**Supporting information S4: Functions to calculate microclimate indices**

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library(lubridate)  
library(dplyr)  
  
  
#---AVERAGE INDICES-----------------------------------------------  
  
# mean offset  
mean\_offset <- function(macroclimate, microclimate){  
 offset <- microclimate - macroclimate  
 mean\_offset <- mean(offset, na.rm=TRUE)  
 return(mean\_offset)  
}  
  
# median offset  
median\_offset <- function(macroclimate, microclimate){  
 offset <- microclimate - macroclimate  
 median\_offset <- median(offset, na.rm=TRUE)  
 return(median\_offset)  
}  
  
# sum of offsets  
sum\_of\_offsets <- function(macroclimate, microclimate){  
 offset <- microclimate - macroclimate  
 return(sum(offset, na.rm=TRUE))  
}  
  
#equilibrium (following Gril et al. 2023)  
equilibrium <- function(macroclimate, microclimate){  
 mod = lm(microclimate ~ macroclimate, na.action=na.omit) #create linear model  
 cf = coef(mod) # get coefficients  
 intercept = unname(cf[1])  
 slope = unname(cf[2])  
   
 equilibrium = intercept/(1-slope)  
 return(equilibrium)  
}  
  
  
#---VARIABILITY INDICES--------------------------------------------  
  
# offset of SD  
sd\_offset <- function(macroclimate, microclimate){  
 sd\_micro = sd(microclimate, na.rm=TRUE)  
 sd\_macro = sd(macroclimate, na.rm=TRUE)  
 return(sd\_micro - sd\_macro)  
}  
  
# mean offset of sd of daily mean   
sd\_offset\_mean\_daily <- function(time.index, macroclimate, microclimate){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::day(time.index)) %>%  
 dplyr::summarize(sd\_macro = sd(macroclimate, na.rm=TRUE),  
 sd\_micro = sd(microclimate, na.rm=TRUE))  
   
 df$sd\_offset = df$sd\_micro - df$sd\_macro  
 return(mean(df$sd\_offset, na.rm=TRUE))  
}  
  
# amplitude offset  
amplitude\_offset <- function(macroclimate, microclimate, percentile\_min = .05, percentile\_max = .95){  
 macro\_max <- quantile(macroclimate, percentile\_max, na.rm=TRUE)  
 micro\_max <- quantile(microclimate, percentile\_max, na.rm=TRUE)  
 macro\_min <- quantile(macroclimate, percentile\_min, na.rm=TRUE)  
 micro\_min <- quantile(microclimate, percentile\_min, na.rm=TRUE)  
   
 amplitude\_macro = macro\_max - macro\_min  
 amplitude\_micro = micro\_max - micro\_min  
 amplitude\_offset = amplitude\_micro - amplitude\_macro  
 return(unname(amplitude\_offset))  
}  
  
# mean offset of daily amplitude  
amplitude\_offset\_mean\_daily <- function(time.index, macroclimate, microclimate){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(max\_macro = max(macroclimate, na.rm=TRUE), min\_macro = min(macroclimate, na.rm=TRUE),  
 max\_micro = max(microclimate, na.rm=TRUE), min\_micro = min(microclimate, na.rm=TRUE))  
   
 df$daily\_amplitude\_macro <- df$max\_macro - df$min\_macro  
 df$daily\_amplitude\_micro <- df$max\_micro - df$min\_micro  
 df$amplitude\_offset <- df$daily\_amplitude\_micro - df$daily\_amplitude\_macro  
   
 return(mean(df$amplitude\_offset, na.rm=TRUE))   
}  
  
# amplitude ratio  
amplitude\_ratio <- function(macroclimate, microclimate, percentile\_min = .05, percentile\_max = .95){  
 macro\_max <- quantile(macroclimate, percentile\_max, na.rm=TRUE)  
 micro\_max <- quantile(microclimate, percentile\_max, na.rm=TRUE)  
 macro\_min <- quantile(macroclimate, percentile\_min, na.rm=TRUE)  
 micro\_min <- quantile(microclimate, percentile\_min, na.rm=TRUE)  
   
 amplitude\_macro = macro\_max - macro\_min  
 amplitude\_micro = micro\_max - micro\_min  
   
 return(unname(amplitude\_micro/amplitude\_macro))  
}  
  
# CV offset  
CV\_offset <- function(macroclimate, microclimate){  
 cv\_macro = mean(macroclimate, na.rm=TRUE)/sd(macroclimate, na.rm=TRUE)  
 cv\_micro = mean(microclimate, na.rm=TRUE)/sd(microclimate, na.rm=TRUE)  
   
 return(cv\_micro - cv\_macro)  
}  
  
# CV offset mean daily  
CV\_offset\_mean\_daily <- function(time.index, macroclimate, microclimate){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(mean\_macro = mean(macroclimate, na.rm=TRUE), sd\_macro = sd(macroclimate, na.rm=TRUE),  
 mean\_micro = mean(microclimate, na.rm=TRUE), sd\_micro = sd(microclimate, na.rm=TRUE))  
   
 df$cv\_macro = df$mean\_macro/df$sd\_macro  
 df$cv\_micro = df$mean\_micro/df$sd\_micro  
 return(mean(df$cv\_micro - df$cv\_macro, na.rm=TRUE))  
}  
  
# CV ratio  
CV\_ratio <- function(macroclimate, microclimate){  
 cv\_macro = mean(macroclimate, na.rm=TRUE)/sd(macroclimate, na.rm=TRUE)  
 cv\_micro = mean(microclimate, na.rm=TRUE)/sd(microclimate, na.rm=TRUE)  
   
 return(cv\_micro/cv\_macro)  
}  
  
# slope (following Gril et al. 2023)  
slope <- function(macroclimate, microclimate){  
 mod = lm(microclimate ~ macroclimate, na.action=na.omit) #create linear model  
 cf = coef(mod) # get coefficients  
 slope = unname(cf[2])  
   
 return(slope)  
}  
  
# ratio of change between two time points in microclimate to change in macroclimate  
change\_ratio <- function(macroclimate, microclimate){  
   
 macro = macroclimate[!is.na(macroclimate)]  
 micro = microclimate[!is.na(microclimate)]  
   
 if(length(macro) != length(micro)){  
 print("Error: Macroclimate and microclimate do not contain the same number of observations. Please correct.")  
 }  
   
 else {  
 ratios <- numeric(length(macroclimate) - 1)  
 for (i in 2:(length(macroclimate) - 1)) {  
 # round to 2 decimals to prevent extremely high ratios if divided by numbers close to 0  
 diff\_macro <- round(macroclimate[i],2) - round(macroclimate[i - 1],2)  
 diff\_micro <- round(microclimate[i],2) - round(microclimate[i - 1],2)  
   
 if (is.na(diff\_macro)==TRUE){   
 ratios[i - 1] <- NA # handle NAs  
 } else if(diff\_macro == 0) {  
 ratios[i - 1] <- NA # handle division by zero  
 } else {  
 ratios[i - 1] <- diff\_micro / diff\_macro  
 }  
 }  
 return(median(ratios, na.rm=TRUE))  
 }  
}  
  
  
#---EXTREME INDICES--------------------------------------------------

# Maxima  
  
# offset of maxima  
offset\_of\_maxima <- function(macroclimate, microclimate, percentile = .95){  
 macro\_max <- unname(quantile(macroclimate, percentile, na.rm = TRUE)) #unname removes name (quantile) from value  
 micro\_max <- unname(quantile(microclimate, percentile, na.rm = TRUE))  
 offset\_of\_maxima <- micro\_max - macro\_max  
 return(offset\_of\_maxima)   
}  
  
# mean offset of daily maxima  
offset\_of\_maxima\_mean\_daily <- function(time.index, macroclimate, microclimate, percentile = 1.00){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(max\_macro = unname(quantile(macroclimate, percentile, na.rm = TRUE)),  
 max\_micro = unname(quantile(microclimate, percentile, na.rm = TRUE)))  
   
 df$daily\_max\_offset <- df$max\_micro - df$max\_macro  
 return(mean(df$daily\_max\_offset, na.rm=TRUE))  
}  
  
# 95th percentile of daily differences between the maxima of the microclimate and the macroclimate  
p95\_daily\_maxima\_offset <- function(time.index, macroclimate, microclimate){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(max\_macro = max(macroclimate, na.rm=TRUE),  
 max\_micro = max(microclimate, na.rm=TRUE))  
   
 df$daily\_max\_offset <- df$max\_micro - df$max\_macro  
 max\_offset\_p95 <- unname(quantile(df$daily\_max\_offset, 0.95, na.rm=TRUE))  
 return(max\_offset\_p95)  
}  
  
  
# Minima  
  
# offset of minima  
  
offset\_of\_minima <- function(macroclimate, microclimate, percentile = .05){  
 macro\_min <- unname(quantile(macroclimate, percentile, na.rm=TRUE))  
 micro\_min <- unname(quantile(microclimate, percentile, na.rm=TRUE))  
 offset\_of\_minima <- micro\_min - macro\_min  
 return(offset\_of\_minima)  
}  
  
# Mean offset of daily minima  
offset\_of\_minima\_mean\_daily <- function(time.index, macroclimate, microclimate, percentile = .05){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(min\_macro = unname(quantile(macroclimate, percentile, na.rm=TRUE)),  
 min\_micro = unname(quantile(microclimate, percentile, na.rm=TRUE)))  
   
 df$daily\_min\_offset <- df$min\_micro - df$min\_macro  
 return(mean(df$daily\_min\_offset, na.rm=TRUE))  
}  
  
# 5th percentile of daily differences between the minima of the microclimate and the macroclimate  
p5\_daily\_minima\_offset <- function(time.index, macroclimate, microclimate){  
 df <- data.frame(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 df <- df %>% dplyr::group\_by(day = lubridate::yday(time.index)) %>%  
 dplyr::summarize(min\_macro = min(macroclimate, na.rm=TRUE),  
 min\_micro = min(microclimate, na.rm=TRUE))  
   
 df$daily\_min\_offset <- df$min\_micro - df$min\_macro  
 min\_offset\_p5 <- unname(quantile(df$daily\_min\_offset, 0.05, na.rm=TRUE))  
 return(min\_offset\_p5)  
}  
  
  
  
### calculate all indices together ###  
  
microclimate\_indices <- function(macroclimate, microclimate, time.index){  
   
 #calculate indices  
 # the As  
 mn\_offset <- mean\_offset(macroclimate = macroclimate, microclimate = microclimate)  
 md\_offset <- median\_offset(macroclimate = macroclimate, microclimate = microclimate)  
 total\_mod <- sum\_of\_offsets(macroclimate = macroclimate, microclimate = microclimate)  
 equilibrium <- equilibrium(macroclimate = macroclimate, microclimate = microclimate)  
   
 # the Vs  
 sd\_offset <- sd\_offset(macroclimate = macroclimate, microclimate = microclimate)  
 sd\_offset\_daily <- sd\_offset\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
 amplitude\_offset.95 <- amplitude\_offset(macroclimate = macroclimate, microclimate = microclimate, percentile\_max = .95, percentile\_min = .05)  
 amplitude\_offset.975 <- amplitude\_offset(macroclimate = macroclimate, microclimate = microclimate, percentile\_max = .975, percentile\_min = .025)  
 daily\_amp <- amplitude\_offset\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
 amplitude\_r.95 <- amplitude\_ratio(macroclimate = macroclimate, microclimate = microclimate, percentile\_max = .95, percentile\_min = .05)  
 amplitude\_r.975 <- amplitude\_ratio(macroclimate = macroclimate, microclimate = microclimate, percentile\_max = .975, percentile\_min = .25)  
 cv\_offset <- CV\_offset(macroclimate = macroclimate, microclimate = microclimate)  
 cv\_offset\_daily <- CV\_offset\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
 cv\_r <- CV\_ratio(macroclimate = macroclimate, microclimate = microclimate)  
 slope <- slope(macroclimate = macroclimate, microclimate = microclimate)  
 change\_ratio <- change\_ratio(macroclimate = macroclimate, microclimate = microclimate)  
 corr <- cor(macroclimate, microclimate, use="complete.obs")  
   
 #the Es  
 ## Emax  
 max\_offset.95 <- offset\_of\_maxima(macroclimate = macroclimate, microclimate = microclimate, percentile = .95)  
 max\_offset.975 <- offset\_of\_maxima(macroclimate = macroclimate, microclimate = microclimate, percentile = .975)  
 max\_offset1.00 <- offset\_of\_maxima(macroclimate = macroclimate, microclimate = microclimate, percentile = 1)  
 daily\_max\_offset.95 <- offset\_of\_maxima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = .95)  
 daily\_max\_offset.975 <- offset\_of\_maxima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = .975)  
 daily\_max\_offset1.00 <- offset\_of\_maxima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = 1)  
 p95\_daily\_max <- p95\_daily\_maxima\_offset(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
 ## Emin  
 min\_offset.05 <- offset\_of\_minima(macroclimate = macroclimate, microclimate = microclimate, percentile = .05)  
 min\_offset.025 <- offset\_of\_minima(macroclimate = macroclimate, microclimate = microclimate, percentile = .025)  
 min\_offset.00 <- offset\_of\_minima(macroclimate = macroclimate, microclimate = microclimate, percentile = 0)  
 daily\_min\_offset.05 <- offset\_of\_minima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = .05)  
 daily\_min\_offset.025 <- offset\_of\_minima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = .025)  
 daily\_min\_offset.00 <- offset\_of\_minima\_mean\_daily(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate, percentile = 0)  
 p5\_daily\_min <- p5\_daily\_minima\_offset(time.index = time.index, macroclimate = macroclimate, microclimate = microclimate)  
   
 #return named vector  
 indices <- c(# the As  
 "mean\_offset" = mn\_offset,  
 "median\_offset" = md\_offset,  
 "sum\_of\_offsets" = total\_mod,  
 "equilibrium" = equilibrium,  
 # the Vs  
 "sd\_offset" = sd\_offset,  
 "sd\_offset\_mean\_daily" = sd\_offset\_daily,  
 "amplitude\_offset.95" = amplitude\_offset.95,  
 "amplitude\_offset.975" = amplitude\_offset.975,  
 "amplitude\_offset\_mean\_daily" = daily\_amp,  
 "amplitude\_ratio.95" = amplitude\_r.95,  
 "amplitude\_ratio.975" = amplitude\_r.975,  
 "CV\_offset" = cv\_offset,  
 "CV\_offset\_mean\_daily" = cv\_offset\_daily,  
 "CV\_ratio" = cv\_r,  
 "slope" = slope,  
 "change\_ratio" = change\_ratio,  
 "correlation\_micro\_macro" = corr,  
 # the Es  
 ## Emax  
 "offset\_of\_maxima.95" = max\_offset.95,  
 "offset\_of\_maxima.975" = max\_offset.975,  
 "offset\_of\_maxima1.00" = max\_offset1.00,  
 "offset\_of\_maxima\_mean\_daily.95" = daily\_max\_offset.95,  
 "offset\_of\_maxima\_mean\_daily.975" = daily\_max\_offset.975,  
 "offset\_of\_maxima\_mean\_daily1.00" = daily\_max\_offset1.00,  
 "p95\_daily\_maxima\_offset" = p95\_daily\_max,  
 ## Emin  
 "offset\_of\_minima.05" = min\_offset.05,  
 "offset\_of\_minima.025" = min\_offset.025,  
 "offset\_of\_minima.00" = min\_offset.00,  
 "offset\_of\_minima\_mean\_daily.05" = daily\_min\_offset.05,  
 "offset\_of\_minima\_mean\_daily.025" = daily\_min\_offset.025,  
 "offset\_of\_minima\_mean\_daily.00" = daily\_min\_offset.00,  
 "p5\_daily\_minima\_offset" = p5\_daily\_min)   
  
 return(indices)   
}  
  
  
### calculate only selected indices  
  
best\_microclimate\_indices <- function(macroclimate, microclimate, time.index){  
   
 #calculate indices  
 # the As  
 mn\_offset <- mean\_offset(macroclimate = macroclimate, microclimate = microclimate)  
 md\_offset <- median\_offset(macroclimate = macroclimate, microclimate = microclimate)  
   
 # the Vs  
 amplitude\_offset.95 <- amplitude\_offset(macroclimate = macroclimate, microclimate = microclimate, percentile\_max = .95, percentile\_min = .05)  
 change\_ratio <- change\_ratio(macroclimate = macroclimate, microclimate = microclimate)  
   
 #the Es  
 ## Emax  
 max\_offset.975 <- offset\_of\_maxima(macroclimate = macroclimate, microclimate = microclimate, percentile = .975)  
 ## Emin  
 min\_offset.025 <- offset\_of\_minima(macroclimate = macroclimate, microclimate = microclimate, percentile = .025)  
   
 #return named vector  
 indices <- c(  
 "mean offset" = mn\_offset,  
 "median offset" = md\_offset,  
 "amplitude offset(p5-p95)" = amplitude\_offset.95,  
 "change ratio" = change\_ratio,  
 "offset of maxima (p97.5)" = max\_offset.975,  
 "offset of minima (p2.5)" = min\_offset.025  
 )  
   
 return(indices)   
}