

Package ‘CSTools’

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Title Assessing Skill of Climate Forecasts on Seasonal-to-Decadal Timescales

Version 1.0.1

Description Exploits dynamical seasonal forecasts in order to provide information relevant to stakeholders at the seasonal timescale. The package contains process-based methods for forecast calibration, bias correction, statistical and stochastic downscaling, optimal forecast combination and multivariate verification, as well as basic and advanced tools to obtain tailored products. This package was developed in the context of the ERA4CS project MEDSCOPE.

Doblas-Reyes et al. (2005) <doi:10.1111/j.1600-0870.2005.00104.x>.

Mishra et al. (2018) <doi:10.1007/s00382-018-4404-z>.

Terzago et al. (2018) <doi:10.5194/nhess-18-2825-2018>.

Torralba et al. (2017) <doi:10.1175/JAMC-D-16-0204.1>.

D'Onofrio et al. (2014) <doi:10.1175/JHM-D-13-096.1>.

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areave_data	<i>Sample Of Experimental And Observational Climate Data Averaged Over A Region</i>
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Description

This sample data set contains area-averaged seasonal forecast and corresponding observational data from the Copernicus Climate Change ECMWF-System 5 forecast system, and from the Copernicus Climate Change ERA-5 reconstruction. Specifically, for the 'tas' (2-meter temperature) variable, for the 15 first forecast ensemble members, monthly averaged, for the 3 first forecast time steps (lead months 1 to 4) of the November start dates of 2000 to 2005, for the Mediterranean region (27N-48N, 12W-40E).

Details

It is recommended to use the data set as follows:

```
require(zeallot)
c(exp, obs)
```

The 'CST_Load' call used to generate the data set in the infrastructure of the Earth Sciences Department of the Barcelona Supercomputing Center is shown next. Note that 'CST_Load' internally calls 's2dverification::Load', which would require a configuration file (not provided here) expressing the distribution of the 'system5c3s' and 'era5' NetCDF files in the file system.

```
library(CSTools)
require(zeallot)

startDates <- c('20001101', '20011101', '20021101',
                '20031101', '20041101', '20051101')

areave_data <-
  CST_Load(
    var = 'tas',
    exp = 'system5c3s',
    obs = 'era5',
    nmember = 15,
    sdates = startDates,
    leadtimemax = 3,
    latmin = 27, latmax = 48,
    lonmin = -12, lonmax = 40,
    output = 'areave',
    nprocs = 1
  )
```

Author(s)

Nicolau Manubens <nicolau.manubens@bsc.es>

CST_Anomaly

Anomalies relative to a climatology along selected dimension with or without cross-validation

Description

This function computes the anomalies relative to a climatology computed along the selected dimension (usually starting dates or forecast time) allowing the application or not of crossvalidated climatologies. The computation is carried out independently for experimental and observational data products.

Usage

```
CST_Anomaly(exp = NULL, obs = NULL, cross = FALSE, memb = TRUE,
            dim_anom = 3)
```

Arguments

exp	an object of class <code>s2dv_cube</code> as returned by <code>CST_Load</code> function, containing the seasonal forecast experiment data in the element named <code>\$data</code> .
obs	an object of class <code>s2dv_cube</code> as returned by <code>CST_Load</code> function, containing the observed data in the element named <code>\$data</code> .
cross	A logical value indicating whether cross-validation should be applied or not. Default = <code>FALSE</code> .
memb	A logical value indicating whether <code>Clim()</code> computes one climatology for each experimental data product member(<code>TRUE</code>) or it computes one sole climatology for all members (<code>FALSE</code>). Default = <code>TRUE</code> .
dim_anom	An integer indicating the dimension along which the climatology will be computed. It usually corresponds to 3 (sdates) or 4 (ftime). Default = 3.

Value

A list with two S3 objects, 'exp' and 'obs', of the class 's2dv_cube', containing experimental and date-corresponding observational anomalies, respectively. These 's2dv_cube's can be ingested by other functions in `CSTools`.

Author(s)

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Pena Jesus, <jesus.pena@bsc.es>

See Also

[Ano_CrossValid](#), [Clim](#) and [CST_Load](#)

Examples

```
# Example 1:
mod <- 1 : (2 * 3 * 4 * 5 * 6 * 7)
dim(mod) <- c(dataset = 2, member = 3, sdate = 4, ftime = 5, lat = 6, lon = 7)
obs <- 1 : (1 * 1 * 4 * 5 * 6 * 7)
dim(obs) <- c(dataset = 1, member = 1, sdate = 4, ftime = 5, lat = 6, lon = 7)
lon <- seq(0, 30, 5)
lat <- seq(0, 25, 5)
exp <- list(data = mod, lat = lat, lon = lon)
obs <- list(data = obs, lat = lat, lon = lon)
attr(exp, 'class') <- 's2dv_cube'
attr(obs, 'class') <- 's2dv_cube'

anom1 <- CST_Anomaly(exp = exp, obs = obs, cross = FALSE, memb = TRUE)
str(anom1)
```

```
anom2 <- CST_Anomaly(exp = exp, obs = obs, cross = TRUE, memb = TRUE)
str(anom2)

anom3 <- CST_Anomaly(exp = exp, obs = obs, cross = TRUE, memb = FALSE)
str(anom3)

anom4 <- CST_Anomaly(exp = exp, obs = obs, cross = FALSE, memb = FALSE)
str(anom4)
```

CST_BiasCorrection *Bias Correction based on the mean and standard deviation adjustment*

Description

This function applies the simple bias adjustment technique described in Torralba et al. (2017). The adjusted forecasts have an equivalent standard deviation and mean to that of the reference dataset.

Usage

```
CST_BiasCorrection(exp, obs)
```

Arguments

exp	an object of class <code>s2dv_cube</code> as returned by <code>CST_Load</code> function, containing the seasonal forecast experiment data in the element named <code>\$data</code>
obs	an object of class <code>s2dv_cube</code> as returned by <code>CST_Load</code> function, containing the observed data in the element named <code>\$data</code> .

Value

an object of class `s2dv_cube` containing the bias corrected forecasts in the element called `$data` with the same dimensions of the experimental data.

Author(s)

Verónica Torralba, <veronica.torralba@bsc.es>

References

Torralba, V., F.J. Doblas-Reyes, D. MacLeod, I. Christel and M. Davis (2017). Seasonal climate prediction: a new source of information for the management of wind energy resources. *Journal of Applied Meteorology and Climatology*, 56, 1231-1247, doi:10.1175/JAMC-D-16-0204.1. (CLIM4ENERGY, EUPORIAS, NEWA, RESILIENCE, SPECS)

Examples

```
# Example
# Creation of sample s2dverification objects. These are not complete
# s2dverification objects though. The Load function returns complete objects.
mod1 <- 1 : (1 * 3 * 4 * 5 * 6 * 7)
dim(mod1) <- c(dataset = 1, member = 3, sdate = 4, ftime = 5, lat = 6, lon = 7)
obs1 <- 1 : (1 * 1 * 4 * 5 * 6 * 7)
dim(obs1) <- c(dataset = 1, member = 1, sdate = 4, ftime = 5, lat = 6, lon = 7)
lon <- seq(0, 30, 5)
lat <- seq(0, 25, 5)
exp <- list(data = mod1, lat = lat, lon = lon)
obs <- list(data = obs1, lat = lat, lon = lon)
attr(exp, 'class') <- 's2dv_cube'
attr(obs, 'class') <- 's2dv_cube'
a <- CST_BiasCorrection(exp = exp, obs = obs)
str(a)
```

CST_Calibration

Forecast Calibration based on the ensemble inflation

Description

This function applies a variance inflation technique described in Doblas-Reyes et al. (2005) in leave-one-out cross-validation. This bias adjustment method produces calibrated forecasts with equivalent mean and variance to that of the reference dataset, but at the same time preserve reliability.

Usage

```
CST_Calibration(exp, obs)
```

Arguments

exp	an object of class s2dv_cube as returned by CST_Load function, containing the seasonal forecast experiment data in the element named \$data.
obs	an object of class s2dv_cube as returned by CST_Load function, containing the observed data in the element named \$data.

Value

an object of class s2dv_cube containing the calibrated forecasts in the element \$data with the same dimensions of the experimental data.

Author(s)

Verónica Torralba, <veronica.torralba@bsc.es>

References

Doblas-Reyes F.J, Hagedorn R, Palmer T.N. The rationale behind the success of multi-model ensembles in seasonal forecasting-II calibration and combination. *Tellus A*. 2005;57:234-252. doi:10.1111/j.1600-0870.2005.00104.x

See Also

[CST_Load](#)

Examples

```
# Example
# Load data using CST_Load or use the sample data provided:
library(zeallot)
c(exp, obs) %<-% areave_data
exp_calibrated <- CST_Calibration(exp = exp, obs = obs)
str(exp_calibrated)
```

CST_Load

CSTools Data Retrieval Function

Description

This function aggregates, subsets and retrieves sub-seasonal, seasonal, decadal or climate projection data from NetCDF files in a local file system or on remote OPeNDAP servers, and arranges it for easy application of the CSTools functions.

Usage

```
CST_Load(...)
```

Arguments

... Parameters that are automatically forwarded to the 's2dverification::Load' function. See details in '?s2dverification::Load'.

Details

It receives any number of parameters ('...') that are automatically forwarded to the 's2dverification::Load' function. See details in '?s2dverification::Load'.

It is recommended to use this function in combination with the 'zeallot::'

Value

A list with one or two S3 objects, named 'exp' and 'obs', of the class 's2dv_cube', containing experimental and date-corresponding observational data, respectively. These 's2dv_cube's can be ingested by other functions in CSTools. If the parameter 'exp' in the call to 'CST_Load' is set to 'NULL', then only the 'obs' component is returned, and viceversa.

Author(s)

Nicolau Manubens, <nicolau.manubens@bsc.es>

Examples

```
## Not run:
library(zeallot)
startDates <- c('20001101', '20011101', '20021101',
               '20031101', '20041101', '20051101')
c(exp, obs) %<-%
  CST_Load(
    var = 'tas',
    exp = 'system5c3s',
    obs = 'era5',
    nmember = 15,
    sdates = startDates,
    leadtimemax = 3,
    latmin = 27, latmax = 48,
    lonmin = -12, lonmax = 40,
    output = 'lonlat',
    nprocs = 1
  )

## End(Not run)
```

CST_MultiMetric

Multiple Metrics applied in Multiple Model Anomalies

Description

This function calculates correlation (Anomaly Correlation Coefficient; ACC), root mean square error (RMS) and the root mean square error skill score (RMSSS) of individual anomaly models and multi-models mean (if desired) with the observations.

Usage

```
CST_MultiMetric(exp, obs, metric = "correlation", multimodel = TRUE)
```

Arguments

exp	an object of class <code>s2dv_cube</code> as returned by <code>CST_Anomaly</code> function, containing the anomaly of the seasonal forecast experiment data in the element named <code>\$data</code> .
obs	an object of class <code>s2dv_cube</code> as returned by <code>CST_Anomaly</code> function, containing the anomaly of observed data in the element named <code>\$data</code> .
metric	a character string giving the metric for computing the maximum skill. This must be one of the strings <code>'correlation'</code> , <code>'rms'</code> or <code>'rmsss'</code> .
multimodel	a logical value indicating whether a Multi-Model Mean should be computed.

Value

an object of class `s2dv_cube` containing the statistics of the selected metric in the element `$data` which is an array with two dataset dimensions equal to the 'dataset' dimension in the `exp$data` and `obs$data` inputs. If `multimodel` is `TRUE`, the greatest first dimension corresponds to the Multi-Model Mean. The third dimension contains the statistics selected. For metric `correlation`, the third dimension is of length four and they corresponds to the lower limit of the 95% confidence interval, the statistics itselfs, the upper limit of the 95% confidence interval and the 95% significance level. For metric `rms`, the third dimension is length three and they corresponds to the lower limit of the 95% confidence interval, the RMSE and the upper limit of the 95% confidence interval. For metric `rmsss`, the third dimension is length two and they corresponds to the statistics itselfs and the p-value of the one-sided Fisher test with $H_0: RMSSS = 0$.

Author(s)

Mishra Niti, <niti.mishra@bsc.es>

Perez-Zanon Nuria, <nuria.perez@bsc.es>

References

Mishra, N., Prodhomme, C., & Guemas, V. (n.d.). Multi-Model Skill Assessment of Seasonal Temperature and Precipitation Forecasts over Europe, 29-31.<http://link.springer.com/10.1007/s00382-018-4404-z>

See Also

[Corr](#), [RMS](#), [RMSSS](#) and [CST_Load](#)

Examples

```
library(zeallot)
mod <- 1 : (2 * 3 * 4 * 5 * 6 * 7)
dim(mod) <- c(dataset = 2, member = 3, sdate = 4, ftime = 5, lat = 6, lon = 7)
obs <- 1 : (1 * 1 * 4 * 5 * 6 * 7)
dim(obs) <- c(dataset = 1, member = 1, sdate = 4, ftime = 5, lat = 6, lon = 7)
lon <- seq(0, 30, 5)
lat <- seq(0, 25, 5)
exp <- list(data = mod, lat = lat, lon = lon)
obs <- list(data = obs, lat = lat, lon = lon)
attr(exp, 'class') <- 's2dv_cube'
attr(obs, 'class') <- 's2dv_cube'
c(ano_exp, ano_obs) %<-% CST_Anomaly(exp = exp, obs = obs, cross = TRUE, memb = TRUE)
a <- CST_MultiMetric(exp = ano_exp, obs = ano_obs)
str(a)
```

CST_MultivarRMSE *Multivariate Root Mean Square Error (RMSE)*

Description

This function calculates the RMSE from multiple variables, as the mean of each variable's RMSE scaled by its observed standard deviation. Variables can be weighted based on their relative importance (defined by the user).

Usage

```
CST_MultivarRMSE(exp, obs, weight = NULL)
```

Arguments

exp	a list of objects, one for each variable, of class <code>s2dv_cube</code> as returned by <code>CST_Anomaly</code> function, containing the anomaly of the seasonal forecast experiment data in the element named <code>\$data</code> .
obs	a list of objects, one for each variable (in the same order than the input in 'exp') of class <code>s2dv_cube</code> as returned by <code>CST_Anomaly</code> function, containing the observed anomaly data in the element named <code>\$data</code> .
weight	(optional) a vector of weight values to assign to each variable. If no weights are defined, a value of 1 is assigned to every variable.

Value

an object of class `s2dv_cube` containing the RMSE in the element `$data` which is an array with two dataset dimensions equal to the 'dataset' dimension in the `exp$data` and `obs$data` inputs. An array with dimensions: `c(number of exp, number of obs, 1 (the multivariate RMSE value), number of lat, number of lon)`

Author(s)

Deborah Verfaillie, <deborah.verfaillie@bsc.es>

See Also

[RMS](#) and [CST_Load](#)

Examples

```
# Creation of sample s2dverification objects. These are not complete
# s2dverification objects though. The Load function returns complete objects.
# using package zeallot is optional:
library(zeallot)
# Example with 2 variables
mod1 <- 1 : (1 * 3 * 4 * 5 * 6 * 7)
mod2 <- 1 : (1 * 3 * 4 * 5 * 6 * 7)
```

```

dim(mod1) <- c(dataset = 1, member = 3, sdate = 4, ftime = 5, lat = 6, lon = 7)
dim(mod2) <- c(dataset = 1, member = 3, sdate = 4, ftime = 5, lat = 6, lon = 7)
obs1 <- 1 : (1 * 1 * 4 * 5 * 6 * 7)
obs2 <- 1 : (1 * 1 * 4 * 5 * 6 * 7)
dim(obs1) <- c(dataset = 1, member = 1, sdate = 4, ftime = 5, lat = 6, lon = 7)
dim(obs2) <- c(dataset = 1, member = 1, sdate = 4, ftime = 5, lat = 6, lon = 7)
lon <- seq(0, 30, 5)
lat <- seq(0, 25, 5)
exp1 <- list(data = mod1, lat = lat, lon = lon, Datasets = "EXP1",
             source_files = "file1", Variable = list('pre'))
attr(exp1, 'class') <- 's2dv_cube'
exp2 <- list(data = mod2, lat = lat, lon = lon, Datasets = "EXP2",
             source_files = "file2", Variable = list('tas'))
attr(exp2, 'class') <- 's2dv_cube'
obs1 <- list(data = obs1, lat = lat, lon = lon, Datasets = "OBS1",
             source_files = "file1", Variable = list('pre'))
attr(obs1, 'class') <- 's2dv_cube'
obs2 <- list(data = obs2, lat = lat, lon = lon, Datasets = "OBS2",
             source_files = "file2", Variable = list('tas'))
attr(obs2, 'class') <- 's2dv_cube'

c(ano_exp1, ano_obs1) %<-% CST_Anomaly(exp1, obs1, cross = TRUE, memb = TRUE)
c(ano_exp2, ano_obs2) %<-% CST_Anomaly(exp2, obs2, cross = TRUE, memb = TRUE)
ano_exp <- list(exp1, exp2)
ano_obs <- list(ano_obs1, ano_obs2)
weight <- c(1, 2)
a <- CST_MultivarRMSE(exp = ano_exp, obs = ano_obs, weight = weight)
str(a)

```

CST_RainFARM

RainFARM stochastic precipitation downscaling of a CStools object

Description

This function implements the RainFARM stochastic precipitation downscaling method and accepts a CStools object (an object of the class 's2dv_cube' as provided by 'CST_Load') as input. Adapted for climate downscaling and including orographic correction as described in Terzago et al. 2018.

Usage

```

CST_RainFARM(data, nf, weights = 1, slope = 0, kmin = 1, nens = 1,
             fglob = FALSE, fsmooth = TRUE, time_dim = NULL, verbose = FALSE,
             drop_realization_dim = FALSE)

```

Arguments

data An object of the class 's2dv_cube' as returned by 'CST_Load', containing the spatial precipitation fields to downscale. The data object is expected to have an element named \$data with at least two spatial dimensions named "lon" and

	"lat" and one or more dimensions over which to compute average spectral slopes (unless specified with parameter <code>slope</code>), which can be specified by parameter <code>time_dim</code> . The number of longitudes and latitudes in the input data is expected to be even and the same. If not the function will perform a subsetting to ensure this condition.
<code>nf</code>	Refinement factor for downscaling (the output resolution is increased by this factor).
<code>weights</code>	Matrix with climatological weights which can be obtained using the <code>CST_RFWeights</code> function. If <code>weights=1</code> . (default) no weights are used. The matrix should have dimensions (lon, lat) in this order. The names of these dimensions are not checked.
<code>slope</code>	Prescribed spectral slope. The default is <code>slope=0</code> . meaning that the slope is determined automatically over the dimensions specified by <code>time_dim</code> .
<code>kmin</code>	First wavenumber for spectral slope (default: <code>kmin=1</code>).
<code>nens</code>	Number of ensemble members to produce (default: <code>nens=1</code>).
<code>fglob</code>	Logical to conserve global precipitation over the domain (default: <code>FALSE</code>).
<code>fsmooth</code>	Logical to conserve precipitation with a smoothing kernel (default: <code>TRUE</code>).
<code>time_dim</code>	String or character array with name(s) of dimension(s) (e.g. "ftime", "sdate", "member" ...) over which to compute spectral slopes. If a character array of dimension names is provided, the spectral slopes will be computed as an average over all elements belonging to those dimensions. If omitted one of c("ftime", "sdate", "time") is searched and the first one with more than one element is chosen.
<code>verbose</code>	Logical for verbose output (default: <code>FALSE</code>).
<code>drop_realization_dim</code>	Logical to remove the "realization" stochastic ensemble dimension (default: <code>FALSE</code>) with the following behaviour if set to <code>TRUE</code> : 1) if <code>nens==1</code> : the dimension is dropped; 2) if <code>nens>1</code> and a "member" dimension exists: the "realization" and "member" dimensions are compacted (multiplied) and the resulting dimension is named "member"; 3) if <code>nens>1</code> and a "member" dimension does not exist: the "realization" dimension is renamed to "member".

Value

`CST_RainFARM()` returns a downscaled `CSTools` object (i.e., of the class 's2dv_cube'). If `nens>1` an additional dimension named "realization" is added to the `$data` array after the "member" dimension (unless `drop_realization_dim=TRUE` is specified). The ordering of the remaining dimensions in the `$data` element of the input object is maintained.

Author(s)

Jost von Hardenberg - ISAC-CNR, <j.vonhardenberg@isac.cnr.it>

References

Terzago, S. et al. (2018). NHESS 18(11), 2825-2840. <http://doi.org/10.5194/nhess-18-2825-2018> ;
 D'Onofrio et al. (2014), J of Hydrometeorology 15, 830-843; Reborá et. al. (2006), JHM 7, 724.

Examples

```
#Example using CST_RainFARM for a CStools object
nf <- 8 # Choose a downscaling by factor 8
exp <- 1 : (2 * 3 * 4 * 8 * 8)
dim(exp) <- c(dataset = 1, member = 2, sdate = 3, ftime = 4, lat = 8, lon = 8)
lon <- seq(10, 13.5, 0.5)
dim(lon) <- c(lon = length(lon))
lat <- seq(40, 43.5, 0.5)
dim(lat) <- c(lat = length(lat))
data <- list(data = exp, lon = lon, lat = lat)
# Create a test array of weights
ww <- array(1., dim = c(8 * nf, 8 * nf))
res <- CST_RainFARM(data, nf, ww, nens=3)
str(res)
#List of 3
# $ data: num [1:4, 1:64, 1:64, 1, 1:2, 1:3] 201 115 119 307 146 ...
# $ lon : num [1:64] 9.78 9.84 9.91 9.97 10.03 ...
# $ lat : num [1:64] 39.8 39.8 39.9 40 40 ...
dim(res$data)
# dataset member sdate ftime lat lon realization
#      1      2      3      4      64      64      3
```

CST_RFSlope

RainFARM spectral slopes from a CStools object

Description

This function computes spatial spectral slopes from a CStools object to be used for RainFARM stochastic precipitation downscaling method and accepts a CStools object (of the class 's2dv_cube') as input.

Usage

```
CST_RFSlope(data, kmin = 1, time_dim = NULL)
```

Arguments

data	An object of the class 's2dv_cube', containing the spatial precipitation fields to downscale. The data object is expected to have an element named \$data with at least two spatial dimensions named "lon" and "lat" and one or more dimensions over which to average these slopes, which can be specified by parameter time_dim.
kmin	First wavenumber for spectral slope (default kmin=1).

`time_dim` String or character array with name(s) of dimension(s) (e.g. "ftime", "sdate", "member" ...) over which to compute spectral slopes. If a character array of dimension names is provided, the spectral slopes will be computed as an average over all elements belonging to those dimensions. If omitted one of c("ftime", "sdate", "time") is searched and the first one with more than one element is chosen.

Value

`CST_RFSlope()` returns spectral slopes using the RainFARM convention (the logarithmic slope of $k*|A(k)|^2$ where $A(k)$ are the spectral amplitudes). The returned array has the same dimensions as the `exp` element of the input object, minus the dimensions specified by `lon_dim`, `lat_dim` and `time_dim`.

Author(s)

Jost von Hardenberg - ISAC-CNR, <j.vonhardenberg@isac.cnr.it>

Examples

```
#Example using CST_RFSlope for a CStools object
exp <- 1 : (2 * 3 * 4 * 8 * 8)
dim(exp) <- c(dataset = 1, member = 2, sdate = 3, ftime = 4, lat = 8, lon = 8)
lon <- seq(10, 13.5, 0.5)
dim(lon) <- c(lon = length(lon))
lat <- seq(40, 43.5, 0.5)
dim(lat) <- c(lat = length(lat))
data <- list(data = exp, lon = lon, lat = lat)
slopes <- CST_RFSlope(data)
dim(slopes)
# dataset member sdate
#      1      2      3
slopes
#      [,1]    [,2]    [,3]
#[1,] 1.893503 1.893503 1.893503
#[2,] 1.893503 1.893503 1.893503
```

CST_RFWeights

Compute climatological weights for RainFARM stochastic precipitation downscaling

Description

Compute climatological ("orographic") weights from a fine-scale precipitation climatology file.

Usage

```
CST_RFWeights(climfile, nf, lon, lat, varname = "", fsmooth = TRUE)
```

Arguments

<code>climfile</code>	Filename of a fine-scale precipitation climatology. The file is expected to be in NetCDF format and should contain at least one precipitation field. If several fields at different times are provided, a climatology is derived by time averaging. Suitable climatology files could be for example a fine-scale precipitation climatology from a high-resolution regional climate model (see e.g. Terzago et al. 2018), a local high-resolution gridded climatology from observations, or a reconstruction such as those which can be downloaded from the WORLDCLIM (http://www.worldclim.org) or CHELSA (http://chelsa-climate.org) websites. The latter data will need to be converted to NetCDF format before being used (see for example the GDAL tools (https://www.gdal.org)).
<code>nf</code>	Refinement factor for downscaling (the output resolution is increased by this factor).
<code>lon</code>	Vector of longitudes.
<code>lat</code>	Vector of latitudes. The number of longitudes and latitudes is expected to be even and the same. If not the function will perform a subsetting to ensure this condition.
<code>varname</code>	Name of the variable to be read from <code>climfile</code> .
<code>fsmooth</code>	Logical to use smooth conservation (default) or large-scale box-average conservation.

Value

A matrix containing the weights with dimensions (lon, lat).

Author(s)

Jost von Hardenberg - ISAC-CNR, <j.vonhardenberg@isac.cnr.it>

References

Terzago, S., Palazzi, E., & von Hardenberg, J. (2018). Stochastic downscaling of precipitation in complex orography: A simple method to reproduce a realistic fine-scale climatology. *Natural Hazards and Earth System Sciences*, 18(11), 2825-2840. <http://doi.org/10.5194/nhess-18-2825-2018>.

Examples

```
# Create weights to be used with the CST_RainFARM() or RainFARM() functions
# using an external fine-scale climatology file.

## Not run:
# Specify lon and lat of the input
lon <- seq(10,13.5,0.5)
lat <- seq(40,43.5,0.5)
nf <- 8
ww <- CST_RFWeights("./worldclim.nc", nf, lon, lat, fsmooth = TRUE)

## End(Not run)
```

lonlat_data

*Sample Of Experimental And Observational Climate Data In Function
Of Longitudes And Latitudes*

Description

This sample data set contains gridded seasonal forecast and corresponding observational data from the Copernicus Climate Change ECMWF-System 5 forecast system, and from the Copernicus Climate Change ERA-5 reconstruction. Specifically, for the 'tas' (2-meter temperature) variable, for the 15 first forecast ensemble members, monthly averaged, for the 3 first forecast time steps (lead months 1 to 4) of the November start dates of 2000 to 2005, for the Mediterranean region (27N-48N, 12W-40E). The data was generated on (or interpolated onto, for the reconstruction) a rectangular regular grid of size 360 by 181.

Details

It is recommended to use the data set as follows:

```
require(zeallot)
c(exp, obs)
```

The 'CST_Load' call used to generate the data set in the infrastructure of the Earth Sciences Department of the Barcelona Supercomputing Center is shown next. Note that 'CST_Load' internally calls 's2dverification::Load', which would require a configuration file (not provided here) expressing the distribution of the 'system5c3s' and 'era5' NetCDF files in the file system.

```
library(CSTools)
require(zeallot)

startDates <- c('20001101', '20011101', '20021101',
                '20031101', '20041101', '20051101')

lonlat_data <-
  CST_Load(
    var = 'tas',
    exp = 'system5c3s',
    obs = 'era5',
    nmember = 15,
    sdates = startDates,
    leadtimemax = 3,
    latmin = 27, latmax = 48,
    lonmin = -12, lonmax = 40,
    output = 'lonlat',
    nprocs = 1
  )
```


Author(s)

Nicolau Manubens <nicolau.manubens@bsc.es>

lonlat_prec

Sample Of Experimental Precipitation Data In Function Of Longitudes And Latitudes

Description

This sample data set contains a small cutout of gridded seasonal precipitation forecast data from the Copernicus Climate Change ECMWF-System 5 forecast system, to be used to demonstrate downscaling. Specifically, for the 'pr' (precipitation) variable, for the first 6 forecast ensemble members, daily values, for all 31 days in March following the forecast starting dates in November of years 2010 to 2012, for a small 4x4 pixel cutout in a region in the North-Western Italian Alps (44N-47N, 6E-9E). The data resolution is 1 degree.

Details

The 'CST_Load' call used to generate the data set in the infrastructure of the Marconi machine at CINECA is shown next, working on files which were extracted from forecast data available in the MEDSCOPE internal archive.

```
library(CSTools)
```

```
infile <- list(path = '../medscope/nwalps/data/$VAR_NAME$_$START_DATE$_nwalps.nc')
lonlat_prec <- CST_Load('prlr', exp = list(infile), obs = NULL,
                      sdates = c('20101101', '20111101', '20121101'),
                      leadtimemin = 121, leadtimemax = 151,
                      latmin = 44, latmax = 47,
                      lonmin = 5, lonmax = 9,
                      nmember = 25,
                      storefreq = "daily", sampleperiod = 1,
                      output = "lonlat"
                      )$exp
```

Author(s)

Jost von Hardenberg <j.vonhardenberg@isac.cnr.it>

PlotCombinedMap	<i>Plot Multiple Lon-Lat Variables In a Single Map According to a Decision Function</i>
-----------------	---

Description

Plot a number a two dimensional matrices with (longitude, latitude) dimensions on a single map with the cylindrical equidistant latitude and longitude projection.

Usage

```
PlotCombinedMap(maps, lon, lat, map_select_fun, display_range,
  map_dim = "map", brks = NULL, cols = NULL, col_unknown_map = "white",
  mask = NULL, col_mask = "grey", bar_titles = NULL, legend_scale = 1,
  fileout = NULL, width = 8, height = 5, size_units = "in", res = 100,
  ...)
```

Arguments

maps	List of matrices to plot, each with (longitude, latitude) dimensions, or 3-dimensional array with the dimensions (longitude, latitude, map). Dimension names are required.
lon	Vector of longitudes. Must match the length of the corresponding dimension in 'maps'.
lat	Vector of latitudes. Must match the length of the corresponding dimension in 'maps'.
map_select_fun	Function that selects, for each grid point, which value to take among all the provided maps. This function receives as input a vector of values for a same grid point for all the provided maps, and must return a single selected value (not its index!) or NA. For example, the min and max functions are accepted.
display_range	Range of values to be displayed for all the maps. This must be a numeric vector c(range min, range max). The values in the parameter 'maps' can go beyond the limits specified in this range. If the selected value for a given grid point (according to 'map_select_fun') falls outside the range, it will be coloured with 'col_unknown_map'.
map_dim	Optional name for the dimension of 'maps' along which the multiple maps are arranged. Only applies when 'maps' is provided as a 3-dimensional array. Takes the value 'map' by default.
brks	Colour levels to be sent to PlotEquiMap. This parameter is optional and adjusted automatically by the function.
cols	List of vectors of colours to be sent to PlotEquiMap for the colour bar of each map. This parameter is optional and adjusted automatically by the function (up to 5 maps). The colours provided for each colour bar will be automatically interpolated to match the number of breaks. Each item in this list can be named, and the name will be used as title for the corresponding colour bar (equivalent to the parameter 'bar_titles').

col_unknown_map	Colour to use to paint the grid cells for which a map is not possible to be chosen according to 'map_select_fun' or for those values that go beyond 'display_range'. Takes the value 'white' by default.
mask	Optional numeric array with dimensions (latitude, longitude), with values in the range [0, 1], indicating the opacity of the mask over each grid point. Cells with a 0 will result in no mask, whereas cells with a 1 will result in a totally opaque superimposed pixel coloured in 'col_mask'.
col_mask	Colour to be used for the superimposed mask (if specified in 'mask'). Takes the value 'grey' by default.
bar_titles	Optional vector of character strings providing the titles to be shown on top of each of the colour bars.
legend_scale	Scale factor for the size of the colour bar labels. Takes 1 by default.
fileout	File where to save the plot. If not specified (default) a graphics device will pop up. Extensions allowed: eps/ps, jpeg, png, pdf, bmp and tiff
width	File width, in the units specified in the parameter size_units (inches by default). Takes 8 by default.
height	File height, in the units specified in the parameter size_units (inches by default). Takes 5 by default.
size_units	Units of the size of the device (file or window) to plot in. Inches ('in') by default. See ?Devices and the creator function of the corresponding device.
res	Resolution of the device (file or window) to plot in. See ?Devices and the creator function of the corresponding device.
...	Additional parameters to be passed on to PlotEquiMap.

Author(s)

Nicolau Manubens, <nicolau.manubens@bsc.es>

Veronica Torralba, <veronica.torralba@bsc.es>

See Also

PlotCombinedMap and PlotEquiMap

Examples

```
# Simple example
x <- array(1:(20 * 10), dim = c(lat = 10, lon = 20)) / 200
a <- x * 0.6
b <- (1 - x) * 0.6
c <- 1 - (a + b)
lons <- seq(0, 359.5, length = 20)
lats <- seq(-89.5, 89.5, length = 10)
PlotCombinedMap(list(a, b, c), lons, lats,
                 toptitle = 'Maximum map',
                 map_select_fun = max,
                 display_range = c(0, 1),
```

```
bar_titles = paste('% of belonging to', c('a', 'b', 'c')),
brks = 20, width = 10, height = 8)
```

PlotForecastPDF

Plot one or multiple ensemble forecast pdfs for the same event

Description

This function plots the probability distribution function of several ensemble forecasts for the same event, either initialized at different moments or by different models. Probabilities for tercile categories are computed, plotted in colors and annotated. An asterisk marks the tercile with higher probabilities. Probabilities for extreme categories (above P90 and below P10) can also be included as hatched areas. Individual ensemble members can be plotted as jittered points. The observed value is optionally shown as a diamond.

Usage

```
PlotForecastPDF(fcst, tercile.limits, extreme.limits = NULL, obs = NULL,
  plotfile = NULL, title = "Set a title", var.name = "Varname (units)",
  fcst.names = NULL, add.ensmemb = c("above", "below", "no"),
  color.set = c("ggplot", "s2s4e", "hydro"))
```

Arguments

<code>fcst</code>	a dataframe or array containing all the ensemble members for each forecast. If 'fcst' is an array, it should have two labelled dimensions, and one of them should be 'members'. If 'fcsts' is a data.frame, each column should be a separate forecast, with the rows being the different ensemble members.
<code>tercile.limits</code>	an array with P33 and P66 values that define the tercile categories.
<code>extreme.limits</code>	(optional) an array with P10 and P90 values that define the extreme categories. (Default: extreme categories are not shown).
<code>obs</code>	(optional) a number with the observed value. (Default: observation is not shown).
<code>plotfile</code>	(optional) a filename (pdf, png...) where the plot will be saved. (Default: the plot is not saved).
<code>title</code>	a string with the plot title.
<code>var.name</code>	a string with the variable name and units.
<code>fcst.names</code>	(optional) an array of strings with the titles of each individual forecast.
<code>add.ensmemb</code>	either to add the ensemble members 'above' (default) or 'below' the pdf, or not ('no').
<code>color.set</code>	a selection of predefined color sets: use 'ggplot' (default) for blue/green/red, 's2s4e' for blue/grey/orange, or 'hydro' for yellow/gray/blue (suitable for precipitation and inflows).

Value

a ggplot object containing the plot.

Author(s)

Llorenç Lledó <l1lledo@bsc.es>

Examples

```
fcsts <- data.frame(fcst1 = rnorm(10), fcst2 = rnorm(10, 0.5, 1.2),
                   fcst3 = rnorm(10, -0.5, 0.9))
PlotForecastPDF(fcsts, c(-1, 1))

fcsts2 <- array(rnorm(100), dim = c(members = 20, fcst = 5))
PlotForecastPDF(fcsts2, c(-0.66, 0.66), extreme.limits = c(-1.2, 1.2),
                fcst.names = paste0('random fcst ', 1 : 5), obs = 0.7)
```

PlotMostLikelyQuantileMap

Plot Maps of Most Likely Quantiles

Description

This function receives as main input (via the parameter `probs`) a collection of longitude-latitude maps, each containing the probabilities (from 0 to 1) of the different grid cells of belonging to a category. As many categories as maps provided as inputs are understood to exist. The maps of probabilities must be provided on a common rectangular regular grid, and a vector with the longitudes and a vector with the latitudes of the grid must be provided. The input maps can be provided in two forms, either as a list of multiple two-dimensional arrays (one for each category) or as a three-dimensional array, where one of the dimensions corresponds to the different categories.

Usage

```
PlotMostLikelyQuantileMap(probs, lon, lat, cat_dim = "bin",
                          bar_titles = NULL, col_unknown_cat = "white", ...)
```

Arguments

<code>probs</code>	a list of bi-dimensional arrays with the named dimensions 'latitude' (or 'lat') and 'longitude' (or 'lon'), with equal size and in the same order, or a single tri-dimensional array with an additional dimension (e.g. 'bin') for the different categories. The arrays must contain probability values between 0 and 1, and the probabilities for all categories of a grid cell should not exceed 1 when added.
<code>lon</code>	a numeric vector with the longitudes of the map grid, in the same order as the values along the corresponding dimension in <code>probs</code> .

lat	a numeric vector with the latitudes of the map grid, in the same order as the values along the corresponding dimension in probs.
cat_dim	the name of the dimension along which the different categories are stored in probs. This only applies if probs is provided in the form of 3-dimensional array. The default expected name is 'bin'.
bar_titles	vector of character strings with the names to be drawn on top of the color bar for each of the categories. As many titles as categories provided in probs must be provided.
col_unknown_cat	character string with a colour representation of the colour to be used to paint the cells for which no category can be clearly assigned. Takes the value 'white' by default.
...	additional parameters to be sent to PlotCombinedMap and PlotEquiMap.

Author(s)

Veronica Torralba, <veronica.torralba@bsc.es>, Nicolau Manubens, <nicolau.manubens@bsc.es>

See Also

PlotCombinedMap and PlotEquiMap

Examples

```
# Simple example
x <- array(1:(20 * 10), dim = c(lat = 10, lon = 20)) / 200
a <- x * 0.6
b <- (1 - x) * 0.6
c <- 1 - (a + b)
lons <- seq(0, 359.5, length = 20)
lats <- seq(-89.5, 89.5, length = 10)
PlotMostLikelyQuantileMap(list(a, b, c), lons, lats,
                           toptitle = 'Most likely tercile map',
                           bar_titles = paste('% of belonging to', c('a', 'b', 'c')),
                           brks = 20, width = 10, height = 8)

# More complex example
n_lons <- 40
n_lats <- 20
n_timesteps <- 100
n_bins <- 4

# 1. Generation of sample data
lons <- seq(0, 359.5, length = n_lons)
lats <- seq(-89.5, 89.5, length = n_lats)

# This function builds a 3-D gaussian at a specified point in the map.
make_gaussian <- function(lon, sd_lon, lat, sd_lat) {
  w <- outer(lons, lats, function(x, y) dnorm(x, lon, sd_lon) * dnorm(y, lat, sd_lat))
  min_w <- min(w)
```

```

w <- w - min_w
w <- w / max(w)
w <- t(w)
names(dim(w)) <- c('lat', 'lon')
w
}

# This function generates random time series (with values ranging 1 to 5)
# according to 2 input weights.
gen_data <- function(w1, w2, n) {
  r <- sample(1:5, n,
             prob = c(.05, .9 * w1, .05, .05, .9 * w2),
             replace = TRUE)
  r <- r + runif(n, -0.5, 0.5)
  dim(r) <- c(time = n)
  r
}

# We build two 3-D gaussians.
w1 <- make_gaussian(120, 80, 20, 30)
w2 <- make_gaussian(260, 60, -10, 40)

# We generate sample data (with dimensions time, lat, lon) according
# to the generated gaussians
sample_data <- multiApply::Apply(list(w1, w2), NULL,
                                gen_data, n = n_timesteps)$output1

# 2. Binning sample data
prob_thresholds <- 1:n_bins / n_bins
prob_thresholds <- prob_thresholds[1:(n_bins - 1)]
thresholds <- quantile(sample_data, prob_thresholds)

binning <- function(x, thresholds) {
  n_samples <- length(x)
  n_bins <- length(thresholds) + 1

  thresholds <- c(thresholds, max(x))
  result <- 1:n_bins
  lower_threshold <- min(x) - 1
  for (i in 1:n_bins) {
    result[i] <- sum(x > lower_threshold & x <= thresholds[i]) / n_samples
    lower_threshold <- thresholds[i]
  }

  dim(result) <- c(bin = n_bins)
  result
}

bins <- multiApply::Apply(sample_data, 'time', binning, thresholds)$output1

# 3. Plotting most likely quantile/bin
PlotMostLikelyQuantileMap(bins, lons, lats,
                          toptitle = 'Most likely quantile map',

```

```

bar_titles = paste('% of belonging to', letters[1:n_bins]),
mask = 1 - (w1 + w2 / max(c(w1, w2))),
brks = 20, width = 10, height = 8)

```

RainFARM

RainFARM stochastic precipitation downscaling (reduced version)

Description

This function implements the RainFARM stochastic precipitation downscaling method and accepts in input an array with named dims ("lon", "lat") and one or more dimension (such as "ftime", "sdate" or "time") over which to average automatically determined spectral slopes. Adapted for climate downscaling and including orographic correction. References: Terzago, S. et al. (2018). NHESS 18(11), 2825-2840. <http://doi.org/10.5194/nhess-18-2825-2018>, D'Onofrio et al. (2014), J of Hydrometeorology 15, 830-843; Reborá et. al. (2006), JHM 7, 724.

Usage

```

RainFARM(data, lon, lat, nf, weights = 1, nens = 1, slope = 0, kmin = 1,
fglob = FALSE, fsmooth = TRUE, time_dim = NULL, lon_dim = "lon",
lat_dim = "lat", drop_realization_dim = FALSE, verbose = FALSE)

```

Arguments

data	Precipitation array to downscale. The input array is expected to have at least two dimensions named "lon" and "lat" by default (these default names can be changed with the lon_dim and lat_dim parameters) and one or more dimensions over which to average these slopes, which can be specified by parameter time_dim. The number of longitudes and latitudes in the input data is expected to be even and the same. If not the function will perform a subsetting to ensure this condition.
lon	Vector or array of longitudes.
lat	Vector or array of latitudes.
nf	Refinement factor for downscaling (the output resolution is increased by this factor).
weights	Matrix with climatological weights which can be obtained using the CST_RFWeights function. If weights=1. (default) no weights are used. The matrix should have dimensions (lon, lat) in this order. The names of these dimensions are not checked.
nens	Number of ensemble members to produce (default: nens=1).
slope	Prescribed spectral slope. The default is slope=0. meaning that the slope is determined automatically over the dimensions specified by time_dim.
kmin	First wavenumber for spectral slope (default: kmin=1).
fglob	Logical to conserve global precipitation over the domain (default: FALSE)

fsmooth	Logical to conserve precipitation with a smoothing kernel (default: TRUE)
time_dim	String or character array with name(s) of time dimension(s) (e.g. "ftime", "sdate", "time" ...) over which to compute spectral slopes. If a character array of dimension names is provided, the spectral slopes will be computed over all elements belonging to those dimensions. If omitted one of c("ftime", "sdate", "time") is searched and the first one with more than one element is chosen.
lon_dim	Name of lon dimension ("lon" by default).
lat_dim	Name of lat dimension ("lat" by default).
drop_realization_dim	Logical to remove the "realization" stochastic ensemble dimension (default: FALSE) 1) if nens==1: the dimension is dropped; 2) if nens>1 and a "member" dimension exists: the "realization" and "member" dimensions are compacted (multiplied) and the resulting dimension is named "member"; 3) if nens>1 and a "member" dimension does not exist: the "realization" dimension is renamed to "member".
verbose	logical for verbose output (default: FALSE).

Value

RainFARM() returns a list containing the fine-scale longitudes, latitudes and the sequence of nens downscaled fields. If nens>1 an additional dimension named "realization" is added to the output array after the "member" dimension (if it exists and unless drop_realization_dim=TRUE is specified). The ordering of the remaining dimensions in the exp element of the input object is maintained.

Author(s)

Jost von Hardenberg - ISAC-CNR, <j.vonhardenberg@isac.cnr.it>

Examples

```
# Example for the 'reduced' RainFARM function
nf <- 8 # Choose a downscaling by factor 8
nens <- 3 # Number of ensemble members
# create a test array with dimension 8x8 and 20 timesteps
# or provide your own read from a netcdf file
pr <- rnorm(8 * 8 * 20)
dim(pr) <- c(lon = 8, lat = 8, ftime = 20)
lon_mat <- seq(10, 13.5, 0.5) # could also be a 2d matrix
lat_mat <- seq(40, 43.5, 0.5)
# Create a test array of weights
ww <- array(1., dim = c(8 * nf, 8 * nf))
# or create proper weights using an external fine-scale climatology file
# Specify a weightsfn filename if you wish to save the weights
## Not run:
ww <- CST_RFWeights("./worldclim.nc", nf, lon = lon_mat, lat = lat_mat,
                    fsmooth = TRUE)
```

```
## End(Not run)
# downscale using weights (ww=1. means do not use weights)
res <- RainFARM(pr, lon_mat, lat_mat, nf,
               fsmooth = TRUE, fglob = FALSE,
               weights = ww, nens = 2, verbose = TRUE)

str(res)
#List of 3
# $ data: num [1:3, 1:20, 1:64, 1:64] 0.186 0.212 0.138 3.748 0.679 ...
# $ lon : num [1:64] 9.78 9.84 9.91 9.97 10.03 ...
# $ lat : num [1:64] 39.8 39.8 39.9 40 40 ...
dim(res$data)
# lon      lat      ftime realization
#  64      64      20         2
```

RFSlope

RainFARM spectral slopes from an array (reduced version)

Description

This function computes spatial spectral slopes from an array, to be used for RainFARM stochastic precipitation downscaling method.

Usage

```
RFSlope(data, kmin = 1, time_dim = NULL, lon_dim = "lon",
        lat_dim = "lat")
```

Arguments

<code>data</code>	Array containing the spatial precipitation fields to downscale. The input array is expected to have at least two dimensions named "lon" and "lat" by default (these default names can be changed with the <code>lon_dim</code> and <code>lat_dim</code> parameters) and one or more dimensions over which to average the slopes, which can be specified by parameter <code>time_dim</code> .
<code>kmin</code>	First wavenumber for spectral slope (default <code>kmin=1</code>).
<code>time_dim</code>	String or character array with name(s) of dimension(s) (e.g. "ftime", "sdate", "member" ...) over which to compute spectral slopes. If a character array of dimension names is provided, the spectral slopes will be computed as an average over all elements belonging to those dimensions. If omitted one of <code>c("ftime", "sdate", "time")</code> is searched and the first one with more than one element is chosen.
<code>lon_dim</code>	Name of lon dimension ("lon" by default).
<code>lat_dim</code>	Name of lat dimension ("lat" by default).

Value

RFSlope() returns spectral slopes using the RainFARM convention (the logarithmic slope of $k \cdot |A(k)|^2$ where $A(k)$ are the spectral amplitudes). The returned array has the same dimensions as the input array, minus the dimensions specified by `lon_dim`, `lat_dim` and `time_dim`.

Author(s)

Jost von Hardenberg - ISAC-CNR, <j.vonhardenberg@isac.cnr.it>

Examples

```
# Example for the 'reduced' RFSlope function
# Create a test array with dimension 8x8 and 20 timesteps,
# 3 starting dates and 20 ensemble members.
pr <- 1:(4*3*8*8*20)
dim(pr) <- c(ensemble = 4, sdate = 3, lon = 8, lat = 8, ftime = 20)

# Compute the spectral slopes ignoring the wavenumber
# corresponding to the largest scale (the box)
slopes <- RFSlope(pr, kmin=2)
dim(slopes)
# ensemble    sdate
#           4      3
slopes
#           [,1]    [,2]    [,3]
#[1,] 1.893503 1.893503 1.893503
#[2,] 1.893503 1.893503 1.893503
#[3,] 1.893503 1.893503 1.893503
#[4,] 1.893503 1.893503 1.893503
```

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