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Energy balance from images in humid climate – SEBAL and METRIC

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ABSTRACT

Evapotranspiration is an important phenomenon to agriculture; therefore, this work aims at verifying the suitability of the SEBAL and METRIC models to estimate latent heat flux using remote sensing data from grain cultivation areas in the northwestern subtropical region of Rio Grande do Sul. This region stands out for grain production. The analyzed data set consisted of 84 dates distributed over a 3-year period of areas planted with soy, corn, oats, wheat, and vetch crops. The data estimated from the remote images were compared with the reference measurements acquired in a micrometeorological station using the Eddy Covariance technique. Both models presented satisfactory results. However, the LE estimated by the METRIC model had the lowest error for all 3 types of soil cover analyzed. The best performance of the METRIC model is attributed to the fact that it does not require extreme water condition, i.e. for LE equal to zero, to determine the hot pixel when estimating the sensible heat flux, unlike the SEBAL model.

Introduction

Evapotranspiration is the main component of the water balance since the water leaves the surface especially via this phenomenon and it is, therefore, very important to understand it in the agronomic context, from modeling studies of crop development to field management. Also, the high temporal and spatial variability of this component and its complex determination gives rise to several studies and modeling using remote sensing (RS) images. Images acquired in different regions of the electromagnetic spectrum allow to determine few physical properties of the surface such as albedo, surface temperature, and vegetation index, which enable quantifying the energy and mass fluxes between the surface and the atmosphere (Timmermans et al., 2007; Cammalleri et al., 2014; Kustas et al., 2004).

Locally, fluxes can be obtained from data from meteorological stations or micrometeorological stations (Wilson et al., 2002, Brotzge & Crawford, 2003, Sumner

& Jacobs, 2005, Baldocchi 1988), but the collected data are restricted to the area near the station where the measurements take place. At the regional level, the combined use of satellite images and surface data (Allen et al., 2007, French et al., 2015, Kustas et al., 2016, Kilic et al., 2016) allows acquiring data on mass and energy fluxes under natural conditions and defining their partition in areas where the earth surface coverage is diversified.

Most studies estimating energy balance (EB) components use images based on unidimensional flux models to describe mechanisms of radiation exchange and heat fluxes between the surface and the atmosphere, observing the energy conservation principle (Brutsaert, 1984). The EB defines how the (Rn) radiation incident on the surface is partitioned into latent heat flux (LE), and air (H) and ground (G) sensible heat fluxes (Friedl 2002, Timmermans et al., 2007). The Rn and G are easily estimated (Kustas et al., 2004, Sánchez et al., 2008), while the turbulent flows, LE and H, have a more complex estimation.

In most EB estimation models, LE is obtained as a residual term in the EB equation. The main difference between models lies on how sensible heat flux (H) is determined. Two main approaches can be highlighted. The first, the OSEB models (One-Source Energy Balance or one-layer models) consider fully vegetated surface while H is estimated from the difference between the radiometric temperature of the vegetated surface and the air temperature, determining a single aerodynamic resistance to different levels of vegetation cover (Boegh et al., 2002, Friedl, 2002, Kustas et al., 2004, Wang et al., 2006, Sánchez et al., 2008, Timmermans et al., 2007, and Tang et al., 2013). The second, the TSEB models (Two-Source Energy Balance models) treat differently the heat exchanges between the atmosphere and vegetated areas and between the atmosphere and bare soil areas, using different equations to obtain H and determining different aerodynamic resistances for areas with vegetation and soil (Sánchez et al., 2008, Cammalleri et al., 2012, Tang et al., 2013).

The MODIS products stand out among the various spatial, temporal and spectral resolution images that remote sensing makes available; the sensor is aboard the Terra and Aqua satellites. These products consist of a series of surface parameters already modeled and processed that allow calculating surface EB with accuracy and the spatial and temporal resolution necessary for monitoring the agricultural systems. Depending on the size of the monitored areas, the spatial resolution of the images may lead to loss of accuracy given the generalization of the spectral mixture within the pixel. On the other hand, the MODIS images have great temporal detail due to the shorter period of the satellite orbits, and the possibility of building continuous time series from 2000 onward.

The OSEB models have a subgroup in which the spatial variations of the surface conditions is represented by mapping anchor pixels, that is, the cold and hot pixels of the image that respectively characterize the image wet

Figure 1. Local of the study area.

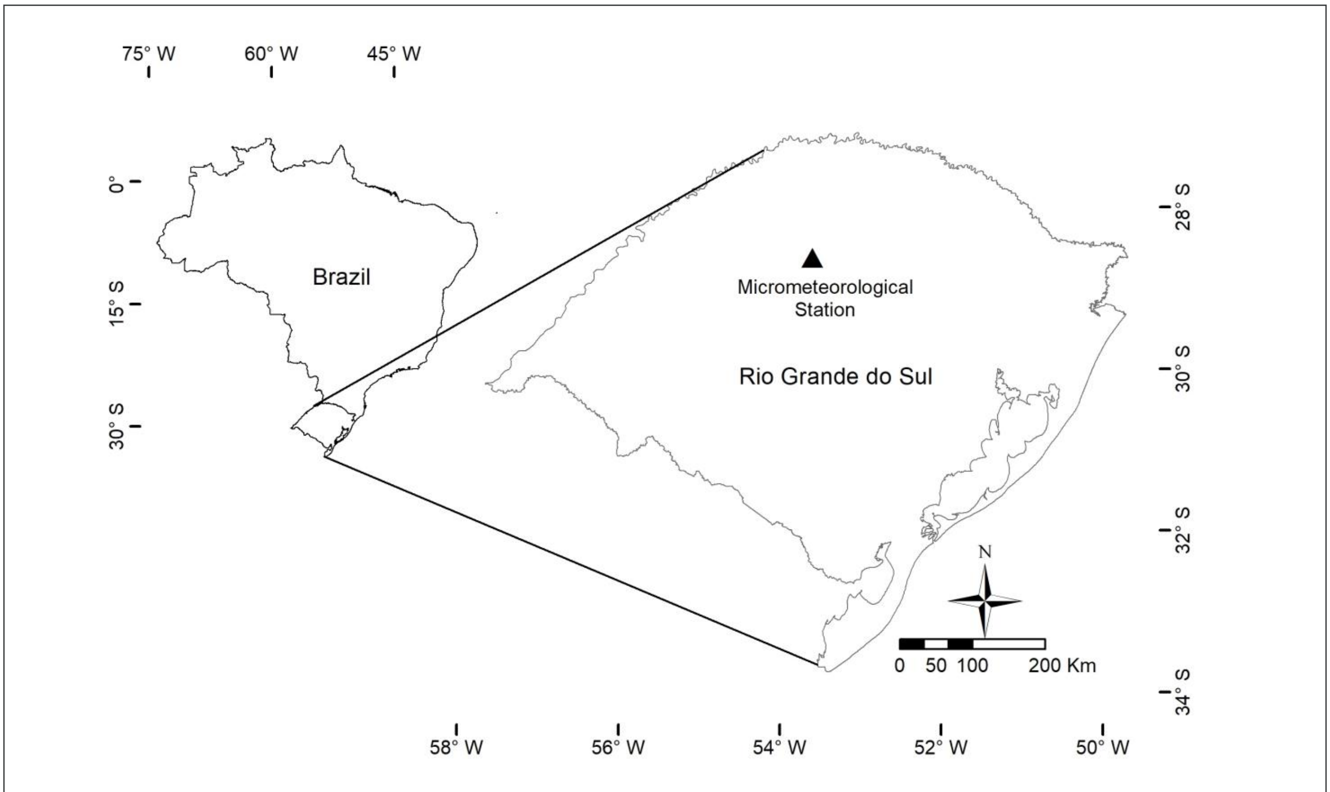
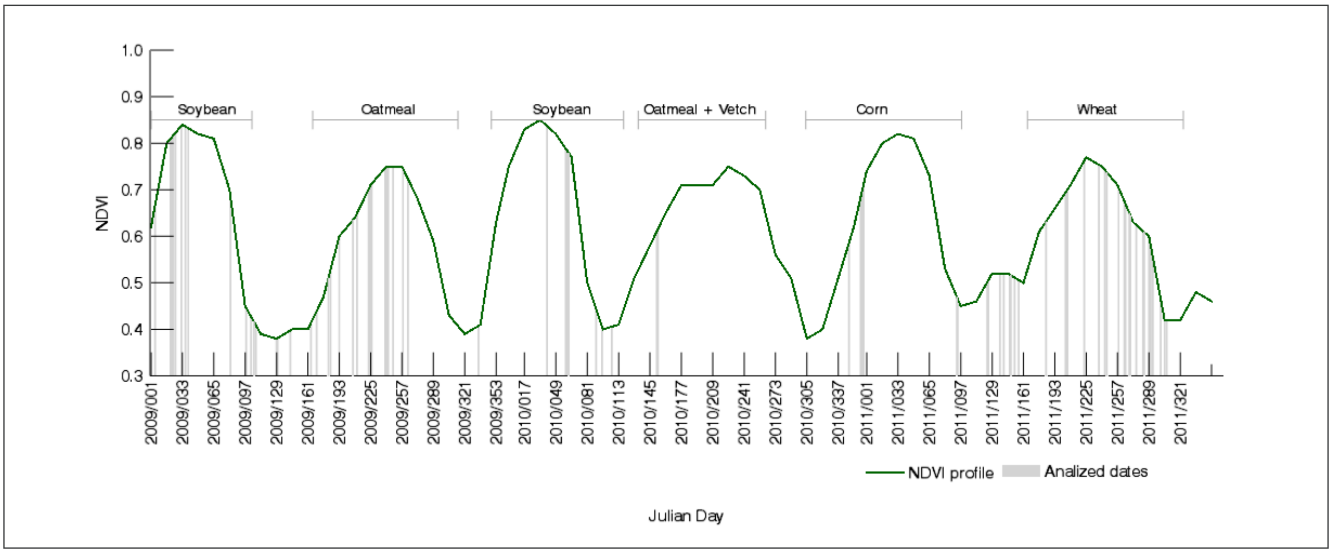


Figure 2. NDVI in Cruz Alta over the studied period of three years. Gray bars show the dates of the images selected for analysis.



and dry boundaries. These models include the SEBAL (Surface Energy Balance Algorithm for Land, Bastiaanssen, 1995) and METRIC (Mapping Evapotranspiration with Internalized Calibration, Allen et al., 2007). Although criticized for some physical simplifications, these models offer great advantages such as the self-calibration approach, thus avoiding errors and uncertainties that are difficult to solve (French et al., 2015).

The SEBAL and METRIC models have been used to fit data from different parts of the world and the results are encouraging, but questions about their operation or the need for some local scale calibration remain. This is especially true for areas in humid climate, which is distinct from those where the methods were developed. The study area in Rio Grande do Sul is predominantly humid subtropical climate, with no dry season, and intense agricultural activity, especially in the spring-summer period. Grain production is the main economic activity in the state, the crop successes and failures are closely associated with water conditions, evidencing the importance of accurate methods to determine it.

The state humid climate may not provide the necessary water conditions for the correct parameterization of OSEB models using MODIS images. Two problems may occur. Firstly, in the process of determining the hot and cold pixels, the spatial resolution of the MODIS images may introduce uncertainties since the 1km pixel of the products used reflect a combination of different surfaces, making the occurrence of pure pixels with extreme water conditions difficult (Roerink et al., 2000). According to the Ecoclimatic conditions of Rio Grande do Sul, high vegetation cover rates occur throughout the year, making critical the determination of hot pixels, which as defined by the model authors are pixels with little or no vegetation cover.

Evapotranspiration is an important phenomenon to the agriculture of Rio Grande do Sul. Furthermore, because the SEBAL and METRIC models are widely used and, especially, due to the fact that the humid subtropical climate predominant in the region affects negatively the performance of the models, this study aims at verifying the suitability of the SEBAL and METRIC models to estimate the latent heat flux in grain cultivation areas of Rio Grande do Sul.

Material and Methods

Study area and period

The methodology to estimate the EB components was applied in Rio Grande do Sul, an important grain producer in Brazil.

The study period covered three years, from 2009 to 2011, using data from three different sources: a) surface temperature, albedo, and vegetation index from the MODIS products; b) air temperature, relative air humidity/moisture, global solar radiation and wind speed from the INMET meteorological station of Cruz Alta; and, c) reference data from the micrometeorological station in Cruz Alta for verifying the accuracy of the EB components' estimates, Rn, LE, H and G energy fluxes.

During the three-year period, a total of 84 dates/images were analyzed, 20 for summer crops, predominantly soybean, and 32 for winter crops, predominantly wheat, and another 32 for partial vegetation cover. The NDVI temporal pattern and the analyzed date distribution (Figure 2) aimed to understand how the results varied regarding time of the year, crop, and surface coverage.

The 84 dates were selected according to two criteria. First, only days with clear skies and no cloud coverage throughout the day at the station based on the diurnal cycle of the global radiation (Rg) were chosen. Second, the simultaneous availability of images and data at a local scale are a requirement for estimating and evaluating EB components.

MODIS Products

The MODIS products were used to obtain Earth Surface Temperature - MOD11A2, Vegetation Index - MOD13A2 and Albedo - MCD43B3. All products had spatial resolution of 1,000 m while time resolution consisted of temporal compositions of 16 and 8 days for MOD13 and MOD43, respectively, and daily for MOD11.

These products are available as fixed cutouts always providing coverage for a specific area of the globe. The study area was covered by a mosaic of the H13V11 and H13V12 quadrants, which were obtained from the Land Processes Distributed Active Archive Center (LP DAAC).

Reference Measurements

The EB surface components were measured in an experimental plot cultivated with soybeans in the summer and wheat in the winter, in Cruz Alta, RS, at -28.60859º latitude, -53.672153º longitude, and 432 m altitude. This experimental site was part of the SULFLUX Network (www.ufsm.br/sulfux) operated by the Micrometeorology Laboratory of the Federal University of Santa Maria (Lμmet-UFSM).

The radiation balance (Rn) and ground heat flux (G) were measured at 3 m height, using the Kipp & Zonen - NR LI TE and Hukseflux-HFP01SC-L sensors, respectively. The turbulent sensible (H) and latent (LE) heat fluxes were estimated by the Eddy Covariance method. For this purpose, high frequency (10 Hz) measurements of a 3D sonic anemometer, CSAT3 (Campbell Scientific Inc.) and an infrared gas analyzer (LI-7500, LI-COR, Inc.) were used. The EB components were computed as 30 min averages. Further information on the experimental site and experimental measures can be obtained from Moreira et al. (2015)

Estimates of EB components

The detailed methodology to obtain the Rn, G, H and LE components follow the original assumptions proposed by Bastiaanssen et al. (1998) and Bastiaanssen (2000) for the SEBAL model and by Allen et al. (2007) for the METRIC model. In this section, we discuss only the differences and details pertinent to the performance of the models used.

The SEBAL and METRIC models are practically identical, based on using hot and cold anchor pixels for determining H, from an iterative self-calibration process of aerodynamic resistance and vertical temperature differential in the first few meters of the atmosphere. The main difference between the models lies on how the latent and sensitive heat fluxes of the anchor pixels are determined. The SEBAL model adopts extreme limits. In the cold pixel, all available energy is consumed by LE, so LE = Rn - G and H = 0. In the hot pixel LE = 0 and H is maximum (H = Rn - G). The METRIC model considers the possible occurrence of residual H and LE in the cold and hot pixels, respectively; therefore, for the cold pixel, LE ≈ 1.05ETo (reference evapotranspiration; Allen et al., 1998) and H = Rn - G - LE. Whereas a possible residual evaporation from the bare soil is considered for the hot pixel, so LE = E (soil evaporation obtained from soil water balance proposed by Allen et al., 1998) and H = Rn - G - LE.

Furthermore, the hot pixels were assumed to have a 50% vegetation cover since the METRIC model requires the occurrence of completely bare pixels to determine residual LE of the hot pixel, but the ecoclimatic conditions of the region hamper the occurrence of completely bare/uncovered pixels.

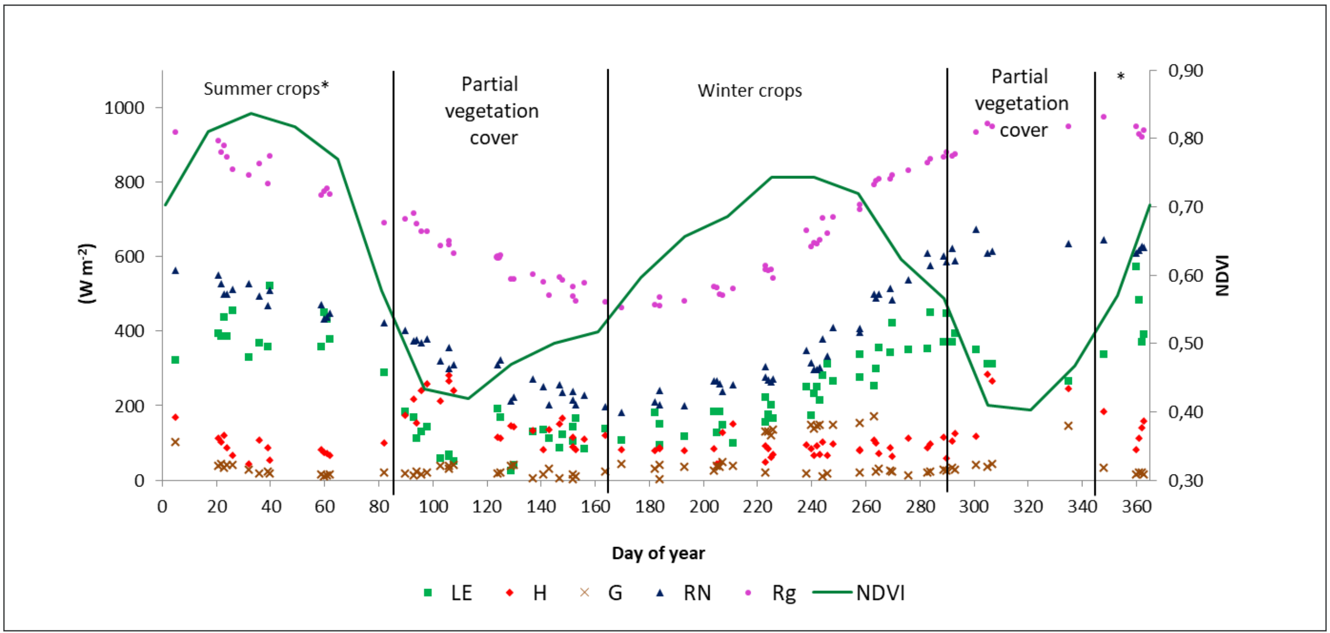
Another relevant aspect when estimating the EB components is that each image requires the user to perform a calibration process, that consists of selecting pixels with temperature extremes (Long & Singh, 2013). In the SEBAL and METRIC models, this selection is subjective, and it is up to the user to list the hot and cold pixels of the images. In addition to being time-consuming, this process is highly dependent on the user, making it difficult to assess whether the uncertainties in the LE estimates are due to model deficiency or inadequate selection of anchor pixels. This is one of the most critical points of the SEBAL and METRIC models (Long & Singh, 2012, Long & Singh, 2013, Morton et al., 2013, French et al., 2015). It is, therefore, convenient to adopt an objective selection criterion.

The present work uses an objective and predetermined method to select the hot and cold anchor pixels. First, the reference values were based on pixel grouping, never on a single pixel. Second, the selection was based on statistics, cold pixels were those with temperature values corresponding to the accumulated frequency of 2% while the hot pixels corresponded to the 98% accumulated frequency. Third, the pixels close to those that showed cloud coverage were eliminated from the selection process (a 2-pixel buffer was applied to the cloud-occurrence mask of the TS product). The same set of pixels selected as hot and cold limits was used in both models.

Results evaluation

The obtained results were analyzed and compared by plotting dispersion graphs of the EB components, Rn, LE, H and G, reference measurements versus the results obtained by the two models, OSEB and METRIC. The RMSE

Figure 3. Annual pattern of the EB components obtained in the micrometeorological station in Cruz Alta, recorded at the time of satellite passage (10:30 local time) and annual NDVI. Data referring to the days analyzed over the 2009 to 2011 period.



MBE errors and Willmott's concordance index (d) between the estimated values and reference measures were also plotted. In addition, dispersion graphs of the LE and H components throughout the year; H and LE components obtained by each model; and the annual pattern of the EB components together with the annual average NDVI were plotted.

Results and Discussion

The incident global solar radiation (Rg) at the time of the satellite passage (10:30h UTC - 3:00h) (Figure 3) varied greatly between summer and winter, being consistent with subtropical climate conditions. Values ranged from 974 W m^{-2} (summer) to 462 W m^{-2} (winter). As expected, the radiation balance and global solar radiation followed a similar annual pattern, but values were 45% lower than Rg, on average, due to surface radiation loss by reflection. The average albedo extracted from the images in the meteorological station area was 17%, besides the surface emission loss in long-wavelength.

The records of the EB components show that LE was responsible for consuming the largest portion of Rn, surpassing H (Figure 3) practically every year. This pattern was predominant, but less frequently, inversion was observed and H was higher than LE at the end of the summer growing cycle (between days 90 and 110) while LE and H values were close at the beginning (days 120 to 220) and end (days 300 and 320) of the winter cycle.

The LE component decreased markedly during partial coverage periods due to accumulated dry vegetation on the soil. According to Dalmago et al. (2010), the straw acts as an insulation layer that partially interrupts the process of soil evaporation. LE consumed about 75% of Rn during the summer growth period, decreasing to 61% in the winter.

It has been concluded that the ground heat flux usually consumes the least portion of the energy (Timmermans et al., 2007; Tang et al., 2013), which was corroborated in this work.

The average energy values estimated by the SEBAL and METRIC models equivalent to each EB component, Rn proportion, and errors for each model and cover analyzed, are shown in Table 1. Similar to the micrometeorological station, the models estimated a higher energy availability (Rn) for summer crops (545 W m^{-2}), with the lowest standard deviation. The values were similar for winter crops (387 W m^{-2}) and partial coverage (385 W m^{-2}), but standard deviations were higher compared to summer.

Rn was the EB component closest to the experimental values for all three coverages (Figure 4) and the data approached a straight line 1: 1. The RMS error was always less than or equal to 50 W m^{-2} and concordance indices close to 1 (0.97 for summer crops and 0.99 for both, winter crops and partial vegetation cover). This result is expected, as the Rn estimates are generally satisfactory, easy to estimate and have the smallest errors (Tang et al., 2013, Timmermans et al., 2007).

The G estimates were low, on average, for both models (Table 1) and similar to the reference values of the micrometeorological station. Moreover, G estimates had higher deviations during some days of the winter crop (Figure 4) but the pattern of the reference measurements (station) was also abnormal, with values above the observed standard, leading to the assumption that some

Table 1. Components of the energy balance estimated from the SEBAL and METRIC models for data obtained from the images of the micrometeorological station coordinates. Statistics extracted in a 3x3 window from the images of the Cruz Alta experimental site analyzed over the 2009 to 2011 period.

Component	Model	Mean W m^{-2}	%Rn	Deviation W m^{-2}	RMSE W m^{-2}	MBE W m^{-2}	d
Summer crops							
Rn	SEBAL & METRIC	545	100	60	40	-22	0.97
G	SEBAL & METRIC	57	11	21	40	-30	0.60
H	METRIC	107	20	64	73	-6	0.81
H	SEBAL	129	24	66	78	-28	0.73
LE	METRIC	381	70	9W5	92	14	0.65
LE	SEBAL	358	66	96	104	37	0.63
Partial vegetation coverage							
Rn	SEBAL & METRIC	385	100	121	49	-23	0.99
G	SEBAL & METRIC	50	13	25	32	-22	0.59
H	METRIC	209	54	72	91	-50	0.78
H	SEBAL	249	65	79	121	-93	0.61
LE	METRIC	126	33	66	99	46	0.93
LE	SEBAL	84	22	62	120	94	0.87
Winter crops							
Rn	SEBAL & METRIC	387	100	103	50	-38	0,99
G	SEBAL & METRIC	31	8	14	67	32	0,29
H	METRIC	120	31	47	71	-48	0,26
H	SEBAL	156	40	64	109	-84	0,14
LE	METRIC	235	61	94	95	-21	0,96
LE	SEBAL	198	51	109	107	16	0,96

Where: LE – latent heat flux, H – sensible heat flux, Rn – radiation balance, and G – ground heat flux, RMSE – Root Mean Square Error, MBE – Mean Bias Error, d –Willmott's concordance index

external factor affected these measurements, e.g., sensor maintenance or some soil manipulation that caused the sensor to remain uncovered. It is noteworthy that the distribution of the records and the estimates of Rn and G are identical for both models because they were obtained by the same methodology.

The H and LE components deviated the most from the straight line 1:1 (Figure 4). The LE component is obtained as residual term in EB equation; therefore, its estimate is connected with the H estimates, which are responsible for the second largest share of surface energy consumption.

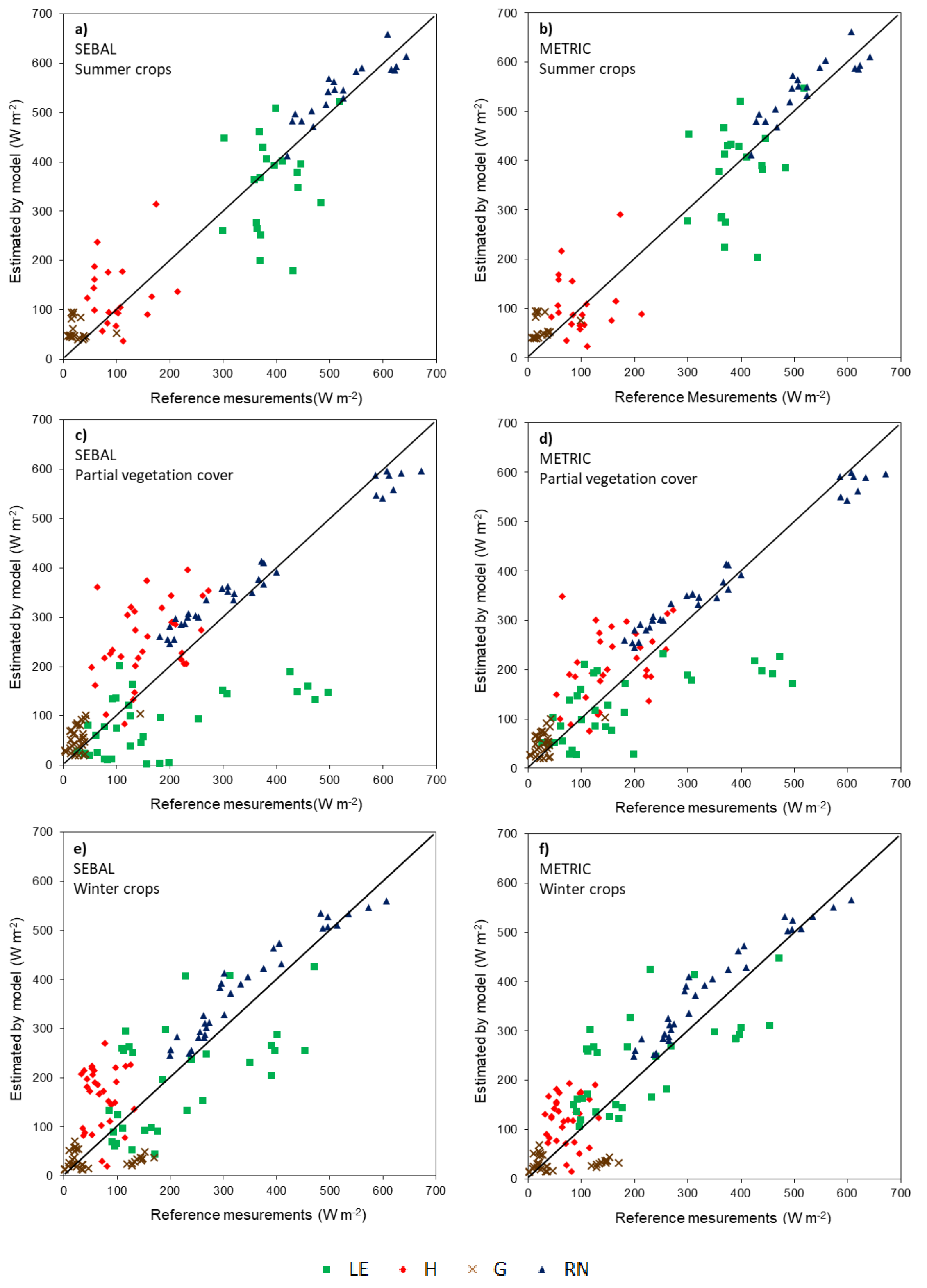
In general, the METRIC model estimated mean H values slightly lower than SEBAL for all three coverages. Consequently, the inverse was observed for LE. Nevertheless, it is noteworthy that both components are coherent with the pattern observed in the micrometeorological station. The LE/Rn proportions were, on average, higher than H/Rn in the summer and winter crops. Only during the partial vegetation cover period, average H estimates were higher than LE.

In the partial coverage period for both models, SEBAL (Figure 4c) and METRIC (Figure 4d), H and LE data points are seen above and below the straight line 1:1, respectively, characterizing over and underestimation. This trend is quantified by MBE errors, with negative values for H and positive for LE (Table 1). In this period, the estimates presented the highest RMS and MBE errors (in module), especially for the SEBAL model. The poor determination of the H and LE components is attributed to the high proportion of uncovered soil or accumulated dry straw in this period. The authors hypothesized that the lack of vegetation caused the evapotranspiration process to be directly influenced by meteorological variables and not by the physiological processes of the vegetation, since the physiological processes control the evapotranspiration, leaving the process less sensitive to small variations of the meteorological conditions.

The subtle errors detected for both LE and H estimates by the METRIC model and all three coverages were lower than those observed in the SEBAL model (Table 1 and Figure 4), with lower RMSE and higher d.

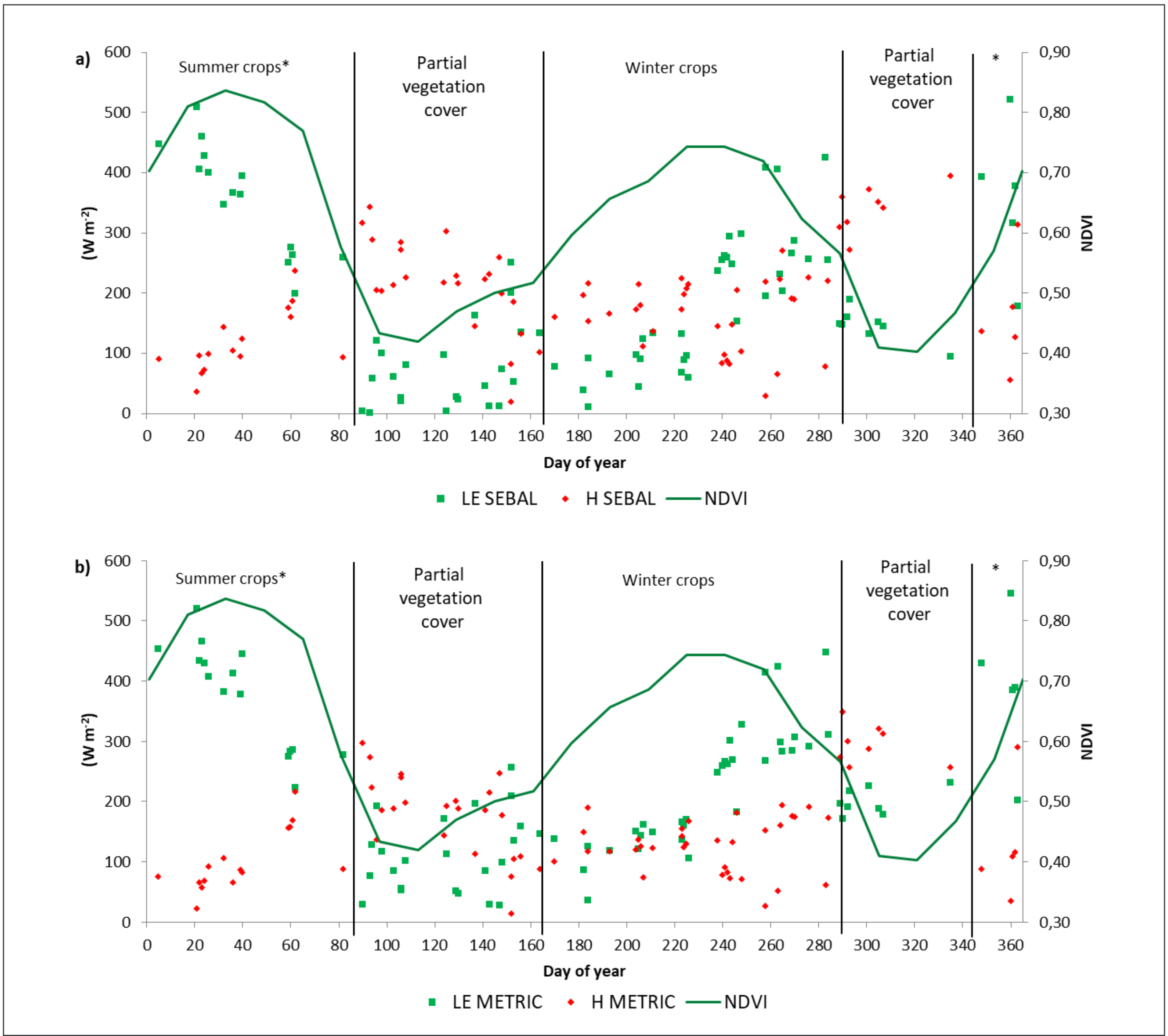
Coherent with the mean values, the temporal pattern

Figure 4. Dispersion graphs of Energy Balance components: experimental (reference) X simulation (models), for summer, winter and partial coverage of the 84 days analyzed over the 2009 to 2011 period. The boxes on the left show the results for the SEBAL model and on the right for the METRIC model. The experimental values correspond to reference measurements in Cruz Alta.



of H and LE estimated by the SEBAL (Figure 5a) and METRIC (Figure 5b) models was similar to the experimental data (Figure 3). Generally, LE surpassed H most of the year for both models, but the proportion of these components inverted especially at the end of the summer cycle, already in the period classified as partial vegetation cover, between 90 and 120 days, which was also observed in the micrometeorological station data (Figure 3). This inversion also occurred on some days at the beginning and end of the winter cycle, between 120 and 150 days, which was

Figure 5. Annual pattern of the LE and H components estimated from the images and NDVI annual profile. a) data estimated by the SEBAL model and b) data estimated by the METRIC model. Statistics extracted in a 3x3 window from the images of the Cruz Alta experimental site, analyzed over the 2009 to 2011 period.



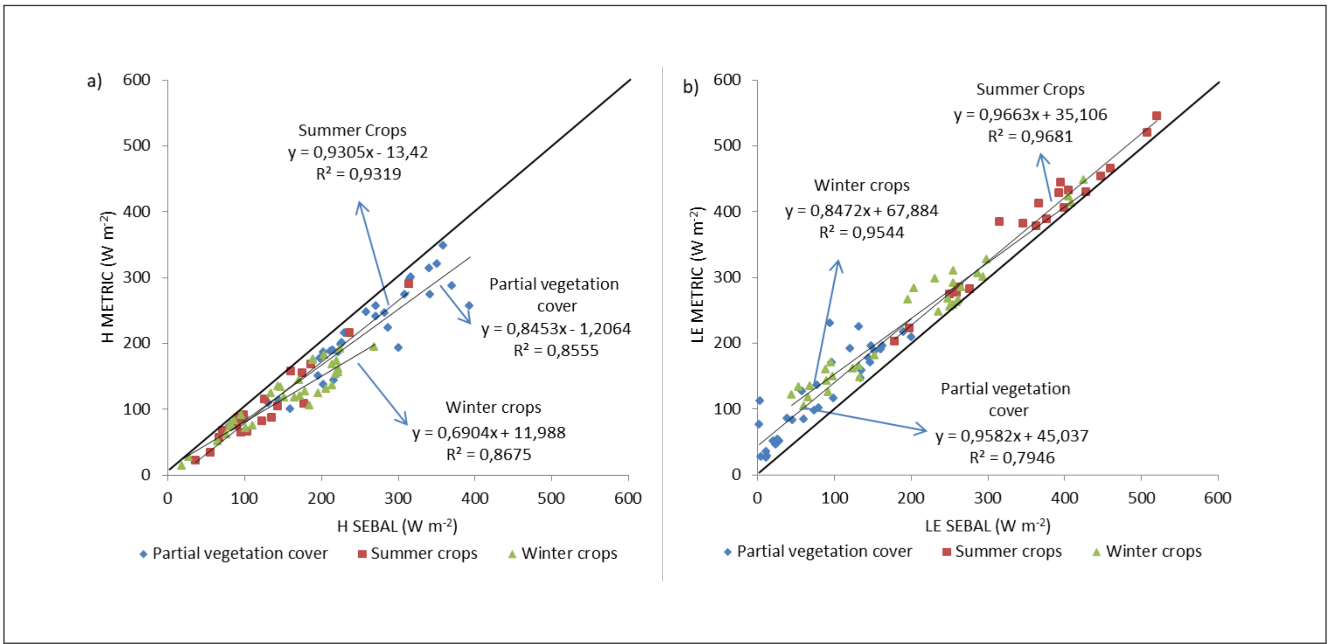
not observed in the micrometeorological station. For the SEBAL model, the inversion of the components lasted for a longer period until approximately the 230th day, with higher values compared to the METRIC model.

The inverted proportions observed in these periods show the difficulty of adjusting the parameters for determining the hot and cold pixels required by both models, consequently causing H to be overestimated. This difficulty arises from three main factors: a) the region humid climate makes it difficult to obtain the hot pixel; B) 1km spatial resolution of the image does not deliver pure pixels (pixel with 100% bare soil), and c) ecoclimatic conditions of Rio Grande do Sul characterizes high vegetation cover rates throughout the year. For the METRIC model, this deficiency extends for a shorter period, considering that the use of the soil water balance to determine the residual LE in the hot pixel aims to minimize this deficiency observed in the study.

The comparison of the results obtained from both models shows that dispersion between the H values of the SEBAL versus the METRIC model (Figure 6a) is very close to a straight line 1:1. The two models generated very close estimates for both H and LE. In the summer period, the dispersion of the H component had a 0.93 coefficient of determination while the values were lower, 0.86 and 0.87, for the winter crops and partial vegetation coverage periods, respectively. In this dispersion plot, practically all data points are below the straight line 1:1, showing that H was overestimated by the SEBAL model compared to METRIC.

Therefore, because LE is obtained as the residual term from the EB equation, the dispersion plot of the LE components obtained by both models (Figure 6b) shows the data points concentrated above the straight line

Figure 6. Dispersion graphs of LE and H components estimated by the SEBAL and METRIC models. Data extracted from window 3x3 pixels centered on station coordinates a) LE - Latent heat flux b) H - Sensitive heat flux. Statistics extracted in a 3x3 window from the images of the Cruz Alta experimental site analyzed over the 2009 to 2011 period.



1:1, so that the LE component is underestimated by the SEBAL model compared to METRIC. The coefficients of determination were 0.97, 0.95, and 0.79, respectively, for summer and winter crops, and partial vegetation cover.

Conclusions

The comparison between estimated values and reference measurements demonstrates that it is possible to use the images, with the temporal space resolution provided by the MODIS products, to characterize consistently the partition of the EB components and their variability throughout the year for both models.

The SEBAL and METRIC models performed similarly under Rio Grande do Sul conditions, yielding consistent results for summer and winter crops. Both models present, however, uncertainties regarding the correct partitioning of the H and LE components in periods of lower vegetation cover and energy availability.

The METRIC model yields results that are more consistent with the reference measurements. The assumptions of this model are formally more consistent for the ecoclimatic conditions of Rio Grande do Sul, since it allows determining the residual LE for the hot pixel. On the other hand, an additional effort is required, the daily calculation of soil water balance, which may be limiting since it depends on availability of continuous data for a long period, such as building a time series of the EB components.

Furthermore, the METRIC model is recommended to obtain the LE on a regional scale in the humid climate of Rio Grande do Sul for studies covering short time intervals with available data since the obtained results had higher consistency and smaller errors.

Acknowledgments

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Balanço de energia a partir de imagens em clima úmido – SEBAL e METRIC

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RESUMO

Tendo em vista importância da evapotranspiração no contexto agronômico, o objetivo do presente trabalho foi verificar a adequação dos modelos SEBAL e METRIC para estimar o fluxo de calor latente, a partir de dados de sensoriamento remoto, em áreas de cultivo de grãos nas condições de clima subtropical úmido na região noroeste do estado do Rio Grande do Sul. Esta região se destaca pela produção de grãos. A metodologia foi aplicada a um total de 84 datas distribuídas ao longo do período de 3 anos, abrangendo o cultivos de soja, milho, aveia, trigo e ervilhaca. Os dados estimados a partir de imagens remotas foram comparados com medidas de referências efetuadas em torre micrometeorológica utilizando a técnica de Eddy Covariance. Ambos os modelos apresentaram resultados satisfatórios. O modelo METRIC apresentou os menores erros nas estimativas de LE para os 3 tipos de cobertura do solo analisadas. Atribui-se o melhor desempenho do modelo METRIC ao fato de o mesmo não considerar a necessidade da condição hídrica extrema, ou seja, LE igual a zero, para a determinação do pixel quente no processo de estimativa do fluxo de calor sensível, como ocorre no modelo SEBAL.

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