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The ECOMS User Data Gateway: Towards seasonal forecast data provision and research reproducibility in the era of Climate Services

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ABSTRACT

Sectorial applications of seasonal forecasting require data for a reduced number of variables from different datasets, mainly (gridded) observations, reanalysis, and predictions from state-of-the-art seasonal forecast systems (such as NCEP/CFSv2, ECMWF/System4 or UKMO/GloSea5). Whilst this information can be obtained directly from the data providers, the resulting formats, temporal aggregations, and vocabularies may not be homogeneous across datasets. Moreover, different data policies hold for the different databases, being only some of them publicly available. Therefore, obtaining and harmonizing multi-model seasonal forecast data for sector-specific applications is an error-prone, time consuming task.

In order to facilitate this, the ECOMS User Data Gateway (ECOMS-UDG) was developed in the framework of the ECOMS initiative as a one-stop-service for climate data. To this aim, the variables required by end users were identified, downloaded from the data providers and locally stored as virtual datasets in a THREDDS Data Server (TDS), implementing fine-grained user management and authorization via the THREDDS Access Portal (TAP). As a result, users can retrieve the subsets best suited to their particular research needs in a user-friendly manner using the standard TDS data services. Moreover, an open source, R-based interface for data access and postprocessing was developed in the form of a bundle of packages implementing harmonized data access (one single vocabulary), data collocation, bias adjustment and downscaling, and forecast visualization and validation. This provides a unique comprehensive framework for end-to-end applications of seasonal predictions, hence favoring the reproducibility of the ECOMS scientific outcomes, extensible to the whole scientific community.

Practical Implications

The integration of seasonal predictions in different impact sectors such as agriculture, energy, hydrology and health require data from different sources, including observations, reanalysis and seasonal predictions/hindcasts from state-of-the-art forecasting systems. Typically, only a reduced number of surface variables is needed, which can be directly obtained from the different data providers. However, the resulting formats, temporal scales/aggregations and vocabularies (variable naming and units) may not be homogeneous across datasets. Thus, obtaining and harmonizing the datasets (particularly seasonal predictions) is typically an error-prone, time consuming task. Moreover, different data policies hold for the various datasets (which are freely available only in some cases) and therefore data access may not be straightforward.

The ECOMS User Data Gateway (ECOMS-UDG) was developed in order to mitigate the above mentioned problems, facilitating data provision to end users and favouring science transparency, openness and reproducibility. To this aim, ECOMS-UDG was built upon different open-source software components publicly available: The UNIDATA THREDDS data server, the THREDDS Access Portal implementing fine-grained user management and authorization, and the *climate4R bundle* providing data access and post-processing tools (including bias adjustment and downscaling) based on the R language and computing environment. As a result, ECOMS-UDG provides a unique framework to explore seasonal predictability allowing for the development of end-to-end seasonal

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forecast applications using state-of-the-art seasonal forecasting systems (such as NCEP/CFSv2, ECMWF/System4 or UKMO/GloSea5).

The functionalities of ECOMS-UDG are illustrated with a case study application over Europe, analyzing seasonal predictability of winter (DJF) temperatures and precipitation, in connection to North Atlantic Oscillation (NAO) predictability at seasonal time scales. Although some of the datasets used in this work are restricted to ECOMS partners due to data access constraints imposed by the data providers, there is a minimum amount of information (e.g. WFDEI observations, NCEP/NCAR reanalysis and CFSv2 seasonal forecasts) openly accessible, which allows reproducing the results here presented and undertaking further research activities.

Currently, ECOMS-UDG does not provide operational forecasts, but only retrospective forecasts (hindcasts) and reference data (observations and reanalysis). Therefore, operational applications would require accessing (downloading) the operational predictions directly from the data provider; however, the tools provided in ECOMS-UDG can be used to transparently access the downloaded local dataset (e.g. using the corresponding hindcast dictionary), thus facilitating this task.

1. Introduction

The European Climate Observations, Modelling and Services (ECOMS) initiative coordinates the activities of three European projects (EUPORIAS, SPECS and NACLIM) focusing on seasonal to decadal prediction. Different studies carried out in these projects have tested the integration of seasonal prediction in several impact sectors such as agriculture, energy, hydrology and health (Lowe et al., 2016; Ogutu et al., 2016; Bedia et al., 2018). These sectorial studies require data from different sources (observations, reanalysis and seasonal predictions/hindcasts) for verification and downscaling purposes. Typically, only a reduced number of surface (and upper-air for downscaling) variables is needed, which can be directly obtained from the different data providers. However, the resulting formats, temporal scales/aggregations and vocabularies (variable naming and units) may not be homogeneous across datasets. Thus, obtaining and harmonizing the datasets (particularly seasonal predictions) is typically an error prone, time consuming task. Moreover, different data policies hold for the various datasets (which are freely available only in some cases) and therefore data access may not be straightforward. These difficulties and challenges for moving towards end-to-end climate data services have been reported in several studies (Coelho and Costa, 2010) and constitute a major bottleneck for real-world applications.

The ECOMS User Data Gateway (ECOMS-UDG) was developed as part of the ECOMS data management activities in order to mitigate the above mentioned problems, facilitating data provision to end users (see Fig. 1 for a schematic illustration of the main components). To this aim, the variables required in the sectorial applications were identified, downloaded from data providers, and stored locally in a THREDDS (THematic Real-time Environmental Distributed Data Services) data server implementing fine-grained user authorization via the TAP (THREDDS Access Portal). This provides a one-stop-service for climate data access where users can efficiently retrieve the subsets best suited to their particular research aims (for particular regions, periods and/or ensemble members). Besides the standard data access services (such as OPeNDAP or NetCDF Subset Service), an additional interface (the `loadeR` package) is provided for R users (R Core Team, 2017), providing also appropriate R data structures for data manipulation. Thus, ECOMS-UDG data subsets can be efficiently accessed directly from R using a single line of code.

Furthermore, some common transformation/calibration postprocessing steps are typically applied to raw model data before their use in sectorial models, including data collocation (e.g. regridding, temporal aggregation, subsetting), bias adjustment (e.g. local scaling or quantile mapping) and forecast validation. In some cases, these steps are very technical and they are not always appropriately documented in practical applications, thus making the reproducibility of the results difficult. In order to facilitate these tasks, an R bundle for data postprocessing was developed as an extra layer of ECOMS-UDG, implementing a generic package for data

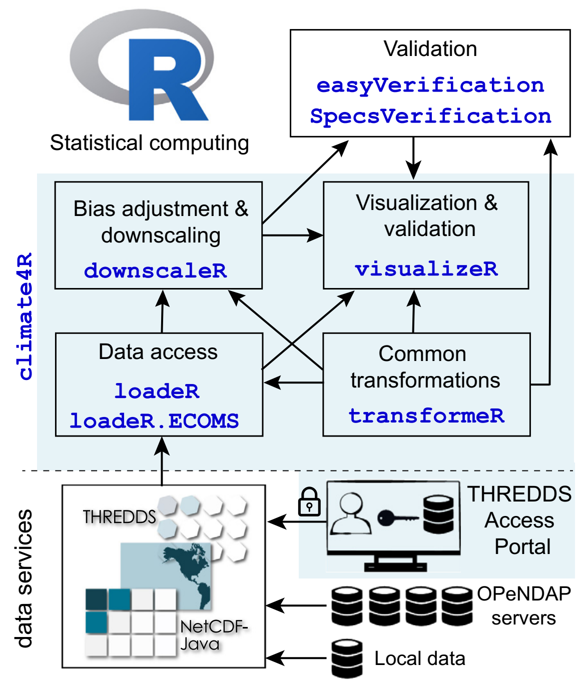

Fig. 1. Schematic illustration of the ECOMS-UDG components, including the THREDDS Data Server (TDS), the THREDDS Access Portal (TAP) and the `climate4R` interface for data access and postprocessing, formed by several packages for data access, transformation, bias adjustment and visualization and validation. Compatibility with some external packages has been achieved by appropriate two-way bridging functions (for the corresponding data structures). Arrows indicate data flow and blue shading indicates in–house developments. All componentes are distributed under GNU General Public License. Some of the images are courtesy of UCAR/Unidata. The R logo is ©2016 The R Foundation.

transformation (`transformeR` package, Bedia and Iturbide, 2017) and bridging some existing packages developed in the framework of ECOMS for bias adjustment and downscaling (`downscaleR` package, Bedia et al., 2017), and forecast visualization and validation (`visualizeR` package, Frías et al., 2017). Moreover, transparent connection to other external packages (e.g. `easyVerification` package, MeteoSwiss, 2017) was also developed by implementing two-way bridging functions for the corresponding data structures (documented in the corresponding packages). The resulting R bundle (referred to as `climate4R`) provides a unique framework with which data access, postprocessing and validation can be performed using a few lines of code. This allows end-to-end experimental reproducibility and facilitates the description (metadata) and documentation of the whole data flow. An up-to-date description of ECOMS-UDG, including information on the available datasets, variables and tools is provided in the wiki page: http://www.meteo.unican.es/ecoms-udg.

This work describes the structure of ECOMS-UDG and illustrates its application with a case study over Europe, analyzing seasonal predictability of winter (DJF) temperatures and precipitation, in connection to NAO predictability. Research reproducibility has been a major concern in the development of ECOMS-UDG. Therefore, it was developed using open-source tools (THREDDS server, the THREDDS Access Portal, and R), thus favoring transparency, openness and reproducibility of the results. Although some of the datasets used in this work are restricted to ECOMS partners, there is a minimum amount of information (e.g. WFDEI observations, NCEP/NCAR reanalysis, CFSv2 seasonal forecasts) openly accesible, which allows reproducing the results here presented (the full code is provided in a companion vignette available at http://meteo.unican.es/work/UDG/climate-services-manuscript.html) and also allows a public unrestricted use of ECOMS-UDG for other research activities.

This paper is structured as follows: Section 2 describes the main components of the ECOMS-UDG. An illustrative application case study focusing on NAO predictability is presented in Section 3. Finally, conclusions are given in Section 4.

2. The ECOMS-UDG data service

The ECOMS User Data Gateway consists of three main componentes: (1) THREDDS Data Server, (2) THREDDS Access Portal and (3) an API/bundle of R packages for data access and postprocessing (the `climate4R` bundle). The fist two components provide standard services for data access (e.g. OPeNDAP and NetCDF Subset Service) and user management and authentication (based on data policies associated with virtual datasets). The third component is an extra layer for data access and postprocessing based on the R statistical computing language. Fig. 1 provides an schematic view of the service. These components are described in detail in the following sections (full documentation at http://www.meteo.unican.es/ecoms-udg).

2.1. The THREDDS Data Server (TDS)

The THREDDS Data Server (TDS) developed by unidata/NCAR provides catalog, metadata, and data access services (HTTP, OPeNDAP, OGC WCS, OGC, and WMS) for scientific data. The catalogs are XML documents that list (virtual) datasets and the data access services available for the datasets. This allows separating the data/metadata service layer from the physical organization of the datasets (in files), aggregating a collection of data resources into a single virtual dataset, thus greatly simplifying user access to the data collection.

ECOMS-UDG builds on a TDS with an extra layer for user management and authentication (see next section). The variables required in the ECOMS sectorial applications were identified (see Table 1), downloaded from data providers, and stored locally in a TDS. These include:

- Observational data: WFDEI (Weedon et al., 2014).
- Reanalysis data: NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996) and ERA-Interim (Dee et al., 2011).
- Seasonal forecasts from state-of-the-art forecasting systems: NCEP-CFSv2 (Saha et al., 2011), ECMWF-System4 (Molteni et al., 2011) and UKMO-GloSea5 (Scaife et al., 2014). For the latter two models, two different virtual datasets were defined to aggregate homogeneous datasets (with an equal number of members) from all the available information. The labels S4(15) and S4(51) refer to the seasonal System4 datasets with 15 and 51 members, respectively, with monthly initializations in the first case, and four initializations per year in the latter (1st of Nov, Feb, May and Aug). The labels GS5(12) and GS5(24) correspond to the GloSea5 hindcast with 12 and 24 mem-

Table 1
Variables available at ECOMS-UDG for some observational, reanalysis and seasonal hindcast datasets (see text for details). The codes used by the R interface and the variable description (including the corresponding CF standard names; see http://cfconventions.org/standard-names.html) are given in the first two columns. The different cell codes indicate the temporal resolution(s) of the available data: 6 h (six-hourly instantaneous data), 12 h (12-hourly instantaneous data), 6hA (six-hourly accumulated), DM (daily mean), MM (monthly mean), DX (daily maximum), DN (daily minimum), DA (daily accumulated), DAr (accumulated since the initialization time); 'fx' denotes statistic fields (i.e. no time dimension). The code '@' indicates that data is available at the following pressure levels (1000,850,700,500,300,200 mb, except for hus, which is not available at 200mb in some models). The codes of open access datasets are boldfaced. Some codes refer to variables only accessible through the R interface: Codes ended by '(∗)' indicate variables which do not exist in the dataset, but are derived/approximated from other available ones through the R interface; similarly, variables ended by '(#)' indicate daily aggregated values obtained from the corresponding original 3-hourly data.

		Obs.	Reanalysis		Seasonal hindcasts			
R code	Variable description (Inc. **standard_names**)	**WFDEI**	**NCEP**	ERAInt	**CFSv2**	S4(15)	S4(51)	GS5(12&14)
tas	Near-surface **air_temperature**	DM	6 h	DM	6 h	6 h/DM	DM/MM	DM
tasmax	Maximum near-surface **air_temperature**	DX(#)	6 h	DX	6 h	DX	DX	DX
tasmin	Minimum near-surface **air_temperature**	DN(#)	6 h	DN	6 h	DN	DN	DN
pr	**precipitation_amount**	DA(∗)	6hA	DA	6 h	DAr	DAr/MA	DA
psl	**air_pressure_at_sea_level**	–	6 h	DM	6 h	6 h	6 h/MM	DM
ps	**surface_air_pressure**	DM	–	–	6 h	6 h(∗)		–
wss	Near-surface **wind_speed**	DM	–	–	6 h(∗)	6 h(∗)	–	–
tdps	Near-surface **dew_point_temperature**	–	–	–	–	6 h	–	–
huss	Near-surface **specific_humidity**	DM	6 h	–	6 h	6 h(∗)	–	–
hurs	Near-surface **relative_humidity**	DM	6 h	–	6 h(∗)	6 h(∗)	–	–
rsds	**surface_downwelling_shortwave_flux**	DA	6hA	–	–	DAr	–	DA
rlds	**surface_downwelling_longwave_flux**	DA	6hA	–	–	DAr	–	–
uas	Near-surface **eastward_wind**	–	6 h	–	6 h	6 h	–	–
vas	Near-surface **northward_wind**	–	6 h	–	6 h	6 h	–	–
ua	**eastward_wind**	–	6 h@	DM@	–	12 h@	–	–
va	**northward_wind**	–	6 h@	DM@	–	12 h@	–	–
zg	**geopotential_height**	–	6 h@	DM@	–	12 h@	–	–
ta	**air_temperature**	–	6 h@	DM@	–	12 h@	–	–
hus	**specific_humidity**	–	6 h@	DM@	–	12 h@	-	-
zgs	Surface **geopotential_height**	–	–	–	–	fx	–	–
orog	**surface_altitude**	–	–	–	fx	–	–	–
lm	**land_binary_mask**	–	–	–	fx	–	–	–

bers, respectively, with four initializations per year in the first case and a single initialization (November, to focus on Boreal winter) in the latter. Full information about ensemble formation is provided at the wiki page http://www.meteo.unican.es/ecoms-udg.

Table 1 shows the great heterogeneity of temporal resolutions available for the different datasets (specified by different codes in the table). The harmonization of these datasets is performed via the R interface for data access (see Section 2.3).

2.2. The THREDDS Access Portal (TAP)

The TAP is the user management and authorization web application which controls user access to data resources (datasets via virtual catalogs) exposed in a TDS. This is done by defining thematic groups which are sets of datasets (sharing a common data policy) together with the corresponding data access policy. For instance, there is a PUBLIC_DATA thematic group which includes data from publicly available datasets: observations (WFDEI), reanalysis (NCEP/NCAR reanalysis1), seasonal hindcasts (CFSv2), etc. The TAP also includes different thematic groups for particular projects and initiatives. The ECOMS thematic group (restricted to members of the ECOMS projects) focuses on seasonal forecasting and includes restricted seasonal hindcasts (e.g. System4 and GloSea5), as well as some other restricted products (ERA-Interim), which are only accessible to project partners, according to the particular data policies obtained from the data providers. TAP users are associated with some of the different thematic groups, which allow accessing different datasets with the corresponding data policies. Registration in TAP (http://meteo.unican.es/ecoms-udg/dataserver/registration) is free and provides access by default to the PUBLIC_DATA thematic group.

The goal of the TAP project was providing a solution to the problem of user management, roles definition (datasets + data policies) and dataset access existing in the Unidata THREDDS application and it is distributed under GNU General Public License. More technical information is given at http://meteo.unican.es/trac/wiki/tap.

2.3. Data Access and PostProcessing (`climate4R` bundle)

The `loadeR` package was developed to provide a user-friendly connection to the User Data Gateway (UDG), implementing transparent user authentication and data access building on NetCDF-Java (see Fig. 1). More information about this package is given at https://github.com/SantanderMetGroup/loadeR/wiki.

The different nature of the datasets, and the idiosyncratic naming and storage conventions of the ECOMS thematic group (particularly for seasonal forecast data), made it necessary to develop an harmonization module across datasets in order to implement a truly user-friendly toolbox for data access. To this aim, an extension of the `loadeR` package (`loadeR.ECOMS`) was developed, including (1) the definition of the available datasets (with all the necessary information for data access), (2) a single common vocabulary (the variables and codes are shown in the first two columns of Table 1; units are not shown) and (3) a dictionary for each of the datasets to map the particular existing variables to the common vocabulary, including transformations (for unit conversion, e.g. −273.15 for conversion of K to °C, de-accumulation, etc.) when needed. Note that these functionalities are needed in order to cope with the great heterogeneity of temporal resolutions available for the different ECOMS-UDG datasets (Table 1, specified by different cell codes). In some cases, the values are daily mean values (DM) or daily accumulated values (DA), whereas in others the values correspond to the accumulated values since the initialization time (DAr) —so differences with the previous day (de-accumulation) have to be taken in order to obtain daily accumulated value.—.

Moreover, in some particular cases the requested variables are not available in the original dataset, but can be derived/approximated using existing variables. Codes ended by '(*)' in Table 1 indicate variables which do not exist in the dataset, but are derived/approximated from other available ones through the R interface. For instance, for the System 4 15-members dataset, relative humidity is obtained from surface temperature (tas) and surface dew point temperature (tdps). Similarly, variables ended by '(#)' indicate daily aggregated values obtained from the corresponding original 3-hourly data. All the details are described in http://meteo.unican.es/ecoms-udg/catalog

In addition to the packages for data loading and harmonization, the interface was extended including a number of packages for postprocessing, building on the same data structures:

- `transformeR` (Bedia and Iturbide 2017) performs data postprocessing tasks such as re-gridding/interpolation, principal component/EOF analysis, detrending, aggregation, subsetting, etc., being fully integrated with the different packages here enumerated. Examples of application are available in the transformeR's wiki (https://github.com/SantanderMetGroup/transformeR/wiki).
- `downscaleR` (Bedia et al., 2017) is an R package for bias adjustment and statistical downscaling of daily data, including several standard techniques such as local scaling, quantile mapping, analogs, linear and generalized linear regression, etc. An introduction to the package and examples of application are available in the downscaleR's wiki (https://github.com/SantanderMetGroup/downscaleR/wiki).
- `visualizeR` (Frías et al., 2017) is an R package implementing a set of advanced tools for forecast visualization and verification, such as tercile plots, bubble and pie plots, reliability categories, etc. It allows visualizing seasonal predictions and/or validation results, in a form suitable to communicate the underlying uncertainty (https://github.com/SantanderMetGroup/visualizeR).
- Integration with other external packages. As part of the ECOMS initiative, two different verification R packages have been developed: `SpecsVerification`, (Siegert, 2017) in SPECS and `easyVerification` (MeteoSwiss, 2017) in EUPORIAS, implementing new verification metrics for probabilistic forecasts. Several bridging functions have been developed for a complete integration with the previous in–house packages so these packages can be transparently used within the ECOMS-UDG R interface.

The resulting `climate4R` R bundle provides a unique postprocessing framework where data access, postprocessing and validation can be performed using a few lines of code, as shown in the illustrative example below.

3. Illustrative example: NAO predictability

The North Atlantic Oscillation (NAO) emerges over the middle and high latitudes of the Northern Hemisphere as the most prominent pattern of atmospheric variability, affecting European climate (Hurrell et al., 2003). The potential predictability of NAO interannual variability has been an active topic of research in the last decade, and new encouraging advances have been recently reported with state-of-the-art operational seasonal forecasting models (such as GloSea5, Scaife et al., 2014). However, there is some controversy around this topic due to the impact of hindcast length on estimates of seasonal climate predictability (Shi et al., 2015). The restricted access to the data and the above mentioned problems related to data access makes it very difficult for end users to replicate the results, study the sensitivity to different factors, and analyze the potential applicability in their particular sectors. In the present example we illustrate the added value of ECOMS-UDG in this context.

We focus on NAO during Boreal winter (DJF) and investigate (1) to what extent NAO interannual variability can be skillfully reproduced by state-of-the-art forecasting systems and (2) how this is related to their skill in predicting regional precipitation and temperature over western Europe.

3.1. Loading data

The steps followed for data loading are next briefly described, considering observations, reanalysis (for the definition of the NAO index) and seasonal forecast data. Some code is interwoven within the text in order to illustrate the main characteristics of the R interface. Each line of code is identified by the R prompt symbol (>). Extended reproducible examples to obtain the different datasets and the figures presented in this paper are included in the companion vignette (http://meteo.unican.es/work/UDG/climate-services-manuscript.html).

Prior to data access, authentication is required to access the UDG. The authentication is performed in one step:

```
> library(loadeR.ECOMS)
> loginUDG(username = "jDoe", password = "****")
```

The following call to the function `loadECOMS` retrieves the NCEP/NCAR reanalysis (`dataset = "NCEP_reanalysis1"`) sea-level pressure field (`var = "psl"`), considering the NAO spatial domain (`lonLim = c(-90,40)`, `latLim = c(20,80)`). Note that `"psl"` corresponds to the harmonized nomenclature defined by the UDG vocabulary for sea-level pressure (see Section 2.3). Furthermore, the requested seasonal data correspond to boreal winter (DJF, `season = c(12,1,2)`), and considers the whole available period (1949–2010, thus the argument `"years"` is omitted). As the original data are 6-hourly, data are aggregated on-the-fly by the R interface through the arguments `time = "DD"` (to convert the data from 6-h to daily), `aggr.d = "mean"` (to indicate the aggregation function) and `aggr.m = "mean"` (which indicates that the resulting daily data will be monthly averaged).

```
> loadECOMS(dataset = "NCEP_reanalysis1",
           var = "psl", season = c(12,1,2),
           lonLim = c(-90,40), latLim = c(20,80),
           time = "DD",
           aggr.d = "mean",
           aggr.m = "mean")
```

The corresponding seasonal forecast data are loaded in a similar way, but in this case it is necessary to specify two additional parameters to unequivocally define the data requested: the members (for instance, the first 24 members: `members = 1:24`) and the initialization to be considered (e.g., 1-month ahead predictions: `leadMonth = 1`; this will correspond to November initialization in the present example). Here, we illustrate this step using the data from the CFSv2 hindcast (`dataset = "CFSv2_seasonal"`).

```
> loadECOMS(dataset = "CFSv2_seasonal",
           var = "psl", season = c(12,1,2),
           lonLim = c(-90,40), latLim = c(20,80),
           time = "DD",
           aggr.d = "mean", aggr.m = "mean",
           members = 1:24,
           leadMonth = 1)
```

Note that the only difference between this example and the other two hindcasts compared in this paper lies just in the dataset specification: `dataset = "Glosea5_seasonal_24"` for the UKMO Glosea5 hindcast of 24 members, or `dataset = "System4_seasonal_51"` for the ECMWF System4 seasonal hindcast of 51 members. Thanks to the data harmonization performed by the R interface to ECOMS-UDG, the rest of parameters remain exactly the same. Member selection is also transparent to the user, who doesn't need to worry about the different member configurations for different hindcasts. As an example, see the CFSv2 lagged runtime member configuration and its translation by `loadECOMS` in this link: http://meteo.unican.es/ecoms-udg/dataserver/datasets/CFSv2.

Similarly, loading the data for near-surface air temperature in the same domain is directly achieved by just replacing the harmonized variable name from sea-level pressure (`var = "psl"`) to air temperature (`var = "tas"`) in the examples above.

In order to perform the regional forecast verification over western Europe, the E-OBS dataset (v15, Klein Tank et al., 2002) is used as observed reference. In this example, we load observations from

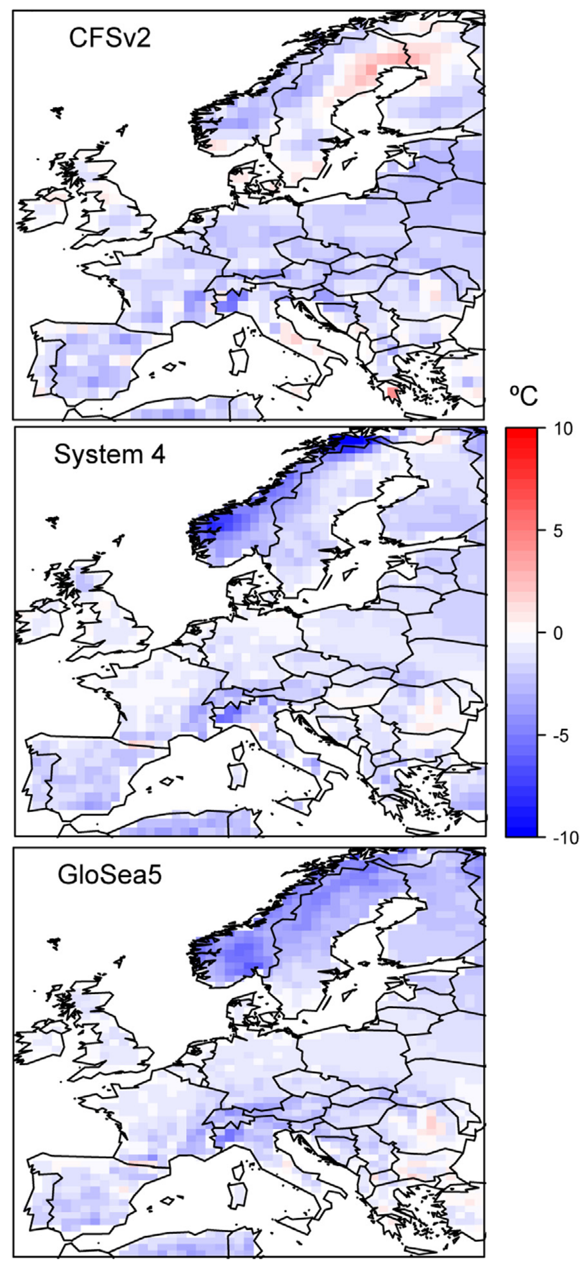

Fig. 2. Ensemble mean bias of winter surface temperature for the multimodel common period 1993–2010, using the E-OBS dataset (Klein Tank et al., 2002) as reference. The original resolution of each model has been preserved.

the E-OBS database directly from the KNMI OPeNDAP server, demonstrating the capabilities of the R interface developed for climate data load beyond the ECOMS-UDG. The main difference with the previous loading examples is the replacement of the argument dataset by a valid OPeNDAP URL. In this particular example `dataset = "http://opendap.knmi.nl/knmi/thredds/dodsC/e-obs_0.50regular/tg_0.50deg_reg_v15.0.nc"`. In this case, however, data harmonization is not automatic, since there is no dictionary for this external dataset, and the user needs to take care of the necessary data transformations and variable names. A full example is provided in the companion vignette.

3.2. Analyzing model biases

Global seasonal forecast systems exhibit systematic biases when compared with observations. This is related to complex topography and land-sea contrasts, which are not well represented in the global models (current model resolutions range from ~60 to 100 km). For instance, Fig. 2 shows the temperature biases of the three seasonal forecasting datasets available from ECOMS-UDG, considering the E-OBS observation data, as loaded in the previous section. Note that System4 and GloSea5 exhibit a very similar bias pattern, with a strong cold bias in Northern Europe, whereas CFSv2 exhibits a more uniform bias pattern. Moreover, these models are unable to provide information at the regional or local spatial scales required in a number of sectors.

Therefore, a number of bias adjustment and downscaling methods have been recently proposed to calibrate the raw model outputs, providing suitable regional inputs for impact models. The R package downscaleR (Bedia et al., 2017) allows to easily bias correct and downscale the global model outputs. A comprehensive example of bias-correction of seasonal forecast data using ECOMS-UDG is provided in a separate paper in this special issue (Bedia et al., 2018).

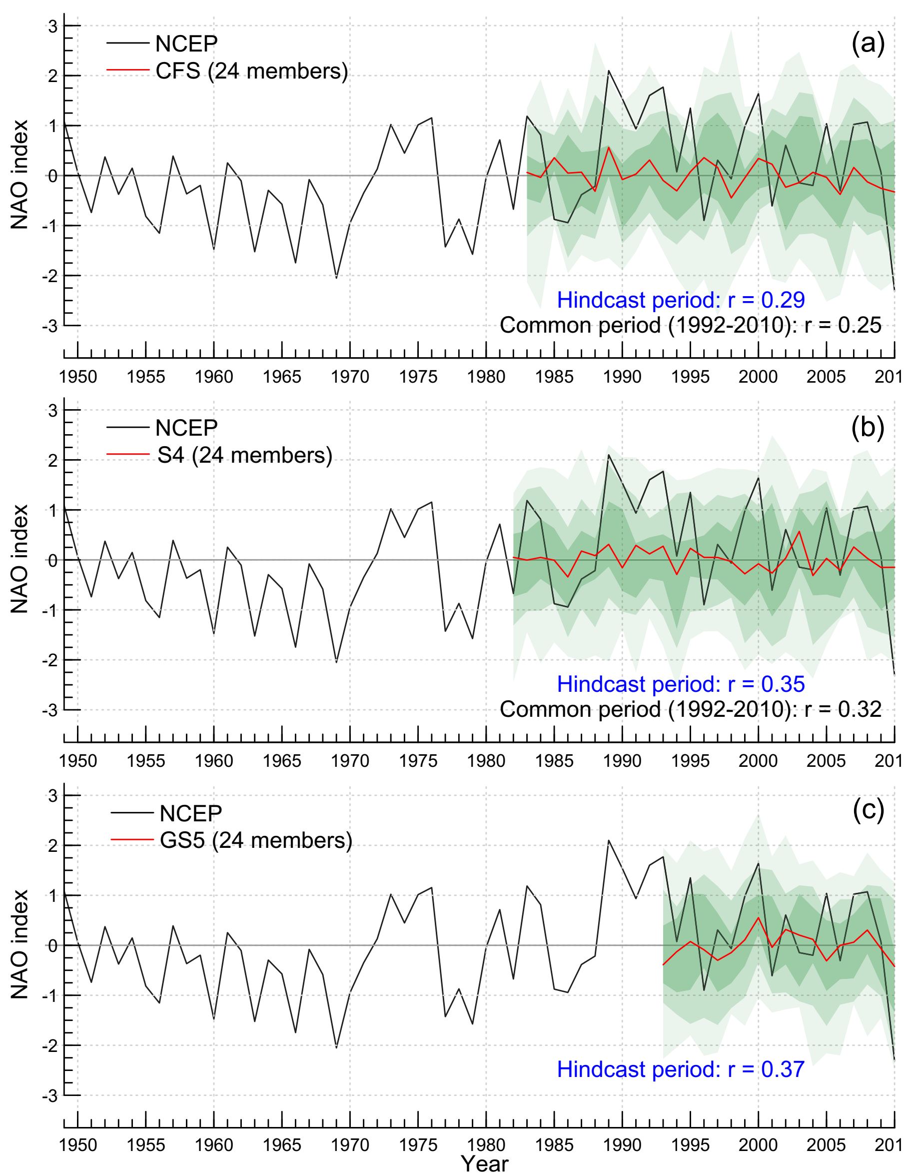

Fig. 3. Seasonal predictions of the winter NAO interannual variability by three different seasonal products: CFSv2 (a), System 4 (b) and Glosea5 (c). The observed NAO (calculated from the mean sea-level pressure anomalies over the North Atlantic as represented by the NCEP/NCAR reanalysis) is depicted in all panels by the black line. The ensemble mean is represented by the red line. The green shading indicates, from lighter to darker, the envelopes delimited by min–max (range), 10th–90th percentiles and interquartile range of the ensemble respectively. The Pearson's correlation coefficients (r) between the observations and the ensemble mean series are indicated in each plot, calculated upon the complete pairs of observations/predictions in each case.

3.3. Analysing Winter NAO predictability

There is no unique way to define the spatial structure of NAO and its temporal evolution. Here, we consider the definition based on the principal component time series of the leading EOF of the mean winter (DJF) sea-level pressure anomalies over the Atlantic sector (Hurrell, 2016). First, we use NCEP/NCAR reanalysis data to compute the EOF and the corresponding PC time series. Afterwards, we projected the seasonal forecast model data on the resulting EOFs to obtain the predicted NAO time series. The post-processing capabilities of the R package `transformeR` allow calculating these indices with a few simple commands, using the function `computeEOF` to compute the NCEP EOF and the function `PC2grid` to project the CFSv2 data (see the companion vignette for full details).

Fig. 3 shows the resulting observed and predicted NAO interannual series together with their correlation, as a simple measure of association. These correlations are computed both for the full hindcast periods and also for the common period for the three datasets (1993–2010). It can be seen that GloSea5 provides the better results for the common period. However, these results are sensitive to the particular definition of the NAO index (the companion vignette shows the results for a point-based NAO definition, based on the Icelandic low and Azores high). Moreover, as shown by Shi et al. (2015), the result may strongly depend on the hindcast length. Furthermore, there is also uncertainty linked to the ensemble size and the member selection. Therefore, some kind of sensitivity analysis is necessary to fully analyze the performance of the forecasting systems to predict the NAO interannual fluctuations.

This kind of sensitivity analysis (using, e.g. bootstrapping) can be performed in R in a simple and efficient way (see the companion vignette for full details). For instance, Fig. 4 shows the sensitivity of the correlation results for CFSv2 after a simple bootstrapping analysis sampling (5000 samples with replacement) the members of the ensemble, the years of the hindcast and both factors simultaneously. This figure shows the large variability of results that could be obtained under this experimental framework, with larger correlations obtained when sampling the years. This may allow end users to better understand the potential predictability results shown in Fig. 3 and decide whether or not to use bootstrapped series in their applications in order to sample this uncertainty.

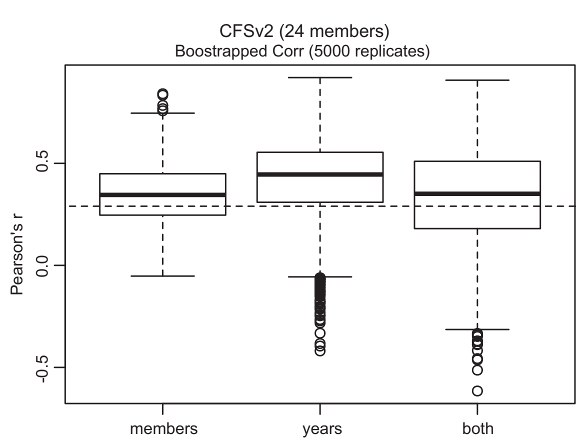

Fig. 4. Boxplot of bootstrapped interannual correlations of observed and predicted (CFSv2) NAO time series obtained from 5000 samples of the ensemble members (left), the years (centers) and both (right). The horizontal dashed line indicates the correlation of the full set without bootstrapping.

3.4. Validation of temperature in the North-Atlantic domain

The results above suggest a slight improvement of the skill of System4 and GloSea5 as compared to CFSv2 in the representation of the Winter NAO. In order to ascertain whether this has an impact on temperature predictability over the NAO domain, a correlation analysis is performed (Fig. 5). While the results show a significant improvement of correlation for GloSea5 over a sizable proportion of the study area, the results over western Europe remain similar for the three forecasting systems tested, slightly better for CFSv2 over NE Europe. These results are in agreement with Scaife et al. (2014) for the case of GloSea5, thus giving some prospect of research reproducibility, although we couldn't fully reproduce the results of the NAO index correlation, most likely due to the different ways in which alternative NAO calculations can differ (see Section 3.3). This particular NAO example highlights the compelling need for research reproducibility.

3.5. Regional validation over Europe

Besides the above synoptic analysis of model performance considering the NAO index (or temperatures over the North Atlantic domain), end users are usually more interested in the regional validation of the predictions for the different variables used in impact applications (e.g. temperature and precipitation) at a suitable resolution (using high-resolution observations). It is clear that improving the skill of the models to predict NAO interannual fluctuations would have a positive effect in the regional skill of the models. However, quantifying this effect is not evident, since the NAO explains a small fraction of the regional climatic variability in Europe. Therefore, in order to obtain comprehensible and actionable information of model performance for particular end-user applications, tools are needed allowing for a regional validation of these models.

ECOMS-UDG offers the possibility to efficiently compute a variety of validation indices (both for the ensemble mean and for probabilistic forecasts) building on external packages (such as `easyVerification`) which have been bridged to the ECOMS-UDG R bundle. For instance, Fig. 6 shows the anomaly correlation scores obtained for temperature and precipitation for the common hindcast period. In this case, GloSea5 exhibits the lowest correlations, although it shows the highest NAO correlation in the common hindcast period (see Fig. 3). A description of further validation measures is provided in the companion vignette.

3.6. Visualization of model predictions and validation

Finally, in recent times there has been an intense work in developing suitable tools for the communication of the uncertainty of seasonal forecasts, both the uncertainty inherent to probabilistic predictions, and the uncertainty derived from the skill of the model. The R package `visualizeR` includes a number of graphical tools to visualize model predictions, filtering non-skilful regions and/or including information about past model performance. For instance, tercile plots allow to visualize the series of predictions and observations for a particular period over a selected domain (it may be computed on single gridboxes as well). The corresponding terciles for the joint ensemble are then calculated to define three categories (i.e. below-normal, normal and above-normal conditions). The observed terciles (the events that actually occurred) are also represented on top, allowing for a quick visual overview of observations and predictions. Finally, the ROC Skill Score (ROCSS) is indicated in the secondary (right) Y axis. ROCSS is directly derived from the area under the ROC (*Receiver Operating Characteristic*) curve, and it is an indicator of the quality of a forecast by describing the system's ability to discriminate correctly

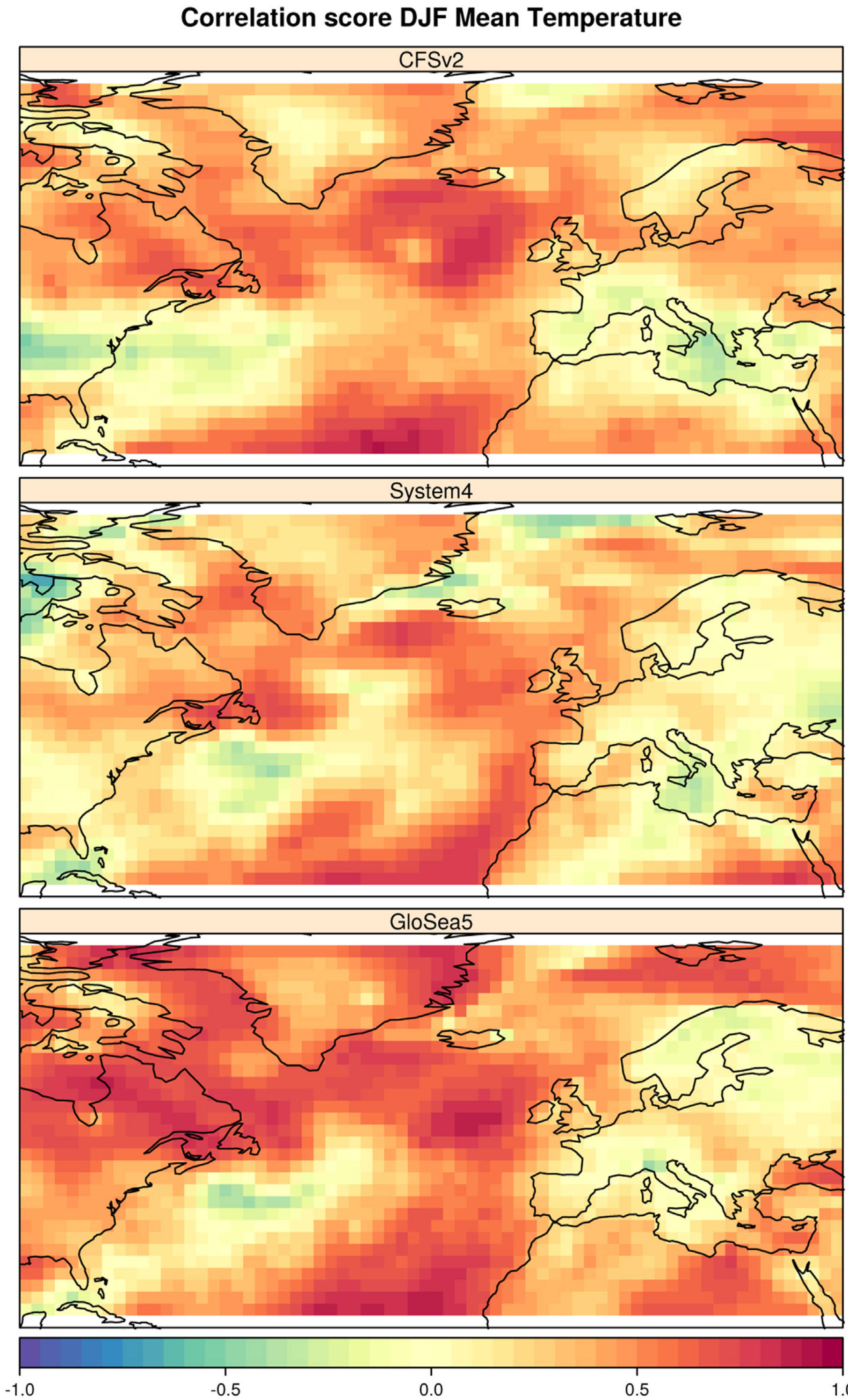

Fig. 5. Forecast skill (Pearson's correlation coefficient) of surface winter mean temperature against the observations from the NCEP/NCAR reanalysis, considering the predictions of CFSv2 (top), System 4 (middle) and GloSea5 (bottom) forecasting systems.

between the binary variable occurrence/non-occurrence of a certain event (Jolliffe and Stephenson, 2003).

A typical end-user need is the assessment of forecast quality over a small region of interest. Fig. 7 illustrates the use of tercile plots (see e.g. Díez et al., 2011; Bedia et al., 2018), calculated for a small domain centred on southern UK (-5.5–2.5°E, 50.5–54°N).

4. Conclusions

The ECOMS User Data Gateway (ECOMS-UDG) was developed in the framework of the ECOMS initiative as a one-stop-service for climate data building on a THREDDS server and including a fine-grained user management and authorization scheme through the THREDDS Access Portal (TAP). This allows (1) integrating

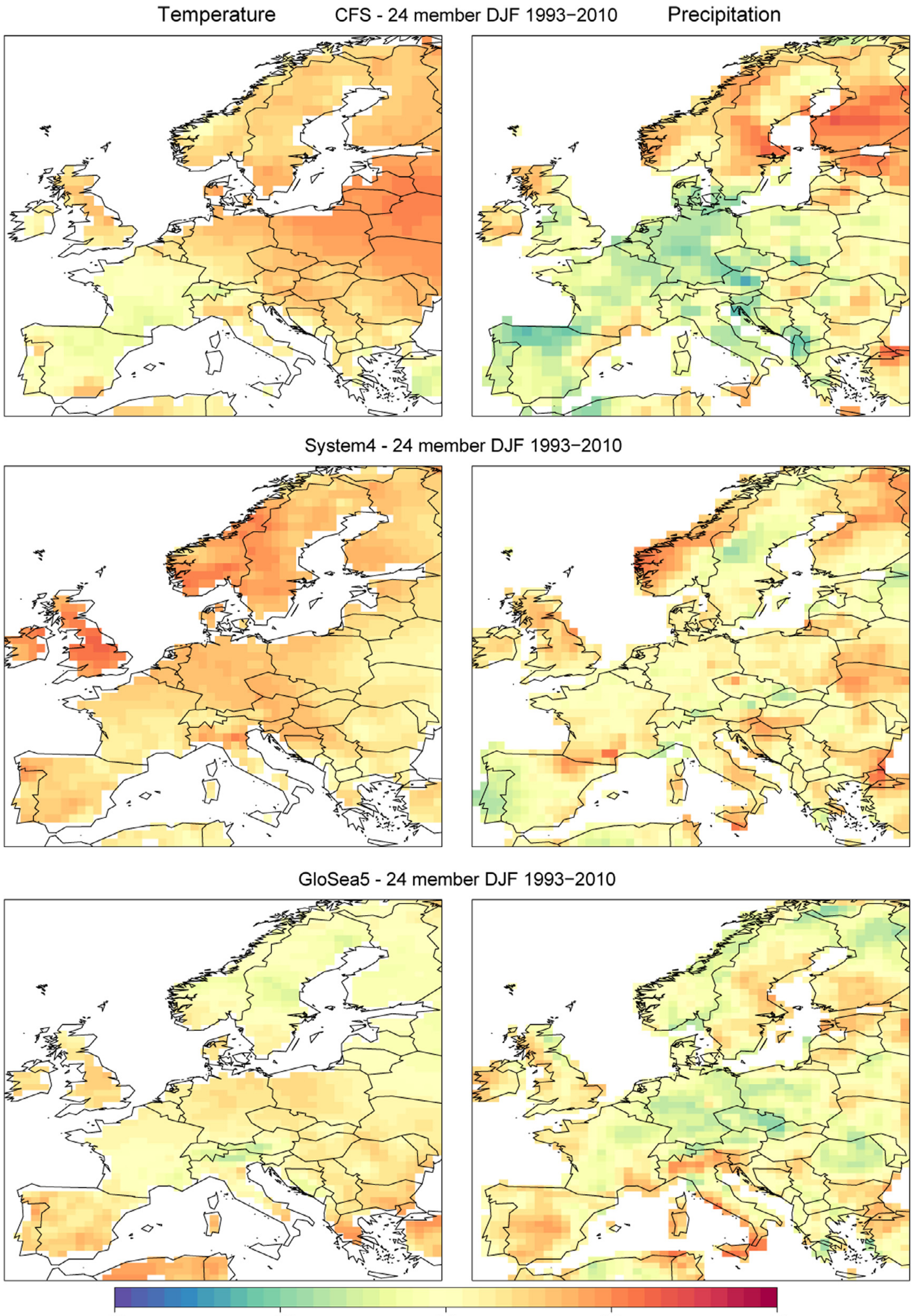

Fig. 6. Skill maps (Pearson's correlation coefficient) of the seasonal predictions of winter surface temperature (left) and precipitation (right) over western Europe by three different seasonal products: CFSv2 (top), System 4 (middle) and Glosea5 (bottom). The maps show the correlation of the ensemble mean predictions against observed temperature from the NCEP/NCAR reanalysis and precipitation from the E-OBS dataset (v15, Klein Tank et al., 2002).

heterogeneous datasets (observations, reanalysis, seasonal reforecasts) with different terms of use (e.g. public or restricted to participants in the ECOMS initiative), and (2) harmonizing formats, temporal aggregations, and vocabularies across datasets. As a result, users can transparently access harmonized data (including multi-model seasonal forecasts) for sector-specific applications. Besides the standard data access services, an additional interface is provided for R users, formed by a bundle of seamlessly

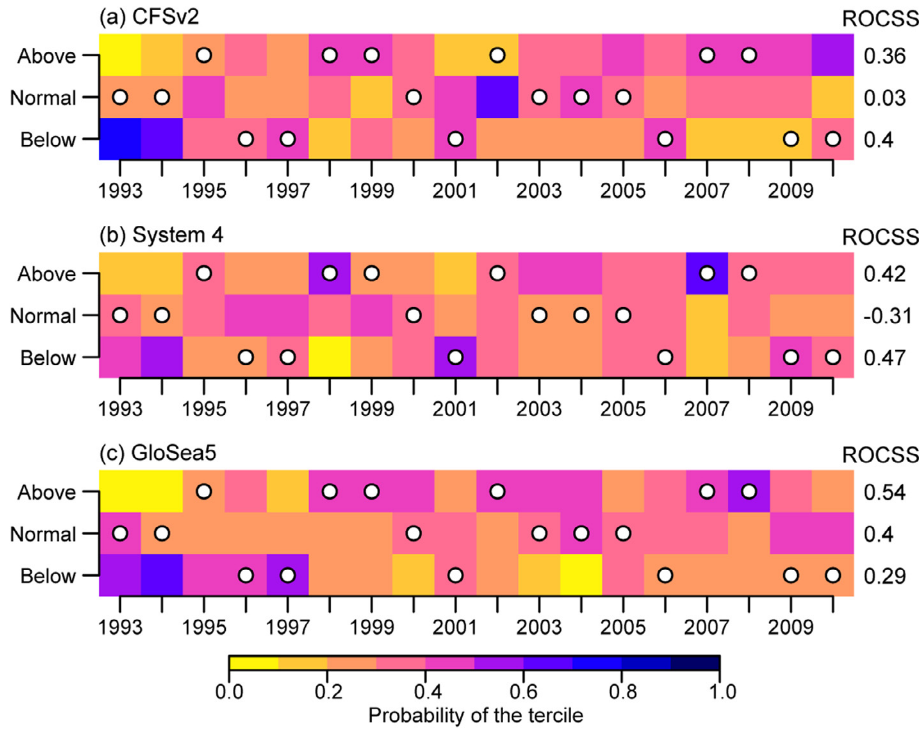

Fig. 7. Forecast skill visualization by means of tercile plots, implemented in package `visualizeR`. The tercile plots are presented for the three forecasting systems available in ECOMS-UDG: CFSv2 (top), System 4 (middle) and GloSea5 (bottom). The results correspond to the spatially averaged predictions for a domain encompassing southern UK. Terciles are arranged by rows. White dots indicate the tercile of the observations for each particular year. Further details for graph interpretation are given in the text.

integrated R packages. The `climate4R` bundle allows accessing user-defined subsets of data from ECOMS-UDG, and provide tools for climate data manipulation (aggregation, interpolation, subsetting, etc.), bias adjustment and statistical downscaling, and seasonal forecast verification and visualization. This allows end-to-end experimental reproducibility and facilitates the description (metadata) and documentation of the whole data flow. An up-to-date description of ECOMS-UDG, including information on the available datasets, variables and tools is provided in the wiki page: http://www.meteo.unican.es/ecoms-udg.

The main characteristics and capabilities of ECOMS-UDG are briefly illustrated with a worked case study over Europe, analyzing seasonal predictability of winter (DJF) temperatures and precipitation, in connection with the North Atlantic Oscillation (NAO) predictability at seasonal time scales. Although some of the datasets used are restricted to ECOMS partners due to data access constraints imposed by the data providers, there is a minimum amount of information (e.g. WFDEI observations, NCEP/NCAR reanalysis and CFSv2 seasonal forecasts) openly accessible, which allows reproducing the results here presented and for a public, unrestricted use of the ECOMS-UDG for other research activities. The code to reproduce the results presented in this paper examples are included in a companion vignette (http://meteo.unican.es/work/UDG/climate-services-manuscript.html), with all the necessary instructions for registration and worked examples.

ECOMS-UDG is built upon different open-source software components publicly available: The UNIDATA THREDDS data server, the THREDDS Access Portal (TAP, https://meteo.unican.es/trac/wiki/tap), and the `climate4R` R bundle. Therefore, the entire architecture could be replicated in any server (although the difficult part is downloading and harmonizing the datasets). Finally, it is important to remark that the ECOMS-UDG does not provide operational forecasts, but only retrospective forecasts (hindcasts) and reference data (observations and reanalysis) for exploring the skill and potential application of state-of-the-art seasonal forecasting systems in specific impact sectors. Therefore, operational applications would require accessing (downloading) the operational predictions directly from the provider; however, `climate4R` could still be used to transparently access the downloaded local dataset (e.g. using the corresponding hindcast dictionary), thus facilitating this task.

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