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LocalCop: An R package for local likelihood inference for conditional copulas

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Summary

Conditional copulas models allow the dependence structure between multiple response variables to be modelled as a function of covariates. **LocalCop** (Acar & Lysy, 2024) is an R/C++ package for computationally efficient semiparametric conditional copula modelling using a local likelihood inference framework developed in Acar, Craiu, & Yao (2011), Acar, Craiu, & Yao (2013) and Acar, Czado, & Lysy (2019).

Statement of Need

There are well-developed R packages such as **copula** (Hofert, Kojadinovic, Mächler, & Yan, 2023; Hofert & Mächler, 2011; Kojadinovic & Yan, 2010; Yan, 2007) and **VineCopula** (Nagler et al., 2023) for fitting copulas in various multivariate data settings. However, these software focus exclusively on unconditional dependence modelling and do not accommodate covariate information.

Aside from **LocalCop**, R packages for fitting conditional copulas are **gamCopula** (Nagler & Vatter, 2020) and **CondCopulas** (Derumigny, 2023). **gamCopula** estimates the covariate-dependent copula parameter using spline smoothing. While this typically has lower variance than the local likelihood estimate provided by **LocalCop**, it also tends to have lower accuracy (Acar et al., 2019). **CondCopulas** estimates the copula parameter using a semi-parametric maximum-likelihood method based on a kernel-weighted conditional concordance metric. **LocalCop** also uses kernel weighting, but it uses the full likelihood information of a given copula family rather than just that contained in the concordance metric, and is therefore more statistically efficient.

Local likelihood methods typically involve solving a large number of low-dimensional optimization problems and thus can be computationally intensive. To address this issue, **LocalCop** implements the local likelihood function in C++, using the R/C++ package **TMB** (Kristensen, Nielsen, Berg, Skaug, & Bell, 2016) to efficiently obtain the associated score function using automatic differentiation. Thus, **LocalCop** is able to solve each optimization problem very quickly using gradient-based algorithms. It also provides a means of easily parallelizing the optimization across multiple cores, rendering **LocalCop** competitive in terms of speed with other available software for conditional copula estimation.

Background

For any bivariate response vector (Y_1, Y_2), the conditional joint distribution given a covariate X is given by

$$F_X(y_1, y_2 \mid x) = C_X(F_{1|X}(y_1 \mid x), F_{2|X}(y_2 \mid x) \mid x), \tag{1}$$

where $F_{1|X}(y_1 \mid x)$ and $F_{2|X}(y_2 \mid x)$ are the conditional marginal distributions of Y_1 and Y_2 given X, and $C_X(u, v \mid x)$ is a conditional copula function. That is, for given $X = x$, the function $C_X(u, v \mid x)$ is a bivariate CDF with uniform margins.

The focus of **LocalCop** is on estimating the conditional copula function, which is modelled semi-parametrically as

$$C_X(u, v \mid x) = \mathcal{C}(u, v \mid \theta(x), \nu), \tag{2}$$

where $\mathcal{C}(u, v \mid \theta, \nu)$ is a parametric copula family, the copula dependence parameter $\theta \in \Theta$ is an arbitrary function of X, and $\nu \in \Upsilon$ is an additional copula parameter present in some models. Since most parametric copula families have a restricted range $\Theta \subsetneq \mathbb{R}$, we describe the data generating model (DGM) in terms of the calibration function $\eta(x)$, such that

$$\theta(x) = g^{-1}(\eta(x)), \tag{3}$$

where $g^{-1} : \mathbb{R} \to \Theta$ an inverse-link function which ensures that the copula parameter has the correct range. The choice of $g^{-1}(\eta)$ is not unique and depends on the copula family.

Local likelihood estimation of the conditional copula parameter $\theta(x)$ uses Taylor expansions to approximate the calibration function $\eta(x)$ at an observed covariate value $X = x$ near a fixed point $X = x_0$, i.e.,

$$\eta(x) \approx \eta(x_0) + \eta^{(1)}(x_0)(x - x_0) + \ldots + \frac{\eta^{(p)}(x_0)}{p!}(x - x_0)^p.$$

One then estimates $\beta_k = \eta^{(k)}(x_0)/k!$ for $k = 0, \ldots, p$ using a kernel-weighted local likelihood function

$$\ell(\beta) = \sum_{i=1}^{n} \log\left\{c\left(u_i, v_i \mid g^{-1}(x_i^T\beta), \nu\right)\right\} K_h\left(\frac{x_i - x_0}{h}\right), \tag{4}$$

where (u_i, v_i, x_i) is the data for observation i, $x_i = (1, x_i - x_0, (x_i - x_0)^2, \ldots, (x_i - x_0)^p)$, $\beta = (\beta_0, \beta_1, \ldots, \beta_p)$, and $K_h(z)$ is a kernel function with bandwidth parameter $h > 0$. Having maximized $\ell(\beta)$ in Equation 4, one estimates $\eta(x_0)$ by $\hat{\eta}(x_0) = \hat{\beta}_0$. Usually, a linear fit with $p = 1$ suffices to obtain a good estimate in practice.

Usage

LocalCop is available on CRAN and GitHub. The two main package functions are:

- `CondiCopLocFit()`: For estimating the calibration function at a sequence of values $x_0 = (x_{01}, \ldots, x_{0m})$.
- `CondiCopSelect()`: For selecting a copula family and bandwidth parameter using leave-one-out cross-validation (LOO-CV) with subsampling as described in Acar et al. (2019).

In the following example, we illustrate the model selection/tuning and fitting steps for data generated from a Clayton copula with conditional Kendall τ displayed in Figure 2. The CV metric for each combination of family and bandwidth are displayed in Figure 1.

```
library(LocalCop)   # local likelihood estimation
library(VineCopula) # simulate copula data
```

```
set.seed(2024)

# simulation setting
family <- 3                    # Clayton Copula
n_obs <- 300                   # number of observations
eta_fun <- function(x) {       # calibration function
  sin(5*pi*x) + cos(8*pi*x^2)
}
```

```r
# simulate covariate values
x <- sort(runif(n_obs))

# simulate response data
eta_true <- eta_fun(x)                          # calibration parameter eta(x)
par_true <- BiCopEta2Par(family = family,  # copula parameter theta(x)
                         eta = eta_true)
udata <- VineCopula::BiCopSim(n_obs, family = family, par = par_true)

# model selection and tuning
bandset <- c(.02, .05, .1, .2) # set of bandwidth parameters
famset <- c(1, 2, 3, 4, 5)     # set of copula families
kernel <- KernGaus             # kernel function
degree <- 1                    # degree of local polynomial
n_loo <- 100                   # number of LOO-CV observations
                               # (can be much smaller than n_obs)

# calculate cv for each combination of family and bandwidth
cvselect <- CondiCopSelect(u1= udata[,1], u2 = udata[,2],
                           x = x, xind = n_loo,
                           kernel = kernel, degree = degree,
                           family = famset, band = bandset)
```

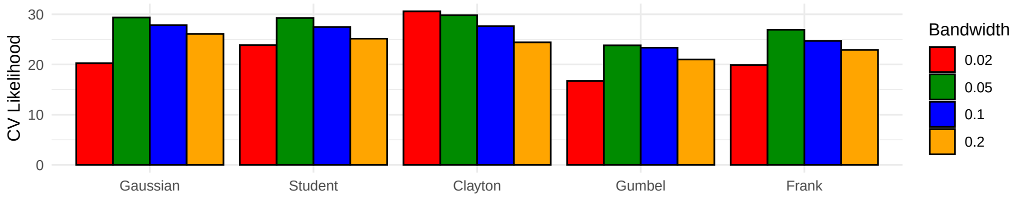

Figure 1: Cross-validation metric for each combination of family and bandwidth.

```r
# extract the selected family and bandwidth from cvselect
cv_res <- cvselect$cv
i_opt <- which.max(cv_res$cv)
fam_opt <- cv_res[i_opt,]$family
band_opt <- cv_res[i_opt,]$band

# calculate eta(x) on a grid of values
x0 <- seq(0, 1, by = 0.01)
copfit <- CondiCopLocFit(u1 = udata[,1], u2 = udata[,2],
                         x = x, x0 = x0,
                         kernel = kernel, degree = degree,
                         family = fam_opt, band = band_opt)
# convert eta to Kendall tau
tau_loc <- BiCopEta2Tau(copfit$eta, family= fam_opt)

# simulate covariate values
x <- sort(runif(n_obs))

# simulate response data
eta_true <- eta_fun(x)                          # calibration parameter eta(x)
par_true <- BiCopEta2Par(family = family,  # copula parameter theta(x)
                         eta = eta_true)
udata <- VineCopula::BiCopSim(n_obs, family = family, par = par_true)
```

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```r
# model selection and tuning
bandset <- c(.02, .05, .1, .2) # set of bandwidth parameters
famset <- c(1, 2, 3, 4, 5)     # set of copula families
kernel <- KernGaus             # kernel function
degree <- 1                    # degree of local polynomial
n_loo <- 100                   # number of LOO-CV observations
                               # (can be much smaller than n_obs)

# calculate cv for each combination of family and bandwidth
cvselect <- CondiCopSelect(u1= udata[,1], u2 = udata[,2],
                           x = x, xind = n_loo,
                           kernel = kernel, degree = degree,
                           family = famset, band = bandset)

# extract the selected family and bandwidth from cvselect
cv_res <- cvselect$cv
i_opt <- which.max(cv_res$cv)
fam_opt <- cv_res[i_opt,]$family
band_opt <- cv_res[i_opt,]$band

# calculate eta(x) on a grid of values
x0 <- seq(0, 1, by = 0.01)
copfit <- CondiCopLocFit(u1 = udata[,1], u2 = udata[,2],
                         x = x, x0 = x0,
                         kernel = kernel, degree = degree,
                         family = fam_opt, band = band_opt)
# convert eta to Kendall tau
tau_loc <- BiCopEta2Tau(copfit$eta, family= fam_opt)
```

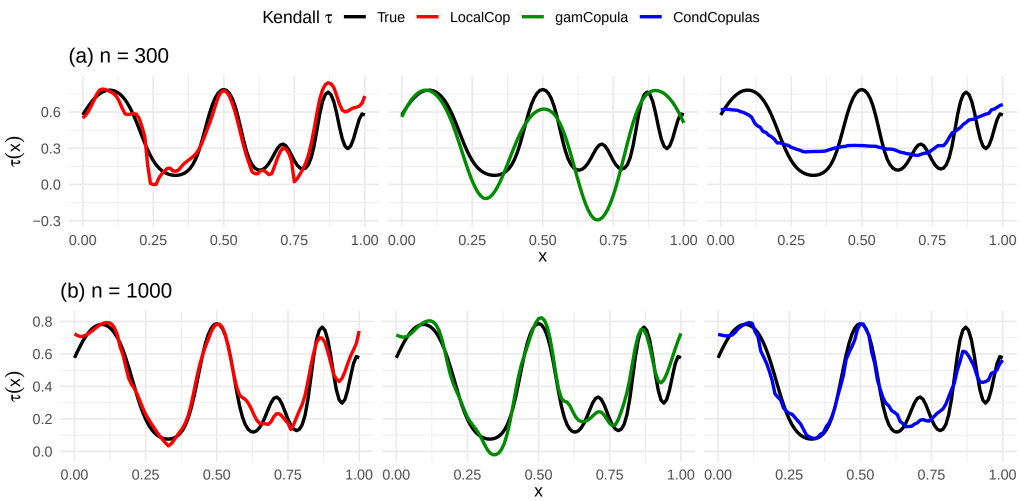

Figure 2: True vs estimated conditional Kendall τ using various methods.

In Figure 2, we compare the true conditional Kendall τ to estimates using each of the three conditional copula fitting packages **LocalCop**, **gamCopula**, and **CondCopulas**, for sample sizes $n = 300$ and $n = 1000$. In **gamCopula**, selection of the copula family smoothing splines is done using the generalized CV framework provided by the R package **mgcv** (Wood, 2017). In **CondCopulas**, selection of the bandwidth parameter is done using LOO-CV. In this particular example, the sample size of $n = 300$ is not large enough for **gamCopula** to pick a sufficiently flexible spline basis, and **CondCopulas** picks a large bandwidth which oversmooths the data.

For the larger sample size $n = 1000$, the three methods exhibit similar accuracy.

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