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CSIndicators: Get tailored climate indicators for applications in your sector

HIGHLIGHTS

- CSIndicators aims for flexible computation of climate-related indicators.
- Functions are named by the applied algebraic equation and allow time period selection to tailor the indicator.
- This package is intended for sub-seasonal, seasonal and decadal climate predictions, but its methods are also applicable to other scales.
- Its compatible with CSTools enables the full climate forecast post-processing (e.g.: bias adjustment and downscaling).
- The vignettes attached to the software package are key pieces of documentation to showcase the use of the package.

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ABSTRACT

CSIndicators is an R package that gathers generalised methods for the flexible computation of climate-related indicators. Each method represents a specific mathematical approach which is combined with the possibility of selecting a flexible time period to define the indicator. This enables a wide range of possibilities for tailoring indicators to sectorial climate service applications. This package is intended for sub-seasonal, seasonal and decadal climate predictions, but its methods are also applicable to other time scales. Additionally, this package is compatible with the CSTools R package for climate forecast post-processing.

1. Introduction

The urgent need for robust climate change adaptation and mitigation strategies, including the improvement of climate risk management, has triggered the development of climate services in recent years. Climate services products have to be customised based on the available scientific knowledge and user-specific information needs. Choosing the appropriate data sources (such as climate observations, forecasts and projections), the most suitable tools, and appealing visualisations is key to tailor climate products to each sectoral application. While data access is granted by initiatives like the Climate Data Store (CDS) from the Copernicus Climate Change Service (C3S), climate services tools are scattered in the scientific community and are usually devoted to specific analyses. Strategic and consistent development of climate services tools is thus a major need to profit from the number of available datasets.

One pathway to tailor climate services products to each sectoral application is through the definition of climate indicators. A climate indicator is an aggregation or combination of climatic variable(s) that captures climate change and variability or its impact on a specific application. From a climate sciences perspective, the Expert Team on Climate Change Detection and Indices (ETCCDI) defined a set of 27 core indicators (Karl et al., 1999; Peterson et al., 2001). However, for sectoral applications (e.g. energy, agriculture, tourism, health, insurance, or logistics; White et al., 2017), climate indicators are adapted to specific needs. For instance, in the agricultural sector, the frost day indicator can be reinterpreted by changing the threshold from 0 °C to the temperature that damages the plant leaf (Rozante et al., 2020). Climate indicators have been exploited for observed and predicted climate research. To bridge the gap between research and services, climate indicators tools become essential to change the focus toward the user needs and activities that allow capacity building (Bojovic et al., 2021).

Existing software allows for the calculation of some climate indicators either for specific climate sources or specific sectors. Some examples are: the Earth System Model Evaluation Tool (ESMValTool) for the CMIP5 and CMIP6 analysis of extreme events (Weigel et al., 2021); R-based packages (R Core Team, 2022) such as climdex.pcic (Bronaugh, 2020) and climInd (Reig-Gracia et al., 2021) for computing a variety of indicators based on in-situ observations; or sector-specific software packages such as the Clisagri package (Ceglar et al., 2020) for the agriculture sector or the MVSE package (Obolski et al., 2019) for the health sector.

Here we present the Climate Services Indicators (CSIndicators) R package, which is based on the research expertise in sub-seasonal to decadal climate predictions at the Earth Sciences Department of the Barcelona Supercomputing Center (BSC) and the interactions with stakeholders from diverse socioeconomic sectors. To our knowledge, CSIndicators is the first software intended to cover the earlier-mentioned gap between climate research and climate services under the premise of satisfying any sector requiring indicators based on sub-seasonal to decadal climate forecasts. At the same time, CSIndicators

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should be compatible with other packages available in the services community (i.e. CSTools, Pérez-Zanón et al., 2022) that allow post-processing sub-seasonal to decadal climate forecasts. Furthermore, this software benefits from multiApply (BSC-CNS et al., 2021) to parallel computing and it is compatible with startR (Manubens et al., 2022) for big data processing and verification and assessment R packages (e.g.: s2dverification; Manubens et al., 2018; s2dv; BSC-CNS et al., 2022, SpecsVerification; Siegert, 2020). The next section presents an overview of the software and its documentation. Final remarks are listed in section 3, highlighting the continuous development plans for the tool.

2. CSIndicators overview

Considering the objectives of CSIndicators, the software is built on multiple separated functionalities. This provides flexibility to combine them to follow specific requirements even in combination with other tools. Three main groups of functions can be distinguished in the package:

1. indicators, functions that calculate an indicator;
2. transformations, functions that process the data to obtain required information such as thresholds; and
3. formatting, helper functions to format the data, for instance, by merging forecast data and reference data for a blending analysis (see Chou et al., 2023).

All functionalities follow the development guidelines of CSTools package. That is, functionalities are made of functions at three nested levels: the most basic one or atomic function performs specific calculations using the minimum required data, this function is not exposed to the user; the level above parallelises the computation of the atomic function by using multiApply package, the user should provide multi-dimensional arrays with named dimensions as data input; the last level is built on a function working on s2dv_cube objects which are meant to keep data and metadata in a single object to ensure data provenance at each stage of the analysis. To distinguish between the last two levels of this nested structure, the 'CST_' prefix is added to the functions working on s2dv_cube objects. Further details on this design and guidelines are provided in Pérez-Zanón et al. (2022).

Currently, there are 13 functionalities included in CSIndicators version 0.0.2, 7 of them to compute Indicators and the others are helper functions (Table S1). To satisfy any sector that requires climate indicators, the functions calculating these indicators have been named by the description of the output they return. Next, we describe how one of these functions can be used for a specific application in the agricultural sector using the retrospective (hindcast) seasonal climate forecast.

The Spring Total Precipitation (sprR) is one of the important bioclimatic indicators for the wine sector (Dell'Aquila et al., 2022). Given its definition (for the northern hemisphere), the total (or accumulated) precipitation from the 21st of April to the 21st of June, the required function is CST_PeriodAccumulation. This function requires an s2dv_cube object and, optionally, the arguments start, end, time_dim, na.rm and ncores. The s2dv_cube is made at least of an $data element that stores the daily total precipitation in a multi-dimensional array with named dimensions. This structure is useful to manipulate seasonal climate forecasts because the data is well organised. Typically, the array has at least the start date dimension in which initialisations of several years are organised, the ensemble member dimension, for the different runs of the forecasts system, the forecast time (called 'ftime') dimension and the spatial dimensions (i.e., longitude and latitude). Note that these dimensions can be in any order. The approach to obtain the aforementioned structure using CST_Load from CSTools or other R-packages was documented in Pérez-Zanón et al. (2022).

Considering the seasonal climate forecast initialised in April and that the typical length of a run is 215 days, the forecast time dimension that stores the time series needs to be temporally subsetted. The $Dates element of the s2dv_cube object contains dates for each forecast time and CST_PeriodAccumulation function will subset the input data with the start and end parameters provided. So, all the required parameters to execute the function are known as below.

```
CST_PeriodAccumulation(data = described_s2dv_cube,

start = c(21, 4),

end = c(21, 6),

time_dim = 'ftime')
```

The function returns an s2dv_cube object in which its new $data element contains the sprR indicator for all grid points, members and initialisations in a data array. Furthermore, the other two arguments can be optionally tuned: the na.rm to decide whether to return a missing value when the forecast times have a missing value (FALSE) or to obtain results by neglecting NA values (TRUE); and the ncores argument to parallelise in the set number of cores.

To conclude this example, Fig. 1 shows a possible product for the sprR for the western Iberian Peninsula (10°W-º0°E, 35°N-40°N) by using CSTools to bias adjust and visualise the output, CSIndicators to compute sprR and s2dv to calculate the fair Rank Probability Skill Score (fRPSS; code in the supplementary material). The SEAS5 forecast (Johnson et al., 2019) initialised on the 1st of April, 2022 shows a probability of 65% being below normal values (i.e. below 54.3 mm) matching the observed tercile from ERA5 (Hersbach et al., 2020) with a positive skill score.

An analogous design is followed by the rest of the functions computing indicators but with a few differences: some functions are expected to apply calculations over a period like in the example above which returns total precipitation values. Others allow to count occurrences under conditional threshold(s) and one function allows to set a minimum spell length. All these cases are independent of the variable being analysed and the temporal frequency of the data. Therefore, the same function could be used to obtain different indicators or to create new indicators by tailoring the parameters to each application (e.g., different varieties of crops may have different phenological cycles considering different periods). Table S1 includes some examples of known bioclimatic indicators that can be obtained with the current functions. The function naming conventions reduce the number of functionalities while preserving the flexibility needed by climate applications.

Note that the development strategy of CSIndicators is open to including functionalities with more restrictions. That is the case of the functions for the wind energy sector, CST_WindCapacityFactor and CST_WindPowerDensity whose inputs are instantaneous (or high frequency) wind speeds.

Some climate indicators require using more than one function, such as those based on thresholds that need to be calculated in advance. To facilitate the usage, apart from the user manual describing each function individually (including inputs, output, arguments and examples), there are extra pieces of documentation called vignettes aimed to explain, step by step, how to obtain some specific climate indicators. Currently, there are 2 vignettes, one for the agricultural sector and a second one for the wind energy sector.

3. Final remarks

CSIndicators and its compatibility with other tools have already successfully led to agricultural services (Chou et al., 2023) and wind energy applications (Lledó et al., 2019). New indicators will be added following the naming conventions. Table S1 includes potential functionalities for future releases based on the well-known climate indicators found in the literature although others, that may be defined in collaboration with social scientists, users and stakeholders, are desired as well. As an example, the malaria indicator vignette for the health sector is

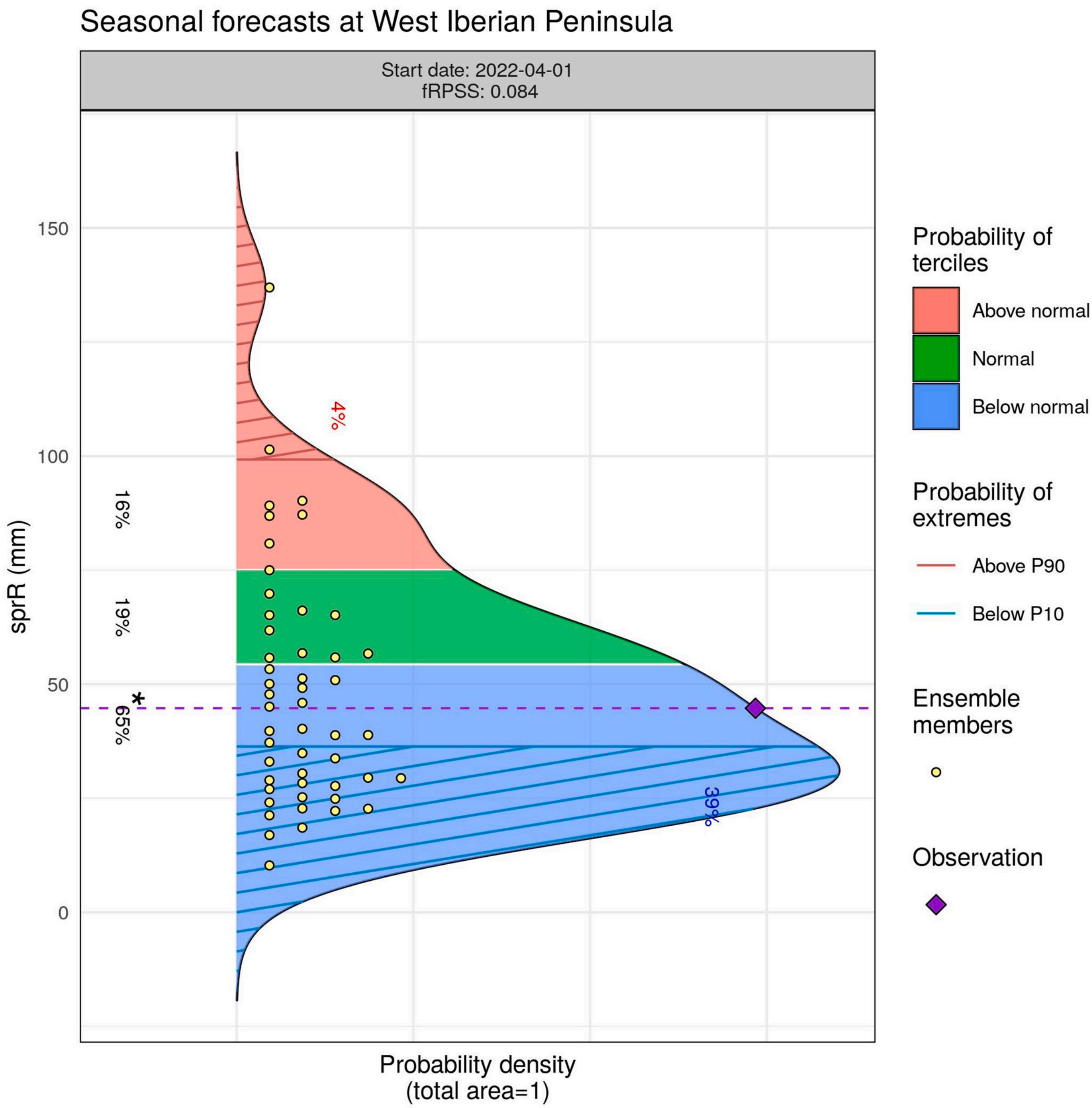

Fig. 1. sprR probability distribution of the forecast initialised on the 1st of April, 2022 for the western Iberian peninsula. The daily values of the hindcast and forecast have been corrected before calculating the sprR and the spatial aggregation. The adjusted hindcast has been used to calculate the fRPSS and the terciles and extremes thresholds.

currently under development. All developments are based on software development best practices including branch strategy and unit testing.

CSIndicators is publicly available on CRAN https://CRAN.R-project.org/package=CSIndicators and a GitLab repository https://earth.bsc.es/gitlab/es/csindicators.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2023.100393.

References

Bojovic, D., st Clair, A.L., Christel, I., Terrado, M., Stanzel, P., Gonzalez, P., Palin, E.J., 2021. Engagement, involvement and empowerment: three realms of a coproduction framework for climate services. Global Environ. Change 68, 102271. https://doi.org/10.1016/j.gloenvcha.2021.102271.

Bronaugh, D., for the Pacific Climate Impacts Consortium, 2020. climdex.pcic: PCIC Implementation of Climdex Routines. R Package Version 1.1-11. https://CRAN.R-project.org/package=climdex.pcic. (Accessed 21 September 2022).

BSC-CNS, Manubens, N., Hunter, A., 2021. multiApply: apply Functions to Multiple Multidimensional Arrays or Vectors. R Package Version 2.1.3. https://CRAN.R-project.org/package=multiApply. (Accessed 11 January 2023).

BSC-CNS, Ho, A., Pérez-Zanón, N., 2022. s2dv: a set of Common Tools for Seasonal to Decadal Verification. R Package Version 1.3.0. https://earth.bsc.es/gitlab/es/s2dv/. (Accessed 11 January 2023).

Ceglar, A., Toreti, A., Zampieri, M., Manstretta, V., Bettati, T., Bratu, M., 2020. Clisagri: an R package for agro-climate services. Clim. Serv. 20, 100197 https://doi.org/10.1016/J.CLISER.2020.100197.

Chou, C., Marcos-Matamoros, R., Palma Garcia, L., Pérez-Zanón, N., Teixeira, M., Silva, S., Fontes, N., Graça, A., Dell'Aquila, A., Calmanti, S., González-Reviriego, N., 2023. Advanced seasonal predictions for vine management based on bioclimatic indicators tailored to the wine sector. Clim. Serv. 30, 2405–8807. https://doi.org/10.1016/j.cliser.2023.100343.

Dell'Aquila, A., Graça, A., Teixeira, M., Fontes, N., Gonzalez-Reviriego, N., Marcos-Matamoros, R., Chou, C., Terrado, M., Giannakopoulos, C., Varotsos, K.v., Caboni, F., Locci, R., Nanu, M., Porru, S., Argiolas, G., Soares, M.B., Sanderson, M., 2022. Monitoring climate related risk and opportunities for the wine sector: the MED-GOLD pilot service. https://doi.org/10.5281/ZENODO.6357144.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803.

Johnson, S.J., Stockdale, T.N., Ferranti, L., Balmaseda, M.A., Molteni, F., Magnusson, L., Tietsche, S., Decremer, D., Weisheimer, A., Balsamo, G., Keeley, S.P.E., Mogensen, K., Zuo, H., Monge-Sanz, B.M., 2019. SEAS5: the new ECMWF seasonal forecast system. Geosci. Model Dev. (GMD) 12, 1087–1117. https://doi.org/10.5194/GMD-12-1087-2019.

Karl, T.R., Nicholls, N., Ghazi, A., 1999. CLIVAR/GCOS/WMO workshop on Indices and indicators for climate extremes workshop summary. Weather Clim. Extrem. 3–7. https://doi.org/10.1007/978-94-015-9265-9_2.

Lledó, L., Torralba, V., Soret, A., Ramon, J., Doblas-Reyes, F.J., 2019. Seasonal forecasts of wind power generation. Renew. Energy 143, 91–100. https://doi.org/10.1016/J.RENENE.2019.04.135.

Manubens, N., Caron, L.-P., Hunter, A., Bellprat, O., Exarchou, E., Fuckar, N.S., Garcia-Serrano, J., Massonnet, F., En Egoz, M.M., Sicardi, V., Batt, E.C., Chlo, E., Prodhomme, L., Onica Torralba, V., Cortesi, N., Mula-Valls, O., Serradell, K., Guemas, V., Doblas-Reyes, F.J., 2018. An R package for climate forecast verification. Environ. Model. Software 103, 29–42. https://doi.org/10.1016/j.envsoft.2018.01.018.

Manubens, N., Ho, A., Pérez-Zanón, N., BSC-CNS, 2022. startR: automatically Retrieve Multidimensional Distributed Data Sets. R Package Version 2.2.1. https://CRAN.R-project.org/package=startR. (Accessed 11 January 2023).

Obolski, U., Perez, P.N., Villabona-Arenas, C.J., Thézé, J., Faria, N.R., Lourenço, J., 2019. MVSE: an R-package that estimates a climate-driven mosquito-borne viral suitability index. Methods Ecol. Evol. 10, 1357–1370. https://doi.org/10.1111/2041-210X.13205.

Pérez-Zanón, N., Caron, L.-P., Terzago, S., Van Schaeybroeck, B., Lledó, L., Manubens, N., Roulin, E., Alvarez-Castro, M.C., Batté, L., Bretonnière, P.-A., Corti, S., Delgado-Torres, C., Domínguez, M., Fabiano, F., Giuntoli, I., von Hardenberg, J., Sánchez-García, E., Torralba, V., Verfaillie, D., 2022. Climate Services Toolbox (CSTools) v4.0: from climate forecasts to climate forecast information. Geosci. Model Dev. (GMD) 15, 6115–6142. https://doi.org/10.5194/GMD-15-6115-2022.

Peterson, T.C., Folland, C., Hogg, W., Plummer, N., 2001. Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs [WWW Document]. http://etccdi.pacificclimate.org/docs/wgccd.2001.pdf. (Accessed 13 September 2022).

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. (Accessed 11 January 2023).

Reig-Gracia, F., Vicente-Serrano, S.M., Dominguez-Castro, F., Bedia-Jiménez, J., 2021. ClimInd: Climate Indices. R Package Version 0.1-3. https://CRAN.R-project.org/package=ClimInd. (Accessed 21 September 2022).

Rozante, J.R., Gutierrez, E.R., da Silva Dias, P.L., de Almeida Fernandes, A., Alvim, D.S., Silva, V.M., 2020. Development of an index for frost prediction: technique and validation. Meteorol. Appl. 27, e1807 https://doi.org/10.1002/met.1807.

Siegert, S., 2020. SpecsVerification: forecast Verification Routines for Ensemble Forecasts of Weather and Climate. R package Version 0.5-3. https://CRAN.R-project.org/package=SpecsVerification. (Accessed 14 September 2022).

Weigel, K., Bock, L., Gier, B.K., Lauer, A., Righi, M., Schlund, M., Adeniyi, K., Andela, B., Arnone, E., Berg, P., Caron, L.P., Cionni, I., Corti, S., Drost, N., Hunter, A., Lledó, L., Mohr, C.W., Paçal, A., Pérez-Zanón, N., Predoi, V., Sandstad, M., Sillmann, J., Sterl, A., Vegas-Regidor, J., Von Hardenberg, J., Eyring, V., 2021. Earth System Model Evaluation Tool (ESMValTool) v2.0-diagnostics for extreme events, regional and impact evaluation, and analysis of Earth system models in CMIP. Geosci. Model Dev. (GMD) 14, 3159–3184. https://doi.org/10.5194/GMD-14-3159-2021.

White, C.J., Carlsen, H., Robertson, A.W., Klein, R.J.T., Lazo, J.K., Kumar, A., Vitart, F., Coughlan de Perez, E., Ray, A.J., Murray, V., Bharwani, S., MacLeod, D., James, R., Fleming, L., Morse, A.P., Eggen, B., Graham, R., Kjellström, E., Becker, E., Pegion, K. V., Holbrook, N.J., McEvoy, D., Depledge, M., Perkins-Kirkpatrick, S., Brown, T.J., Street, R., Jones, L., Remenyi, T.A., Hodgson-Johnston, I., Buontempo, C., Lamb, R., Meinke, H., Arheimer, B., Zebiak, S.E., 2017. Potential applications of subseasonal-to-seasonal (S2S) predictions. Meteorol. Appl. 24, 315–325. https://doi.org/10.1002/met.1654.

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