Uncertainty persists after 50 years of global irrigation modelling

R code

Arnald Puy

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"))

# 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 = 7.8),
          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"
```

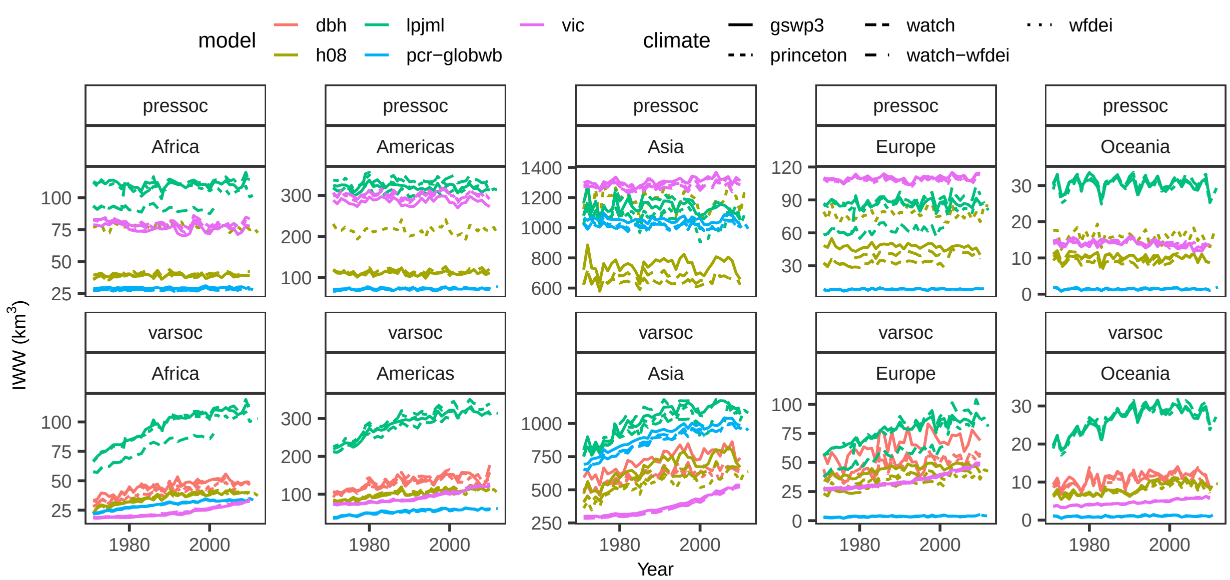
```
##  [8] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012.nc4"
##  [9] "h08_princeton_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2012(1).nc4"
## [10] "h08_princeton_nobc_hist_varsoc_co2_airrww_global_monthly_1971_2012.nc4"
## [11] "h08_watch_nobc_hist_pressoc_co2_airrww_global_monthly_1971_2001.nc4"
## [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")
```

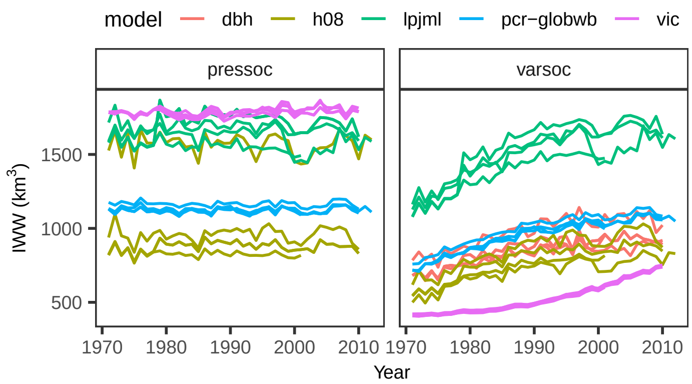
```
# Pressoc: constant human impacts in the form of dams and reservoirs
# varsoc: variable human impacts.
```

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

```r
# 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 --------------------------------------------------------------
```

```r
list.of.files.projections
```

```
##  [1] "h08_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [2] "h08_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [3] "h08_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [4] "h08_miroc5_ewembi_rcp60_rcp60soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [5] "h08_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [6] "lpjml_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [7] "lpjml_miroc5_ewembi_rcp26_rcp26soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [8] "lpjml_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
##  [9] "lpjml_miroc5_ewembi_rcp85_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [10] "mpi-hm_miroc5_ewembi_picontrol_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [11] "mpi-hm_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [12] "mpi-hm_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [13] "pcr-globwb_miroc5_ewembi_rcp26_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
## [14] "pcr-globwb_miroc5_ewembi_rcp60_2005soc_co2_airrww_global_monthly_2006_2099.nc4"
```

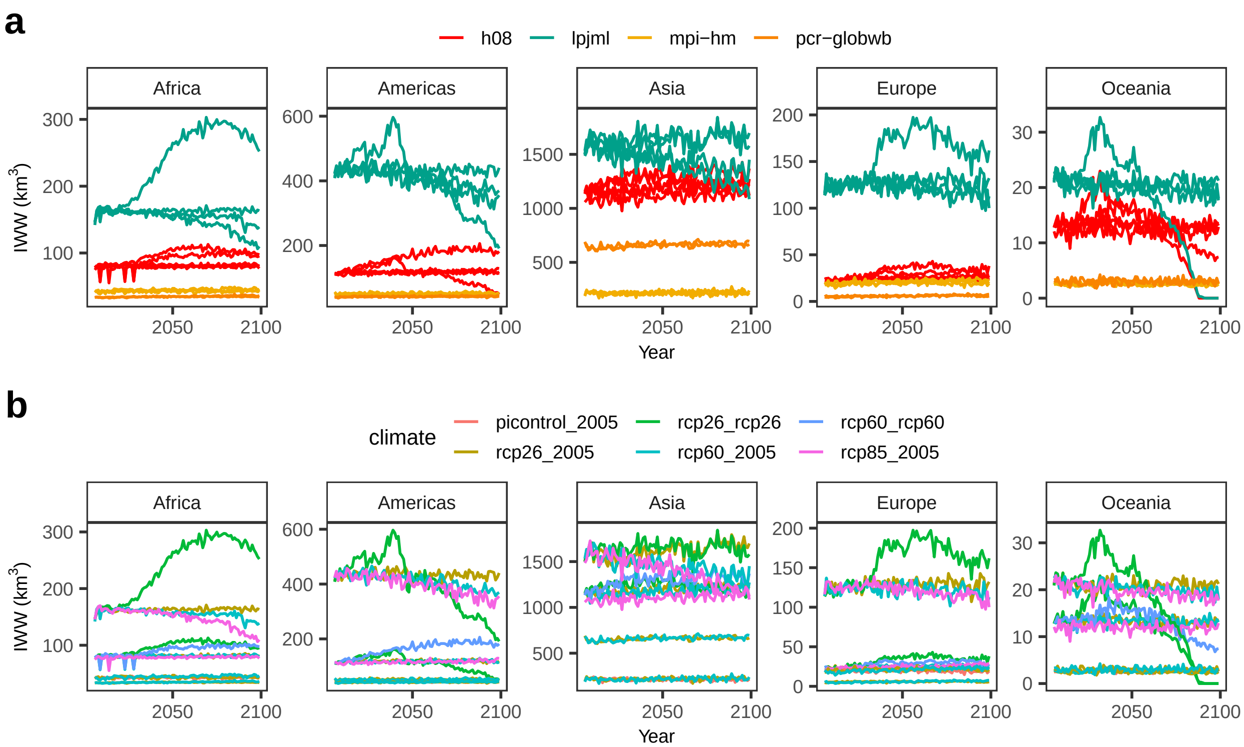
```r
# Arrange names ----------------------------------------------------------------

model.names <- sub("^(.*?)_.*", "\\1", list.of.files.projections)
pattern <- "ewembi_(.*?)soc"
climate <- sub(".*ewembi_(.*?)soc.*", "\\1", list.of.files.projections)
names(isimip.future) <- paste(model.names, climate, 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") := 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)] %>%
  .[, climate:= gsub("_", "\\\\_", climate)] %>%
  ggplot(., aes(year, V1, group = climate, color = climate)) +
  facet_wrap(model~Continent, scales = "free_y", ncol = 5) +
  geom_line() +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme_AP() +
```

```
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme(legend.position = "top")
```


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

a <- isimip.future.dt[, sum(V1, na.rm = TRUE), .(year, Continent, model, climate)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), 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)] %>%
  ggplot(., aes(year, V1, group = interaction(climate, model), color = climate)) +
  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")
```

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



2.3 ANOVA

```r
# 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, model, year)]

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

columns_to_factor <- c("Continent", "climate", "model")
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,
```

```r
                  gamm = gamm_fun,
                  rf = rf_fun,
                  bayes = bayes_fun)

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

results <- mclapply(names(functions), function(fun_name) {

  isimip.anova[, functions[[fun_name]](.SD), .(Continent, context)]

},
mc.cores = detectCores() * 0.75)
```

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

results
```

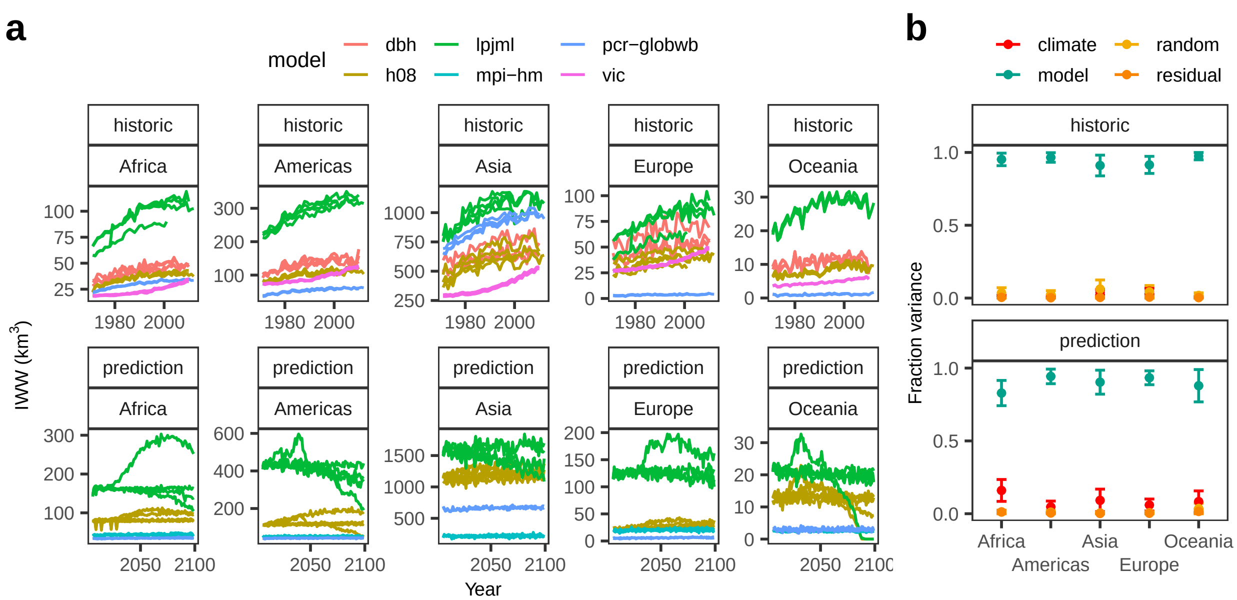
```
## [[1]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##   1:       Asia   historic     0.0182441856      0.9815439    1.604121e-04
##   2:     Europe   historic     0.0265735831      0.9732386    7.928135e-05
##   3:     Africa   historic     0.0046293623      0.9952289    7.974990e-05
##   4:   Americas   historic     0.0015875370      0.9983346    4.897266e-05
##   5:    Oceania   historic     0.0003011393      0.9996366    2.836314e-05
##   6:       Asia prediction     0.0144443043      0.9855396    1.802974e-21
##   7:     Europe prediction     0.0188199322      0.9811568    9.455137e-07
##   8:     Africa prediction     0.0847272814      0.9151935    1.015636e-22
##   9:   Americas prediction     0.0070916322      0.9928739    2.351915e-06
##  10:    Oceania prediction     0.0099009112      0.9899272    2.436002e-05
##     residual_variance
##                 <num>
##   1:      5.146166e-05
##   2:      1.085044e-04
##   3:      6.196443e-05
##   4:      2.885478e-05
##   5:      3.387542e-05
##   6:      1.606501e-05
##   7:      2.232385e-05
##   8:      7.922237e-05
##   9:      3.208885e-05
##  10:      1.475610e-04
##
## [[2]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##   1:       Asia   historic     0.0582396865      0.9326743    3.492825e-06
##   2:     Europe   historic     0.0665137789      0.9204392    2.795270e-04
```

```
##  3:    Africa   historic     0.0058233555      0.9841575    3.265345e-04
##  4:  Americas   historic     0.0027474682      0.9923858    3.009048e-05
##  5:   Oceania   historic     0.0004492087      0.9905800    2.549049e-03
##  6:      Asia prediction     0.0233855736      0.9728348    1.274156e-10
##  7:    Europe prediction     0.0472909695      0.9462095    8.071134e-05
##  8:    Africa prediction     0.1977722547      0.7786924    6.947724e-05
##  9:  Americas prediction     0.0228104251      0.9679342    9.751115e-06
## 10:   Oceania prediction     0.0213692004      0.9437060    3.414224e-03
##     residual_variance
##                 <num>
##  1:       0.009082472
##  2:       0.012767490
##  3:       0.009692578
##  4:       0.004836623
##  5:       0.006421754
##  6:       0.003779619
##  7:       0.006418860
##  8:       0.023465907
##  9:       0.009245593
## 10:       0.031510534
##
## [[3]]
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic       0.03651589      0.8392607      0.12421897
##  2:    Europe   historic       0.05732503      0.8561269      0.08615885
##  3:    Africa   historic       0.01925291      0.9091631      0.07124754
##  4:  Americas   historic       0.01621633      0.9325713      0.05118237
##  5:   Oceania   historic       0.01243839      0.9494631      0.03595673
##  6:      Asia prediction       0.16884042      0.8208680      0.01029125
##  7:    Europe prediction       0.10083726      0.8857703      0.01334813
##  8:    Africa prediction       0.23492099      0.7417898      0.02324906
##  9:  Americas prediction       0.08681625      0.8927305      0.02044727
## 10:   Oceania prediction       0.15674244      0.7680757      0.07252973
##     residual_variance
##                <lgcl>
##  1:                NA
##  2:                NA
##  3:                NA
##  4:                NA
##  5:                NA
##  6:                NA
##  7:                NA
##  8:                NA
##  9:                NA
## 10:                NA
##
## [[4]]
```

```
##     Continent    context climate_variance model_variance random_variance
##        <fctr>     <char>            <num>          <num>           <num>
##  1:      Asia   historic     0.0585877490      0.9114970    2.307509e-02
##  2:    Europe   historic     0.0679479627      0.9104088    9.472626e-03
##  3:    Africa   historic     0.0069267842      0.9713291    1.254960e-02
##  4:  Americas   historic     0.0030365269      0.9846379    7.963846e-03
##  5:   Oceania   historic     0.0003067787      0.9899282    4.641493e-03
##  6:      Asia prediction     0.0233300054      0.9728583    1.131701e-05
##  7:    Europe prediction     0.0469288511      0.9463859    2.596976e-04
##  8:    Africa prediction     0.1977676855      0.7778277    5.262552e-05
##  9:  Americas prediction     0.0228624389      0.9669629    7.071621e-04
## 10:   Oceania prediction     0.0208228448      0.9423662    5.325046e-03
##     residual_variance
##                 <num>
##  1:       0.006840208
##  2:       0.012170596
##  3:       0.009194540
##  4:       0.004361695
##  5:       0.005123568
##  6:       0.003800369
##  7:       0.006425531
##  8:       0.024351981
##  9:       0.009467473
## 10:       0.031485861
```

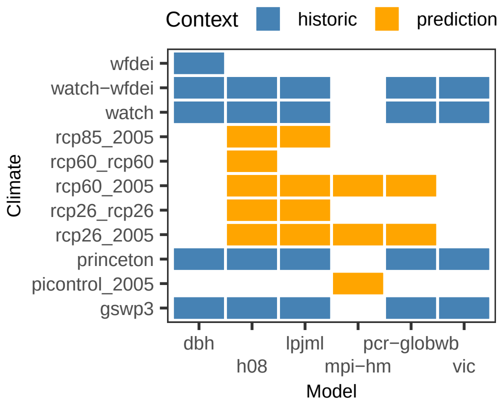
```
results.dt <- rbindlist(results)

a <- isimip.full[, .(estimation = sum(V1)), .(model, Continent, climate, year, context)] %>%
  ggplot(., aes(year, estimation, color = model, group = interaction(climate, model))) +
  geom_line() +
  facet_wrap(context~Continent, scale = "free", ncol = 5) +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  theme_AP() +
  guides(colour = guide_legend(nrow = 2)) +
  labs(x = "Year", y = bquote("IWW (km"^3 * ")"))  +
  theme(legend.position = "top",
        legend.box.spacing = unit(0, "pt"))

b <- results.dt %>%
  melt(., measure.vars = c("climate_variance", "model_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) +
  scale_color_manual(name = "", values=wes_palette(selected.palette, n = 4)) +
```

```
  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 = 2)) +
  theme(legend.position = "top") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2))

plot_grid(a, b, ncol = 2, labels = "auto", rel_widths = c(0.72, 0.28))
```




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

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 = "Context") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(legend.position = "top")
```

```
## 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.
```



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)
```

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

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

                                  df
                                }

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

stopCluster(cl)
```

```r
# 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")
```

```r
# 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
```

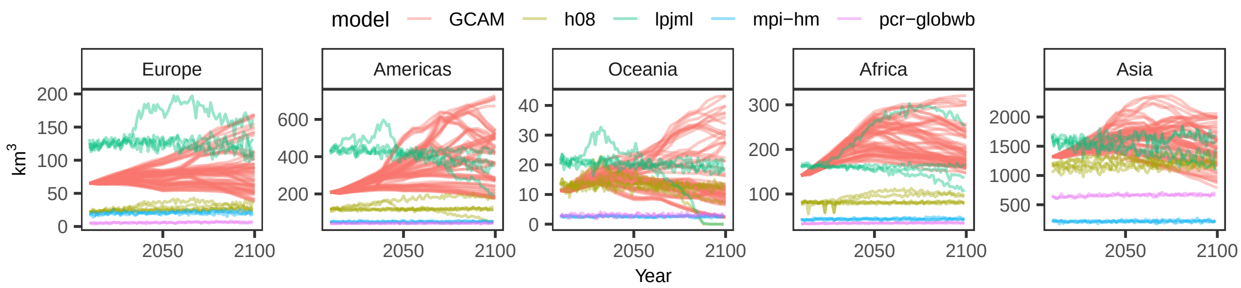
```r
# PLOT #########################################################################

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

plot.khan.global <- khan.dt[, sum(value), .(Year, Use, Dataset)] %>%
  ggplot(., aes(Year, V1, group = Dataset)) +
  geom_line(alpha = 0.3) +
```

```r
  facet_wrap(~Use) +
  theme_AP() +
  theme(legend.position = "top") +
  labs(x = "Year", y = bquote("km"^3))

plot.khan.global
```

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

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

```r
# 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))
```

```r
# 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, estimati
  setnames(., "Year", "year")

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

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

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

merged.dt <- rbind(khan.dt2, isimip.full2)

ggplot(merged.dt, aes(year, estimation, group = interaction(climate, model), 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 272.8320 2529.235
## 2:  2040 281.8063 2958.560
## 3:  2050 278.4169 3188.283
```

4 Bibliographical study

```
# NAOMI DATASET ################################################################

references.projected <- data.table(read.xlsx("./data/references_projection.xlsx")) %>%
  .[, focus:= "projected"]

references.current <- data.table(read.xlsx("./data/references_current.xlsx")) %>%
  .[, focus:= "current"]

references.full.dt <- rbind(references.projected, references.current) %>%
  .[, study:= paste(author, model, climate.scenario, sep = ".")]

# CLEAN THE DATASET ############################################################

colnames_vector <- c("title", "author", "region")

# Remove leading and trailing spaces -------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, trimws), .SDcols = (colnames_vector)]
references.full.dt[, (colnames_vector):= lapply(.SD, str_squish), .SDcols = (colnames_vector)]

# Lowercaps --------------------------------------------------------------------

references.full.dt[, (colnames_vector):= lapply(.SD, tolower), .SDcols = (colnames_vector)]

# Remove multiple spaces -------------------------------------------------------
```

```r
references.full.dt[, (colnames_vector):= lapply(.SD, function(x)
  gsub("\\s+", " ", x)), .SDcols = (colnames_vector)]

# Correct America ---------------------------------------------------------------

references.full.dt[, region:= ifelse(region == "america", "americas", region)]

# Extract the publication year --------------------------------------------------

references.full.dt[, publication.date:= str_extract(author, "\\d{4}")] %>%
  .[, publication.date:= as.numeric(publication.date)]
```

```r
# FEATURES OF THE DATASET #######################################################

# Name of different studies -----------------------------------------------------

sort(unique(references.full.dt[variable == "iww" & region == "global", title]))
```

```
##  [1] "a global water scarcity assessment under shared socio-economic pathways - part 2: wate
##  [2] "a pathway of global food supply adaptation in a world with increasingly constrained gr
##  [3] "agricultural green and blue water consumption and its influence on the global water sy
##  [4] "an estimation of global virtual water flow and sources of water withdrawal for major c
##  [5] "an integrated assessment of global and regional water demands for electricity generati
##  [6] "an interpreted model for the assessment of global water resources - part 2: applicatio
##  [7] "appraisal and assessment of world water resources"
##  [8] "aquastat: fao's global information system on water and agriculture"
##  [9] "climate change impacts on irrigation water requirements: effects of mitigation, 1990-2
## [10] "climate impacts on global irrigation requirements under 19 gcms, simulated with a vege
## [11] "climate policy implications for agricultural water demand"
## [12] "future long-term changes in global water resources driven by socio-economic and climat
## [13] "global and regional evaluation of energy for water"
## [14] "global impacts of conversions from natural to agricultural ecosystems on water resourc
## [15] "global irrigation characteristics and effects simulated by fully coupled land surface
## [16] "global irrigation water demand: variability and uncertainties arising from agricultura
## [17] "global modeling of irrigation water requirements"
## [18] "global monthly sectoral water use for 2010-2100 at 0.5° resolution across alternative
## [19] "global water demand and supply projections"
## [20] "globwat - a global water balance model to assess water use in irrigated agriculture"
## [21] "how can we cope with the water resources situation by the year 2050?"
## [22] "human appropriation of renewable fresh water"
## [23] "implementation and evaluation of irrigation techniques in the community land model"
## [24] "incorporating anthropogenic water regulation modules into a land surface model"
## [25] "incorporation of groundwater pumping in a global land surface model with the represent
## [26] "isimip database"
## [27] "long-term global water projections using six socioeconomic scenarios in an intgrated a
## [28] "modelling global water stress of the recent past: on the relative importance of trends
## [29] "multimodel projections and uncertainties of irrigation water demand under climate chan
```

```
## [30] "pcr-globwb 2: a 5 arcmin global hydrological and water resources model"
## [31] "recent global cropland water consumption constrained by observations"
## [32] "reconciling irrigated food production with environmental flows for sustainable develop
## [33] "reconstructing 20th century global hydrography: a contribution to the global terrestri
## [34] "the state of the world's land and water resources for food and agriculture"
## [35] "the world’s water, 2000-2001: the biennial report on freshwater resources"
## [36] "water 2050. moving toward a sustainable vision fot the earth's fresh water"
## [37] "water and sustainability. global pattern and long-range problems"
## [38] "world agriculture towards 2030/2055"
## [39] "world water demand and supply, 1990 to 2025: scenarios and issues"
## [40] "world water in 2025 - global modeling and scenario analysis for the world commission o
## [41] "world water resources and their future"
```

```r
# Number of data points ---------------------------------------------------------

nrow(references.full.dt[variable == "iww" & region == "global"])
```

```
## [1] 1194
```

```r
# Number of different studies per variable ---------------------------------------

references.full.dt[region == "global", unique(title), variable] %>%
  .[, .N, variable]
```

```
##    variable     N
##      <char> <int>
## 1:      iww    42
## 2:      tww    27
## 3:      iwc    17
## 4:      twc     6
## 5:      iwr     2
```

```r
# Number of data points for 2000, 2050, 2070, 2100 -----------------------------

references.full.dt[variable == "iww" & region == "global" &
                     estimation.year %in% c(2000, 2050, 2070, 2100), .N, estimation.year]
```

```
##    estimation.year     N
##              <num> <int>
## 1:            2000    55
## 2:            2070   119
## 3:            2100   106
## 4:            2050    98
```

```r
# Number of unique studies estimating for 2000, 2050, 2070, 2100 ---------------

references.full.dt[variable == "iww" & region == "global" &
                     estimation.year %in% c(2000, 2050, 2070, 2100), unique(title), estimation
  .[, .N, estimation.year]
```

```
##    estimation.year     N
```

```
##                <num> <int>
## 1:              2000    17
## 2:              2070     4
## 3:              2100     3
## 4:              2050     7
```

```r
# Number of data points for every targeted year -----------------------------

references.full.dt[variable == "iww" & region == "global", .N, estimation.year] %>%
  .[order(estimation.year)]
```

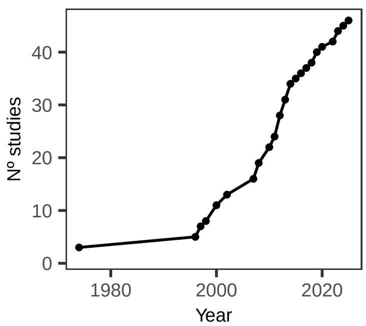
```
##     estimation.year     N
##                <num> <int>
##  1:             1900     2
##  2:             1940     2
##  3:             1950     2
##  4:             1960     3
##  5:             1970     3
##  6:             1975    22
##  7:             1980    26
##  8:             1983     1
##  9:             1985    26
## 10:             1990    25
## 11:             1994     6
## 12:             1995    38
## 13:             1996     2
## 14:             2000    55
## 15:             2002     2
## 16:             2003     1
## 17:             2004     1
## 18:             2005    19
## 19:             2006     2
## 20:             2008     1
## 21:             2010   100
## 22:             2015     3
## 23:             2020    84
## 24:             2021     1
## 25:             2025     6
## 26:             2030    82
## 27:             2040    93
## 28:             2050    98
## 29:             2055     2
## 30:             2060    82
## 31:             2070   119
## 32:             2075     2
## 33:             2080    91
## 34:             2090    79
## 35:             2095     7
```

```
## 36:             2100   106
##     estimation.year     N
```

```r
# Cumulative sum of published studies ------------------------------------------

cumulative.iww <- references.full.dt[, .(title, publication.date, variable)] %>%
  .[variable == "iww"] %>%
  .[!duplicated(.)] %>%
  setorder(., publication.date) %>%
  .[, .N, publication.date] %>%
  .[, cumulative_sum := cumsum(N)] %>%
  ggplot(., aes(publication.date, cumulative_sum)) +
  geom_line() +
  scale_x_continuous(breaks = breaks_pretty(n = 3)) +
  geom_point(size = 0.7) +
  theme_AP() +
  labs(x = "Year", y = "Nº studies")

cumulative.iww
```

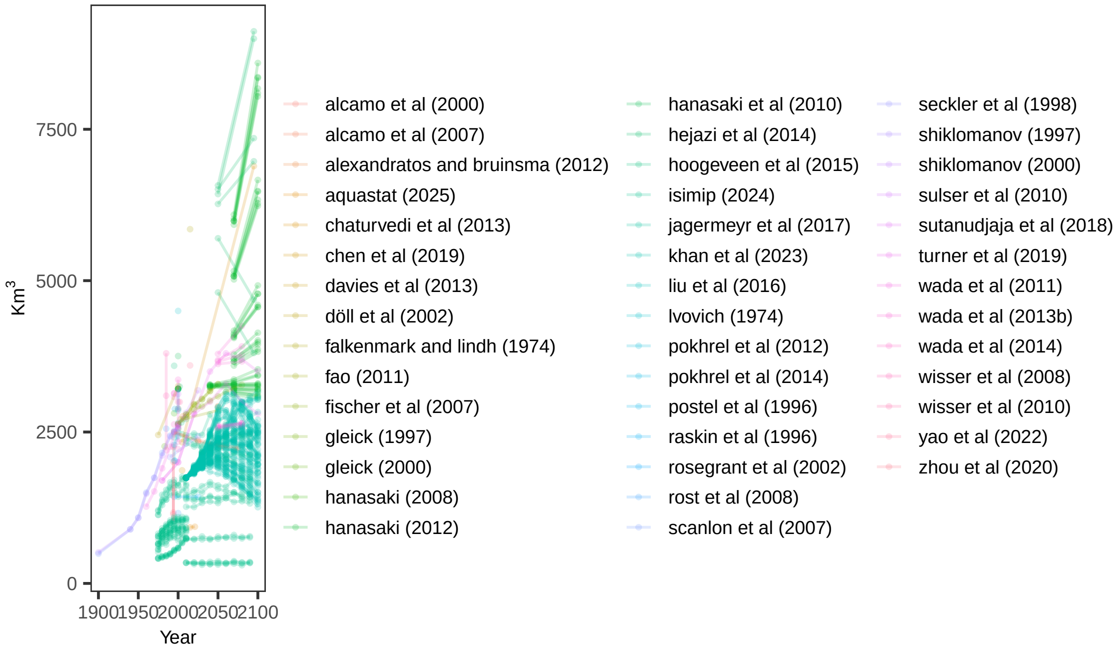
```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

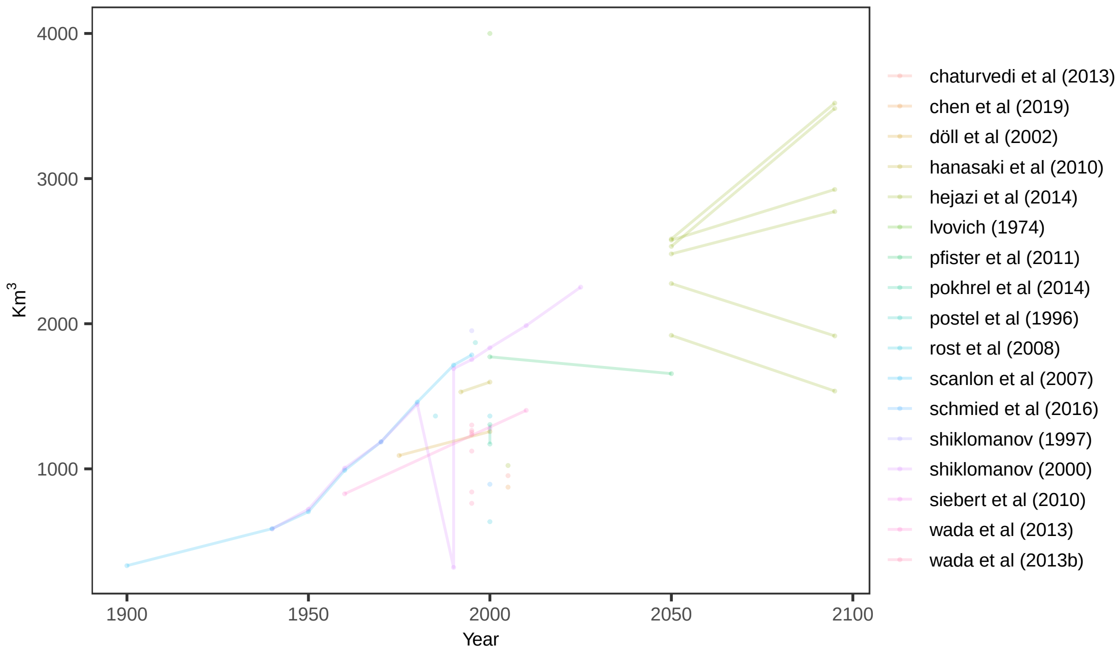



```r
# PLOT ALL ESTIMATIONS #########################################################

def.alpha <- 0.2

plot.iww <- references.full.dt[variable == "iww" & region == "global"] %>%
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.5) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP()
```

```
plot.iww
```




```
references.full.dt[variable == "iwc" & region == "global"] %>%
  .[, .(author, study, estimation.year, value)] %>%
  na.omit() %>%
  ggplot(., aes(estimation.year, value, color = author, group = study)) +
  geom_point(alpha = def.alpha, size = 0.2) +
  labs(x = "Year", y = bquote("Km"^3)) +
  scale_color_discrete(name = "") +
  geom_line(alpha = def.alpha) +
  theme_AP()
```



4.1 The garden of forking paths

```
# DEFINE THE UNCERTAINTY SPACE ##################################################

# Target year -----------------------------------------------------------------

target_year <- c(2000, 2050, 2070, 2100)

# Target year interval --------------------------------------------------------

target_year_interval <- c("yes", "no")

# Interval publication --------------------------------------------------------

interval <- c(10, 15, 20)

# Metrics of study ------------------------------------------------------------

metrics <- c("cv", "range", "sd", "var", "entropy", "iqr")

# Inclusion criteria ----------------------------------------------------------

inclusion_criteria <- c("all", "exclude_before_1990")

# Rolling windows -------------------------------------------------------------

rolling_window_factor <- c(1, 0.5)
```

```r
# Define the forking paths -----------------------------------------------------

forking_paths <- expand.grid(target_year = target_year,
                             target_year_interval = target_year_interval,
                             interval = interval,
                             inclusion_criteria = inclusion_criteria,
                             rolling_window_factor = rolling_window_factor,
                             metric = c(metrics, paste(metrics, "_normalized", sep = ""))) %>%
  data.table()

# Number of simulations --------------------------------------------------------

nrow(forking_paths)
```

```
## [1] 1152
```

```r
# RUN MODEL ####################################################################

trend <- list()

for (i in 1:nrow(forking_paths)) {

  trend[[i]] <- forking_paths_fun(dt = references.full.dt,
                                  target_year = forking_paths[[i, "target_year"]],
                                  target_year_interval = forking_paths[[i, "target_year_interva
                                  interval = forking_paths[[i, "interval"]],
                                  rolling_window_factor = forking_paths[[i, "rolling_window_fac
                                  inclusion_criteria = forking_paths[[i, "inclusion_criteria"]]
                                  metric = forking_paths[[i, "metric"]])
}
```

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

output.dt <- lapply(trend, function(x) x[["results"]]) %>%
  do.call(rbind, .) %>%
  data.table() %>%
  setnames(., "V1", "trend")

final.dt <- cbind(forking_paths, output.dt)

# Print the fraction of simulations in each classification ---------------------

final.dt %>%
  .[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  print()
```

```
##            trend total   fraction
##           <char> <int>      <num>
```

```
## 1:       Random   515 0.44704861
## 2:    Ascending   300 0.26041667
## 3:   Descending   289 0.25086806
## 4: single point    48 0.04166667
```

```
# Now remove all simulations that produced just one single point ---------------

final.dt <- final.dt[!trend == "single point"]

# Simulations that did not lead to a reduction in uncertainty ------------------

final.dt %>%
  .[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  .[!trend == "Descending"] %>%
  .[, sum(fraction)]
```

```
## [1] 0.7074653
```

```
# PLOTS FORKING PATHS EXAMPLES #################################################

plots.dt <- lapply(trend, function(x) x[["plot"]])

random.plots <- c(1, 986, 345)
decreasing.plots <- c(1093, 556, 4)
increasing.plots <- c(10, 602, 770)

out.random <- out.decreasing <- out.increasing <- list()

for (i in 1:length(random.plots)) {

  out.random[[i]] <- plot_plots_forking_paths_fun(random.plots[i])
  out.decreasing[[i]] <- plot_plots_forking_paths_fun(decreasing.plots[i])
  out.increasing[[i]] <- plot_plots_forking_paths_fun(increasing.plots[i])
}

pt.random <- plot_grid(out.random[[1]] + geom_smooth() + labs(x = "", y = "+ Uncertainty"),
                       out.random[[2]] + geom_smooth() + labs(x = "", y = ""),
                       out.random[[3]] + geom_smooth() + labs(x = "", y = ""),
                       ncol = 3)
```

```
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
```

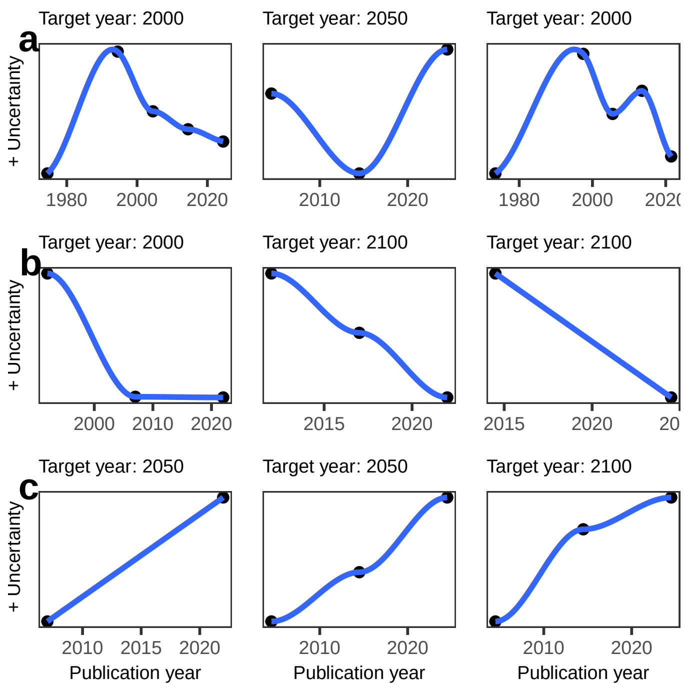
```
pt.decreasing <- plot_grid(out.decreasing[[1]] + geom_smooth() + labs(x = "", y = "+ Uncertain
                           out.decreasing[[2]] + geom_smooth() + labs(x = "", y = ""),
                           out.decreasing[[3]] + geom_smooth(method = "lm", se = F) + labs(x =
                           ncol = 3)
```

```
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using formula = 'y ~ x'
```

```
pt.increasing <- plot_grid(out.increasing[[1]] + geom_smooth(method = "lm", se = F),
                           out.increasing[[2]] + geom_smooth() + labs(x = "Publication year", y
                           out.increasing[[3]] + geom_smooth() + labs(x = "Publication year", y
                           ncol = 3)
```

```
## `geom_smooth()` using formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
## `geom_smooth()` using method = 'loess' and formula = 'y ~ x'
```

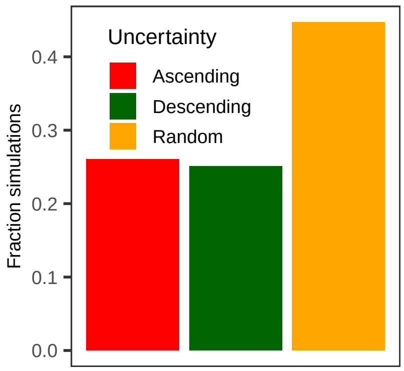
```
plot_grid(pt.random, pt.decreasing, pt.increasing, ncol = 1, labels = "auto")
```




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

selected_colors <- c("Ascending" = "red", "Descending" = "darkgreen", "Random" = "orange")

plot.fraction <- final.dt[, .(total = .N), trend] %>%
  .[, fraction:= total / nrow(output.dt)] %>%
  ggplot(., aes(trend, fraction, fill = trend)) +
  geom_bar(stat = "identity") +
  labs(x = "", y = "Fraction simulations") +
  scale_fill_manual(values = selected_colors, name = "Uncertainty") +
  scale_x_discrete(guide = guide_axis(n.dodge = 2)) +
  theme_AP() +
  theme(axis.ticks.x = element_blank(),
        axis.text.x = element_blank(),
        legend.position = c(0.33, 0.77))
```

```
## Warning: A numeric `legend.position` argument in `theme()` was deprecated in ggplot2
## 3.5.0.
## i Please use the `legend.position.inside` argument of `theme()` instead.
## This warning is displayed once every 8 hours.
## Call `lifecycle::last_lifecycle_warnings()` to see where this warning was
## generated.
```

```
plot.fraction
```

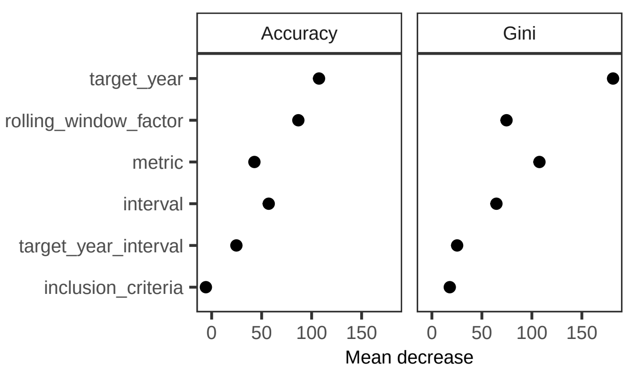



```
# RANDOM FOREST ###################################################################

# Convert categorical variables to factors ------------------------------------

df <- data.frame(final.dt)
df$inclusion_criteria <- as.factor(final.dt$inclusion_criteria)
df$metric <- as.factor(final.dt$metric)
df$trend <- as.factor(df$trend)
df$target_year_interval <- as.factor(df$target_year_interval)

# Train the model --------------------------------------------------------------

rf_model <- randomForest(trend ~ target_year + target_year_interval + interval +
                           inclusion_criteria + rolling_window_factor + metric,
                         data = df, importance = TRUE)

# View variable importance -----------------------------------------------------

dt_rf_model <- data.frame(importance(rf_model))
dt_rf_model
```

```
##                       Ascending Descending    Random MeanDecreaseAccuracy
## target_year            58.82274  84.764119 94.622667           107.382975
## target_year_interval   25.70447   9.853205  8.164398            24.733313
## interval               39.06084  30.958593 46.892258            57.058990
## inclusion_criteria    -24.19508   4.749013  4.471091            -5.770201
## rolling_window_factor  49.95345  34.466797 80.799476            86.706311
## metric                 37.90890  27.888115 21.941872            42.765101
##                       MeanDecreaseGini
```

```
## target_year                     181.20505
## target_year_interval             25.24297
## interval                         64.54198
## inclusion_criteria               17.88005
## rolling_window_factor            74.63270
## metric                          107.56085
```

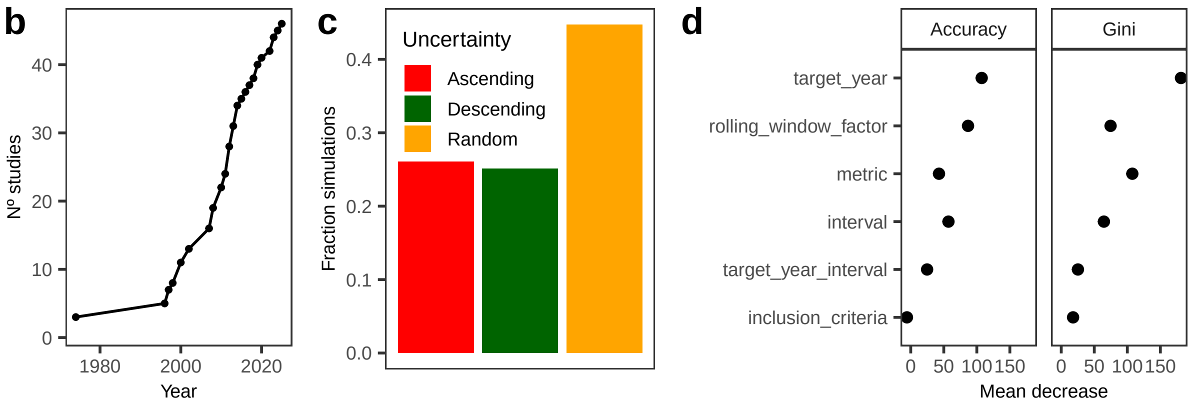
```r
# Plot ---------------------------------------------------------------------

plot.rf <- dt_rf_model %>%
  rownames_to_column(., var = "factors") %>%
  data.table() %>%
  setnames(., c("MeanDecreaseAccuracy", "MeanDecreaseGini"),
           c("Accuracy", "Gini")) %>%
  melt(., measure.vars = c("Accuracy", "Gini")) %>%
  ggplot(., aes(reorder(factors, value), value)) +
  geom_point() +
  coord_flip() +
  facet_wrap(~variable) +
  scale_y_continuous(breaks = breaks_pretty(n = 3)) +
  labs(x = "", y = "Mean decrease") +
  theme_AP()

plot.rf
```



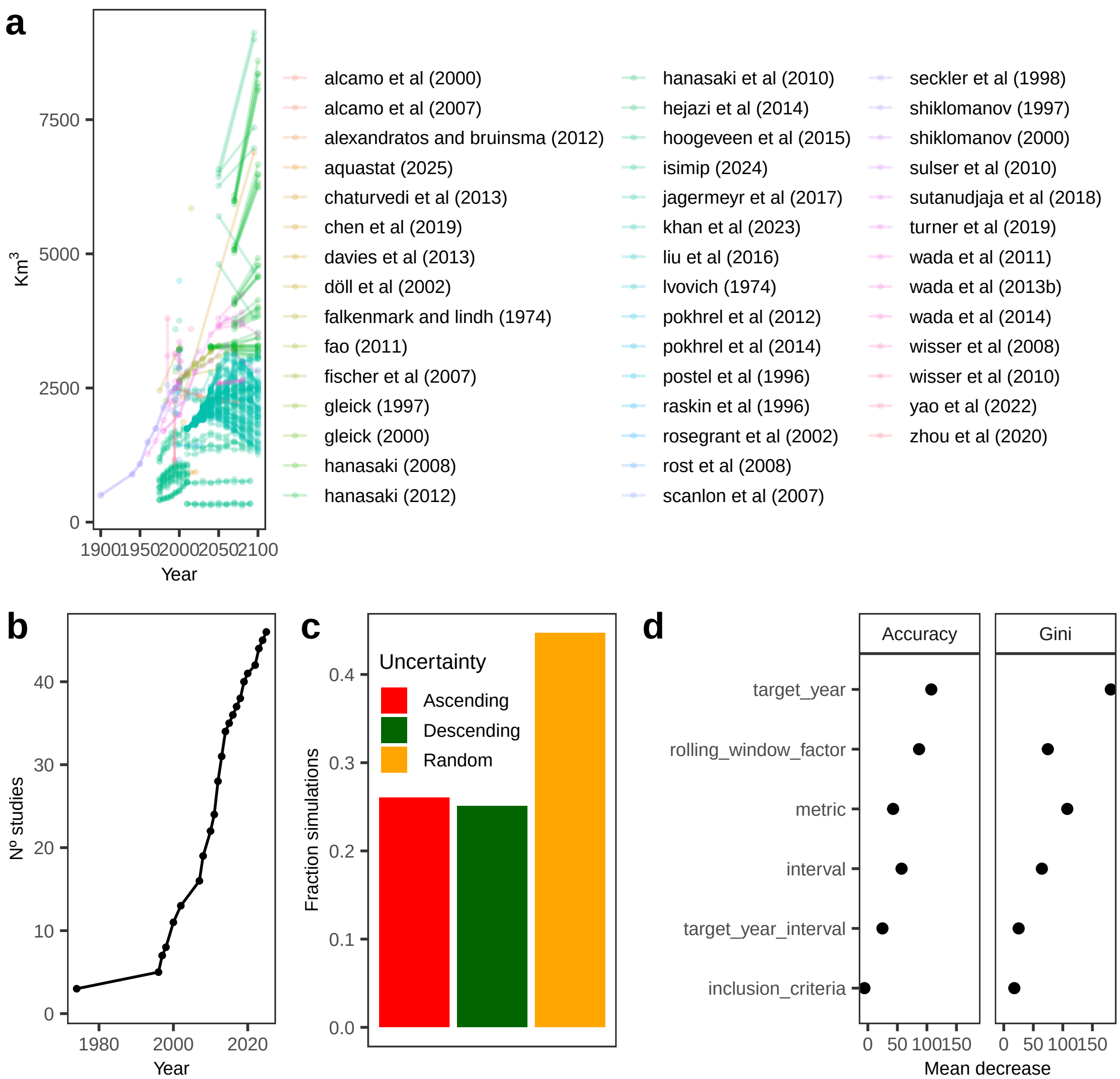

```r
bottom <- plot_grid(cumulative.iww, plot.fraction, plot.rf, ncol = 3, labels = c("b", "c", "d"
          rel_widths = c(0.26, 0.3, 0.44))
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).

## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

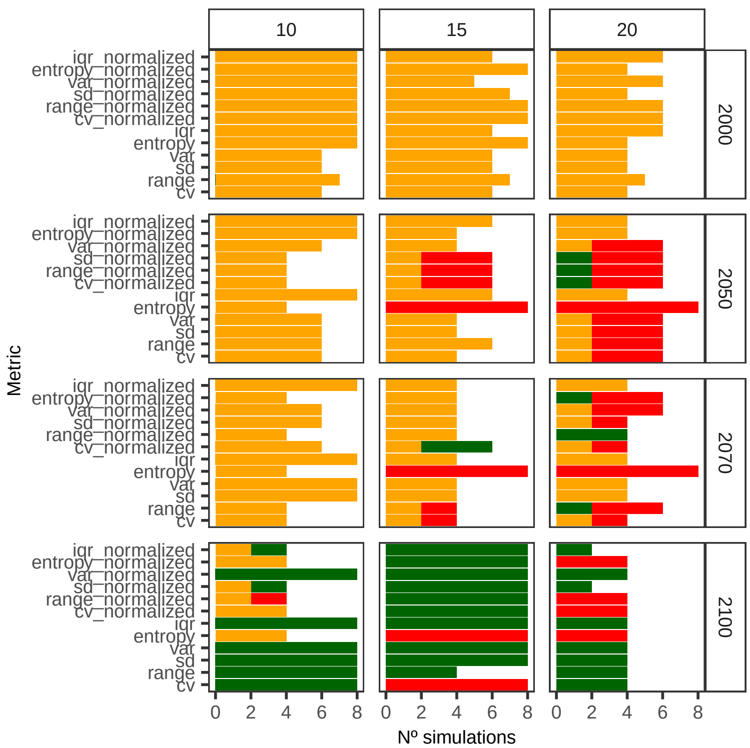
```r
bottom
```




```
#
final.faceted.plot <- plot_grid(plot.iww, bottom, ncol = 1, labels = c("a", ""),
                                rel_heights = c(0.55, 0.45))

final.faceted.plot
```



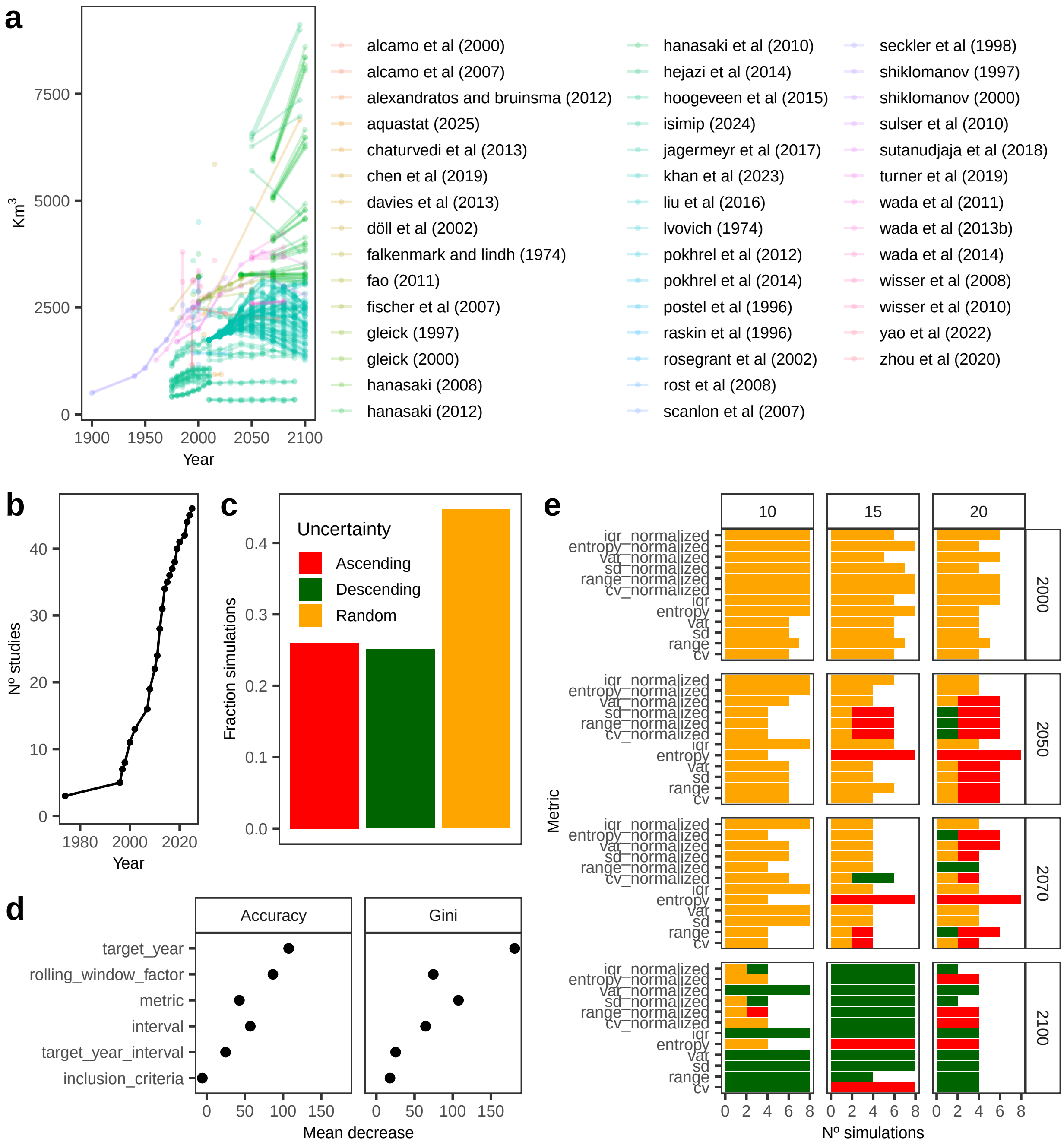
```
# RESULTS FACETED BY INTERVAL AND TARGET YEAR, X AXIS METRICS ##################

plot.faceted.metrics <- final.dt %>%
  ggplot(., aes(x = factor(metric), fill = trend)) +
  geom_bar(position ="identity") +
  facet_grid(target_year ~ interval, scales = "free_y") +
  scale_fill_manual(values = selected_colors, name = "Uncertainty") +
  theme_AP() +
  labs(x = "Metric", y = "Nº simulations") +
  theme(legend.position = "none") +
  coord_flip()

plot.faceted.metrics
```




```
bottom <- plot_grid(cumulative.iww, plot.fraction, ncol = 2, rel_widths = c(0.4, 0.6),
                    labels = c("b", "c"))
```

```
## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_line()`).

## Warning: Removed 1 row containing missing values or values outside the scale range
## (`geom_point()`).
```

```
left <- plot_grid(bottom, plot.rf, ncol = 1, labels = c("", "d"), rel_heights = c(0.6, 0.4))
bottom2 <- plot_grid(left, plot.faceted.metrics, ncol = 2, labels = c("", "e"))
plot_grid(plot.iww, bottom2, rel_heights = c(0.42, 0.58), ncol = 1, labels = c("a", ""))
```


a
b
c
d
e
Km^3
Year
alcamo et al (2000)
alcamo et al (2007)
alexandratos and bruinsma (2012)
aquastat (2025)
chaturvedi et al (2013)
chen et al (2019)
davies et al (2013)
döll et al (2002)
falkenmark and lindh (1974)
fao (2011)
fischer et al (2007)
gleick (1997)
gleick (2000)
hanasaki (2008)
hanasaki (2012)
hanasaki et al (2010)
hejazi et al (2014)
hoogeveen et al (2015)
isimip (2024)
jagermeyr et al (2017)
khan et al (2023)
liu et al (2016)
lvovich (1974)
pokhrel et al (2012)
pokhrel et al (2014)
postel et al (1996)
raskin et al (1996)
rosegrant et al (2002)
rost et al (2008)
scanlon et al (2007)
seckler et al (1998)
shiklomanov (1997)
shiklomanov (2000)
sulser et al (2010)
sutanudjaja et al (2018)
turner et al (2019)
wada et al (2011)
wada et al (2013b)
wada et al (2014)
wisser et al (2008)
wisser et al (2010)
yao et al (2022)
zhou et al (2020)
Nº studies
Fraction simulations
Uncertainty
Ascending
Descending
Random
Accuracy
Gini
target_year
rolling_window_factor
metric
interval
target_year_interval
inclusion_criteria
Mean decrease
Metric
iqr_normalized
entropy_normalized
var_normalized
sd_normalized
range_normalized
cv_normalized
iqr
entropy
var
sd
range
cv
10
15
20
2000
2050
2070
2100
Nº simulations

5 Session information

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

sessionInfo()
```

```
## R version 4.3.3 (2024-02-29)
## Platform: aarch64-apple-darwin20 (64-bit)
## Running under: macOS Sonoma 14.2.1
##
## 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] microbenchmark_1.5.0 lme4_1.1-35.5        Matrix_1.6-5
##  [4] here_1.0.1           doParallel_1.0.17    iterators_1.0.14
##  [7] foreach_1.5.2        rworldmap_1.3-8      sp_2.1-4
## [10] countrycode_1.6.0    ncdf4_1.23           scales_1.3.0
## [13] wesanderson_0.3.7    benchmarkme_1.0.8    cowplot_1.1.3
## [16] lubridate_1.9.3      forcats_1.0.0        stringr_1.5.1
## [19] dplyr_1.1.4          purrr_1.0.2          readr_2.1.5
## [22] tidyr_1.3.1          tibble_3.2.1         ggplot2_3.5.1
## [25] tidyverse_2.0.0      data.table_1.16.2    openxlsx_4.2.7.1
##
## loaded via a namespace (and not attached):
##  [1] dotCall64_1.2         benchmarkmeData_1.0.4 gtable_0.3.6
##  [4] spam_2.11-0           xfun_0.49             raster_3.6-30
##  [7] lattice_0.22-6        tzdb_0.4.0            Rdpack_2.6.2
## [10] vctrs_0.6.5           tools_4.3.3           generics_0.1.3
## [13] fansi_1.0.6           pkgconfig_2.0.3       lifecycle_1.0.4
## [16] compiler_4.3.3        fields_16.3           munsell_0.5.1
## [19] terra_1.7-78          codetools_0.2-20      htmltools_0.5.8.1
## [22] maps_3.4.2.1          yaml_2.3.10           nloptr_2.1.1
## [25] pillar_1.9.0          MASS_7.3-60.0.1       boot_1.3-31
## [28] nlme_3.1-166          tidyselect_1.2.1      zip_2.3.1
## [31] digest_0.6.37         stringi_1.8.4         splines_4.3.3
## [34] sensobol_1.1.5        rprojroot_2.0.4       fastmap_1.2.0
```

```
## [37] grid_4.3.3          colorspace_2.1-1     cli_3.6.3
## [40] magrittr_2.0.3      utf8_1.2.4           withr_3.0.2
## [43] timechange_0.3.0    rmarkdown_2.29       httr_1.4.7
## [46] hms_1.1.3           evaluate_1.0.1       knitr_1.49
## [49] rbibutils_2.3       viridisLite_0.4.2    rlang_1.1.4
## [52] Rcpp_1.0.13-1       glue_1.8.0           minqa_1.2.8
## [55] rstudioapi_0.17.1   R6_2.5.1
```

```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
```