

Earthquake Forecasting

Dissertation Project 2

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```
1 require(ETAS.inlabru)
2 require(ggplot2)
3 require(dplyr)
4 require(magrittr)
5 require(tidyquant)
6 require(rnaturalearth)
7 require(terra)
8 require(sf)
9 require(ggspatial)
10 require(rnaturalearthdata)
11 require(lubridate)
12
13 # Increase/decrease num.cores if you have more/fewer cores on your computer.
14 # future::multisession works on both Windows, MacOS, and Linux
15 num.cores <- 1
16 future::plan(future::multisession, workers = num.cores)
17 INLA::inla.setOption(num.threads = num.cores)
18 # To deactivate parallelism, run
19 # future::plan(future::sequential)
20 # INLA::inla.setOption(num.threads = 1)
```

Copula transformation of the priors

```
1 # set copula transformations list
2 link.f <- list(
3   mu = \(x) gamma_t(x, 0.3, 0.6),
4   K = \(x) unif_t(x, 0, 10),
5   alpha = \(x) unif_t(x, 0, 10),
6   c_ = \(x) unif_t(x, 0, 10),
```

```

7   p = \(x) unif_t(x, 1, 10)
8   )
9
10  # set inverse copula transformations list
11  inv.link.f <- list(
12    mu = \(x) inv_gamma_t(x, 0.3, 0.6),
13    K = \(x) inv_unif_t(x, 0, 10),
14    alpha = \(x) inv_unif_t(x, 0, 10),
15    c_ = \(x) inv_unif_t(x, 0, 10),
16    p = \(x) inv_unif_t(x, 1, 10)
17  )

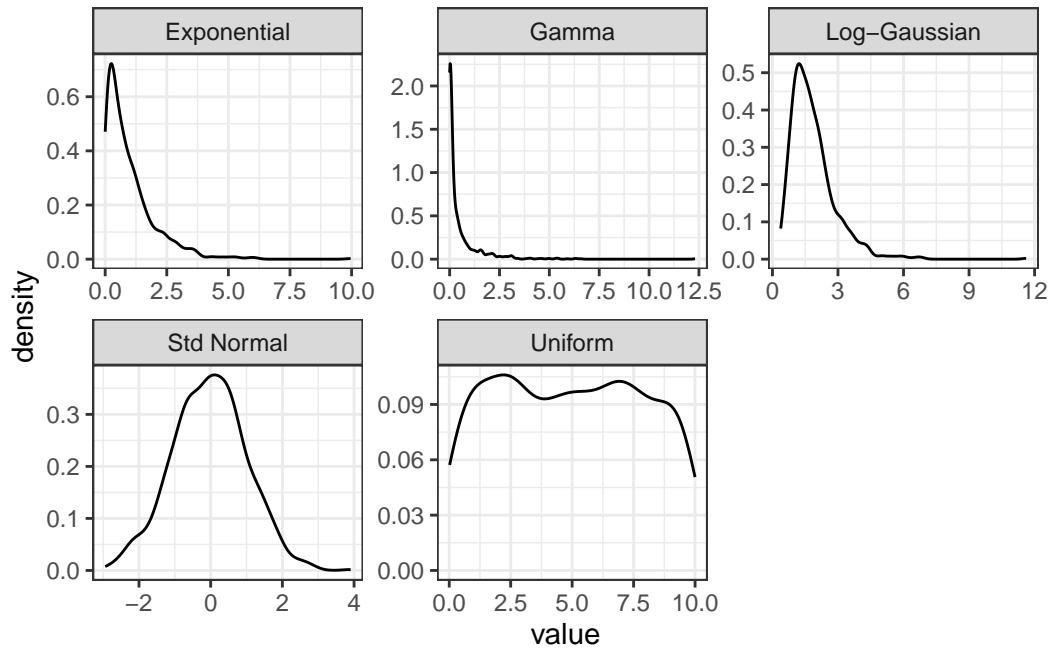
1  # obtain sample from standard normal distribution
2  X <- rnorm(1000)
3  # apply copula transformations
4  gamma.X <- gamma_t(X, .3, .6)
5  unif.X <- unif_t(X, 0, 10)
6  exp.X <- exp_t(X, 1)
7  loggaus.X <- loggaus_t(X, .5, .5)
8
9  # build data.frame for plotting
10 df.to.plot <- rbind(
11   data.frame(
12     value = X,
13     distribution = "Std Normal"
14   ),
15   data.frame(
16     value = gamma.X,
17     distribution = "Gamma"
18   ),
19   data.frame(
20     value = unif.X,
21     distribution = "Uniform"
22   ),
23   data.frame(
24     value = exp.X,
25     distribution = "Exponential"
26   ),
27   data.frame(
28     value = loggaus.X,
29     distribution = "Log-Gaussian"

```

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30   )
31   )
32   # plot them
33   ggplot(df.to.plot, aes(value)) +
34     geom_density() +
35     theme_bw() +
36     facet_wrap(facets = ~ distribution, scales = "free")

```



Italy

```

1  # transform time string in Date object
2  horus$time_date <- as.POSIXct(
3    horus$time_string,
4    format = "%Y-%m-%dT%H:%M:%OS",
5    tz = "UTC"
6  )
7  # There may be some incorrectly registered data-times in the original data set,
8  # that as.POSIXct() can't convert, depending on the system.
9  # These should ideally be corrected, but for now, we just remove the rows that
10 # couldn't be converted.
11 # horus <- na.omit(horus)

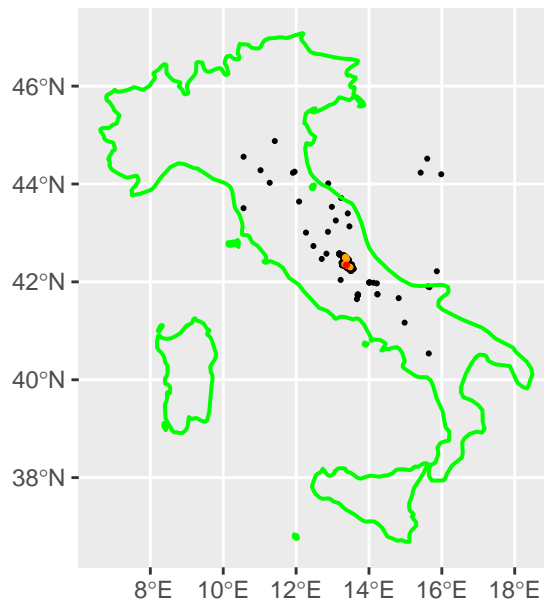
```

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12
13 # set up parameters for selection
14 start.date <- as.POSIXct("2009-01-01T00:00:00",
15                           format = "%Y-%m-%dT%H:%M:%OS")
16 end.date <- as.POSIXct("2010-01-01T00:00:00", format = "%Y-%m-%dT%H:%M:%OS")
17 min.longitude <- 10.5
18 max.longitude <- 16
19 min.latitude <- 40.5
20 max.latitude <- 45
21 M0 <- 2.5
22
23 # set up conditions for selection
24 aquila.sel <- (horus$time_date >= start.date) &
25   (horus$time_date < end.date) &
26   (horus$lon >= min.longitude) &
27   (horus$lon <= max.longitude) &
28   (horus$lat >= min.latitude) &
29   (horus$lat <= max.latitude) &
30   (horus$M >= M0)
31
32 # select
33 aquila <- horus[aquila.sel, ]
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```

Map of event locations



```
1 ggplot(aquila, aes(time_date, M)) +  
2   geom_point() +  
3   theme_bw()
```

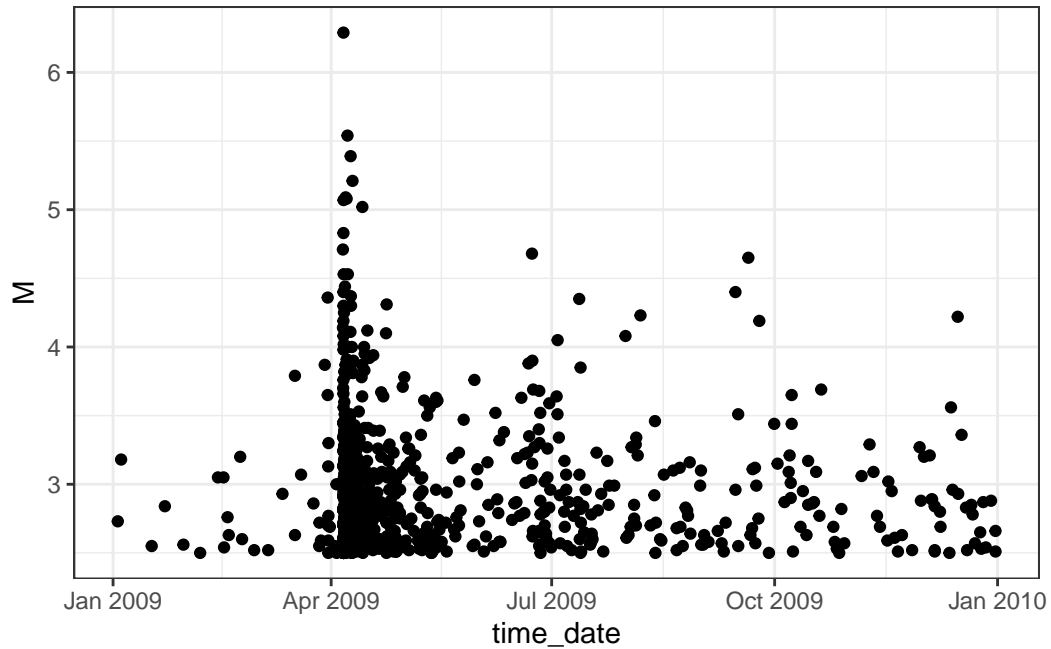


Figure 1: L'Aquila seismic sequence, times versus magnitudes

```

1  # set up data.frame for model fitting
2  aquila.bru <- data.frame(
3    ts = as.numeric(
4      difftime(aquila$time_date, start.date, units = "days")
5    ),
6    magnitudes = aquila$M,
7    idx.p = 1 : nrow(aquila)
8  )

1  # set up list of initial values
2  th.init <- list(
3    th.mu = inv.link.f$mu(0.5),
4    th.K = inv.link.f$K(0.1),
5    th.alpha = inv.link.f$alpha(1),
6    th.c = inv.link.f$c_(0.1),
7    th.p = inv.link.f$p(1.1)
8  )

```

```

1  # set starting and time of the time interval used for model fitting.
2  # In this case, we use the interval covered by the data.
3  T1 <- 0
4  T2 <- max(aquila.bru$ts) + 0.2 # Use max(..., na.rm = TRUE) if there may
5  # still be NAs here

1  # set up list of bru options
2  bru.opt.list <- list(
3    bru_verbose = 3, # type of visual output
4    bru_max_iter = 70, # maximum number of iterations
5    # bru_method = list(max_step = 0.5),
6    bru_initial = th.init # parameters' initial values
7  )

1  ETAS <- function(data = aquila.bru, m0 = M0, t1 = T1, t2 = T2,
2                    ncore = num.cores, Link.f = link.f,
3                    Bru.opt.list = bru.opt.list, n.samp = 1000,
4                    max.batch = 1000, mag = 4.5, n.breaks = 100,
5                    t.end.tri.post = 5, t.end.tri.prior = 10,
6                    t.end.omori.post = 5, t.end.omori.prior = 5){
7
8    # maximum likelihood estimator for beta
9    beta.p <- 1 / (mean(data$magnitudes) - m0)
10
11   # fit the model
12   model.fit <- Temporal.ETAS(
13     total.data = data,
14     M0 = m0,
15     T1 = t1,
16     T2 = t2,
17     link.functions = Link.f,
18     coef.t. = 1,
19     delta.t. = 0.1,
20     N.max. = 5,
21     bru.opt = Bru.opt.list
22   )
23
24   # create input list to explore model output
25   input_list <- list(
26     model.fit = model.fit,
27     link.functions = Link.f

```

```

28 )
29
30 # get marginal posterior information
31 post.list <- get_posterior_param(input.list = input_list)
32
33 # plot marginal posteriors
34 postplot <- post.list$post.plot
35
36 # posterior sampling
37 post.samp <- post_sampling(
38   input.list = input_list,
39   n.samp = n.samp,
40   max.batch = max.batch,
41   ncore = num.cores
42 )
43
44 # taking the averages of the posterior parameter estimates
45 post.par <- apply(post.samp, 2, mean)
46
47 # pair plot
48 pair.plot <- post_pairs_plot(
49   post.samp = post.samp,
50   input.list = NULL,
51   n.samp = NULL,
52   max.batch = max.batch
53 )
54 pairplot <- pair.plot$pair.plot
55
56 # set additional elements of the list
57 input_list$T12 <- c(t1, t2)
58 input_list$M0 <- m0
59 input_list$catalog.bru <- data
60
61 # posterior number of events
62 N.post <- get_posterior_N(input.list = input_list)
63 Npostplot <- N.post$post.plot
64 Npostmean <- N.post$post.df[which.max(N.post$post.df$mean), 1]
65
66 # number of large events
67 large_events <- data[data$magnitudes >= mag,]
68 Nlarge <- nrow(large_events)

```



```

69
70   # mean absolute distance of the differences in magnitudes
71   diff_mag <- diff(data$magnitudes)
72   abs_dist_mag <- mean(abs(diff_mag))
73
74   # mean absolute distance of the inter-arrival time
75   interarrival <- diff(data$ts)
76   abs_dist_int <- mean(abs(interarrival))
77
78   # check if overdispersion occurs
79   m_int_time <- mean(interarrival)
80   v_int_time <- var(interarrival)
81   overdisp <- m_int_time ^ 2 < v_int_time
82
83   # triggering function plots
84   # posterior
85   triplotpost <- triggering_fun_plot(
86     input.list = input_list,
87     post.samp = post.samp,
88     n.samp = NULL, magnitude = mag,
89     t.end = t.end.tri.post, n.breaks = n.breaks
90   )
91
92   # prior
93   triplotprior <- triggering_fun_plot_prior(input.list = input_list,
94     magnitude = mag, n.samp = n.samp,
95     t.end = t.end.tri.prior)
96
97   # omori plots
98   # posterior
99   omoripost <- omori_plot_posterior(input.list = input_list,
100     post.samp = post.samp,
101     n.samp = NULL, t.end = t.end.omori.post)
102
103   # prior
104   omoriprior <- omori_plot_prior(input.list = input_list,
105     n.samp = n.samp,
106     t.end = t.end.omori.prior)
107
108   # returns the whole environment
109   envir <- as.list(environment())
110   return(tibble::lst(envir))

```

```

111 }
112 etas <- ETAS()

```

Start creating grid...

Finished creating grid, time 4.643445

Effect of mis-specifying parameters

```

1  ## set copula transformations list
2  # link.f1 <- list(
3  #   mu = \ (x) gamma_t(x, 0.3, 0.6),
4  #   K = \ (x) unif_t(x, 0, 10),
5  #   alpha = \ (x) unif_t(x, 0, 10),
6  #   c_ = \ (x) unif_t(x, 0, 10),
7  #   p = \ (x) unif_t(x, 1, 10)
8  # )

```

Synthetic catalogues generation

```

1  mult.synth.ETAS <- function(t1 = NULL, t2 = NULL, n.cat = 1000,
2                             ht = etas$envir$data[which.max(
3                             etas$envir$data$magnitudes), ]){
4
5     # inherits the environment from function `ETAS`
6     envir <- etas$envir
7
8     # updates environments if specified by users
9     envir$t1 <- ifelse(!is.null(t1), t1, envir$t1)
10    envir$t2 <- ifelse(!is.null(t2), t2, envir$t2)
11
12    # Function to generate a synthetic catalogue
13    synth.gen <- function(i){
14        iteration <- i
15        synth <- generate_temporal_ETAS_synthetic(
16            theta = envir$post.par %>% as.list,
17            beta.p = envir$beta.p,
18            M0 = envir$m0, T1 = envir$t1,
19            T2 = envir$t2, Ht = ht, ncore = num.cores)
20        return(synth)
21    }
22

```

```

23   # generates catalogues as list of lists
24   multi.synth.cat.list <- lapply(seq_len(n.cat), \(x)
25     synth.gen(x))
26
27   # stores catalogues as list of data.frames
28   multi.synth.cat.list.df <- lapply(multi.synth.cat.list,
29     \(x) do.call(rbind, x))
30
31   # calculates the number of events in each catalogue
32   Nevents <- unlist(lapply(seq_len(n.cat), \(i) nrow(
33     multi.synth.cat.list.df[[i]])))
34
35   # sets catalogue identifier
36   multi.synth.cat.list.df <- lapply(seq_len(n.cat),
37     \(x) cbind(
38       multi.synth.cat.list.df[[x]],
39       cat.idx = x,
40       num_events = Nevents[x]))
41
42   # merges catalogues in unique data.frame
43   multi.synth.cat.df <- do.call(rbind, multi.synth.cat.list.df)
44
45   # returns the whole environment
46   environ <- as.list(environment())
47   return(tibble::lst(environ))
48 }
49 mult.synth <- mult.synth.ETAS(ht = NULL)

```

Fitting Models on the Synthetic Catalogues

```

1  synth.fit <- function(breaks = c(0, 110, 130, 150, 170, 190, 210),
2    samp.each.class = 1){
3
4    # selecting catalogues
5    Nevents <- mult.synth$environ$Nevents
6    classes <- cut(Nevents, breaks = breaks)
7    samp.id <- rep(0, samp.each.class * (classes %>% levels %>% length))
8    for(i in classes %>% levels %>% length %>% seq_len){
9      samp.id[(samp.each.class * (i - 1) + 1) : (samp.each.class * i)] <-
10       sample(which(classes == levels(classes)[i]), samp.each.class)
11    }
12

```

```

13 # we need to bind the synthetics with the observed catalogue
14 # for plotting
15 cat.df.for.plotting <- rbind(
16   mult.synth$enviro$multi.synth.cat.df[
17     which(
18       mult.synth$enviro$multi.synth.cat.df$cat.idx %in% samp.id),
19   ],
20   cbind(mult.synth$enviro$envir$data[, c("ts", "magnitudes")],
21     gen = NA, cat.idx = "observed", num_events = nrow(etas$envir$data)
22   )
23 )
24
25 # plot them
26 multi.synth.cat.plot <- ggplot(cat.df.for.plotting,
27   aes(ts, magnitudes)) +
28   geom_point(size = 0.5) +
29   geom_point(
30     data = mult.synth$enviro$ht,
31     mapping = aes(ts, magnitudes), colour = "black"
32   ) +
33   facet_wrap(facets = vars(cat.idx, num_events),
34     labeller = 'label_both')
35
36 # modelling
37 input <- rep(list(NULL), classes %>% levels %>% length)
38 post <- rep(list(NULL), classes %>% levels %>% length)
39 post.par <- matrix(rep(0, (classes %>% levels %>% length) * 5),
40   ncol = 5)
41 Npost <- rep(list(NULL), classes %>% levels %>% length)
42 Npostmean <- rep(0, classes %>% levels %>% length)
43 Nlarge <- rep(0, classes %>% levels %>% length)
44 abs_dist_int <- rep(0, classes %>% levels %>% length)
45 abs_dist_mag <- rep(0, classes %>% levels %>% length)
46 overdisp <- rep(0, classes %>% levels %>% length)
47
48 for(i in classes %>% levels %>% length %>% seq_len){
49   multi.synth.etas <- ETAS(data =
50     mult.synth$enviro$multi.synth.cat.list.df[[samp.id[i]]],
51     t1 = mult.synth$enviro$envir$t1,
52     t2 = mult.synth$enviro$envir$t2)
53   post[[i]] <- multi.synth.etas$envir$post.list

```

```

54     post.par[i,] <- multi.synth.etas$envir$post.par
55     Npost[[i]] <- multi.synth.etas$envir$N.post
56     Npostmean[i] <- multi.synth.etas$envir$Npostmean
57     Nlarge[i] <- multi.synth.etas$envir$Nlarge
58     abs_dist_int[i] <- multi.synth.etas$envir$abs_dist_int
59     abs_dist_mag[i] <- multi.synth.etas$envir$abs_dist_mag
60     overdisp[i] <- multi.synth.etas$envir$overdisp
61   }
62
63   for(i in samp.id %>% length %>% seq_len){
64     post[[i]]$post.df$Catalogues <-
65       paste('Random Catalogue', i, ': ', Nevents[samp.id[i]],
66             'Events')
67   }
68
69   df.true.param <- data.frame(x = etas$envir$post.par,
70                               param = names(etas$envir$post.par %>% as.list))
71
72   # bind marginal posterior data.frames
73   bind.post.df <- do.call(rbind,
74                           lapply(samp.id %>% length %>% seq_len,
75                                 \(i) post[[i]]$post.df))
76
77   # plot them
78   post.par.plot <- ggplot(bind.post.df,
79                             aes(x = x, y = y, colour = Catalogues)) +
80     geom_line() +
81     facet_wrap(facets = ~ param, scales = "free") +
82     xlab("param") +
83     ylab("pdf") +
84     geom_vline(
85       data = df.true.param,
86       mapping = aes(xintercept = x), linetype = 2
87     )
88
89   ##
90   for(i in samp.id %>% length %>% seq_len){
91     Npost[[i]]$post.df$Catalogues <-
92       paste('Random Catalogue', i, ': ', Nevents[samp.id[i]],
93             'Events')
94   }

```

```

95
96 df.true.N <- data.frame(N = etas$envir$Npostmean, param = 'N')
97
98 # bind marginal posterior data.frames
99 bind.post.N.df <- do.call(rbind,
100                             lapply(samp.id %>% length %>% seq_len,
101                                     \ (i) Npost[[i]]$post.df))
102
103 # plot them
104 post.N.plot <- ggplot(bind.post.N.df,
105                         aes(x = N, y = mean, colour = Catalogues)) +
106   geom_line() +
107   xlab("N") +
108   ylab("pdf") +
109   geom_vline(
110     data = df.true.N,
111     mapping = aes(xintercept = N), linetype = 2
112   )
113
114 # returns the whole environment
115 environ <- as.list(environment())
116 return(tibble::lst(environ))
117 }
118 mult.synth.fit <- rep(list(NULL), 3)
119 mult.synth.fit[[1]] <- synth.fit()

Start creating grid...
Finished creating grid, time 0.2027328
Start creating grid...
Finished creating grid, time 0.2167971
Start creating grid...
Finished creating grid, time 0.344548
Start creating grid...
Finished creating grid, time 0.369961
Start creating grid...
Finished creating grid, time 0.79897
Start creating grid...
Finished creating grid, time 0.9608929

1 mult.synth.fit[[2]] <- synth.fit(breaks =
2                                   c(210, 240, 270, 300, 330, 360, 400))

```

```

Start creating grid...
Finished creating grid, time 0.6186411
Start creating grid...
Finished creating grid, time 0.6089611
Start creating grid...
Finished creating grid, time 0.5968621
Start creating grid...
Finished creating grid, time 0.6932831
Start creating grid...
Finished creating grid, time 0.8530071
Start creating grid...
Finished creating grid, time 0.8823462

```

```

1 mult.synth.fit[[3]] <- synth.fit(breaks = c(400, 600, 800, 1600))

```

```

Start creating grid...
Finished creating grid, time 1.390939
Start creating grid...
Finished creating grid, time 2.207845
Start creating grid...
Finished creating grid, time 3.399027

```

Analysis on the Behaviours of the Time-between-Events

```

1 ECDF.interarrival <- function(i){
2
3   samp.id <- mult.synth.fit[[i]]$environ$samp.id
4   Nevents <- mult.synth$environ$Nevents
5
6   data.list <- lapply(samp.id %>% length %>% seq_len, \(i) data.frame(
7     Time_between_events =
8       mult.synth$environ$multi.synth.cat.list.df[[samp.id[i]]]$ts %>%
9       sort %>% diff,
10    Num_Events = paste(Nevents[samp.id[i]], '(synthetic)')
11  )
12 )
13
14 data.list[[length(samp.id) + 1]] <- data.frame(
15   Time_between_events = etas$envir$interarrival,
16   Num_Events = paste(nrow(etas$envir$data), '(observed)'))
17

```

```

18 data.list[[length(samp.id) + 2]] <- data.frame(
19   Time_between_events =
20     rexp(length(etas$envir$interarrival),
21         1 / etas$envir$m_int_time),
22   Num_Events = paste(nrow(etas$envir$data),
23                       '(under exponential assumption)'))
24
25 df <- do.call(rbind, data.list)
26
27 ECDF.plot <- ggplot(df, aes(x = Time_between_events,
28                             colour = Num_Events)) +
29   stat_ecdf() +
30   xlab('Time between Events') +
31   ylab('Empirical Cumulative Probability')
32
33 return(ECDF.plot)
34 }
35
36 ecdf_interarrival <- lapply(seq_len(3), \(i) ECDF.interarrival(i))

```

Forecasting

```

1 ETAS.forecast <- function(){
2
3   # inherits the environment from function `ETAS`
4   envir <- etas$envir
5
6   # express 1 minute in days
7   min.in.days <- 1 / (24 * 60)
8   # find time of the event with the greatest magnitude
9   t.max.mag <- envir$data$ts[which.max(envir$data$magnitudes)]
10  # set starting time of the forecasting period
11  T1.fore <- t.max.mag + min.in.days
12  # set forecast length
13  fore.length <- 1
14  # set end time of the forecasting period
15  T2.fore <- T1.fore + fore.length
16  # set known data
17  Ht.fore <- envir$data[envir$data$ts < T1.fore, ]
18
19  # produce forecast

```



```

20 daily.fore <- Temporal.ETAS.forecast(
21   post.samp = enviro$post.samp, # ETAS parameters posterior samples
22   n.cat = nrow(enviro$post.samp), # number of synthetic catalogues
23   beta.p = enviro$beta.p, # magnitude distribution parameter
24   M0 = enviro$m0, # cutoff magnitude
25   T1 = T1.fore, # forecast starting time
26   T2 = T2.fore, # forecast end time
27   Ht = Ht.fore, # known events
28   ncore = num.cores # number of cores
29 )
30
31 # find number of events per catalogue
32 N.fore <- vapply(
33   seq_len(daily.fore$n.cat),
34   \x sum(daily.fore$fore.df$cat.idx == x), 0
35 )
36 # find number of observed events in the forecasting period
37 N.obs <- sum(enviro$data$ts >= T1.fore & enviro$data$ts <= T2.fore)
38 # plot the distribution
39 histfore <- ggplot() +
40   geom_histogram(aes(x = N.fore, y = after_stat(density)),
41     binwidth = 1) +
42   geom_vline(xintercept = N.obs) +
43   xlim(100, 500)
44
45   return(tibble::lst(N.fore, N.obs, histfore))
46 }
47 fore <- ETAS.forecast()

1 # save.image(file = 'Robin_new.RData')

```