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Temporal and Spatial Variability of Soil-Vegetation Variables in the West Region of Santa Catarina State

Variabilidade Temporal e Espacial das Variáveis de Solo-Vegetação na Região Oeste do Estado de Santa Catarina

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Abstract

Western region of the State of Santa Catarina (SC) has suffered several episodes of drought that impact vegetation, agricultural production and water availability. This study aimed to evaluate the spatial and temporal variability of soil-vegetation variables in the Western SC region. Monthly data of evapotranspiration, precipitation, radiation, air and soil moisture and temperature were obtained from the NASA-funded Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS). Evapotranspiration anomalies showed that the years 2015 and 2020 had the lowest values in the last years, i.e., between 1990 to 2022. Precipitation had greater variability in recent years, having months of high rainfall combined with periods of severe drought. Xanxerê city region demonstrated that the year 2020 presented records of low precipitation, evapotranspiration, soil moisture and NDVI, compared to the entire time series. Spatial correlation of the evapotranspiration controlling variables showed that precipitation, air temperature and humidity, and short-wave radiation presented variable correlations in different regions of SC. However, soil moisture had the highest positive correlation in the entire territory, demonstrating that this is the main controlling variable of local evapotranspiration. Therefore, soil moisture is an indicator of the vegetation transpiration importance in the latent heat fluxes. Equivalent water thickness obtained from the GRACE satellite showed that after a maximum occurred in December 2015, its magnitudes steadily decreased, reaching very low groundwater values in 2022. This trend represents a 3.3 mm decrease per year. These results suggest that the region is undergoing a change in these soil-vegetation variables that needs to be better monitored and understood.

Keywords: Evapotranspiration; Soil moisture; FLDAS

Resumo

A região oeste do estado de Santa Catarina (SC) tem sofrido vários episódios de estiagem que impacta a vegetação, a produção agrícola e a disponibilidade de água. Este estudo teve como objetivo avaliar a variabilidade espacial e temporal das variáveis de solo-vegetação na região oeste de SC. Dados mensais de variáveis como evapotranspiração, precipitação, radiação, umidade e temperatura do ar e do solo foram obtidos do projeto Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) subsidiado pela NASA. O estudo teve como foco a região oeste de SC. Anomalias de evapotranspiração mostram que os anos de 2015 e 2020 apresentaram os valores mais baixos dos últimos anos, ou seja, entre 1990 a 2022. Dados de precipitação mostram maior variabilidade nos últimos anos apresentando meses de alta precipitação combinados com períodos de forte estiagem. A região do município de Xanxerê mostrou que o ano de 2020 apresentou recordes de baixa precipitação, evapotranspiração, umidade de solo e NDVI, comparados a toda série temporal. Correlação espacial das variáveis controladoras da evapotranspiração, mostraram que precipitação, temperatura e umidade do ar, e radiação de onda curta apresentam correlações variáveis nas diferentes regiões de SC. No entanto, a umidade do solo apresentou a mais alta correlação positiva em todo território, mostrando ser esta a principal variável controladora da evapotranspiração local. Portanto, a umidade do solo é um indicador da importância da transpiração da vegetação nos fluxos de calor latente. Dados da espessura de água equivalente obtidos pelo satélite GRACE mostraram que após um máximo ocorrido em dezembro de 2015 suas magnitudes diminuíram constantemente atingindo valores muito baixos de água de sub-solo em 2022. Esta tendência corresponde um decréscimo de 3,3 mm por ano. Estes resultados sugerem que a região está sofrendo uma mudança nestas variáveis de solo-vegetação que precisam ser melhor monitorados e compreendidos.

Palavras-chave: Evapotranspiração; Umidade do solo; FLDAS

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1 Introduction

The hydrological cycle has several dynamic physical processes that constantly changes the major water storages. The vegetation has a fundamental importance on controlling the fluxes between the surface and the atmosphere, for instance through the evapotranspiration. Extreme changes in the energy and water cycle in this land-atmosphere interface can impact several important resources such as the water availability, the agricultural production and the food availability.

Recent results from the IPCC reports show that the hydrological cycle is likely to suffer a higher frequency of extremes in the coming decades (IPCC 2021). Annually, the American Meteorological Society (AMS) publish a synthesis of extreme events from a climate perspective (Herring et al. 2022, 2023). In these annual bulletins, selected articles explore the insights on the causes of climate extremes that may have occurred on several regions of the globe.

Extreme events may be defined as anomalies from a historical meteorological or climate data series. In general, it is estimated considering some upper and lower limits thresholds from the historical records. It may assume for instance, a percentage (e.g., 5% or 10%) threshold high or low from historical observations. Some special events such as heat waves and droughts have specific thresholds definitions. It can also be defined from an unprecedent event anomaly as compared to a past previous observed record (Seneviratne et al. 2012).

Since the extreme events can cause strong damages, economic losses and fatalities, improving the knowledge of its causes is today a challenging scientific problem. A major question is to understand if such events may become more frequent and stronger in the coming decades. Some events in the South America may have influence from the modes of climate variability (Grimm et al. 2020; Kayano, Andreoli & de Souza 2020). Also, there is today several research groups studying the influence of the global warming on the extreme events (Herring et al. 2022, 2023). Thus, detecting the recent occurrences of these extreme events can help us to better estimate their possible recurrence in the coming years.

In the recent years, several satellite new platforms have been placed in orbit and thus, many new data is available globally in higher spatial and temporal resolution. These new data combined with land surface models (LSM) have provided important global hydro-meteorological maps (McNally et al. 2017). A new program supported by the National Science Administration (NASA) was recently developed in order to build a global soil-vegetation variables dataset. This program named Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) combines a LSM model with observed and remote sensing data to calculate several soil-vegetation variables, such as evapotranspiration and soil moisture (McNally et al. 2017). The system uses satellite data retrievals and observed precipitation data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset (Funk et al. 2015).

LSMs implementation are important for several reasons. For instance, they can estimate the sub-grid scales at the land-atmosphere interface. Furthermore, at this interface they provide important fluxes for the entire boundary layer (about 1 km height) that has an impact on the shallow clouds formation and mesoscale meteorological systems development. The high spatial heterogeneity of soil moisture, temperature, vegetation fraction and land cover change cause high complexity and variability on the near surface atmospheric boundary. In general, LSMs provide four variables to the atmosphere: sensible and latent flux, upward long wave radiation and reflected short wave radiation. At the interface, diffusivity of momentum, heat and water vapor is an important physical process of transfer (Chen et al. 1996).

A widely used example of LSM is the Noah model (Chen & Duddia 2001; Ek et al. 2003). Noah is a state-of-the-art system that model the major biophysical, hydrological, and bio-geochemical interactions between the land-surface and the atmosphere. Noah simulates several variables such as, soil moisture, soil temperature, skin temperature, canopy water content, and the energy and water fluxes. The model can run forced with observed data or coupled to an atmospheric model system. This LSM model is now broadly used and coupled to several atmospheric models. The FLDAS NASA program has incorporated Noah model into its system in order to provide several soil-vegetation variables.

Along with LSM, water balance models have been incorporated also in order to account for the water availability. An applied state-of-the-art model that accounts for this balance is the Variable Infiltration Capacity (VIC) model (Hamman et al. 2018). The FLDAS NASA program has also incorporated VIC into its core system.

Vegetation vigor and leaf area can be estimated by satellite data based on the absorption of red light and the reflection of near-infra-red light. Today, several satellite platforms can retrieve in these channels, such as the Landsat series, Terra and Aqua satellites, for instance. Based on these sensor bands it is possible to estimate the Normalized Difference Vegetation Index (NDVI) (Jackson & Huete 1991). Dry and wet periods can then be monitored by the NDVI evolution on space and time.

During dry years vegetation and humans usually take water from the sub-surface soil layers. Thus, estimate this water cycle storage variability is of great importance. In order to map the mass of subsurface water a new approach using remote sensing was developed. This system named Gravity Recovery & Climate Experiment (GRACE) uses a pair of satellites in near approach orbit and from the surface gravity force, it can estimate the local equivalent water thickness variability (Landerer & Swenson 2012; Wahr, Molenaar & Bryan 1998). Recent studies show that monitoring the sub-surface water from this approach is a promising tool for evaluation of the water table and aquifers variability and trends (Castle et al. 2014; Rodell, Velicogna & Famiglietti 2009; Vasco et al. 2022).

The western region of the Santa Catarina state has suffered several episodes of drought periods (Freitas & Oliveira 2017). At this region, cities such as Chapecó and Xanxerê have their economies strongly dependent of the climate regimes and water availability. Drought periods at this region has impacted the economy mainly for the agriculture farmers (Spinelli 2018). A deep study of the major variables associated with these dry episodes were not yet developed for this region.

This study aimed to evaluate the spatial and temporal variability of soil-vegetation variables in the western region of Santa Catarina State. The analysis was performed for the last three decades, as it includes the satellite data assimilation on the global soil-vegetation variables dataset. The location around the city of Xanxerê was chosen as a proxy for better understand the local temporal changes on these variables.

2 Methodology and Data

Presented below are a description of the study region, the major dataset and methods applied to evaluate the spatial and temporal variability of the soil vegetation variables for the SC study region.

2.1 Study Area

The study areas comprised the state of Santa Catarina (SC) and nearby regions (Figure 1). A special time series analysis was performed for the city of Xanxerê-SC region located at the west of SC (26.9S; 52.4W), in order to evaluate the time variability of soil-vegetation variables. Spatial correlation maps were constructed in order to investigate the major variable impacts on the evapotranspiration fluxes over the region. The correlation maps were estimated using a simple linear regression between two variables over time within each grid cell. These correlation analyses can be done straightforward at the *giovanni* NASA portal dataset and then post-processed.

2.2 FLDAS Soil-vegetation Data

The monthly soil-vegetation variables were obtained from the FLDAS dataset. The major analyzed variables were evapotranspiration, precipitation, radiation, and air and soil moisture. This dataset is available globally at spatial resolution of 0.1 degree (latitude-longitude) for the period from 1982 up to present day (McNally 2018). The methods to the establishment of this dataset are fully described by

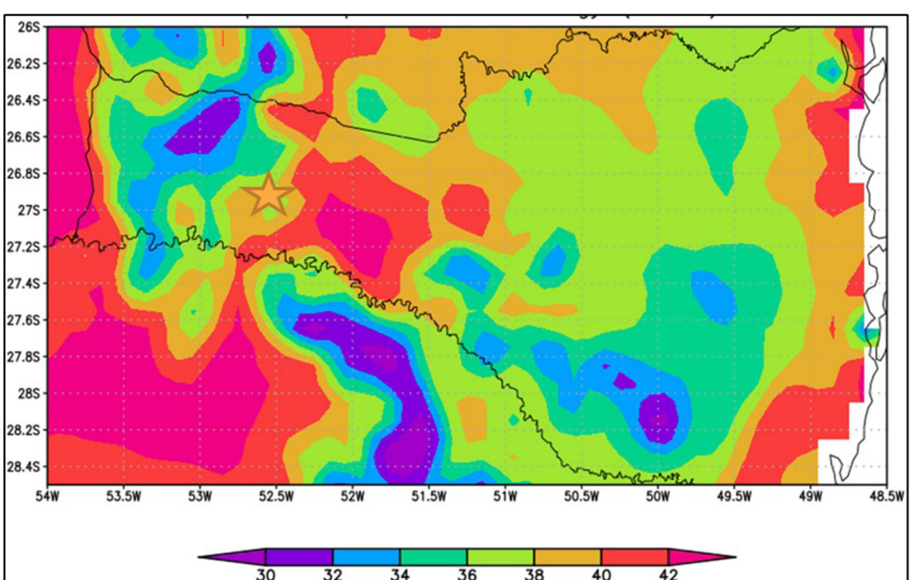

Figure 1 Evapotranspiration (mm/s) climatology (1982-2021). The star at the west region shows the Xanxerê-SC city location.

McNally et al. (2017) and can be obtained at the NASA portal (https://lis.gsfc.nasa.gov/projects/fewsnet/data) and the Google engine cloud data bank. Table 1 presents the major specifications of the FLDAS system and Figure 2 shows a diagram with the main features that describes its methodological procedures. Monthly anomalies were also downloaded from the FLDAS dataset. They are estimated for each grid point from the difference between the monthly data and the monthly climatology that is computed for the period between 1982 and 2016.

2.3 NDVI Data

The NDVI index were obtained by estimates from the Landsat satellite images. This Landsat series uses the satellites 4 to 8 and provides data on a 30 meters grid cell. This index is available globally since 2000 up to recent days. The NDVI index were then analyzed to estimate the vegetation variability. Time series were specially analyzed over the western region of SC for the Xanxerê-SC. This NDVI dataset is freely available at google engine cloud data and *giovanni* NASA portal.

2.4 GRACE Water Thickness Data

The underground water thickness changes estimates were obtained from GRACE. monthly land data. The available computed thickness is obtained relative to a time-mean baseline (Wahr, Molenaar & Bryan 1998). This global dataset is freely available from JPL NASA at http://grace.jpl.nasa.gov, supported by the NASA MEaSUREs Program. This data is available globally from 2002 up to today. Time series area averaged was computed over the Xanxerê-SC region in order to evaluate the local underground water mass variability.

Table 1 FLDAS dataset description parameters.

Parameter	Description
Soil model	LIS7.3 Noah3.6
Spatial Extent	Global (179.95W, 59.95S; 179.95E, 89.95N)
Spatial Resolution*	0.1 degree (10km)
Temporal Resolution**	15-minute time steps, daily output
Forcing	satellite measurements (CHIRPS rain, MERRA2)
Forcing Heights	2 m air temperature and humidity, 10 m wind
Elevation Definition	SRTM
Vegetation Definition	NCEP-modified IGBP(MODIS), 1 km
Soils Definition	Reynolds, Jackson & Rawls (2000)
Albedo	monthly climatology, NCEP_Native
Soil Texture	STATSGOFAO
Soil layers: 4	0-0.1 m, 0.1-0.4 m, 0.4-1.0 m, 1.0-2.0 m

Source: McNally (2018).

2.5 Summary and Further Details

In summary, the monthly land-surface variables such as evapotranspiration, soil and air moisture, soil and air temperature, radiation and precipitation were obtained from the FLDAS NASA dataset. Also, vegetation index (NDVI) was adopted from the estimates by the Landsat images. Furthermore, underground land water amount was obtained from the GRACE project.

Variables such as evapotranspiration, precipitation, soil moisture, NDVI index and water thickness were averaged over the area within 26S-27S latitudes and 52W-53W longitudes to construct the time series evolution. This corresponds to the location of the city of Xanxere-SC region and is a proxy for the western SC variability. The anomalies for evapotranspiration, precipitation and soil moisture were then computed from the analyzed period in order to evaluate possible extreme events.

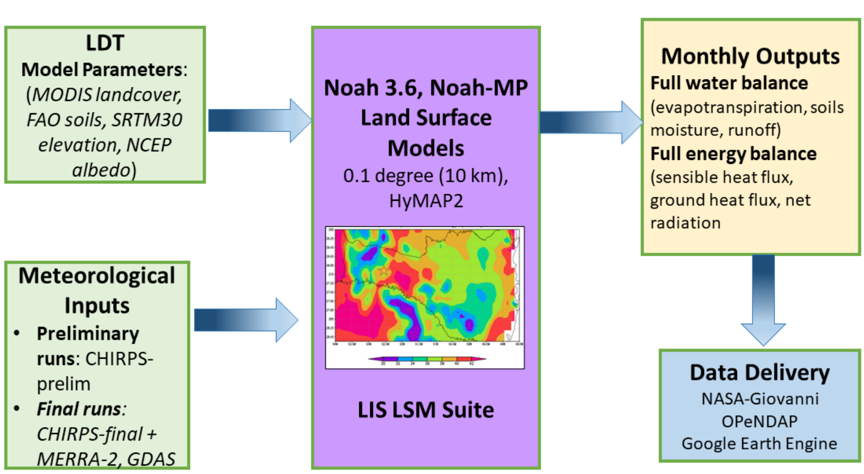

Figure 2 FLDAS diagram showing the major source, the model setup and output options. Adapted from McNally (2018).

3 Results

The evapotranspiration climatology for the study region is shown at Figure 1. This climatological map corresponds to data for the period between 1982 and 2021. The results show a higher evapotranspiration over the western of the domain over the Argentina and the Rio Grande do Sul state and at the eastern region near the coast. The distribution of evapotranspiration can be associated with distribution of precipitation and vegetation cover. For instance, in the state of Santa Catarina higher evapotranspiration over the center west and over the east coast can be associated with distribution of precipitation. The Climatological Atlas show higher precipitation on these locations as compared to other regions of the state (Pandolfo et al. 2002). At the east coast beyond higher precipitation, there is the presence of the Atlantic Forest that can contribute to transpiration. A previous evapotranspiration Atlas for the state of Santa Catarina shows similar pattern of distribution (Pandolfo et al. 2002).

Figure 3 shows map correlations between evapotranspiration and several land-surface variables in order to investigate their influence on the evapotranspiration variability. The results show that the soil moisture has the strongest correlation highlighting that this variable is the major controlling factor of evapotranspiration at this region.

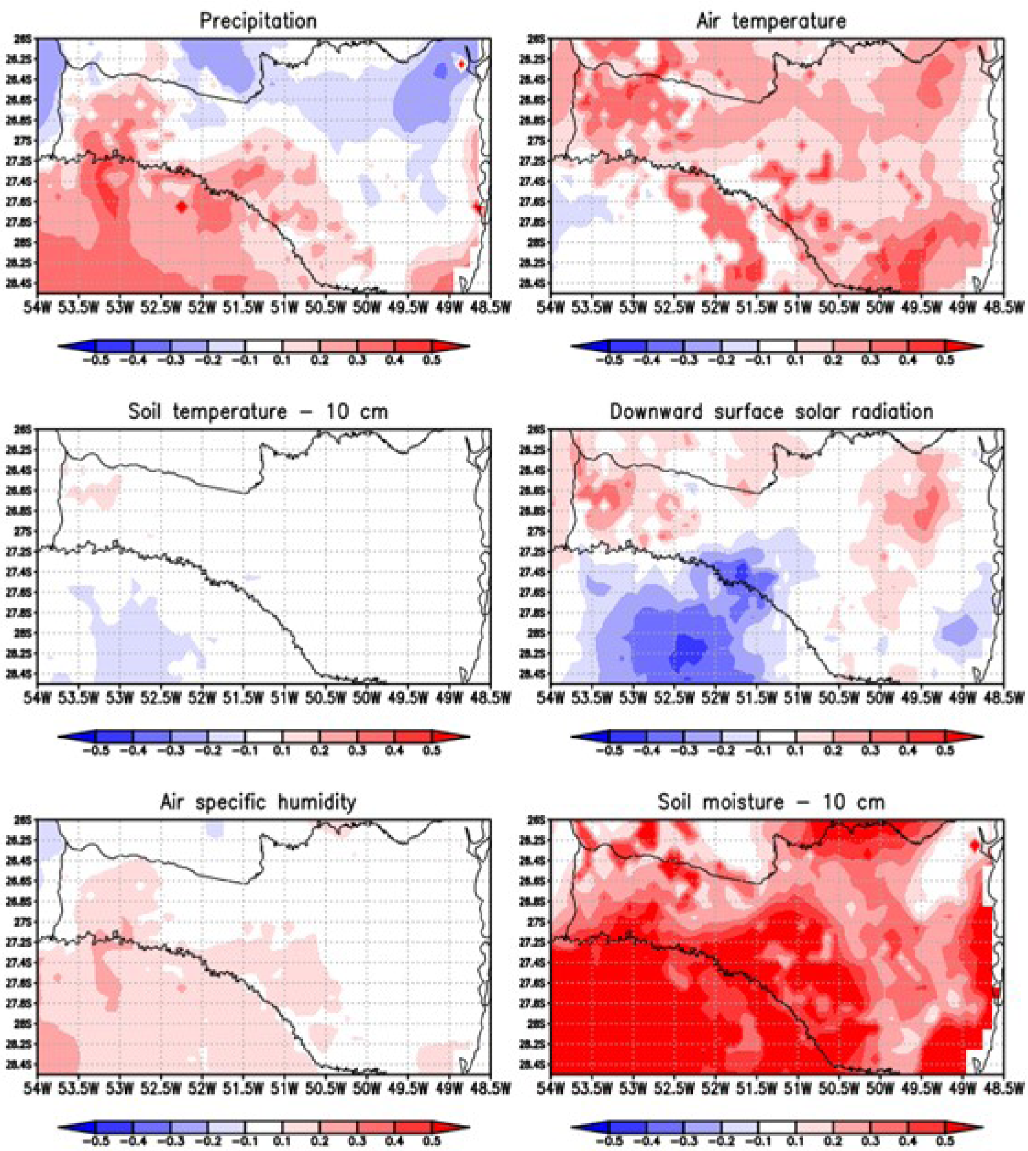

Figure 3 Temporal correlation for each grid point between evapotranspiration and the land-surface variables.

Figure 4 shows the spatial averaged evapotranspiration anomaly time evolution over the Xanxerê region. The results show that this western region suffered lower anomaly records of evapotranspiration during December 2015 (-1.39×10^{-5} mm/s) and November 2020 (-1.06×10^{-5} mm/s). The results show also a recent longer sequence of negative anomalies. During the years of 2020 and 2021 there was 19 months with negative anomalies. These anomalies suggest that the region is undergoing environmental changes not measured on the previous recorded years.

Figure 5 shows the spatial averaged accumulated precipitation anomalies at the Xanxerê nearby region. The results show that this western location is suffering a series of extreme events. The region had anomaly records of high precipitation in June 2014 ($+11.9 \times 10^{-5}$ mm/s) and lower records in October 2020 (-7.0×10^{-5} mm/s) and April 2021 (-6.2×10^{-5} mm/s). A recent study for this region shows a possible influence of combined modes of climate variability for the drought conditions of 2020 (Grimm et al. 2020). These conditions include occurrence of a La Niña pattern, a positive Atlantic Multidecadal Oscillation (AMO) and a negative Interdecadal Pacific Oscillation (IPO).

Further analysis for the local evolution of soil moisture content is presented at Figure 6. The results show that soil moisture reached the lower values in recent years as compared to the previous decades. It decreased

Figure 4 Time series, area-averaged total and anomaly evapotranspiration (mm/s) evolution at Xanxerê-SC region based on the FLDAS estimates.

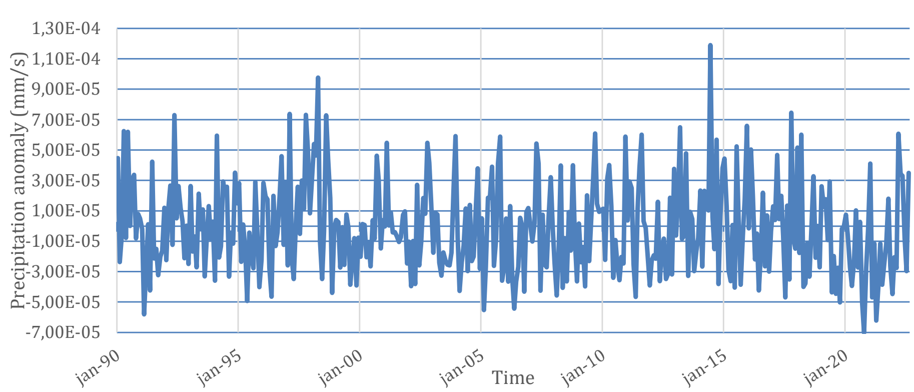

Figure 5 Time series of the area-averaged anomaly precipitation (mm/s) evolution at Xanxerê-SC region based on the FLDAS-CHIRPS estimates.

constantly since 2020 reaching the lowest moisture content at the layer near the surface (0-10 cm) in May 2021 (0.27 m^3m^{-3}) and in February 2022 (0.29 m^3m^{-3}). This recorded low measurement is about 10% lower than the lowest observation made in March 1991 (0.30 m^3m^{-3}). Similar anomalies were observed on the deeper layer (40-100 cm). In this layer, it was observed lower values in May 2021 (0.27 m^3m^{-3}) and in February 2022 (0.26 m^3m^{-3}). It also, corresponded to about 10% decrease on the lowest observation from March 1991 (0.29 m^3m^{-3}).

Figure 7 shows the NDVI index for the western region of SC based on Landsat high resolution images around the city of Xanxerê-SC surroundings. The time-series evolution for this region shows that in the recent years the index reached its lower records. Very low NDVI index was recorded in November 2007, November 2015 and September 2020, reaching only 0.23, 0.19 and 0.46, respectively. Therefore, these low NDVI index may affect the local evapotranspiration fluxes and the water cycle.

Figure 8A shows the water equivalent thickness around Xanxere-SC as obtained from GRACE. It reached a maximum of 31.91 cm in December 2015. After then, it decreased constantly reaching a minimum of -12.91 cm in Abril 2020, -5.65 cm in April 2021 and -13.13 cm in January 2022. A linear trend obtained from a 25 cm decrease for the period between December 2015 and February 2022 represents a negative trend of 3.3 mm per year (Figure 8B).

4 Conclusion and Final Remarks

Analysis of the soil vegetation variables for the state of Santa Catarina suggest that the western region of the state is undergoing changes in these variables with more frequent cases of extremes. More specifically near the Xanxarê city located at this western region shows several extreme events, including: periods of extremes (positive and negative anomalies) of precipitation; lower records of evapotranspiration fluxes, soil moisture and NDVI index.

Soil moisture shows the strongest influence (correlation) on the evapotranspiration fluxes. It implies that a decrease on the local evapotranspiration lower the atmospheric latent heat fluxes and therefore has negative influence on clouds formation (Ramos-da-Silva, Werth & Avissar 2008). Thus, it can maintain positive feedback during dry periods having lower soil moisture and evapotranspiration.

GRACE satellite underground water mass shows a local decrease in the last years since 2016. Dry periods with lower precipitation and local demand for water

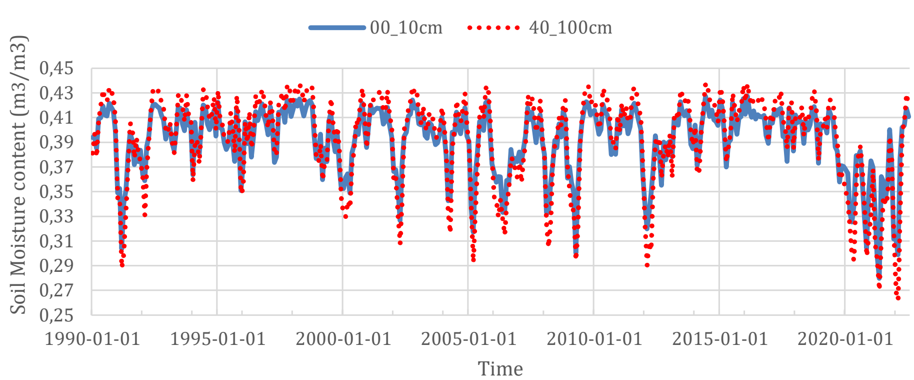

Figure 6 Time series of the area averaged soil moisture content (0-10 cm and 40-100 cm) underground layers ($m^3.m^{-3}$) evolution at Xanxerê-SC region based on FLDAS estimates.

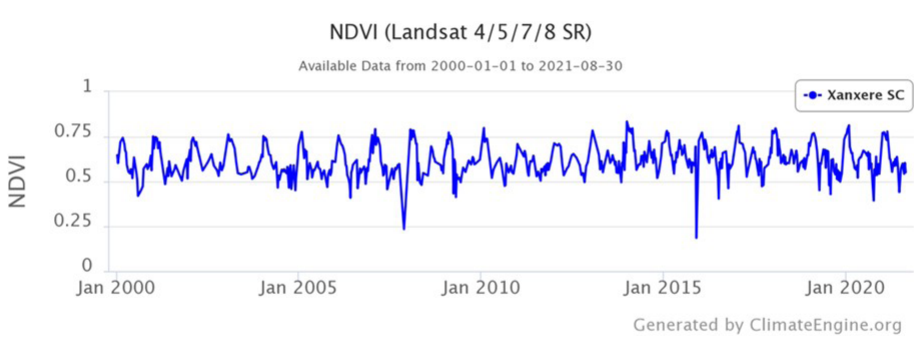

Figure 7 NDVI index from Landsat satellite images time series spatial averaged for the city of Xanxerê-SC for 2000 to 2020.

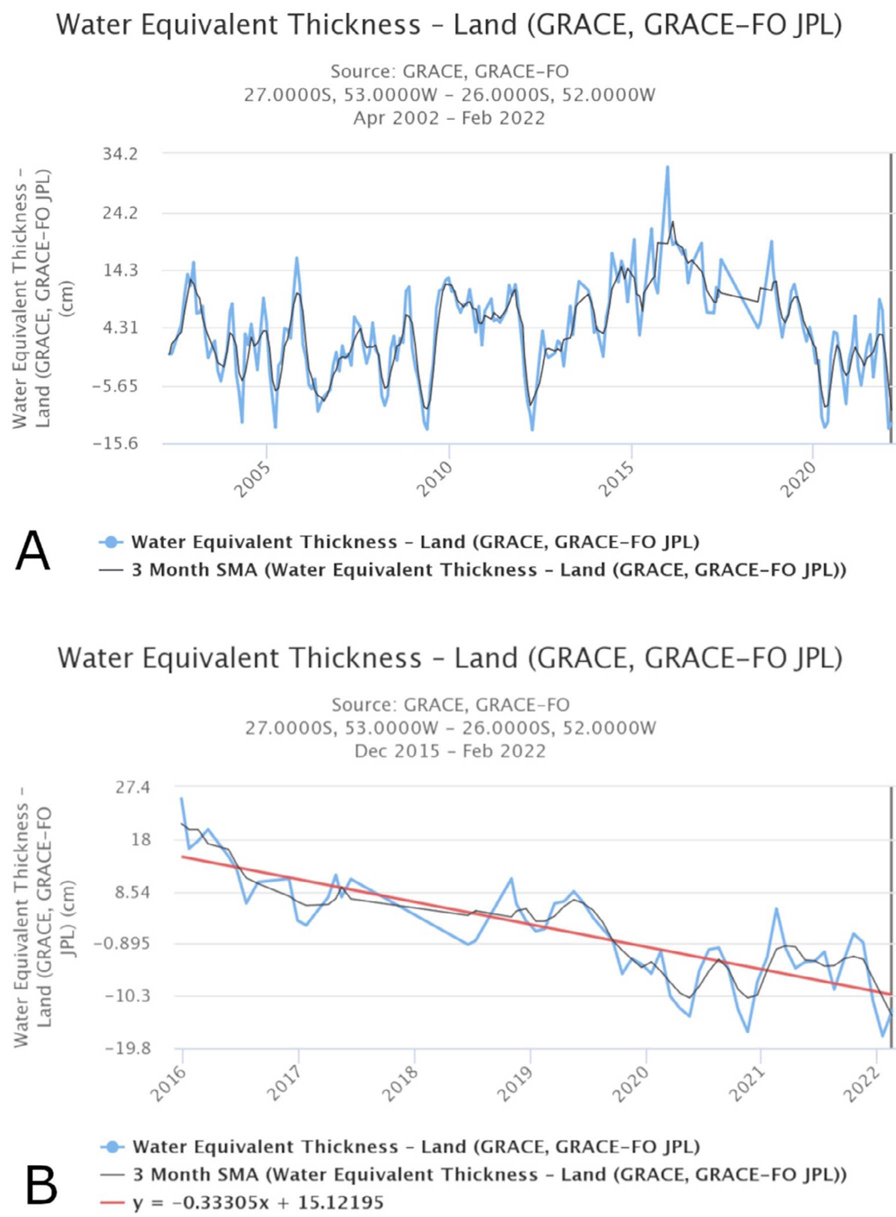

Figure 8 A. Monthly water equivalent thickness (cm) from GRACE; B. Subset for the period 2016-2022.

supply has induced to local sub-surface water exploration. Today, there is a negative local trend of 3.3 mm per year. Other regions show similar decrease mainly due to strong pumping during dry periods (Castle et al. 2014; Rodell, Velicogna & Famiglietti 2009; Vasco et al. 2022). This local subsurface water decreases shows that this storage has to be continuously monitored, as it is fundamental for the agriculture, the economy and local society.

The methodology conduced for this particular region of the western SC can be applied for other regions of interest. The ongoing climate change is affecting several regions of the globe (Herring et al. 2022, 2023). Thus, the application of these land-surface type of analysis and monitoring will be of greater importance in the coming years. Also, further studies should be conducted to help improving our understand if climate change is affecting the occurrence of extreme events in the region.

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6 References

Castle, S.L., Thomas, B.F., Reager, J.T., Rodell, M., Swenson, S.C. & Famiglietti, J.S. 2014, 'Groundwater depletion during drought threatens future water security of the Colorado River Basin', *Geophysical Research. Letters*, vol. 1, no. 16, pp. 5904–11, DOI:10.1002/2014GL061055.

Chen, F. & Dudhia J. 2001, 'Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity', *Monthly Weather Review*, vol. 129, no. 4, pp. 569-85, DOI:10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2.

Chen, F., Mitchell, K., Schaake, J., Xue, Y., Pan, H., Koren, V., Duan, Y., Ek, M. & Betts, A. 1996, 'Modeling of land-surface evaporation by four schemes and comparison with FIFE observations', *Journal of Geophysical Research Atmospheres*, vol. 101, pp. 7251-68, DOI:10.1029/95JD02165.

Ek, M.B., Mitchell, K.E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G. & Tarpley, J.D. 2003, 'Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model', *Journal of Geophysical Research Atmospheres,* vol. 108, no. D22, e8851, DOI:10.1029/2002JD003296.

Freitas, M.J.C.C. & Oliveira, F.H. 2017, *Estiagem no Oeste Catarinense: diagnóstico e resiliência*, Florianópolis, viewed 25 February 2023, <https://www.defesacivil.sc.gov.br/images/ESTIAGEM_NO_OESTE_miolo_180417.pdf>

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. 2015, 'The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes', *Scientific Data,* vol. 2, e150066, DOI:10.1038/sdata.2015.66.

Grimm, A.M., Almeida, A.S., Beneti, C.A.A. & Leite, E.A. 2020, 'The combined effect of climate oscillations in producing extremes: the 2020 drought in southern Brazil' *Brazilian Journal of Water Resources*, vol. 25, e48, DOI:10.1590/2318-0331.252020200116.

Hamman, J.J., Nijssen, B., Bohn, T.J., Gergel, D.R. & Mao, Y. 2018, 'The Variable Infiltration Capacity model version 5 (VIC-5): infrastructure improvements for new applications and reproducibility', *Geoscientific Model Development*, vol. 11, no. 8, pp. 3481–96, DOI:10.5194/gmd-11-3481-2018.

Herring, S.C., Christidis, N., Hoell, A., Hoerling, M.P. & Stott, P.A. 2022, 'Explaining Extreme Events of 2020 from a Climate Perspective', *Bulletin of the American Meteorological Society*, vol. 103, no. 3, DOI:10.1175/BAMS-ExplainingExtremeEvents2020.1.

Herring, S.C., Christidis, N., Hoell, A., Hoerling, M.P. & Stott, P.A. 2023, *Explaining Extreme Events of 2021 and 2022 from a Climate Perspective*, viewed 16 January 2022, <https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/>.

IPCC 2021, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, viewed 25 February 2023, <https://www.ipcc.ch/report/ar6/wg1/>.

Jackson, R.D. & Huete, A.R. 1991, 'Interpreting vegetation indices', *Preventive Veterinary Medicine,* vol. 11, no. 3-4, pp. 185-200, DOI:10.1016/S0167-5877(05)80004-2.

Kayano, M.T., Andreoli, R.V. & de Souza, R.A.F. 2020, 'Pacific and Atlantic multidecadal variability relations to the El Niño events and their effects on the South American rainfall', *International Journal of Climatology*, vol. 40, no. 4, pp. 2183–2200, DOI:10.1002/joc.6326.

Landerer, F.W. & Swenson, S.C. 2012, 'Accuracy of scaled GRACE terrestrial water storage estimates', *Water Resources Research*, vol 48, no. 4, DOI:10.1029/2011WR011453.

McNally, A., Arsenault, K., Kumar, S., Shukla, S., Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D. & Verdin. J.P. 2017, 'A land data assimilation system for sub-Saharan Africa food and water security applications', *Scientific Data,* vol. 4, no. 170012, DOI:10.1038/sdata.2017.12.

McNally, A. 2018, *NASA/GSFC/HSL (2018), FLDAS Noah Land Surface Model L4 Global Monthly 0.1 x 0.1 degree (MERRA-2 and CHIRPS), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC)*, viewed 25 February 2023, <https://disc.gsfc.nasa.gov/datasets/FLDAS_NOAH01_C_GL_M_001/summary>.

Pandolfo, C., Braga, H.J., Silva Jr, V.P., Massignan, A.M., Pereira, E.S., Thomé, V.M.R. & Valci, F.V. 2002, *Atlas climatológico do Estado de Santa Catarina*, Florianópolis, Epagri, viewed 10 January 2023, <https://ciram.epagri.sc.gov.br/index.php/solucoes/climatologia/>.

Ramos-da-Silva, R., Werth, D. & Avissar, R. 2008, 'Regional Impacts of Future Land-Cover Changes on The Amazon Basin During the Wet-Season Climate Impacts', *Journal of Climate*, vol. 21, no. 6, pp. 1153-70, DOI:10.1175/2007JCLI1304.1.

Reynolds, C.A., Jackson, T.J. & Rawls, W.J. 2000, 'Estimating Available Water Content by Linking the FAO Soil Map of the World with Global Soil Profile Databases and Pedo-transfer Functions', *Water Resources Research,* vol. 36, no. 12, pp. 3653–62, DOI:10.1029/2000WR900130.

Rodell, M., Velicogna, I. & Famiglietti, J.S. 2009, 'Satellite-based estimates of groundwater depletion in India', *Nature*, vol. 460, pp. 999–1002, DOI:10.1038/nature08238.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. & Zhang, X. 2012, 'Changes in climate extremes and their impacts on the natural physical environment', in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*, Cambridge University Press, Cambridge, pp. 109-230, viewed 26 February 2023, <https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap3_FINAL-1.pdf>.

Spinelli, K. 2018, 'Estiagem e a vulnerabilidade social no oeste de Santa Catarina no período de 1999 a 2012', PhD thesis, Universidade Federal de Santa Catarina.

Vasco, D.W., Kim, K.H., Farr, T.G., Reager, J.T., Bekaert, D., Sangha, S.S., Rutqvist, J. & Beaudoing, H.K. 2022, 'Using Sentinel-1 and GRACE satellite data to monitor the hydrological variations within the Tulare Basin, California', *Nature, Scientific Report*, vol. 12, no. 1, e3867, DOI:10.1038/s41598-022-07650-1.

Wahr, J., Molenaar, M. & Bryan, F. 1998, 'Time-variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE', *Journal of Geophysical Research*, vol. 103, no. B12, pp. 30205–29, DOI:10.1029/98JB02844.

Author contributions

Renato Ramos da Silva: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

All data included in this study are publicly available in the literature. It can be downloaded and analyzed using the Google Engine (https://app.climateengine.com/climateEngine), the NASA Giovanni visualization portal (https://giovanni.gsfc.nasa.gov/giovanni/) and JPL NASA data tool (https://grace.jpl.nasa.gov/data-analysis-tool).

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