Fifty years of research have deepened uncertainties in global irrigation water use

R code of the analysis of variance (ISI-MIP data)

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Contents

1 Preliminary functions

```r
#   PRELIMINARY FUNCTIONS ######################################################

sensobol::load_packages(c("openxlsx", "data.table", "tidyverse","cowplot",
                          "benchmarkme", "parallel", "wesanderson", "scales", "ncdf4",
                          "countrycode", "rworldmap", "sp", "doParallel", "here", "lme4",
                          "microbenchmark", "mgcv", "brms", "randomForest", "here",
                          "igraph", "ggraph", "gganimate", "magick",
                          "randomForestExplainer", "ggrepel"))

# Create custom theme -----------------------------------------------------------

theme_AP <- function() {
  theme_bw() +
    theme(panel.grid.major = element_blank(),
          panel.grid.minor = element_blank(),
          legend.background = element_rect(fill = "transparent",
                                           color = NA),
          legend.key = element_rect(fill = "transparent",
                                    color = NA),
          strip.background = element_rect(fill = "white"),
          legend.text = element_text(size = 7.3),
          axis.title = element_text(size = 10),
          legend.key.width = unit(0.4, "cm"),
          legend.key.height = unit(0.4, "cm"),
          legend.key.spacing.y = unit(0, "lines"),
          legend.box.spacing = unit(0, "pt"),
          legend.title = element_text(size = 7.3),
          axis.text.x = element_text(size = 7),
          axis.text.y = element_text(size = 7),
          axis.title.x = element_text(size = 7.3),
          axis.title.y = element_text(size = 7.3),
          plot.title = element_text(size = 8),
          strip.text.x = element_text(size = 7.4),
          strip.text.y = element_text(size = 7.4))
}

# Select color palette ----------------------------------------------------------

selected.palette <- "Darjeeling1"
```

```r
# SOURCE ALL R FUNCTIONS NEEDED FOR THE STUDY ###################################

# Source all .R files in the "functions" folder --------------------------------

r_functions <- list.files(path = here("functions"), pattern = "\\.R$", full.names = TRUE)
lapply(r_functions, source)
```

2 ISIMIP Data

2.1 Historical data

```
# RETRIEVE DATA FROM ISIMIP #####################################################

# Create vector with list of files ---------------------------------------------

list.of.files <- list.files("./files/isimip")
model.names <- sub("^(.*?)_.*", "\\1", list.of.files)
climate.scenarios <- sapply(strsplit(list.of.files, "_"), function(x) x[2])
social.scenarios <- sapply(strsplit(list.of.files, "_"), function(x) x[which(x == "co2") - 1])
files.directory <- paste("./files/isimip", list.of.files, sep = "/")
start_year <- 1971

# Create parallel cluster -------------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop -----------------------------------------------------------------

isimip.hist <- foreach(i = 1:length(files.directory),
                       .packages = c("data.table", "countrycode", "tidyverse",
                                "sp", "rworldmap", "ncdf4")) %dopar% {

                                  get_isimip_fun(nc_file = files.directory[i],
                                                 variable = "airrww",
                                                 start_year = start_year)
                                }

# Stop the cluster after the computation ---------------------------------------

stopCluster(cl)
```

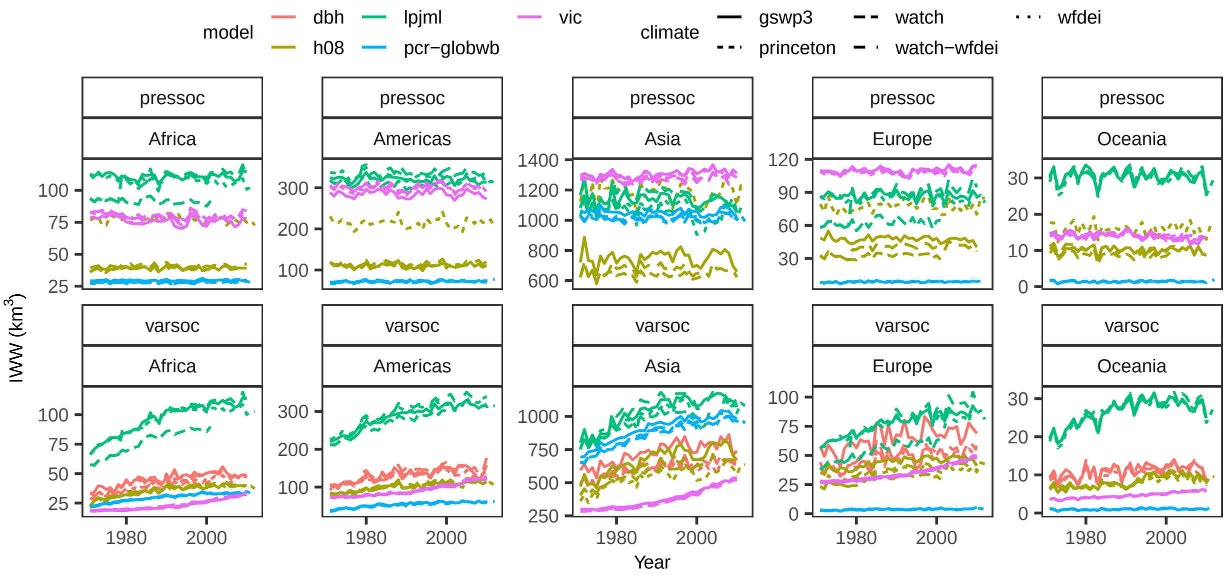
```
# ARRANGE DATA #################################################################

# Number of files --------------------------------------------------------------

list.of.files
```

```
## [1] "dbh_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [2] "dbh_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [3] "dbh_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [4] "dbh_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [5] "dbh_wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc"
##  [6] "h08_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [7] "h08_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
##  [8] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
##  [9] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012(1).nc4"
## [10] "h08_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [11] "h08_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [12] "h08_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [13] "h08_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [14] "h08_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [15] "h08_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [16] "lpjml_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [17] "lpjml_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [18] "lpjml_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
## [19] "lpjml_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [20] "lpjml_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [21] "lpjml_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [22] "lpjml_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [23] "lpjml_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [24] "lpjml_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [25] "pcr-globwb_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [26] "pcr-globwb_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [27] "pcr-globwb_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
## [28] "pcr-globwb_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [29] "pcr-globwb_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [30] "pcr-globwb_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [31] "pcr-globwb_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [32] "pcr-globwb_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [33] "pcr-globwb_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
## [34] "vic_gswp3_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [35] "vic_gswp3_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [36] "vic_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [37] "vic_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [38] "vic_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [39] "vic_watch_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2001.nc4"
## [40] "vic_watch-wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc4"
## [41] "vic_watch-wfdei_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2010.nc4"
## [42] "vic_wfdei_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2010.nc"
```

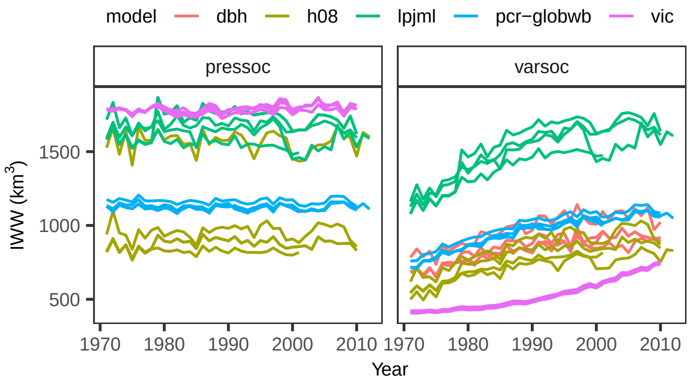
```r
# Name the slots ---------------------------------------------------------------

names(isimip.hist) <- paste(model.names, climate.scenarios, social.scenarios, sep = "/")

# Clean and bind dataset -------------------------------------------------------

isimip.dt <- rbindlist(isimip.hist, idcol = "model") %>%
  na.omit() %>%
  .[, model:= factor(model)] %>%
  .[, c("model", "climate", "social"):= tstrsplit(model, "/")]

fwrite(isimip.dt, "isimip.dt.csv")

# Pressoc: constant human impacts in the form of dams and reservoirs
# varsoc: variable human impacts.
```

2.1.1 Plot data

```
# PLOT ISIMIP #################################################################

# Continental level -----------------------------------------------------------

isimip.dt[, sum(V1, na.rm = TRUE), .(Continent, model, year, climate, social)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = model,
                linetype = climate)) +
  facet_wrap(social~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")")) +
  theme_AP() +
  guides(color = guide_legend(nrow = 2)) +
  guides(linetype = guide_legend(nrow = 2)) +
  theme(legend.position = "top")
```



```
# Global level ----------------------------------------------------------------

isimip.dt[, sum(V1, na.rm = TRUE), .(year, model, climate, social)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = model)) +
  geom_line() +
  facet_wrap(~social) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme_AP() +
  theme(legend.position = "top")
```



2.2 Predictions

```
# RETRIEVE PROJECTIONS FROM ISIMIP ##############################################

# Create vector with list of files ---------------------------------------------

path.projections <- "./files/isimip_future"
list.of.files.projections <- list.files(path.projections)
files.directory.projections <- paste(path.projections, list.of.files.projections, sep = "/")
variable <- "airrww"
start_year <- 2006

# Create parallel cluster -------------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop -----------------------------------------------------------------

isimip.future <- foreach(i = 1:length(files.directory.projections),
                       .packages = c("data.table", "countrycode", "tidyverse",
                                     "sp", "rworldmap", "ncdf4")) %dopar% {

                                       get_isimip_fun(nc_file = files.directory.projections[i]
                                                      variable = variable,
                                                      start_year = start_year)
                                     }

# Stop the cluster after the computation ---------------------------------------

stopCluster(cl)
```

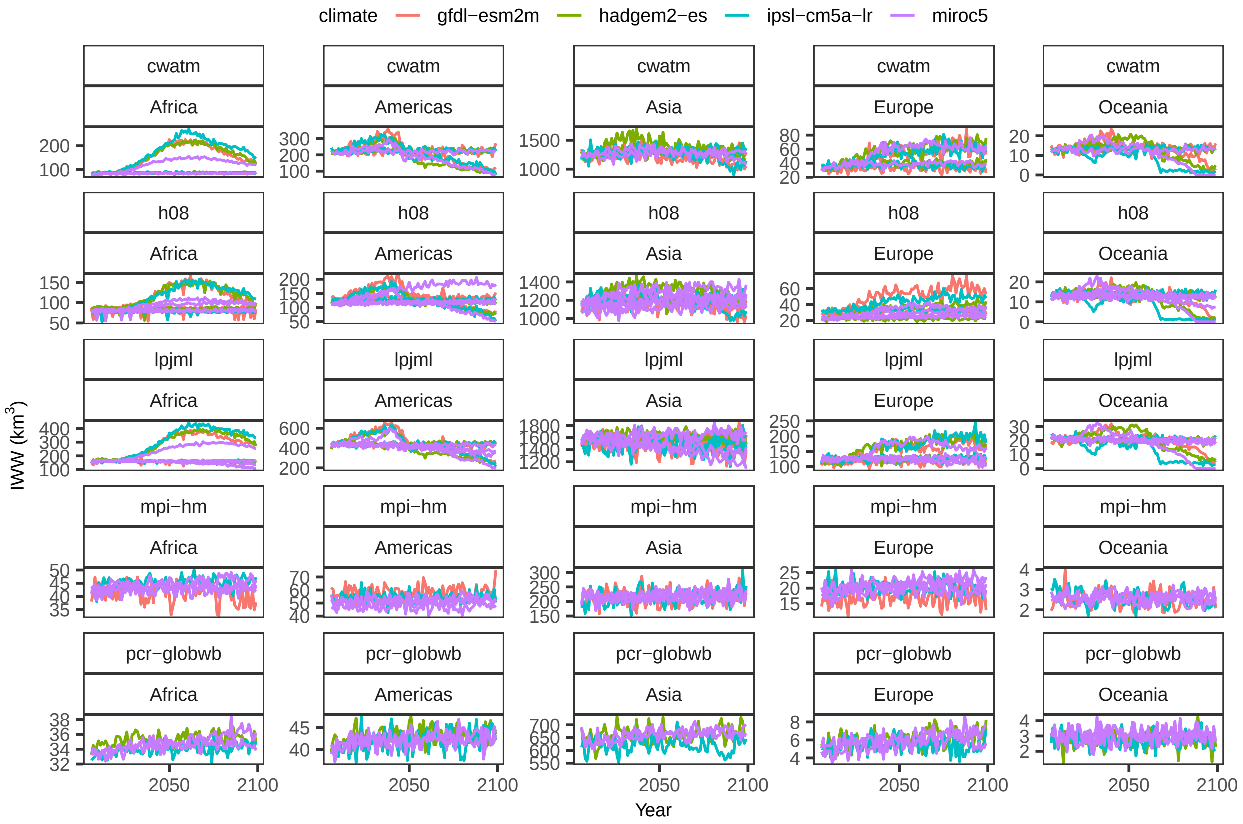
```r
# ARRANGE DATA ##################################################################

# Number of files --------------------------------------------------------------

list.of.files.projections
```

```
##  [1] "cwatm_gfdl-esm2m_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [2] "cwatm_gfdl-esm2m_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [3] "cwatm_hadgem2-es_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [4] "cwatm_hadgem2-es_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [5] "cwatm_ipsl-cm5a-lr_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [6] "cwatm_ipsl-cm5a-lr_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [7] "cwatm_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [8] "cwatm_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [9] "h08_gfdl-esm2m_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [10] "h08_gfdl-esm2m_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [11] "h08_hadgem2-es_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [12] "h08_hadgem2-es_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [13] "h08_ipsl-cm5a-lr_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [14] "h08_ipsl-cm5a-lr_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [15] "h08_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [16] "h08_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [17] "h08_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [18] "h08_miroc5_ewembi_rcp60_rcp60soc_co2_airrww_global_monthly_2006_2099.nc4"
## [19] "h08_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [20] "lpjml_gfdl-esm2m_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [21] "lpjml_gfdl-esm2m_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [22] "lpjml_hadgem2-es_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [23] "lpjml_hadgem2-es_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [24] "lpjml_ipsl-cm5a-lr_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [25] "lpjml_ipsl-cm5a-lr_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [26] "lpjml_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [27] "lpjml_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
## [28] "lpjml_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [29] "lpjml_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [30] "mpi-hm_gfdl-esm2m_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [31] "mpi-hm_ipsl-cm5a-lr_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [32] "mpi-hm_miroc5_ewembi_picontrol_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [33] "mpi-hm_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [34] "mpi-hm_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [35] "pcr-globwb_hadgem2-es_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [36] "pcr-globwb_ipsl-cm5a-lr_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [37] "pcr-globwb_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [38] "pcr-globwb_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
```

```r
# Arrange names ----------------------------------------------------------------

model.names <- sub("^(.*?)_.*", "\\1", list.of.files.projections)
```

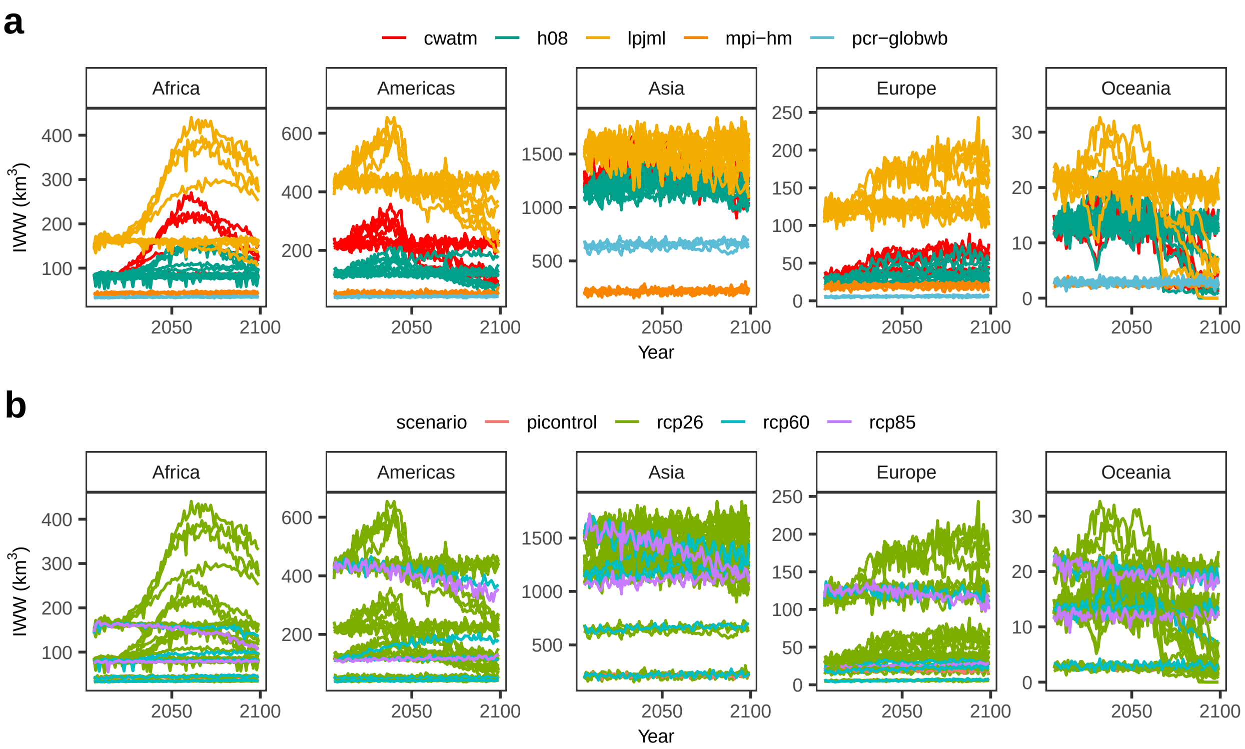
```r
climate.model <- sub("^[^_]*_(.*?)_.*", "\\1", list.of.files.projections)
forcing.data <- sub("^[^_]*_[^_]*_(.*?)_.*", "\\1", list.of.files.projections)
scenario <- sub("^[^_]*_[^_]*_[^_]*_(.*?)_.*", "\\1", list.of.files.projections)
socio.conditions <- sub("^[^_]*_[^_]*_[^_]*_[^_]*_(.*?)_.*", "\\1", list.of.files.projections)
names(isimip.future) <- paste(model.names, climate.model, forcing.data, scenario,
                              socio.conditions, sep = "/")

# Clean and bind dataset -------------------------------------------------------

isimip.future.dt <- rbindlist(isimip.future, idcol = "model") %>%
  na.omit() %>%
  .[, model:= factor(model)] %>%
  .[, year:= as.numeric(year)]

isimip.future.dt[, c("model", "climate", "forcing", "scenario",
                     "socio.conditions") := tstrsplit(model, "/")]

# Export -----------------------------------------------------------------------

fwrite(isimip.future.dt, "isimip.future.dt.csv")
```

```r
# PLOT ISIMIP ##################################################################

# Continental level ------------------------------------------------------------

isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate, forcing, scenario
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")] %>%
  ggplot(., aes(year, V1, group = group, color = climate)) +
  facet_wrap(model~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme(legend.position = "top")
```



```r
# PLOT ISIMIP MERGED ###########################################################

a <- isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate, forcing, sce
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")] %>%
  ggplot(., aes(year, V1, group = group, color = model)) +
  facet_wrap(~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  scale_color_manual(name = "", values = wes_palette(name = selected.palette)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top")

b <- isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate, forcing, sce
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")] %>%
  ggplot(., aes(year, V1, group = group, color = scenario)) +
  facet_wrap(~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top") +
  guides(colour = guide_legend(nrow = 1))
```

```
plot_grid(a, b, ncol = 1, labels = "auto")
```



2.3 ANOVA

```
# ANOVA ##########################################################################

# Arrange ISIMIP datasets ------------------------------------------------------

isimip.full <- isimip.dt[social == "varsoc"][, context:= "historic"] %>%
  rbind(., isimip.future.dt[, context:= "prediction"], fill = TRUE) %>%
  .[, social:= NULL]

isimip.anova <- isimip.full[, .(estimation = sum(V1)),
                            .(Continent, climate, context, forcing,
                              scenario, socio.conditions, model, year)]

# ARRANGE DATA #################################################################

columns_to_factor <- c("Continent", "climate", "model", "scenario", "socio.conditions", "forcin
isimip.full[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]
isimip.anova[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]

# RUN MODEL AND ANALYSIS OF VARIANCE ###########################################

# List of models ---------------------------------------------------------------
```

```
functions <- list(lmm = lmm_fun,
                  gamm = gamm_fun,
                  rf = rf_fun,
                  bayes = bayes_fun)

# Apply each function to the data and combine results ----------------------------

vector.simulation <- c("prediction", "historic")

out <- list()

for (i in seq_along(vector.simulation)) {

  extended <- vector.simulation[i] == "prediction"

  out[[i]] <- mclapply(names(functions), function(fun_name) {

    isimip.anova[context == vector.simulation[i], functions[[fun_name]](.SD, extended = extende
  }, mc.cores = detectCores() * 0.75)

}
```

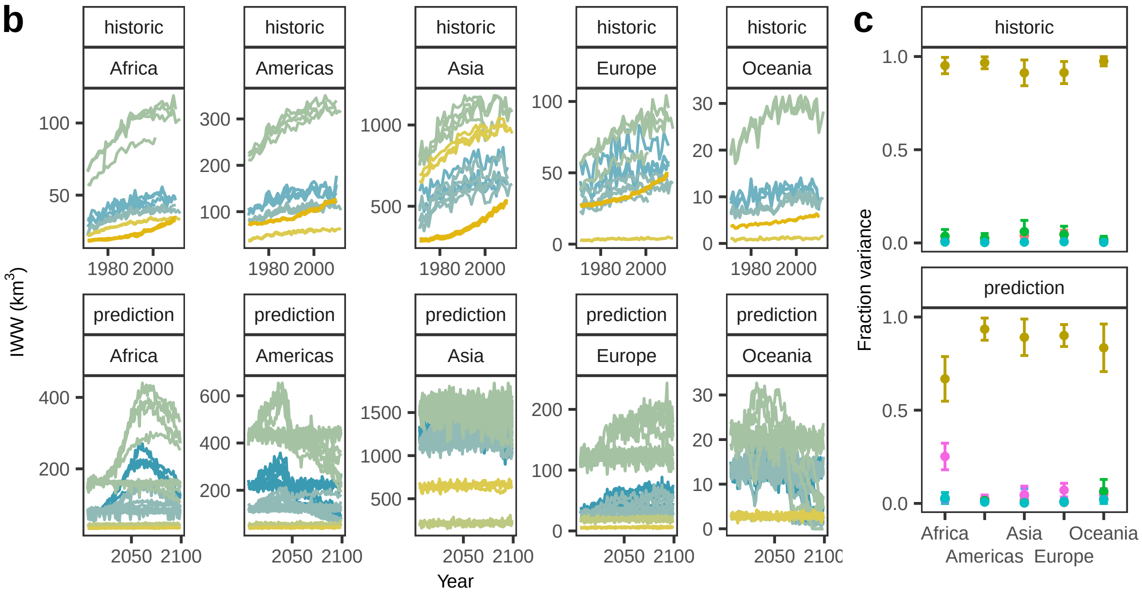
```
# PLOT RESULTS ##################################################################

out
```

```
## [[1]]
## [[1]][[1]]
##    Continent climate_variance model_variance scenario_variance
##       <fctr>            <num>          <num>             <num>
## 1:      Asia      0.004778739      0.9889408      0.0045544118
## 2:    Europe      0.002451284      0.9594155      0.0036202128
## 3:    Africa      0.022271853      0.7877162      0.0094223323
## 4:  Americas      0.002003720      0.9942398      0.0009373538
## 5:   Oceania      0.011935480      0.9623289      0.0008448030
##    socio_conditions_variance random_variance residual_variance
##                        <num>           <num>             <num>
## 1:               0.001714675    7.862427e-07      1.059563e-05
## 2:               0.034495377    2.595910e-06      1.503574e-05
## 3:               0.180510197    1.201007e-05      6.743420e-05
## 4:               0.002793135    5.568105e-06      2.041548e-05
## 5:               0.024778762    2.505090e-05      8.701511e-05
##
## [[1]][[2]]
##    Continent climate_variance model_variance scenario_variance
##       <fctr>            <num>          <num>             <num>
## 1:      Asia      0.009019933      0.9703593      0.0062896233
## 2:    Europe      0.001463545      0.9331400      0.0006915895
## 3:    Africa      0.008249562      0.6408130      0.0049131255
## 4:  Americas      0.005466317      0.9598558      0.0025360560
## 5:   Oceania      0.011876089      0.9221463      0.0029778077
##    socio_conditions_variance random_variance residual_variance
##                        <num>           <num>             <num>
## 1:               0.009663184    1.097493e-10       0.004667923
## 2:               0.051991671    9.075020e-05       0.012622436
## 3:               0.287948073    4.894485e-05       0.058027290
## 4:               0.017914297    8.876704e-06       0.014218660
## 5:               0.018752005    3.389900e-03       0.040857934
##
## [[1]][[3]]
##    Continent climate_variance model_variance scenario_variance
##       <fctr>            <num>          <num>             <num>
## 1:      Asia      0.028760945      0.7933304        0.07851055
## 2:    Europe      0.008175903      0.8416119        0.02648769
## 3:    Africa      0.033423213      0.5484562        0.03732994
## 4:  Americas      0.015254957      0.8753322        0.03388306
## 5:   Oceania      0.037089620      0.7069977        0.04674501
##    socio_conditions_variance random_variance residual_variance
##                        <num>           <num>            <lgcl>
## 1:                0.09250559      0.00689229                NA
## 2:                0.10787052      0.01583655                NA
## 3:                0.32299929      0.05778100                NA
## 4:                0.04492938      0.03059758                NA
## 5:                0.07914711      0.12850278                NA
##
## [[1]][[4]]
##    Continent climate_variance model_variance scenario_variance
##       <fctr>            <num>          <num>             <num>
## 1:      Asia      0.008991597      0.9703531      0.0062893594
## 2:    Europe      0.001454525      0.9315291      0.0006967724
## 3:    Africa      0.008196077      0.6366253      0.0049029716
## 4:  Americas      0.005409551      0.9573435      0.0025448951
## 5:   Oceania      0.011791177      0.9176294      0.0029228949
##    socio_conditions_variance random_variance residual_variance
##                        <num>           <num>             <num>
## 1:               0.009666828    0.0003331048       0.004365965
## 2:               0.051869934    0.0021863080       0.012263368
## 3:               0.285820969    0.0099245504       0.054530101
## 4:               0.017829019    0.0036909579       0.013182100
## 5:               0.018627960    0.0111823975       0.037846180
##
##
## [[2]]
## [[2]][[1]]
##    Continent climate_variance model_variance random_variance residual_variance
##       <fctr>            <num>          <num>           <num>             <num>
## 1:      Asia     0.0182441856      0.9815439    1.604121e-04      5.146166e-05
## 2:    Europe     0.0265735831      0.9732386    7.928135e-05      1.085044e-04
## 3:    Africa     0.0046293623      0.9952289    7.974990e-05      6.196443e-05
## 4:  Americas     0.0015875370      0.9983346    4.897266e-05      2.885478e-05
## 5:   Oceania     0.0003011393      0.9996366    2.836314e-05      3.387542e-05
##
## [[2]][[2]]
##    Continent climate_variance model_variance random_variance residual_variance
##       <fctr>            <num>          <num>           <num>             <num>
## 1:      Asia     0.0582396865      0.9326743    3.492825e-06       0.009082472
## 2:    Europe     0.0665137789      0.9204392    2.795270e-04       0.012767490
## 3:    Africa     0.0058233555      0.9841575    3.265345e-04       0.009692578
## 4:  Americas     0.0027474682      0.9923858    3.009048e-05       0.004836623
## 5:   Oceania     0.0004492087      0.9905800    2.549049e-03       0.006421754
##
## [[2]][[3]]
##    Continent climate_variance model_variance random_variance residual_variance
##       <fctr>            <num>          <num>           <num>            <lgcl>
## 1:      Asia       0.03576058      0.8432847      0.12094998                NA
## 2:    Europe       0.05546279      0.8546251      0.08950090                NA
## 3:    Africa       0.01995226      0.9076825      0.07202544                NA
## 4:  Americas       0.01502286      0.9344138      0.05053658                NA
## 5:   Oceania       0.01274469      0.9496206      0.03551829                NA
##
## [[2]][[4]]
##    Continent climate_variance model_variance random_variance residual_variance
##       <fctr>            <num>          <num>           <num>             <num>
## 1:      Asia     0.0588471019      0.9116481     0.022664397       0.006840365
## 2:    Europe     0.0680062576      0.9104373     0.009398760       0.012157652
## 3:    Africa     0.0069234343      0.9713270     0.012569444       0.009180141
## 4:  Americas     0.0029811586      0.9848791     0.007779968       0.004359748
## 5:   Oceania     0.0003097921      0.9899844     0.004578781       0.005127008
```

```r
results.dt <- rbindlist(lapply(seq_along(out), function(i) {

  rbindlist(lapply(seq_along(out[[i]]), function(j) {

    dt <- out[[i]][[j]]
    dt[, `:=`(context = vector.simulation[i], Function = names(functions)[j])]
    return(dt)

  }), fill = TRUE)

}), fill = TRUE)

a <- isimip.full[, .(estimation = sum(V1)), .(model, Continent, climate, year,
                                              context, forcing, scenario,
                                              socio.conditions)] %>%
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")] %>%
  ggplot(., aes(year, estimation, color = model, group = group)) +
  geom_line() +
  facet_wrap(context~Continent, scale = "free", ncol = 5) +
  scale_x_continuous(breaks = breaks_pretty(n = 2)) +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  guides(colour = guide_legend(nrow = 1)) +
  scale_color_manual(values=wes_palette("Zissou1Continuous", n = 7)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme(legend.position = "none",
        legend.box.spacing = unit(0, "pt"))

b <- results.dt %>%
  melt(., measure.vars = c("climate_variance", "model_variance", "scenario_variance",
                          "socio_conditions_variance", "random_variance",
                          "residual_variance")) %>%
  .[, .(min = min(value, na.rm = TRUE),
        max = max(value, na.rm = TRUE)), .(Continent, context, variable)] %>%
  .[, variance:= tstrsplit(variable, "_", fixed = TRUE)[[1]]] %>%
  ggplot(., aes(x = Continent, ymin = min, ymax = max, y = (min + max) / 2, color = variance))
  geom_errorbar(width = 0.2) +
  geom_point(size = 1) +
  labs(x = "", y = "Fraction variance") +
  facet_wrap(~context, ncol = 1) +
  theme(legend.position = "top") +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  theme(legend.position = "top") +
  guides(color = guide_legend(nrow = 1)) +
  theme(legend.position = "none") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2))

plots.anova <- plot_grid(a, b, ncol = 2, labels = c("b", "c"), rel_widths = c(0.74, 0.26))
```

```
## Warning: Removed 10 rows containing missing values or values outside the scale range
## (`geom_point()`).
```

```
plots.anova
```

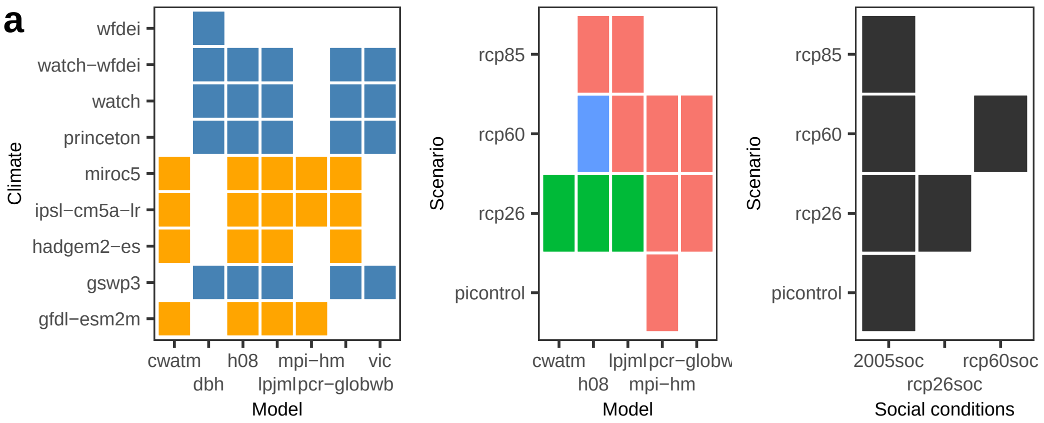


```r
# COUNT COMBINATIONS OF MODEL AND CLIMATE ########################################

plot.tile1 <- unique(isimip.full[, .(model, climate, context)]) %>%
  ggplot(., aes(x = model, y = climate, fill = context)) +
  geom_tile(color = "white", size = 0.5) +
  scale_fill_manual(values = c("historic" = "steelblue", "prediction" = "orange")) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Model", y = "Climate", fill = "simulation") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")
```

```
## Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
## i Please use `linewidth` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```

```r
plot.tile2 <- unique(isimip.full[, .(model, scenario, context, socio.conditions)]) %>%
  na.omit() %>%
  ggplot(., aes(x = model, y = scenario, fill = socio.conditions)) +
  geom_tile(color = "white", size = 0.5) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Model", y = "Scenario", fill = "social conditions") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")

plot.tile3 <- unique(isimip.full[, .(model, climate, scenario, context, socio.conditions)]) %>
```

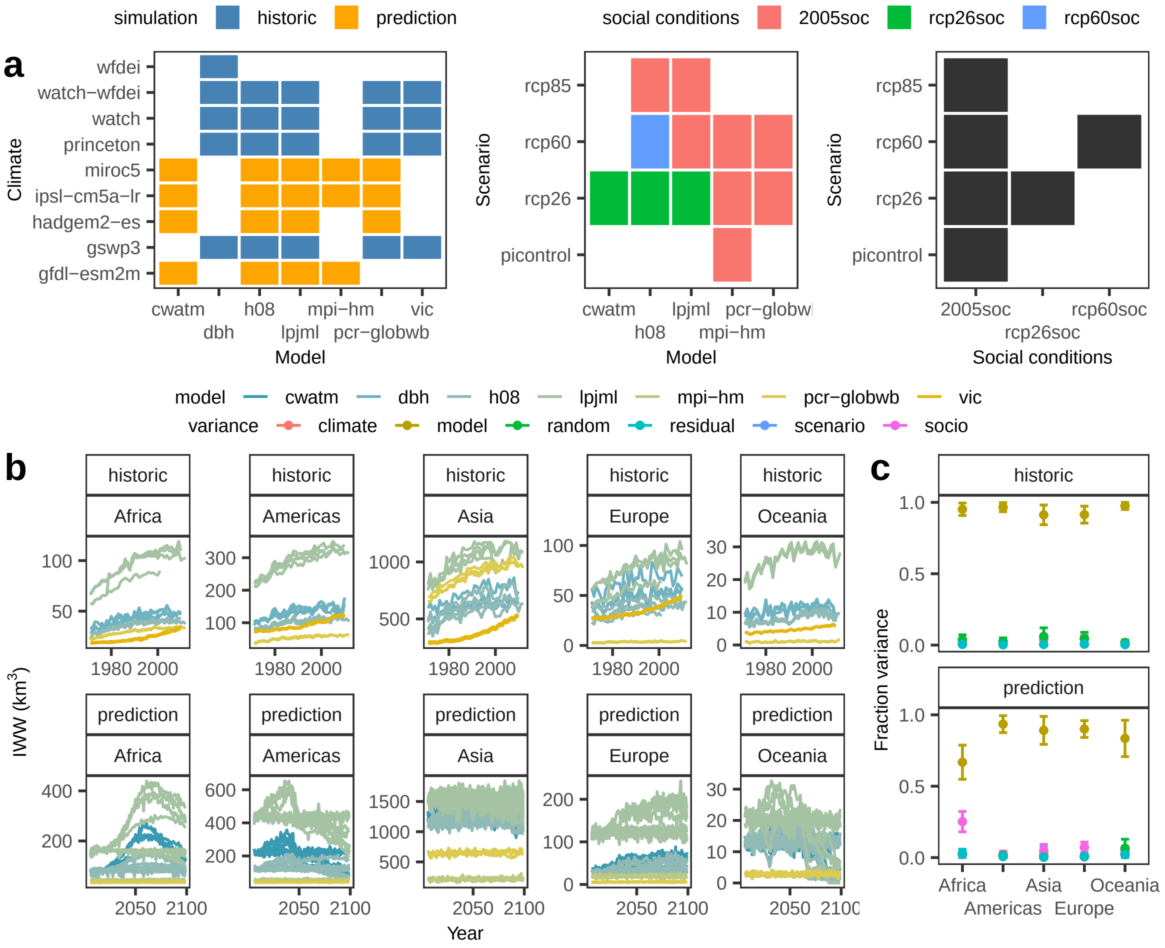
```
  na.omit() %>%
  ggplot(., aes(x = socio.conditions, y = scenario)) +
  geom_tile(color = "white", size = 0.5) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Social conditions", y = "Scenario") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")

all.tiles <- plot_grid(plot.tile1, plot.tile2, plot.tile3, ncol = 3,
                       rel_widths = c(0.4, 0.3, 0.3), labels = c("a", "", ""))
all.tiles
```



```
# MERGE PLOTS ##################################################################

legend1 <- get_legend_fun(plot.tile1 + theme(legend.position = "top"))
legend2 <- get_legend_fun(plot.tile2 + theme(legend.position = "top"))

legend3 <- get_legend_fun(a + theme(legend.position = "top"))
legend4 <- get_legend_fun(b + theme(legend.position = "top"))
```

```
## Warning: Removed 10 rows containing missing values or values outside the scale range
## (`geom_point()`).
```

```
all.legends1 <- plot_grid(legend1, legend2, ncol = 2)
top <- plot_grid(all.legends1, all.tiles, ncol = 1, rel_heights = c(0.1, 0.9))

all.legends2 <- plot_grid(legend3, legend4, ncol = 1)
bottom <- plot_grid(all.legends2, plots.anova, ncol = 1, rel_heights = c(0.1, 0.9))

plot_grid(top, bottom, ncol = 1, rel_heights = c(0.4, 0.6))
```

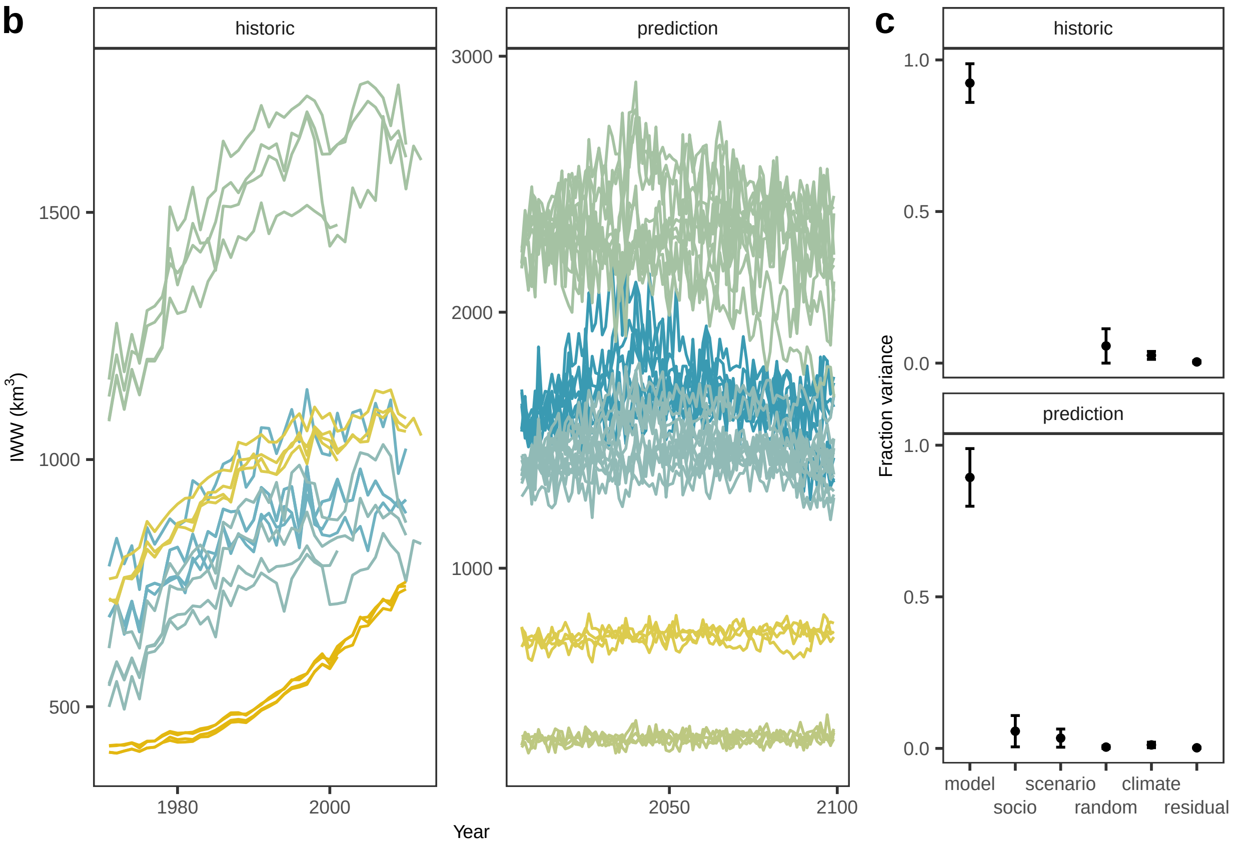


```
isimip.full <- isimip.dt[social == "varsoc"][, context:= "historic"] %>%
  rbind(., isimip.future.dt[, context:= "prediction"], fill = TRUE) %>%
  .[, social:= NULL]

isimip.anova <- isimip.full[, .(estimation = sum(V1)),
                            .(climate, context, forcing,
                              scenario, socio.conditions, model, year)]

# ARRANGE DATA #################################################################

columns_to_factor <- c("climate", "model", "scenario", "socio.conditions", "forcing")
isimip.full[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]
isimip.anova[, (columns_to_factor):= lapply(.SD, as.factor), .SDcols = (columns_to_factor)]

# RUN MODEL AND ANALYSIS OF VARIANCE ###########################################

# List of models ---------------------------------------------------------------

functions <- list(lmm = lmm_fun,
                  gamm = gamm_fun,
                  rf = rf_fun,
                  bayes = bayes_fun)

# Apply each function to the data and combine results ---------------------------

vector.simulation <- c("prediction", "historic")

out <- list()

for (i in seq_along(vector.simulation)) {

  extended <- vector.simulation[i] == "prediction"

  out[[i]] <- mclapply(names(functions), function(fun_name) {

    isimip.anova[context == vector.simulation[i], functions[[fun_name]](.SD, extended = extende
  }, mc.cores = detectCores() * 0.75)

}

# PLOT RESULTS ###################################################################

out

results.dt <- rbindlist(lapply(seq_along(out), function(i) {

  rbindlist(lapply(seq_along(out[[i]]), function(j) {

    dt <- out[[i]][[j]]
    dt[, `:=`(context = vector.simulation[i], Function = names(functions)[j])]
    return(dt)

  }), fill = TRUE)

}), fill = TRUE)

a <- isimip.full[, .(estimation = sum(V1)), .(model, climate, year,
                                              context, forcing, scenario,
                                              socio.conditions)] %>%
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")] %>%
  ggplot(., aes(year, estimation, color = model, group = group)) +
  geom_line() +
  facet_wrap(~context, scale = "free", ncol = 5) +
  scale_x_continuous(breaks = breaks_pretty(n = 2)) +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  guides(colour = guide_legend(nrow = 1)) +
  scale_color_manual(values=wes_palette("Zissou1Continuous", n = 7)) +
```

```r
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme(legend.position = "none",
        legend.box.spacing = unit(0, "pt"))

fwrite(results.dt, "results_isimip_variance.csv")

plot_data <- results.dt %>%
  melt(., measure.vars = c("climate_variance", "model_variance", "scenario_variance",
                           "socio_conditions_variance", "random_variance",
                           "residual_variance" )) %>%
  .[, .(min = min(value, na.rm = TRUE),
        max = max(value, na.rm = TRUE)), .(context, variable)] %>%
  .[, variance:= tstrsplit(variable, "_", fixed = TRUE)[[1]]] %>%
  .[, mean:= (min + max) / 2]

# Create order based on descending mean across all contexts --------------------

variance_order <- plot_data[, .(avg = mean(mean, na.rm = TRUE)), variance] %>%
  .[order(-avg), variance]

# Convert to factor with desired order -----------------------------------------

plot_data[, variance := factor(variance, levels = variance_order)]

b <- ggplot(plot_data, aes(x = variance, ymin = min, ymax = max, y = mean)) +
  geom_errorbar(width = 0.2) +
  geom_point(size = 1) +
  labs(x = "", y = "Fraction variance") +
  facet_wrap(~context, ncol = 1) +
  scale_y_continuous(breaks = scales::breaks_pretty(n = 3)) +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")

plots.anova <- plot_grid(a, b, ncol = 2, labels = c("b", "c"), rel_widths = c(0.7, 0.3))
```

```
## Warning: Removed 2 rows containing missing values or values outside the scale range
## (`geom_point()`).
```

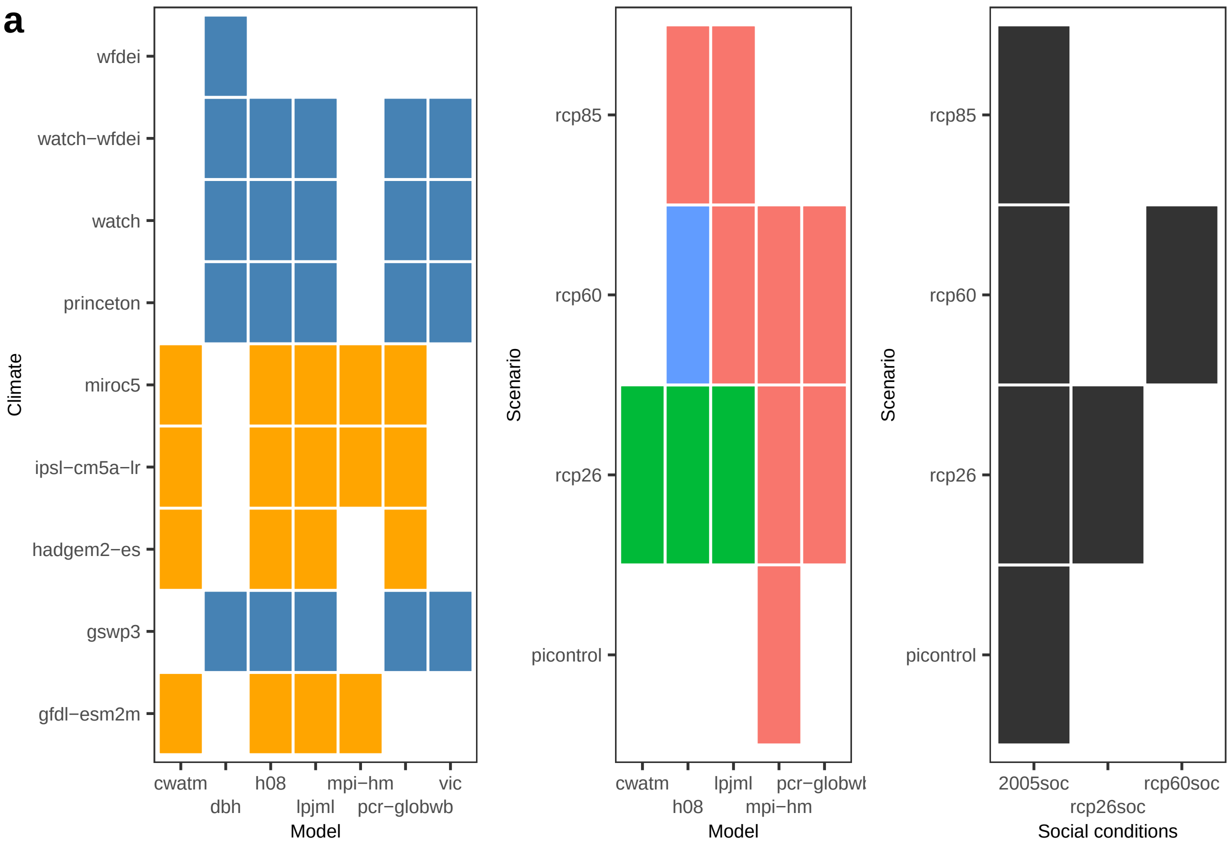
```r
plots.anova
```



```
# COUNT COMBINATIONS OF MODEL AND CLIMATE ########################################

plot.tile1 <- unique(isimip.full[, .(model, climate, context)]) %>%
  ggplot(., aes(x = model, y = climate, fill = context)) +
  geom_tile(color = "white", size = 0.5) +
  scale_fill_manual(values = c("historic" = "steelblue", "prediction" = "orange")) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Model", y = "Climate", fill = "simulation") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")
```

```
## Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
## i Please use `linewidth` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```

```
plot.tile2 <- unique(isimip.full[, .(model, scenario, context, socio.conditions)]) %>%
  na.omit() %>%
  ggplot(., aes(x = model, y = scenario, fill = socio.conditions)) +
  geom_tile(color = "white", size = 0.5) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Model", y = "Scenario", fill = "social conditions") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")

plot.tile3 <- unique(isimip.full[, .(model, climate, scenario, context, socio.conditions)]) %>
  na.omit() %>%
  ggplot(., aes(x = socio.conditions, y = scenario)) +
  geom_tile(color = "white", size = 0.5) +
  theme_minimal() +
  theme(axis.text.x = element_text(angle = 45, hjust = 1)) +
  labs(x = "Social conditions", y = "Scenario") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "none")

all.tiles <- plot_grid(plot.tile1, plot.tile2, plot.tile3, ncol = 3,
                       rel_widths = c(0.4, 0.3, 0.3), labels = c("a", "", ""))
all.tiles
```



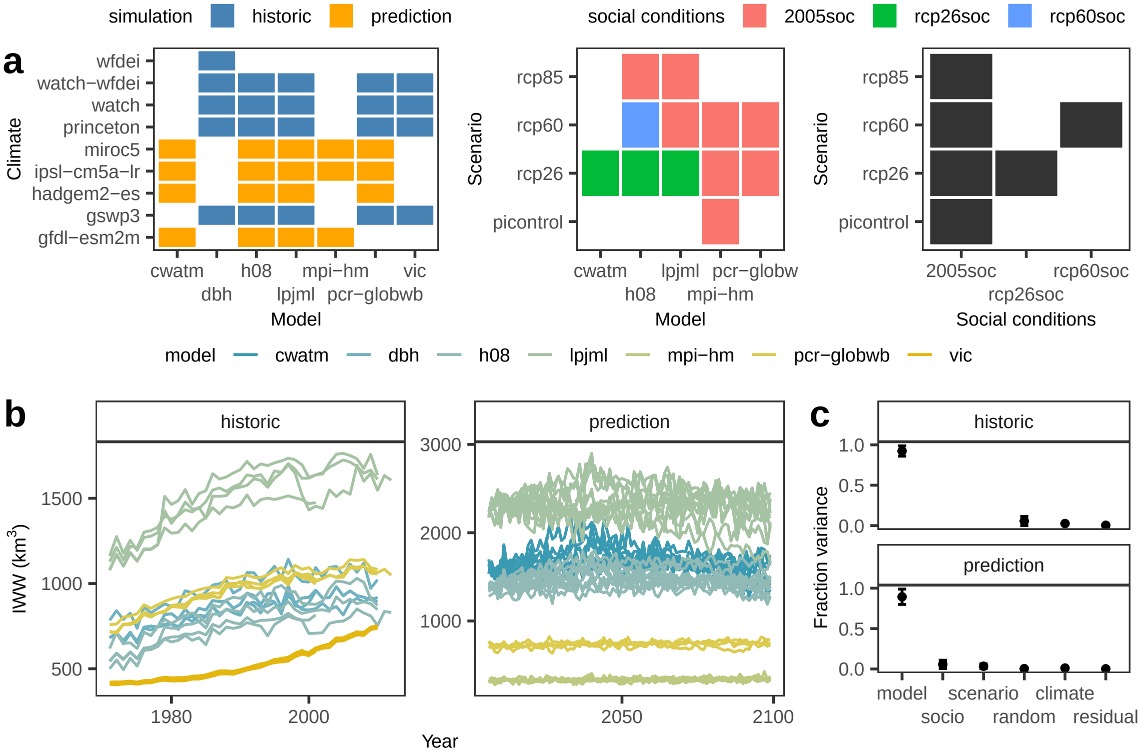
```
# MERGE PLOTS ##################################################################

legend1 <- get_legend_fun(plot.tile1 + theme(legend.position = "top"))
```

```
## Warning: `is.ggplot()` was deprecated in ggplot2 3.5.2.
## i Please use `is_ggplot()` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```

```
legend2 <- get_legend_fun(plot.tile2 + theme(legend.position = "top"))

legend3 <- get_legend_fun(a + theme(legend.position = "top"))
legend4 <- get_legend_fun(b + theme(legend.position = "top"))
```

```
## Warning: Removed 2 rows containing missing values or values outside the scale range
## (`geom_point()`).
```

```
all.legends1 <- plot_grid(legend1, legend2, ncol = 2)
top <- plot_grid(all.legends1, all.tiles, ncol = 1, rel_heights = c(0.1, 0.9))

all.legends2 <- plot_grid(legend3, legend4, ncol = 1)
bottom <- plot_grid(all.legends2, plots.anova, ncol = 1, rel_heights = c(0.1, 0.9))

plot_grid(top, bottom, ncol = 1, rel_heights = c(0.45, 0.55))
```



3 Khan et al dataset

```
# KHAN ET AL 2023 DATASET ####################################################
```

```
path.projections <- "./files/khan_et_al_2023"
list.of.files <- list.files(path.projections, pattern = "\\.csv$")
combinations <- lapply(list.of.files, function(x) strsplit(x, "_")[[1]][1:4]) %>%
  do.call(rbind, .) %>%
  data.frame()
colnames(combinations) <- c("SSP", "RCP", "Climate", "Use")

# READ FILES IN PARALLEL #######################################################

# Create parallel cluste -------------------------------------------------------

numCores <- detectCores() * 0.75
cl <- makeCluster(numCores)
registerDoParallel(cl)

# Run for loop -----------------------------------------------------------------

result <- foreach(i = 1:length(list.of.files),
                  .combine = "rbind",
                  .packages = c("data.table", "countrycode",
                                "sp", "rworldmap")) %dopar% {

                                  out <- fread(paste("./files/khan_et_al_2023/", list.of.files
                                  out[, `:=`(SSP = combinations[i, 1],
                                             RCP = combinations[i, 2],
                                             Climate = combinations[i, 3],
                                             Use = combinations[i, 4])]

                                  Country <- coords2country(out[1:nrow(out), 2:3])

                                  df <- cbind(Country, out)

                                  df[, Continent := countrycode(Country, origin = "country.name

                                  df[, Dataset := list.of.files[i]]

                                  df
                                }

# Stop the cluster after the computation ---------------------------------------

stopCluster(cl)
```

```
# ARRANGE DATA #################################################################

numeric_cols <- grep("^[0-9]+$", names(result), value = TRUE)
khan.dt <- melt(result, measure.vars = numeric_cols, variable.name = "Year") %>%
  .[, Year:= as.numeric(as.character(Year))] %>%
  .[, model:= "GCAM"] %>%
  na.omit()

# EXPORT DATA #################################################################

khan.dt.continent <- khan.dt[, .(estimation = sum(value)),
                             .(Year, Continent, Use, RCP, SSP, Climate, Dataset, model)] %>%
  .[, climate:= paste(Climate, RCP, SSP, sep = "_")]

fwrite(khan.dt.continent, "khan.dt.continent.csv")
```

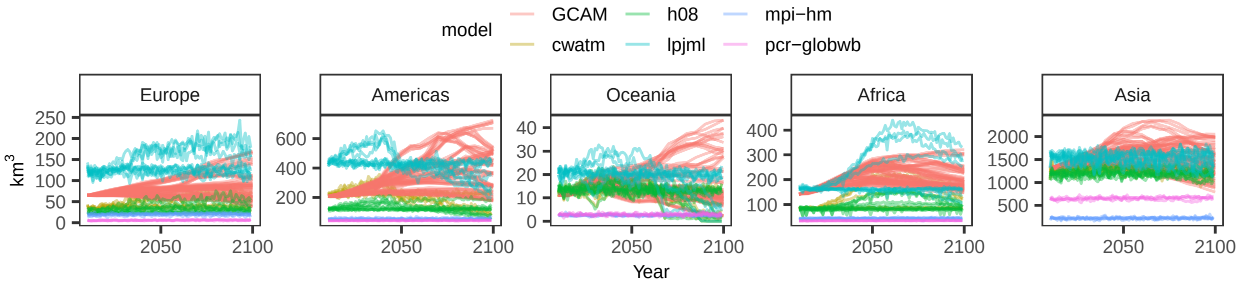
```
# PLOT ########################################################################

# Continental -----------------------------------------------------------------

plot.khan.continental <- khan.dt.continent %>%
  ggplot(., aes(Year, estimation, color = Continent, group = interaction(Dataset, Continent))) +
  geom_line(alpha = 0.3) +
  facet_wrap(~Use) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "", y = bquote("km"^3))

plot.khan.continental
```

```
# PLOT ########################################################################

# Global ----------------------------------------------------------------------

plot.khan.global <- khan.dt[, sum(value), .(Year, Use, Dataset)] %>%
  ggplot(., aes(Year, V1, group = Dataset)) +
  geom_line(alpha = 0.3) +
  facet_wrap(~Use) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))

plot.khan.global
```

```
# MERGE KHAN ET AL DATASETS ###################################################

plot_grid(plot.khan.continental, plot.khan.global, ncol = 1, labels = "auto",
          rel_heights = c(0.53, 0.47))
```

```
# PLOT SSPS VS RCPS ###########################################################

khan.dt[, sum(value), .(Year, Use, Dataset, RCP, SSP)] %>%
  ggplot(., aes(Year, V1, group = Dataset, color = Use)) +
  geom_line() +
  facet_grid(RCP~SSP) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))
```

```
# MERGE KHAN ET AL DATA WITH ISIMIP ############################################

# Arrange data -----------------------------------------------------------------

khan.dt.continent <- fread("khan.dt.continent.csv")

khan.dt2 <- khan.dt.continent[Use == "withdrawals", .(model, Continent, climate, Year, estimat
  setnames(., "Year", "year")

# Extract prediction data from ISIMIP ------------------------------------------

isimip.full2 <- isimip.full[context == "prediction" & year >= 2010,
            .(estimation = sum(V1)), .(model, Continent, climate, year, context,
                                       forcing, scenario, socio.conditions)] %>%
  .[, context:= NULL]

# Merge and plot ---------------------------------------------------------------

merged.dt <- rbind(khan.dt2, isimip.full2, fill = TRUE) %>%
  .[, group:= paste(model, climate, forcing, scenario, socio.conditions, sep = ".")]

ggplot(merged.dt, aes(year, estimation, group = group, color = model)) +
  geom_line(alpha = 0.4) +
  facet_wrap(~Continent, scale = "free_y", ncol = 5) +
  theme_AP() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))
```



```
# Calculate the min and max in 2030-2050 given uncertainty and the global level -----

merged.dt[year %in% c(2030, 2040, 2050),
           .(min = min(estimation), max = max(estimation)), .(Continent, year)] %>%
  .[, .(sum_min = sum(min), sum_max = sum(max)), year]
```

```
##      year  sum_min  sum_max
##     <num>    <num>    <num>
## 1:   2030 272.6478 2648.003
## 2:   2040 280.5123 3053.378
## 3:   2050 252.9897 3273.957
```

4 Session information

```r
# SESSION INFORMATION ##########################################################

sessionInfo()
```

```
## R version 4.3.3 (2024-02-29)
## Platform: aarch64-apple-darwin20 (64-bit)
## Running under: macOS 15.3.2
## 
## Matrix products: default
## BLAS:   /Library/Frameworks/R.framework/Versions/4.3-arm64/Resources/lib/libRblas.0.dylib 
## LAPACK: /Library/Frameworks/R.framework/Versions/4.3-arm64/Resources/lib/libRlapack.dylib;
## 
## locale:
## [1] en_US.UTF-8/en_US.UTF-8/en_US.UTF-8/C/en_US.UTF-8/en_US.UTF-8
## 
## time zone: Europe/London
## tzcode source: internal
## 
## attached base packages:
## [1] parallel  stats     graphics  grDevices utils     datasets  methods  
## [8] base     
## 
## other attached packages:
##  [1] ggrepel_0.9.6                randomForestExplainer_0.10.1
##  [3] magick_2.8.5                 gganimate_1.0.9             
##  [5] ggraph_2.2.1                 igraph_2.1.1                
##  [7] randomForest_4.7-1.2         brms_2.22.0                 
##  [9] Rcpp_1.0.13-1                mgcv_1.9-1                  
## [11] nlme_3.1-166                 microbenchmark_1.5.0        
## [13] lme4_1.1-35.5                Matrix_1.6-5                
## [15] here_1.0.1                   doParallel_1.0.17           
## [17] iterators_1.0.14             foreach_1.5.2               
## [19] rworldmap_1.3-8              sp_2.1-4                    
## [21] countrycode_1.6.0            ncdf4_1.23                  
## [23] scales_1.3.0                 wesanderson_0.3.7           
## [25] benchmarkme_1.0.8            cowplot_1.1.3               
## [27] lubridate_1.9.3              forcats_1.0.0               
## [29] stringr_1.5.1                dplyr_1.1.4                 
## [31] purrr_1.0.2                  readr_2.1.5                 
## [33] tidyr_1.3.1                  tibble_3.2.1                
## [35] ggplot2_3.5.1                tidyverse_2.0.0             
## [37] data.table_1.16.2            openxlsx_4.2.7.1            
## 
## loaded via a namespace (and not attached):
##   [1] gridExtra_2.3         rlang_1.1.4           magrittr_2.0.3       
##   [4] matrixStats_1.4.1     compiler_4.3.3        loo_2.8.0            
##  [7] vctrs_0.6.5           maps_3.4.2.1          crayon_1.5.3
## [10] pkgconfig_2.0.3       fastmap_1.2.0         backports_1.5.0
## [13] utf8_1.2.4            rmarkdown_2.29        tzdb_0.4.0
## [16] nloptr_2.1.1          xfun_0.49             cachem_1.1.0
## [19] progress_1.2.3        tweenr_2.0.3          terra_1.7-78
## [22] prettyunits_1.2.0     R6_2.5.1              RColorBrewer_1.1-3
## [25] stringi_1.8.4         GGally_2.2.1          boot_1.3-31
## [28] estimability_1.5.1    knitr_1.49            fields_16.3
## [31] bayesplot_1.11.1      splines_4.3.3         timechange_0.3.0
## [34] tidyselect_1.2.1      viridis_0.6.5         rstudioapi_0.17.1
## [37] abind_1.4-8           yaml_2.3.10           codetools_0.2-20
## [40] plyr_1.8.9            lattice_0.22-6        withr_3.0.2
## [43] bridgesampling_1.1-2  benchmarkmeData_1.0.4 posterior_1.6.0
## [46] coda_0.19-4.1         evaluate_1.0.1        ggstats_0.7.0
## [49] polyclip_1.10-7       RcppParallel_5.1.9    zip_2.3.1
## [52] pillar_1.9.0          tensorA_0.36.2.1      DT_0.33
## [55] checkmate_2.3.2       distributional_0.5.0  generics_0.1.3
## [58] rprojroot_2.0.4       hms_1.1.3             rstantools_2.4.0
## [61] munsell_0.5.1         minqa_1.2.8           xtable_1.8-4
## [64] glue_1.8.0            emmeans_1.10.5        tools_4.3.3
## [67] graphlayouts_1.2.1    mvtnorm_1.3-2         dotCall64_1.2
## [70] tidygraph_1.3.1       grid_4.3.3            colorspace_2.1-1
## [73] raster_3.6-30         ggforce_0.4.2         cli_3.6.3
## [76] spam_2.11-0           fansi_1.0.6           viridisLite_0.4.2
## [79] Brobdingnag_1.2-9     gtable_0.3.6          digest_0.6.37
## [82] htmlwidgets_1.6.4     gifski_1.32.0-1       farver_2.1.2
## [85] memoise_2.0.1         htmltools_0.5.8.1     lifecycle_1.0.4
## [88] httr_1.4.7            MASS_7.3-60.0.1
```

```r
## Return the machine CPU ------------------------------------------------------

cat("Machine:     "); print(get_cpu()$model_name)
```

```
## Machine:

## [1] "Apple M1 Max"
```

```r
## Return number of true cores -------------------------------------------------

cat("Num cores:   "); print(detectCores(logical = FALSE))
```

```
## Num cores:

## [1] 10
```

```r
## Return number of threads ---------------------------------------------------

cat("Num threads: "); print(detectCores(logical = FALSE))
```

```
## Num threads:

## [1] 10
```