The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-88-AC1, 2020

Interactive comment on "How vadose zone mass and energy transfer physics affects the ecohydrological dynamics of a Tibetan meadow?" *by* Lianyu Yu et al.

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Received and published: 31 July 2020

We thank the editor for the time and effort in facilitating the reviewing process and the reviewers for their constructive comments. Please see our point by point response as follows. The reviewers' comments are in black fonts indexed by numbers. Our response is in blue fonts and red fonts are the updates in the manuscript.

General Comment: The manuscript by Yu et al. presents a study assessing the role of model complexity of soil physics processes on simulation of vegetation dynamics for a Tibetan meadow site. Three different model versions of the T&C model, with a gradual increase in the complexity of the freezing-thawing treatment, are compared: (1) the original T&C model, lacking soil freezing processes; (2) a modification of T&C in which an ice fraction and freezing/thawing are accounted for; and (3) a coupling of T&C to the soil physics model STEMMUS. The model versions are parameterized and driven with data from a Tibetan meadow site to evaluate their performance. Differences between results with the three versions of the model are small for most variables, generally smaller than the model-to-data difference, and the simulated differences are confined to parts of the year where freezing dynamics are likely to play a role. The analysis would benefit from a focus on specific periods of the year where differences arise.

This manuscript is potentially of interest to the readers of The Cryosphere and contains an interesting discussion on the role of freezing-thawing for ecosystem processes in high latitude and high altitude environments, and the importance of model complexity in ecohydrological models. However, in its current form, it contains many inaccuracies in the presentation of the results and ambiguity in the presentation of the model versions, simulation setup and the results, which make it hard to judge the models' qualities. I cannot recommend publication given the current state of the manuscript, but with substantial modifications in the texts and the presentation of the results, I expect that this could become suitable for publication in The Cryosphere.

Response: Thanks a lot for your insightful comments. We rearranged the manuscript structure to make it more readable. The experimental site (and its multi-component measurements) was introduced in Section 2. The STEMMUS and T&C models (and their coupling), as well as numerical experiment designs (and key governing equations) were introduced in Section 3. Equations for different model versions were clearly presented in Sect. 3.1-3.4. Section 4 detailed results and discussions on the role of different vadose zone physics in the ecohydrological response to freeze-thaw cycles. Section 5 summarized the potential influential pathways of different vadose zone physics, and the study was concluded in Section 6. We added Table 1 to clarify the difference among three models (see Sect. 3.5). The constitutive equations regarding unfrozen water content, ice effect on hydraulic conductivity, the temperature dependence of water flow, water vapor density were given in Supplement S1. We added figures in supplement materials to present the surface energy fluxes simulations during the non-frozen and frozen period, respectively. The relevant text was added to the manuscript and supplement Section S2 to explain the differences among the three models. We added Figure 1 to illustrate the geophysical location of Maqu soil moisture and soil temperature (SMST) monitoring network, indicating the central experimental site where our data were collected. Thus the figure numbers in the revised manuscript were all updated correspondingly.

1. The introduction discusses model improvement in very broad terms, but it does not give a rationale for focusing on soil freezing processes specifically in this study. I would suggest using the introduction instead for a more in-depth discussion of the role of freezing-thawing processes for ecosystem dynamics and the limitations of current models in representing these.

Response: Thank you very much. We updated the introduction part adding more focus on the role of the freezing-thawing process for ecosystem dynamics and we discussed the limitation of current models in representing these processes.

2. - Title: The current title is grammatically incorrect. I would suggest removing the question mark at the end of the sentence. Alternatively, "affects" can be replaced by "does affect" (i.e., How does vadose zone mass and energy transfer physics affect the : : :")

Response: Thanks a lot. We removed the question mark and rephrased the title as "On the Role of Vadose Zone Physics in the Ecohydrological Response of a Tibetan Meadow to Freeze-Thaw Cycles "

3. – Introduction: The first part of the introduction (L. 33-43) is not very informative for the problem assessed in this manuscript: It describes in general terms the gradual improvements that have been undertaken in many different types of models, without a clear focus on the research

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Response: Thanks a lot for your insightful comments. We modified the first part of the introduction and focused on the response of ecosystem dynamics in cold regions, and on the ongoing modeling efforts with consideration of vegetation and freeze/thaw process. Then we further stressed the relevance to consider the coupling water and heat physics in cold regions.

Changes in the manuscript: "Recent climatic changes have accelerated frozen soil dynamics in cold regions, as for instance favoring permafrost thawing and degradation of frozen soils (Cheng and Wu, 2007;Hinzman et al., 2013;Peng et al., 2017;Yao et al., 2019;Zhao et al., 2019). In consequence of these changes, vegetation cover and phenology, land surface water and energy balances, subsurface soil hydrothermal regimes, water flow pathways were reported to be affected (Campbell and Laudon, 2019;Gao et al., 2018;Schuur et al., 2015;Walvoord and Kurylyk, 2016;Wang et al., 2012). Understanding how ecosystem functioning interacts with changing environmental conditions is a crucial yet challenging problem of Earth system research for high latitude/altitude regions and deserves further attention.
Land surface models, terrestrial biosphere models, ecohydrology models, and hydrological models have been widely utilized to enhance our knowledge in terms of land surface processes, ecohydrological processes (Fatichi et al., 2016a;Fisher et al., 2014), and freezing/thawing process (Cuntz and Haverd, 2018;Druel et al., 2019;Ekici et al., 2014;Wang and Yang, 2018;Wang et al., 2017b). For instance, Zhuang et al. (2001) incorporated a permafrost model into a large scale ecosystem model to investigate soil thermal temporal dynamics. Zhang et al. (2018) investigated the long term high-latitude Arctic tundra ecosystem response to the interannual variations of climate with the process based CoupModel. The LPJ-WHy model, with consideration of permafrost dynamics and peatland, was used to analyze land surface processes by Wania et al., (2009). Lyu and Zhuang (2018) coupled a soil thermal model with the Terrestrial Ecosystem Model (TEM) to explore snowpack effects on soil thermal and carbon dynamics of the Arctic ecosystem under different climate scenarios. "

4. - L. 16: consider inserting “those relevant for” after “parameterizations” Response: We rephrased the text here. “The physical representation is increased from T&C without, and with the explicit consideration of ice effect, to T&C coupling with STEMMUS enabling the simultaneous mass and energy transfer in the soil system (liquid, vapor, ice).”

5. - L. 23: “The difference among various complexity: : :”: This sentence is unclear; the meaning of “among various complexity” needs to be specified.

Response: We modified this sentence as “The physical representation is increased from T&C without, and with the explicit consideration of ice effect, to T&C coupling with STEMMUS enabling the simultaneous mass and energy transfer in the soil system (liquid, vapor, ice).”

6. - L. 26: Remove comma; also, I think that “in ecosystem functioning” should read “for ecosystem functioning”.

Response: We have removed the comma and replaced “in ecosystem functioning” with“for ecosystem functioning”.

7. - L. 58: “there are divergences”. Please explain these divergences.

Response: We explain the divergences in the context as “In response to climate warming, the degradation of frozen ground can positively affect the vegetation growth in Tibetan Plateau mountainous region (Qin et al., 2016), but it can also lead to degradation of grasslands (Cheng and Wu, 2007), depending on soil hydrothermal regimes and climate conditions (Qin et al., 2016;Wang et al., 2016).”

8. - L. 69: “The limited knowledge of including or not complex vadose zone processes: : :” Please clarify this sentence.

Response: Here the complex vadose zone processes is referring to the “explicit consideration of ice effect, water and heat coupling”. We want to say that there has not been too much effort investigating the role of the increasing complexity of soil physical processes in cold region ecosystems. we rephrased it as “The inclusion or not of different soil physical processes, i.e., explicit considering ice effect and tightly coupled water and heat transfer, in such environment frames the scope here.”

9. Methods: The model descriptions in the methods are somewhat unstructured and in part difficult to follow. I see the value of presenting the equations, but I would suggest to introduce the three model setups in the beginning of the methods section, and to describe the processes and equations per setup. For the numerical experiments (section 2.6), please specify which driving variables were used and at which temporal resolution, and how the initial state of the model was determined – without understanding the driving variables of the model, it is hard to evaluate the performance.

Response: The method part regarding the model descriptions has been modified accordingly. We first present the soil physical processes used in T&C, T&C-FT, and STEMMUS model in Section 3.1-3.4. Then the coupling T&C and STEMMUS procedure is introduced in Section 3.4, followed by the design of numerical experiments in Section 3.5. The description of driving variables was added in Section 3.5 as “Hourly meteorological forcing (including downwelling solar radiation, precipitation, air temperature, relative humidity, wind speed, air pressure) was utilized to drive the models. For the adaptive time step of STEMMUS simulation, linear interpolation between two adjacent hourly meteorological measurements was used to generate the required second values.”

10. - L. 101: Please specify whether you use remote sensing data for one pixel only, or whether you use it for a spatial analysis, and what it hence is “representative” (L. 102) for.

Response: As the lack of in situ measurements of time series of vegetation dynamics, here we intended to use remote sensing data (MCD15A3H and MOD17A2H) as the auxiliary data for the vegetation dynamics of the in situ site (corresponding to the central experimental site ($33°54'59"N$, $102°09'32"$, elevation: 3430m)). One pixel data corresponding to the study location was employed here in terms of the spatial scale. We rephrased the “representative” with “We downloaded MCD15A3H (Myneni et al., 2015) and MOD17A2H (Running et al., 2015) products for this site as the auxiliary vegetation dynamics data...”.

11. - Fig. 1b: It is hard to interpret the freezing front data, in particular for winter 2017-18 because of the missing data. Is it possible to mark the times and depths of missing data? Also, smaller symbols in the figure would probably allow to differentiate the dynamics at the surface better.

Response: Figure 2b (original Figure 1b) was replotted accordingly. Here we generated the dynamics of freezing/thawing front by interpolating the measured soil temperature data at soil depths of 2.5, 5, 10, 20, 60, and 100cm, neglecting 40cm (at which depth the data is missing for 2017-18 winter). The missing data periods of soil moisture/temperature measurements were described in the text.

Changes in the manuscript: “Note that there are data gaps (25th Mar – 8th June, 2016; 29th Mar – 27th July, 2017, extended to 12th Aug, 2018 for 40 cm) due to the malfunction of instruments and the difficulty to maintain the network under harsh environment."

12. - For the subscripts used in the equations, please separate the i used for layering (Eq. 2) from the i used for ice (Eq. 3, L. 196, Eq. 5).

Response: We made modifications as: ‘i ‘ is specifically used for layering and ‘ice‘ is used for soil ice (changes can be found as Eq. 4, Eq. 6, L. 233, Eq. 7, Eq. 8).

13. - Eq. 4: Please check this equation: the left-hand side is mass-based, and the right-hand side volume-based. I assume that soil density should be added to the equation.

Response: Many thanks for pointing it out. Eq. 4 (now Eq. 3): We added the soil density term (ρ_{soil}) in Eq. 3, making the left-hand side consistent with the right-hand side both as volume-based terms. In addition, such modifications are made in Eq. 6 &

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14. - L. 235: Convergence of which variables, and which criterion is used to determine if convergence has been achieved?

Response: The iteration solution is used in STEMMUS to solve the soil moisture and temperature states. The convergency criteria are both set as 0.001 for soil matric potential and soil temperature.
Furthermore, the maximum desirable change of soil moisture and soil temperature within one step was set as 0.02 cm^3cm^{-3} and 2 $^{\circ}C$, respectively, to prevent too large change in state variables that may cause numerical instabilities. If the changes between two adjacent soil moisture/temperature states are less than the maximum desirable change, then STEMMUS continues without changing time step. Otherwise, STEMMUS will adjust the time step and repeat the current time step. During the freezing/thawing transition periods, we added the additional constraint on the time step to keep the smooth change of soil energy content. By decreasing the time step, the soil temperatures from two adjacent iterations were ensured either greater (smaller) than or equal to the freezing temperature (i.e., heating, cooling or zero-curtain effect).

Changes in the manuscript: "After convergence is achieved in the soil module (i.e., convergence criteria is set as 0.001 for both soil matric potential [in cm] and soil temperature [in $^{\circ}C$])"

15. The energy fluxes displayed in Fig. 3 and 4 are too large, probably by a constant factor (the seasonal dynamics look fine), resulting in fluxes that exceed theoretical limits set by incoming radiation – please check the averaging method. Numbers in Fig. 9 seem more realistic.

Response: Thanks a lot for pointing it out. In the original Fig. 3 and 4, we used wrong units summing values of hourly surface energy fluxes (ranging from -500 to 1000 W/m^2 for net radiation) into daily values. For the updated Fig. 4 and 5, we corrected the mistake and we properly averaged the surface energy fluxes at the daily time scale then presented the 5-day moving average values of surface energy fluxes (ranging from -20 to 200 W/m^2 for net radiation). For Fig. 10 (original Figure 9), the hourly values of surface energy fluxes, plotted as the scattered figures between the observed and model simulated values, were used to indicate the energy balance closure problem. We made some modifications in captains of Figures 4, 5 and Figure 10 to clearly indicate whether the hourly or daily average values are used.

16. In general, the analysis focuses on the entire period of simulation. This is fine for a general overview, but differences between the three model versions tend to be small for most of the period. I would recommend focusing on specific times of the year where the three model versions deviate, and discuss the abilities of the three models for these periods specifically. Also, the authors could consider displaying differences from observations rather than absolute amounts, to make differences between model versions more visible. At the moment, the main conclusion that one draws as reader is that the choice of model version does not matter too much, whereas the differences between the model versions may well provide important insights e.g. in representing fluxes during freezing times.

Response: Thanks for the suggestion. We added additional figures in the supplement materials to highlight differences in specific periods (see supplement Figures S1-3). We zoomed in a new figure (Fig. S1) in the frozen period and we showed the relative differences between observations and model simulations. We add an appropriate reference in the manuscript and supplement accordingly.

17. - Can the authors comment on the differences in the models' abilities to capture LE and H? The model is doing a very good job in capturing LE, but variations in H are poorly captured. Regarding the "overall performance : : : in terms of turbulent flux simulation", I think this difference between LE and H should be noted. Also, the models simulate consistently a large difference in H between the summer from 2017 and those from 2016 and 2018, whereas observations indicate less variations between summers. What is the reason for the simulated differences between 2016 and 2018 on the one

hand and 2017 on the other?

Response: It is difficult to attribute such a difference mostly to the model inaccuracy or mostly to the data inaccuracy. On one hand, the energy balance closure problem rises as the potential source of error and reason of discrepancy. The Eddy covariance observed LE and mostly H fluxes are underestimated when constrained by the surface energy closure during the summer periods (see Table 2). On the other hand, in T&C model, surface temperature is simplified and ‘one single prognostic surface temperature’ is computed, i.e. soil surface and vegetation surface temperature have the same value. The difference between the soil surface, vegetation surface and the assumed surface temperature can be a potential cause for such discrepancies in H.
In addition, soil moisture and temperature simulation fit changes corresponding to that of surface energy fluxes simulations (i.e., slightly better in 2017 than that in 2016 and 2018, see Fig. 6). The uncertainties in the precipitation measurements thus can be an additional potential reason for the simulated differences between 2016 & 2018 and 2017.

18. - L. 304 and Fig. 7ab: What causes the pronounced difference in simulated ice content between the two model versions, and is the band of high ice content in unCPLD-FT in the first winter season a model artefact or a real phenomenon? For comparing, it would be preferable to have the same colour scale for plots 7a and 7b.

Response: Soil ice content measurements are not easy to achieve in the field. It is hard to accurately assess the model performance regarding the soil ice content simulations. We simply rely on the freezing/thawing front propagation to validate the general spatiotemporal shape of soil ice content dynamics.
For the band of high ice content in unCPLD-FT in the first winter season, this is generated by cryosuction of liquid water in the upper soil layers. The freezing-induced water potential decrease moves the available liquid water towards the freezing front. The high accumulation of ice content indicates that unCPLD-FT model simulated a relatively strong cryosuction effect, probably mitigated in the fully coupled model by effects

of water vapor transfer and thermal gradients, as well as different solutions in the parameterization of soil-freezing curves.
We now used the same colour scale for Figure 8a &b (original Figure 7).

Changes in the manuscript: "It is to note that compared to unCPLD-FT model, CPLD model presented a relatively lower presence of soil ice content, while its temporal dynamics was closer to the observed freezing/thawing front propagation. The difference between the two simulations can be attributed to the constraints imposed by the interdependence of liquid, ice and vapor in the soil pores that is considered only in CPLD model."

19. - L. 326: What causes the difference in onset between unCPLD and CPLD on the one hand and unCPLD-FT on the other? How do the soil physics processes impact GPP?

Response: The onset of vegetation depends on the soil temperature in the root zone averaged over the previous 30 days. For the first winter season, unCPLD-FT model simulated a prolonged freezing period than unCPLD and CPLD model. Thus, there is a delay in the vegetation onset date. For the second winter season, all three models produce similar vegetation onset dates. For the third winter season, more spread was detected among the three model simulations. unCPLD produced the earliest onset date while unCPLD-FT produced the latest onset date, with CPLD fell in between.
The difference in soil physics processes alters the soil liquid water/temperature profile simulations and especially the strong cryosuction effect in the unCPLD-FT generates larger ice accumulation and a delay in the melting that leads to lower average temperatures. These processes affect the leaf onset date, i.e., the phenology of the grassland. Additionally, the changes in soil liquid water content can result in variations of water stress for the plants, thus they affect the photosynthetic assimilation rate and GPP. Differences in soil temperature profiles can also affect root respiration in generating additional small differences in GPP.

Changes in the manuscript: “The difference in the soil liquid water/temperature profile simulations between the CPLD and unCPLD models (as shown in Figures 6 & 7) resulted in differences in simulated vegetation dynamics, especially concerning the leaf onset date, which is affected by integrated winter soil temperatures. The unCPLD-FT model has a delay in the vegetation onset date when compared to other simulations, due to the significant cryosuction that prolongs freezing conditions and keep lower soil temperatures. This makes the unCPLD simulation having slightly shorter vegetation active season compared to the CPLD model simulations. The lower GPP in the unCPLD simulations is instead related to a slightly enhanced water-stress induced by the different soil-moisture dynamics during the winter and summer season with a lower root zone moisture produced by the unCPLD model (Figure 6), which affects the plant photosynthesis and growth. Differences in soil temperature profiles can also affect root respiration in generating additional small differences in GPP. ”

20. The discussion is generally fine and provides insights in how soil physics processes are expected to affect other parts of the ecohydrological system. It would be nice to see whether conclusions from the authors corroborate existing literature, and where they agree. The conclusion provides a balanced assessment of the advantages and disadvantages of enhanced model complexity for representing the dynamics.

Response: We thank the reviewer for this perspective. Additional references were added in the discussion part to expand it. For example, the 10yr CO_2 fluxes observation in an alpine shrubland on the Qinghai-Tibetan Plateau by (Li et al. 2016) aligns well with this study as it indicated that the non-growing season soil temperature can exert important effects on the carbon flux dynamics, as it can enhance the vegetation activities and prolongs the growing season.

21. - L. 361: Specify which slope is discussed here (it is clear from the figure, but hard to understand from the text).

Response:. We added the description text here to specify the meaning of slope as

"The sum of measured LE and H was significantly less than Rn, with the slope of LE+H versus Rn equal to 0.59 (Fig. 9a)."

22. The language would benefit from editing by a native speaker. Also, references should be checked carefully; references seem to be missing from the reference list (Fisher et al. 2014) or need to be specified (Yu et al. 2016a and 2016b in the reference list, but the text refers to Yu et al. 2016).

Response: We carefully checked the references and made it consistent between the text and reference list. References (Fisher et al. 2014) were added to the reference list. As the changes in the introduction part, Yu et al. (2016a) were no longer there. Accordingly, the newly added references were inserted both in the context and the reference list. The English grammar and fluency have been re-checked carefully throughout the entire manuscript.

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Table 1. Numerical experiments with various mass and energy transfer processes

Experiment	Soil Physical Processes Unfrozen period	 Unfrozen period	Model Components
unCPLD	independent WHT	independent WHT; no ice effect; no LH due to phase change	T&C (Eqs. 1 & 3)
unCPLD-FT	independent WHT	FT induced WHT coupling; ice effect; LH due to phase change	T&C-FT (Eqs. 1 & 4)
CPLD	tightly coupled WHT	tightly coupled WHT; ice effect; LH due to phase change; CH due to liquid/vapor flow	T&C-STEMMUS (Eqs. 7 & 8)

Note: Independent WHT, Soil Water and Heat Transfer process is independent.

FT induced WHT coupling, Soil Water and Heat Transfer process is coupled only during the freezing/thawing (FT) period. Soil water flow is affected by temperature due to the temperature dependency of hydraulic conductivity (the impedance effect as the presence of soil ice content). Tightly coupled WHT, Soil Water and Heat Transfer process is tightly coupled; vapor flow, which links the soil water and heat flow, is taken into account; thermal effect on water flow is considered (the hydraulic conductivity and matric potential is dependent on soil temperature; when soil freezes, the hydraulic conductivity is reduced by the presence of soil ice, which is temperature dependent); the convective/advective heat due to liquid/vapor flow can be calculated.

Ice effect, the explicit simulation of ice content and its effect on the hydraulic/thermal properties.

LH due to phase change, latent heat due to the phase change. CH due to liquid/vapor flow, convective heat due to liquid/vapor flow.

Table 2. Monthly values of energy closure ratio derived from eddy covariance measured LE + H versus Rn and $Rn - G_0$, respectively (Dec. 2017-Aug. 2018). G_0, the ground heat flux, was estimated by CPLD model.

Figure 1. Geographical location of Maqu soil moisture/temperature (SMST) monitoring network and the Centre station.

Figure 2. Observed cumulative precipitation (P) and evapotranspiration (ET) (a) and observed propagation of freezing/thawing front (FTFP), with the blue and red color for the propagation of freezing front and thawing front (FFP & TFP), respectively (b) for the period 25 Mar. 2016- 12 Aug. 2018 at Maqu site.

Figure 4. Comparison of observed and simulated 5-day moving average dynamics of net radiation (Rn), latent heat flux (LE), and sensible heat flux (H) using the original (uncoupled) T&C (unCPLD) , T&C with consideration of FT process (unCPLD-FT) and coupled T&C and STEMMUS (CPLD) model.

Figure 5. Scatter plots of observed and model simulated daily average surface fluxes (net radiation: Rn, latent heat: LE and sensible heat flux: H) using the original (uncoupled) T&C (unCPLD), T&C with consideration of FT process (unCPLD-FT) and coupled T&C and STEMMUS (CPLD) model, with the color indicating the frequency of surface flux values.

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Figure 8. Soil ice content from (a) unCPLD-FT and (b) CPLD model simulations with freezing front propagation derived from the measured soil temperature; and vertical water flux from (c) unCPLD, (d) unCPLD-FT and (e) CPLD model simulations. Note that soil ice content is not represented in the unCPLD model and the fluxes of top 2 cm soil layers were erased to highlight fluxes of the lower layers.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-88/tc-2020-88-AC1-supplement.pdf

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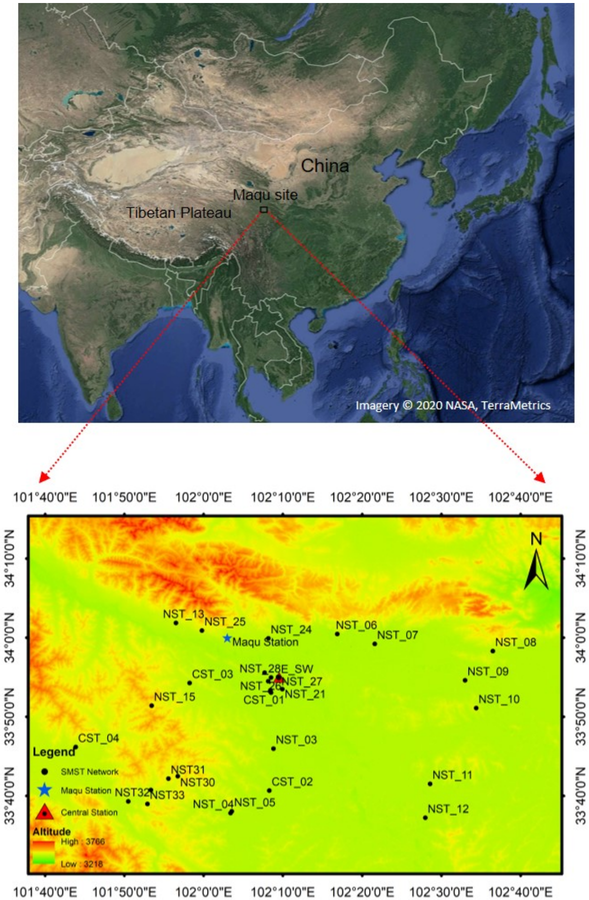
Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-88, 2020.



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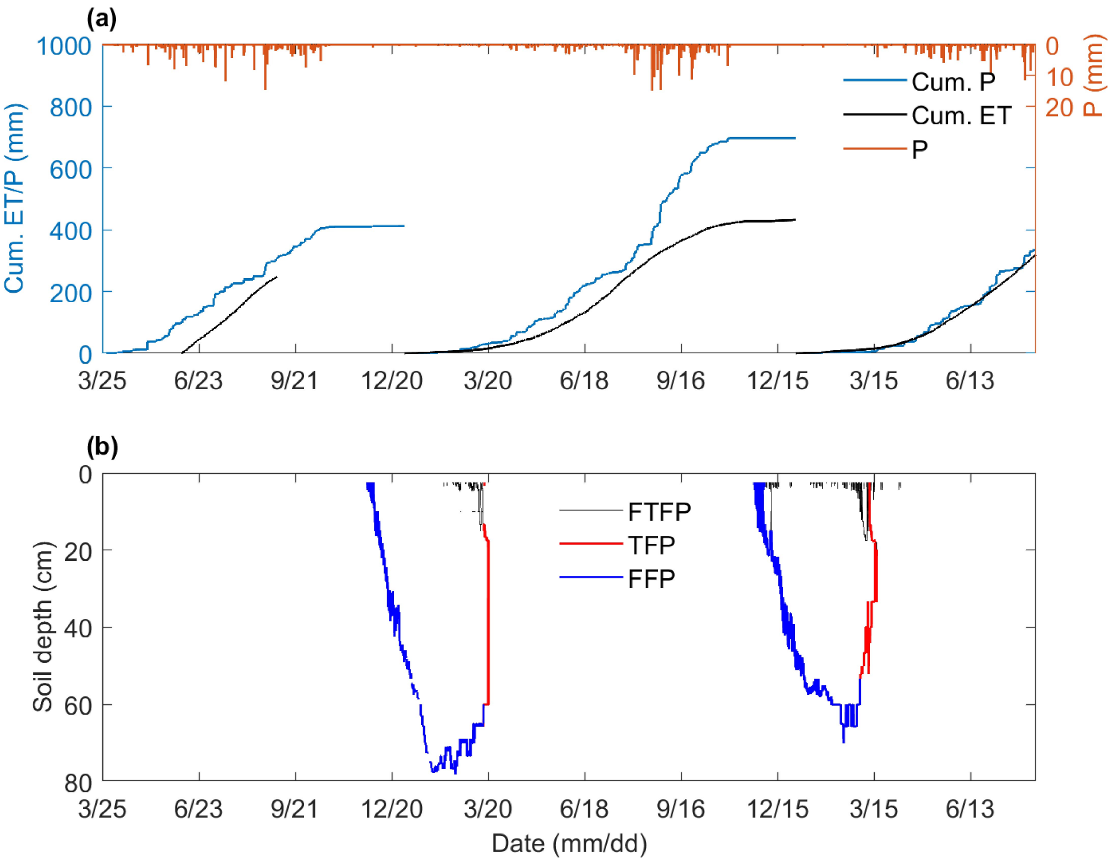

Fig. 2. Figure 2. Observed cumulative precipitation (P) and evapotranspiration (ET) (a) and observed propagation of freezing/thawing front (FTFP)(b) for the period 25 Mar. 2016- 12 Aug. 2018 at Maqu site.

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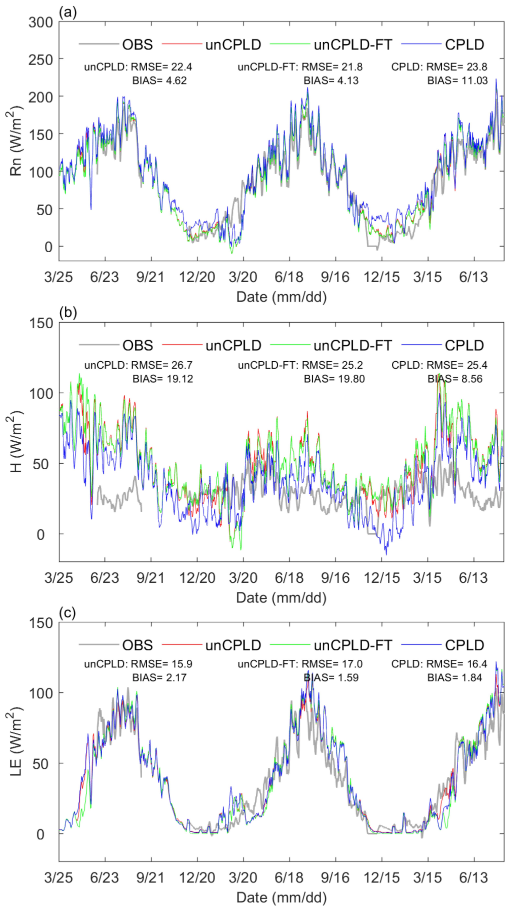

Fig. 3. Figure 4. Comparison of observed and simulated 5-day moving average dynamics of net radiation (Rn), latent heat flux (LE), and sensible heat flux (H) using unCPLD, unCPLD-FT and CPLD model.

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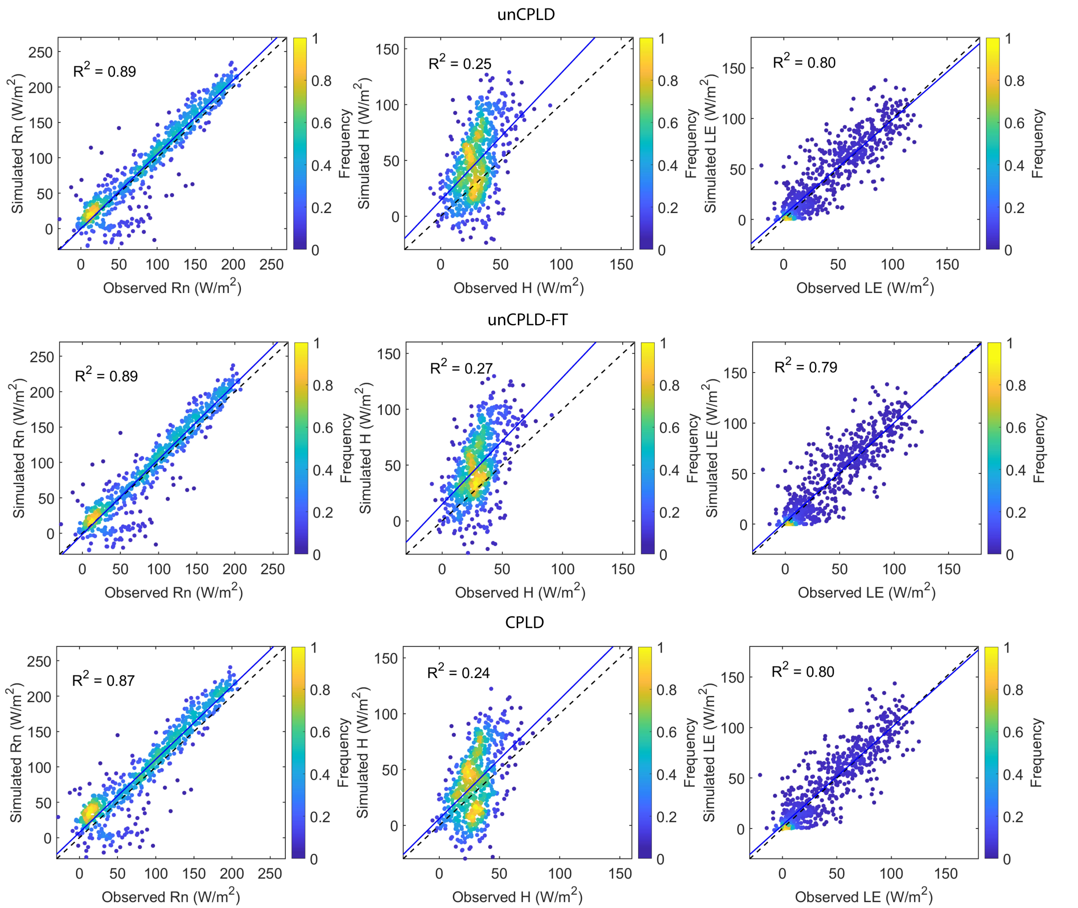

Fig. 4. Figure 5. Scatter plots of observed and model simulated daily average surface fluxes (net radiation: Rn, latent heat: LE and sensible heat flux: H) using unCPLD, unCPLD-FT and CPLD model.

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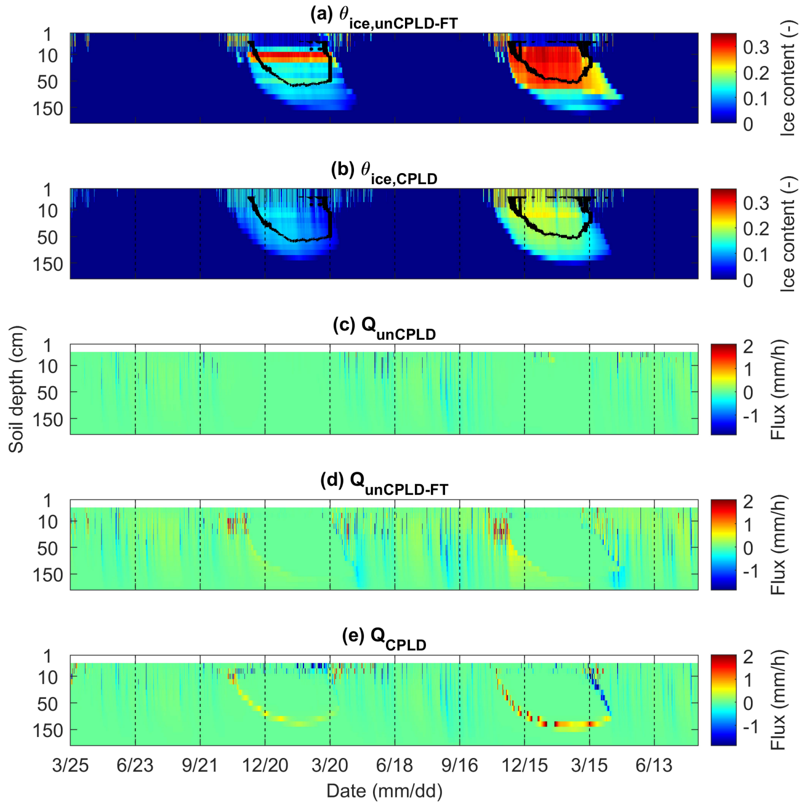

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