Package 'bmgarch'

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Title Bayesian Multivariate GARCH Models

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Description Fit Bayesian multivariate GARCH models using 'Stan' for full Bayesian inference. Generate (weighted) forecasts for means, variances (volatility) and correlations. Currently DCC(P,Q), CCC(P,Q), pdBEKK(P,Q), and BEKK(P,Q) parameterizations are implemented, alongside a constant covariance baseline (that can be used for testing whether GARCH is warranted), based either on a multivariate gaussian normal or student-t distribution. DCC and CCC models are based on Engle (2002) <doi:10.1198/073500102288618487> and Bollerslev (1990). The BEKK parameterization follows Engle and Kroner (1995) <doi:10.1017/S0266466600009063> while the pdBEKK as well as the estimation approach for this package is described in Rast et al. (2020) <doi:10.31234/osf.io/j57pk>. The fitted models contain 'rstan' objects and can be examined with 'rstan' functions.

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Depends methods, R (>= 4.0.0), Rcpp (>= 1.0.5)

Imports forecast, ggplot2, loo, MASS, Rdpack, rstan (>= 2.26.0), rstantools (>= 2.1.1)

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Author Philippe Rast [aut, cre] (ORCID:
<https://orcid.org/0000-0003-3630-6629>),
Stephen Martin [aut] (ORCID: <https://orcid.org/0000-0001-8085-2390>)

Maintainer Philippe Rast <rast.ph@gmail.com>

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Usage

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as.data.frame(x, ...)
```

Arguments

x	fitted.bmgarch object.
...	Not used.

Value

Data frame.

Author(s)

Stephen R. Martin

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as.data.frame.forecast.bmgarch

as.data.frame method for forecast.bmgarch objects.

Description

as.data.frame method for forecast.bmgarch objects.

Usage

```
## S3 method for class 'forecast.bmgarch'
as.data.frame(x, ..., backcast = TRUE)
```

Arguments

x	forecast.bmgarch object.
...	Not used.
backcast	Logical (Default: True). Whether to include "backcasted" values from `fitted.bmgarch` in data frame.

Value

Data frame.

Author(s)

Stephen R. Martin

bmgarch *Estimate Bayesian Multivariate GARCH*

Description

Draw samples from a specified multivariate GARCH model using 'Stan', given multivariate time-series. Currently supports CCC, DCC, BEKK, and pdBEKK model parameterizations.

Usage

```
bmgarch(
  data,
  xC = NULL,
  parameterization = "CCC",
  P = 1,
  Q = 1,
  iterations = NULL,
  chains = 4,
  standardize_data = FALSE,
  distribution = "Student_t",
  meanstructure = "constant",
  sampling_algorithm = "MCMC",
  backend = "rstan",
  ...
)
```

Arguments

data	Time-series or matrix object. A time-series or matrix object containing observations at the same interval.
xC	Numeric vector or matrix. Covariates(s) for the constant variance terms in C, or c, used in a log-linear model on the constant variance terms (Rast et al. 2022). If vector, then it acts as a covariate for all constant variance terms. If matrix, must have columns equal to number of time series, and each column acts as a covariate for the respective time series (e.g., column 1 predicts constant variance for time series 1).
parameterization	Character (Default: "CCC"). The type of of parameterization. Must be one of "CCC", "DCC", "BEKK", or "pdBEKK".
P	Integer. Dimension of GARCH component in MGARCH(P,Q).
Q	Integer. Dimension of ARCH component in MGARCH(P,Q).
iterations	Integer (Default: 2000 for MCMC, 30000 for VB). Number of iterations. For MCMC, this includes warmup. For VB, this is the maximum number of ADVI gradient ascent iterations.
chains	Integer (Default: 4). The number of Markov chains.

`standardize_data`
: Logical (Default: FALSE). Whether data should be standardized to easy computations.

`distribution`
: Character (Default: "Student_t"). Distribution of innovation: "Student_t" or "Gaussian"

`meanstructure`
: Character (Default: "constant"). Defines model for means. Either 'constant' or 'ARMA'. Currently ARMA(1,1) only. OR 'VAR' (VAR1).

`sampling_algorithm`
: Character (Default" "MCMC"). Define sampling algorithm. Either 'MCMC'for Hamiltonian Monte Carlo or 'VB' for variational Bayes. 'VB' is inherited from stan and is currently in heavy development – do not trust estimates.

`backend`
: Select backend. Defaults to 'rstan' or select 'cmdstanr' if installed.

`...`
: Additional arguments can be 'chain_id', 'init_r', 'test_grad', 'append_samples', 'refresh', 'enable_random_init' etc. See the documentation in `stan`.

Details

Four types of paramerizations are implemented. The constant conditional correlation (CCC) and the dynamic conditional correlation (DCC; Engle2002,Engle2001a), as well as BEKK (Engle and Kroner 1995) and a BEKK model with positivity constraints on the diagonals of the ARCH and GARCH parameters "pdBEKK" (Rast et al. 2022).

The fitted models are 'rstan' objects and all posterior parameter estimates can be obtained and can be examined with either the 'rstan' toolbox, plotted and printed using generic functions or passed to 'bmgarch' functions to 'forecast' or compute 'model_weights' or compute fit statistics based on leave-future-out cross-validation.

Value

`bmgarch` object.

Author(s)

Philippe Rast, Stephen R. Martin

References

Engle RF, Kroner KF (1995). "Multivariate simultaneous generalized arch." *Econometric Theory*, **11**(1), 122–150. doi:10.1017/S0266466600009063.

Rast P, Martin SR, Liu S, Williams DR (2022). "A New Frontier for Studying Within-Person Variability: Bayesian Multivariate Generalized Autoregressive Conditional Heteroskedasticity Models." *Psychological Methods*, **27**, 856–873. doi:10.1037/met0000357. `https://psycnet.apa.org/doi/10.1037/met0000357`.()

Examples

```
## Not run:
data(panas)
```

```
# Fit BEKK(1,1) mgarch model with a ARMA(1,1) meanstructure,
# and student-t residual distribution
fit <- bmgarch(panas, parameterization = "BEKK",
               P = 1, Q = 1,
               meanstructure = "arma",
               distribution = "Student_t")

# Summarize the parameters
summary(fit)

# Forecast 5 ahead
fit.fc <- forecast(fit, ahead = 5)
print(fit.fc)

# Plot mean forecasts
plot(fit.fc, type = "mean")

# Plot variance forecasts
plot(fit.fc, type = "var")

# Plot correlation forecasts
plot(fit.fc, type = "cor")

# Plot modeled data ("backcasted values").
plot(fit, type = "mean")

# Save "backcasted" values
fit.bc <- fitted(fit)

# Save estimated and forecasted data as a data.frame
df.fc <- as.data.frame(fit.fc)

# Access rstan's model fit object
mf <- fit$model_fit

# Return diagnostics and a plot of the first 10 parameters
rstan::check_hmc_diagnostics(mf)
rstan::plot(mf)

## End(Not run)
```

`bmgarch_list` *Collect bmgarch objects into list.*

Description

Collect bmgarch objects into list.

Usage

```
bmgarch_list(...)
```

Arguments

...	bmgarch objects.

Value

List of bmgarch objects. Class: bmgarch_list and bmgarch.

`fitted.bmgarch` *Fitted (backcasting) method for bmgarch objects.*

Description

Extracts the model-predicted means, variances, and correlations for the fitted data.

Usage

```
## S3 method for class 'bmgarch'
fitted(
  object,
  CrI = c(0.025, 0.975),
  digits = 2,
  weights = NULL,
  inc_samples = FALSE,
  ...
)
```

Arguments

object	bmgarch object.
CrI	Numeric vector (Default: `c(.025, .975)`). Lower and upper bound of predictive credible interval.
digits	Integer (Default: 2, optional). Number of digits to round to when printing.
weights	Takes weights from model_weight function. Defaults to 1 – this parameter is not typically set by user.
inc_samples	Logical (Default: FALSE). Whether to return the MCMC samples for the fitted values.
...	Not used.

Details

Whereas `forecast.bmgarch` computes the *forecasted* values for future time periods, `fitted.bmgarch` computes the *backcasted* (model-predicted) values for the observed time periods.

Value

fitted.bmgarch object. List containing metadata and the backcast. Backcast is a list containing three elements:

mean [N, 7, TS] array of mean backcasts, where N is the timeseries length, and TS is the number of time series. E.g., bc$backcast$mean[3,,"tsA"] is the mean backcast for the third observation in time series "tsA".

var [N, 7, TS] array of variance backcasts, where N is the timeseries length, and TS is the number of time series. E.g., bc$backcast$var[3,,"tsA"] is the variance backcast for the third observation in time series "tsA".

cor [N, 7, TS(TS - 1)/2] array of correlation backcasts, where N is the timeseries length, and TS(TS - 1)/2 is the number of correlations. E.g., bc$backcast$cor[3,, "tsB_tsA"] is the backcast for the correlation between "tsB" and "tsA" on the third observation. Lower triangular correlations are saved.

samples List. If inc_samples is TRUE, then a list of arrays of MCMC samples for means, vars, and cors. Each array is [Iteration, Period, ..., ...].

Examples

```
## Not run:
data(panas)
# Fit CCC(1,1) and constant meanstructure.
fit <- bmgarch(panas, parameterization = "CCC", meanstructure = "constant")

# Obtain fitted values
fit.bc <- fitted(fit)

# Print fitted values
print(fit.bc)

# Plot fitted values (plot.bmgarch calls fitted internally)
plot(fit, type = "var")

# Save fitted values as data frame
fit.bc.df <- as.data.frame(fit.bc)

## End(Not run)
```

---

forecast.bmgarch *Forecast method for bmgarch objects.*

Description

Estimates (weighted) forecasted means, variances, and correlations from a fitted bmgarch model.

Usage

```
## S3 method for class 'bmgarch'
forecast(
  object,
  ahead = 1,
  xC = NULL,
  newdata = NULL,
  CrI = c(0.025, 0.975),
  seed = NA,
  digits = 2,
  weights = NULL,
  L = NA,
  method = "stacking",
  inc_samples = FALSE,
  ...
)
```

Arguments

object	bmgarch object.
ahead	Integer (Default: 1). Periods to be forecasted ahead.
xC	Numeric vector or matrix. Covariates(s) for the constant variance terms in C, or c. Used in a log-linear model on the constant variance terms. If vector, then it acts as a covariate for all constant variance terms. If matrix, must have columns equal to number of time series, and each column acts as a covariate for the respective time series (e.g., column 1 predicts constant variance for time series 1).
newdata	Future datapoints for LFO-CV computation
CrI	Numeric vector (Default: c(.025, .975)). Lower and upper bound of predictive credible interval.
seed	Integer (Optional). Specify seed for sampling.
digits	Integer (Default: 2, optional). Number of digits to round to when printing.
weights	Takes weights from model_weight function. Defaults to 1 – this parameter is not typically set by user.
L	Minimal length of time series before engaging in lfocv
method	Ensemble methods, 'stacking' (default) or 'pseudobma'
inc_samples	Logical (Default: FALSE). Whether to return the MCMC samples for the fitted values.
...	Not used

Value

forecast.bmgarch object. List containing forecast, backcast, and metadata. See fitted.bmgarch for information on backcast. forecast is a list of four components:

mean `[N, 7, TS]` array of mean forecasts, where N is the timeseries length, and TS is the number of time series. E.g., `fc$forecast$mean[3,,"tsA"]` is the 3-ahead mean forecast for time series "tsA".

var `[N, 7, TS]` array of variance forecasts, where N is the timeseries length, and TS is the number of time series. E.g., `fc$forecast$var[3,,"tsA"]` is the 3-ahead variance forecast for time series "tsA".

cor `[N, 7, TS(TS - 1)/2]` array of correlation forecasts, where N is the timeseries length, and `TS(TS - 1)/2` is the number of correlations. E.g., `fc$forecast$cor[3,, "tsB_tsA"]` is the 3-ahead forecast for the correlation between "tsB" and "tsA". Lower triangular correlations are saved.

meta Meta-data specific to the forecast. I.e., TS_length (number ahead) and xC.

samples List. If inc_samples is `TRUE`, then a list of arrays of MCMC samples for means, vars, and cors. Each array is [Iteration, Period, ..., ...].

Examples

```
## Not run:
data(panas)
# Fit DCC(2,2) with constant mean structure.
fit <- bmgarch(panas, parameterization = "DCC", P = 2, Q = 2, meanstructure = "constant")

# Forecast 8 ahead
fit.fc <- forecast(fit, ahead = 8)

# Print forecasts
fit.fc
print(fit.fc)

# Plot variance forecasts
plot(fit.fc, type = "var")

# Plot correlation forecasts
plot(fit.fc, type = "cor")

# Save backcasted and forecasted values as data frame.
fit.fc.df <- as.data.frame(fit.fc)

# Save only forecasted values as data frame.
fit.fc.df <- as.data.frame(fit.fc, backcast = FALSE)

# Add another model, compute model weights and perform a model weighted forecast

# Fit a DCC(1,1) model
fit1 <- bmgarch(panas, parameterization = "DCC", P = 1, Q = 1, meanstructure = "constant")

# Compute model stacking weights based on the last 19 time points (with L = 80)
blist <- bmgarch_list( fit1, fit )
mw <- model_weights(blist, L = 80)

# Weighted forecasts:
```

```
w.fc <- forecast(object = blist, ahead = 8, weights = mw)

## End(Not run)
```

`loo.bmgarch` *Leave-Future-Out Cross Validation (LFO-CV)*

Description

`lfocv` returns the LFO-CV ELPD by either computing the exact ELDP or by approximating it via forward or backward approximation strategies based on Pareto smoothed importance sampling described in (Bürkner et al. 2020).

Usage

```
## S3 method for class 'bmgarch'
loo(x, ..., type = "lfo", L = NULL, M = 1, mode = "backward")
```

Arguments

`x`	Fitted bmgarch model. `lfocv` inherits all attributes from the bmgarch object
`...`	Not used
`type`	Takes `lfo` (default) or `loo`. LFO-CV is recommended for time-series but LOO-CV may be obtained to assess the structural part of the model.
`L`	Minimal length of times series before computing LFO
`M`	M step head predictions. Defines to what period the LFO-CV should be tuned to. Defaults to M=1.
`mode`	backward elpd_lfo approximation, or exact elpd-lfo; Takes 'backward', and 'exact'. 'exact' fits N-L models and may take a *very* long time to complete. `forward` works too but is not complete yet.

Value

Approximate LFO-CV value and log-likelihood values across (L+1):N timepoints

References

Bürkner P, Gabry J, Vehtari A (2020). "Approximate leave-future-out cross-validation for Bayesian time series models." *Journal of Statistical Computation and Simulation*, 1–25. doi:10.1080/00949655.2020.1783262.

Examples

```
## Not run:
data(stocks)
# Fit a DCC model
fit <- bmgarch(data = stocks[1:100, c("toyota",  "nissan" )],
               parameterization = "DCC", standardize_data = TRUE,
               iterations = 500)

# Compute expected log-predictive density (elpd) using the backward mode
# L is the upper boundary of the time-series before we engage in LFO-CV
lfob <- loo(fit, mode = 'backward',  L = 50 )
print(lfob)

## End(Not run)
```

`model_weights` *Model weights*

Description

Compute model weights for a list of candidate models based on leave-future-out cross validation (lfocv) expected log-predictive density (elpd). elpd can be approximated via the 'backward' mode described in Bürkner et al. (2020) or via exact cross-validation. The obtained weights can be passed to the forecast function to obtain weighted forecasts. `bmgarch_objects` takes a `bmgarch_object` lists.

Usage

```
model_weights(
  bmgarch_objects = NULL,
  L = NULL,
  M = 1,
  method = "stacking",
  mode = "backward"
)
```

Arguments

`bmgarch_objects`	list of bmgarch model objects in `bmgarch_object`
`L`	Minimal length of time series before engaging in lfocv
`M`	M step head predictions. Defines to what period the LFO-CV should be tuned to. Defaults to M=1.
`method`	Ensemble methods, 'stacking' (default) or 'pseudobma'
`mode`	Either 'backward' (default) or 'exact'

Details

'model_weights()' is a wrapper around the leave-future-out 'lfo' type in 'loo.bmgarch()'. The weights can be either obtained from an approximate or exact leave-future-out cross-validation to compute expected log predictive density (ELPD).

We can either obtain stacking weights or pseudo-BMA+ weigths as described in (Yao et al. 2018).

Value

Model weights

References

Bürkner P, Gabry J, Vehtari A (2020). "Approximate leave-future-out cross-validation for Bayesian time series models." *Journal of Statistical Computation and Simulation*, 1–25. doi:10.1080/00949655.2020.1783262.

Yao Y, Vehtari A, Simpson D, Gelman A (2018). "Using Stacking to Average Bayesian Predictive Distributions." *Bayesian Analysis*, **13**(3), 917–1007. doi:10.1214/17BA1091.

Examples

```
## Not run:
data(stocks)
# Fit at least two models on a subset of the stocks data
# to compute model weights
fit <- bmgarch(data = stocks[1:100, c("toyota",  "nissan" )],
               parameterization = "DCC", standardize_data = TRUE,
               iterations = 500)

fit2 <- bmgarch(data = stocks[1:100, c("toyota",  "nissan" )],
                P = 2, Q =  2,
               parameterization = "DCC", standardize_data = TRUE,
               iterations = 500)
# create a bmgarch_list object
blist <- bmgarch_list(fit, fit2 )

# Compute model weights with the default stacking metod
# L is the upper boundary of the time-series before we engage in LFO-CV
mw <- model_weights( blist, L =  50, method = 'stacking', order = 'backwards' )

# Print model weights in the ordert of the bmgarch_list()
print(mw)

## End(Not run)
```

panas *Positive and Negative Affect Scores.*

Description

A dataset containing simulated values for Positive and Negative Affect scores across 200 measurement occasions for a single individual.

Usage

```
panas
```

Format

Data frame with 200 rows and 2 variables:

Pos Positive Affect score

Neg Negative Affect score

plot.bmgarch *Plot method for bmgarch objects.*

Description

Plot method for bmgarch objects.

Usage

```
## S3 method for class 'bmgarch'
plot(x, type = "mean", askNewPage = TRUE, CrI = c(0.025, 0.975), ...)
```

Arguments

x	bmgarch object.
type	String (Default: "mean"). Whether to plot conditional means ("mean"), variance ("var"), or correlations ("cor").
askNewPage	askNewPage Logical (Default: True). Whether to ask for new plotting page.
CrI	CrI Numeric vector (Default: c(.025, .975)). Lower and upper bound of predictive credible interval.
...	Not used

Value

List of ggplot objects (one per time series).

Author(s)

Stephen R. Martin

`plot.forecast.bmgarch` *Plot method for forecast.bmgarch objects.*

Description

Plot method for forecast.bmgarch objects.

Usage

```
## S3 method for class 'forecast.bmgarch'
plot(x, type = "mean", askNewPage = TRUE, last_t = 100, ...)
```

Arguments

`x`	forecast.bmgarch object. See `forecast.bmgarch`.
`type`	String (Default: "mean"). Whether to plot conditional means ("mean"), variance ("var"), or correlations ("cor").
`askNewPage`	Logical (Default: True). Whether to ask for new plotting page.
`last_t`	Integer (Default: 100). Only show `last_t` observations in plot.
`...`	Not used

Value

List of ggplot objects (one per time series).

Author(s)

Stephen R. Martin

`print.fitted.bmgarch` *Print method for fitted.bmgarch objects.*

Description

Print method for fitted.bmgarch objects.

Usage

```
## S3 method for class 'fitted.bmgarch'
print(x, ...)
```

Arguments

x	fitted.bmgarch object.
...	Not used.

Value

object (invisible).

Author(s)

Stephen R. Martin

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print.forecast.bmgarch

Print method for forecast.bmgarch objects.

Description

Print method for forecast.bmgarch objects.

Usage

```
## S3 method for class 'forecast.bmgarch'
print(x, ...)
```

Arguments

x	forecast.bmgarch object. See forecast.bmgarch
...	Not used.

Value

x (invisible).

Author(s)

Stephen R. Martin

print.loo.bmgarch *print method for lfocv*

Description

print method for lfocv

Usage

```
## S3 method for class 'loo.bmgarch'
print(x, ...)
```

Arguments

x	lfo object
...	Not used.

Value

Invisible lfocv object

Author(s)

philippe

print.model_weights *Print method for model_weights*

Description

Print method for model_weights

Usage

```
## S3 method for class 'model_weights'
print(x, ...)
```

Arguments

x	Model weights object
...	Not used.

Value

model_weights objects with weights, list of log-likelihoods, and r_eff_list

Author(s)

philippe

`print.summary.bmgarch` *Print method for bmgarch.summary objects.*

Description

Print method for bmgarch.summary objects.

Usage

```
## S3 method for class 'summary.bmgarch'
print(x, ...)
```

Arguments

`x`	summary.bmgarch object.
`...`	Not used.

Value

x (invisible).

Author(s)

Philippe Rast, Stephen R. Martin

`stocks` *Daily data on returns of Toyota, Nissan, and Honda stocks.*

Description

A dataset used by Stata to illustrate MGARCH models containing daily data on returns of Toyota, Nissan, and Honda stocks.

Usage

```
stocks
```

Format

Data frame with 2015 rows and 5 variables:

date Date

t Sequential time index

toyota Daily returns for Toyota stock

nissan Daily returns for Nissan stock

honda Daily returns for Honda stock

`summary.bmgarch` *Summary method for bmgarch objects.*

Description

Computes posterior summaries for all parameters of interest for bmgarch objects.

Usage

```
## S3 method for class 'bmgarch'
summary(object, CrI = c(0.025, 0.975), digits = 2, ...)
```

Arguments

`object`	bmgarch object.
`CrI`	Numeric vector (Default: `c(.025, .975)`). Lower and upper bound of predictive credible interval.
`digits`	Integer (Default: 2, optional). Number of digits to round to when printing.
`...`	Not used.

Value

summary.bmgarch object. A named list containing "meta" and "model_summary". `model_summary` contains summary table for all model parameters.

Author(s)

Stephen R. Martin, Philippe Rast

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