Package ‘MBC’

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Title Multivariate Bias Correction of Climate Model Outputs

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Description Calibrate and apply multivariate bias correction algorithms for climate model simulations of multiple climate variables. Three methods described by Cannon (2016) <doi:10.1175/JCLI-D-15-0679.1> and Cannon (2018) <doi:10.1007/s00382-017-3580-6> are implemented -- (i) MBC Pearson correlation (MBCp), (ii) MBC rank correlation (MBCr), and (iii) MBC N-dimensional PDF transform (MBCn) -- as is the Rank Resampling for Distributions and Dependences (R2D2) method. An additional multivariate rescaling method based on the linear Monge-Kantorovich map for Gaussian optimal transport of dependence structure is also included.

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Depends R (>= 2.10), Matrix, energy, FNN

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Contents

`MBC-package` *Multivariate Bias Correction of Climate Model Outputs*

Description

Calibrate and apply multivariate bias correction algorithms for climate model simulations of multiple climate variables. Three iterative methods are supported: (i) MBC Pearson correlation (MBCp), (ii) MBC rank correlation (MBCr), and (iii) MBC N-dimensional probability density function transform (MBCn).

The first two, MBCp and MBCr (Cannon, 2016), match marginal distributions and inter-variable dependence structure. Dependence structure can be measured either by the Pearson correlation (`MBCp`) or by the Spearman rank correlation (`MBCr`). The energy distance score (`escore`) is recommended for model selection.

The third, `MBCn` (Cannon, 2018), which operates on the full multivariate distribution, is more flexible and can be considered to be a multivariate analogue of univariate quantile mapping. All aspects of the observed distribution are transferred to the climate model simulations.

In each of the three methods, marginal distributions are corrected by the change-preserving quantile delta mapping (`QDM`) algorithm (Cannon et al., 2015). Finally, an implementation of the Rank Resampling for Distributions and Dependences (R2D2) method introduced by Vrac (2018), as well as multivariate rescaling using the linear Monge-Kantorovich map (Pitié and Kokaram, 2007) are also included.

An example application of the three MBC methods using the `cccma` dataset can be run via:

```
example(MBC, run.dontrun=TRUE)
```

Note: these functions apply bias correction to the supplied data without reference to other conditioning variables (e.g., time of year or season). The user must partition their data in a way that makes sense for a particular application. Furthermore, if `MBCn` is being applied to multiple spatial locations or grid cells, it is recommended that the same sequence of random rotations be used for each location. This can be achived by generating the random rotations first and then passing the sequence using the `rot.seq` argument:

```
rot.seq <- replicate(niterations, list(rot.random(nvars)))
bias_correction <- MBCn(..., rot.seq=rot.seq)
```

Details

Package:	MBC
Type:	Package
License:	GPL-2
LazyLoad:	yes

References

Cannon, A.J., 2018. Multivariate quantile mapping bias correction: An N-dimensional probability density function transform for climate model simulations of multiple variables. Climate Dynamics, 50(1-2):31-49. doi:10.1007/s00382-017-3580-6

Cannon, A.J., 2016. Multivariate bias correction of climate model output: Matching marginal distributions and inter-variable dependence structure. Journal of Climate, 29:7045-7064. doi:10.1175/JCLI-D-15-0679.1

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

Francois, B., M. Vrac, A.J. Cannon, Y. Robin, and D. Allard, 2020. Multivariate bias corrections of climate simulations: Which benefits for which losses? Earth System Dynamics, 11:537-562. doi:10.5194/esd-11-537-2020

Pitié, F., and A. Kokaram, 2007. The linear Monge-Kantorovich linear colour mapping for example-based colour transfer. In 4th European Conference on Visual Media Production, 1-9 pp. IET.

Vrac, M., 2018. Multivariate bias adjustment of high-dimensional climate simulations: the Rank Resampling for Distributions and Dependences (R2D2) bias correction. Hydrology and Earth System Sciences, 22:3175-3196. doi:10.5194/hess-22-3175-2018

See Also

QDM, MBCp, MBCr, MBCn, R2D2, MRSmk, escore, rot.random, cccma

Examples

```
## Not run:
data(cccma)
set.seed(1)

# Univariate quantile mapping
qdm.c <- cccma$gcm.c*0
qdm.p <- cccma$gcm.p*0
for(i in seq(ncol(cccma$gcm.c))){
    fit.qdm <- QDM(o.c=cccma$rcm.c[,i], m.c=cccma$gcm.c[,i],
                   m.p=cccma$gcm.p[,i], ratio=cccma$ratio.seq[i],
                   trace=cccma$trace[i])
    qdm.c[,i] <- fit.qdm$mhat.c
    qdm.p[,i] <- fit.qdm$mhat.p
}

# Multivariate MBCp bias correction
fit.mbcp <- MBCp(o.c=cccma$rcm.c, m.c=cccma$gcm.c,
                 m.p=cccma$gcm.p, ratio.seq=cccma$ratio.seq,
                 trace=cccma$trace)
mbcp.c <- fit.mbcp$mhat.c
mbcp.p <- fit.mbcp$mhat.p
```

```
# Multivariate MBCr bias correction
fit.mbcr <- MBCr(o.c=cccma$rcm.c, m.c=cccma$gcm.c,
                 m.p=cccma$gcm.p, ratio.seq=cccma$ratio.seq,
                 trace=cccma$trace)
mbcr.c <- fit.mbcr$mhat.c
mbcr.p <- fit.mbcr$mhat.p

# Multivariate MBCn bias correction
fit.mbcn <- MBCn(o.c=cccma$rcm.c, m.c=cccma$gcm.c,
                 m.p=cccma$gcm.p, ratio.seq=cccma$ratio.seq,
                 trace=cccma$trace)
mbcn.c <- fit.mbcn$mhat.c
mbcn.p <- fit.mbcn$mhat.p
colnames(mbcn.c) <- colnames(mbcn.p) <-
    colnames(cccma$rcm.c)

# Correlation matrices (Pearson and Spearman)
# MBCp
dev.new()
par(mfrow=c(2, 2))
plot(c(cor(cccma$rcm.c)), c(cor(qdm.c)), col='black',
     pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCp',
     main='Pearson correlation\nMBCp calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c)), c(cor(mbcp.c)), col='red')
plot(c(cor(cccma$rcm.p)), c(cor(qdm.p)),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCp',
     main='Pearson correlation\nMBCp evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p)), c(cor(mbcp.p)), col='red')
plot(c(cor(cccma$rcm.c, m='s')), c(cor(qdm.c, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCp',
     main='Spearman correlation\nMBCp calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c, m='s')), c(cor(mbcp.c, m='s')),
       col='red')
plot(c(cor(cccma$rcm.p, m='s')), c(cor(qdm.p, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCp',
     main='Spearman correlation\nMBCp evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p, m='s')), c(cor(mbcp.p, m='s')),
       col='red')

# MBCr
```

```
dev.new()
par(mfrow=c(2, 2))
plot(c(cor(cccma$rcm.c)), c(cor(qdm.c)), col='black',
     pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCr',
     main='Pearson correlation\nMBCr calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c)), c(cor(mbcr.c)), col='blue')
plot(c(cor(cccma$rcm.p)), c(cor(qdm.p)),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCr',
     main='Pearson correlation\nMBCr evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p)), c(cor(mbcr.p)), col='blue')
plot(c(cor(cccma$rcm.c, m='s')), c(cor(qdm.c, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCr',
     main='Spearman correlation\nMBCr calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c, m='s')), c(cor(mbcr.c, m='s')),
       col='blue')
plot(c(cor(cccma$rcm.p, m='s')), c(cor(qdm.p, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCr',
     main='Spearman correlation\nMBCr evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p, m='s')), c(cor(mbcr.p, m='s')),
       col='blue')

# MBCn
dev.new()
par(mfrow=c(2, 2))
plot(c(cor(cccma$rcm.c)), c(cor(qdm.c)), col='black',
     pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCn',
     main='Pearson correlation\nMBCn calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c)), c(cor(mbcn.c)), col='orange')
plot(c(cor(cccma$rcm.p)), c(cor(qdm.p)),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCn',
     main='Pearson correlation\nMBCn evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p)), c(cor(mbcn.p)), col='orange')
plot(c(cor(cccma$rcm.c, m='s')), c(cor(qdm.c, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCn',
```

```
     main='Spearman correlation\nMBCn calibration')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.c, m='s')), c(cor(mbcn.c, m='s')),
       col='orange')
plot(c(cor(cccma$rcm.p, m='s')), c(cor(qdm.p, m='s')),
     col='black', pch=19, xlim=c(-1, 1), ylim=c(-1, 1),
     xlab='CanRCM4', ylab='CanESM2 MBCn',
     main='Spearman correlation\nMBCn evaluation')
abline(0, 1)
grid()
points(c(cor(cccma$rcm.p, m='s')), c(cor(mbcn.p, m='s')),
       col='orange')

# Pairwise scatterplots
dev.new()
pairs(cccma$gcm.c, main='CanESM2 calibration', col='#0000001A')
dev.new()
pairs(cccma$rcm.c, main='CanRCM4 calibration', col='#0000001A')
dev.new()
pairs(qdm.c, main='QDM calibration', col='#0000001A')
dev.new()
pairs(mbcp.c, main='MBCp calibration', col='#FF00001A')
dev.new()
pairs(mbcr.c, main='MBCr calibration', col='#0000FF1A')
dev.new()
pairs(mbcn.c, main='MBCn calibration', col='#FFA5001A')

# Energy distance skill score relative to univariate QDM
escore.qdm <- escore(cccma$rcm.p, qdm.p, scale.x=TRUE)
escore.mbcp <- escore(cccma$rcm.p, mbcp.p, scale.x=TRUE)
escore.mbcr <- escore(cccma$rcm.p, mbcr.p, scale.x=TRUE)
escore.mbcn <- escore(cccma$rcm.p, mbcn.p, scale.x=TRUE)

cat('ESS (MBCp):', 1-escore.mbcp/escore.qdm, '\n')
cat('ESS (MBCr):', 1-escore.mbcr/escore.qdm, '\n')
cat('ESS (MBCn):', 1-escore.mbcn/escore.qdm, '\n')

# Post-process QDM using MRSmk
fit.qdmmk <- MRSmk(o.c=cccma$rcm.c, m.c=cccma$gcm.c, m.p=cccma$gcm.p,
                   mhat.c=qdm.c, mhat.p=qdm.p)
escore.qdmmk <- escore(cccma$rcm.p, fit.qdmmk$mhat.p, scale.x=TRUE)
cat('ESS (QDMmk):', 1-escore.qdmmk/escore.qdm, '\n')


## End(Not run)
```

---

cccma *Sample CanESM2 and CanRCM4 data*

Description

Sample CanESM2 (T63 grid) and CanRCM4 (0.22-deg grid) data (122.5 deg W, 50 deg N).

```
pr: precipitation (mm day-1)
tas: average surface temperature (deg. C)
dtr: diurnal temperature range (deg. C)
sfcWind: surface wind speed (m s-1)
ps: surface pressure (ps)
huss: surface specific humidity (kg kg-1)
rsds: surface downwelling shortwave radiation (W m-2)
rlds: surface downwelling longwave radiation (W m-2)
```

Value

a list of with elements consisting of:

`gcm.c`	matrix of CanESM2 variables for the calibration period.
`gcm.p`	matrix of CanESM2 variables for the validation period.
`rcm.c`	matrix of CanRCM4 variables for the calibration period.
`rcm.p`	matrix of CanRCM4 variables for the validation period.
`ratio.seq`	vector of logical values indicating if samples are of a ratio quantity.
`trace`	numeric values indicating trace thresholds for each ratio quantity.

`escore` *Energy distance score*

Description

Calculate the energy distance score measuring the statistical discrepancy between samples `x` and `y` from two multivariate distributions.

Usage

```
escore(x, y, scale.x=FALSE, n.cases=NULL, alpha=1, method='cluster')
```

Arguments

`x`	numeric matrix.
`y`	numeric matrix.
`scale.x`	logical indicating whether data should be standardized based on `x`.
`n.cases`	the number of sub-sampled cases; `NULL` uses all data.
`alpha`	distance exponent in (0,2]
`method`	method used to weight the statistics

References

Székely, G.J. and M.L. Rizzo, 2004. Testing for equal distributions in high dimension, InterStat, November (5).

Székely, G.J. and M.L. Rizzo, 2013. Energy statistics: statistics based on distances. Journal of Statistical Planning and Inference, 143(8):1249-1272. doi:10.1016/j.jspi.2013.03.018

Rizzo, M.L. and G.L. Székely, 2016. Energy distance. Wiley Interdisciplinary Reviews: Computational Statistics, 8(1):27-38.

MBCn *Multivariate bias correction (N-pdft)*

Description

Multivariate bias correction that matches the multivariate distribution using `QDM` and the N-dimensional probability density function transform (N-pdft) following Cannon (2018).

Usage

```
MBCn(o.c, m.c, m.p, iter=30, ratio.seq=rep(FALSE, ncol(o.c)),
     trace=0.05, trace.calc=0.5*trace, jitter.factor=0,
     n.tau=NULL, ratio.max=2, ratio.max.trace=10*trace,
     ties='first', qmap.precalc=FALSE, rot.seq=NULL,
     silent=FALSE, n.escore=0, return.all=FALSE, subsample=NULL,
     pp.type=7)
```

Arguments

`o.c`	matrix of observed samples during the calibration period.
`m.c`	matrix of model outputs during the calibration period.
`m.p`	matrix of model outputs during the projected period.
`iter`	maximum number of algorithm iterations.
`ratio.seq`	vector of logical values indicating if samples are of a ratio quantity (e.g., precipitation).
`trace`	numeric values indicating thresholds below which values of a ratio quantity (e.g., `ratio=TRUE`) should be considered exact zeros.
`trace.calc`	numeric values of thresholds used internally when handling of exact zeros; defaults to one half of `trace`.
`jitter.factor`	optional strength of jittering to be applied when quantities are quantized.
`n.tau`	number of quantiles used in the quantile mapping; `NULL` equals the length of the `m.p` series.
`ratio.max`	numeric values indicating the maximum proportional changes allowed for ratio quantities below the `ratio.max.trace` threshold.

`ratio.max.trace`
: numeric values of trace thresholds used to constrain the proportional change in ratio quantities to `ratio.max`; defaults to ten times `trace`.

`ties`
: method used to handle ties when calculating ordinal ranks.

`qmap.precalc`
: logical value indicating if `m.c` and `m.p` are outputs from `QDM`.

`rot.seq`
: use a supplied list of random rotation matrices. `NULL` generates on the fly.

`silent`
: logical value indicating if algorithm progress should be reported.

`n.escore`
: number of cases used to calculate the energy distance when monitoring convergence.

`return.all`
: logical value indicating whether results from all iterations are returned.

`subsample`
: use `subsample` draws of size `n.tau` to calculate initial empirical quantiles; if `NULL`, calculate normally.

`pp.type`
: type of plotting position used in `quantile`.

Value

a list of with elements consisting of:

`mhat.c`
: matrix of bias corrected `m.c` values for the calibration period.

`mhat.p`
: matrix of bias corrected `m.p` values for the projection period.

References

Cannon, A.J., 2018. Multivariate quantile mapping bias correction: An N-dimensional probability density function transform for climate model simulations of multiple variables. Climate Dynamics, 50(1-2):31-49. doi:10.1007/s00382-017-3580-6

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

Pitié, F., A.C. Kokaram, and R. Dahyot, 2005. N-dimensional probability density function transfer and its application to color transfer. In Tenth IEEE International Conference on Computer Vision, 2005. ICCV 2005. (Vol. 2, pp. 1434-1439). IEEE.

Pitié, F., A.C. Kokaram, and R. Dahyot, 2007. Automated colour grading using colour distribution transfer. Computer Vision and Image Understanding, 107(1):123-137.

See Also

`QDM`, `MBCp`, `MBCr`, `MRS`, `escore`, `rot.random`

MBCp *Multivariate bias correction (Pearson correlation)*

Description

Multivariate bias correction that matches marginal distributions using QDM and the Pearson correlation dependence structure following Cannon (2016).

Usage

```
MBCp(o.c, m.c, m.p, iter=20, cor.thresh=1e-4,
     ratio.seq=rep(FALSE, ncol(o.c)), trace=0.05,
     trace.calc=0.5*trace, jitter.factor=0, n.tau=NULL,
     ratio.max=2, ratio.max.trace=10*trace, ties='first',
     qmap.precalc=FALSE, silent=FALSE, subsample=NULL,
     pp.type=7)
```

Arguments

`o.c`	matrix of observed samples during the calibration period.
`m.c`	matrix of model outputs during the calibration period.
`m.p`	matrix of model outputs during the projected period.
`iter`	maximum number of algorithm iterations.
`cor.thresh`	if greater than zero, a threshold indicating the change in magnitude of Pearson correlations required for convergence.
`ratio.seq`	vector of logical values indicating if samples are of a ratio quantity (e.g., precipitation).
`trace`	numeric values indicating thresholds below which values of a ratio quantity (e.g., `ratio=TRUE`) should be considered exact zeros.
`trace.calc`	numeric values of thresholds used internally when handling of exact zeros; defaults to one half of `trace`.
`jitter.factor`	optional strength of jittering to be applied when quantities are quantized.
`n.tau`	number of quantiles used in the quantile mapping; `NULL` equals the length of the `m.p` series.
`ratio.max`	numeric values indicating the maximum proportional changes allowed for ratio quantities below the `ratio.max.trace` threshold.
`ratio.max.trace`	numeric values of trace thresholds used to constrain the proportional change in ratio quantities to `ratio.max`; defaults to ten times `trace`.
`ties`	method used to handle ties when calculating ordinal ranks.
`qmap.precalc`	logical value indicating if `m.c` and `m.p` are outputs from `QDM`.
`silent`	logical value indicating if algorithm progress should be reported.
`subsample`	use `subsample` draws of size `n.tau` to calculate initial empirical quantiles; if `NULL`, calculate normally.
`pp.type`	type of plotting position used in `quantile`.

Value

a list of with elements consisting of:

- `mhat.c` matrix of bias corrected `m.c` values for the calibration period.
- `mhat.p` matrix of bias corrected `m.p` values for the projection period.

References

Cannon, A.J., 2016. Multivariate bias correction of climate model output: Matching marginal distributions and inter-variable dependence structure. Journal of Climate, 29:7045-7064. doi:10.1175/JCLI-D-15-0679.1

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

See Also

`QDM`, `MBCr`, `MRS`, `MBCn escore`

MBCr — *Multivariate bias correction (Spearman rank correlation)*

Description

Multivariate bias correction that matches marginal distributions using `QDM` and the Spearman rank correlation dependence structure following Cannon (2016).

Usage

```
MBCr(o.c, m.c, m.p, iter=20, cor.thresh=1e-4,
     ratio.seq=rep(FALSE, ncol(o.c)), trace=0.05,
     trace.calc=0.5*trace, jitter.factor=0, n.tau=NULL,
     ratio.max=2, ratio.max.trace=10*trace, ties='first',
     qmap.precalc=FALSE, silent=FALSE, subsample=NULL,
     pp.type=7)
```

Arguments

- `o.c` matrix of observed samples during the calibration period.
- `m.c` matrix of model outputs during the calibration period.
- `m.p` matrix of model outputs during the projected period.
- `iter` maximum number of algorithm iterations.
- `cor.thresh` if greater than zero, a threshold indicating the change in magnitude of Spearman rank correlations required for convergence.

`ratio.seq`	vector of logical values indicating if samples are of a ratio quantity (e.g., precipitation).
`trace`	numeric values indicating thresholds below which values of a ratio quantity (e.g., `ratio=TRUE`) should be considered exact zeros.
`trace.calc`	numeric values of thresholds used internally when handling of exact zeros; defaults to one half of `trace`.
`jitter.factor`	optional strength of jittering to be applied when quantities are quantized.
`n.tau`	number of quantiles used in the quantile mapping; `NULL` equals the length of the `m.p` series.
`ratio.max`	numeric values indicating the maximum proportional changes allowed for ratio quantities below the `ratio.max.trace` threshold.
`ratio.max.trace`	numeric values of trace thresholds used to constrain the proportional change in ratio quantities to `ratio.max`; defaults to ten times `trace`.
`ties`	method used to handle ties when calculating ordinal ranks.
`qmap.precalc`	logical value indicating if `m.c` and `m.p` are outputs from `QDM`.
`silent`	logical value indicating if algorithm progress should be reported.
`subsample`	use `subsample` draws of size `n.tau` to calculate empirical quantiles; if `NULL`, calculate normally.
`pp.type`	type of plotting position used in `quantile`.

Value

a list of with elements consisting of:

`mhat.c`	matrix of bias corrected `m.c` values for the calibration period.
`mhat.p`	matrix of bias corrected `m.p` values for the projection period.

References

Cannon, A.J., 2016. Multivariate bias correction of climate model output: Matching marginal distributions and inter-variable dependence structure. Journal of Climate, 29:7045-7064. doi:10.1175/JCLI-D-15-0679.1

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

See Also

`QDM`, `MBCp`, `MRS`, `MBCn` `escore`

`MRS` *Multivariate linear rescaling using Cholesky decomposition*

Description

Multivariate linear bias correction based on Cholesky decomposition of the covariance matrix following Scheuer and Stoller (1962) and Bürger et al. (2011). Bias correction matches the multivariate mean and covariance structure.

Usage

```
MRS(o.c, m.c, m.p, o.c.chol=NULL, o.p.chol=NULL, m.c.chol=NULL,
    m.p.chol=NULL)
```

Arguments

`o.c`	matrix of observed samples during the calibration period.
`m.c`	matrix of model outputs during the calibration period.
`m.p`	matrix of model outputs during the projected period.
`o.c.chol`	precalculated Cholesky decomposition of the `o.c` covariance matrix; `NULL` calculates internally.
`o.p.chol`	precalculated Cholesky decomposition of the target `o.p` covariance matrix; `NULL` defaults to `o.c.chol`.
`m.c.chol`	precalculated Cholesky decomposition of the `m.c` covariance matrix; `NULL` calculates internally.
`m.p.chol`	precalculated Cholesky decomposition of the `m.p` covariance matrix; `NULL` calculates internally.

Value

a list of with elements consisting of:

`mhat.c`	matrix of bias corrected `m.c` values for the calibration period.
`mhat.p`	matrix of bias corrected `m.p` values for the projection period.

References

Scheuer, E.M. and D.S. Stoller, 1962. On the generation of normal random vectors. Technometrics, 4(2):278-281.

Bürger, G., J. Schulla, and A.T. Werner, 2011. Estimates of future flow, including extremes, of the Columbia River headwaters. Water Resources Research, 47(10):W10520. doi:10.1029/2010WR009716

See Also

`MBCp`, `MBCr`

MRSmk *Multivariate Rescaling Using the Linear Monge-Kantorovich Map*

Description

Applies a multivariate dependence adjustment based on a Gaussian optimal transport, or linear Monge-Kantorovich, map. Variables are first transformed to van der Waerden normal scores. Correlation changes are represented either in the log-Euclidean geometry of positive-definite correlation matrices or by additive changes in Fisher-z transformed correlations. Separate maps are then applied to current- and projected-period adjusted simulations, and the original marginal values are restored by rank reordering.

Usage

```
MRSmk(o.c, m.c, m.p, mhat.c, mhat.p,
      cor_change = c("logdelta", "fisherz"), ties.method = "random")
```

Arguments

`o.c`	Matrix of observed current-period data. Rows are cases and columns are variables.
`m.c`	Matrix of modelled current-period data.
`m.p`	Matrix of modelled projected-period data.
`mhat.c`	Matrix of already marginally adjusted current-period model data.
`mhat.p`	Matrix of already marginally adjusted projected-period model data.
`cor_change`	Character string specifying how the model-projected change in dependence is transferred. The default, `"logdelta"`, applies the change in the log-Euclidean geometry of correlation matrices. The alternative, `"fisherz"`, applies the change in Fisher-z transformed pairwise correlations.
`ties.method`	Method passed to `rank` when computing van der Waerden normal scores.

Details

`MRSmk` is designed to be applied after marginal bias adjustment, for example after `QDM` or another univariate adjustment has produced `mhat.c` and `mhat.p`. The observed current-period dependence is estimated from `o.c`. The model-projected change in dependence between `m.c` and `m.p` is used to define a projected target correlation matrix for the adjusted future simulation. The linear Monge-Kantorovich map then transforms the normal-score representation of `mhat.c` and `mhat.p` to the target correlation matrices. Finally, each transformed normal-score column is used as a rank template to reorder the original adjusted values, preserving their marginal distributions.

All inputs must be numeric matrices with the same number of columns and no missing values. The method requires at least two variables.

Value

A list with components:

mhat.c	Current-period adjusted matrix after dependence rescaling.
mhat.p	Projected-period adjusted matrix after dependence rescaling.

QDM *Univariate bias correction via quantile delta mapping*

Description

Univariate bias correction based on the quantile delta mapping QDM version of the quantile mapping algorithm from Cannon et al. (2015). QDM constrains model-projected changes in quantiles to be preserved following bias correction by quantile mapping.

Usage

```
QDM(o.c, m.c, m.p, ratio=FALSE, trace=0.05, trace.calc=0.5*trace,
    jitter.factor=0, n.tau=NULL, ratio.max=2,
    ratio.max.trace=10*trace, ECBC=FALSE, ties='first',
    subsample=NULL, pp.type=7)
```

Arguments

o.c	vector of observed samples during the calibration period.
m.c	vector of model outputs during the calibration period.
m.p	vector of model outputs during the projected period.
ratio	logical value indicating if samples are of a ratio quantity (e.g., precipitation).
trace	numeric value indicating the threshold below which values of a ratio quantity (e.g., ratio=TRUE) should be considered exact zeros.
trace.calc	numeric value of a threshold used internally when handling of exact zeros; defaults to one half of trace.
jitter.factor	optional strength of jittering to be applied when quantities are quantized.
n.tau	number of quantiles used in the quantile mapping; NULL equals the length of the m.p series.
ratio.max	numeric value indicating the maximum proportional change allowed for ratio quantities below the ratio.max.trace threshold.
ratio.max.trace	numeric value of a trace threshold used to constrain the proportional change in ratio quantities to ratio.max; defaults to ten times trace.
ECBC	logical value indicating whether mhat.p outputs should be ordered according to o.c ranks, i.e., as in the empirical copula-bias correction (ECBC) algorithm.
ties	method used to handle ties when calculating ordinal ranks.
subsample	use subsample draws of size n.tau to calculate empirical quantiles; if NULL, calculate normally.
pp.type	type of plotting position used in quantile.

Value

a list of with elements consisting of:

mhat.c — vector of bias corrected m.c values for the calibration period.

mhat.p — vector of bias corrected m.p values for the projection period.

References

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

See Also

MBCp, MBCr, MRS, MRSmk, escore

R2D2 — *Multivariate bias correction (R2D2)*

Description

Multivariate bias correction that matches the multivariate distribution using QDM and the R2D2 algorithm following Vrac (2018).

Usage

```
R2D2(o.c, m.c, m.p, ref.column=1, ratio.seq=rep(FALSE, ncol(o.c)),
     trace=0.05, trace.calc=0.5*trace, jitter.factor=0,
     n.tau=NULL, ratio.max=2, ratio.max.trace=10*trace,
     ties='first', qmap.precalc=FALSE, subsample=NULL, pp.type=7)
```

Arguments

o.c — matrix of observed samples during the calibration period.

m.c — matrix of model outputs during the calibration period.

m.p — matrix of model outputs during the projected period.

ref.column — index of the reference column used for the 1D nearest neighbour matching

ratio.seq — vector of logical values indicating if samples are of a ratio quantity (e.g., precipitation).

trace — numeric values indicating thresholds below which values of a ratio quantity (e.g., ratio=TRUE) should be considered exact zeros.

trace.calc — numeric values of thresholds used internally when handling of exact zeros; defaults to one half of trace.

jitter.factor — optional strength of jittering to be applied when quantities are quantized.

`n.tau`	number of quantiles used in the quantile mapping; `NULL` equals the length of the `m.p` series.
`ratio.max`	numeric values indicating the maximum proportional changes allowed for ratio quantities below the `ratio.max.trace` threshold.
`ratio.max.trace`	numeric values of trace thresholds used to constrain the proportional change in ratio quantities to `ratio.max`; defaults to ten times `trace`.
`ties`	method used to handle ties when calculating ordinal ranks.
`qmap.precalc`	logical value indicating if `m.c` and `m.p` are outputs from `QDM`.
`subsample`	use `subsample` draws of size `n.tau` to calculate initial empirical quantiles; if `NULL`, calculate normally.
`pp.type`	type of plotting position used in `quantile`.

Value

a list of with elements consisting of:

`mhat.c`	matrix of bias corrected `m.c` values for the calibration period.
`mhat.p`	matrix of bias corrected `m.p` values for the projection period.

References

Cannon, A.J., S.R. Sobie, and T.Q. Murdock, 2015. Bias correction of simulated precipitation by quantile mapping: How well do methods preserve relative changes in quantiles and extremes? Journal of Climate, 28:6938-6959. doi:10.1175/JCLI-D-14-00754.1

Vrac, M., 2018. Multivariate bias adjustment of high-dimensional climate simulations: the Rank Resampling for Distributions and Dependences (R2D2) bias correction. Hydrology and Earth System Sciences, 22:3175-3196. doi:10.5194/hess-22-3175-2018

See Also

`QDM`, `MBCp`, `MBCr`, `MRS`, `MRSmk`, `MBCn`

`rot.random` *Random orthogonal rotation*

Description

Generate a k-dimensional random orthogonal rotation matrix.

Usage

```
rot.random(k)
```

Arguments

`k`	the number of dimensions.

References

Mezzadri, F. 2007. How to generate random matrices from the classical compact groups, Notices of the American Mathematical Society, 54:592–604.

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