Package 'QUALYPSO'

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Title Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections

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Imports MASS, expm, Rfast, stats, graphics, grDevices, gamlss, gamlss.dist, statmod

Description

These functions apply an analysis of variance to incomplete ensembles of climate projections. It provides estimates of climate change responses of all simulation chains and of all uncertainty variables. The current notations correspond to Evin et al. (2026) <doi:10.5194/hess-30-1023-2026>.
QUALYPSO has been applied to different ensembles of projections simulated to study the impact of climate
change: for climate indicators in Evin et al. (2019) <doi:10.1175/JCLI-D-18-0606.1>; seasonal precipitation
and temperature in Evin, Somot and Hingray (2021) <doi:10.5194/esd-12-1543-2021>; hydrological variables
in Evin et al. (2026) <doi:10.5194/hess-30-1023-2026>; photovoltaic energy in Bichet et al. (2019)
<doi:10.1088/1748-9326/ab500a>.

Depends R (>= 3.5.0)

Suggests knitr, rmarkdown, bookdown

VignetteBuilder knitr

URL https://github.com/guillaumeevin/QUALYPSO

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`Bayesian_ANOVA` *Perform ANOVA using a Bayesian approach*

Description

Partition uncertainty in climate responses using an ANOVA inferred with a Bayesian approach.

Usage

```
Bayesian_ANOVA(CCR_tfut, scen, listOption = NULL, namesEff)
```

Arguments

`CCR_tfut`	matrix of climate change responses: `nS` x `nFut`.
`scen`	data.frame `nS` x `nFactor` for the `nS` scenarios and the `nFactor` factors (e.g. type of GCM)
`listOption`	list of options (see `QUALYPSO`)
`namesEff`	names of the main effects

Value

list with the following fields:

- **M_tfut**: List of estimates for the grand mean:
  - **MEAN**: vector of length `nFut` of posterior means
  - **SD**: vector of length `nFut` of posterior standard dev.
  - **CI**: matrix `nFut` x 2 of credible intervals of probability `probCI` given in `listOption`.
  - **QUANT**: matrix `nFut` x `nQ` of quantiles related to the probabilities `quantilePosterior` given in `listOption`
- **RV_tfut**: List of estimates for the variance of the residual errors:
  - **MEAN**: vector of length `nFut` of posterior means
  - **SD**: vector of length `nFut` of posterior standard dev.
  - **CI**: matrix `nFut` x 2 of credible intervals of probability `probCI` given in `listOption`.
  - **QUANT**: matrix `nFut` x `nQ` of quantiles related to the probabilities `quantilePosterior` given in `listOption`
- **E_tfut**: List of estimates for the main effects. For each main effect (GCM, RCM,..), each element of the list contains a list with:
  - **MEAN**: matrix `nFut` x `nEffect` of posterior means
  - **SD**: matrix `nFut` x `nEffect` of posterior standard dev.
  - **CI**: array `nFut` x 2 x `nEffect` of credible intervals of probability `probCI` given in `listOption`.
  - **QUANT**: array `nFut` x `nQ` x `nEffect` of quantiles related to the probabilities `quantilePosterior` given in `listOption`
- **VARE_tfut**: variability related to the main effects (i.e. variability between the different RCMs, GCMs,..). Matrix `nFut` x `nEffect`
- **CONTRIB_VARE_tfut**: Contribution of each individual effect to its component (percentage), e.g. what is the contribution of GCM1 to the variability related to GCMs. For each main effect (GCM, RCM,..), each element of the list contains a matrix `nFut` x `nEffect`
- **listOption**: list of options used to obtained these results (obtained from `check_option`)
- **listScenario**: list of scenario factors (obtained from `process_scen`)

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. <doi:10.1175/JCLI-D-18-0606.1>.

`Bayesian_ANOVA_i` *Perform ANOVA using a Bayesian approach for a future time i*

Description

Partition sources of uncertainty in climate change responses for one lead time or one grid point.

Usage

```
Bayesian_ANOVA_i(CCR_tfut_i, nMCMC, listScenario)
```

Arguments

`CCR_tfut_i`	vector of `nS` climate change response for one lead time: `nS x 1`
`nMCMC`	number of MCMC simulation required
`listScenario`	list containing specifications, provided by `process_scen`

Value

list with the following fields:

- **mu**: vector of length `nMCMC`, mean climate change response
- **sigma2**: vector of length `nMCMC`, variance of the residual terms
- **effect**: list with `nEffect` elements, where each element corresponds to a different factor Each element is a matrix `nMCMC x nMainFactor`, and `nMainFactor` is the number of main effects (e.g. number of GCMs, RCMs, etc.)

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. <doi:10.1175/JCLI-D-18-0606.1>.

check_arguments *Check arguments provided to QUALYPSO*

Description

Check type and dimensions of the arguments provided to QUALYPSO main function

Usage

```
check_arguments(Y, scen, X)
```

Arguments

Y	matrix nS x nY
scen	data.frame nS x nFactor with the nFactor factors for each of the nS scenarios. The number of factors nFactor corresponds to the number of main effects that will be included in the ANOVA model.
X	(optional) predictors corresponding to the projections, e.g. time or global temperature. It can be a vector if the predictor is the same for all scenarios (e.g. X=2001:2100) or a matrix of the same size as Y if these predictors are different for the different scenarios. By default, a vector 1:nY is created.

Author(s)

Guillaume Evin

check_option *Check validity of options provided in listOption*

Description

Check if input options provided in QUALYPSO are valid and assign default values if missing.

Usage

```
check_option(listOption)
```

Arguments

listOption	list of options

Value

List containing the complete set of options.

Author(s)

Guillaume Evin

`fit_ClimateResponse` *Fit the climate response for each simulation chain*

Description

Fit the climate response for each simulation chain of an ensemble of `nS` projections. Each simulation chain is a time series of `nY` time steps (e.g. number of years).

Usage

```
fit_ClimateResponse(
  Y,
  typeClimateResponse,
  parClimateResponse,
  Xmat,
  Xfut,
  typeChangeVariable
)
```

Arguments

`Y`	matrix of simulation chains: `nS` x `nY`
`typeClimateResponse`	type of climate response fitted to the projections.
`parClimateResponse`	parameter of the model applied for the extraction of the climate response.
`Xmat`	matrix of predictors corresponding to the projections, e.g. time or global temperature.
`Xfut`	values of the predictor over which the ANOVA will be applied.
`typeChangeVariable`	type of change variable: "abs" (absolute, value by default) or "rel" (relative)

Details

See `QUALYPSO` for further information on arguments `indexReferenceYear` and `typeChangeVariable`.

Value

list with the following fields for each simulation chain:

- **CR_tfut**: `nS` x `nF`, climate responses
- **CCR_tfut**: `nS` x `nF`, climate change responses
- **D_t**: `nS` x `nY`, deviation from the climate change response
- **CHANGEVAR_t**: `nS` x `nY`, change variable
- **IV_tfut**: `nF`, internal variability

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. J. Climate, 32, 2423–2440. <doi:10.1175/JCLI-D-18-0606.1>.

`get_Qmat` *Provide the matrix Q derived from Qstar*

Description

Provide matrix Q derived from a matrix Q* of Helmert contrasts:

$$Q = Q^*(Q^{*T}Q^*)^{-1/2}$$

See Eq. A6 in Evin et al., 2019.

Usage

```
get_Qmat(p)
```

Arguments

`p`	integer

Value

`matrix`	p x p matrix

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. J. Climate, 32, 2423–2440. <doi:10.1175/JCLI-D-18-0606.1>.

get_Qstar_mat *Provide Qstar matrix containing Helmert contrasts*

Description

Provide matrix containing Helmert contrasts (see Eq. A7 in Evin et al., 2019).

Usage

```
get_Qstar_mat(p)
```

Arguments

p	integer

Value

matrix	p x (p-1) matrix containing Helmert contrasts

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. J. Climate, 32, 2423–2440. <doi:10.1175/JCLI-D-18-0606.1>.

lm_ANOVA *Perform ANOVA using a linear model*

Description

Partition uncertainty in climate responses using an ANOVA inferred with a linear model.

Usage

```
lm_ANOVA(CCR_tfut, scen, listOption = NULL, namesEff)
```

Arguments

CCR_tfut	matrix of climate change responses: nS x nFut.
scen	data.frame nS x nFactor for each of the nS scenarios and the nFactor factors (e.g. type of GCM)
listOption	list of options (see QUALYPSO)
namesEff	names of the main effects

Value

list with the following fields:

- **M_tfut**: List of estimates for the grand mean:
  - **MEAN**: vector of length `nFut` of means
  - **SD**: vector of length `nFut` of standard dev.
  - **CI**: matrix `nFut` x 2 of credible intervals of probability `probCI` given in `listOption`.
- **RV_tfut**: List of estimates for the variance of the residual errors:
  - **MEAN**: vector of length `nFut`
- **E_tfut**: List of estimates for the main effects. For each main effect (GCM, RCM,..), each element of the list contains a list with:
  - **MEAN**: matrix `nFut` x `nEffect`
- **VARE_tfut**: variability related to the main effects (i.e. variability between the different RCMs, GCMs,..). Matrix `nFut` x `nEffect`
- **CONTRIB_VARE_tfut**: Contribution of each individual effect to its component (percentage), e.g. what is the contribution of GCM1 to the variability related to GCMs. For each main effect (GCM, RCM,..), each element of the list contains a matrix `nFut` x `nEffect`
- **listOption**: list of options used to obtained these results (obtained from `check_option`)
- **listScenario**: list of scenario factors (obtained from `process_scen`)

Author(s)

Guillaume Evin

`plotQUALYPSO_CCR` *Plot climate change responses for all simulation chains.*

Description

Plot the climate change responses CCR(t) for all simulation chains.

Usage

```
plotQUALYPSO_CCR(QUALYPSOOUT, lim = NULL, xlab = "", ylab = "CCR(t)", ...)
```

Arguments

`QUALYPSOOUT`	output from `QUALYPSO`
`lim`	y-axis limits (default is NULL)
`xlab`	x-axis label
`ylab`	y-axis label
`...`	additional arguments to be passed to `plot`

Author(s)

Guillaume Evin

plotQUALYPSO_CR *Plot the climate response for one simulation chain*

Description

Plot the climate response CR(t) for one simulation chain and the corresponding raw projection. The choice of the simulation chain can be given or randomly sampled.

Usage

```
plotQUALYPSO_CR(
  QUALYPSOOUT,
  iS = NULL,
  lim = NULL,
  xlab = "X",
  ylab = "Y",
  ...
)
```

Arguments

QUALYPSOOUT	output from QUALYPSO
iS	index of the projection (integer). If NULL, one scenario is chosen randomly
lim	y-axis limits (default is NULL)
xlab	x-axis label
ylab	y-axis label
...	additional arguments to be passed to plot

Author(s)

Guillaume Evin

plotQUALYPSO_effect *Plot estimated ANOVA effects for one factor*

Description

Plot estimated ANOVA effects for one factor. By default, we plot the estimation uncertainty corresponding to a probability 0.95.

Usage

```
plotQUALYPSO_effect(
  QUALYPSOOUT,
  nameEff,
  lim = NULL,
  col = 1:20,
  xlab = "",
  ylab = "Effect",
  addLegend = TRUE,
  ...
)
```

Arguments

QUALYPSOOUT	output from QUALYPSO
nameEff	name of the main effect to be plotted in QUALYPSOOUT$namesEff
lim	y-axis limits (default is NULL)
col	colors for each effect
xlab	x-axis label
ylab	y-axis label
addLegend	if TRUE, a legend is added
...	additional arguments to be passed to plot

Author(s)

Guillaume Evin

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plotQUALYPSO_FV_CCRV_IV

plotQUALYPSO_FV_CCRV_IV

Description

Plot fraction of total variance explained by each source of uncertainty.

Usage

```
plotQUALYPSO_FV_CCRV_IV(
  QUALYPSOOUT,
  vecEff = NULL,
  col = c("orange", "yellow", "cadetblue1", "blue1", "darkgreen", "darkgoldenrod4",
    "darkorchid1"),
  xlab = "",
  ylab = "% Total Variance",
  addLegend = TRUE,
  ...
)
```

Arguments

QUALYPSOOUT	output from QUALYPSO
vecEff	vector of indices corresponding to the main effects (NULL by default), so that the order of appearance in the plot can be modified
col	colors for each source of uncertainty, the first two colors corresponding to internal variability and residual variability, respectively
xlab	x-axis label
ylab	y-axis label
addLegend	if TRUE, a legend is added
...	additional arguments to be passed to plot

Author(s)

Guillaume Evin

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plotQUALYPSO_IV *Plot deviations from the climate change response and an interval representing the magnitude of the estimated internal variability*

Description

Plot D(t) as a function of X as well as +/- 1.645*sqrt(IV_tfut), where IV_tfut is a function of Xfut.

Usage

```
plotQUALYPSO_IV(QUALYPSOOUT, lim = NULL, xlab = "X", ylab = "D(t)", ...)
```

Arguments

QUALYPSOOUT	output from QUALYPSO
lim	y-axis limits (default is NULL)
xlab	x-axis label
ylab	y-axis label
...	additional arguments to be passed to plot

Author(s)

Guillaume Evin

plotQUALYPSO_M *Plot the estimated grand mean*

Description

Plot the estimated grand mean and the corresponding estimation uncertainty.

Usage

```
plotQUALYPSO_M(
  QUALYPSOOUT,
  lim = NULL,
  col = "black",
  xlab = "",
  ylab = "Grand mean",
  addLegend = T,
  ...
)
```

Arguments

QUALYPSOOUT	output from QUALYPSO
lim	y-axis limits (default is NULL)
col	color for the overall mean and the credible interval
xlab	x-axis label
ylab	y-axis label
addLegend	if TRUE, a legend is added
...	additional arguments to be passed to plot

Author(s)

Guillaume Evin

process_scen *Process scen*

Description

Process factors describing each scenario (i.e each simulation chain)

Usage

```
process_scen(scen)
```

Arguments

scen	data.frame nS x nFactor with the nFactor factors (e.g. type of GCM) for each of the nS x nS scenarios

Value

list of preprocessed objects (listEff, scen, scenComp, nFactor, nEffect, nComp, isMissing, nMissing, iMatchScen, indexEffInCompScen, Qmat)

Author(s)

Guillaume Evin

QUALYPSO *Main function*

Description

Partition uncertainty in climate responses using an ANOVA applied to climate change responses. The main function of the package needs at least two arguments: Y is an ensemble of climate projections, i.e. a matrix nS x nY where nS projections are provided for nY years or future time steps; scen is a data.frame which provides nFactor factors for each projection.

Usage

```
QUALYPSO(Y, scen, X = NULL, Xfut = NULL, listOption = NULL)
```

Arguments

Y	matrix nS x nY of climate projections.
scen	data.frame nS x nFactor with the nFactor factors (e.g. type of GCM) for each of the nS scenarios. The number of factors nFactor corresponds to the number of main effects that will be included in the ANOVA model.
X	(optional) predictors corresponding to the projections, e.g. time or global temperature. It can be a vector if the predictor is the same for all scenarios (e.g. X=2001:2100) or a matrix of the same size as Y if these predictors are different for the different scenarios. By default, a vector 1:nY is created.
Xfut	(optional) nF values of the predictor over which the ANOVA will be applied. It must be a vector of values within the range of values of X. By default, it corresponds to X if X is a vector, 1:nY if X is NULL or a vector of 10 values equally spaced between the minimum and maximum values of X if X is a matrix. The first value defines the reference period or warming level.
listOption	(optional) list of options

- **typeClimateResponse**: type of climate response fitted to the projections. Can be either "smooth.spline" (`smooth.spline`) where the parameter `df` in (1,nY] is the equivalent number of degrees of freedom (value by default), "poly" (polynomial model fitted with `lm`) where the parameter `degree` is an integer indicating the degree of the polynomial (`poly`), "lowess" (`lowess`) where the parameter `f` in (0,1) is the proportion of points which influence the smooth at each value, or "tweedie" (`tweedie`), a Generalized Linear Model with the Tweedie distribution where the parameter `var.power` is the index of power variance function (positive value). The tweedie model is the only model that handles zeros in the climate projections, typically with `var.power` in (1,2).
- **parClimateResponse**: parameter of the model applied for the extraction of the climate response (i.e. `df`, `degree`, `f`, or `var.power`). Default values are `df=4`, `degree=1`, `f=0.4` or `var.power=1.5` for the smoothing spline, polynomial, lowess, or tweedie models, respectively.
- **typeChangeVariable**: type of change variable: "abs" (absolute, value by default) or "rel" (relative).
- **ANOVAmethod**: ANOVA method: "lm" (default) applies a linear model (`lm`) to estimate the main effects. "Bayesian" applies the method described in Evin et al. (2020).
- **nBurn**: if `ANOVAmethod=="Bayesian"`, number of burn-in samples (default: 1000). If `nBurn` is too small, the convergence of MCMC chains might not be obtained.
- **nKeep**: if `ANOVAmethod=="Bayesian"`, number of kept samples (default: 2000). If `nKeep` is too small, MCMC samples might not represent correctly the posterior distributions of inferred parameters.
- **probCI**: probability (in [0,1]) for the confidence intervals, `probCI = 0.9` by default.
- **quantilePosterior**: vector of probabilities (in [0,1]) for which we compute the quantiles from the posterior distributions `quantilePosterior = c(0.005,0.025,0.05,0.1,0.25,0.33,0.5,0.66,0.75,0.9,0.95,0.975,0.995)` by default.
- **ClimateResponse**: NULL by default. If it is provided, it must correspond to the outputs of `fit_ClimateResponse`, i.e. a list with `CR_tfut` [nS x nF], `CCR_tfut` [nS x nF], `D_t` [nS x nY], `CHANGEVAR_t` [nS x nY], and `IV_tfut` [nF].

Value

List providing the results for each of the `nFut` values of `Xfut`:

- **CR_tfut**: Fitted climate responses [nS x nF],
- **CCR_tfut**: Climate change responses [nS x nF],
- **D_t**: Deviation from the climate change responses [nS x nY],
- **CHANGEVAR_t**: Change variable from the projections [nS x nY],
- **M_tfut**: List of estimates for the grand mean:

  - **MEAN**: vector of length nFut of means.
  - **SD**: vector of length nFut of standard dev.
  - **CI**: matrix nFut x 2 of credible intervals of probability probCI given in listOption
  - **QUANT**: matrix nFut x nQ of quantiles of probability quantilePosterior given in listOption if ANOVAmethod=="Bayesian".
- **E_tfut**: List of estimates for the main effects. For each main effect (GCM, RCM,..), each element of the list contains a list with:
  - **MEAN**: matrix nFut x nEffect
  - **SD**: matrix nFut x nEffect of standard dev.
  - **CI**: array nFut x 2 x nEffect of credible intervals of probability probCI given in listOption
  - **QUANT**: array nFut x nQ x nEffect of quantiles of probability quantilePosterior given in listOption if ANOVAmethod=="Bayesian".
- **VARE_tfut**: Matrix nFut x nEffect giving the variability related to the main effects (i.e. variability between the different RCMs, GCMs,..).
- **CONTRIB_VARE_tfut**: Contribution of each individual effect to its component (percentage), e.g. what is the contribution of GCM1 to the variability related to GCMs. For each main effect (GCM, RCM,..), each element of the list contains a matrix nFut x nEffect
- **RV_tfut**: List of estimates for the variance of the residual errors:
  - **MEAN**: vector of length nFut.
  - **SD**: vector of length nFut of standard dev. if ANOVAmethod=="Bayesian".
  - **CI**: matrix nFut x 2 of credible intervals of probability probCI given in listOption if ANOVAmethod=="Bayesian".
  - **QUANT**: matrix nFut x nQ of quantiles of probability quantilePosterior given in listOption if ANOVAmethod=="Bayesian".
- **IV_tfut**: Internal variability
- **CCRV_tfut**: total uncertainty CCRV(t) i.e. the sum of variability related to the main effects and residual variability
- **FV_CCRV_tfut**: Fraction of total uncertainty CCRV(t) (in variance) explained by the different sources of uncertainty
- **CCRV_IV_tfut**: total uncertainty CCRV(t) + IV(t), i.e. the sum of variability related to the main effects residual variability and internal variability
- **FV_CCRV_IV_tfut**: Fraction of total uncertainty CCRV(t) + IV(t) (in variance) explained by the different sources of uncertainty
- **RESERR**: differences between the climate change responses and the additive anova formula (grand mean + main effects)
- **Xmat**: matrix of predictors
- **Xfut**: future predictor values
- **namesEff**: names of the main effects
- **Y**: matrix of available combinations given as inputs
- **listOption**: list of options used to obtained these results (output of check_option)
- **listScenario**: list of scenario factors (output of process_scen)

Author(s)

Guillaume Evin

References

Evin, G., B. Hingray, J. Blanchet, N. Eckert, S. Morin, and D. Verfaillie (2020) Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. Journal of Climate. <doi:10.1175/JCLI-D-18-0606.1>.

Examples

```
#_____________________________________________________________
# CALLING QUALYPSO
#_____________________________________________________________
# call main QUALYPSO function: two arguments are mandatory:
# - Y: Climate projections for nS scenarios and nY time steps. Y is a matrix nS x nY, we
# run QUALYPSO nY times, for each time step.
# - scen: matrix or data.frame of available combinations nS x nFactor. The number of
# factors nFactor corresponds to the number of main effects that will be included in the
# ANOVA model. In the following example, we have nFactor=2 main effects corresponding to the GCMs
# and RCMs.

# Many options can be specified in the argument "listOption".

#_____________________________________________________________
# Example 1: Synthetic scenarios
#_____________________________________________________________
# create nS=3 fictive climate scenarios with 2 GCMs and 2 RCMs, for a period of nY=20 years
n=20
t=0:n/n

# GCM effects (sums to 0 for each t)
effGCM1 = t*2
effGCM2 = t*1
effGCM3 = t*-3

# RCM effects (sums to 0 for each t)
effRCM1 = t*1
effRCM2 = t*-1

# These climate scenarios are a sum of effects and a random gaussian noise
scenGCM1RCM1 = effGCM1 + effRCM1 + rnorm(n=n+1,sd=0.5)
scenGCM1RCM2 = effGCM1 + effRCM2 + rnorm(n=n+1,sd=0.5)
scenGCM2RCM1 = effGCM2 + effRCM1 + rnorm(n=n+1,sd=0.5)
scenGCM2RCM2 = effGCM2 + effRCM2 + rnorm(n=n+1,sd=0.5)
scenGCM3RCM1 = effGCM3 + effRCM1 + rnorm(n=n+1,sd=0.5)
Y_synth = rbind(scenGCM1RCM1,scenGCM1RCM2,scenGCM2RCM1,scenGCM2RCM2,scenGCM3RCM1)

# Here, scen indicates that the first scenario is obtained with the combination of the
# GCM "GCM1" and RCM "RCM1", the second scenario is obtained with the combination of
# the GCM "GCM1" and RCM "RCM2" and the third scenario is obtained with the combination
# of the GCM "GCM2" and RCM "RCM1".
```

```
scen_synth = data.frame(GCM=c('GCM1','GCM1','GCM2','GCM2','GCM3'),
RCM=c('RCM1','RCM2','RCM1','RCM2','RCM1'))


# run QUALYPSO
QUALYPSO_synth = QUALYPSO(Y=Y_synth, scen=scen_synth, X=2000:2020,
listOption = list(typeClimateResponse="poly"))

# plot main GCM effects
plotQUALYPSO_effect(QUALYPSO_synth,nameEff="GCM",xlab="Years")
lines(2000:2020, effGCM1,lty=2,lwd=2,col="black")
lines(2000:2020, effGCM2,lty=2,lwd=2,col="red")
lines(2000:2020, effGCM3,lty=2,lwd=2,col="green")

# plot main RCM effects
plotQUALYPSO_effect(QUALYPSO_synth,nameEff="RCM",xlab="Years")
lines(2000:2020, effRCM1,lty=2,lwd=2,col="black")
lines(2000:2020, effRCM2,lty=2,lwd=2,col="red")

# plot fraction of total variance for the differences sources of uncertainty
plotQUALYPSO_FV_CCRV_IV(QUALYPSO_synth,xlab="Years")

#_____________________________________________________________
# Example 2: climate projections of mean winter (DJF) temperature
# with time as the predictor
#_____________________________________________________________

# list of options
listOption = list(typeChangeVariable='abs')

# call QUALYPSO
QUALYPSO_time = QUALYPSO(Y=Y_DJFTas,scen=scen_DJFTas,X=1971:2099,
                         Xfut=1990:2099,listOption=listOption)

# diagnostic of the climate responses
plotQUALYPSO_CR(QUALYPSO_time)

# diagnostic of the internal variability
plotQUALYPSO_IV(QUALYPSO_time)

# grand mean effect
plotQUALYPSO_M(QUALYPSO_time,xlab="Years")

# main GCM effects
plotQUALYPSO_effect(QUALYPSO_time,nameEff="GCM",xlab="Years")

# main RCM effects
plotQUALYPSO_effect(QUALYPSO_time,nameEff="RCM",xlab="Years")

# variance decomposition
plotQUALYPSO_FV_CCRV_IV(QUALYPSO_time,xlab="Years")

#_____________________________________________________________
```

```
# Example 3: climate projections of mean winter (DJF) temperature
# with global temperature as the predictor
#_____________________________________________________________

# list of options
listOption = list(typeChangeVariable='abs')

# call QUALYPSO
QUALYPSO_wl = QUALYPSO(Y=Y_DJFTas,scen=scen_DJFTas,X=X_DJFTas_WL,
                               Xfut=seq(from=0.5,to=3,by=0.1),listOption=listOption)

# diagnostic of the climate responses
plotQUALYPSO_CR(QUALYPSO_wl)

# diagnostic of the internal variability
plotQUALYPSO_IV(QUALYPSO_wl)

# grand mean effect
plotQUALYPSO_M(QUALYPSO_wl,xlab="Global warming (Celsius)")

# main GCM effects
plotQUALYPSO_effect(QUALYPSO_wl,nameEff="GCM",xlab="Global warming (Celsius)")

# main RCM effects
plotQUALYPSO_effect(QUALYPSO_wl,nameEff="RCM",xlab="Global warming (Celsius)")

# variance decomposition
plotQUALYPSO_FV_CCRV_IV(QUALYPSO_wl,xlab="Global warming (Celsius)")
```

`scen_DJFTas` *data.frame indicating which GCMs and RCMs have been used for the 20 climate projections of mean winter temperature over CEU*

Description

scen_DJFTas gives the GCM and RCM which have been used for the 20 climate projections (obtained with the RCP8.5)

Usage

```
data(scen_DJFTas)
```

Format

data.frame with 20 rows and two columns: GCM and RCM

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

scen_SWE *data.frame indicating which GCM, RCM and RCP scenarios have been used to produce the 18 projections of SWE maxima.*

Description

SWE maxima are provided for 18 projections obtained with 9 different combinations of GCMs and RCMs and two emission scenarios (RCP4.5 and RCP8.5).

Usage

```
data(scen_SWE)
```

Format

matrix 18 scenarios x 149 years

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

References

Evin, G., E. Le Roux, E. Kamir, and S. Morin. « Estimating changes in extreme snow load in Europe as a function of global warming levels ». Cold Regions Science and Technology 231 (2025): 104424. https://doi.org/10.1016/j.coldregions.2025.104424.

X_DJFTas_WL *Annual warming levels simulated by different CMIP5 GCMs*

Description

Annual warming levels at the planetary scales simulated by different CMIP5 GCMs for the period 1971-2099. Warming levels are obtained with respect to the year 1860 (common starting year of the CMIP5 simulations). These warming levels have been obtained with the following steps:

1. Annual tas averages simulated by different CMIP5 have first been smoothed using a smoothing spline. Let us denote these smoothed values by tas_GCM(y) for a year y.
2. Large discrepancies can be observed for tas_GCM_smooth(y) even in the past due to large first-order biases in the GCM simulations. In order to obtain a common reference, we also consider observed tas estimates at the global scale. HadCRUT5 (Morice et al., 2021, 10.1029/2019JD032361) provides anomalies with respect to the period 1961-1990. An estimate of absolute average temperature for this period is 14°C (Jones et al., 1999, 10.1029/1999RG900002). Smoothed estimates of absolute tas averages are obtained using a smoothing spline and is denoted by tas_obs(y).
3. Warming levels are obtained as anomalies with respect to the period 1860 and considering a reference year, here 1990, where the warming levels WL are in agreement: WL(y) = tas_GCM(y)-tas_GCM(1990)+tas_obs(1990)-tas_obs(1860)

Usage

```
data(X_DJFTas_WL)
```

Format

matrix 20 scenarios x 129 years

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

X_SWE_WL *Annual warming levels simulated by different CMIP5 GCMs corresponding to the 18 projections Y_SWE*

Description

Annual warming levels at the planetary scales simulated by different CMIP5 GCMs for the period 1951-2099. Warming levels are obtained with respect to the year 1860 (common starting year of the CMIP5 simulations). See Evin et al. (2025) for further details.

Usage

```
data(X_SWE_WL)
```

Format

matrix 18 scenarios x 149 years

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

References

Evin, G., E. Le Roux, E. Kamir, and S. Morin. « Estimating changes in extreme snow load in Europe as a function of global warming levels ». Cold Regions Science and Technology 231 (2025): 104424. https://doi.org/10.1016/j.coldregions.2025.104424.

Y_DJFTas *Mean winter temperature over CEU with 20 GCM/RCM combinations for 1971-2099*

Description

climate projections of mean winter (DJF) temperature over the SREX region CEU simulated by 20 combinations of CMIP5 GCMs and RCMs for the period 1971-2099

Usage

```
data(Y_DJFTas)
```

Format

matrix 20 scenarios x 129 years

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

References

Seneviratne, S. I. et al. Changes in Climate Extremes and their Impacts on the Natural Physical Environment, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change, edited by: Field, C., Barros, V., Stocker, T., and Dahe, Q., Cambridge University Press, Cambridge, 109-230, https://doi.org/10.1017/CBO9781139177245.006, 2012

Y_SWE *Annual maxima of snow water equivalent for Loire-Atlantique, France, a NUTS-3 region located at a low mean elevation (0 m) and has a suboceanic climate with quite mild and rainy winters. SWE maxima are provided for 18 projections obtained with 9 different combinations of GCMs and RCMs and two emission scenarios (RCP4.5 and RCP8.5).*

Description

Annual maxima of snow water equivalent for Loire-Atlantique, France, a NUTS-3 region located at a low mean elevation (0 m) and has a suboceanic climate with quite mild and rainy winters. SWE maxima are provided for 18 projections obtained with 9 different combinations of GCMs and RCMs and two emission scenarios (RCP4.5 and RCP8.5).

Usage

```
data(Y_SWE)
```

Format

matrix 18 scenarios x 149 years

Author(s)

Guillaume Evin <guillaume.evin@inrae.fr>

References

Evin, G., E. Le Roux, E. Kamir, and S. Morin. « Estimating changes in extreme snow load in Europe as a function of global warming levels ». Cold Regions Science and Technology 231 (2025): 104424. https://doi.org/10.1016/j.coldregions.2025.104424.

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