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Source: Air, Soil and Water Research, 6(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/ASWR.S11364

Air, Soil and Water Research

ORIGINAL RESEARCH

Geothermal Dynamics in Vochysia Divergens Forest in a Brazilian Wetland

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Abstract: Research involving the thermal soil dynamics of wetland areas has not yet been explored in a way that promotes a deeper understanding of the dynamics of this region. This makes it necessary for further studies to contribute to the understanding of this biome. In the present work, we studied the thermal dynamics of the soil contrasting seasonal conditions in the Vochysia Divergens Forest. The Fourier equation was used to analyze the influence of the thermal conductivity and thermal gradient on the soil heat flux. We determined how variable water content causes the system to behave differently in the four seasons, observing seasonality in soil when completely dry and when completely flooded.

Keywords: soil heat flux, temperature gradient, thermal conductivity, Fourier`s equation

Air, Soil and Water Research 2013:6 47–52

doi: 10.4137/ASWR.S11364

Introduction

The determination of the distribution of matter and energy in ecosystems is of paramount importance for the characterization and understanding of a particular location; therefore, the part of the net radiation used in the soil heat flux has to be understood in order to improve the modeling of geothermal variables and parameters. Soil temperature affects microbial processes, influences the phenology of plants such as seed germination, and influences the diffusion of solutes and soil gases.

Knowledge of the geothermal flux variation induced by solar radiation in the upper layers is important for geosciences because these layers are the main stage for many geochemical processes such as weathering and lateralization and geophysical processes such as changes in values of thermal conductivity and thermal diffusivity of the material in the zone of aeration.[1]

The study was conducted in the Pantanal, which is one of the largest wetland systems in the world, stretching across western Brazil and parts of Bolivia and Paraguay. It comprises a range of tropical forest and savanna, and its geological formation consists of large alluvial plains and deltas in the Paraguay basin and forms a link between the Amazon biome, Savanna, Chaco, and Atlantic Forest.[2]

The flooding accompanies the rainy season in the Pantanal region, starting in October and ending between the months of February and May. July and August are characterized by the beginning of the period of extreme drought, often causing water stress in local vegetation, with only one portion of the Pantanal flooded throughout the year.

In the rainy season, there is a stream of water from the higher regions of the savanna to the lowest region in the Pantanal, increasing the volume of water trapped there. Due to the low slope of the site, the water in the rivers overflow, causing flooding and movement of sediment, which may dampen the daily soil temperature curve.

In studies of energy balance, the variation of heat flux in the forest soil environments is usually found to be small due to low values observed during the day,[3–6] but in the previous work by Bellaver[7] and Novais et al,[8] the presence of a water layer sparked interest in assessing the behavior of the energy flux in flooded soil.

The aim of this research was to analyze the geothermal dynamics in a Vochysia *divergens* forest in the Brazilian wetland under conditions of seasonal flooding.

Study Area Description

The study was conducted in an area located in the Private Reserve of Natural Heritage—RPPN SESC—Pantanal, municipality of Barão de Melgaço, estate of Mato Grosso Brazil, in which a 32 m high micrometeorological tower was installed (16 ° 39 ′50″ S, 56 ° 47′50″ W).

This area has vegetation monodominant *Vochysia divergens* Phol, known locally as cambarazal, with canopy heights ranging from 28 to 30 m.[9]

The soil is classified as Haplic Gleysol aluminate, which are mineral soils, hydromorphic presenting horizons A (mineral) or H (organic), followed by a horizon of gray-olive, greenish, or bluish, the result of changes suffered by iron oxides in the soil (decrease) in drenching conditions throughout the year or part thereof.[10]

The climate is Aw, corresponding to dry winters and rainy summers. The letter A corresponds to the humid tropical climate zone, characterized by tropical vegetation, with temperatures and relative humidity remaining high. The letter w corresponds to an average annual rainfall between 1000 and 1500 mm, with the driest month having less than 40 mm, on average. The average annual air temperature in RPPN SESC—Pantanal is between 22 °C and 32 °C, and the average annual rainfall is between 1100 and 1200 mm.

Materials and Methods

The micrometeorological tower has two Model L-108 (Campbell Scientific, Inc., Logan, Utah, USA) thermistors installed 0.03 m and 0.07 m deep, a fluximetter (Campbell HFT3 Soil Plate Heat Flux) at a depth of 0.05 m, a net radiometer (Kipp & Zonen Delft, Inc., Holland), and a model CR 10X datalogger (Campbell Scientific, Inc., Logan, Utah, USA).

Thermal conductivity K can be determined from Fourier's equation, according to which the heat flux density in the ground G (Wm^2) is proportional to the temperature gradient in the depth dT/dz ($°C\ m^{-1}$):[11]

$$G = -K\, dt/dz \tag{1}$$

Table 1. Mean values of soil thermal conductivity (*K*), soil heat flux (*G*), and temperature gradient (*dT/dz*) in periods of transition from wet to dry, dry, transition from dry to wet, and rainy.

	Trasition wet/dry	Dry	Trasition dry/wet	Wet
K (W · m^{-1} · °C^{-1})	1.12	0.78	1.15	1.75
G (W · m^{-2})	3.53	7.49	8.78	8.61
dT/dZ (°C · m^{-1})	5.84	19.42	16.39	9.84

$$K = -\frac{G}{dT/dz} \quad (2)$$

G = density of soil heat flux (W · m^{-2})
dT/dz = temperature gradient in the soil (°C · m^{-1})
K = thermal soil conductivity (W · m^{-1} · °C)

Using the equation, it is possible to analyze the heat flow and temperature gradient as well as observe how the variation influences the conductivity values.

For the analysis of soil thermal dynamics of the Pantanal, we used data collected in 2008 and 2009, and the data collected was divided into four periods according to the monthly accumulated rainfall: (1) April–May 2008, the transitional period between the rainy season and the dry season; (2) June, July, August, and September 2008, the dry season; (3) October and November 2008, the transition between the dry season and rainy season; and (4) December 2008 and January, February, and March 2009, the rainy season.

Results and Discussion

The average values of thermal conductivity (*K*), soil heat flux (*G*), and the temperature gradient (*dT/dz*) at the depths 0.03 and 0.07 are shown in Table 1.

When comparing the dry season with the rainy season, ignoring the transitions, there is a mean difference of 55.44%. The thermal conductivity decreases during the transition from rainy/dry to dry and then increases as it changes from the dry season to the rainy season. It is observed from Figure 1 and Table 1 that the thermal conductivity increases according to the start of the rainy season.

With the onset of rain, the soil floods with water filling in the voids, which promotes faster conduction of heat, as conduction through the water is faster than through air filled voids.[8]

Figure 1 presents an increase in the values of thermal conductivity and their maximum values from the month of November. With the onset of water flow, even with precipitation, the values begin to decline in February.

Increasing the soil temperature increases the kinetic energy of water molecules and causes dispersion. When the water content varies in the soil, there is a change in thermal conductivity, and a change in the temperature gradient.

With the same humidity, clay soils have a lower thermal conductivity than sandy soils, indicating that the density influences the conductivity value. Similarly, for the same soil type with the same density, increased water content increases the thermal conductivity.[12] When the soil surface begins to receive energy, this energy is transferred to the lower layers via conduction, and this clearly depends on the bonding between the atoms. If there is a variation in soil moisture, this reflects a variation in thermal conductivity and therefore affects the temperature distribution in the soil. There is an increase in thermal conductivity in soils with a higher moisture content because the empty spaces present in the structure of

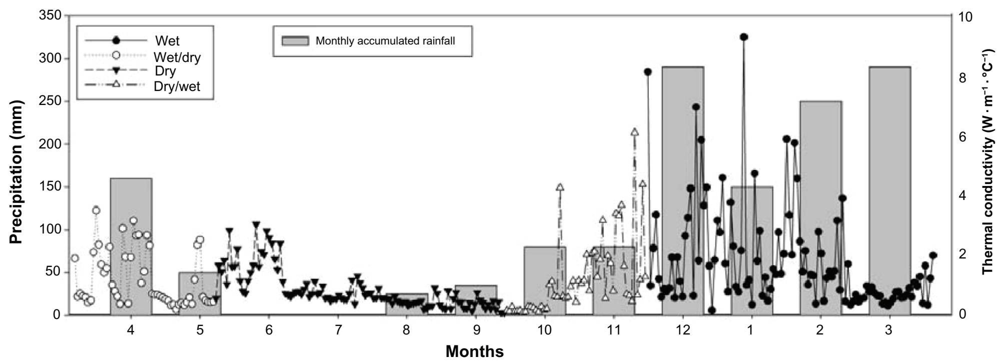

Figure 1. Soil thermal conductivity (*K*) between depths 0.03 m and 0.07 m, the transition period rainy/dry, dry, transition period dry/wet, rainy, and monthly accumulated rainfall in mm.

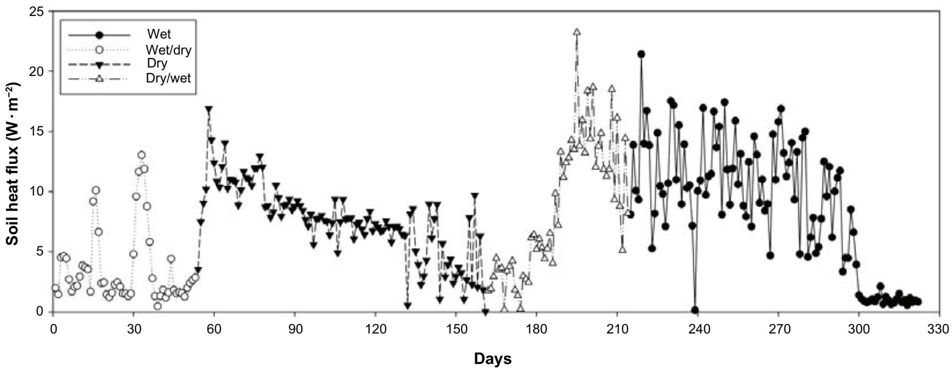

Figure 2. Soil heat flux between 0.03 m and 0.07 m.

the dry soil are filled by the water, which has a higher thermal conductivity.[13]

The higher the thermal conductivity is, the lower the surface temperature variation and the greater the heat storage. The thermal conductivity depends on soil texture, porosity, and moisture. So the moisture content is a factor that significantly affects the thermal conductivity of the soil.[8,14]

When comparing the mean soil heat flux in the rainy season with the dry season (Fig. 2), there is a difference of 13.03%. The higher net radiation with the increased thermal conductivity increases the heat flux of the soil during the rainy season when compared with the dry season. The transition period between rainy season to dry season showed the lowest values of heat flux in the soil.

Although the large difference in thermal conductivity between the seasons (Fig. 1), the soil heat flux (Fig. 2) did not show much variation between the dry and rainy seasons. This variation was caused by the fact that in the dry season, water scarcity means that the portion of energy for the latent heat is reduced when compared with the sensible heat flux and soil heat flux.

Another factor influencing the values of thermal conductivity was the temperature gradient (Fig. 3). Unlike the thermal conductivity and soil heat flux, the thermal gradient had maximum values during the dry season, an increase of 49.3% over the rainy season. This is explained by the fact that during the rainy season, much of the solar radiation incident on the surface is consumed as latent heat of evaporation in the tropical region.[15]

The high value of the latent heat of water, 540 cal/g, means that large amounts of energy is consumed by ground water evaporation and, thus, during the dry season, the absence of water means that this energy is available to heat the soil, resulting in a higher temperature variation with depth. The largest temperature gradient was observed in the dry season, 19.42 °C/m, a value that decreased as the incidence of rainfall increased (Fig. 1) until reaching its lowest value in the transition from dry to rainy season, 5.84 °C/m.

Another contribution to raising the thermal gradient in the dry season is the difference between the specific heat of water and soil. As the soil has a much

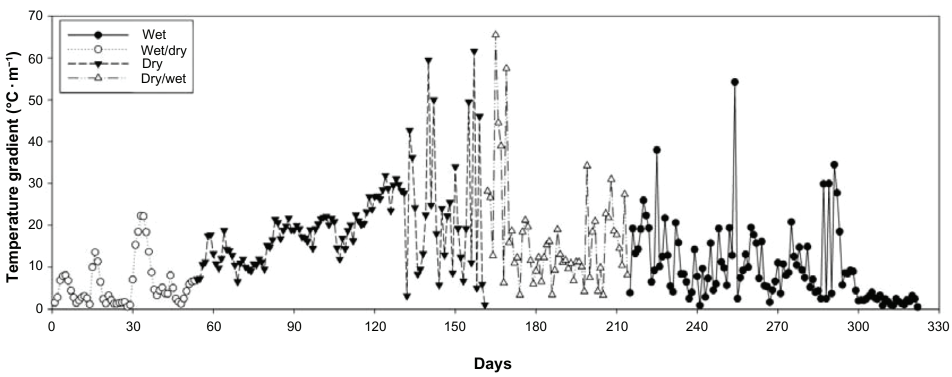

Figure 3. Temperature gradient betwen 0.03 m and 0.07 m.

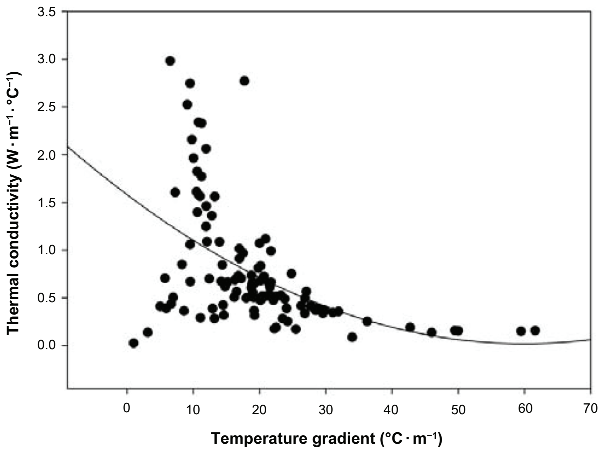

Figure 4. Linear regression between thermal conductivity and temperature gradient in dry season.

lower specific heat than water, the same amount of solar radiation will cause a significantly larger increase in the temperature of the dry soil at the surface.

The absence of water in soil hinders the soil heat flux, making it difficult for the soil surface layer to conduct heat to the lower layers, providing a greater temperature gradient, which consequently makes the mean temperature gradient of the dry season larger than the rainy season.

According to Equation (2), the temperature gradient (*dT/dz*) is in the denominator, therefore, increasing the thermal gradient (Fig. 3) and causing a decrease in thermal conductivity of the soil (Fig. 1).

To analyze the behavior of the temperature gradient in relation to thermal conductivity, two regression charts for the dry and rainy seasons were made (Figs. 4 and 5).

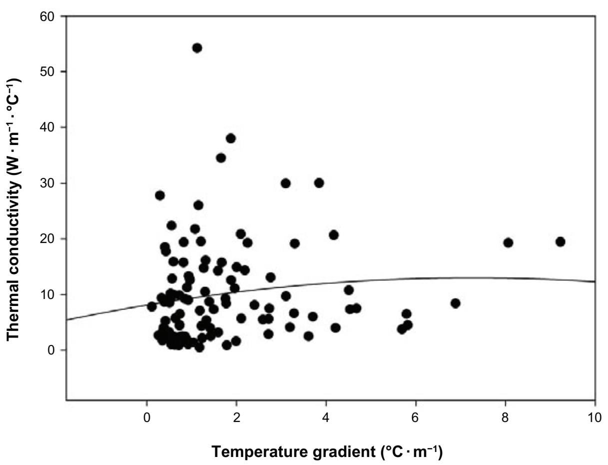

Figure 5. Linear regression between thermal conductivity and temperature gradient in rainy season.

Note in Figure 4 that where the temperature gradients are greater than 20 °C · m^{-1}, the values of thermal conductivity tend to a constant; considerations can be made to the value of thermal conductivity of the Cambará forest soil during the dry season by about 0.3 $Wm^{-1} \cdot C^{-1}$. This tendency is explained by the sensitivity of the thermal conductivity small temperature gradients according Equation (2).

However, during the rainy season it is difficult to find a constant value for the thermal conductivity due to variations in water content in the soil and global radiation.

Conclusion

The flood surge in the Pantanal causes great variability in the geothermal dynamic during the year. The pores of the soil were completely filled with water, facilitating heat transfer, during the rainy season, unlike during the dry season where the presence of air in the pores hinders heat conduction. The variable water content causes the system to behave differently in the different seasons with the most extreme variation between completely dry and completely flooded, which was confirmed by the analysis performed in this study.

Acknowledgements

We thank the Postgraduate program in Environmental Physics at supporting research.

Author Contributions

Conceived and designed the experiments: JWZN, TRR, JSN. Analyzed the data: JWZN, SRP, LFAC. Wrote the first draft of the manuscript: JWZN, LFAC. RGO, AGO. Contributed to the writing of the manuscript: JWZN, TRR, JSN. LFAC. RGO, AGO, SRP. Agree with manuscript results and conclusions: JWZN, TRR, JSN. LFAC. RGO, AGO, SRP. Jointly developed the structure and arguments for the paper: JWZN, TRR, JSN. LFAC. RGO, AGO, SRP. Made critical revisions and approved final version: JWZN, TRR, JSN. LFAC. RGO, AGO, SRP. All authors reviewed and approved of the final manuscript. JWZN, TRR, JSN. LFAC. RGO, AGO, SRP.

Funding

The authors thank Coordenação de Aperfeiçoamento de Pessoal do Ensino Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for Scholarship and Fundo de Amparo a Pesquisa do Estado de Mato Grosso (FAPEMAT) through the Support Program for Centers of Excellence (PRONEX) for financial support to the research project process no. 823971/.

Competing Interests

Author(s) disclose no potential conflicts of interest.

Disclosures and Ethics

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