Supplementary Information: Paleoclimate Modeling

Nicolas Gauthier

Last Updated: 2017-03-24

Introduction

In this two-part analysis we first compare temporal patterns of temperature and precipitation, derived from a transient paleoclimate simulation, at three points in the west Mediterranean. Then we analyze the spatial pattern of climate change from the LGM to the Mid Holocene using an ensemble of downscaled equilibrium paleoclimate simulations.

Setup

Load all the packages needed for this analysis.

```
library(ncdf4) # import GCM data
library(rgdal) # read GCM data
library(raster) # process GCM data
library(rasterVis) # plotting GCM data
library(tidyverse) # data management and plotting
library(magrittr) # pipes for code readability
library(EMD) # calculate trends in the data
library(dismo) # for latitudinally weighted samples
library(mgcv) # fit GAM for downscaling
```

Temporal Patterns: TraCE-21k

Sample Locations

Create a matrix with the coordinates for the three locations of interest in the west Mediterranean.

```
samp.pts <- matrix(c(0, 40, 4, 44, 12, 46, 14, 43),
                   ncol = 2, byrow = T)
```

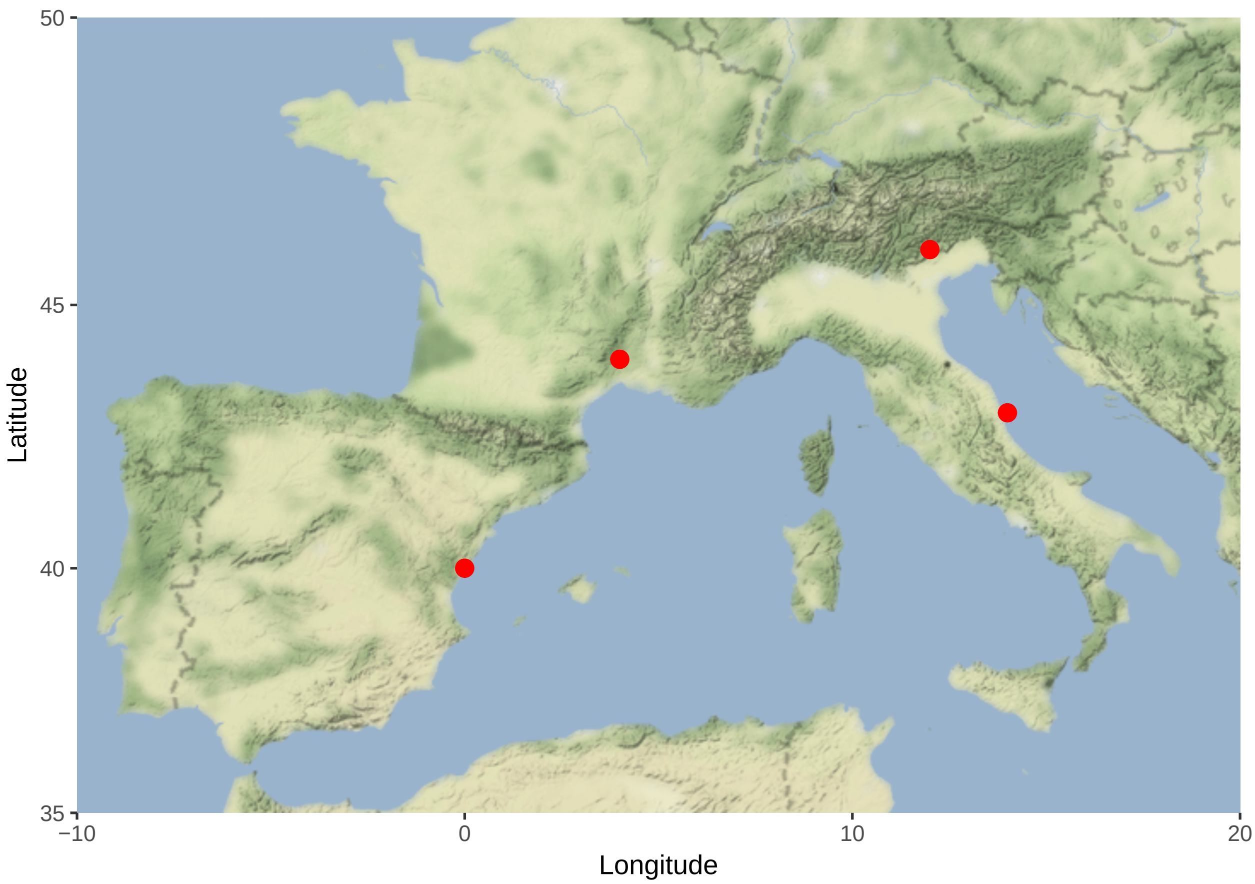
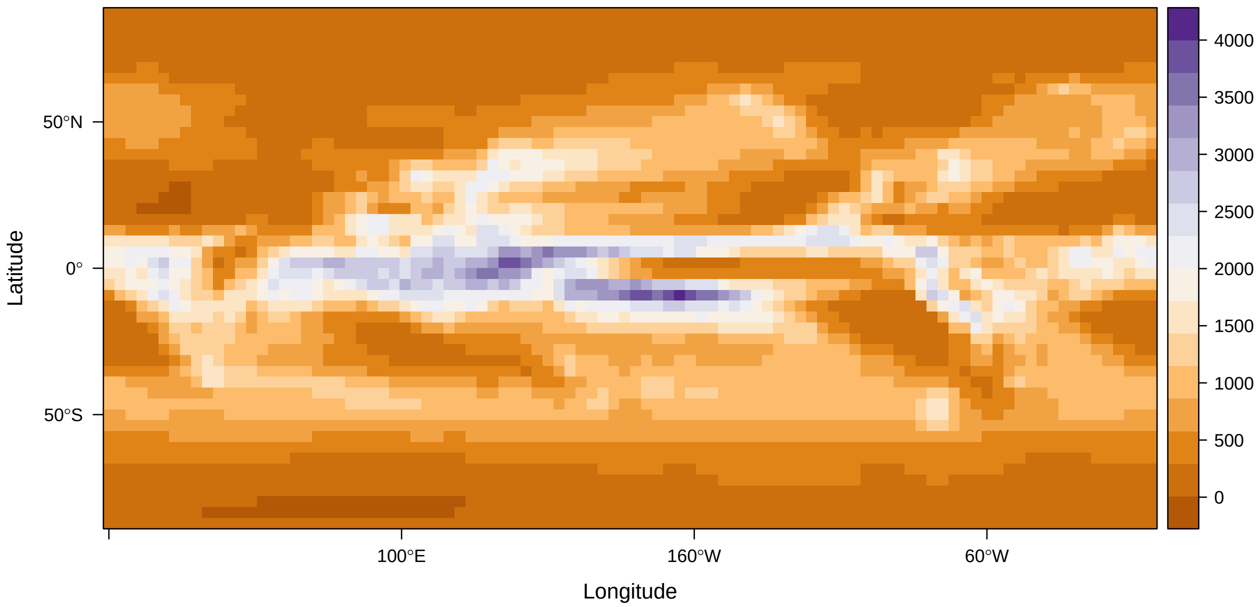
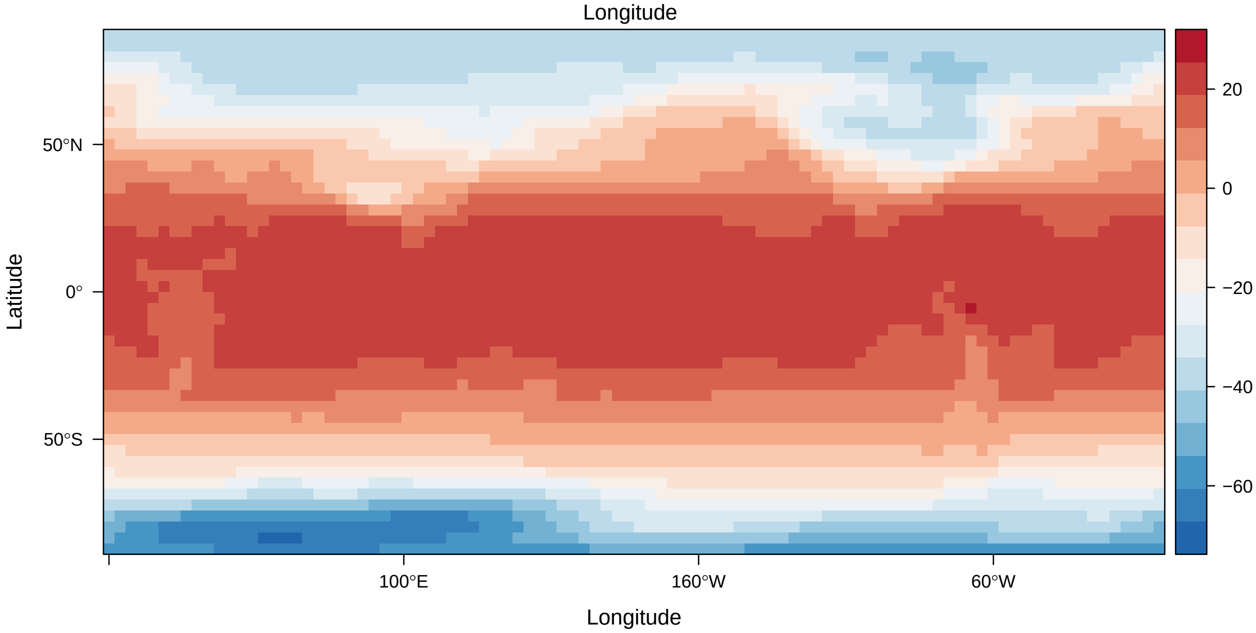


Figure 1: Locations of 3 sample points.

TraCE-21k Import and Preprocessing

First, import data from the TraCE-21k paleoclimate simulation. Then extract temperature and precipitation values at three locations in the west Mediterranean. Use the *brick* function from **raster** to import decadal averages from the simulation. Put the coordinates for the three locations in a matrix, and use that matrix to and **raster's** *extract* function to get the values from the climate model brick. Convert the precipitation values to mm/year and temperature values to degrees Celsius. Finally, name the columns for each region appropriately.



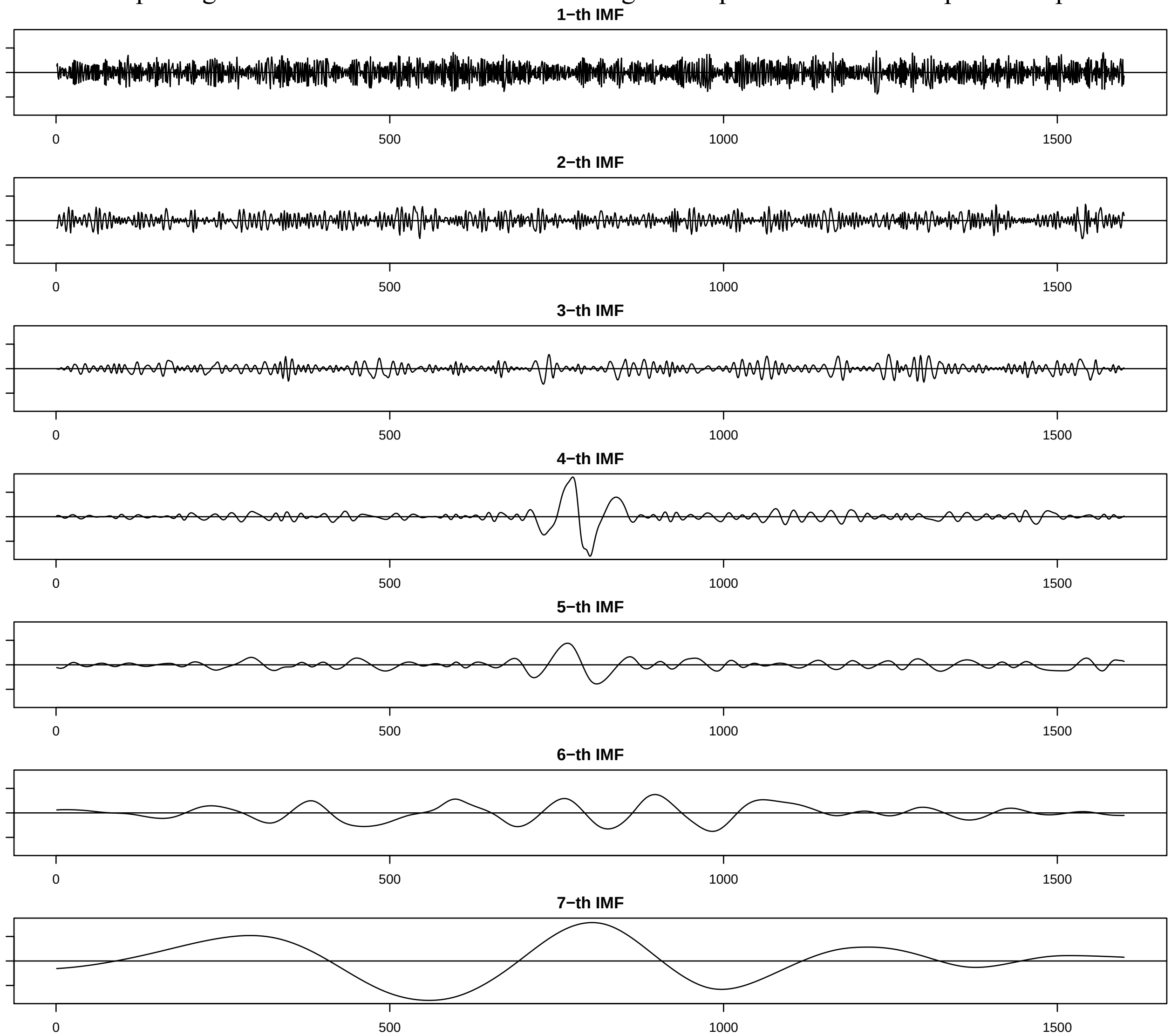


Now pull all the TraCE data into one data frame, with one row per year, and one column per variable/location combination. First *rbind* the two sets of TraCE data and *transpose* the results, turning the 6 rows into 6 columns. Add a column for the Year (in ka BP), and use to select only the entries earlier than 6,000 BP.

```r
trace.dat <- rbind(
  brick('trace.01-36.22000BP.cam2.TREFHT.22000BP_decavg_400BCE.nc') %>%
    raster::extract(samp.pts) %>%
    subtract(273.15), # convert from kelvin to C
  brick('trace.01-36.22000BP.cam2.PRECT.22000BP_decavg_400BCE.nc') %>%
    raster::extract(samp.pts) %>% # extract data at these coordinates
    multiply_by(3.154e+10)) %>% # convert to mm/year
  t %>% # transpose
  as.data.frame %>%
  set_colnames(c('tmp,Southwest', 'tmp,North Central', 'tmp,Northeast', 'tmp,Southeast',
                 'prc,Southwest', 'prc,North Central', 'prc,Northeast', 'prc,Southeast')) %>%
  rownames_to_column('Year') %>%
  mutate(Year = as.numeric(substring(Year, 3))) %>%
  filter(Year > 6) # get all the decades up to 6ka BP
```

Trend Analysis

Let's use the **EMD** package to calculate actual trend lines using the empirical mode decomposition ap-



proach.

Now organize the temperature and precipitation data to make plotting easier using functions from **tidyr**.

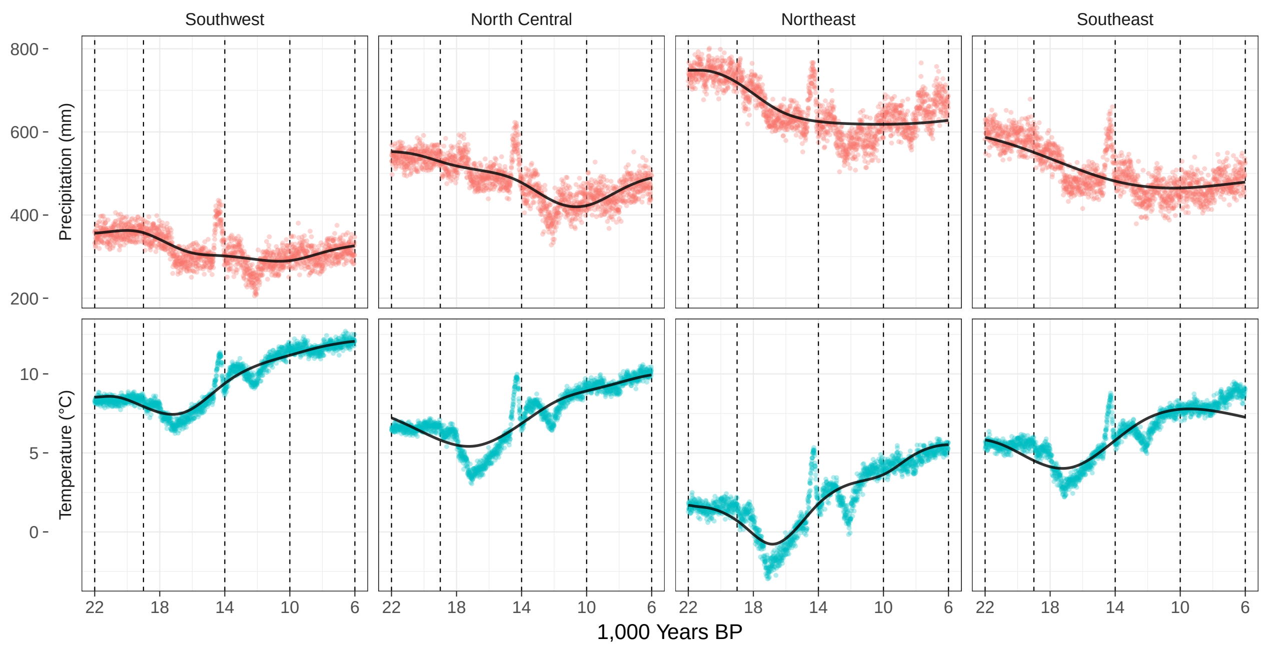
```
trace.plot <- trace.dat %>%
  gather(key, value, - Year) %>%
  separate(key, c('Variable', 'Region'), ',') %>%
  mutate(Region = factor(Region, levels = c('Southwest', 'North Central',
                                            'Northeast', 'Southeast')),
         Variable = ifelse(
    Variable == 'tmp', 'Temperature (°C)', 'Precipitation (mm)'))

emd.res <- function(x) emd(x, boundary = 'wave')$residue
trace.emd <- trace.dat %>%
  mutate_at(vars(-Year), emd.res) %>%
```

```
  gather(key, value, - Year) %>%
  separate(key, c('Variable', 'Region'), ',') %>%
  mutate(Region = factor(Region, levels = c('Southwest', 'North Central', 'Northeast', 'Southeast')),
         Variable = ifelse(
    Variable == 'tmp', 'Temperature (°C)', 'Precipitation (mm)'))
```

Plotting

Plot everything with **ggplot2**.

```
ggplot(data = trace.plot, aes(x = Year, y = value)) +
  facet_grid(Variable ~ Region, switch = 'y', scale = 'free_y') +
  geom_vline(xintercept = c(22, 19, 14, 10, 6), lty = 2) +
  geom_point(aes(color = Variable), alpha = .3) +
  geom_line(data = trace.emd, size = 1.2, color = "black", alpha = .8) +
  scale_x_reverse(breaks = seq(6,22,4)) +
  labs(x = '1,000 Years BP', y = '') +
  guides(color = "none") +
  theme_bw(base_size = 20) +
  theme(strip.background  = element_blank())
```



Variance

Calculate the detrended variances.

```
emd.dat <- trace.dat %>%
  mutate_at(vars(-Year), emd.res)
```

```r
(trace.dat - emd.dat) %>%
  select(-Year) %>%
  cbind(Year = trace.dat$Year, .) %>%
  mutate(Period = cut(Year, c(22, 19, 14, 10, 6))) %>%
  group_by(Period) %>%
  summarise_each(funs(var)) %>%
  select(-Year) %>%
    print(width = Inf)
```

```
## # A tibble: 4 × 9
##    Period ‘tmp,Southwest‘ ‘tmp,North Central‘ ‘tmp,Northeast‘
##    <fctr>           <dbl>               <dbl>           <dbl>
## 1  (6,10]      0.08704209           0.0922012       0.1853124
## 2 (10,14]      0.27096878           0.3907428       0.8121861
## 3 (14,19]      0.40989953           1.4185010       1.3565404
## 4 (19,22]      0.10400222           0.2620887       0.2029233
##   ‘tmp,Southeast‘ ‘prc,Southwest‘ ‘prc,North Central‘ ‘prc,Northeast‘
##             <dbl>           <dbl>               <dbl>           <dbl>
## 1       0.4481085        488.1919            778.4795       1230.0957
## 2       0.3543841        772.4411           1015.4651       1191.1768
## 3       0.9364233       1317.6964           1308.8443       1567.4188
## 4       0.2716865        313.4281            391.5337        531.6333
##   ‘prc,Southeast‘
##             <dbl>
## 1        739.1441
## 2        936.9639
## 3       2021.5821
## 4        649.1395
```

How do these compare to the overall regional variance?

```r
bbox <- extent(c(-10, 20, 35, 47))

trace.reg.avg <- rbind(
  brick('trace.01-36.22000BP.cam2.TREFHT.22000BP_decavg_400BCE.nc') %>%
    raster::extract(bbox, fun = mean) %>%
    subtract(273.15), # convert from kelvin to C
  brick('trace.01-36.22000BP.cam2.PRECT.22000BP_decavg_400BCE.nc') %>%
    raster::extract(bbox, fun = mean) %>%
    multiply_by(3.154e+10)) %>% # convert to mm/year
  t %>% # transpose
  as.data.frame %>%
  set_colnames(c('tmp,StudyArea', 'prc,StudyArea')) %>%
  rownames_to_column('Year') %>%
  mutate(Year = as.numeric(substring(Year, 3))) %>%
```

```
  filter(Year > 6)

emd.reg.avg <- trace.reg.avg %>%
  mutate_at(vars(-Year), emd.res)

(trace.dat - emd.dat) %>%
  select(-Year) %>%
  cbind(Year = trace.dat$Year, .) %>%
  mutate(Period = cut(Year, c(22, 19, 14, 10, 6))) %>%
  group_by(Period) %>%
  summarise_each(funs(var)) %>%
  select(-Year) %>%
  subtract(((trace.reg.avg - emd.reg.avg) %>%
  magrittr::extract(c(2,2,2,2,3,3,3,3)) %>%
  cbind(Year = trace.dat$Year, .) %>%
  mutate(Period = cut(Year, c(22, 19, 14, 10, 6))) %>%
  group_by(Period) %>%
  summarise_each(funs(var)) %>%
  select(-Year))) %>%
    print(width = Inf)
```

```
## Warning in Ops.factor(left, right): '-' not meaningful for factors

##   Period tmp,Southwest tmp,North Central tmp,Northeast tmp,Southeast
## 1     NA   -0.03803870       -0.03287960    0.06023160    0.32302766
## 2     NA   -0.16399338       -0.04421932    0.37722393   -0.08057806
## 3     NA   -0.58309403        0.42550744    0.36354680   -0.05657024
## 4     NA   -0.06821138        0.08987510    0.03070968    0.09947292
##   prc,Southwest prc,North Central prc,Northeast prc,Southeast
## 1      127.1965          417.4842      869.1004      378.1488
## 2      288.8544          531.8784      707.5902      453.3773
## 3      109.8887          101.0366      359.6112      813.7744
## 4      102.7977          180.9033      321.0029      438.5091
```

Spatial Patterns: PMIP3 Ensemble

Data Preprocessing

First change the study area to all of Europe and the Mediterranean. Import observed precipitation and temperature normals.

```
bbox <- extent(c(-10, 45, 30, 50))

tmean.obs <- list.files('~/gdrive/Data/MOD11C3v5.0-CHIRPSv2.0_MONTHLY_03m/meantemp', full.names = T) %>%
```

```
    stack %>%
    set_names(month.name) %>%
    crop(bbox)
tmean.obs[tmean.obs == -9999] <- NA

p.obs <- list.files('~/gdrive/Data/MOD11C3v5.0-CHIRPSv2.0_MONTHLY_03m/precip', full.names = T) %>%
    stack %>%
    set_names(month.name) %>%
    crop(bbox)
p.obs[p.obs == -9999] <- NA
```

Import and reproject SRTM DEM.

```
elev <- raster('~/gdrive/Data/SRTM_1km.tif') %>% projectRaster(p.obs[[1]]) %>% mask(p.obs[[1]])
```

Use the DEM to calculate a diffusive continentality (DCO) map, with distance to the sea in km.

```
dco <- elev %>%
  reclassify(c(-Inf, Inf, NA, NA, NA, 1)) %>% # reverse NA and non-NA cells
  distance(doEdge = T) %>% # calculate the distances
  mask(elev) %>% # mask out ocean cells
  divide_by(1000) # convert to km
```

Import and preprocess of ECMWF-interim reanalysis data, monthly means of daily means, 1979-2010

```
processECMWF <- function(file, var){
  brick(paste0('~/gdrive/Data/', file), varname = var) %>%
      stackApply(indices = 1:12, fun = mean) %>%
      rotate %>%
      set_names(month.name) %>% projectRaster(eu.p) %>% mask(eu.p)
}

tcw <- processECMWF('ecmwf_surface.nc', 'tcw')
msl <- processECMWF('ecmwf_surface.nc', 'msl')
t2m <- processECMWF('ecmwf_surface.nc', 't2m')
lsp <- processECMWF('ECMWF Precip.nc', 'lsp')
cp <- processECMWF('ECMWF Precip.nc', 'cp')
```

Put all the predictor and response variables together, month by month.

```
cal.vars <- sapply(1:12, function(x){
  brick(tmean.obs[[x]], p.obs[[x]], msl[[x]], t2m[[x]], tcw[[x]], lsp[[x]], cp[[x]], elev, dco) %>%
    setNames(c('tmean.obs', 'p.obs', 'msl', 't2m', 'tcw', 'lsp', 'cp','elev','dco'))
})
```

Sample the variables at random points, weighting for latitude

```
cal.data <- lapply(cal.vars, function(x) (raster::extract(x, randomPoints(elev, 20000)) %>% data.frame)) %>%
  do.call(rbind, .)
```

Model Fitting

Use *mgcv* to fit gams to the combined calibration data. Model precipitation occurence and amounts separately.

```
tmean.gam <- gam(tmean.obs ~ s(t2m, bs = 'cr') +
             s(msl, bs = 'cr') +
             s(elev, bs = 'cr'),
           method = 'REML', data = cal.data)

p.occur.gam <- gam(factor(p.obs >= .1) ~ s(t2m) + s(cp),
                   family = binomial, method = 'REML', data = cal.data)

prcp.gam <- bam(p.obs ~ s(msl, bs = 'cr') +
              s(tcw, bs = 'cr') +
              s(lsp, bs = 'cr') +
              s(cp, bs = 'cr') +
              s(elev, bs = 'cr') +
              s(dco, bs = 'cr'),
            family = Gamma(link = 'log'), method = 'REML',
            data = cal.data[cal.data$p.obs >= .1, ])
```

Predictions

Write a function to import, process, and generate a monthly average ensemble from PMIP3 data.

```
getEns <- function(period, variable){
  var.dir <- paste0('~/gdrive/Data/PMIP3 Data/', period, '/', variable)
  files.in <- list.files(var.dir, full.names = T)

  sapply(files.in, function(x){
    brick(x) %>% rotate %>% projectRaster(elev)
  }) %>% brick %>% stackApply(indices = 1:12, fun = mean)
}
```

Mid Holocene

Use this function to import all the necessary variables. Generate a single prediction set.

```
t2m <- getEns('MH', 'tas')
msl <- getEns('MH', 'psl')
cp <- getEns('MH', 'prc' ) %>% multiply_by(86.4)
lsp <- (getEns('MH', 'pr') %>% multiply_by(86.4))  - cp
tcw <- getEns('MH', 'clivi') + getEns('MH', 'clwvi') + getEns('MH', 'prw')
```

```
pred.vars.mh <- sapply(1:12, function(x){
  brick(t2m[[x]], msl[[x]], tcw[[x]], cp[[x]], lsp[[x]], elev, dco) %>%
    setNames(c('t2m', 'msl', 'tcw', 'cp', 'lsp', 'elev', 'dco'))
})
```

Make predictions for the Mid Holocene.

```
tmean.mh <- sapply(1:12, function(x){
    predict(pred.vars.mh[[x]], tmean.gam)
  }) %>% brick

prec.occur.mh <- sapply(1:12, function(x){
    predict(pred.vars.mh[[x]], p.occur.gam, type = 'response')
  }) %>% brick %>% is_weakly_greater_than(.5)

prec.mh <- sapply(1:12, function(x){
    predict(pred.vars.mh[[x]], prcp.gam, type = 'response')
  }) %>% brick %>% mask(prec.occur.mh, maskvalue = 0, updatevalue = 0)
```

LGM

Repeat for the LGM

```
t2m <- getEns('LGM', 'tas')
msl <- getEns('LGM', 'psl')
cp <- getEns('LGM', 'prc' ) %>% multiply_by(86.4)
lsp <- (getEns('LGM', 'pr') %>% multiply_by(86.4))  - cp
tcw <- getEns('LGM', 'clivi') + getEns('LGM', 'clwvi') + getEns('LGM', 'prw')

pred.vars.lgm <- sapply(1:12, function(x){
  brick(t2m[[x]], msl[[x]], tcw[[x]], cp[[x]], lsp[[x]], elev, dco) %>%
    setNames(c('t2m', 'msl', 'tcw', 'cp', 'lsp', 'elev', 'dco'))
})

tmean.lgm <- sapply(1:12, function(x){
    predict(pred.vars.lgm[[x]], tmean.gam)
  }) %>% brick

prec.occur.lgm <- sapply(1:12, function(x){
    predict(pred.vars.lgm[[x]], p.occur.gam, type = 'response')
  }) %>% brick %>% is_weakly_greater_than(.5)

prec.lgm <- sapply(1:12, function(x){
    predict(pred.vars.lgm[[x]], prcp.gam, type = 'response')
  }) %>% brick %>% mask(prec.occur.lgm, maskvalue = 0, updatevalue = 0)
```

Analysis of Spatial Patterns

Use the downscaled ensemble data to estimate how the spatial patterns of climate variability have changed over time, and to test for consistency with the transient TraCE simulation.

First crop the downscaled data to the West Mediterranean.

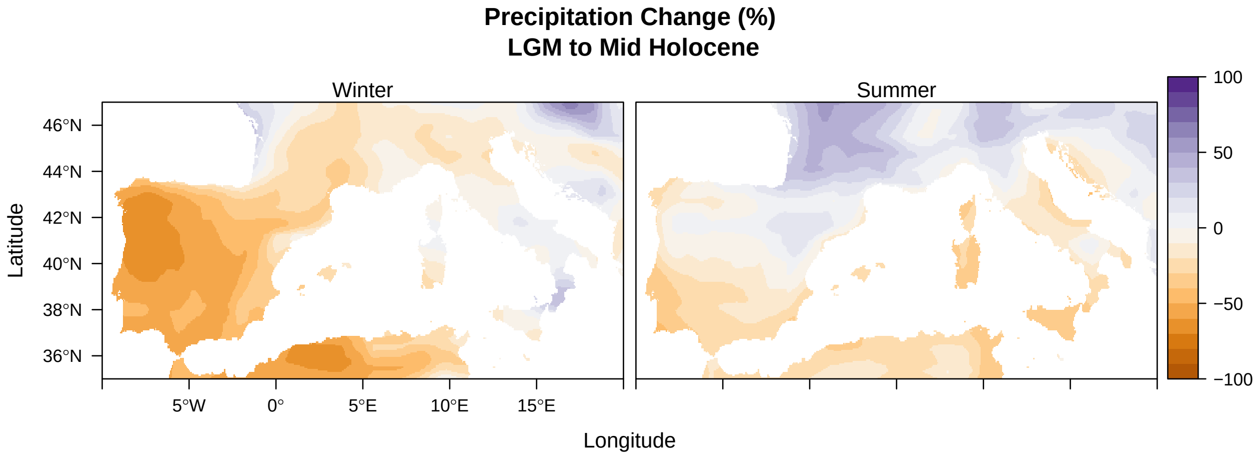
```
bbox <- extent(c(-10, 20, 35, 47))

lgm.prc <- prec.lgm %>% crop(bbox)
mh.prc <- prec.mh %>% crop(bbox)

lgm.tmp <- tmean.lgm %>% crop(bbox)
mh.tmp <- tmean.mh %>% crop(bbox)
```

Calculate changes in seasonal precipitation and temperature.

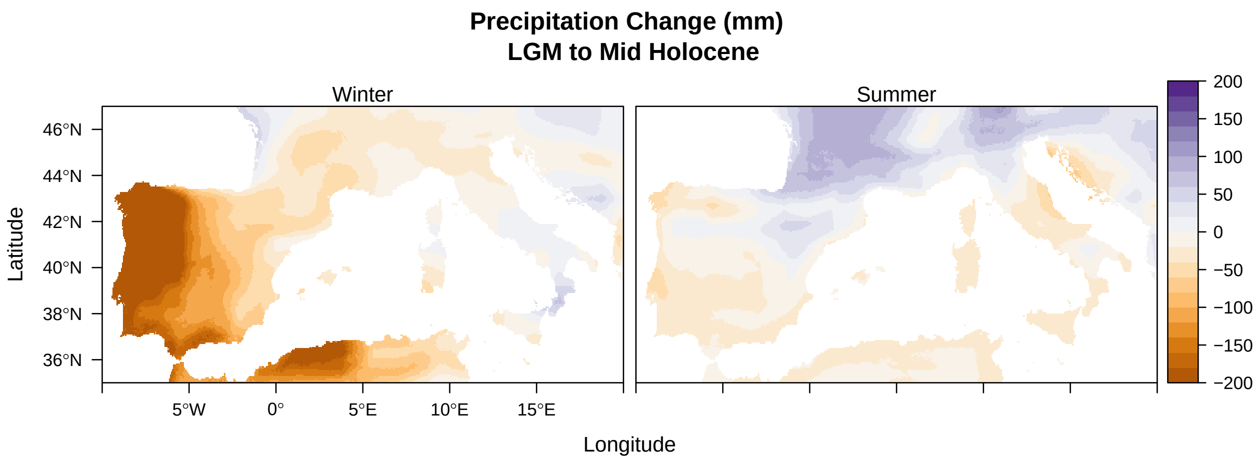
```
bySeason <- function(x, season, var){
  if(season == 'djf') {ids <- c(1,2,12)}
  if(season == 'jja') {ids <- c(6,7,8)}

  if(var == 'tmp') return(mean(x[[ids]]))
  if(var == 'prc') return(sum(x[[ids]]))
}

prc.change.map <- brick(c(
  bySeason(mh.prc, 'djf', 'prc') - bySeason(lgm.prc, 'djf', 'prc'),
  bySeason(mh.prc, 'jja', 'prc') - bySeason(lgm.prc, 'jja', 'prc')))
prc.change.map[prc.change.map < -200] <- -200 # so the plot isn't washed out by large precip values


prc.change.map.percent <- brick(c(
  (bySeason(mh.prc, 'djf', 'prc') - bySeason(lgm.prc, 'djf', 'prc')) * 100 / bySeason(lgm.prc, 'djf', 'prc'),
  (bySeason(mh.prc, 'jja', 'prc') - bySeason(lgm.prc, 'jja', 'prc')) * 100 / bySeason(lgm.prc, 'jja', 'prc'))

tmp.change.map <- brick(c(
  bySeason(mh.tmp, 'djf', 'tmp') - bySeason(lgm.tmp, 'djf', 'tmp'),
  bySeason(mh.tmp, 'jja', 'tmp') - bySeason(lgm.tmp, 'jja', 'tmp')))
```

Plot the results

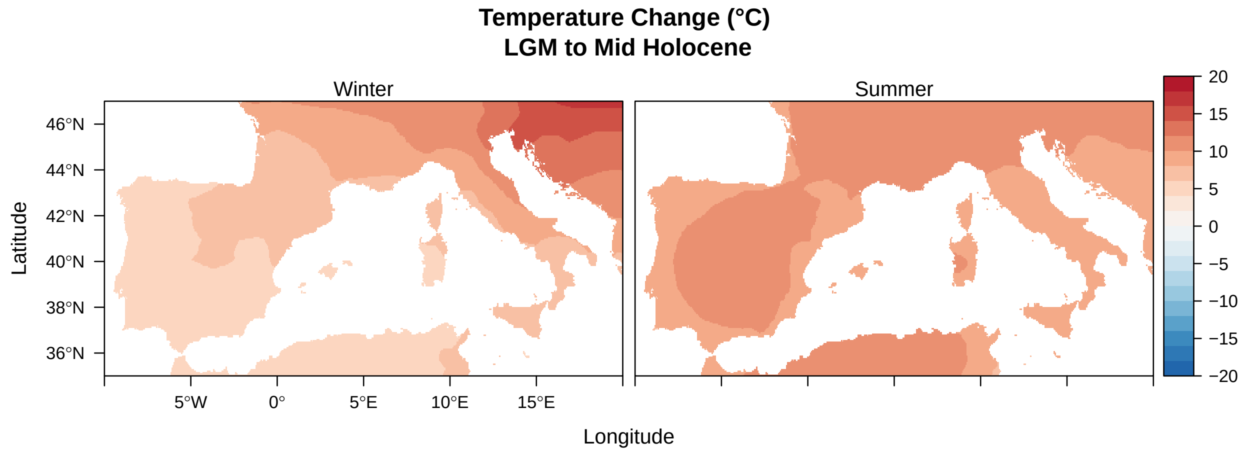
```
levelplot(prc.change.map.percent, margin = F, names.attr = c('Winter', 'Summer'),
          main = 'Precipitation Change (%)\n LGM to Mid Holocene',
          par.settings = PuOrTheme(),
          at = seq(-100,100,10))
```




```
# note in the next plot all values less than -200 have been turned into -200
levelplot(prc.change.map, margin = F, names.attr = c('Winter', 'Summer'),
          main = 'Precipitation Change (mm) \n LGM to Mid Holocene',
          par.settings = PuOrTheme(),
          at = seq(-200,200,20))
```




```
levelplot(tmp.change.map, margin = F, names.attr = c('Winter', 'Summer'),
          main = 'Temperature Change (°C)\n LGM to Mid Holocene',
          par.settings = BuRdTheme(),
          at = seq(-20,20,2))
```

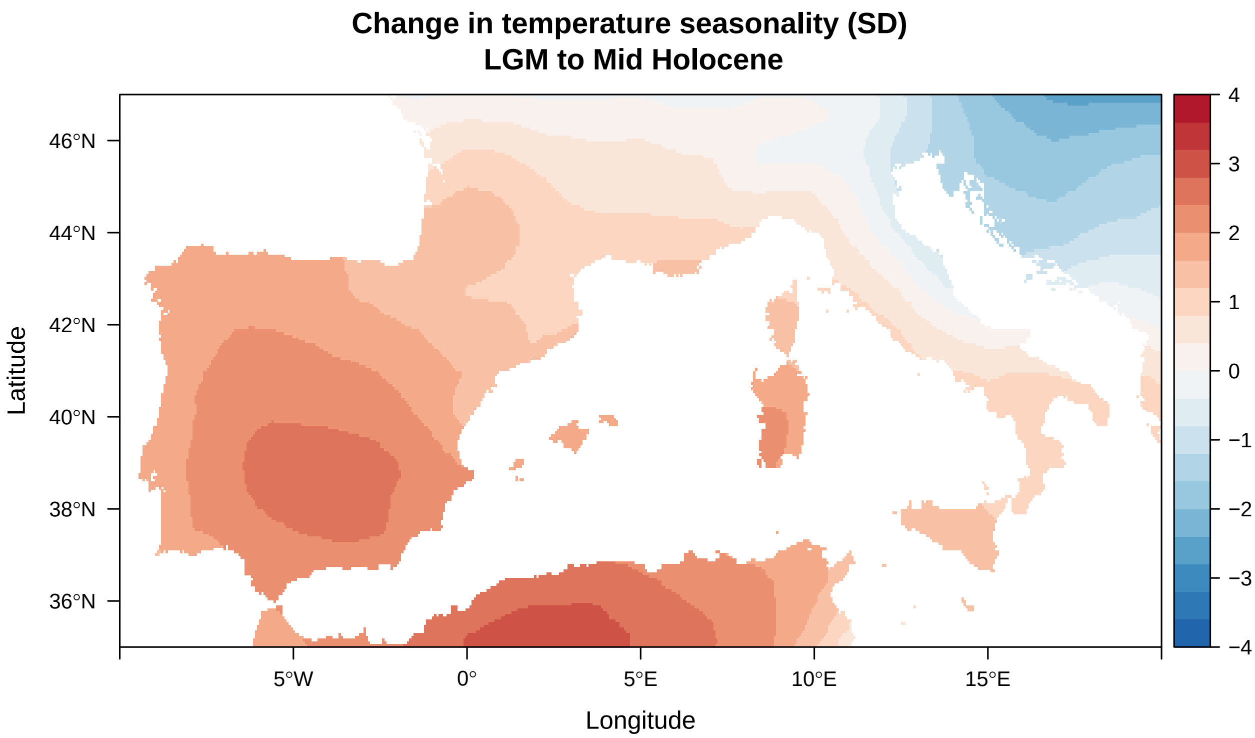


Now we can calculate changes in seasonality. For temperature, this is just the standard deviation of all 12 monthly averages. For precipitation, we will use the coefficient of variation.

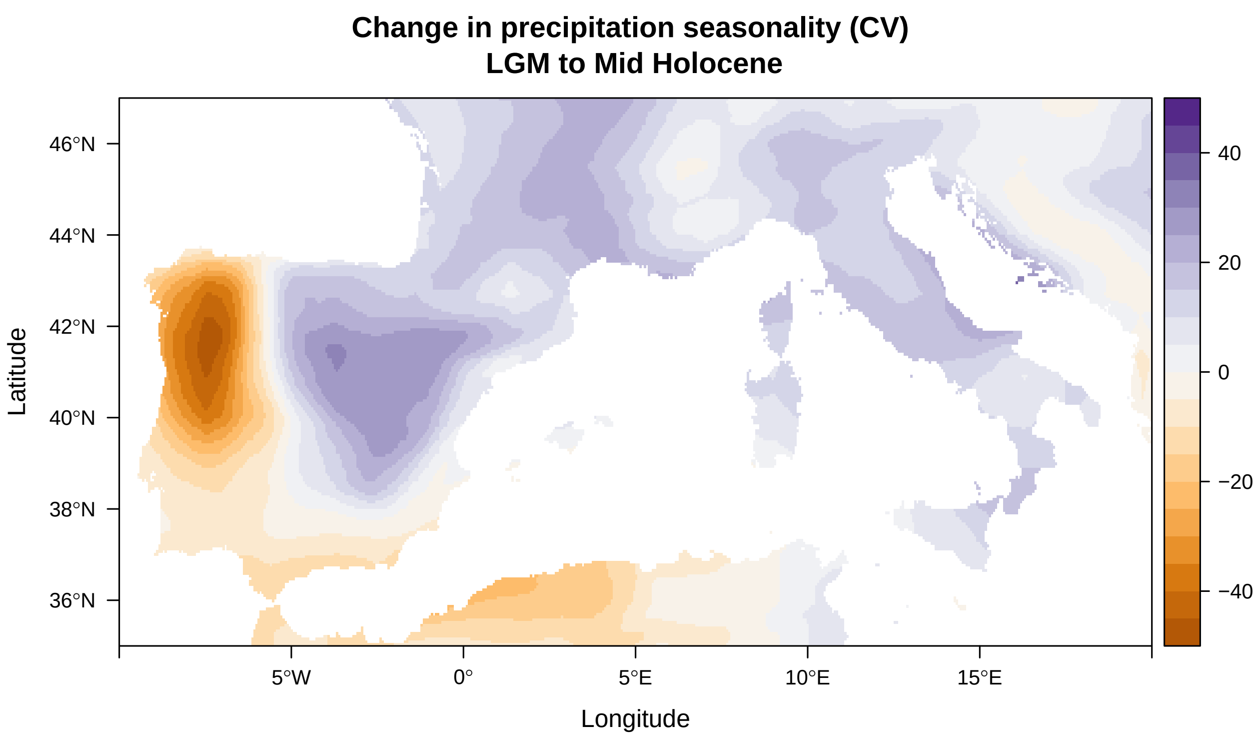
```
tmp.seasonality <- calc(mh.tmp, sd) - calc(lgm.tmp, sd)
prc.seasonality <- cv(mh.prc) - cv(lgm.prc)
```

Plot the results.

```
levelplot(tmp.seasonality, margin = F,
          main = 'Change in temperature seasonality (SD)\n LGM to Mid Holocene',
          par.settings = BuRdTheme(),
          at = seq(-4, 4, .4))
```




```
levelplot(prc.seasonality, margin = F,
        main = 'Change in precipitation seasonality (CV)\n LGM to Mid Holocene',
        par.settings = PuOrTheme(),
        at = seq(-50, 50, 5))
```

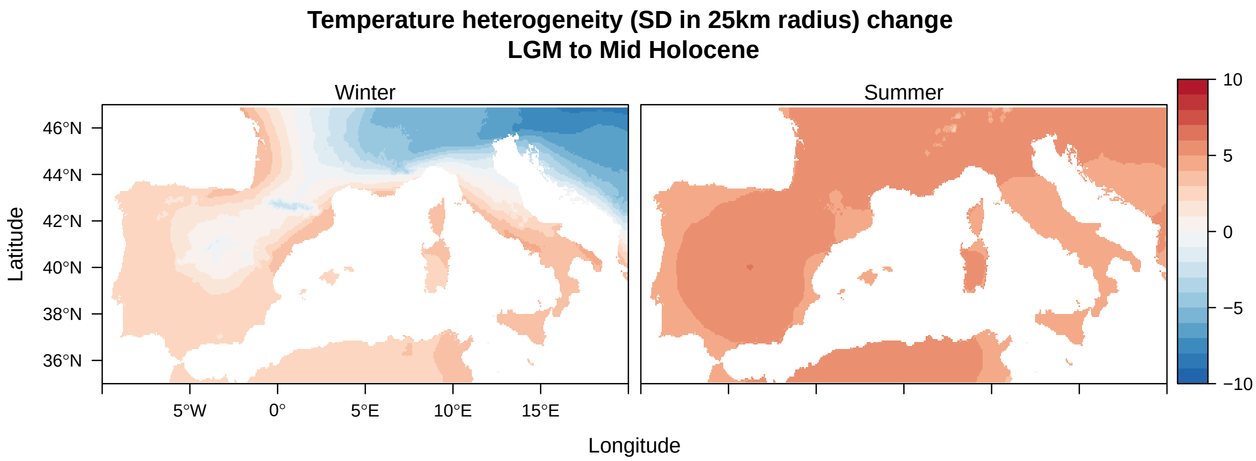


What about changes in spatial hetergeneity? First define a 5x5 weights matrix within which to sample the climate maps

```
wts <- matrix(c(0,0,1,0,0,0,1,1,1,0,1,1,1,1,1,0,1,1,1,0,0,0,1,0,0), nrow = 5)
```

Temperature

```
tmp.hetero <- brick(c(
  bySeason(mh.tmp, 'djf', 'tmp') %>%
    focal(w = wts, sd, na.rm = T) %>%
    subtract(
      bySeason(lgm.tmp, 'djf', 'tmp') %>%
        focal(w = wts, sd, na.rm = T)),
  bySeason(mh.tmp, 'jja', 'tmp') %>%
    focal(w = wts, sd, na.rm = T) %>%
    subtract(
      bySeason(lgm.tmp, 'jja', 'tmp') %>%
        focal(w = wts, sd, na.rm = T)))) %>%
  mask(mh.tmp[[1]]) # clip buffer added by window

levelplot(tmp.hetero, margin = F, names.attr = c('Winter', 'Summer'),
          main = 'Temperature heterogeneity (SD in 25km radius) change\n LGM to Mid Holocene',
          par.settings = BuRdTheme(), at = seq(-10, 10, 1))
```



Same for precipitaiton.

```
prc.hetero.sd <- brick(c(
  bySeason(mh.prc, 'djf', 'prc') %>%
    focal(w = wts, sd, na.rm = T) %>%
    subtract(
      bySeason(lgm.prc, 'djf', 'prc') %>%
        focal(w = wts, sd, na.rm = T)),
  bySeason(mh.prc, 'jja', 'prc') %>%
    focal(w = wts, sd, na.rm = T) %>%
    subtract(
      bySeason(lgm.prc, 'jja', 'prc') %>%
```

```r
      focal(w = wts, sd, na.rm = T)))) %>%
  mask(mh.prc[[1]]) # clip buffer added by window function

# capped at -60 to reveal patterns
prc.hetero.sd[prc.hetero.sd < -60] <- -60
levelplot(prc.hetero.sd, margin = F, names.attr = c('Winter', 'Summer'),
          main = 'Precipitation heterogeneity (SD in 25km radius) change\n LGM to Mid Holocene',
          par.settings = BuRdTheme(), at = seq(-60, 60, 6))
```