

## ***Interactive comment on “Regional evapotranspiration from image-based implementation of the Surface Temperature Initiated Closure (STIC1.2) model and its validation across an aridity gradient in the conterminous United States” by Nishan Bhattarai et al.***

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Response to Referee's (#1) comments

Comment: This paper has enlightened ET remote sensing community about the importance of aerodynamic conductance/resistance. Currently, most of the ET algorithms do not take into account the diurnal variation in this resistance. The authors have implemented STIC model at regional scale. STIC model integrates remote sensed surface

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temperature into Penman-Monteith equation to derive an analytical solution for the resistance and use the resolved resistance to calculate surface heat fluxes/ET. They also compare its performance with other two ET algorithms, SEBS and MOD16. SEBS model provide direct solution for surface and boundary layer conductance/resistance from momentum/heat roughness and stability. However, MOD16 uses a kind of constant resistance in its ET calculation, which explains its worst performance among the three methods. STIC use an energy balance and meteorological information to inversely retrieve the surface and boundary layer conductance. The results are sufficient to support their conclusions. The paper address very relevant scientific questions within the scope of HESS. Thus I suggest an acceptance for publication.

Response: We thank the reviewer for appreciating our work and considering the manuscript to be interesting and relevant to the HESS community.

Comment: Figure 5 shows that SEBS has a similar performance as STIC, and MOD16 for CRO, DBF, and ENF, but worse result at WSA and GRA. Please check if this is due to inaccuracy of satellite input data.

Response: Fig. 5 suggests significant overestimation of SEBS ET in WSA and GRA sites. Specifically, at one of the WSA sites (e.g., US-Ton), all of the three models performed poorly, where observed ET values were extremely low (0.6 mm per day; Fig. 5). In this specific site, 10% of the observed LST pixels were within 2-3 K LST errors with surface emissivity errors of 0.01 to 0.03, based on the MODIS QA/QC data. Similarly, in another WSA site (i.e. US-SRM), 37% of observed LST pixels were within a similar error range. The literature also suggests high emissivity correction uncertainties and systematic underestimation of MODIS LST in arid and semiarid ecosystems (Wan and Li, 2008; Jin and Liang, 2006; Hulley et al., 2012). The significantly poor performance of SEBS in the US-SRM site could also be attributed to these uncertainties. We have added text in the discussion section about the performance of STIC1.2 at the US-Ton site (Page 15, Lines 13). It is also important to note that uncertainties also exist in

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the Bowen ratio energy balance closure correction of energy balance at the arid and semi-arid sites, which is also discussed on Page 15, Lines 16-20. Regarding the poor performance of SEBS in the GRA sites, the errors are mostly due to large differences in SEBS ET and observed ET in the two semi-arid desert grasslands sites (US-SRG and US-Wkg) (Supplementary Table S1). In the two other grassland sites (US-Kon and US-KFS), SEBS performed relatively better and was comparable with STIC1.2 (Supplementary Table S1). In those two semi-arid desert grasslands sites (US-SRG and US-Wkg), the MODIS QC/QA bin suggested that 27% (US-Wkg) and 4% (US-SRG) of MODIS LST were within 2-3 K errors with emissivity errors within the 0.01 to 0.02 range, based on the MODIS QA/QC data. These errors are however more predominant in SEBS, and, as in the semi-arid and arid conditions, substantial differences exist between TR and T0 due to strong soil water limitations. Such water-limited conditions may not have been properly characterized in the kB-1 parameterization, which could lead to large differences between modeled and observed ET. We discussed these potential limitations on Page 15, Line 27 to Page 16, Line 10. We will add additional discussion of the performances of SEBS and other models in GRA and WSA sites and how the model performed differently in two GSA sites in two different climates in the revised paper as following in Page 15 after Line 26:

“The overall performance metrics from the three models may be slightly biased due to their strikingly poor performances at some specific sites (Table S1). For example, SEBS overestimated ET by over 64% in the two semi-arid WSA (US-Ton, US-SRM) and GRA (US-SRG and US-Wkg) sites (Table S1); however, its performance in US-Ne1 (CRO), US-Kon (GRA), US-KFS (GRA), US-NR1 (ENF) were better or comparable than the other two models. Interestingly, the performance of SEBS in the two wet GRA sites (i.e. US-Kon and US-KFS) was found to be significantly better compared to its performance at the two semi-arid GRA sites. This could be due to the inability of the kB-1 parameterization scheme in SEBS to account for the substantial differences between TR and T0 due to strong soil water limitations. MOD16 underestimated ET from all but three sites (US-Ton, US-MMS, US-NC1) and underestimated mean ET by over 50% in

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US-Ne1 (CRO), US-SRM (WSA), US-SRG (GRA), and US-Wkg (GRA) sites. STIC1.2 appears to be most consistent among the three models, as the mean bias errors were within 20% for all but three sites (US-Ton, US-Kon, US-Ne1).”

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Comment: Fig. 8, 9, 10 shows that SEBS ET maps have higher ET than STIC and MOD16, this is due to sensible heat flux is low-estimated, because of high kB\_1. Please check the reference of Chen et al. 2013.

Response: This is a correct statement. The underestimation of sensible heat flux (H) by SEBS (nearly 41% underestimation) was mostly seen in arid and semi-arid sites, which eventually led to overestimation of ET in these sites. Chen et al. (2013) provided an extensive discussion on how H is underestimated by the original SEBS model and proposed an improved way of estimating roughness length for heat transfer through a new parametrization of kB-1 adopted from Yang et al. (2002) for bare soil and snow surfaces. In this paper, we incorporated the same kB-1 formulation from Yang et al. (2002) (source code obtained from Abouali et al., 2013); however, the new kB-1 formulation needs substantial modification in arid and semi-arid conditions. Fig. 13 suggests that ET biases (SEBS ET-Observed ET) were typically random and large when kB-1 values were within 5 ( $r = -0.03$ ) and slightly negative when kB-1 values were within 5 and 8 ( $r = -0.16$ ). However, for kB-1 values  $> 8$ , a linear trend in ET bias was evident (underestimation of H) with an increase in kB-1 ( $r = 0.24$ ). We will add some discussions on how uncertainties in kB-1 parametrization could lead to biases in estimated fluxes in the revised version (Page 16, after Line 11) as:

“Overestimation of SEBS is mostly associated with the underestimation of sensible heat flux (H) in the arid and semi-arid sites (nearly 41% underestimation in this study). Such underestimation of H by SEBS is highlighted by Chen et al. (2013), who proposed an improved way of estimating roughness length for heat transfer through a new parametrization of kB-1 adopted from Yang et al. (2002) for bare soil and snow surfaces. Our study adopted the same kB-1 parametrization. Fig. 13 suggests that ET

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biases (SEBS ET-Observed ET) were typically random and large when kB-1 values were within 5 ( $r = -0.03$ ) and slightly negative when kB-1 values were within 5 and 8 ( $r = -0.16$ ). However, for kB-1 values  $> 8$ , a linear trend in ET bias was evident (i.e. underestimation of H) with an increase in kB-1 ( $r = 0.24$ ). Our study suggests that substantial modification in kB-1 parametrization is still needed in arid and semi-arid conditions for improving SEBS accuracies.”

References:

Yang, K., et al. "Improvement of surface flux parametrizations with a turbulence-related length." *Quarterly Journal of the Royal Meteorological Society* 128.584 (2002): 2073-2087.

Chen, X., et al. "An improvement of roughness height parameterization of the Surface Energy Balance System (SEBS) over the Tibetan Plateau." *Journal of Applied Meteorology and Climatology* 52.3 (2013): 607-622.

Abouali, Mohammad, et al. "A high performance GPU implementation of Surface Energy Balance System (SEBS) based on CUDA-C." *Environmental modelling & software* 41 (2013): 134-138.

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Comment: Which method or model is used to calculate kB\_1 and z0m in figure 13? Or kB\_1 and z0m is derived from flux tower measurement?

Response: In this paper, the roughness height for heat transfer from Yang et al. (2002) was used to parametrize kB-1 . This approach provides a relatively better estimate of kB-1 as compared to other kB-1 formulations (Su et al., 2001; Su, 2002) over bare soil and low canopies as demonstrated by Chen et al. (2013). z0M was derived using a simple empirical relationship between the roughness length of momentum transfer, z0M, and NDVI, as suggested by Van der Kwast et al. (2009) [Page 9, Lines 23-24]. Most sub-models of SEBS were either adapted or modified from Abouali et al.

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(2013). We will add these details with appropriate citations in the revised version of the manuscript (After Page 9, Line 24) as:

“z0M was derived using a simple empirical relationship between the roughness length of momentum transfer, z0M, and NDVI, as suggested by Van der Kwast et al. (2009). The roughness height for heat transfer proposed by Yang et al. (2002), was used to parametrize kB-1. This new parametrization of kB-1 was designed to improve the SEBS model performances on bare soil, low canopies, and snow surfaces as was proposed by Chen et al. (2013).” In Page 10, Line 6, We will add the following sentences to provide information on source codes of SEBS and STIC1.

“The source codes for different sub-models within SEBS were either adapted or modified from Abouali et al. (2013). The STIC1.2 source code was modified from the original STIC1.2 code (Mallick et al. 2016) in Matlab (Mathworks Inc, Natick, USA).”

References:

Su, Z. (2002). The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. *Hydrology and earth system sciences*, 6(1), 85-100.

Su, Z., Schmugge, T., Kustas, W. P., & Massman, W. J. (2001). An evaluation of two models for estimation of the roughness height for heat transfer between the land surface and the atmosphere. *Journal of applied meteorology*, 40(11), 1933-1951.

Yang, K., et al. "Improvement of surface flux parametrizations with a turbulence-related length." *Quarterly Journal of the Royal Meteorological Society* 128.584 (2002): 2073-2087.

Chen, X., et al. "An improvement of roughness height parameterization of the Surface Energy Balance System (SEBS) over the Tibetan Plateau." *Journal of Applied Meteorology and Climatology* 52.3 (2013): 607-622.

Van der Kwast, J., et al. "Evaluation of the Surface Energy Balance System (SEBS) applied to ASTER imagery with flux-measurements at the SPARC 2004 site (Barrax,

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Spain)." *Hydrology and Earth System Sciences Discussions* 6.1 (2009): 1165-1196.

Abouali, M., et al. "A high performance GPU implementation of Surface Energy Balance System (SEBS) based on CUDA-C." *Environmental modelling & software* 41 (2013): 134-138.

Mallick, K., Trebs, I., Boegh, E., Giustarini, L., Schlerf, M., Drewry, D. T., ... & Saleska, S. (2016). Canopy-scale biophysical controls of transpiration and evaporation in the Amazon Basin. *Hydrology and Earth System Sciences*, 20(10), 4237-4264.

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Comment: Figure. 12, please have more discussion about the higher SEBS annual ET, is this due to the method in annual accumulation or SEBS model.

Response: We have briefly discussed that this overestimation is mostly due to consistent overestimation of 8-day ET by the SEBS model (Page 14, lines 10-16). In addition, the 8-day average net radiation was also overestimated by 9% (Supplementary: Fig. 1), which could also add some positive biases by SEBS (and also STIC). In the two cropland sites (US-ARM and US-Ne1), SEBS annual ET estimates were within 2% of observed annual ET, which is better than the performance of STIC (22% underestimation) and MOD16 (49% underestimation). SEBS mostly overestimated annual ET from the arid and semi-arid sites (47%). We will add these additional discussions in section 4 of the revised manuscript (After Page 14, Line 16) as:

"In addition, the 8-day average net radiation was also overestimated by about 9% (Supplementary: Fig. 1). SEBS overestimation of annual ET was mostly observed in the arid and semi-arid sites (47%). In the two cropland sites (US-ARM and US-Ne1), SEBS annual ET estimates were within 2% of observed annual ET, which is better than the performance of STIC (22% underestimation) and MOD16 (49% underestimation)."

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Comment: Fig. 4 and 5 does not show SEBS ET has different performance over

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different land covers, at least does not always show high ET estimation.

Response: Here we disagree. According to Fig. 4, RMSE and MAE of SEBS is similar to MOD16 across different precipitation conditions, but STIC1.2 performed better overall. According to Fig. 5, we noticed that SEBS performed best in CRO sites among all the models and its performance was similar to MOD16 in ENF sites compared to its performances in other biomes (GRA and WSA). We agree with the reviewer that SEBS does not overestimate ET all the time; as seen in Fig. 4 and 5, there are several instances when SEBS ET was lower than the observed ET. However, the overestimation tendency of ET by SEBS was predominant during the dry year (Fig. 4). The term "overestimation" refers to the mean ET observed at the flux sites. Notably, SEBS ET estimates were within 3%, 8%, and 17% of observed ET at croplands, ENF, and DBF sites, respectively, which were comparable or sometimes better than the other two models. We have briefly stated these in section 4 (Page 16, Line 18-20 and Page 16, Lines 30-35, Page 17, Lines 1-4). In page 17, between Line 2 and Line 3, we will add the following sentences:

"It should be noted that the performance of SEBS was not entirely poor. The overestimation tendency of ET by SEBS was predominant during the dry year (Fig. 4 and Fig. S2). Notably, SEBS ET estimates were within 3%, 8%, and 17% of observed ET at croplands, ENF, and DBF sites, respectively, which were comparable or sometimes better than the other two models (Fig. 5 and Table S1). In addition, the performance of SEBS was relatively good in cropland (Fig. 5)."

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