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Hydrology and Earth System Sciences Discussions

Interactive comment on "Estimating Daily Evapotranspiration Based on a Model of Evapotranspiration Fraction (EF) for Mixed Pixels" *by* Fugen Li et al.

Fugen Li et al.

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Received and published: 2 October 2018

P1 L24 More commonly referred to as the evaporative fraction Response: Thanks for your suggestion. We have revised this phrasing throughout the manuscript.

P2L3-6 Reference? This statement can be argued otherwise. The data that is captured at the coarser resolution can be considered representative at that spatial scale (1 km). If validation/verification of the simulated ET were undertaken at this scale would there necessarily be a larger degree of bias? I think it is important to take cognizance of the spatial resolution associated with the data that is being assessed, as well as the data that it is being compared to. It would also be useful to define, at the outset what is con-

sidered fine and coarse resolution for this particular study. Response: This argument is very important and helpful for understanding the nature of the spatial scale error in remote sensing. The spatial scale errors in remotely sensed ET (and other parameters inversed from remote sensing data) are mainly caused by the combination of nonlinear models and surface heterogeneity, which are more likely to occur in coarser resolution data (Hu and Islam, 1997; McCabe and Wood, 2006; Z. L. Li et al., 2013). Therefore, the data captured at coarser resolution cannot be considered representative at that spatial scale (1 km) without considering spatial scale errors. Accordingly, the validation/verification of the simulated ET undertaken at the same scale as coarse resolution data will not be able to mitigate the bias itself. Special techniques and more information are needed to eliminate these errors (Cammalleri et al., 2013; Ha et al., 2013; Kustas et al.,2003; Maayar and Chen, 2006). The authors have reported on an approach that is able to address spatial scale issues when estimating the daily ET, and it should be useful under most circumstances of coarse resolution data (i.e., from 102∼104 m). This statement was not sufficiently clear and has been revised as follows:

Studies have shown that different landscapes (Blyth and Harding, 1995; Bonan et al., 2002; McCabe and Wood, 2006; Moran et al., 1997) and subpixel variations of surface variables, such as stomatal conductance (Bin and Roni, 1994), or leaf area index (Bonan et al., 1993; Maayar and Chen, 2006), can cause errors in heat flux estimations. Models that are successful for fine-resolution remote sensing data (e.g., 30 m Landsat data) may not be appropriate for coarser resolution data (e.g., 1 km resolution MODIS and AVHRR data). The spatial scale errors in remotely sensed ET (and other parameters inversed from remote sensing data) primarily occur under the combination of nonlinear models and surface heterogeneity, which is more likely to occur in coarser resolution data (Garrigues et al., 2006; Gottschalk et al., 1999;Hu and Islam, 1997; Jin et al., 2007;Z. L. Li et al., 2013; McCabe and Wood, 2006; Tian et al., 2002; Xin et al., 2012).

Bin, L., and Roni, A.: The Impact of Spatial Variability of Land-Surface Characteristics on Land-Surface Heat Fluxes, Journal of Climate, 7, 527-537, 10.1175/1520-0442(1994)007<0527:TIOSVO>2.0.CO;2, 1994. Blyth, E. M., and Harding, R. J.: Application of aggregation models to surface heat flux from the Sahelian tiger bush, Agricultural & Forest Meteorology, 72, 213-235, 1995. Bonan, G. B., Pollard, D., and Thompson, S. L.: Influence of Subgrid-Scale Heterogeneity in Leaf Area Index, Stomatal Resistance, and Soil Moisture on Grid-Scale Land–Atmosphere Interactions, Journal of Climate, 6, 1882-1897, 10.1175/1520-0442(1993)006<1882:IOSSHI>2.0.CO;2, 1993. Bonan, G. B., Levis, S., Kergoat, L., and Oleson, K. W.: Landscapes as patches of plant functional types: An integrating concept for climate and ecosystem models, Global Biogeochemical Cycles, 16, 5-1-5-23, 10.1029/2000GB001360, 2002. Cammalleri, C., Anderson, M. C., Gao, F., Hain, C. R., and Kustas, W. P.: A data fusion approach for mapping daily evapotranspiration at field scale, Water Resour. Res., 49, 4672-4686, 10.1002/wrcr.20349, 2013. Ha, W., Gowda, P. H., and Howell, T. A.: A review of downscaling methods for remote sensing-based irrigation management: part I, Irrigation Science, 31, 831-850, 10.1007/s00271-012-0331-7, 2013. Hu, Z. L., and Islam, S.: A framework for analyzing and designing scale invariant remote sensing algorithms, Geoscience and Remote Sensing, IEEE Transactions on, 35, 747-755, 10.1109/36.581996, 1997. Kustas, W. P., Norman, J. M., Anderson, M. C., and French, A. N.: Estimating subpixel surface temperatures and energy fluxes from the vegetation index–radiometric temperature relationship, Remote Sens. Environ., 85, 429-440, http://dx.doi.org/10.1016/S0034-4257(03)00036-1, 2003. Li, Z. L., Tang, B. H., Wu, H., Ren, H., Yan, G., Wan, Z., Trigo, I. F., and Sobrino, J. A.: Satellite-derived land surface temperature: Current status and perspectives, Remote Sensing of Environment, 131, 14-37, http://dx.doi.org/10.1016/j.rse.2012.12.008, 2013. Maayar, E. M., and Chen, J. M.: Spatial scaling of evapotranspiration as affected by heterogeneities in vegetation, topography, and soil texture, Remote Sens. Environ., 102, 33-51, http://dx.doi.org/10.1016/j.rse.2006.01.017, 2006. McCabe, M. F., and Wood, E. F.: Scale influences on the remote estimation of evapotranspiration using multiple satellite sensors, Remote Sensing of Environment, 105, 271-285, 10.1016/j.rse.2006.07.006,

2006. Moran, M. S., Humes, K. S., and Pinter Jr, P. J.: The scaling characteristics of remotely-sensed variables for sparsely-vegetated heterogeneous landscapes, Journal of Hydrology, 190, 337-362, http://dx.doi.org/10.1016/S0022-1694(96)03133-2, 1997.

P2L7-8 Should references be in chronological order or alphabetic order?Check throughout the manuscript. Response: Thanks for your reminder. We have reordered the references in chronological order throughout the manuscript.

P2L10-12 What is the difference between distributed and lumped as discussed here? Response: Thank you for this thoughtful comment. We had revised this sentence to brieïňĆy discuss the difference between distributed and lumped calculations: To address the scale effect on energy fluxes, many studies have compared distributed calculations with lumped calculations. Distributed calculations are retrieved at fine resolutions and then aggregated to a coarser resolution, and the calculations are assumed to be correct in common scaling studies because the fine resolution calculation closely represents actual conditions, whereas lumped calculations aggregate fine resolution parameters to a coarser resolution. Distributed calculations and lumped calculations may not be the same at different scales.

P4L3-4 state the resampling methodology that was used and why? Response: Thanks for your thoughtful comment. We revised these sentences to brieïňĆy discuss the difference between distributed and lumped calculations: Surface thermal dynamics controls energy partitioning and ET. However, the spatial resolution of thermal-infrared (TIR) images is usually not as high as the spatial resolution of visible near-infrared (VNIR) bands because the energy of VNIR photons is higher than the energy of thermal photons (Peng et al., 2016). The IPUS (input parameter upscaling), a widely used one-source energy balance model that can handle the upscaling of all surface variables to a large scale before calculating the heat flux and does not consider the surface heterogeneities at all, is as the lumped method in this study. This model was designed to simulate satellites that have identical spatial resolutions in both the visible near-infrared (VNIR) and thermal infrared (TIR) bands and has been described in details in

Peng et al., (2016). The energy flux components net radiation (Rn), soil heat flux (G), sensible heat flux (H) and LE are shown as below (Jiao et al., 2014; Peng et al., 2016).

P4L23 Provide the shortened energy balance equation and define all terms. Response: Thanks for your careful reading of our manuscript. We have added Eq. (4) (P5 L1) to represent that the LE is estimated as the residual term of the surface energy balance equation. Finally, LE is calculated as a residual item of the energy balance equation (Eq. (4)). LE=R_n-G-H , (4) Further details are available in Peng et al. (2016).

P4L26 There are other methods which can/should be included especially if you are making reference to "various" Response: This sentence was adjusted to avoid ambiguity as below: EF is widely used to estimate the daily ET with RS data in different methods (e.g., the feature space of the Land Surface Temperature and Vegetation Index (LST-VI) (Carlson, 2007; Long and Singh, 2012) and SEBS (Su, 2002) models).

P5L3-4 The descriptions of the methodology presented herein are a critical aspect of the study and should therefore be described more clearly, so as to make the technique repeatable by other researchers. As it stands it is difficult to determine exactly how the values are being derived from just interpreting the equations below. See comments below, which detail critical aspects that require attention to improve the presentation of information. Response: The description of the method was not sufficiently clear and lightly misleading before. Section 2.2 (The EF of mixed pixels) was rewritten with an adjusted structure and detailed information. The derivation of EF equation of mixed pixels and use of the equation are two main parts of this method, and each involves one key hypothesis. The first half of section 2.2 presents hypothesis 1 and the equation, and the second half presents how the equation is applied with the aid of hypothesis 2. The first half is the theory and the second half is the technique. 2.2 The EF of mixed pixels (1) Equation for deriving the EF of mixed pixels Evaporative fraction (EF) is the ratio of LE and AE (Rn-G), as follows: EF= LE/(R_n-G) , (5) Studies have shown that the EF is quite stable over time and thus is well suited to denote the status of the surface energy balance for a certain period.

For example, the EF is nearly constant during daytime (Nichols and Cuenca, 2010; Sugita and Brutsaert, 1991) and thus, it can be used for temporal scale extrapolation, i.e., from instantaneous LE at satellite overpassing time to daily ET. EF is widely used to estimate the daily ET with RS data in different methods (e.g., the feature space of the Land Surface Temperature and Vegetation Index (LST-VI) (Carlson, 2007; Long and Singh, 2012) and SEBS (Su, 2002) models). In this section, EF of mixed pixels is investigated and a novel approach is derived to estimate the daily ET of mixed pixels. In other word, EF is used for temporal scale extrapolation and spatial scale correction to the remotely sensed LE and ET at a coarse resolution scale at the same time. Because turbulence transferred by advection is always neglected in RS data, we only consider vertical turbulence. Therefore, the accurate LE (with scaling effects taken into consideration) of a mixed pixel can be weighted by the LE of its sub-pixels as follows: LE= ∑s_iLE_i = ∑[s_iLE_i/(Rn − G)_i(Rn − G)_i], (6)whereLEdenotestheaccurateLEofmixedpixels, sitheareafraction(AF)ofsub− pixeli, andLEitheLEofsub − pixeli.Eq.(5)and(6)canbecombinedasfollows : LE = ∑[s_iEF_i(Rn − G)_i], (7)whereEFiand(Rn − G)idenotetheEFandAEofsub − pixeliinacertainmixedpixelrespectively.Atthisstep, asimplificationisperformedasdescribec Here, Hypothesis1isproposedasfollows : “Theavailableenergy(AE)ofeachsub − pixelisapproximatelyequaltothatofanyothersub−pixelsinthesamemixedpixelwithinanaccep 2) (Seguin B et al.,1999; Kustas and Norman, 2000; Sánchez et al., 2007)) and is equivalent to the AE of the mixed pixel.” Therefore, Eq. (7) can be transformed in to the following expression: (LE) ÌČ= [∑(s_iEF_i)](Rn − G), (8)where(LE)denotesthelatentheatfluxinmixedpixelsbasedonHypothesis1.Thereisamir (LE)/((Rn − G)) = ∑(s_iEF_i), (9)Thus, wehave(EF) = ∑(s_iEF_i), (10)where(EF)denotestheEFofthemixedpixelincludingtheerrorofHypothesi pixels, whichishoweverneedspecifictechniquetogetinoperations.(2)CalculatingtheEFofmix pixelsarerequiredinEq.(10); however, itisnotavailablewithcoarseresolutiondata.Inordertout “TheEFofeachsub−pixelinamixedpixelisapproximatelyequaltotheEFofthenearestpurepix pixelsurfaceandnearby(purepixel)surfacesgiventhesamelandcover.Accordingly, theEFofs

$pixelicanbedeterminedusingtheEFofpurepixel(s)atacoarseresolutionscalebasedonHypothe$
$ifasubpixelinamixedpixelandasetpurepixelshavethesamelandcoverasasubpixelinthestudya$
$closestpurepixel(s)tothesubpixel.Therefore, Eq.(8)maybereducedtothefollowing :$
$(LE) = (Rn-G)(EF), (11)Eq.(10)andHypothesis2togethercanbeusedtocalculatetheEFofm$
$weightedEFiofitssub-pixelswithacceptablesimplifications, whichsimplifiedthecalculation$

P5L5-6 Overall, I agree with this statement but I feel that this still needs to be framed within context i.e. capturing data at coarse resolutions and using this for localized applications may not be the most appropriate decision due to the effects that you have described. This needs to be stated in the introductory section and then reemphasized by stating what spatial scale the data is being verified at. Response: This sentence was moved to the introduction section as general background, and the following information was given here as specific detail on the method. In this section, the EF of mixed pixels is investigated and a novel approach is derived to estimate the daily ET of mixed pixels. In other word, EF is used for temporal scale extrapolation and spatial scale correction to the remotely sensed LE and ET at a coarse resolution scale at the same time.

P5L13 The description herein of the methodology is a bit vague. Is the EF and AE of the sub-pixel calculated using finer resolution imagery? Essentially are you obtaining flux and EF estimates using finer resolution imagery and then determining the proportional contribution of these values to the flux and EF estimates obtained at the coarser resolution Response: As mentioned in response to P5L3-4, this is the first half of the methods and only includes theory and method of deriving the equation. As explained in the second half, the use of the equation does not require the calculation of EF at a finer resolution. Rather, it needs the EF of pure pixels at a coarse resolution instead (see the revised section 2.2 for details).

P5L16 Which is? Response: The term ‘acceptable margin errors’ means that minor differences of available energy (AE) among the subpixels in the same mixed pixel. We assume that the available energy (AE) of each sub-pixel is approximately equal to that of any other sub-pixels in the same mixed pixel. In fact, there are minor differences

among them; however, these differences are within an acceptable margin according to previous research (Seguin B et al.,1999; Kustas andJ.M. Sánchez et al., 2007). More discuss details are presented in section 4.3.1.

P5L24 Similar to previous comment, as it stands this is too vague, is the EF of the sub-pixel for a finer resolution and then being compared to the EF of a pure pixel at the coarser resolution. Response: The use of the equation does not require the calculation of EF at a finer resolution; rather, it needs EF of pure pixels at a coarse resolution instead. The paragraph sequence here is incorrect and was rewritten too. (see the revised section 2.2 for details).

P6L4-6 Essentially the EFAF methodology is predicated on a combination of these hypotheses? Response: this paragraph was deleted because its meaning was vague and not necessary. The following information was given as a summary of this section. In summary, by employing two key hypothesises, EFAF methodology is able to realize temporal scale extrapolation and spatial scale correction for remotely sensed LE and ET at a coarse resolution scale at the same time. The EF of a mixed pixel is expressed as the area-weighted EFi of its sub-pixels with acceptable simplifications, which simplified the calculations, increased the accuracy, and facilitated its use for daily operations.

P8L2 Define what are pure pixels and mixed pixels in the context of this study. Based on Figure 3, I would assume a pure pixel, is a pixel at the 300 m resolution which is entirely made up of 1 particular land cover class mapped at the 30 m resolution? Response: Thank you for this suggestion. We have added the following statement: The pure pixels at 300 m scale are entirely made up of one particular land cover type, and the mixed pixels are made up of two or more land cover types according to the land cover datasets with a spatial resolution of 30 mïijŐ

P8L6 This map is taken from Peng et al., 2016 and should therefore be referenced accordingly. Response: Thanks for your kind reminder. The reference was added here as (Peng et al., 2016): Peng, Z., Xin, X., Jiao, J. J., Zhou, T., and Liu, Q.: Remote sensing algorithm for surface evapotranspiration considering landscape and statistical effects on mixed pixels, Hydrology & Earth System Sciences, 20, 4409-4438, 2016.

P9L10 clear-sky or cloud free Response: This has been revised as “clear-sky”

P9L11 what threshold was used here to decide this? for example less than 20 % cloud coverage over the study area or within the image? Response: Thanks for your thoughtful suggestion. This sentence was rewritten as: the satellite data selected for this study were collected under clear or partly cloudy conditions based on data quality metrics and artificial visual interpretation. We combined data quality information with visual interpretation to select satellite images in this study, and quantity cloud detection was not performed.

P10L6-7 It may prove to be more beneficial to move this information further up within the section before presenting the land cover map for the study area. Response: Thanks for your suggestion. This sentence was moved to the prior section presenting the land cover map for the study area immediately, after the sentence beginning “The percentage of the numbers of land cover types” The percentage of the number of land cover types (Yu et al., 2016) (Fig. 3) for the study area were extracted at a 300 m scale with 30 m land cover classifications, which were developed by Zhong et al. (2014a) based on HJ-1/CCD time series.

P10L21-22 regarding system setup? Response: Thanks for your reminder. This sentence was rewritten as follows: The EC data were based on 30 min intervals; additional information regarding the system setup, data processing and quality control can be found in previous reports (Liu et al., 2011; Liu et al., 2016; Xu et al., 2013)

P10L22 Is there any particular reason for including a description of how these sensors were setup and excluding descriptions for the other sensors? Response: Thanks for your reminder. This sentence was deleted since it is included in the above references and not necessary here.

P10L23-24 This also involves the use of soil temperature averaging probes and volumetric water content sensors Response: Thanks for your reminder. This sentence was deleted since it is included in the above references and not necessary here.

P11L4 Is it possible to provide the footprint of the measurements? Response: Thanks for your suggestion. However, in our opinion, the footprint is as a function of many variables, such as the tower height, wind speed and wind direction. Therefore, each site has different footprints on each day. If we want to provide the footprint of the measurements, a number of figures will be displayed in the manuscript. For the overall arrangement and the emphasis of the manuscript, we do not suggest providing the footprint of the measurements.

P13L4-7 It might prove to be useful to highlight these areas on the EF and LE maps as well. Response: Thanks you for this good suggestion. We have added the difference between lumped and EFAF (EF/LE) in Figure 4 and 5, and highlighted these areas in the Figure 4 and 5 showing the difference between lumped and EFAF LE.

(a) (b) (c)

(d) (e) (f) Figure 4. Maps of (a) lumped EF, (b) EFAF EF, (c) difference between the EFAF and lumped EF (EFAF EF minus the lumped EF), (d) lumped daily LE, (e) EFAF daily LE and (f) difference the between EFAF and lumped LE (EFAF LE minus the lumped LE) on July 8th, 2012

(a) (b) (c)

(d) (e) (f) Figure 5. Maps of (a) lumped EF, (b) EFAF EF, (c) difference between the EFAF and lumped EF (EFAF EF minus the lumped EF), (d) lumped daily LE, (e) EFAF daily LE and (f) difference between the EFAF and lumped LE (EFAF LE minus the lumped LE) on August 22nd, 2012

P15L6 Just a suggestion to consider...EFAF was applied to improve LE and ET estimates through corrections to EF. However, this will also influence the sensible heat

(H). It may prove to be beneficial to the study to also demonstrate how Lumped H and EFAF H compare against in-situ observations. Response: Thanks for your good suggestion. The focus of this study is to discuss the scale effect of LE (or ET); therefore, we proposed the model named EFAF. Using this model to determine the influence on the sensible heat (H) will be discussed in future research.

P15L9 It may also be useful to perform some form of significance testing to demonstrate that EFAF method has improved the flux estimates to an extent that there is no longer any significant differences between the observed and simulated values. Response: Thanks for your suggestion. A significance test is a good method of demonstrating that there are no longer any significant differences between the observed and retrieved values. However, in this study, fewer samples are provided due to the limitation on the number of observed values; therefore, identifying differences as a statistically significant is difficult. To better to demonstrate that EFAF method has improved the flux estimates, we added the decrease in the error percentage between the observed and retrieved values: The correction effect of the EFAF method was most distinct at the EC04 site, and the RMSE at EC04 decreased from 5.36 to 2.72 MJÂům-2 (about decreased by approximately 49.25%); this improvement stemmed from the fact that EC04 had the highest complexity of all sites. Maize-dominated pixels in EC04 included maize, vegetables, buildings and bare soil, at a ratio of 53:26:19:2, respectively. We conclude that maize and vegetables were land cover types with a high EF, while bare soil had a low EF. For buildings, the EF value was 0 in this study. Similarly, the difference of them against the EC measurements had also declined from 4.12 MJÂům-2 to 2.32 MJÂům-2 (decreased by approximately 43.3%).

P16L1-2 This is the point that I was alluding to earlier. See my comment in the introductory section about bias at larger spatial scales. Response: Thanks for your suggestion. As explained earlier, the spatial scale error of remote sensing estimation is not caused from scale mismatches between RS data and the EC footprint (see response to P2L3-6). However, validating the estimation could be affected by this scale mismatch. The

point here is to say that even after spatial scale errors were corrected (partially) by the EFAF method, a validation still need to be performed at the same scale for estimation and field measurement. Otherwise, uncertainties will remain in the validation results, which explains why the footprints of the EC measurements were calculated and used in the validation. To clarify the footprint and scale match technique, the footprint results were provided before used (see response to P11L4).

P20L9-10 Any reference to support this observation? Response: Thanks for your careful reading of our manuscript. We have added the relevant references here. We consider these biases to be acceptable (Seguin B et al., 1999; Kustas and Norman, 2000; Sánchez et al., 2007).

P26L5-7 The method presented herein describes a novel approach to improve the accuracy of daily ET estimates when using coarser spatial resolution data. However I would like to see a discussion within the "discussion section" or a recommendation for future study in the "conclusion section"describing how this technique can be used to assist improving the accuracy of daily (everyday for a period of time) ET estimates when using coarse resolution spatial data. From my understanding the technique was only applied on days in which concurrent coarse and finer resolution data was available. Coarser resolution imagery such as MODIS images are often used for season and inter-annual assessments due to their high temporal resolution. However, finer resolution imagery is not available on a daily time step. Subsequently, the question I am putting forward is, can this approach be applied on a daily basis to improve the accuracy of ET estimates obtained using coarser resolution imagery and if so, how? Response: Thanks for your kind suggestion. This information was added at the end of conclusion section; and can answer the question. In brief, the estimated LE of pure pixels is considered accurate and used to calculate its EF. Based on it, the equation for the EF of mixed pixels was established with two key hypothesises. A finer resolution land cover map is needed to search for “pure pixels” as well as to calculate area ratio of each land cover in mixed pixels. This process can derive the daily ET from coarse resolution remote sensing data with acceptable accuracy, and no other finer resolution data are needed in EFAF method. Thus, this method may be applicable on a daily basis with daily coarse resolution imagery, such as MODIS and only one finer resolution land cover map for a certain length of time, i.e., a week, month or season, as long as the land cover change is not radical in that period. This method is convenient for regional applications that need long term running. This method can also be used as a correcting technique for LE estimations or products of remote sensing since calculating the EF of mixed pixels is carried out after calculating heat fluxes that could be based on an energy balance equation or other methods at the very beginning. It should be admitted that the application of EFAF could be limited in very coarse resolution data since the probability of pure pixel becomes very low. In these circumstances, a compromise may have to be made between the "purity" of pure pixels and the searching distance for the pure pixels. More investigations are needed to evaluate the perfomance of this method with different remote sensing.

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Anonymous Referee #1

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The comments and suggestions were provided in the annotated version of the document (attached as a supplement) . The author's responses are in the sequence of the comments in the manuscript and generally contains (1) comments from Referees, (2) author's response (in blue), and (3) author's changes in manuscript (in red).

P1 L24 More commonly referred to as the evaporative fraction

Response: Thanks for your suggestion. We have revised this phrasing throughout the manuscript.

P2L3-6 Reference? This statement can be argued otherwise. The data that is captured at the coarser resolution can be considered representative at that spatial scale (1 km). If validation/verification of the simulated ET were undertaken at this scale would there necessarily be a larger degree of bias? I think it is important to take cognizance of the spatial resolution associated with the data that is being assessed, as well as the data that it is being compared to. It would also be useful to define, at the outset what is considered fine and coarse resolution for this particular study.

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Bin, L., and Roni, A.: The Impact of Spatial Variability of Land-Surface Characteristics on Land-Surface Heat Fluxes, Journal of Climate, 7, 527-537,

Fig. 1. Reply-RC1x