

# Package ‘bmgarch’

September 17, 2020

**Title** Bayesian Multivariate GARCH Models

**Version** 1.0.0

**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, 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) <doi:10.2307/2109358>. 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.

**License** GPL (>= 3)

**Depends** methods, R (>= 3.5.0), Rcpp (>= 1.0.1)

**Imports** rstan (>= 2.21.2), rstantools (>= 1.5.1), ggplot2, MASS, forecast, loo, Rdpack

**LinkingTo** BH (>= 1.69.0-1), Rcpp (>= 1.0.1), RcppEigen (>= 0.3.3.5.0), rstan (>= 2.18.2), StanHeaders (>= 2.18.1)

**RdMacros** Rdpack

**Encoding** UTF-8

**LazyData** true

**NeedsCompilation** yes

**SystemRequirements** GNU make

**RoxygenNote** 7.1.1

**Suggests** testthat (>= 2.1.0)

**BugReports** <https://github.com/ph-rast/bmgarch/issues>

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bmgarch-package	<i>The 'bmgarch' package.</i>
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**Description**

The `*bmgarch*` package fits Bayesian multivariate GARCH models specified via `stan`, a C++ package providing HMC methods for full Bayesian inference (cf. [<http://mc-stan.org>]). The currently implemented parameterizations are DCC(Q,P), CCC(Q,P), and BEKK(Q,P) with arbitrary lags defined in Q, and P. The package provides summaries and plots for the estimates as well as forecasted series with corresponding plots. The fitted objects are `rstan` class objects that can be inspected and manipulated accordingly.

**Author(s)**

Philippe Rast

**References**

Stan Development Team (2018). RStan: the R interface to Stan. R package version 2.18.2. <http://mc-stan.org>

---

```
as.data.frame.fitted.bmgarch
  as.data.frame method for fitted.bmgarch objects.
```

---

**Description**

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

**Usage**

```
## S3 method for class 'fitted.bmgarch'
as.data.frame(x, ...)
```

**Arguments**

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

**Value**

Data frame.

**Author(s)**

Stephen R. Martin

---

```
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 <a href="#">fitted.bmgarch</a> 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 = 2000,
  chains = 4,
  standardize_data = FALSE,
  distribution = "Student_t",
  meanstructure = "constant",
  ...
)
```

**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. 2020). 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 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). Number of iterations for each chain (including warmup).
chains	Integer (Default: 4). The number of Markov chains.
standardize_data	Logical (Default: FALSE). Whether data should be standardized.
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.
...	Additional arguments can be 'chain_id', 'init_r', 'test_grad', 'append_samples', 'refresh', 'enable_random_init' etc. See the documentation in <a href="#">stan</a> .

### Details

Four types of parameterizations 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. 2020).

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](https://doi.org/10.1017/S0266466600009063).

Rast P, Martin SR, Liu S, Williams DR (2020). "A New Frontier for Studying Within-Person Variability: Bayesian Multivariate Generalized Autoregressive Conditional Heteroskedasticity Models." *Psychological Methods*. <https://psyarxiv.com/j57pk/>.

### Examples

```
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)
```

---

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	<i>Fitted (backcasting) method for bmgarch objects.</i>
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---

**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

```
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)
```

---

forecast.bmgarch	<i>Forecast method for bmgarch objects.</i>
------------------	---

---

## 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 <a href="#">sampling</a> .
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**

```

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)

```

---

loo.bmgarch

*Leave-Future-Out Cross Validation (LFO-CV)*


---

**Description**

lfo returns the LFO-CV ELDP 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, 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
mode	backward elpd_lfo approximation, or exact elpd-lfo; Takes 'backward', and 'exact'. 'exact' fits N-L models and may take a <i>very</i> 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](https://doi.org/10.1080/00949655.2020.1783262).

**Examples**

```
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)
```

---

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,
  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
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+ weights 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](https://doi.org/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](https://doi.org/10.1214/17BA1091).

**Examples**

```
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)

```

---

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 <a href="#">forecast.bmgarch</a> .
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**

<code>x</code>	fitted.bmgarch object.
<code>...</code>	Not used.

**Value**

object (invisible).

**Author(s)**

Stephen R. Martin

---

`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**

<code>x</code>	forecast.bmgarch object. See <a href="#">forecast.bmgarch</a>
<code>...</code>	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**

<code>x</code>	lfo object
<code>...</code>	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**

<code>x</code>	Model weights object
<code>...</code>	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)**

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	<i>Summary method for bmgarch objects.</i>
-----------------	--

---

**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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