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# *Interactive comment on* "Gas transfer velocities of $CO_2$ in subtropical monsoonal climate streams and small rivers" *by* Siyue Li et al.

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The manuscript reports on transfer velocities of CO2 (K) in streams and small rivers for assessing the gas fluxes. CO2 released from lakes and rivers has been recently recognized as an important component in the global carbon cycle. The accurate estimation of CO2 flux is still challenging primarily due to the difficulty in obtaining an appropriate K value. The topic would be of great interest for the community of scientists working on carbon cycles and can be considered for publication. However, the current version need to revised (see below).

Response: We thanked the referee for the positive comment. We revised the Ms based on the comments and suggestions as follows.



General comments As emphasized by the authors, the study focuses on the subtropical monsoonal streams and small rivers which are characterized by large seasonal variations in climate and discharge. Hence, the K value in these rivers should also have obvious seasonality. Unfortunately, the samples presented in this study were collected in the rainy season. The K value were calculated based on the one-time sampling campaign, which might result in a certain amount of errors on the annual flux estimation. Regarding this, the uncertainty of the sampling data and the calculations, as well as the reliability of the argument should be sufficiently discussed.

Response: We agreed the comment. Sampling seasonality largely impacted riverine pCO2 and gas transfer velocity and thus water-air interface CO2 evasion rate. In our Ms, we sampled waters in the rainy season due to that it showed wider range of flow velocity and thus rainy season covered the k levels in the whole hydrological season. Rainy season generally had higher current velocity and thus higher gas transfer velocity, while aquatic pCO2 was variable with seasonality.

We added a section of "4.4. Uncertainty assessment of pCO2 and flux-derived k values" in the part of "Discussion". In this section, effects and uncertainty of sampling seasonality on errors of annual CO2 flux estimation were included.

"Sampling seasonality considerably regulated riverine pCO2 and gas transfer velocity and thus water-air interface CO2 evasion rate (Li et al., 2012; Ran et al., 2015). We sampled waters in the rainy season due to that it showed wider range of flow velocity and thus rainy season covered the k levels in the whole hydrological season. Rainy season generally had higher current velocity and thus higher gas transfer velocity (Ran et al., 2015), while aquatic pCO2 was variable with seasonality. We recently reported that riverine pCO2 in the wet season was 81% the level in the dry season (Li et al., 2018), and prior study on the Yellow River reported that k level in the wet season was 1.8-fold higher than in the dry season (Ran et al., 2015), while another study on the Wuding River demonstrated that k level in the wet season was 83%-130% of that in the dry season (Ran et al., 2017). Thus, we acknowledged a certain amount of errors on the annual flux estimation from one-time sampling campaign during the wet season in the TGR area, while this uncertainty could not be significant because that the diluted pCO2 could alleviate the potentially increased k level in the wet season."

In my point of view, the variation in K value of the rivers studied are obvious and need to be discussed. In addition, the spatial difference of K values is only sorted out for the three river systems (Daning, Qijiang and TGR). I would suggest the authors examine the variations of K following the physical characteristics of rivers (such as the current velocity, slope and the water depth) or/and the river orders.

Response: Spatial differences of k values were discussed for the three rivers systems (please refer to section 4.2). We discussed the controls of physical characteristics of current velocity, slope and the water depth, while river orders were not extracted.

"This could substantiate the higher k600 levels and spatial changes in k600 values of our three river systems. For instance, similar to other turbulent rivers in China (Ran et al., 2015; Ran et al., 2017), high k600 values in the TGR, Daning and Qjiang rivers were due to mountainous terrain catchment, high current velocity (10 – 150 cm/s) (Fig. 4b), bottom roughness, and shallow water depth (10 - 150 cm) (Fig. 4a). It has been suggested that shallow water enhances bottom shear, and the resultant turbulence increases k values (Alin et al., 2011; Raymond et al., 2012). These physical controls are highly variable across environmental types (Figs. 4a and 4b), hence, k values are expected to vary widely (Fig. 3). The k600 values in the TGR rivers showed wider range (1-177 cm/h; Fig. 3; Table S1), spanning more than 2 orders of magnitude across the region, and it is consistent with the considerable variability in the physical processes on water turbulence across environmental settings. Similar broad range of k600 levels was also observed in the China's Yellow basin (ca. 0-123 cm/h) (Ran et al., 2015; Ran et al., 2017).

Contrary to our expectations, no significant relationship was observed between k600 and water depth, and current velocity using the entire data in the three (TGR, Danning



and Qjiang) river systems (Fig. S4). There were not statistically significant relationships between k600 and wind speed using separated data or combined data, and it is consistent with earlier studies (Alin et al., 2011; Raymond et al., 2012). Flow velocity showed linear relation with k600, and the extremely high value of k600 was observed during the periods of higher flow velocity (Fig. S4a) using combined data. Similar trend was also observed between water depth and k600 values (Fig. S4b). The lack of strong correlation between k600 and physical factors are probably due to combined effect of both flow velocity and water depth, as well as large diversity of channel morphology, both across and within river networks in the entire catchment (60, 000 km2). This is further collaborated by weak correlations between k600 and flow velocity in the TGR rivers (Fig. 4), where one or two samples were taken for a large scale examination. k600 as a function of water depth was obtained in the TGR rivers, but it explained only 30% of the variance in k600. However, model using data from Qijiang could explain 68% of the variance in k600 (Fig. 4b), and it was in line with general theory. Nonetheless, k600 from our flow velocity based model (Fig. 4b) was potentially largely overestimated with consideration of other measurements (Alin et al., 2015; Ran et al., 2015; Ran et al., 2017). When several extremely values were removed, k600 (cm/h) was parameterized as follows (k600 = 62.879FV + 6.8357, $R^2$ = 0.52, p=0.019, FV-flow velocity with a unit of m/s), and this revised model was in good agreement with the model in the river networks of the Yellow River (Ran et al., 2017), but much lower than the model developed in the Yangtze system (Liu et al., 2017) (Fig. 4c). This was reasonable because of k600 values in the Yangtze system were from large rivers with higher turbulence than Yellow and our studied rivers. Furthermore, the determined k600 using FCs was, on average, consistent with the revised model (Table 2). These differences in relationship between spatial changes in k600 values and physical characteristics further corroborated heterogeneity of channel geomorphology and hydraulic conditions across the investigated rivers."

The pCO2 calculated in this paper is between 50-4830ppm, which indicates that the river pCO2 value is sometimes much lower than that of the atmosphere, that is, the studied rivers can sometimes absorb $CO_2$ from the atmosphere. It seems that the annual $CO_2$ flux for the whole basin was calculated in this paper based on the averaged K value from the observed results using floating chamber method. The question is that is it reliable to estimate both directions of the $CO_2$ flux at the air-water interface (including river $CO_2$ outgassed to the atmosphere and the atmospheric $CO_2$ input to rivers) by using the same K value? Or what uncertainty will it cause?

Response: We thanked for your critical comment. Worldwide studies reported the dependence of k on flow dynamics; while k average from statistical analysis with âŬşp$CO_2$ >110 $\mu$atm was normally used in riverine $CO_2$ flux estimation in rivers where a broad of range of p$CO_2$ occurred (Alin et al., 2011). Considering that k was largely dependent on hydraulic characteristics, this uncertainty was not discussed. The method employed here for scaling up $CO_2$ estimation was widely used (e.g., Alin et al., 2011). We added one section 4.4 ( see Discussion part) on systematic errors and empiric random errors of p$CO_2$, $CO_2$ areal flux and k from p$CO_2$ determinations, sampling seasonality, flux measurements etc.

This study measured DOC, DTN, and DTP, but the authors did not mention these measurements in the discussion section. What is the relationship between these variables and the K values?

Response: k values are reported to be dominated by physical characteristics of river systems (Borges et al., 2004; Alin et al., 2011; Raymond et al., 2012). The basic water quality parameters were not further discussed. We re-wrote the pattern of nutrients in the “Result” section.

Specific comments L 94-97: I would suggest rephrase these sentences, since they cannot convey clearly the real contribution or scientific merit of this study.

Response: We revised as follows. “Our new contributions to the literature include (1) determination and controls of k levels for small rivers and streams in subtropical areas of China, and (2) new k models developed in the subtropical mountainous river



networks”

L 111-112, 117: The classification method of the river order used here should be clarified. The number of a river order defined by different classification system may represent different size or hierarchy of a river.

Response: We addressed this issue, and provided the map of sampling location (Fig. 1). We also supplied methodology of water areal extraction in section 2.5.

L 214-216: This statement is problematic. Clearly, the studied rivers are not always supersaturated reference to atmospheric $CO_2$ as the p$CO_2$ in rivers is between 50-4830 uatm.

Response: We changed to “p$CO_2$ varied between 50 and 4830 $\mu$atm with mean of 846 $\pm$ 819 $\mu$atm (Table 1). There were 28.7% of samples that had p$CO_2$ levels lower than 410 $\mu$atm, while the studied rivers were overall supersaturated with reference to atmospheric $CO_2$ and act as a source for the atmospheric $CO_2$.”

L 274-285 These arguments need more solid evidence to support. As mentioned in the general comments, I would suggest that the authors focus on discussions on relationship between spatial change in K values and physical characteristics of rivers or/ and the river orders.

Response: Spatial differences of k values were discussed for the three rivers systems (please refer to section 4.2). We discussed the controls of physical characteristics of current velocity, slope and the water depth.

L 497-498 The water area is a very critical parameter for the calculation of $CO_2$ flux in a basin, so the acquisition of water area is essential and should be described more in detail. For example, what is the resolution of the satellite image? In addition, the variation of surface area of water between wet and dry seasons should be considered.

Response: We provided the information for the acquisition of water area and citation was included (please refer to Methodology section).

2.5. Estimation of river water area

Water surface is an important parameter for $CO_2$ efflux estimation, while it depends on its climate, channel geometry and topography. River water area therefore largely fluctuates with much higher areal extent of water surface particularly in monsoonal season. However, most studies do not consider this change, and a fraction of the drainage area is used in river water area calculation (Zhang et al., 2017). In our study, a 90 m resolution SRTM DEM (Shuttle Radar Topography Mission digital elevation model) data and Landsat images in dry season were used to delineate river network, and thus water area (Zhang et al., 2018), whilst, stream orders were not extracted. Water area of river systems is generally much higher in monsoonal season in comparison to dry season, for instance, Yellow River showed 1.4-fold higher water area in the wet season than in the dry season (Ran et al., 2015). Available dry-season image was likely to underestimate $CO_2$ estimation.

Ran, L.S., Lu, X.X., Yang, H., Li, L.Y., Yu, R.H., Sun, H.G., Han, J.T., 2015. $CO_2$ outgassing from the Yellow River network and its implications for riverine carbon cycle. Journal of Geophysical Research-Biogeosciences 120, 1334-1347. Zhang, T., Li, J., Pu, J., Martin, J.B., Khadka, M.B., Wu, F., Li, L., Jiang, F., Huang, S., Yuan, D., 2017. River sequesters atmospheric carbon and limits the $CO_2$ degassing in karst area, southwest China. Science of The Total Environment 609, 92-101. Zhang, J., Li, SY., Dong, RZ., Jiang, CS., 2018. Physical evolution of the Three Gorges Reservoir in Holocene using advanced SVM on Landsat images and SRTM DEM data. Environ Sci Pollut Res 25, 14911-14918.

Finally, I would suggest the authors polish the English grammar and writing, as well as the figs presenting.

Response: We carefully edited the Ms and re-organized the Tables and Figures presentation.

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