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Impact of Soil Heat Flux Attenuation on Surface Energy Balance Closure

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Abstract

In surface energy balance (SEB) measurements, ground heat flux (G) is either reconstructed from soil temperatures using analytical method or from the combination of calorimetric method with soil heat flux measured at 0.05 cm depth or more. Soil heat flux signal attenuation is known to increase with depth. This work intends to investigate the impact of this attenuation, which arises from the placement depths of soil temperature and heat flux plates sensors on SEB closure. Ground heat flux was reconstructed from soil heat flux and temperature measurements at two separate depths of 0.05 and 0.10 cm using calorimetric and analytical methods. The two data sets of G were combined with other SEB components to quantify the impact of placement depth of the soil sensors on SEB closure as a change in residual of SEB measurements (ΔRes). For the calorimetric method, the lowest value of ΔRes in the morning hours was -10W/m^2 and the peak value during the daytime was +43W/m^2. The values of ΔRes $_{\text{fluctuate}}$ between ±20 W/m^2 in the morning hours and ±42W/m^2 during the daytime for the analytical method but with a greater tendency towards positive ΔRes. Thus, SEB closure decreased with the increasing placement depth of the soil sensors, especially during the daytime. The implication of all these results is an irrecoverable signal loss in the soil heat flux as the placement depth of the sensors increases especially during the daytime.

Introduction

The earth-atmosphere interaction and its impacts on weather and climate continue to be areas of active research. Fundamental to the studies of this interaction is the equation of conservation of energy which can be written as:

$R_n = H + LE + G$ (1)

where R_n is the net radiation, H is the sensible heat flux, LE is the latent heat flux, and G is the soil heat flux at the earth's surface. To study this interaction, modellers have to assume the closure of equation (1) at the earth's surface. However, experimental investigations revealed that there is an imbalance in the earth's surface flux measurements and it is difficult to isolate those flux measurements causing the imbalance errors. Mounting evidence of the failure of current measurement systems to capture the closure of the surface energy balance (SEB) has urged researchers in this field to review their measurements and introduced correction methods to net radiation and turbulent heat fluxes (Halldin, 2004; Lee *et al.*, 2004; Moncrief, 2004; Foken, 2006). This resulted in considerable advances for turbulent fluxes. In contrast, soil heat flux, *G*, is often neglected in SEB studies (set to zero) or parameterized as $G = cR_n$ (where c is a constant). However, many empirical studies have shown that *G* is neither constant nor negligible on diurnal time scales. Field observations showed that *c* can range from 0.05 to 0.50 and depends on the time of the day, soil moisture and thermal properties, and vegetation amount and health (Kustas *et al.*, 1993).

In the study by Verhoef (2004) and Ogee, *et al.*, (2001), it was revealed that under conditions such as measurements taken (i) over bare dry soil and (ii) during the night time or right after

Keywords: surface energy balance, closure, soil heat flux, attenuation

sunrise until the turbulent processes start acting; *G* could become the most important of the heat flux components in SEB measurements. In a study carried out on a bare, dry and homogenous soil in an arid region, Heusinkveld *et al* (2004), obtained a nearly perfect closure by accounting for heat storage. In their experiment, soil heat flux was measured very close to the surface (0.001 m) to eliminate heat stored in the soil. *G* is therefore a key factor in the solution of imbalance in SEB measurements. Meyers and Hollinger (2004) showed that the current practice of burying the heat flux plate at some depths (usually 0.05 m or more) without accounting for the heat storage above the plate could account for as much as 10% error in the closure. Therefore, the incorrect determination of *G* is an issue still under consideration in the study of energy balance at the earth's surface.

Several methods have been proposed for the correct determination of *G*. One of such method is the calorimetric correction to soil heat flux measured at a depth by using soil temperature measurements made at such depth and above it. Analytical methods which only required soil temperature measurements could also be employed to calculate *G* at the surface from the placement depths of the temperature sensors. However, these corrections are not without limitations. In a calorimetric method, for example, additional measurements of soil temperature are required above the heat flux plate. Analytical method is limited by the requirement of harmonic solution which has improved accuracy as the number of harmonics increases, in addition to the basic requirements of in-situ soil thermal properties. Aside from these, there are still some other errors in the determination of *G*. Gentine, *et al* (2010) showed that the high-frequency component of the incoming radiative forcing is partitioned into ground heat flux while the long wave component is partitioned into turbulent heat fluxes. A large proportion of this high frequency radiative component is however absorbed within the thin layer of the surface and is attenuated very fast with depth. Hence, the possibility of signal loss as the depth increases may not be accounted for in the determination of *G*. It would therefore be expected that the closer the measurements are made to the surface the better the estimation of *G*.

The present study was aimed at investigating the impact of soil heat flux attenuation due to the placement depth of soil heat flux plates and soil temperature sensors on SEB closure.

Materials and Methods

Experimental Sites and Measurements

The site used in this study is located in the humid equatorial region of West Africa and the climate of the region can be classified as tropical with dry and wet seasons. The year is roughly divided into two: the wet season (April to October) and the dry season (November to March). This change in season occurs in association with the meridional movement of the inter-tropical discontinuity (ITD) line which follows the apparent meridional movement of the sun across West Africa (Adedokun, 1978, Otunla *et al,* 2008). Three prevalent weather conditions characterized the climate of the region of study. These are intense convective activities, south-westerly and harmattan wind (i.e., north-easterly dry wind laden with dust). These three prevalent weather conditions were observed during the measurement campaign carried out at this site (Mauder et al, 2007).

The study is based on the analysis of the data set obtained from the Nigerian Micrometeorology Experiment (NIMEX) conducted at Ile-Ife, Nigeria (lat. $7^{o}33'N$,lon. $4^{o}33'E$; altitude, 288 m a.s.l) during the transition from dry to wet season (the period of intensive observation was from February 19 through to March 9, 2004.). The main focus of this experiment was to measure directly the different components of the earth's surface energy balance equation on a homogeneous land surface. Details about the scientific considerations and measurements can be found in Jegede *et al* (2004). The vegetation of the

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land surface was characterized as fallow bushland of 0.30 m canopy height. The ground surface of this site was flat and homogenous at the time of measurements. The soil is loamy sand and it was in its permanent wilting condition at the beginning of the experiment (Jegede *et al*, 2004, Mauder *et al*, 2007). The soil type changes with depth. At the depth of about 0.20 m the soil type changes from loamy sand to clayey type. Both slow and fast response sensors were deployed during the measurement campaign to measure air temperature and humidity profile, wind speed profile, global radiation, wind speed and direction, soil temperature profile, soil moisture content, rainfall amount, air pressure and components of SEB equation (i.e net radiation, sensible, latent and soil heat flux). The sensors, except turbulent fluxes, were controlled using Campbell CR10X datalogger which sampled the data every second and subsequently stored them as 1-minute averaged values. Table 1 gives the list of equipment that were deployed for the present study. The heights and depths at which they were deployed are also indicated.

Surface energy balance components

The energy balance closure is a good test of the accuracy of flux measurements.-At the surface, the net radiative energy (R_n) should be balanced by the soil heat flux (*G*), sensible heat flux (*H*) and latent heat flux (LE). As these measurements are usually performed at certain heights or depths away from the surface, the energy balance closure test shows an imbalance in favour of the net radiation. To illustrate this, a more complete balanced equation was defined as (Heuskinveld *et al*., 2004):

$$R_n = \mathrm{G} + \mathrm{H} + \mathrm{LE} + \Delta S \quad (2)$$

where H and LE are measured at the height *z*. G is measured at some depths in the soil. ΔS represents additional terms such as advection, radiative flux divergence, change in biomass energy, change in heat storage above the soil heat flux plate, and change in the heat storage in the air between the sensor and soil among others. However, under the condition of the site used in this work, many of the terms that make up were negligible. For instance, advection term was expected to be small in a homogeneous fetch area. Both the heat storage in biomass and air layer between the device measuring turbulent fluxes and the ground is negligible for the scanty vegetation and air mass respectively. What is generally left to be accounted for is the heat storage in the soil.

Net Radiation

Net radiation used in the study was calculated from measurements taken using four radiation components instruments using:

$$R_n = I\downarrow - I\uparrow + L\downarrow - L\uparrow \quad (3)$$

where *I* is short wave and *L* is long wave. $\downarrow$ indicate down-welling radiation and $\uparrow$ is up-welling radiation. The radiometers were properly calibrated before the experiment and the data obtained were also checked for quality assurance. Inter-comparison analyses were also carried out between different types of radiometers (Jegede *et al.*, 2004).

Sensible and Latent Heat Fluxes

Turbulent flux data of very high-quality assurance were obtained and used in this work by applying TK2 (Turbulence Knight Version2), a software package designed by the Department of Micrometeorology, University of Bayreuth, Germany. The software implements various steps that lead to correct calculation of the eddy covariance such as head correction for USA-1 3-D ultrasonic anemometer, electrical and physical plausibility tests, spike detection as given by Vickers and Mahrt (1997), cross-correlation analysis and correction of time delay between various time series. The calculated covariances were also subjected to several other corrections to obtain correct turbulent fluxes as documented in Mauder *et al.* (2007) for the same data set.

Soil heat flux

Soil heat flux was measured at the depths of 0.02 m, 0.05 m and 0.10 m using soil heat flux plate. The damping depth, *D*, for all the days of measurements was calculated using:

$$D = \sqrt{2K_h / \omega} \qquad (4)$$

where K_h is soil thermal diffusivity and $\omega = 2\pi / P$ and P is time for diurnal cycle and it is equal to 24 hours.

The D values were used to evaluate the efficiency of the heat flux plate in measuring the soil heat flux at the surface or at the required layer. The average value of D was obtained to be 0.12 m at the site (Otunla, 2012). At this depth, from the definition of damping depth, only 37% of the heat flux will be measurable by heat flux plate. This would in effect imply that soil heat flux signal penetration decreases with depth and would be less than half of the initial value at the surface when it reaches the measurement depth of 0.10 m for instance.

In order to obtain the ground heat flux G at the ground's surface, calorimetric method was combined with the measurement obtained from the heat flux plate to account for heat storage above the plate. Heat storage above the heat flux plate at 0.10 m and 0.05 m were calculated from the temperature measurements taken at these depths respectively and above. Thus, soil heat flux was reconstructed at the surface from each measurement depths by using (Foken, 2008)

$$G = G_{plate} + \frac{Cz\Delta\overline{T}}{\Delta t} \qquad (5)$$

where G_{plate} is the soil heat flux measured at depth z using the heat flux plate (Table 1), C is the volumetric heat capacity, $\Delta\overline{T}$ is the change of average temperature in the soil layer above the heat flux plate within the time interval Δt. This method has been indicated to be better than all the methods that determine ground heat flux as a function of net radiation (Otunla and Oluwafemi, 2019). Analytical method was also used to calculate soil heat flux. It requires knowledge of soil thermal properties, that is, volumetric heat capacity and thermal diffusivity or thermal conductivity. Thermal diffusivity, K_h, was calculated by using harmonic algorithm (Horton, 1983). Harmonic algorithm was found to give the best estimate of soil thermal diffusivity for the site used in this work (Otunla and Oladiran, 2012) and this was in agreement with other studies carried out elsewhere (Horton *et al,* 1983). Volumetric heat capacity was calculated using (De Vries,1963, Verhoef *et al*,1996)

$$C = C_s f_s + C_\theta \theta \qquad (6)$$

where the volumetric specific heat capacity for the mineral soil components C_s and water, C_θ are 2.0 and 4.2 $Jm^{-3}k^{-1}$, respectively. (Ten Berge, 1990).

and f_s is the ratio of soil bulk density and density of the solid phase and θ is soil moisture content. By combining Fourier equation and the solution of one-dimensional equation of heat conduction, a predictive equation that can be employed to calculate G at the surface from any given depth was derived as:

$$G = \Gamma \sum_{k=1}^{N} \{C_{0k} e^{-z\sqrt{k\omega/2K_h}} \cos(k\omega t - \varphi_{0k} - z\sqrt{k\omega/2K_h})\} \qquad (7)$$

where $\Gamma = T_h\sqrt{K_h}$ is a measure of impedance to heat flow in soil. The values of N that give the best fit for G range between 6 and 9 for all the days of the year used in this study. In order to account for the soil heat flux signal lost using analytical method, equation 7 was used to reconstruct G at the surface from each measuring depth of 0.05 m and 0.10 m respectively.

Surface Energy Balance Residual

The residual of SEB is defined in this study to be

$$\text{Residual} = R_n - G - H - LE \qquad (8)$$

By reconstructing G at the surface from 0.05 m and 0.10 m depths using the two methods stated above we intend to investigate the impact of attenuation of soil heat flux signal due to these two placement depths from which G is reconstructed on SEB closure by calculating the values of the change in SEB residual.

Results and Discussion

Earlier reports have shown good closure of SEB from NIMEX-1 measurements for this site (Mauder *et al,* 2007). A slope of 0.95 was obtained between the turbulent energy fluxes

($H+\lambda E$) and available energy ($-R_n - G$) with $R^2 = 0.97$ and a positive intercept of 3.2 W/m2 in favour of the available energy. In Mauder *et al* (2007), *G* was measured at the depth of 0.02 m with the thin layer of soil above the heat flux plate assumed to have a small heat capacity and the corresponding heat storage is not significant. A typical result of SEB measurements in NIMEX-1 of 7 March 2004 is shown in Figure 1. Net radiation peaked at 507 W/m2 in the afternoon around 1300 hours. The residual of the SEB scattered around ±15 W/m2 in the night and early morning hours, and around ±50 W/m2 during the day hours. Figure 1 indicated that a quality SEB measurement data set was obtained during this experiment when compared with some other famous experiments as the residual of SEB was small compared with the net radiation (Koitzsch et al, 1998; Tsvang, et al, 1991; Kanemasu et al, 1992; Foken et al, 1993, Foken et al, 1997; Foken et al, 1998; Panin et al, 1996; Beyrich et al, 2002, Mauder et al, 2006). The overall residual of 8 days of SEB measurement using G measured at the depth of 0.02 m is given in Figure 2. The result indicated that the SEB residual ranges between -50 to +110 W/m2 for more than 95% of the data points. The morning hours recorded a lower absolute value of SEB residual with the data points spreading around zero compared with the afternoon where there was more scatter around average value of -25 W/m2. The diurnal cycle of the SEB residual shows significant departure from the usual sinusoidal curve that characterizes all changes that respond to solar forcing for the probable reason of the effects of scattered cloud cover on measurement of *G* taken at the depth of 0.02 m.

Table 1: List of equipment that was deployed in NIMEX-1 experiment and used in this study

Parameter	Device	Measurement height (m)	Accuracy	Averaging interval (min)
Soil temperature (°C)	PT-100 Ω	-0.05,-0.10	±1°C	1
Soil heat flux (W/m2)	Hukseflux HFPO1SC Self-calibrating heat flux plate	-0.02,-0.05,-0.10	50µV/W/m2	1
Net radiation(W/m2)	Kipp&CNR1 net radiometer	1.95	+9.6(11.9) µV/W/m2/13.9µV/W/m2	1
Sensible heat flux(W/m2)	Metek USA-1 3-D ultrasonic anenometer	2.48	10Hz	30
Latent heat flux(W/m2)	Campbell Sci.KH20 krypton hygrometer	2.43	8Hz	30
Data acquisition	Datalogger CR10-X			

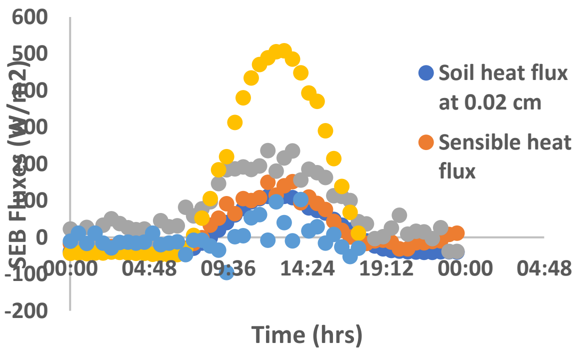

Figure 1: Diurnal cycle of the components of surface energy balance (SEB) and residual of 7 March 2004

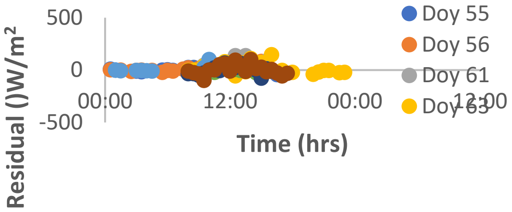

Figure 2: SEB residual with G measured at the depth of 0.02 m using Heat flux plate

Studies have shown that reconstruction of *G* at the earth's surface by including the heat storage (this is usually calculated by using calorimetric method) in the overlying soil layer above the heat flux plate and the biomass would significantly reduce the SEB residue (Heusinkveld et al, 2004, Meyers and Hollinger,2004). Since the intention of this study is not to investigate SEB closure but the impact of soil heat flux attenuation or signal lost with depth on the closure, change in the residual of SEB closure due to two depths of reconstruction of G at the surface is defined as a more appropriate index to quantify the expected impact than the absolute value of the residue. Change in SEB residual, $\Delta \mathrm{Re}\, s$ is defined as:

$$\Delta \mathrm{Re}\, s = \mathrm{Re}\, s(G_{0.10m}) - \mathrm{Re}\, s(G_{0.05m}) \quad (9)$$

where $G_{0.05m}$ and $G_{0.10m}$ are the soil heat flux reconstructed at the surface from the measurements of G taken or predicted from the depths of 0.05m and 0.10 m respectively. $\mathrm{Re}\, s(G_{0.05m})$ and $\mathrm{Re}\, s(G_{0.10m})$ are the SEB residuals with $G_{0.05m}$ and $G_{0.10m}$ respectively.

The results of the calculations of ΔRes using both calorimetric and analytical methods to reconstruct G at the surface from the measurements taken at the depths of 0.05 m and 0.10 m are presented in Figures 3 and 4. Also, Table 2 lists the slopes, intercepts and the coefficients of determination of the scatter plot of $G_{(x)}$ (x is the depth from which ground heat flux is reconstructed at the surface) against the difference between net radiation and turbulent fluxes (i.e R_n - H – LE) of SEB components in equation (1). As residual of SEB (Res) indicates absence of measurement of a quantity (heat storage in soil, air and biomass for instance) or, underestimation or overestimation of any of or all of SEB components, ΔRes as defined in this study could only imply lost in soil heat flux signal or attenuation as placement depth from which G is reconstructed increased.

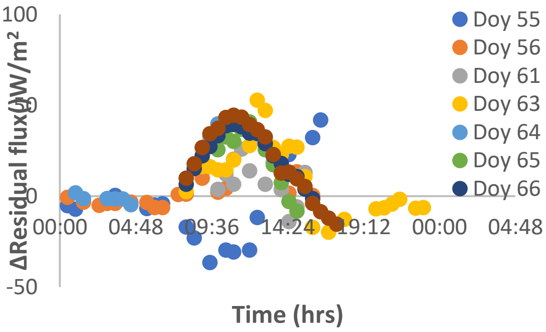

Figure 3: Change in SEB residual ($\Delta \mathrm{Re}\, s$) with G reconstructed at the surface from the depths of 0.05 m and 0.10 m using Calorimetric method

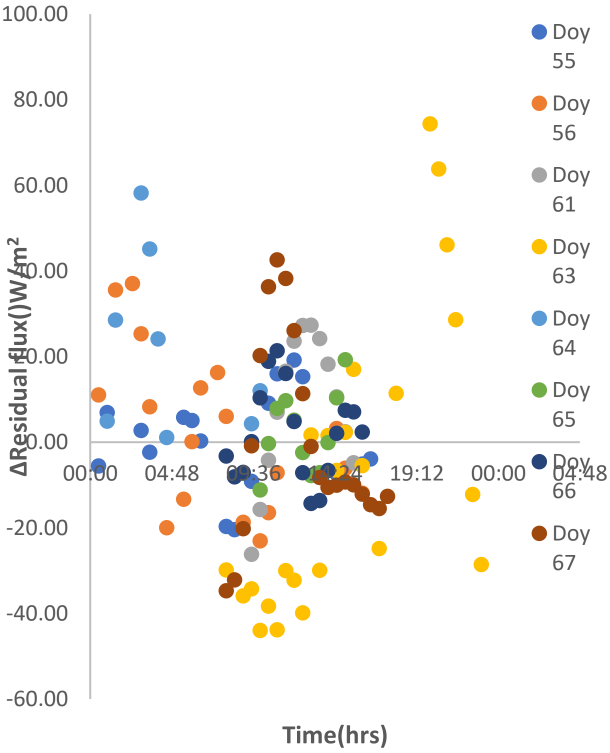

Figure 4: Change in SEB residual ($\Delta \mathrm{Re}s$) with G reconstructed at the surface from the depths of 0.05 m and 0.10 m using Analytical method.

Using the calorimetric method, most of the ΔRes values clustered around -10 W/m2 and +43W/m2 for the site used in this study (Figure 3). The peak value of ΔRes appeared around 11 am UTC with the minimum value of ΔRes occurring in the afternoon around 5 pm. Positive of ΔRes during the daytime indicated a decrease in closure of SEB as placement depth increased from 0.05 m to 0.10 m. ΔRes values ranging from 0 and -10 W/m2 for most of the data points in the morning or night time indicated a lesser impact of placement of soil sensors. Unlike the diurnal variation of SEB residual with G measured at the depth of 0.02 m (Figure 2), the diurnal variation of ΔRes is bounded by a sinusoidal curve of Doy 67, indicating a lower influence of scattered cloud cover at the measurement depths of 0.05 m and 0.10 m. The lower values of ΔRes obtained in both morning and night hours are consistent with similar results obtained elsewhere under the non-turbulent conditions that are common under stable stability. However, since ΔRes is not due to turbulence, it could be explained as due to the cutting off of shortwave solar radiation that is partitioned to *G* (Gentine *et al,* 2010). The influence of solar radiation as the source of G is seen as ΔRes grows with the increase in the amount of shortwave radiation that reaches the surface. Besides, there is a clear change in the linear regression between G against the difference of net radiation and turbulent heat fluxes (i.e. R_n,-*H*-*LE*) as the depths from where *G* is reconstructed are increased from 0.05 m to 0.10 m. The departure of the slope of the regression line from the ideal (i.e. 1.00) increased with the increase in the depth of soil heat flux attenuation when G was reconstructed using calorimetric method. Thus, the implication of all these analyses was lost in soil heat flux signal as the depth of signal penetration increased and this was more prominent during the day-hours. This gave rise to a greater tendency towards surface energy imbalance.

With the application of analytical method to reconstruct G at the surface, ΔRes amounts to ±42 W/m^2 for more than 95% of the data points. This was obtained as the peak-to-peak estimate of ΔRes at around noon-time. The morning hours however recorded much lesser variations with a range between -20 and +20 W/m2 for most of the data points. The diurnal variation of ΔRes did not follow any distinguishable shape, however, there was a greater tendency towards positive ΔRes as most ΔRes data points had positive values. This therefore indicated a tendency towards greater loss of signal as the placement depth of soil temperature sensors increased and this was more prominent during the day hours. The characteristics of the regression lines obtained from plotting G against the difference of net radiation and turbulent heat fluxes indicated that the slope slightly increased with depth but the intercept changed from a value near 1.00 W/m^2 - 2.67 W/m^2. The coefficient of determinations decreased as placement depth was changed from 0.05 m to 0.1 m by almost the same amount of changes indicated for slope.

Methods	A	B	R^2
$G_{(x)}$ was measured using Heat flux plate only			
x= 0.02 m depth	0.64	0.37	0.86
$G_{(x)}$ (reconstructed using Calorimetric method)			
x= 0.05 m depth	0.73	5.19	0.84
x= 0.10 m depth	0.57	2.27	0.83
$G_{(x)}$ (reconstructed using Analytical method)			
x= 0.05 m depth	0.71	0.99	0.83
x= 0.10 m depth	0.83	-2.67	0.73

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Table 2: Slopes (A), intercepts (B) and coefficient of determination (R^2) of regression line between $G_{(x)}$ and R_n-H-LE (the subscript x represent depth in the soil where soil sensors where buried.

Conclusion

This study indicated an increase in soil heat flux attenuation or signal loss typified by positive change in SEB residual during daytime period as the placement depth of soil sensors approached the damping depth of 0.12 m. We suggest that this signal loss could be significantly reduced by taken soil measurements as close as possible to the surface especially when soil moisture is low and in the absence of liquid precipitation. This is especially so as the measurements used in the study were taken during the transition period when soil moisture was low and days with precipitation occurrence were excluded in the analysis.

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