Drought assessment of the impact of water supply and demand over land cover in continental Chile for 2000-2023 from ERA5-Land and MODIS datasets

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Abstract

Human-induced greenhouse gas emissions have increased the frequency and/or intensity of weather and climate extremes. Central Chile has been affected by a persistent drought which is impacting the hydrological system and vegetation development. The region has been the focus of research studies due to the diminishing water supply, this persistent period of water scarcity has been defined as a "mega drought". Nevertheless, our results evidence that the water deficit has expanded beyond. Our goal is to analyze the impact of drought, measured by drought indices of water supply/demand and vegetation status, in the LULCC (land use land cover change) over continental Chile. For the analysis, continental Chile was divided into five zones according to a latitudinal gradient: "Norte Grande", "Norte Chico", "Zona Central", "Zona Sur", and "Zona Austral". We used monthly climatic re-analysis variables for precipitation, temperature and soil moisture for 1981-2023 from ERA5-Land; and MODIS (Moderate-Resolution Imaging Spectroradiometer) product MCD12Q1 for land cover for 2001-2021, and the NDVI vegetation index from product MOD13A2 collection 6.1 for 2000-2023, both from collection 6.1. We estimated atmospheric evaporative demand (AED) by combining the Hargreaves-Samani equation with the ERA5-Land temperature. We derived the drought indices SPI (Standardized Precipitation Index), SPEI (Standardized Precipitation Evapotranspiration Index), EDDI (Evaporative Demand Drought Index), zcSM (standardized anomaly of cumulative soil moisture), and the zcNDVI (standardized anomaly of cumulative NDVI). These indices were calculated for time scales of 1, 3, 6, 12, 24, and 36 months, except for zcNDVI (1, 3, and 6 months). We analyzed the temporal correlation of SPI, SPEI, EDDI, and zcSM with zcNDVI to have insights into the impact of water supply and demand on vegetation. Our results showed that LULCC had an increasing trend of 412 [km2yr−1] of forest expansion in the "Zona Sur", together with a decreasing trend of 24 [km2yr−1] of cropland contraction in the "Zona Central" meanwhile the "Zona Sur" showed an increase of 31 [km2yr−1], and a contraction of 80 [km2yr−1] of bare soil in the "Zona Austral". The EDDI was the less correlated index for the five macro zones and the five types of land cover, showing that the temperature in Chile has little impact on vegetation. Higher r-squared values, between 0.5 and 0.8, were obtained at "Norte Chico" and "Zona Central" for the land cover types of savanna, shrubland, grassland, and croplands for the indices SPEI and zcSM at time scales of 12 and 24 months. The forest type reaches a r-squared of ~0.5 for zcSM of 12 months. The results indicate that the "Norte Chico" and "Zona Central" are the most sensitive regions to water supply deficits longer than a year, potentially explained by a low capacity of water storage in those zones that should be further investigated.

Keywords: drought, land cover change, satellite

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1. Introduction

The sixth assessment report (AR6) of the IPCC [1] indicates that human-induced greenhouse gas emissions have increased the frequency and/or intensity of some weather and climate extremes, and the evidence has been strengthened since AR5 [2]. There is high confidence that increasing global warming can expand the land area affected by increasing drought frequency and severity [3]. Furthermore, drought increases tree mortality and triggers changes in land cover and, consequently, land use, thus impacting ecosystems [4]. Nevertheless, there is a lack of understanding of how the alteration in water supply and demand is affecting land cover transformations.

Precipitation is the primary driver of drought, which impacts soil moisture, hydrological regimes, and vegetation productivity. Initially, drought was commonly classified as meteorological, hydrological, and agricultural [5]. Lately, [6] and [7] have given an updated definition of drought for the Anthropocene, suggesting that it should be considered the feedback of humans' decisions and activities that drives the anthropogenic drought. Even though it has been argued that those definitions do not fully address the ecological dimensions of drought. [4] proposed the ecological drought definition as *"an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedback in natural and/or human systems"*. Moreover, many ecological studies have misinterpreted how to characterize drought, for example, sometimes considering "dry" conditions as "drought" [8]. On the other hand, the AR6 [1] states that even if global warming is stabilized at 1.5°–2°C, many parts of the world will be impacted by more severe agricultural and ecological droughts. Then, there is a challenge in conducting drought research, especially its impact on ecosystems.

Chile has been facing a persistent rainfall deficit for more than a decade [9], which has impacted the hydrological system [10] and consequently the vegetation development [11]. Current drought conditions have affected crop yields in Central Chile. Highlighting the growing seasons 2007-2008 and 2008-2009 [12, [13]], which impacted an extensive surface in [COMPLETAR]. But, in 2019–2020, the drought intensity reached an extreme condition in North 34°S not seen for at least 40 years [11], thus affecting forest, grassland, and cropland areas. The prolonged lack of precipitation in Central Chile is producing changes in ecosystem dynamics that must be studied.

Satellite remote sensing [14, 15] is the primary method to evaluate how meteorological drought impacts vegetation dynamics. Since the 90's multiple vegetation drought indices have been developed, such as (VCI,[16]; TCI, [17]; zNDVI, [18]; VegDri, [19]) that have allowed making spatiotemporal analysis. Although we can derive these indices for any time during the year (depending on satellite revisit), they are more relevant during the the growing season [20]. Although modeling phenology is a complex task (e.g, ...), satellites offer strategies that help to address these issues [21, 22, 23]. Moreover, land cover dynamics products such as the MCD12Q2 from the USGS [24] provide phenology metrics. Rather than estimating these parameters at a given point in time, some authors have proposed aggregating these indices throughout the season. [25] proposes to accumulate the fractional active photosynthetic active radiation (FAPAR) between the start (SOS), and the end of the season (EOS) thus obtaining zCFAPAR as a proxy for biomass productivity. [13] used the same approach but with the NDVI (Normalized Difference Vegetation Index), deriving the zcNDVI for Central Chile. Besides, land use land cover (LULC) change can be driven by drought [26, 27]. To analyze these changes, multiple time-series LULC products exist, such as the MCD12Q1 [24] and the ESA CCI-LC (ESA 2017). The LULC product, together with the vegetation drought index can help evaluate the impact of drought on the ecosystem.

Vegetation drought indices are commonly used as proxies of productivity [28, 29]. The main environmental variables that affect productivity are water supply (i.e., precipitation) and demand (i.e., evapotranspiration)[20] commonly collected from weather stations. In developing countries, such as Chile, gaps in historical records are challenging. However, satellite products can be used to fill these gaps.

To evaluate drought, the World Meteorological Organization (WMO; [30]) has proposed the Standardized Precipitation Index (SPI; [31]), a multiscalar drought index that allows to monitor precipitation deficit from short- to long-term. For water supply, [32] has already correlated i tInfraRed Precipitation against weather Station data (CHIRPS; [33]). On the other hand, vegetation biomass productivity also strongly correlates to ET, which in turns depends on the atmospheric evaporative demand (AED) [34, 35, 36]. Due to increasing trends in air temperatures, AED is increasing, driving a rise in ET [3]. But, it is not always true [37]. For example, regions where AET is highest have the lowest ET.

The MOD16 product [38] provides AET and ET satellite estimates and has been used to derive drought indices [39]. Soil moisture (SM) is an Essential Climate Variable (ECV) that modulates vegetative growth. The climate change initiative (CCI) from the European Space Agency (ESA) delivers the ESA CCI SM product [40] (current version 6.1), which has been helpful to monitor drought [41]. Besides, total water storage can be retrieved by the Gravity Recovery and Climate Experiment (GRACE), which allows analyzing water availability changes [42, 43]. The balance between water demand and supply by remote sensing can be examined against vegetation productivity, also derived from remote sensing.

We aim to analyze the impact of drought over different types of land cover classes in continental Chile for 2000-2023 by combining environmental variables of biomass productivity and water demand/supply gathered from earth observation products. The specific objective for the study are i) to calculate multi-scalar drought indices for water demand and supply for 1981-2023, ii) to analyze the relationship of a proxy o biomass (zcNDVI) with drought indices, iii) to evaluate LULC change for 2001-2021 and its relation with drought indices, and iv) to assess if the observed changes in drought indices and land cover are linked to the TWS.

2. Study area

3. Materials and Methods

3.1. Data

3.1.1. Earth observation data

3.1.2. in-situ data

3.2. Drought indices for water demand and supply

3.3. Analysis of a biomass proxy with drought indices of supply and demand

3.4. LULC change for 2001-2021 and its relation with water supply and demand

![Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone.

3.5. Total water storage and drought indices

Terrestrial Water Storage (TWS) is defined as the total amount of water stored on land that includes any natural or artificial water bodies, such as groundwater, soil moisture, rivers, lakes, snowpack, ice, and biomass water [44, 45]. TWS changes evidence the effects of multiple water fluxes on the hydrological cycle [45]. These are reflected in the temporal variation of observations of the Earth's gravitational field [46, 47] and, in recent decades, the twin Gravity Recovery and Climate Experiment (GRACE) satellites and their Follow-On mission (GRACE-FO) have provided valuable results on globally distributed TWS anomalies [48, 49]. The GRACE mission was launched in March 2002 and was operational until October 2017 [50]. Then its GRACE Follow-On successor was launched in May 2018 [51, 52]. The information provided by these satellites is used to construct monthly maps of the Earth's average gravity field, providing details of the movement of water masses or water mass anomaly estimates relative to the long-term average gravity field [44, 53].

In this study, RL06.1_V3 GRACE mascon (mass concentration) monthly solutions were used, which are provided by the Jet Propulsion Laboratory (JPL-M, https://grace.jpl.nasa.gov). Each GRACE Tellus monthly grid at 0.5 degrees represents the deviation of surface mass for that month relative to a reference time average (2004-2009 baseline), which is subtracted from all other monthly grids to provide terrestrial water storage anomalies (TWSA) [50, 52]. This JPL-M version of the data employs a Coastal Resolution Improvement (CRI) filter that reduces signal leakage errors across coastlines [**? ?**]. Although the mascon

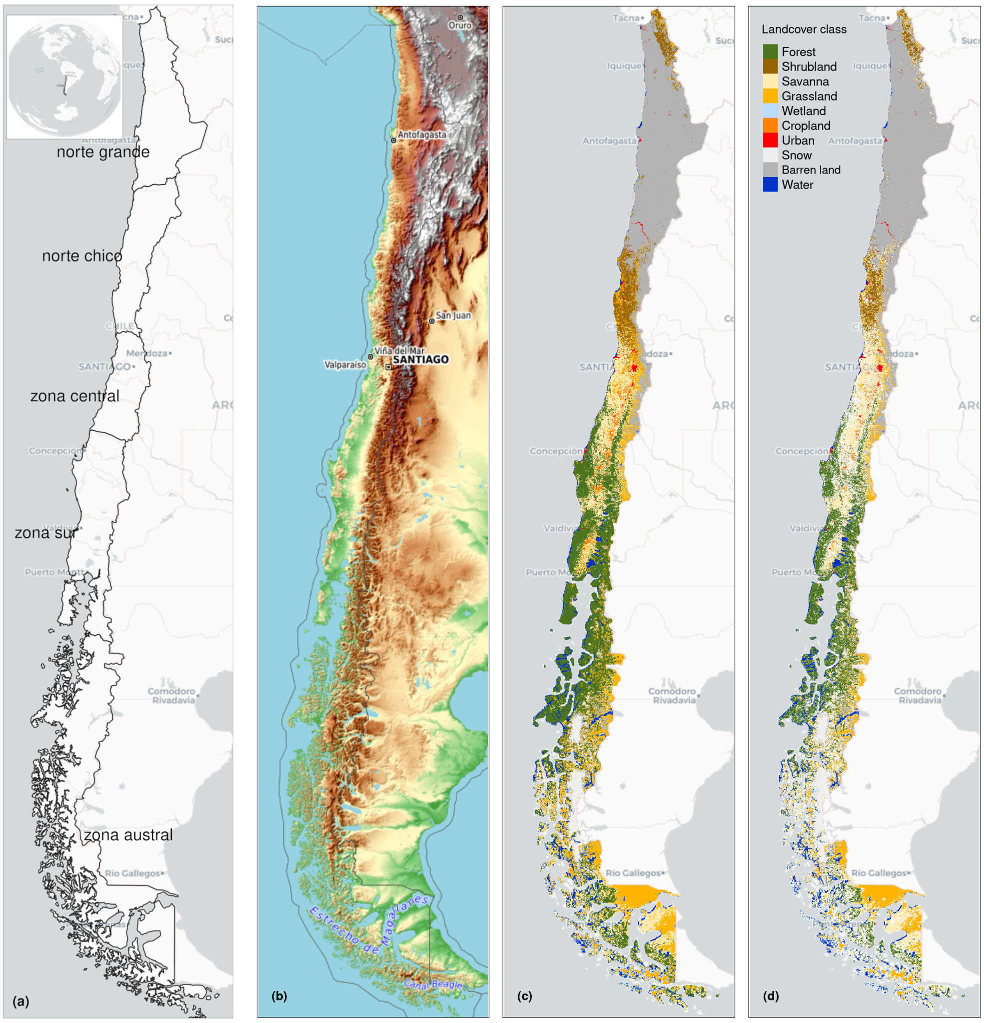
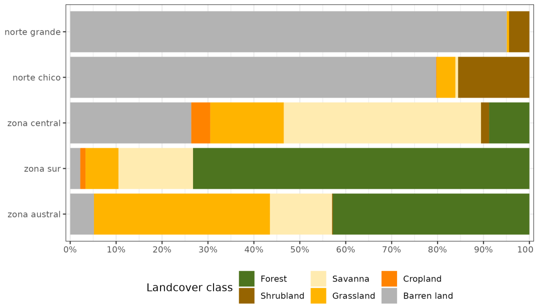


Figure 1: (a) Chile and the five zones “norte grande”, “norte chico”, “zona central”, “zona sur”, and “zona austral”. (b) Topography reference map. (c) Land cover classes for 2021. (d) Persistent land cover classes (> 80%) for 2001-2021.

solutions greatly reduced leakage errors, a gain-factor, which is used to enhance the spatial resolution, was applied to the dataset as recommended for hydrological studies [50, 52]. The water storage/height anomalies are given in Equivalent Water Height or Thickness units (EWH, cm) [47], and its temporal resolution monthly is from April 2002 to May 2023.



Trend of change [km^2 year^{-1}]						
zone	Forest	Cropland	Grassland	Savanna	Shrubland	Barren land
norte grande			−31.2		−2.3	32.8
norte chico			−100.2	−66.1	79.3	104.0
zona central	−66.2	−24.4	89.9	−128.6	130.2	23.3
zona sur	412.4	30.8	−55.9	−316.2	−14.6	2.1
zona austral	−9.1		226.1	163.9		−80.2

Figure 2: Proportion of land cover class from the persistent land cover for 2001-2021 (>80%) per macrozone. The table on the left shows the linear change trend next to time-series plot of surface, per land cover class (IGBP MCD12Q1.006) for 2001-2021 through the fives zones on continental Chile. Blue dots on the plots indicate the maximum and red dots minimum surface reach.

3.6. Validation of ERA5-Land variables

4. Results

4.1. Biomass proxy with drought indices of supply and demand

4.2. LULC change for 2001-2021 and its relation with water supply and demand

4.3. Total water storage (TWS) and drought indices

4.4. Validation of ERA5-Land variables

5. Discussion

6. Conclusion

References

[1] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P. W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W. W. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F. E. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D. C. Roberts, J. Roy, A. C. Ruane, J. Skea, P. R. Shukla, R. Slade, A. Slangen, Y. Sokona, A. A. Sörensson, M. Tignor, D. Van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F. X. Johnson, S. Pachauri, N. P. Simpson, C. Singh, A. Thomas, E. Totin, P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge Vorsatz, C. Xiao, N. Yassaa, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. Van Der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D. J. A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J. S. Fuglestvedt, G. Hansen, C. Ludden, V. Masson-Delmotte, J. R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, C. Péan, IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., Tech. rep., Intergovernmental Panel on Climate Change (IPCC) (Jul. 2023).
URL https://www.ipcc.ch/report/ar6/syr/

[2] IPCC, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK; New York, USA, 2013. doi:10.1017/CBO9781107415324.
URL www.climatechange2013.org

[3] X. a. A. M. a. B. W. a. D. C. a. L. A. a. G. S. a. I. I. a. K. J. a. L. S. a. O. F. a. P. I. a. S. M. a. V.-S. S. a. W. M. a. Z. . M.-D. B. a. V. a. O. Seneviratne, S and Zhang, Weather and Climate Extreme Events in a Changing Climate, Cambridge University Press. In Press., 2021, publication Title: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[4] S. D. Crausbay, A. R. Ramirez, S. L. Carter, M. S. Cross, K. R. Hall, D. J. Bathke, J. L. Betancourt, S. Colt, A. E. Cravens, M. S. Dalton, J. B. Dunham, L. E. Hay, M. J. Hayes, J. McEvoy, C. A. McNutt, M. A. Moritz, K. H. Nislow, N. Raheem, T. Sanford, Defining Ecological Drought for the Twenty-First Century, Bulletin of the American Meteorological Society 98 (12) (2017) 2543–2550, publisher: American Meteorological Society. doi:10.1175/BAMS-D-16-0292.1.
URL https://journals.ametsoc.org/view/journals/bams/98/12/bams-d-16-0292.1.xml

[5] D. A. Wilhite, M. H. Glantz, Understanding: The drought phenomenon: The role of definitions, Water International 10 (3) (1985) 111–120. doi:10.1080/02508068508686328.
URL http://dx.doi.org/10.1080/02508068508686328

[6] A. F. Van Loon, T. Gleeson, J. Clark, A. I. Van Dijk, K. Stahl, J. Hannaford, G. Di Baldassarre, A. J. Teuling, L. M. Tallaksen, R. Uijlenhoet, D. M. Hannah, J. Sheffield, M. Svoboda, B. Verbeiren, T. Wagener, S. Rangecroft, N. Wanders, H. A. Van Lanen, Drought in the Anthropocene, Nature Geoscience 9 (2) (2016) 89–91. doi:10.1038/ngeo2646.

[7] A. AghaKouchak, A. Mirchi, K. Madani, G. Di Baldassarre, A. Nazemi, A. Alborzi, H. Anjileli, M. Azarderakhsh, F. Chiang, E. Hassanzadeh, L. S. Huning, I. Mallakpour, A. Martinez, O. Mazdiyasni, H. Moftakhari, H. Norouzi, M. Sadegh, D. Sadeqi, A. F. Van Loon, N. Wanders, Anthropogenic Drought: Definition, Challenges, and Opportunities, Reviews of Geophysics 59 (2) (2021) e2019RG000683. doi:10.1029/2019RG000683.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019RG000683

[8] I. J. Slette, A. K. Post, M. Awad, T. Even, A. Punzalan, S. Williams, M. D. Smith, A. K. Knapp, How ecologists define drought, and why we should do better, Global Change Biology 25 (10) (2019) 3193–3200. doi:10.1111/gcb.14747.
URL https://onlinelibrary.wiley.com/doi/10.1111/gcb.14747

[9] R. Garreaud, C. Alvarez-Garreton, J. Barichivich, J. P. Boisier, D. Christie, M. Galleguillos, C. LeQuesne, J. McPhee, M. Zambrano-Bigiarini, The 2010-2015 mega drought in Central Chile: Impacts on regional hydroclimate and vegetation, Hydrology and Earth System Sciences Discussions 2017 (2017) 1–37. doi:10.5194/hess-2017-191.
URL http://www.hydrol-earth-syst-sci-discuss.net/hess-2017-191/

[10] J. P. Boisier, C. Alvarez-Garreton, R. R. Cordero, A. Damiani, L. Gallardo, R. D. Garreaud, F. Lambert, C. Ramallo, M. Rojas, R. Rondanelli, Anthropogenic drying in central-southern Chile evidenced by long-term observations and climate model simulations, Elementa 6 (1) (2018) 74. doi:10.1525/elementa.328.
URL https://www.elementascience.org/article/10.1525/elementa.328/

[11] F. Zambrano, Four decades of satellite data for agricultural drought monitoring throughout the growing season in Central Chile, in: R. M. Vijay P. Singh Deepak Jhajharia, R. Kumar (Eds.), Integrated Drought Management, Two Volume Set, CRC Press, 2023, p. 28.

[12] F. Zambrano, M. Lillo-Saavedra, K. Verbist, O. Lagos, Sixteen years of agricultural drought assessment of the biobío region in chile using a 250 m resolution vegetation condition index (VCI), Remote Sensing 8 (6) (2016) 1–20, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/rs8060530.
URL http://www.mdpi.com/2072-4292/8/6/530

[13] F. Zambrano, A. Vrieling, A. Nelson, M. Meroni, T. Tadesse, Prediction of drought-induced reduction of agricultural productivity in Chile from MODIS, rainfall estimates, and climate oscillation indices, Remote Sensing of Environment 219 (2018) 15–30, publisher: Elsevier. doi:10.1016/j.rse.2018.10.006.
URL https://www.sciencedirect.com/science/article/pii/S0034425718304541

[14] H. West, N. Quinn, M. Horswell, Remote sensing for drought monitoring \& impact assessment: Progress, past challenges and future opportunities, Remote Sensing of Environment 232, publisher: Elsevier Inc. (Oct. 2019). doi:10.1016/j.rse.2019.111291.

[15] A. AghaKouchak, A. Farahmand, F. S. Melton, J. Teixeira, M. C. Anderson, B. D. Wardlow, C. R. Hain, Remote sensing of drought: Progress, challenges and opportunities, Reviews of Geophysics 53 (2) (2015) 452–480. doi:10.1002/2014RG000456.
URL http://dx.doi.org/10.1002/2014RG000456.

[16] F. N. Kogan, Remote sensing of weather impacts on vegetation in non-homogeneous areas, Int. J. Remote Sens. 11 (8) (1990) 1405–1419. doi:10.1080/01431169008955102.
URL http://dx.doi.org/10.1080/01431169008955102

[17] F. N. Kogan, Application of vegetation index and brightness temperature for drought detection, Advances in Space Research 15 (11) (1995) 91–100. doi:10.1016/0273-1177(95)00079-T.

[18] A. J. Peters, E. A. Walter-Shea, L. Ji, A. Viña, M. Hayes, M. D. Svoboda, Drought monitoring with NDVI-based Standardized Vegetation Index, Photogrammetric Engineering and Remote Sensing 68 (1) (2002) 71–75.

[19] J. F. Brown, B. D. Wardlow, T. Tadesse, M. J. Hayes, B. C. Reed, The Vegetation Drought Response Index (VegDRI): A new integrated approach for monitoring drought stress in vegetation, GIScience and Remote Sensing 45(1) (2008) 16–46.

[20] A. K. Mishra, A. V. Ines, N. N. Das, C. Prakash Khedun, V. P. Singh, B. Sivakumar, J. W. Hansen, Anatomy of a local-scale drought: Application of assimilated remote sensing products, crop model, and statistical methods to an agricultural drought study, Journal of Hydrology 526 (2015) 15–29. doi:10.1016/j.jhydrol.2014.10.038.
URL http://www.sciencedirect.com/science/article/pii/S0022169414008336

[21] N. Younes, K. E. Joyce, S. W. Maier, All models of satellite-derived phenology are wrong, but some are useful: A case study from northern Australia, International Journal of Applied Earth Observation and Geoinformation 97 (2021) 102285, publisher: Elsevier. doi:10.1016/J.JAG.2020.102285.

[22] A. Vrieling, M. Meroni, R. Darvishzadeh, A. K. Skidmore, T. Wang, R. Zurita-Milla, K. Oosterbeek, B. O'Connor, M. Paganini, Vegetation phenology from Sentinel-2 and field cameras for a Dutch barrier island, Remote Sensing of Environment 215 (2018) 517–529, publisher: Elsevier. doi:10.1016/j.rse.2018.03.014.
URL https://www.sciencedirect.com/science/article/pii/S003442571830107X

[23] Z. Cai, P. Jönsson, H. Jin, L. Eklundh, Performance of Smoothing Methods for Reconstructing NDVI Time-Series and Estimating Vegetation Phenology from MODIS Data, Remote Sensing 9 (12) (2017) 1271. doi:10.3390/rs9121271.
URL http://www.mdpi.com/2072-4292/9/12/1271

[24] M. Friedl, D. Sulla-Menashe, MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC (2019). doi:10.5067/MODIS/MCD12Q1.006.

[25] M. Meroni, F. Rembold, D. Fasbender, A. Vrieling, Evaluation of the Standardized Precipitation Index as an early predictor of seasonal vegetation production anomalies in the Sahel, Remote Sensing Letters 8 (4) (2017) 301–310. doi:10.1080/2150704X.2016.1264020.
URL http://www.tandfonline.com/doi/abs/10.1080/2150704X.2016.1264020

[26] H. T. Tran, J. B. Campbell, R. H. Wynne, Y. Shao, S. V. Phan, Drought and Human Impacts on Land Use and Land Cover Change in a Vietnamese Coastal Area, Remote Sensing 2019, Vol. 11, Page 333 11 (3) (2019) 333, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS11030333.
URL https://www.mdpi.com/2072-4292/11/3/333/htm

[27] F. O. Akinyemi, Vegetation Trends, Drought Severity and Land Use-Land Cover Change during the Growing Season in Semi-Arid Contexts, Remote Sensing 2021, Vol. 13, Page 836 13 (5) (2021) 836, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS13050836.
URL https://www.mdpi.com/2072-4292/13/5/836/htm

[28] J. M. Paruelo, M. Texeira, L. Staiano, M. Mastrángelo, L. Amdan, F. Gallego, An integrative index of Ecosystem Services provision based on remotely sensed data, Ecological Indicators 71 (2016) 145–154, publisher: Elsevier. doi:10.1016/J.ECOLIND.2016.06.054.
URL https://www.sciencedirect.com/science/article/pii/S1470160X16303843

[29] A. Schucknecht, M. Meroni, F. Kayitakire, A. Boureima, A. Schucknecht, M. Meroni, F. Kayitakire, A. Boureima, Phenology-Based Biomass Estimation to Support Rangeland Management in Semi-Arid Environments, Remote Sensing 9 (5) (2017) 463, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/rs9050463.
URL http://www.mdpi.com/2072-4292/9/5/463

[30] WMO, M. Svoboda, M. Hayes, D. A. Wood, Standardized Precipitation Index User Guide, WMO, Geneva, 2012, series Title: WMO Publication Title: WMO-No. 1090 © Issue: 1090.
URL http://library.wmo.int/opac/index.php?lvl=notice_display&id=13682

[31] T. B. Mckee, N. J. Doesken, J. Kleist, The relationship of drought frequency and duration to time scales. In: Proceedings of the Ninth Conference on Applied Climatology., American Metereological Society (Boston) (1993) 179–184.

[32] F. Zambrano, B. Wardlow, T. Tadesse, M. Lillo-Saavedra, O. Lagos, Evaluating satellite-derived long-term historical precipitation datasets for drought monitoring in Chile, Atmospheric Research 186 (2017) 26–42, publisher: Elsevier. doi:10.1016/j.atmosres.2016.11.006.
URL https://www.sciencedirect.com/science/article/pii/S0169809516305865

[33] C. Funk, P. Peterson, M. Landsfeld, D. Pedreros, J. Verdin, S. Shukla, G. Husak, J. Rowland, L. Harrison, A. Hoell, J. Michaelsen, The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes, Scientific Data 2 (150066) (2015) 21. doi:10.1038/sdata.2015.66.

[34] P. Steduto, T. C. Hsiao, E. Fereres, D. Raes, Crop yield response to water.

[35] L. S. Pereira, R. G. Allen, M. Smith, D. Raes, Crop evapotranspiration estimation with FAO56: Past and future, Agricultural Water Management 147 (2015) 4–20, publisher: Elsevier. doi:10.1016/J.AGWAT.2014.07.031.

[36] R. G. Allen, W. O. Pruitt, J. L. Wright, T. A. Howell, F. Ventura, R. Snyder, D. Itenfisu, P. Steduto, J. Berengena, J. B. Yrisarry, M. Smith, L. S. Pereira, D. Raes, A. Perrier, I. Alves, I. Walter, R. Elliott, reference ETo by the FAO56 (2005).

[37] P. C. Milly, K. A. Dunne, Potential evapotranspiration and continental drying, Nature Climate Change 6 (10) (2016) 946–949, publisher: Nature Publishing Group. doi:10.1038/nclimate3046.
URL https://www.nature.com/articles/nclimate3046

[38] Q. a. Z. M. Running, S and Mu, MODIS/Terra Net Evapotranspiration 8-Day L4 Global 500m SIN Grid V061. 2021, distributed by NASA EOSDIS Land Processes DAAC. doi:10.5067/MODIS/MOD16A2.061.

[39] Q. Mu, M. Zhao, J. S. Kimball, N. G. McDowell, S. W. Running, A Remotely Sensed Global Terrestrial Drought Severity Index, Bull. Amer. Meteor. Soc. 94 (1) (2013) 83–98. doi:10.1175/BAMS-D-11-00213.1.
URL http://dx.doi.org/10.1175/BAMS-D-11-00213.1

[40] W. Dorigo, W. Wagner, C. Albergel, F. Albrecht, G. Balsamo, L. Brocca, D. Chung, M. Ertl, M. Forkel, A. Gruber, E. Haas, P. D. Hamer, M. Hirschi, J. Ikonen, R. de Jeu, R. Kidd, W. Lahoz, Y. Y. Liu, D. Miralles, T. Mistelbauer, N. Nicolai-Shaw, R. Parinussa, C. Pratola, C. Reimer, R. van der Schalie, S. I. Seneviratne, T. Smolander, P. Lecomte, ESA CCI Soil Moisture for improved Earth system understanding: State-of-the art and future directions, Remote Sensing of Environment 203 (2017) 185–215, publisher: Elsevier. doi:10.1016/J.RSE.2017.07.001.

[41] L. Zhang, Y. Liu, L. Ren, S. Jiang, X. Yang, F. Yuan, M. Wang, L. Wei, Drought Monitoring and Evaluation by ESA CCI Soil Moisture Products over the Yellow River Basin, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 12 (9) (2019) 3376–3386, publisher: Institute of Electrical and Electronics Engineers. doi:10.1109/JSTARS.2019.2934732.

[42] M. Ahmed, M. Sultan, J. Wahr, E. Yan, The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa, Earth-Science Reviews 136 (2014) 289–300, publisher: Elsevier. doi:10.1016/J.EARSCIREV.2014.05.009.

[43] S. Ma, Q. Wu, J. Wang, S. Zhang, Temporal Evolution of Regional Drought Detected from GRACE TWSA and CCI SM in Yunnan Province, China, Remote Sensing 2017, Vol. 9, Page 1124 9 (11) (2017) 1124, publisher: Multidisciplinary Digital Publishing Institute. doi:10.3390/RS9111124.
URL https://www.mdpi.com/2072-4292/9/11/1124/htm

[44] V. Humphrey, M. Rodell, A. Eicker, Using Satellite-Based Terrestrial Water Storage Data: A Review, Surveys in Geophysics 44 (5) (2023) 1489–1517. doi:10.1007/s10712-022-09754-9.
URL https://link.springer.com/10.1007/s10712-022-09754-9

[45] S. Deng, Y. Liu, W. Zhang, A Comprehensive Evaluation of GRACE-Like Terrestrial Water Storage (TWS) Reconstruction

Products at an Interannual Scale During 1981–2019, Water Resources Research 59 (3) (2023) e2022WR034381. doi:10.1029/2022WR034381.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022WR034381

[46] R. Abolafia-Rosenzweig, M. Pan, J. Zeng, B. Livneh, Remotely sensed ensembles of the terrestrial water budget over major global river basins: An assessment of three closure techniques, Remote Sensing of Environment 252 (2021) 112191. doi:10.1016/j.rse.2020.112191.
URL https://linkinghub.elsevier.com/retrieve/pii/S0034425720305642

[47] F. Sabzehee, A. Amiri-Simkooei, S. Iran-Pour, B. Vishwakarma, R. Kerachian, Enhancing spatial resolution of GRACE-derived groundwater storage anomalies in Urmia catchment using machine learning downscaling methods, Journal of Environmental Management 330 (2023) 117180. doi:10.1016/j.jenvman.2022.117180.
URL https://linkinghub.elsevier.com/retrieve/pii/S0301479722027530

[48] B. D. Tapley, M. M. Watkins, F. Flechtner, C. Reigber, S. Bettadpur, M. Rodell, I. Sasgen, J. S. Famiglietti, F. W. Landerer, D. P. Chambers, J. T. Reager, A. S. Gardner, H. Save, E. R. Ivins, S. C. Swenson, C. Boening, C. Dahle, D. N. Wiese, H. Dobslaw, M. E. Tamisiea, I. Velicogna, Contributions of GRACE to understanding climate change, Nature Climate Change 9 (5) (2019) 358–369. doi:10.1038/s41558-019-0456-2.
URL https://www.nature.com/articles/s41558-019-0456-2

[49] V. Ferreira, B. Yong, H. Montecino, C. E. Ndehedehe, K. Seitz, H. Kutterer, K. Yang, Estimating GRACE terrestrial water storage anomaly using an improved point mass solution, Scientific Data 10 (1) (2023) 234. doi:10.1038/s41597-023-02122-1.
URL https://www.nature.com/articles/s41597-023-02122-1

[50] M. Ramjeawon, M. Demlie, M. Toucher, Analyses of groundwater storage change using GRACE satellite data in the Usutu-Mhlatuze drainage region, north-eastern South Africa, Journal of Hydrology: Regional Studies 42 (2022) 101118. doi:10.1016/j.ejrh.2022.101118.
URL https://linkinghub.elsevier.com/retrieve/pii/S2214581822001318

[51] F. W. Landerer, F. M. Flechtner, H. Save, F. H. Webb, T. Bandikova, W. I. Bertiger, S. V. Bettadpur, S. H. Byun, C. Dahle, H. Dobslaw, E. Fahnestock, N. Harvey, Z. Kang, G. L. H. Kruizinga, B. D. Loomis, C. McCullough, M. Murböck, P. Nagel, M. Paik, N. Pie, S. Poole, D. Strekalov, M. E. Tamisiea, F. Wang, M. M. Watkins, H. Wen, D. N. Wiese, D. Yuan, Extending the Global Mass Change Data Record: GRACE Follow-On Instrument and Science Data Performance, Geophysical Research Letters 47 (12) (2020) e2020GL088306. doi:10.1029/2020GL088306.
URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL088306

[52] W. Yin, S. Yang, L. Hu, S. Tian, X. Wang, R. Zhao, P. Li, Improving understanding of spatiotemporal water storage changes over China based on multiple datasets, Journal of Hydrology 612 (2022) 128098. doi:10.1016/j.jhydrol.2022.128098.
URL https://linkinghub.elsevier.com/retrieve/pii/S0022169422006734

[53] J. Wahr, S. Swenson, V. Zlotnicki, I. Velicogna, Time-variable gravity from GRACE: First results: TIME-VARIABLE GRAVITY FROM GRACE, Geophysical Research Letters 31 (11) (2004) n/a–n/a. doi:10.1029/2004GL019779.
URL http://doi.wiley.com/10.1029/2004GL019779