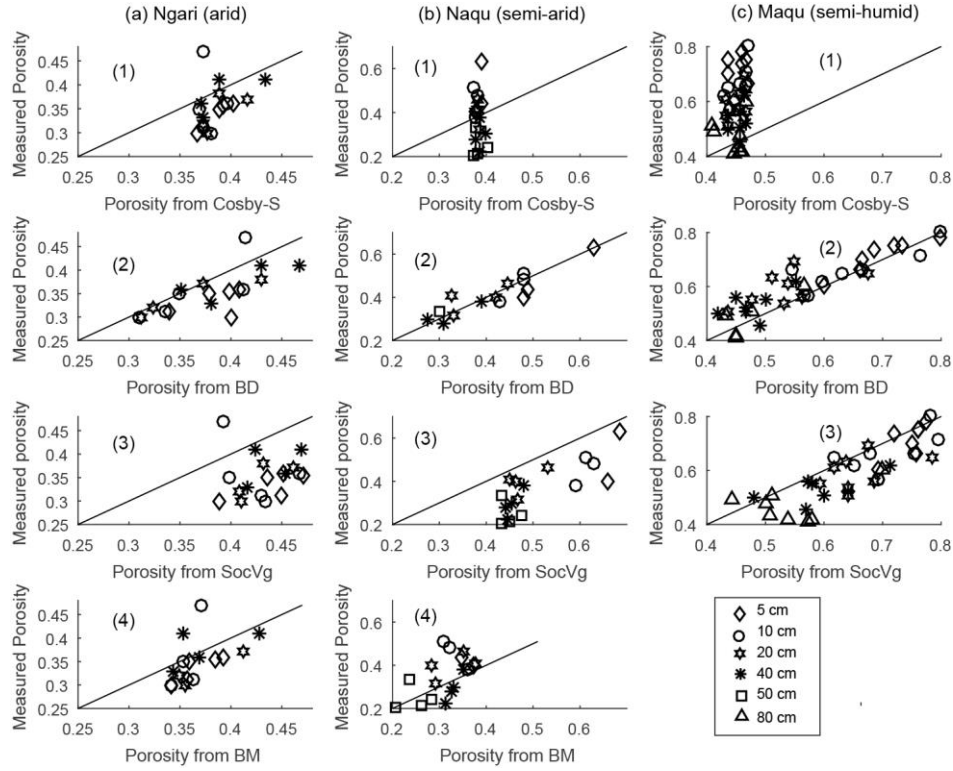


Figure 8 Comparisons of porosity profiles derived from different schemes with those measured for the three climate zones.

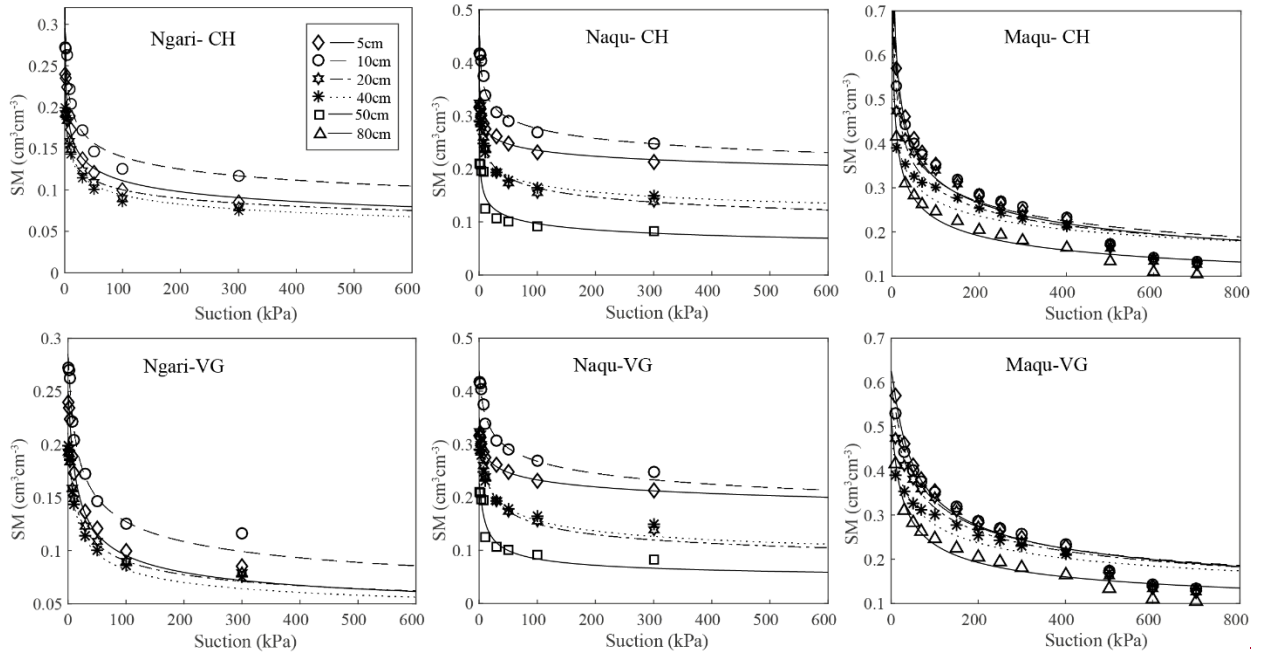
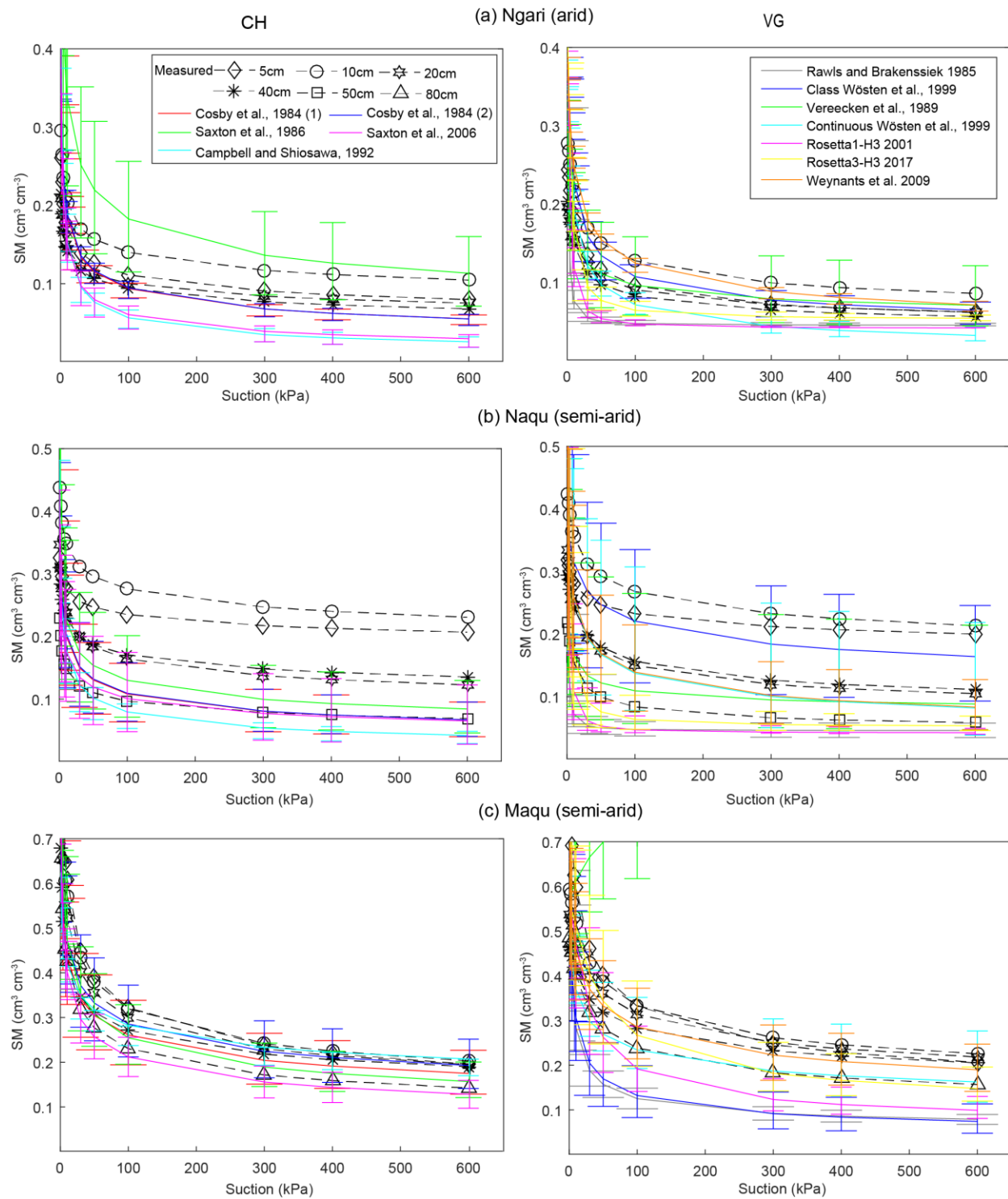


Figure 9 Estimated SWRCs by the CH and VG models with average observational SWCC of the soil profile for the three climate zones: Ngari in the arid zone, Naqu in the semi-arid zone and Maqu in the semi-humid zone. Dots denote average observed soil moisture content at specific suction. Lines represent estimated SWRCs.

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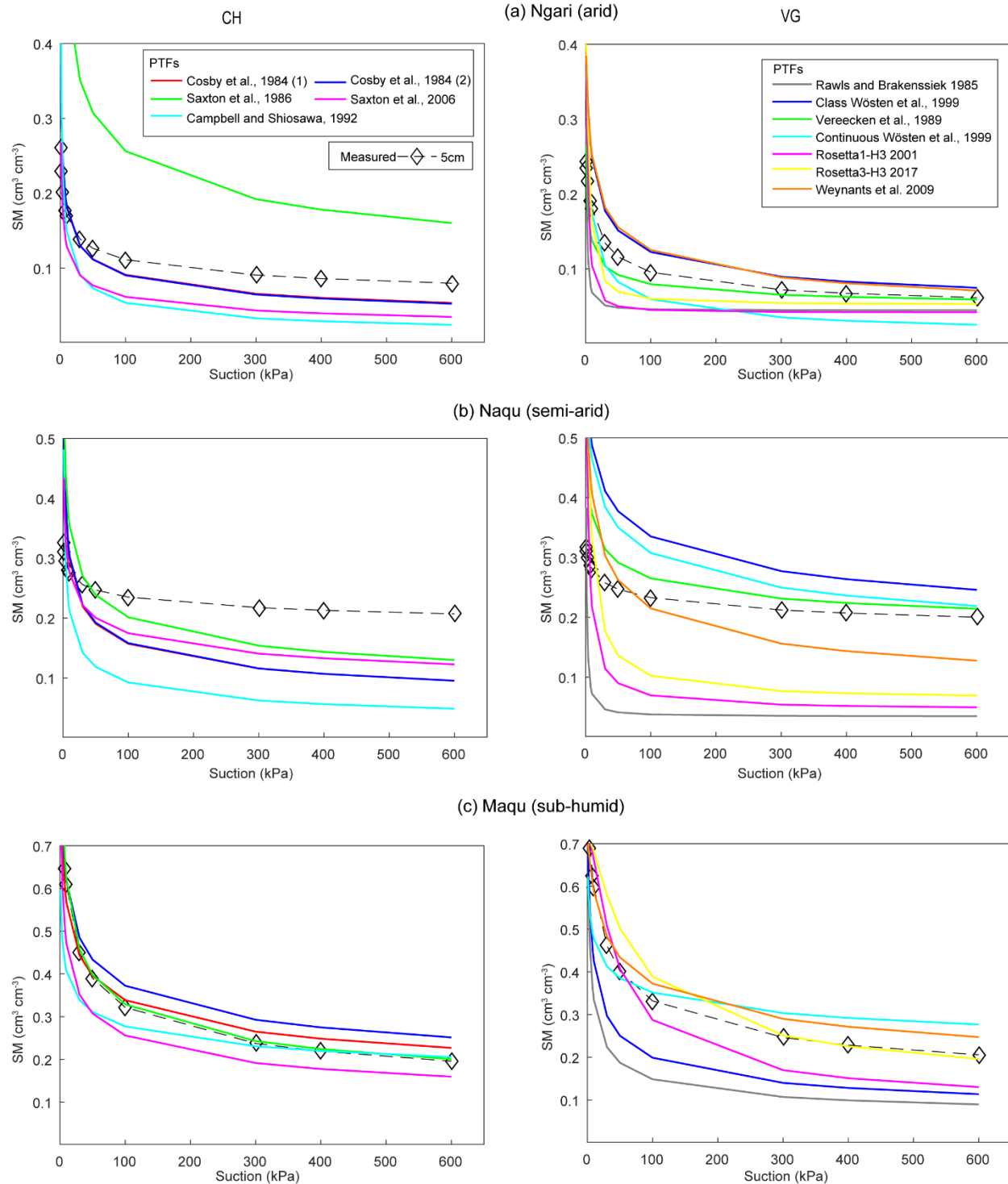


Figure 10-9 Comparisons between mean pressure-cell determined-estimated SWRCs from PTFs combined with the BD scheme, and the laboratory measurements at 5 cm for three climate zones. It is to note that the SWRC estimated from Vereecken et al. (1989) PTFs was out of range over the sub-humid zone and removed (right figure in Fig. 9c). The broken green line in the right-hand figure of (c) denotes SM at > 100 kPa being above 0.7 cm³ cm⁻³. The bar represents the lowest and highest values of the profile.

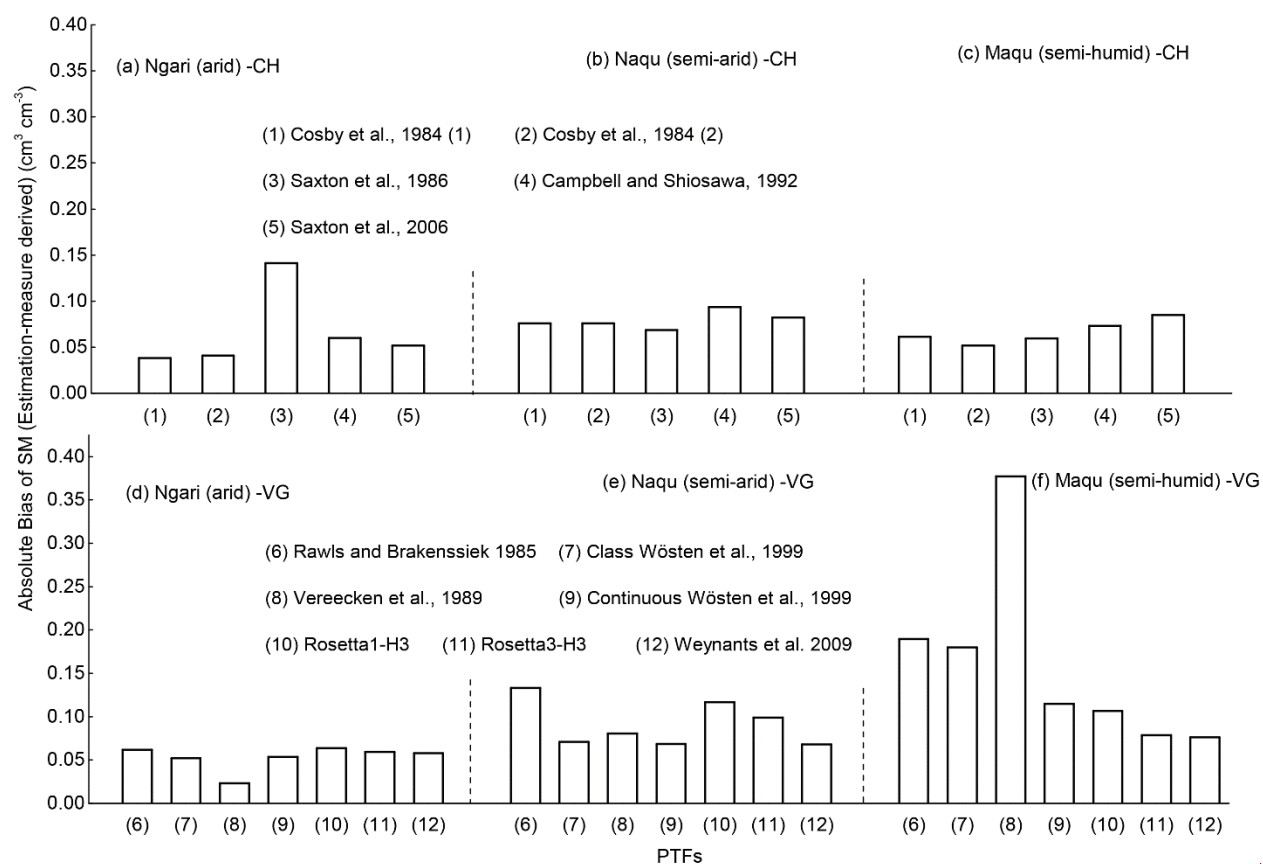
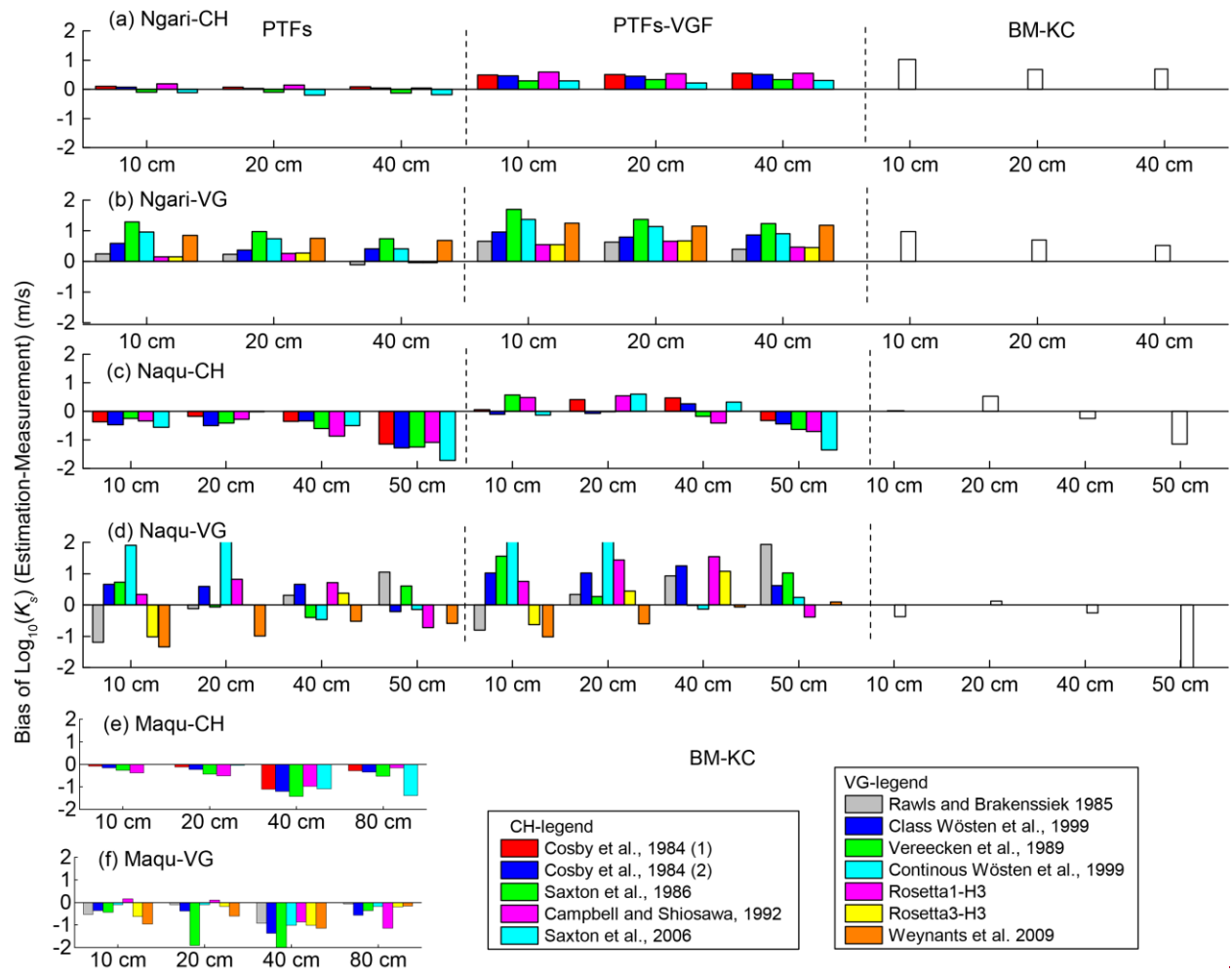


Figure 11 Absolute bias of estimated SWRCs from PTFs combined with the BD-scheme and the measurements at three climate zones.



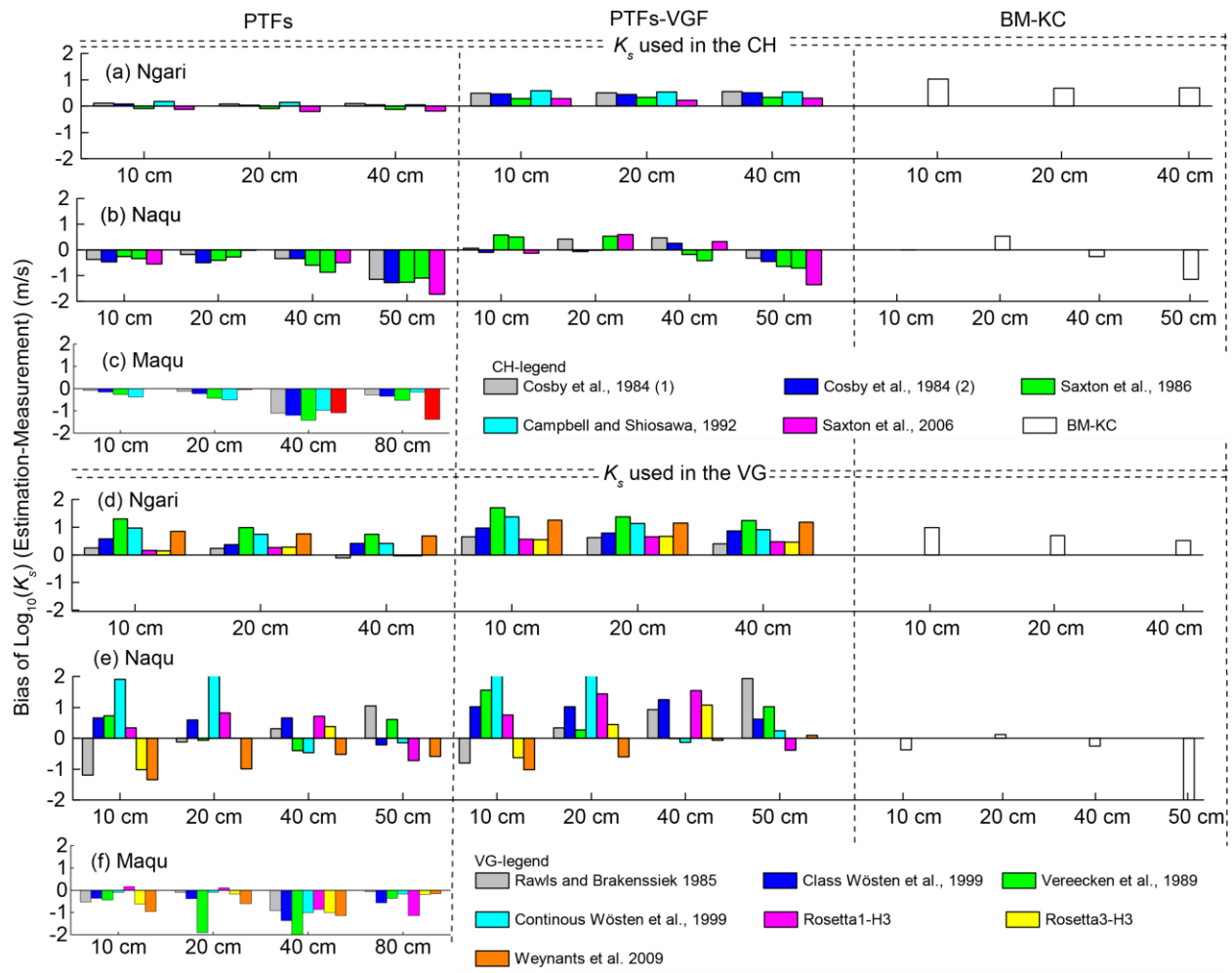


Figure 12-10 Comparisons of K_s , derived from PTFs, PTFs-VGF and BM-KC schemes in the CH and VG models, with field measurements in the profile over three climate zones.

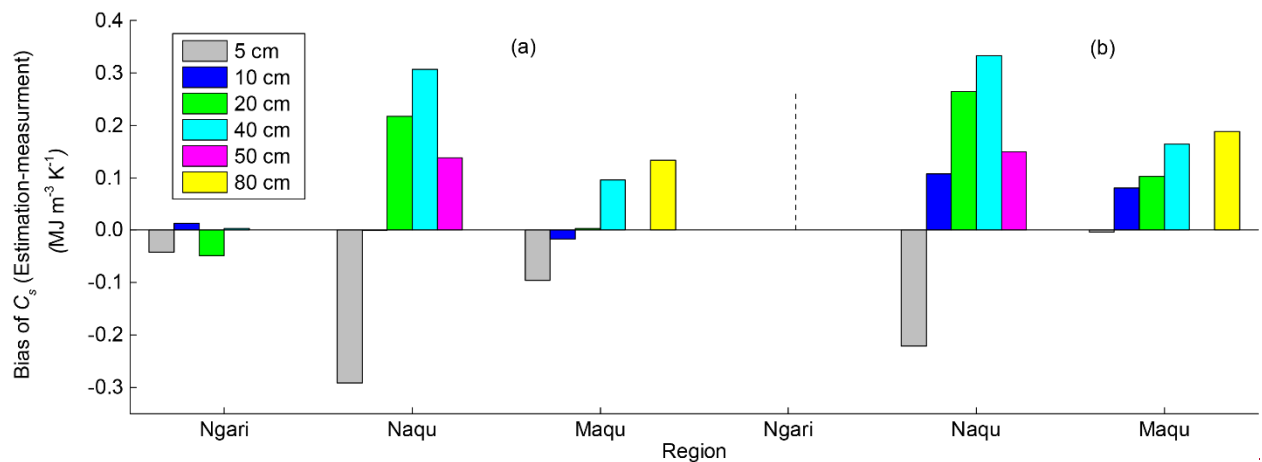


Figure 13 Biases of C_s between estimates, based on the De Vries (1963) model across the three climate zones, and the measurements. (a) and (b) represent the bias derived from estimations without and with considering SOC impact parameterization in the Maqu and Naqu regions. Ngari denotes the arid zone, Naqu the semi-arid zone and Maqu the semi-humid zone.

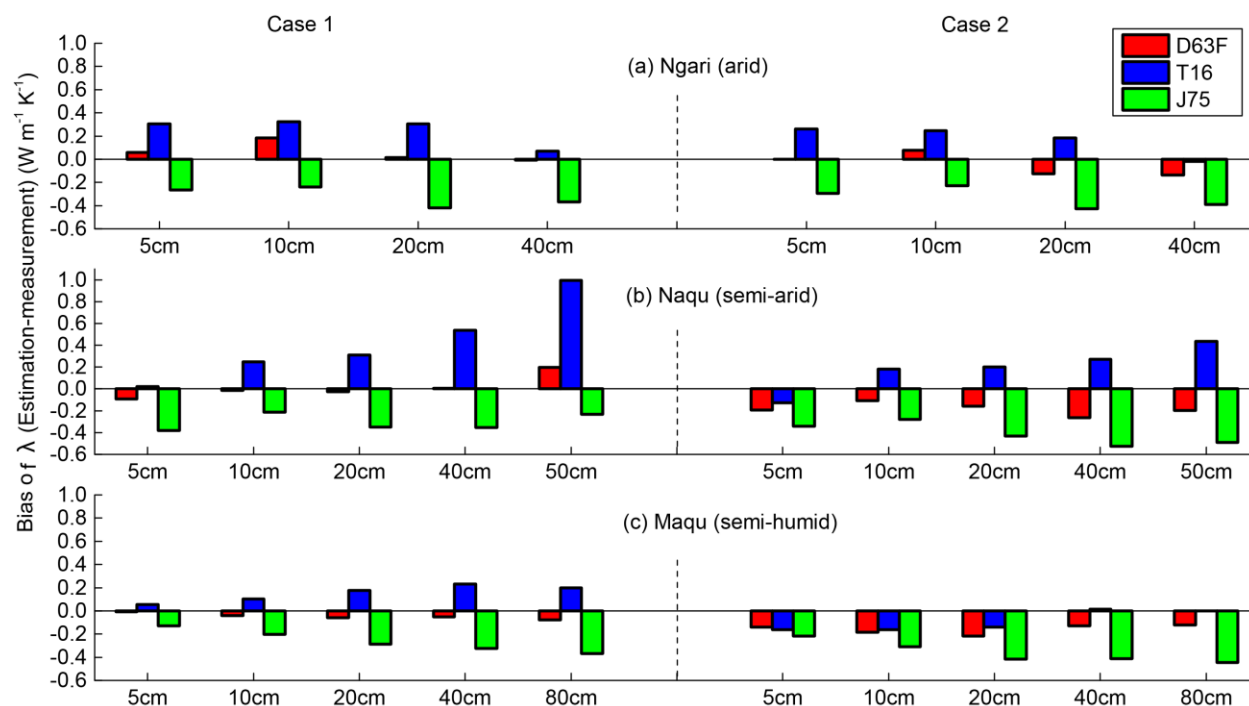
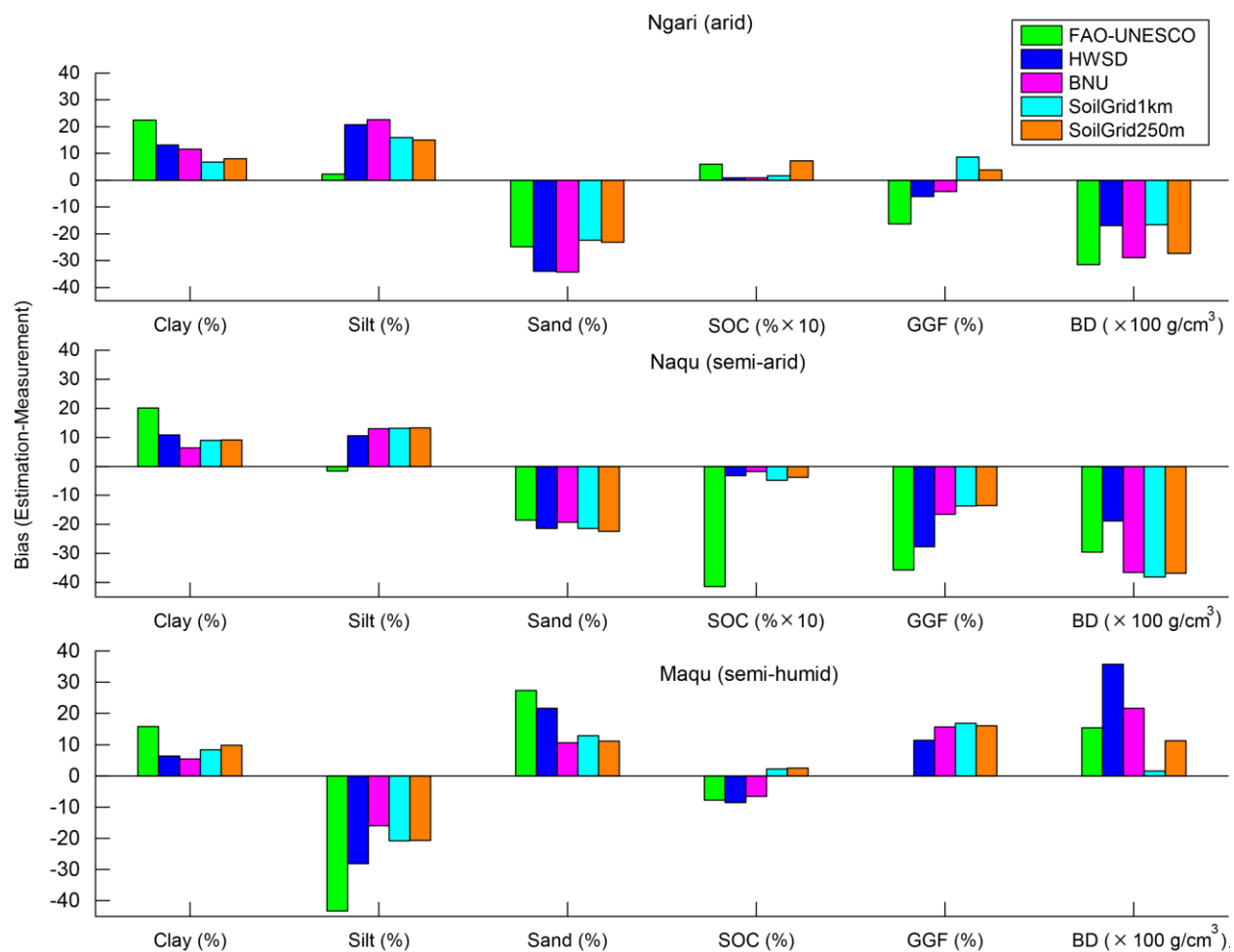


Figure 14 Biases of λ estimates based on D63F, T16 and J75 schemes combined with the BD scheme in the profile profiles across the three climate zones and the measurements. Case 1 is the bias derived from schemes not considering gravel impact parameterization for the arid and semi-arid zone or SOC impact parameterization for the semi-humid zone. Case 2 is the bias with these parameterizations taken into consideration.



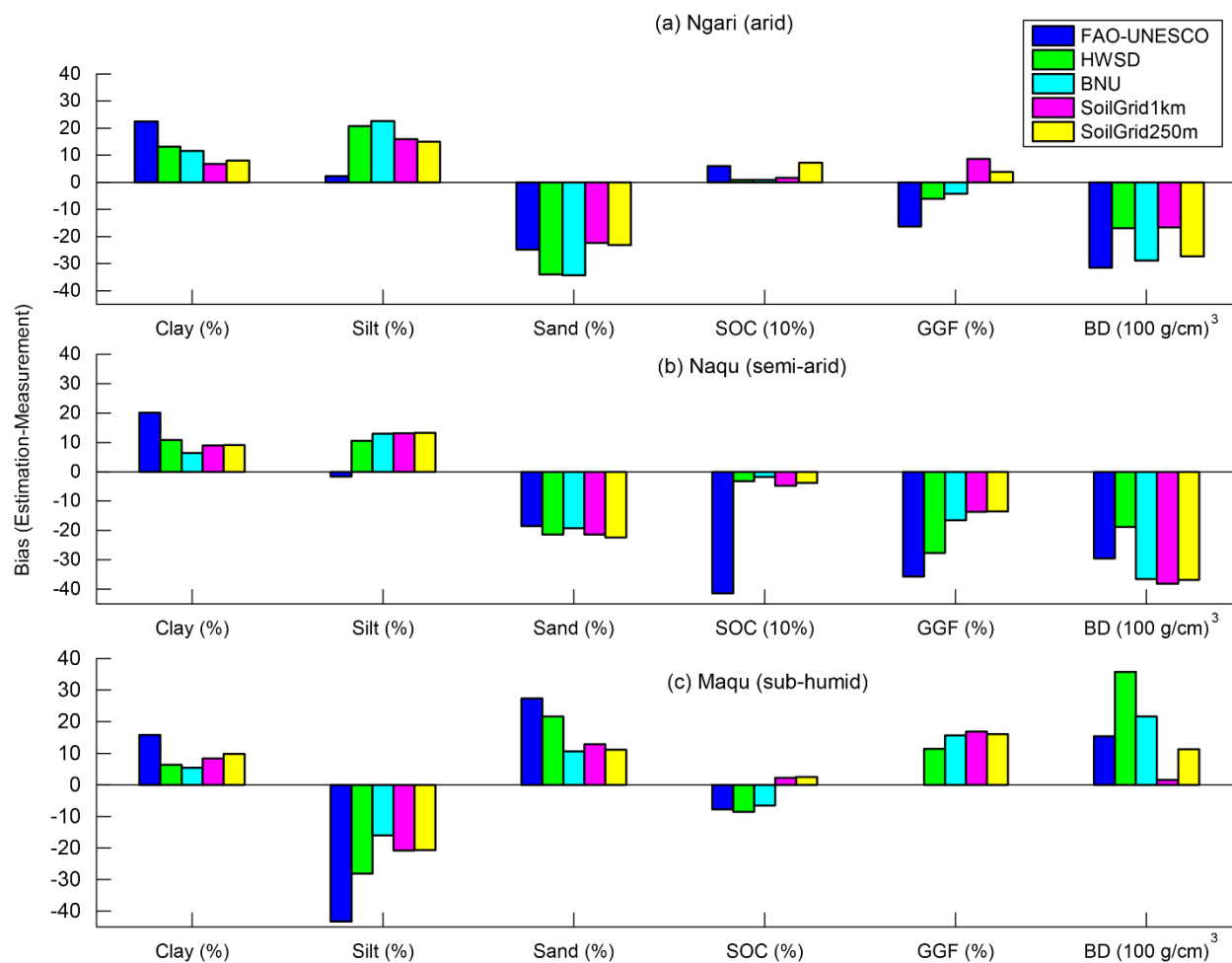


Figure 15-11 Average bias in soil basic properties between the existing products and the laboratory measurements taken for the three climate zones. To enable the comparison of BD with the same order of magnitude as other properties, the original BD was multiplied by 100 (with unit $\times 100 \text{ g/cm}^3$). Likewise, a multiplication ($\% \times 10$) is applied to SOC data on the semi-arid zone. **FAO-UNESCO is the FAO-UNESCO Soil Map of the World (2007). HWSD is the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISSCAS/JR, 2012). BNU is a Chinese data set of soil properties (Shangguan et al., 2012; Shangguan et al., 2013) and soil hydraulic parameters using PTFs (Dai et al., 2013) released by Beijing Normal University. SoilGrids1km** (Hengl et al., 2014) and the updated version of SoilGrids250m (Hengl, 2017) datasets are released by the International Soil Reference and Information Center (ISRIC) - WoSIS institute. HPSS is the hydraulic parameters of the Van Genuchten (1980)-Mualem (1976) model based on SoilGrids1km and Schaap et al. (2001) PTFs (Montzka et al., 2017).

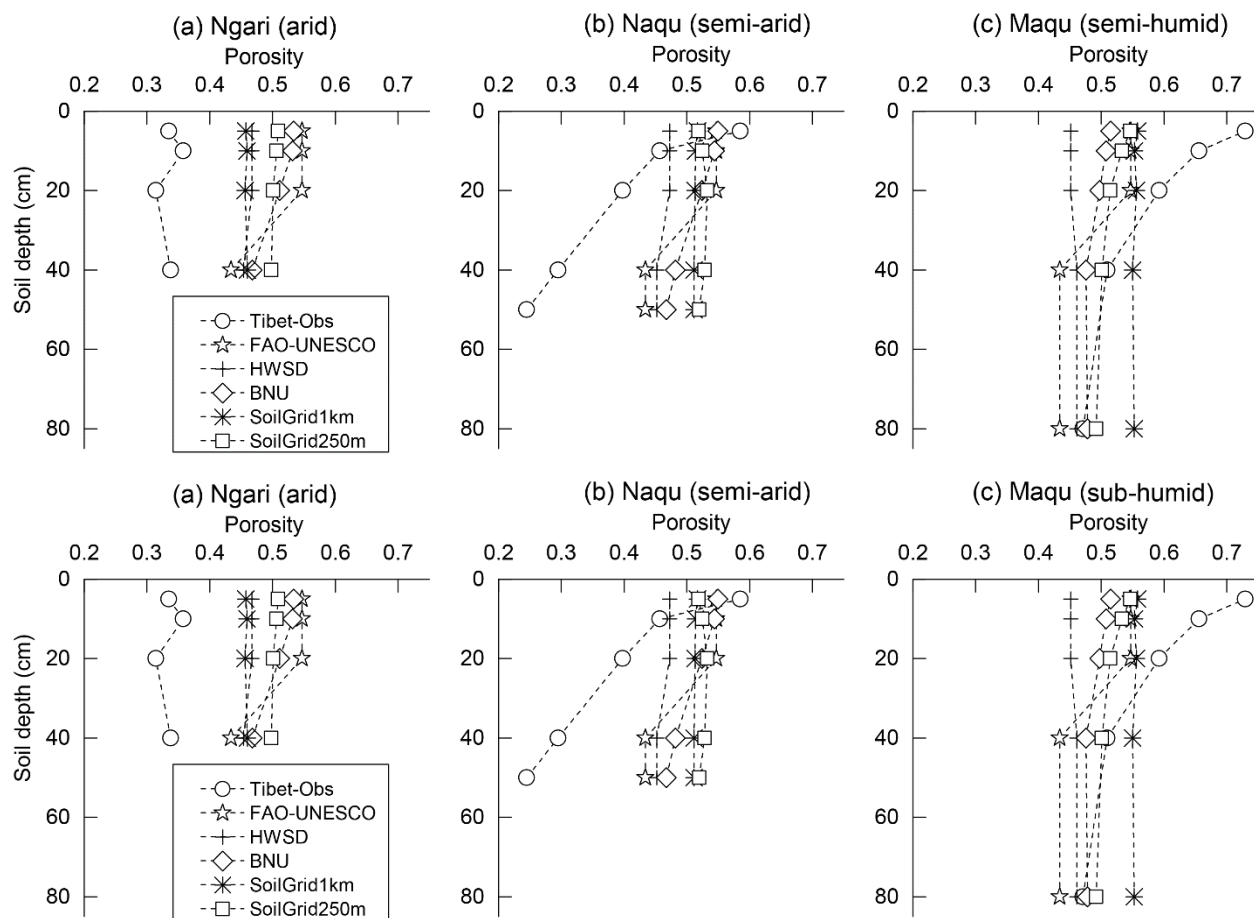
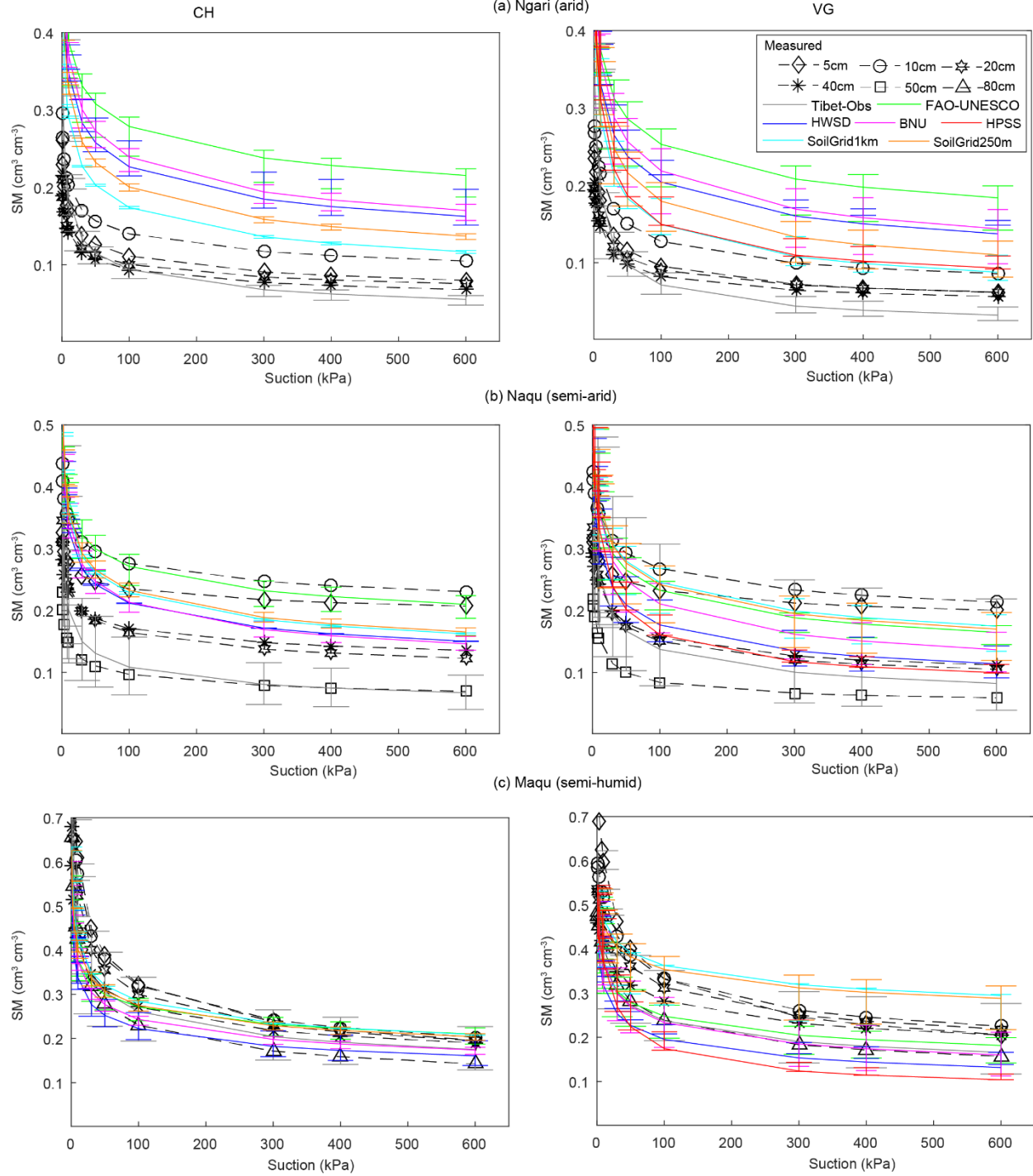


Figure 16-12 Comparisons between the porosity estimated from various existing datasets based on BD scheme, and the *in situ* measurements.



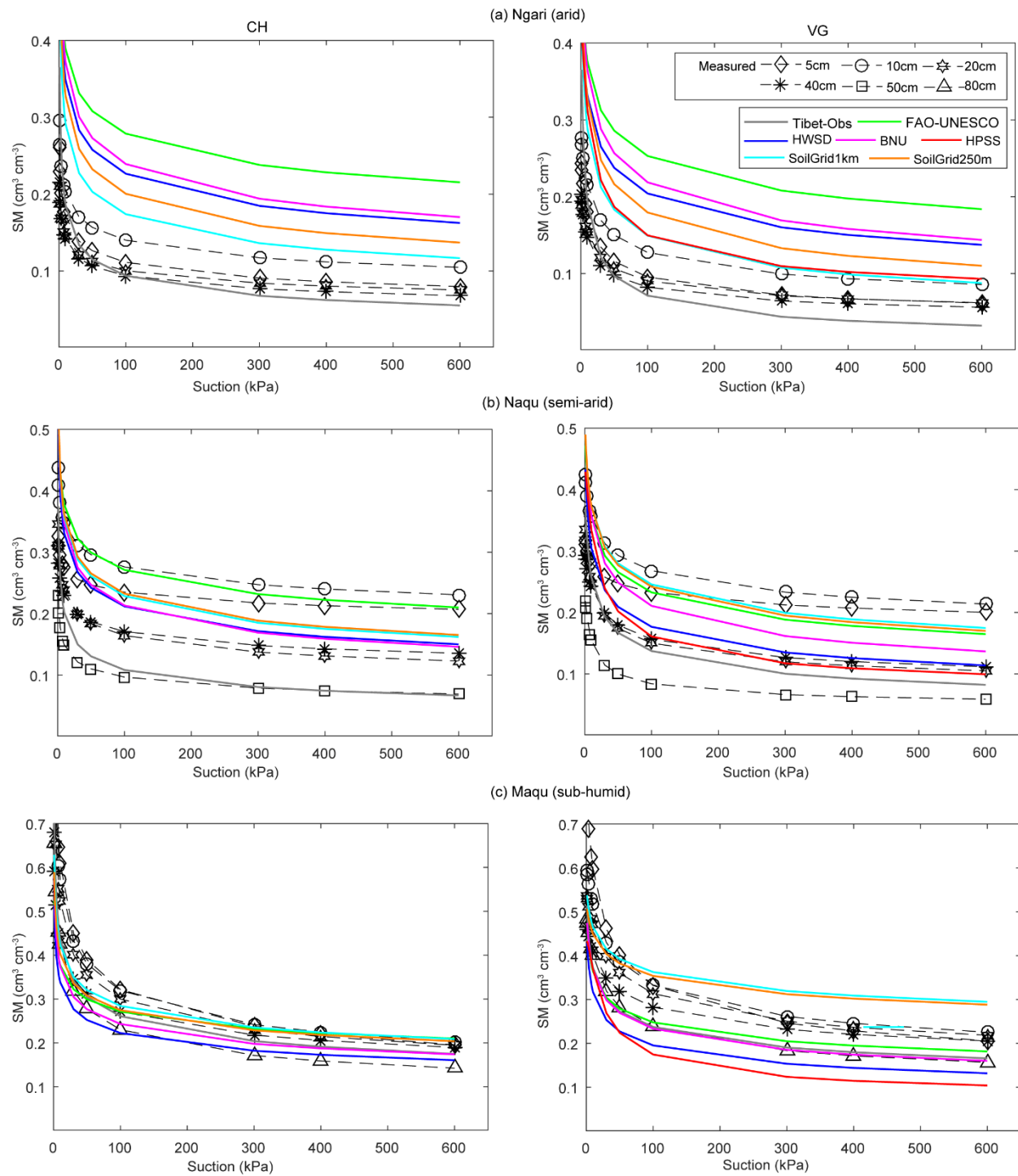


Figure 17-13 Comparisons of SWRCs, derived from the applicable PTFs based on various datasets, with laboratory measurements. **The bar represents the lowest and highest SM at a specific suction.** The left panels represent the SWRCs by the CH model based on six datasets. The right-hand panels represent the SWRCs by the VG model based on seven datasets, in which HPSS only provides hydraulic parameters for the VG model.

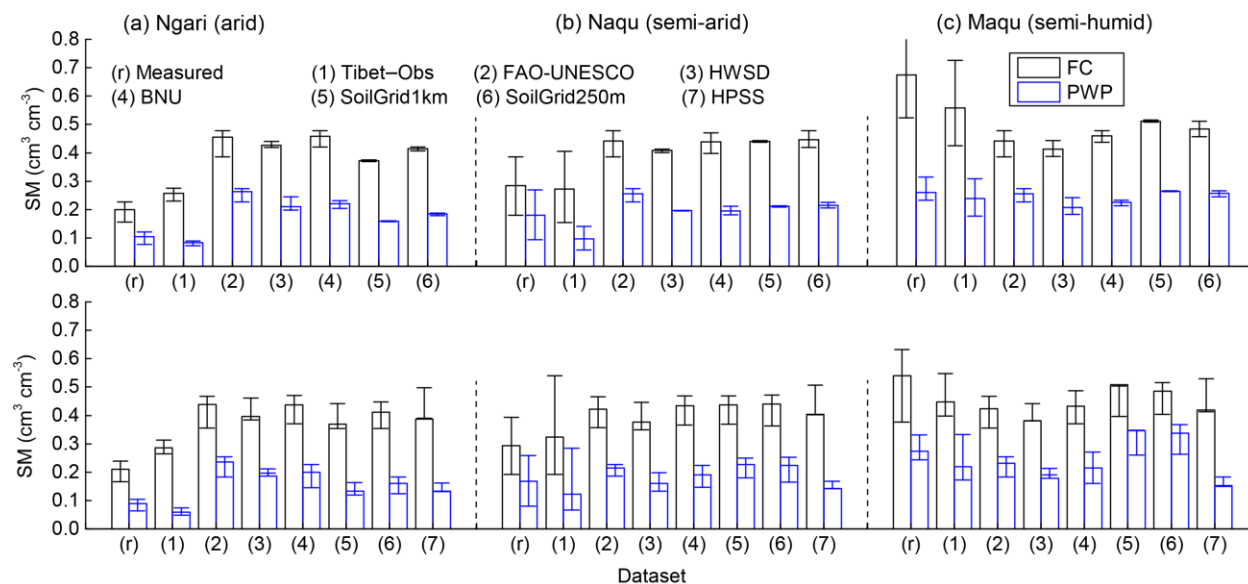


Figure 18 Comparisons of derived FC and PWP from SWRCs by the CH (upper panel) and VG (lower panel) models based on various soil datasets, with the laboratory measurements. The bar represents the lowest and highest FC and PWP of the profile. FC represents field capacity, and PWP denotes permanent wilting point.

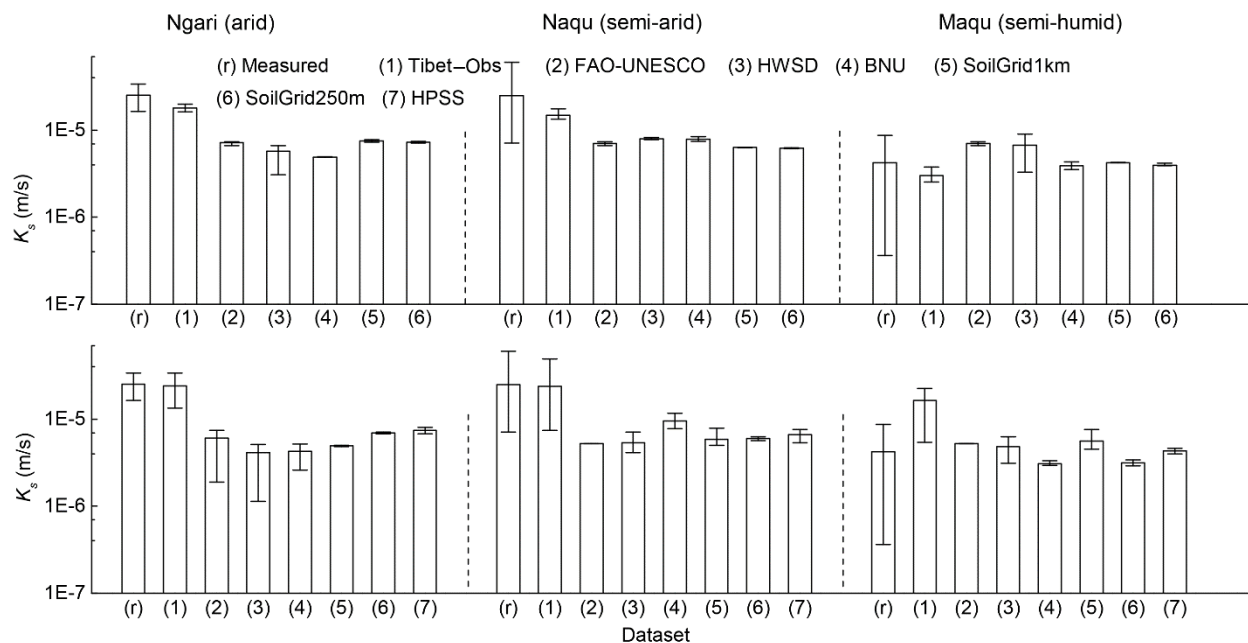


Figure 19 Comparisons of derived K_s from the applicable PTFs for the CH (upper panel) and VG (lower panel) models based on various soil datasets, with the measurements. The bars represent the lowest and highest K_s in the profile.

Appendix

A.1 Porosity scheme

Cosby-S scheme *(univariate)*

Cosby et al. (1984) PTF is used to obtain porosity from sand percentage in soil texture:

$$\phi = 0.489 - 0.001268 \times (\%sand) \quad (A1)$$

where ϕ is the soil porosity, $\%sand$ is the sand proportion of the soil sample.

BD scheme

BD scheme for porosity calculation (Hillel, 2003) is as follows:

$$\phi = 1 - \frac{\rho_b}{\rho_s} \quad (A2)$$

where ρ_b is the ~~bulk density~~ **dry bulk density** (g/cm³). ρ_s is the mineral particle density valued at 2.65g/cm³. For soil mixture, BD scheme assumed that the coarse and fine components share the same particle density.

SocVg scheme

Regarding soils as a mixture of organic and fine minerals, Chen et al. (2012) conceptualized porosity as shown in Eq. (A3). Through the determination of volumetric SOC, the gravel impact was taken into account (Eq. (A4-A5)) and assumed to be equal to the impact from sand particles. The effective sand proportion was equal to Eq. (A6).

$$\phi_m = (1 - V_{soc})\phi_F + V_{soc}\phi_{soc,sat} \quad (A3)$$

$$V_{soc} = \frac{\rho_s(1-\phi_F)m_{soc}}{\rho_{soc}(1-m_{soc}) + \rho_s(1-\phi_F)m_{soc} + (1-\phi_F)\frac{\rho_{soc}GGF}{(1-GGF)}} \quad (A4)$$

$$VGF = \frac{\rho_{soc}(1-\phi_F)GGF}{(1-GGF)(\rho_{soc}(1-m_{soc}) + \rho_s(1-\phi_F)m_{soc} + (1-\phi_F)\frac{\rho_{soc}GGF}{(1-GGF)})} \quad (A5)$$

$$\%sand_e = \%sand * (1 - VGF) + VGF \quad (A6)$$

where ϕ_m is the porosity of soil mixture. V_{soc} and VGF are the volumetric fractions of SOC and gravel, respectively. ϕ_F is the porosity of fine components and was calculated by using Eq. (A1), where $\%sand$ was obtained from Eq. (A6). $-GGF$ and m_{soc} are the gravimetric fractions of gravels and SOC, respectively. $\rho_{soc}=0.13$ g/cm³ is the BD of peat. $\phi_{soc,sat}=0.9$ is the porosity of peat.

Binary mixture (BM) scheme

Zhang et al. (2011) proposed a mixing-coefficient model to estimate the porosity for binary mixtures:

$$\phi_m = \begin{cases} (VGF - \beta_m * VGF + \beta_m)\phi_g + VFF * \phi_F - \beta_m * VFF & \text{if } VFF < \phi_g \\ (1 - \beta_m) * VGF * \phi_g + VFF * \phi_F & \text{if } VFF \geq \phi_g \end{cases} \quad (A7)$$

where VFF is the component fraction by volume for fine minerals. VGF can be determined using Eq. (A8). ϕ_F is defined as in the SocVg scheme. ϕ_g is the porosity for gravels, which is mainly affected by median grain size (Frings et al., 2011). In this study, ϕ_g was calculated by using empirical Eq. (A9) given by Wu and Wang (2006). β_m is the mixing coefficient related with grain size (Eq. (A10)).

$$VGF = \frac{GGF(1-\phi_F)}{GGF(1-\phi_F) + (1-GGF)(1-\phi_g)} \quad (A8)$$

$$\phi_g = 0.13 + \frac{0.21}{(GD+0.002)^{0.21}} \quad (\text{A9})$$

$$\beta_m = \begin{cases} 0.0363 \frac{GD}{FD} + 0.2326 & \text{for } \frac{GD}{FD} \leq 21 \\ 1 & \text{for } \frac{GD}{FD} > 21 \end{cases} \quad (\text{A10})$$

where GD and FD are the mean grain size for gravels and fine minerals, respectively, and the unit is mm.

A.2 Soil water retention curve (SWRC)

The function of Clapp and Hornberger (1978) (i.e. CH) for soil water retention is written as:

$$\varphi = \varphi_s (\theta / \theta_s)^{-1/b} \quad \varphi \leq \varphi_i \quad (\text{A11})$$

where φ_s is the saturated capillary potential (cm). b is pore size distribution index (dimensionless). θ is the SM ($\text{cm}^3\text{cm}^{-3}$) and θ_s is the saturated SM. φ_i defines an inflection point near saturation. The soil conductivity and diffusivity are written as:

$$\begin{cases} K(\theta) = K_s (\theta / \theta_s)^{3+2/b} \\ D(\theta) = D_s (\theta / \theta_s)^{2+1/b} \\ D_s = 1/b * K_s (\varphi_s / \theta_s) \end{cases} \quad (\text{A12})$$

where K and D are the soil hydraulic and thermal conductivity. K_s and D_s are the saturated hydraulic conductivity (m/s) and diffusivity (m^2/s).

The van Genuchten (1980) and Mualem (1976) (i.e. VG) model provides the water retention curve as Eq. (A13) shows,

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + (ah)^n)^{1-1/n}} = f(h, \theta_r, \theta_s, \alpha, n) \quad (\text{A13})$$

where $\theta(h)$ is the SM ($\text{cm}^3\text{cm}^{-3}$) at pressure head h (cm). θ_r is the residual SM ($\text{cm}^3\text{cm}^{-3}$). θ_s has the same meaning as above. α is the inverse of air entry value (cm^{-1}). n is the shape parameter (dimensionless). The soil conductivity and diffusivity are written as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$K = K_s \Theta^{1/2} [1 - (1 - \Theta^{1/(1-1/n)})^{1-1/n}]^2 \quad (\text{A14})$$

$$D(\Theta) = \frac{(1-m)K_s}{\alpha m(\theta_s - \theta_r)} \Theta^{1/2-1/m} [(1 - \Theta^{1/m})^{-m} + (1 - \Theta^{1/m})^m - 2]$$

$$m = 1 - 1/n$$

where Θ is the effective saturation.

Based on measured soil water potential and SM, we adopted the scaling method proposed by Montzka et al. (2017) to estimate hydraulic parameters in the CH and VG models. The expected-scale (representative) parameters of $(\widehat{\theta}_s, \widehat{b}, \widehat{\varphi}_s)$ and $(\widehat{\theta}_r, \widehat{\theta}_s, \widehat{\alpha}, \widehat{n})$ in the water retention curves of $f(h, \theta_s, b, \varphi_s)$ and $f(h, \theta_r, \theta_s, \alpha, n)$ that minimize the sum of squares of the deviations for all respective observations $i = 1 \dots N$ (Eq. (A15)) need to be obtained. The parameter fitting algorithm was the damped least-squares method of Levenberg-Marquardt (Marquardt, 1963). The initial values were taken from the mean of (θ_s, α, n) and $(\theta_r, \theta_s, \alpha, n)$ at each observation.

$$(\widehat{\theta}_s, \widehat{b}, \widehat{\varphi}_s) = \text{argmin} \sum_{i=1}^N [\theta_i - f(h, \theta_{s,i}, b_i, \varphi_{s,i})]^2$$

$$(\widehat{\theta}_r, \widehat{\theta}_s, \widehat{\alpha}, \widehat{n}) = \text{argmin} \sum_{i=1}^N [\theta_i - f(h, \theta_{r,i}, \theta_{s,i}, \alpha_i, n_i)]^2 \quad (\text{A15})$$

1225 A.3 PTFs for SWRC

Various PTFs have been developed to determine soil hydraulic properties. In terms of criterions described in Dai et al. (2013), five PTFs (No. 1-5 in Table A1) were selected for estimating parameters of (θ_s , ϕ_s , b) in the CH model as well as seven PTFs (No. 6-12 in Table A1) for the parameters of (θ_r , θ_s , α , n) in the VG model.

Table A1 List of PTFs for estimating soil water retention curve.

#	PTF	Retentio n/ K_s model	San d %	Sil t %	Clay %	Organic Carbon %	Bulk density Dry bulk density g cm ⁻³	Depth h -
1	Cosby et al., 1984 (1)	CH, K_s^1	√		√			
2	Cosby et al., 1984 (2)	CH, K_s^2	√	√	√			
3	Saxton et al., 1986	CH, K_s^3	√		√	√		
4	Campbell and Shiosawa, 1992	CH, K_s^4	√	√	√		√	
5	Saxton et al., 2006	CH, K_s^5	√		√	√		
6	Rawls and Brakenssiek 1985	VG, K_s^6	√		√		√	
7	Class Wösten et al., 1999	VG, K_s^7	√	√	√			√
8	Vereecken et al., 1989	VG, K_s^8	√		√	√	√	
9	Continuous Wösten et al., 1999	VG, K_s^9		√	√	√	√	√
10	Rosetta1-H3	VG, K_s^{10}	√	√	√		√	
11	Rosetta3-H3	VG, K_s^{11}	√	√	√		√	
12	Weynants et al. 2009	VG, K_s^{12}	√		√	√	√	

1230 where 10 and 11 were cited by Schaap et al. (2001) and Zhang and Schaap (2017), respectively.

$$^1 K_s = 60.96 * 10^{-0.884+0.0153*sand}$$

$$^2 K_s = 60.96 * 10^{-0.6+0.0126*sand-0.0064*clay} \text{ (multi-variate)}$$

$$^3 K_s = 24.0 \exp\{12.012 - 0.0755 * sand + [-3.895 + 0.03671 * sand - 0.1103 * clay + 0.00087546 clay^2]/\theta_s\}$$

$$^4 K_s = 339.0 * \left(\frac{1.3}{BD}\right)^{1.3b} \exp(-0.06888 * clay - 0.03638 * silt - 0.025)$$

$$^5 x = 0.00251 * sand + 0.00195 * clay + 0.011 * SOC + 0.00006 * sand * SOC + 0.00027 * clay * SOC + 0.0000452 * sand * clay + 0.299; K_s = 4632 * (\theta_s - y)^{3-b}$$

$$^6 \theta_s = \phi = 1 - BD/2.65; K_s = 24 \exp(19.52348 * \phi - 8.96847 - 0.028212 * clay + 0.00018107 * sand^2 - 0.0094125 * clay^2 - 8.395215 * \phi^2 + 0.077718 * sand * \phi - 0.00298 * sand^2 * \phi^2 - 0.019492 * clay^2 * \phi^2 + 0.0000173 * sand^2 * clay + 0.02733 * clay^2 * \phi + 0.001434 * sand^2 * \phi - 0.0000035 * sand * clay^2);$$

⁷ The K_s for the FAO textural classes Pachepsky, Y., and Rawls, W. J.: Development of pedotransfer functions in soil hydrology, Elsevier, 2004.

$$^8 \log(K_s) = 20.62 - 0.96 * \log(clay) - 0.66 * \log(sand) - 0.46 * \log(clay) - 8.43 * BD$$

$$^9 K_s = \exp(7.75 + 0.0352 * silt + 0.93 * itop - 0.967 * BD^2 - 0.000484 * clay^2 - 0.000322 * silt^2 + 0.001/silt - 0.0748/SOC - 0.643 * \log(silt) - 0.01398 * BD * clay - 0.1673 * BD * SOC + 0.02986 * itop * clay - 0.03305 * itop * silt), \text{ where topsoil is an ordinal variable having the value of 1 (depth 0–30 cm) or 0 (depth 30 cm).}$$

¹⁰ H3 hierarchical pedotransfer function in Schaap et al. (2001)

¹¹ Updated H3 hierarchical pedotransfer function in Zhang, Y., and Schaap, M. G.: Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3), J. Hydrol., 547, 39-53, doi: 10.1016/j.jhydrol.2017.01.004, 2017.

$$^{12} K_s = \exp(1.9582 + 0.0308sand - 0.6142BD - 0.01566SOC * 1.72)$$

A.4 Saturated hydraulic conductivity scheme

PTFs-VGF scheme

The PTF-VGF scheme estimated K_s of soil mixtures (Peck and Watson, 1979) as follows:

$$K_{sm} = K_{sat,f} \frac{2(1-VGF)}{2+VGF} \quad (\text{A16})$$

where K_{sm} is the K_s of soil mixtures. $K_{sat,f}$ is the K_s of fine minerals and was calculated using PTFs in Table A1. VGF shares the same definition as for Eq. (A8).

BM-Kozeny-Carman equation (BM-KC scheme)

The Kozeny-Carman equation (A17), originally developed to quantitatively describe hydraulic conductivity vs. the mean grain size in capillary flow, was used to estimate K_s of binary mixtures. The porosity was obtained by using the BM scheme in A.1 section. The representative grain diameter was estimated using the power-averaging method (Eq. (A18)) proposed by Zhang et al. (2011). This method introduced a coefficient (Eq. (A19)) with the critical fraction of gravels taking into account.

$$K_{sm} = \left(\frac{\rho g}{\mu} \right) \left[\frac{d_m^2 \phi_m^3}{180(1-\phi_m)^2} \right] \quad (\text{A17})$$

where ϕ_m has the same definition as in Equation (A7). d_m is the representative grain diameter of soil mixture. ρ is the fluid density. g is gravitational acceleration, and μ is the dynamic viscosity.

$$d_m = (VGF * GD^p + VFF * FD^p)^{1/p} \quad (\text{A18})$$

where VGF, VFF, GD and FD have the same definition as in the BM scheme in A.1 section displays. p is a coefficient that varies sigmoidally from -1 to 0 with VGF increasing from 0 to 1 . p is estimated empirically by

$$p = \frac{1}{1 + \exp[(\alpha(VGFC - VGF))]} - 1 \quad (\text{A19})$$

where $VGFC$ is the critical fraction of gravels and is approximated by $VGFC = 1 - \phi_g$ (ϕ_g from Eq. (A9)). α is a shape factor set at a value of 20 as in Zhang et al. (2011).

A.5 Heat capacity and thermal conductivity

Heat capacity

Soil heat capacity C_s depends on the heat capacities of all constituents, and is calculated using Eq. (A20) given by De Vries (1963),

$$C_s = \theta C_w + (1 - \theta_s) C_{soil} + (\theta_s - \theta) C_{air} \quad (\text{A20})$$

where θ and θ_s share the same meaning as in Eq. (A11). C represents the heat capacity ($\text{MJ m}^{-3} \text{K}^{-1}$), and the subscripts 'w', 'soil' and 'air' refer to water, solid soil and air, respectively. C_w , C_{soil} and C_{air} are taken as 4.2 , 2.0 and $0.001 \text{ MJ m}^{-3} \text{K}^{-1}$, respectively. If taking SOC impact into consideration, C_s is calculated as Eq. (A21) shows as follow,

$$C_s = \theta C_w + (1 - \theta_s) * ((1 - Vsoc) * C_{soil} + Vsoc * C_{soc}) + (\theta_s - \theta) C_{air} \quad (\text{A21})$$

where $Vsoc$ shares the same definition as in Eq. (A4). C_{soc} is the heat capacity of organic matter and taken as $2.5 \text{ MJ m}^{-3} \text{K}^{-1}$.

Thermal conductivity by the De Vries (1963) model revised by Farouki (1981) (D63F)

The De Vries (1963) model was developed from the Maxwell equation for electrical conductivity of a mixture of granular materials dispersed in a continuous fluid (Eucken, 1932). Farouki (1981) set liquid water as the continuous

medium and regarded soil minerals as uniform particles. Considering soils as binary mixture of fine minerals and coarse gravels, λ is estimated as follows:

$$\lambda = \frac{x_w \lambda_w + w_a x_a (\lambda_a + \lambda_v) + w_m x_m \lambda_m + w_g x_g \lambda_g + w_{soc} x_{soc} \lambda_{soc}}{x_w + w_a x_a + w_m x_m + w_g x_g + w_{soc} x_{soc}} \quad (24A22)$$

where w is the weighting factor, x is the volume fraction, λ is the thermal conductivity, and the subscripts 'w', 'a', 'v', 'm', 'g' and 'soc' refer to water, air, vapor, fine minerals, gravels and SOC composed of soil, respectively. $\lambda_w = 0.57 \text{ W m}^{-1} \text{ K}^{-1}$, $\lambda_a = 2.0 \text{ W m}^{-1} \text{ K}^{-1}$, $\lambda_g = 2.54 \text{ W m}^{-1} \text{ K}^{-1}$ and $\lambda_{soc} = 0.25 \text{ W m}^{-1} \text{ K}^{-1}$. λ_m was calculated using Eq. (A2322),

$$\lambda_m = \lambda_q^q \lambda_o^{(1-q)} \quad (A2322)$$

where λ_q is the thermal conductivity of quartz ($\lambda_q = 7.7 \text{ W m}^{-1} \text{ K}^{-1}$). λ_o is the thermal conductivity of other minerals ($\lambda_o = 2.0 \text{ W m}^{-1} \text{ K}^{-1}$). V_{soc} shares the same meaning as for Eq. (A4). In this study, q is assumed equal to half of the sand fraction ($q = 1/2 \text{ sand}$) in terms of Chen et al. (2012)'s research.

w in Eq. (23A24) is empirically given by:

$$w_i = \frac{1}{3} \left[\frac{2}{1 + \left(\frac{\lambda_i}{\lambda_w} - 1 \right) g_a} + \frac{1}{1 + \left(\frac{\lambda_i}{\lambda_w} - 1 \right) (1 - 2g_a)} \right] \quad (23A24)$$

where g_a is the shape factor of ellipsoidal particles. A uniform shape factor g_a of 0.125 is used for fine minerals (Farouki, 1981), a g_a of 0.33 for gravels and a g_a of 0.5 for SOC (De Vries, 1963).

For λ_v together with g_a for air, Farouki (1981) provided the following Eq. (24A25).

For $0.09 \text{ m}^3 \text{ m}^{-3} \leq x_w \leq \phi$,

$$\lambda_v = \lambda_v^s \quad \text{and} \quad g_{a(air)} = 0.333 - (0.333 - 0.035)x_a/\phi$$

And for $0 \leq x_w \leq 0.09 \text{ m}^3 \text{ m}^{-3}$,

$$\lambda_v = \frac{x_w}{0.09} \lambda_v^s \quad \text{and} \quad g_{a(air)} = 0.013 + 0.944\phi$$

where λ_v^s is the value of λ_v for saturated vapor. ϕ is defined as in Eq. (2A2).

Simplified De Vries-based model (T16)

The T16 scheme (Tian et al., 2016) assumed the negligible effect of vapor movement (i.e. $\lambda_v = 0$) in the De Vries-based model (Eq. (A2249)). Soil texture was assumed to be determining the physical properties of soil minerals. λ of fine minerals (λ_m) and shape parameters for minerals and air were computed using Eq. (25A26-2728),

$$\lambda_m = \lambda_{sand}^{\%sand} \lambda_{clay}^{\%clay} \lambda_{silt}^{\%silt} \quad (A2625)$$

and

$$g_{a(m)} = g_{a(sand)} \%sand + g_{a(silt)} \%silt + g_{a(clay)} \%clay \quad (26A27)$$

where $\lambda_{sand} = 7.7 \text{ W m}^{-1} \text{ K}^{-1}$, $g_{a(sand)} = 0.782$, $\lambda_{silt} = 2.74 \text{ W m}^{-1} \text{ K}^{-1}$, $g_{a(silt)} = 0.0534$, $\lambda_{clay} = 1.93 \text{ W m}^{-1} \text{ K}^{-1}$, and $g_{a(clay)} = 0.00775$.

$g_{a(air)}$ is assumed to vary linearly with air fraction and is estimated using Eq. (A2827):

$$g_{a(air)} = 0.333 * (1 - x_a/\phi) \quad (27A28)$$

where ϕ is defined as in Eq. (A2). x_a has the same meaning as in Eq. (24A22).

For dry soils, λ_{dry} calculation follows Eq. (26A29) proposed by De Vries (1963),

$$\lambda_{dry} = 1.25 * \frac{w_a x_a \lambda_a + w_m x_m \lambda_m + w_g x_g \lambda_g + w_{soc} x_{soc} \lambda_{soc}}{w_a x_a + w_m x_m + w_g x_g + w_{soc} x_{soc}} \quad (28A29)$$

where parameters share the same definition as in Eq. (24A22).

Johansen model (J75)

The Johansen (1975) model simulated λ given by a combination of dry and saturated state values, which is weighted by a factor known as the Kersten number as Eq. (29A30) depicts,

$$\lambda = K_e (\lambda_{sat} - \lambda_{dry}) + \lambda_{dry} \quad (29A30)$$

where λ_{dry} and λ_{sat} are the dry and saturated thermal conductivity, respectively. K_e is the Kersten number, a normalized thermal conductivity that relates to the logarithm of the moisture content (Kersten, 1949) as Eq. (30A31) shows,

$$\begin{cases} K_e = \frac{\lambda - \lambda_{dry}}{\lambda_{sat} - \lambda_{dry}} \\ K_e = \log(S_r) + 1.0 & \text{for unfrozen fine - grained soils} \\ K_e = 0.7 * \log(S_r) + 1.0 & \text{for unfrozen medium and fine sands} \end{cases} \quad (30A31)$$

where S_r is the saturation degree and defined as Eq. (31A32),

$$S_r = x_w / \theta_s \quad (31A32)$$

where x_w is the SM ($\text{cm}^3 \text{cm}^{-3}$). θ_s is saturated SM ($\text{cm}^3 \text{cm}^{-3}$) and calculated using Eq. (A2).

The saturated thermal conductivity is calculated using Eq. (32A33),

$$\lambda_{sat} = \lambda_m^{1-\theta_s} \lambda_w^{\theta_s} \quad (32A33)$$

where λ_m has the same definition as in Eq. (20A23). If considering the SOC impact, λ_m was calculated using Eq. (33A34),

$$\lambda_m = \lambda_q^{q(1-V_{soc})} \lambda_o^{(1-q)(1-V_{soc})} \lambda_{soc}^{V_{soc}} \quad (33A34)$$

The thermal conductivity for dry state is given as Eq. (34A35):

$$\lambda_{dry} = \frac{0.135\rho_b + 64.7}{2700 - 0.947\rho_b} \quad (34A35)$$

where ρ_b is the ~~bulk density~~ dry bulk density (g/cm^3).

A.6 Soil water flow and heat transport

The vertical movement of water in the unsaturated zone of the soil matrix obeys the following Richards equation (Richards, 1931) for the volumetric water content θ :

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(D(\theta) \frac{\partial \theta}{\partial z} - K(\theta) \right) + S_\theta \quad (A36)$$

where $D(\theta)$ (m^2/s) and $K(\theta)$ (m/s) are the hydraulic diffusivity and hydraulic conductivity, respectively, and S_θ is a volumetric sink term associated to root uptake ($\text{m}^3 \text{m}^{-3} \text{s}^{-1}$), which depends on the surface energy balance and the root profile.

The soil heat transfer is assumed to obey the following Fourier law of diffusion:

$$C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) \quad (A37)$$

where C_s is soil thermal heat capacity ($\text{J m}^{-3} \text{K}^{-1}$), λ is thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$). T is soil temperature ($^\circ\text{C}$).

Table A2

Table A2 Bias and RMSE between simulated porosities with measurements at three climate zones. The unit of listed value is $\text{cm}^3 \text{cm}^{-3}$.

Scheme	Index	Ngari (arid)				Naqu (semi-arid)					Maqu (semi-humid/sub-humid)				
		5 cm	10 cm	20 cm	40 cm	5 cm	10 cm	20 cm	40 cm	50 cm	5 cm	10 cm	20 cm	40 cm	80 cm
Cosby-S	Bias	0.05	0.02	0.07	0.05	0.18	0.08	0.05	0.09	0.14	0.27	0.20	0.14	0.07	0.06
	RMSE	0.05	0.07	0.09	0.09	0.25	0.10	0.05	0.11	0.15	0.28	0.21	0.15	0.09	0.07
BD	Bias	0.06	0.04	0.05	0.07	0.04	0.03	0.03	0.02	0.04	0.02	0.03	0.07	0.06	0.05
	RMSE	0.06	0.04	0.05	0.07	0.05	0.03	0.04	0.02	0.04	0.03	0.05	0.08	0.06	0.06
SocVg	Bias	0.1	0.07	0.09	0.11	0.14	0.15	0.08	0.16	0.20	0.04	0.06	0.07	0.08	0.08
	RMSE	0.11	0.1	0.09	0.15	0.17	0.16	0.09	0.17	0.21	0.05	0.08	0.09	0.09	0.10
BM	Bias	0.03	0.06	0.06	0.07	0.06	0.13	0.07	0.05	0.05					
	RMSE	0.03	0.06	0.06	0.07	0.07	0.15	0.08	0.06	0.06					

Table A3-1 Estimated parameters of CH model by using PTFs over the three climate zones of the TP. It is to note that θ_s aligned with each PTFs were estimated by their own original porosity estimate. θ_s listed in the last line is calculated from *in situ* BD measurement.

PTFs	Parameter	Ngari (arid)				Naqu (semi-arid)					Maqu (sub-humid)				
		5 cm	10 cm	20 cm	40 cm	5 cm	10 cm	20 cm	40 cm	50 cm	5 cm	10 cm	20 cm	40 cm	80 cm
Cosby et al., 1984	$\lambda(-)$	0.30	0.30	0.29	0.30	0.28	0.2	0.27	0.26	0.26	0.22	0.22	0.22	0.22	0.23
	ψ (cm)	-6.22	5.93	8.67	8.37	7.31	7.2			10.9	35.3	33.9	33.5	31.1	29.4
	θ_s ($\text{cm}^3 \text{cm}^{-3}$)	0.38	0.38	0.39	0.39	0.39	0.3	0.39	0.39	0.40	0.46	0.45	0.45	0.45	0.45
	$\lambda(-)$	0.30	0.31	0.29	0.30	0.28	0.2	0.27	0.26	0.26	0.22	0.22	0.22	0.22	0.23
Cosby et al., 1984	ψ (cm)	-6.77	6.43	10.1	9.86	8.09	8.0			12.4	51.0	48.7	47.9	43.6	41.1
	θ_s ($\text{cm}^3 \text{cm}^{-3}$)	0.38	0.38	0.39	0.39	0.39	0.3	0.40	0.39	0.40	0.46	0.46	0.46	0.46	0.45
	$\lambda(-)$	0.26	0.27	0.26	0.27	0.24	0.2	0.24	0.23	0.24	0.28	0.27	0.27	0.27	0.27
	ψ (cm)	164.28	10.67	14.66	18.59	10.27	9.94	10.47		13.25	59.90	55.70	55.04	50.33	50.61
Saxton et al., 1986	θ_s ($\text{cm}^3 \text{cm}^{-3}$)	0.31	0.31	0.34	0.32	0.35	0.3	0.37	0.37	0.37	0.44	0.44	0.44	0.44	0.43
	$\lambda(-)$	0.44	0.47	0.40	0.43	0.36	0.4	0.34	0.33	0.34	0.17	0.17	0.17	0.17	0.19
	ψ (cm)	10.13	9.49	12.20	12.85	5.01	7.26	9.94	15.21	19.03		17.68	28.02	37.95	
	θ_s ($\text{cm}^3 \text{cm}^{-3}$)	0.41	0.38	0.39	0.41	0.62	0.4	0.38	0.29	0.20	0.71	0.64	0.54	0.47	0.44
Saxton et al., 2006	$\lambda(-)$	0.32	0.45	0.42	0.40	0.20	0.2	0.25	0.26	0.30	0.26	0.27	0.27	0.29	0.31
	ψ (cm)	-2.60	7.02	11.42	12.62	1.68	1.77	3.91	2.87	8.49	20.46	21.83	29.39	37.87	44.39
	θ_s ($\text{cm}^3 \text{cm}^{-3}$)	0.43	0.43	0.42	0.43	0.65	0.6	0.46	0.44	0.47	1.00	0.85	0.69	0.53	0.49
	θ_s from BD scheme ($\text{cm}^3 \text{cm}^{-3}$)	0.41	0.38	0.39	0.41	0.62	0.4	0.38	0.29	0.20	0.71	0.64	0.54	0.47	0.44

Table A3-2 Estimated parameters of VG model by using PTFs over the three climate zones of the TP. It is to note that θ_s aligned with each PTFs were estimated by their own original porosity estimate. θ_s listed in the last line is calculated from *in situ* BD measurement.

PTFs	Parameters	Ngari (arid)				Naqu (semi-arid)					Maqu (sub-humid)				
		5 cm	10 cm	20 cm	40 cm	5 cm	10 cm	20 cm	40 cm	50 cm	5 cm	10 cm	20 cm	40 cm	80 cm
Rawls and Brakensiek 1985	θ_r (cm ³ cm ⁻³)	0.0				0.0					0.0				
	θ_r (cm ³ cm ⁻³)	4	0.04	0.05	0.04	3	0.04	0.05	0.05	0.06	4	0.04	0.05	0.05	0.05
	θ_s (cm ³ cm ⁻³)	0.4				0.6					0.7				
	θ_s (cm ³ cm ⁻³)	1	0.38	0.39	0.41	2	0.46	0.38	0.29	0.2	1	0.64	0.54	0.47	0.44
	a (cm ⁻¹)	0.1				0.1					0.0				
	a (cm ⁻¹)	1	0.1	0.08	0.09	3	0.14	0.1	0.06	0.04	6	0.06	0.04	0.03	0.03
Wösten et al., (Class PTF)	n (-)	2.1				2.0					1.4				
	θ_r (cm ³ cm ⁻³)	6	2.21	2.01	2.03	7	2.31	2.18	2.07	2.1	5	1.48	1.48	1.5	1.55
	θ_r (cm ³ cm ⁻³)	0.0				0.0					0.0				
	θ_r (cm ³ cm ⁻³)	3	0.03	0.03	0.03	1	0.01	0.01	0.01	0.01	3	0.03	0.03	0.03	0.03
	θ_s (cm ³ cm ⁻³)	0.4				0.4					0.4				
	θ_s (cm ³ cm ⁻³)	0.4	0.4	0.4	0.37	4	0.44	0.44	0.39	0.39	0.4	0.4	0.4	0.37	0.37
Vereecken et al., 1989	a (cm ⁻¹)	0.0				0.0					0.0				
	a (cm ⁻¹)	4	0.04	0.04	0.04	3	0.03	0.03	0.02	0.02	4	0.04	0.04	0.04	0.04
	n (-)	1.3				1.1					1.3				
	n (-)	8	1.38	1.38	1.52	8	1.18	1.18	1.17	1.17	8	1.38	1.38	1.52	1.52
	θ_r (cm ³ cm ⁻³)	0.0				0.1					0.2				
	θ_r (cm ³ cm ⁻³)	4	0.03	0.04	0.04	2	0.08	0.05	0.04	0.04	1	0.16	0.13	0.1	0.09
Wösten et al., 1999	θ_s (cm ³ cm ⁻³)	0.3				0.5					0.6				
	θ_s (cm ³ cm ⁻³)	7	0.35	0.37	0.37	6	0.41	0.35	0.28	0.22	1	0.55	0.47	0.42	0.4
	a (cm ⁻¹)	0.3				0.1					0.0				
	a (cm ⁻¹)	2	0.34	0.18	0.25	6	0.35	0.25	0.19	0.28	1	0.01	0.01	0.01	0.02
	n (-)	1.3				1.2					0.8				
	n (-)	8	1.45	1.22	1.27	5	1.49	1.41	1.31	1.37	2	0.83	0.82	0.82	0.85
Rosetta1-H3	θ_r (cm ³ cm ⁻³)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	θ_r (cm ³ cm ⁻³)	0.5				0.5					0.6				
	θ_s (cm ³ cm ⁻³)	5	0.36	0.37	0.38	7	0.41	0.35	0.28	0.21	4	0.57	0.48	0.42	0.4
	a (cm ⁻¹)	0.0				0.0					0.2				
	a (cm ⁻¹)	6	0.05	0.05	0.04	4	0.05	0.06	0.03	0.02	0.2	0.09	0.03	0.02	0.02
	n (-)	1.4				1.1					1.1				
Rosetta1-H3	n (-)	8	1.46	1.4	1.44	9	1.35	1.39	1.3	1.2	3	1.16	1.19	1.25	1.28
	θ_r (cm ³ cm ⁻³)	0.0				0.0					0.0				
	θ_r (cm ³ cm ⁻³)	4	0.03	0.04	0.04	4	0.05	0.04	0.04	0.04	7	0.07	0.05	0.05	0.04
	θ_s (cm ³ cm ⁻³)	0.3				0.4					0.5				
	θ_s (cm ³ cm ⁻³)	6	0.35	0.34	0.35	6	0.41	0.34	0.31	0.29	5	0.51	0.43	0.38	0.37
	a (cm ⁻¹)	0.0				0.0					0				
θ_s from BD scheme (cm ³ cm ⁻³)	a (cm ⁻¹)	4	0.04	0.03	0.03	4	0.04	0.04	0.05	0.04	0	0.01	0.01	0.01	0.01
	n (-)	2.2				1.8					1.7				
		6	2.3	1.95	2.07	4	2.41	2.13	1.84	2.45	3	1.7	1.67	1.61	1.54
		0.4				0.6					0.7				
		1	0.38	0.39	0.41	2	0.46	0.38	0.29	0.20	1	0.64	0.54	0.47	0.44

Table A4 Biases of estimated SWRCs from PTFs combined with the BD scheme and the measurements at 5 cm at three climate zones.

PTFs	Ngari (arid)	Naqu (semi-arid)	Maqu (sub-humid)
	Absolute Bias (cm ³ cm ⁻³)	Absolute Bias (cm ³ cm ⁻³)	Absolute Bias (cm ³ cm ⁻³)
Cosby et al., 1984		0.03	0.09
Cosby et al., 1984		0.04	0.09
Saxton et al., 1986		0.15	0.08
			0.12

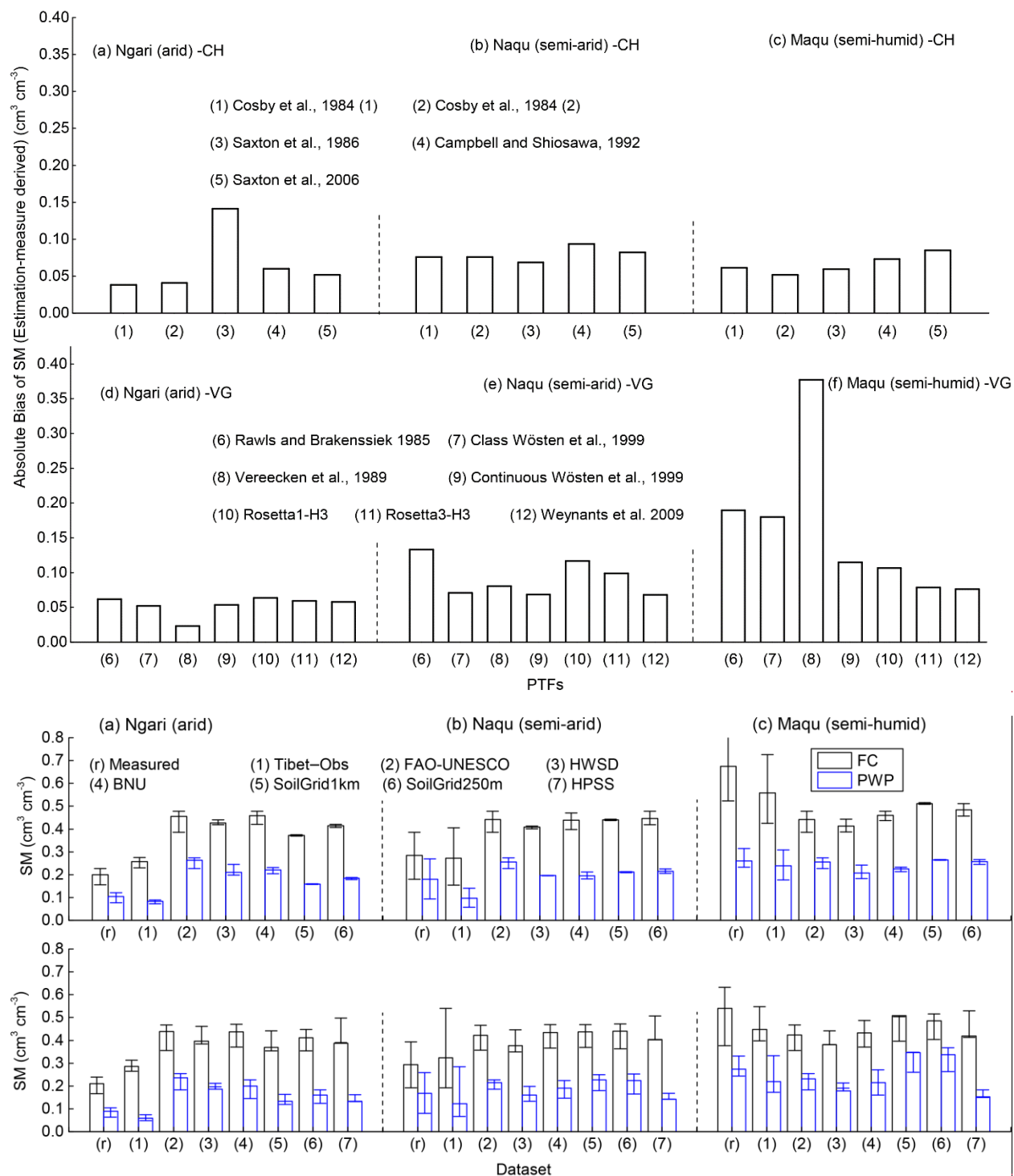
<u>Campbell and Shiosawa, 1992</u>	<u>0.06</u>	<u>0.11</u>	<u>0.17</u>
<u>Saxton et al., 2006</u>	<u>0.05</u>	<u>0.10</u>	<u>0.18</u>
<u>Rawls and Brakensiek 1985</u>	<u>0.06</u>	<u>0.16</u>	<u>0.30</u>
<u>Wösten et al., (Class PTF)</u>	<u>0.05</u>	<u>0.04</u>	<u>0.29</u>
<u>Vereecken et al., 1989</u>	<u>0.01</u>	<u>0.10</u>	<u>0.38</u>
<u>Wösten et al., 1999</u>	<u>0.05</u>	<u>0.07</u>	<u>0.22</u>
<u>Rosetta1-H3</u>	<u>0.06</u>	<u>0.14</u>	<u>0.20</u>
<u>Rosetta3-H3</u>	<u>0.06</u>	<u>0.12</u>	<u>0.16</u>
<u>Weynants et al. 2009</u>	<u>0.06</u>	<u>0.07</u>	<u>0.17</u>

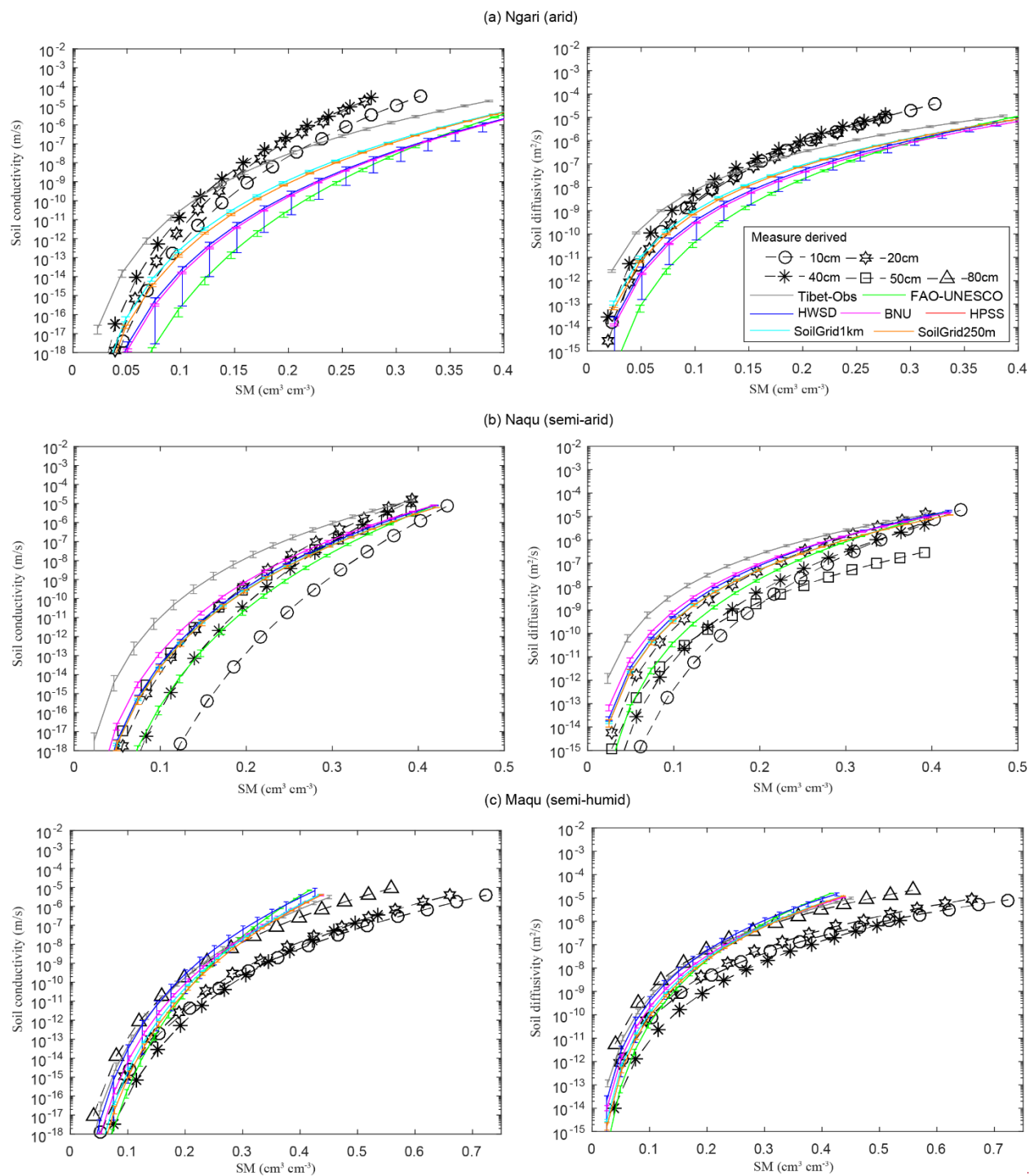
Table A5 Biases of C_s between estimates, based on the De Vries (1963) model across the three climate zones, and the measurements. Upper part of the table lists the bias derived from estimations without considering SOC impact, and lower part of the table for biases from estimations with taking SOC impact into account in the Maqu and Naqu regions. The unit of listed value is $\text{MJ m}^{-3} \text{K}^{-1}$.

<u>Region</u>	<u>5 cm</u>	<u>10 cm</u>	<u>20 cm</u>	<u>40 cm</u>	<u>50 cm</u>	<u>80 cm</u>
<u>Ngari (arid)</u>	<u>-0.04</u>	<u>0.01</u>	<u>-0.05</u>	<u>0.00</u>	<u>-</u>	<u>-</u>
<u>Naqu (semi-arid)</u>	<u>-0.29</u>	<u>0.00</u>	<u>0.22</u>	<u>0.31</u>	<u>0.14</u>	<u>-</u>
<u>Maqu (sub-humid)</u>	<u>-0.10</u>	<u>-0.02</u>	<u>0.00</u>	<u>0.10</u>	<u>-</u>	<u>0.13</u>
<u>Naqu (semi-arid) +SOC</u>	<u>-0.22</u>	<u>0.11</u>	<u>0.26</u>	<u>0.33</u>	<u>0.15</u>	<u>-</u>
<u>Maqu (sub-humid) +SOC</u>	<u>0.00</u>	<u>0.08</u>	<u>0.10</u>	<u>0.16</u>	<u>-</u>	<u>0.19</u>

Table A6 Comparisons of the mean derived FC and PWP from SWRCs-CH and SWRCs-VG models based on various soil datasets, with the laboratory measurements. FC represents field capacity, and PWP denotes permanent wilting point.

<u>Region</u>	<u>Parameters</u>	<u>Measured</u>	<u>Tibet-Obs</u>	<u>FAO-UNESCO</u>	<u>HWSD</u>	<u>BNU</u>	<u>SoilGrid1km</u>	<u>SoilGrid250m</u>
<u>Ngari</u>	<u>FC ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.20</u>	<u>0.26</u>	<u>0.46</u>	<u>0.43</u>	<u>0.46</u>	<u>0.37</u>	<u>0.41</u>
<u>(arid)</u>	<u>PWP ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.10</u>	<u>0.08</u>	<u>0.26</u>	<u>0.21</u>	<u>0.22</u>	<u>0.16</u>	<u>0.18</u>
<u>Naqu</u>	<u>FC ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.28</u>	<u>0.27</u>	<u>0.44</u>	<u>0.41</u>	<u>0.44</u>	<u>0.44</u>	<u>0.45</u>
<u>(semi-arid)</u>	<u>PWP ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.18</u>	<u>0.10</u>	<u>0.26</u>	<u>0.20</u>	<u>0.20</u>	<u>0.21</u>	<u>0.22</u>
<u>Maqu</u>	<u>FC ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.68</u>	<u>0.56</u>	<u>0.44</u>	<u>0.41</u>	<u>0.46</u>	<u>0.51</u>	<u>0.48</u>
<u>(sub-humid)</u>	<u>PWP ($\text{cm}^3 \text{cm}^{-3}$)</u>	<u>0.26</u>	<u>0.24</u>	<u>0.26</u>	<u>0.21</u>	<u>0.23</u>	<u>0.27</u>	<u>0.26</u>





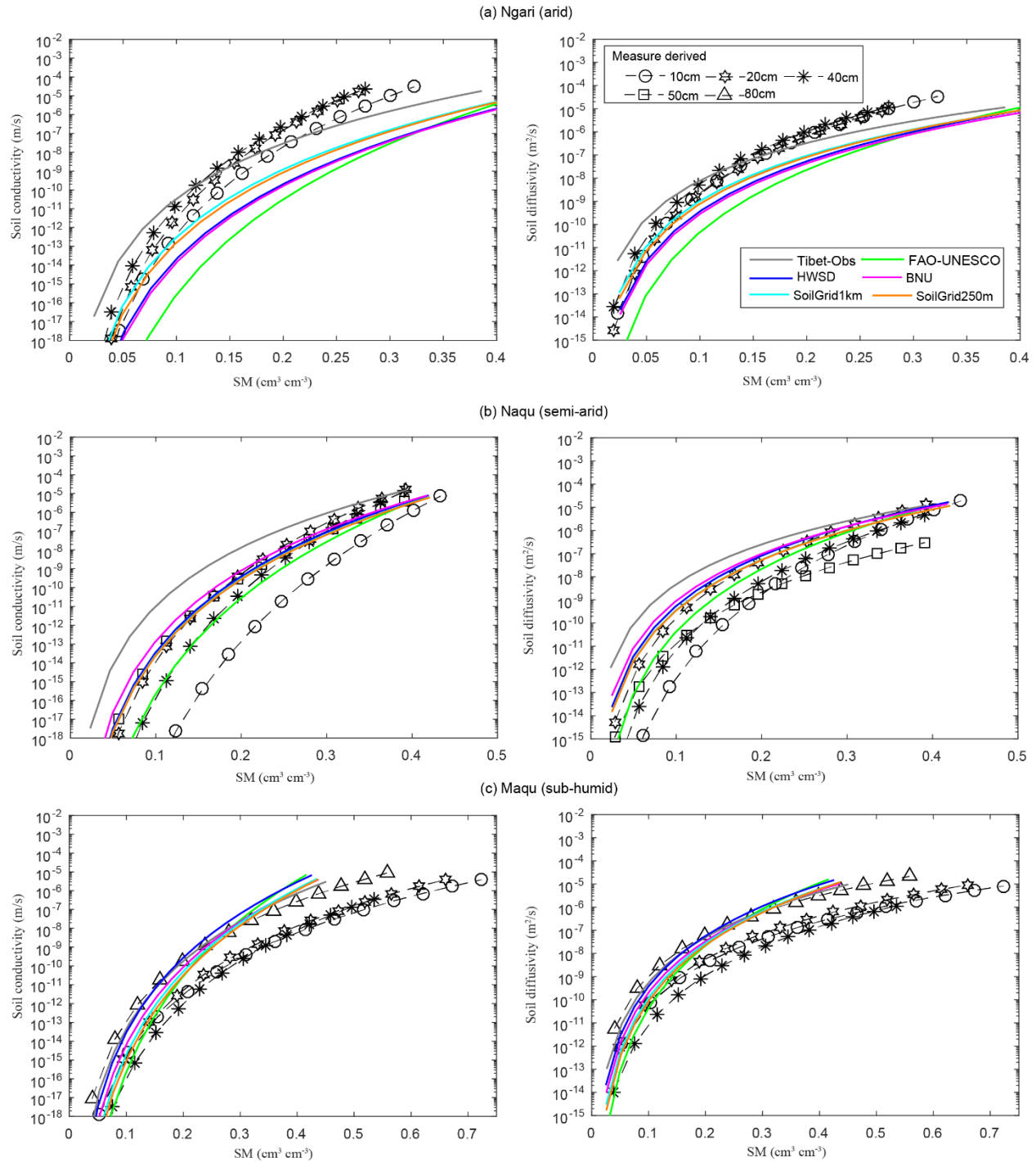
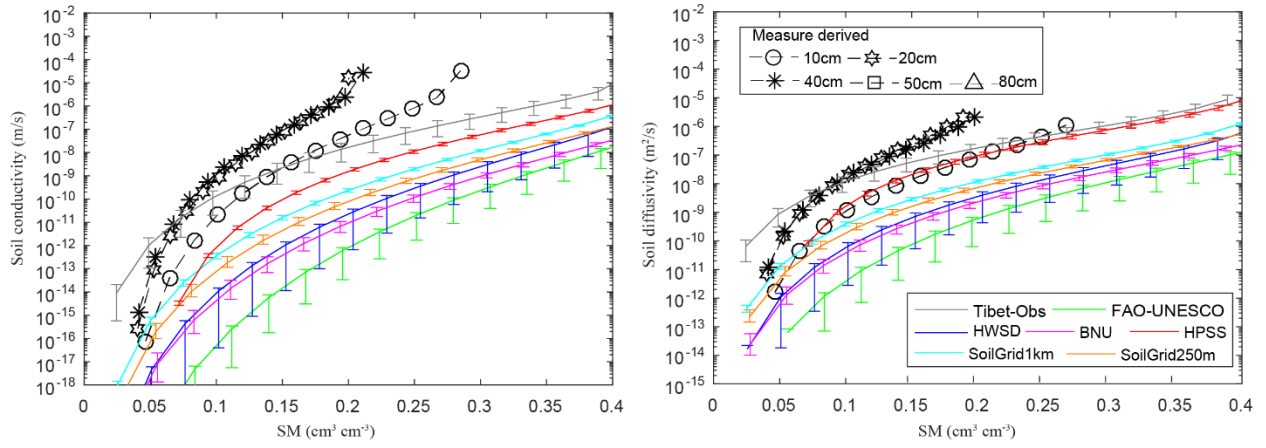
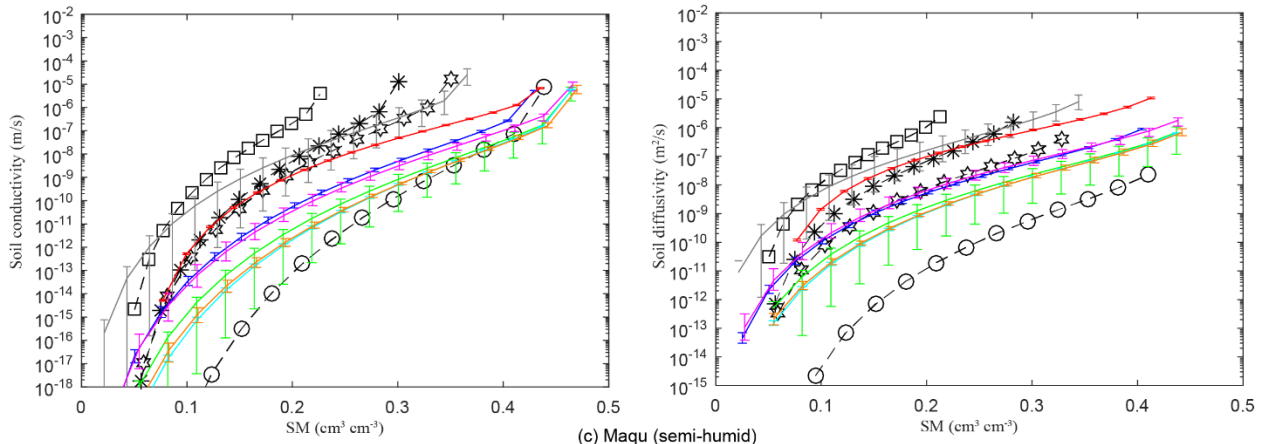


Figure 20A1 Comparisons of derived soil conductivity (K) and soil diffusivity (D) by the CH model based on various soil datasets, with those derived from the laboratory measurements. The bar represents the lowest and highest K and D at specific soil water content in the profile. Given the relatively homogenous soil profile derived from existing datasets (see Fig. 12 in the text), the averaged K and D derived from existing datasets over different depths were illustrated.

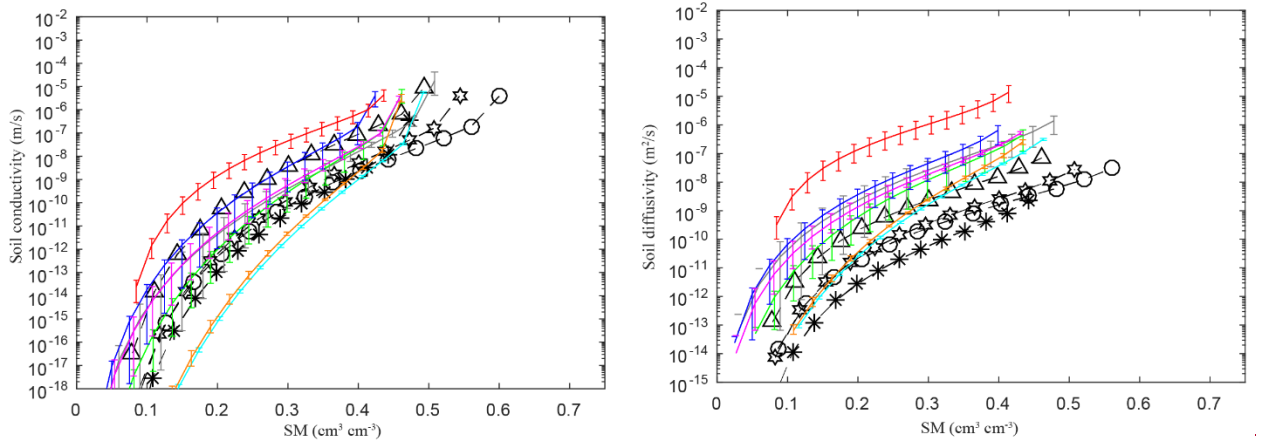
(a) Ngari (arid)



(b) Naqu (semi-arid)



(c) Maqu (semi-humid)



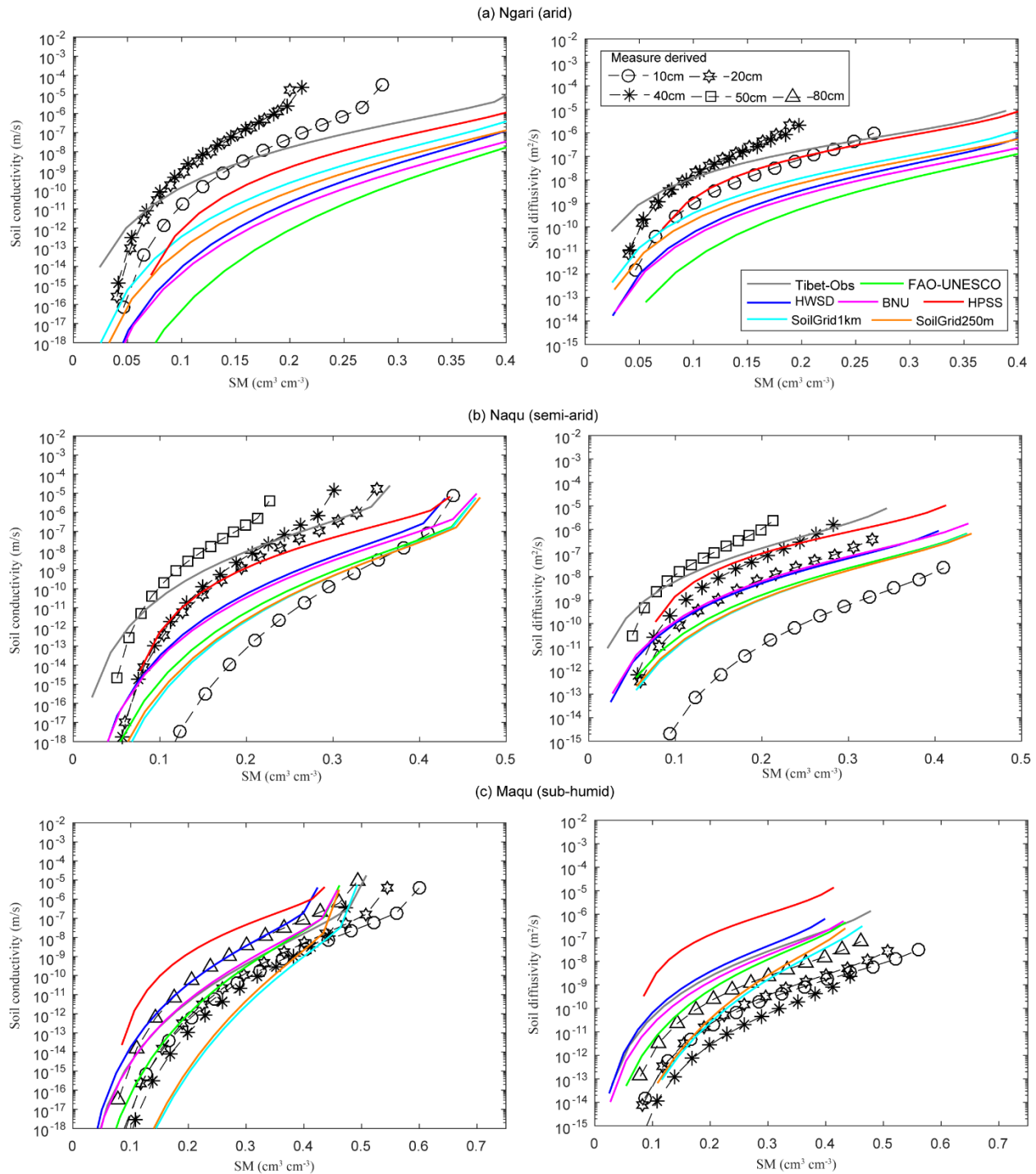
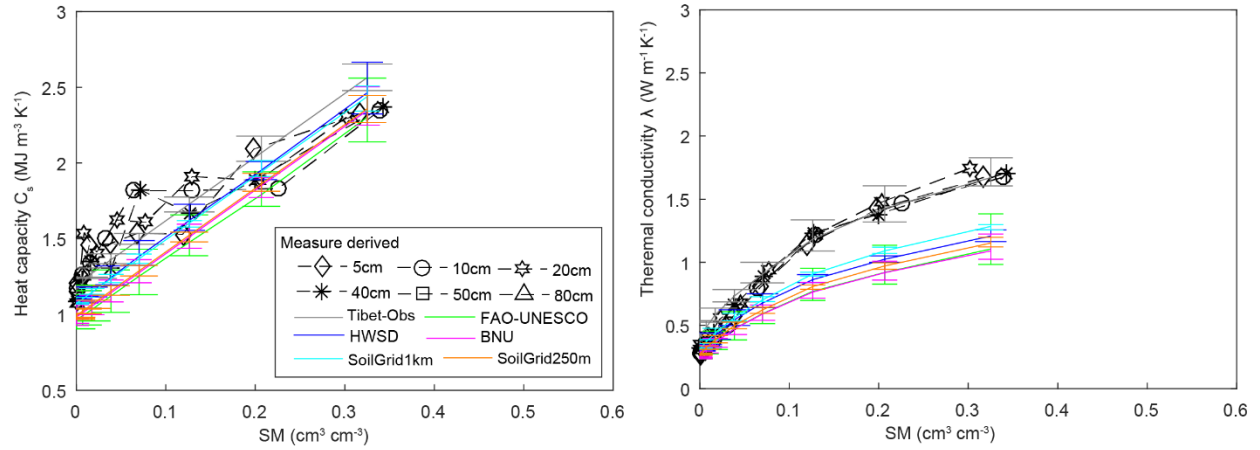
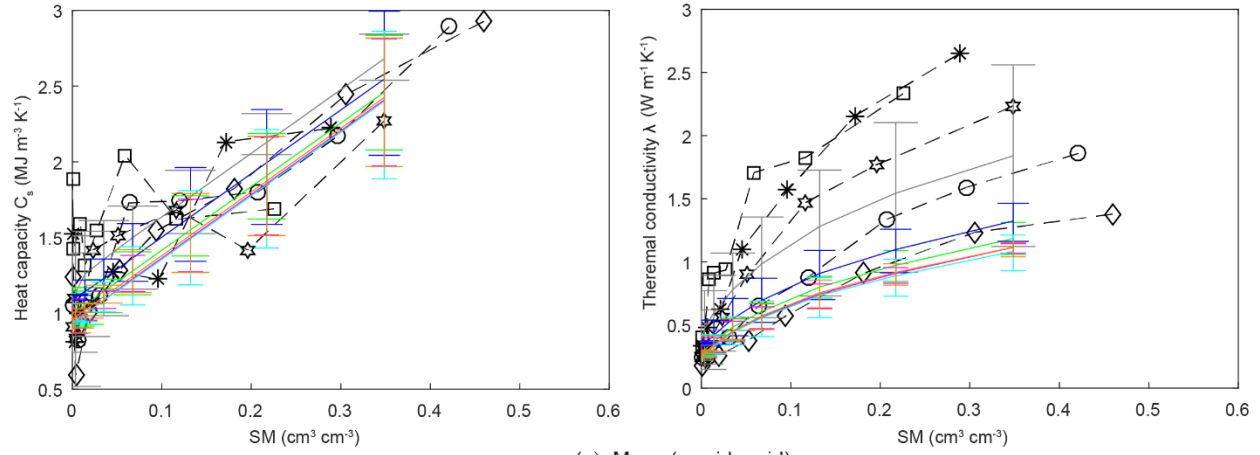


Figure 24A2 Comparisons of derived soil conductivity (K) and soil diffusivity (D) by the VG model based on seven various soil datasets, with those derived from the laboratory measurements. The bar represents the lowest and highest K and D at specific soil water content in the profile. Given the relatively homogenous soil profile derived from existing datasets (see Fig. 12 in the text), the averaged K and D derived from existing datasets over different depths were illustrated. It is to note that HPSS only provides hydraulic parameters for the VG model.

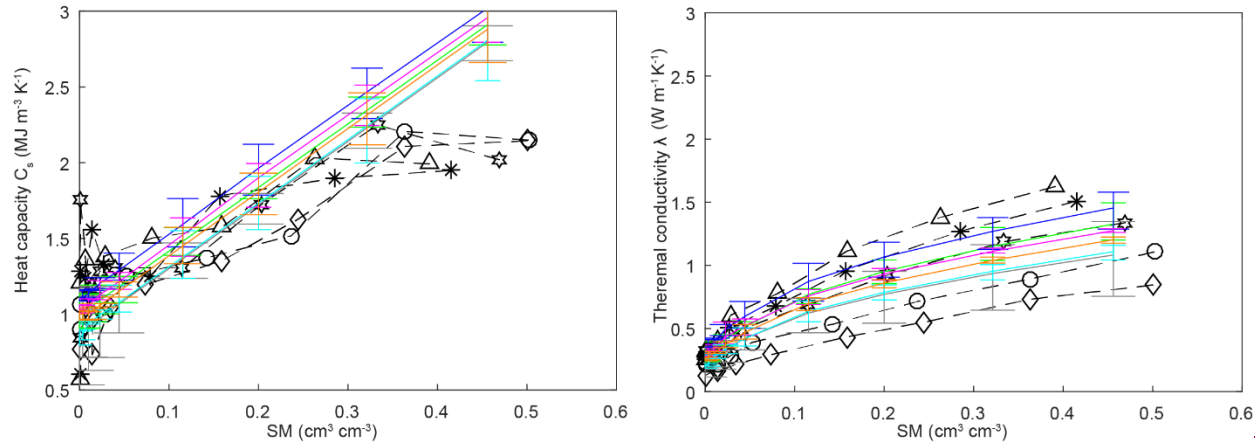
(a) Ngari (arid)



(b) Naqu (semi-arid)



(c) Maqu (semi-humid)



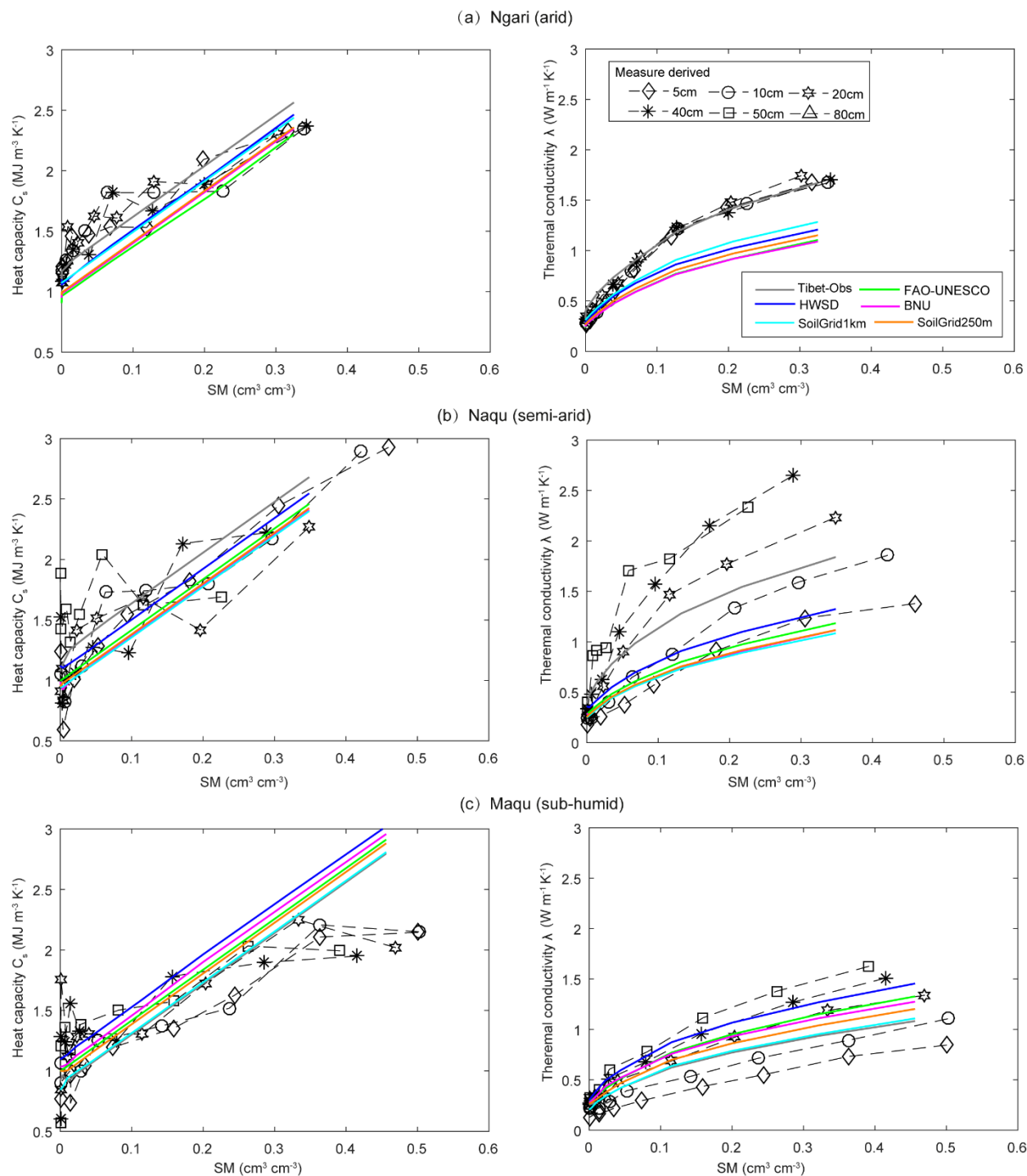


Figure 22A3 Comparisons of averaged derived C_s -SM (left panel) and λ -SM (right-panel) derived from the D63F model based on various datasets, with the measurements. The bar represents the lowest and highest C_s and λ in the profile. Given the relatively homogenous soil profile derived from existing datasets (see Fig. 12 in the text), the averaged C_s -SM and λ -SM derived from existing datasets over different depths were illustrated.