exNGT: an overview of various correlation and other analyses

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Introduction

This document summarises various analyses of the NGT firn core stack:

- comparison of the NGT stack with other temperature data sets from the Arctic2k compilation and weather station measurements;
- comparison of individual NGT firn cores with the Arctic2k data set;
- comparison of the mean temperature anomalies derived from the NGT stack between the recent 15 year period and the reference period 1961-1990 as well as the entire 20th century.

Prepare data

Load relevant source files and packages:

```
source("init.R")
```

Set the running mean filter window size (yr) and the isotope–temperature slope (K/‰):

```
filter.window <- 11
permil2temperature <- 1 / 0.67
```

Load the NGT data, filter it and calculate the isotope stack:

```
stackedNGT <- processNGT() %>%
  stackNGT()

filteredStackedNGT <- processNGT() %>%
  filterData(window = filter.window) %>%
  stackNGT()
```

Load the Arctic2k, weather station, MAR and GBI data and filter it:

```
Arctic2k <- readArctic2k() %>%
  extendWithHadCrut() %>%
  dplyr::select("Year", "TempAnomaly")

filteredExtendedArctic2k <- Arctic2k %>%
  filterData(window = filter.window)

filteredArctic2k <- readArctic2k() %>%
  filterData(window = filter.window)

filteredDMI <- readDMI() %>%
  makeAnomalies() %>%
  filterData(window = filter.window)
```

```
filteredMAR <- readMAR() %>%
  filterData(window = filter.window)

filteredGBI <- readGBI() %>%
  filterData(window = filter.window)
```

Convert the NGT stack data to temperature:

```
stackedTemperatureNGT <- stackedNGT %>%
  dplyr::mutate(stack = permil2temperature * stack)

filteredStackedTemperatureNGT <- filteredStackedNGT %>%
  dplyr::mutate(stack = permil2temperature * stack)
```

Comparison of NGT-2012 temperature stack with Arctic2k

- Overall correlation between NGT-2012 temperature stack and Arctic2k compilation from 1000 CE onwards with and without including HadCrut extension:

```
analysis.period <- 2011 : 1000
res <- estimateCorrelation(stackedTemperatureNGT,
                           filteredStackedTemperatureNGT, filteredExtendedArctic2k,
                           filter.window = filter.window,
                           analysis.period = analysis.period,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.4f)", res$r, res$p)
#> [1] "r = 0.66 (p = 0.0000)"

analysis.period <- 2000 : 1000
res <- estimateCorrelation(stackedTemperatureNGT,
                           filteredStackedTemperatureNGT, filteredArctic2k,
                           filter.window = filter.window,
                           analysis.period = analysis.period,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.4f)", res$r, res$p)
#> [1] "r = 0.58 (p = 0.0000)"
```

- Correlation between NGT temperature stack and Arctic2k compilation for the 20th century and for the 20th century including up to 2011 CE:

```
analysis.period <- 2000 : 1901
res <- estimateCorrelation(stackedTemperatureNGT,
                           filteredStackedTemperatureNGT, filteredArctic2k,
                           filter.window = filter.window,
                           analysis.period = analysis.period,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.29 (p = 0.158)"

analysis.period <- 2011 : 1901
res <- estimateCorrelation(stackedTemperatureNGT,
                           filteredStackedTemperatureNGT, filteredExtendedArctic2k,
                           filter.window = filter.window,
                           analysis.period = analysis.period,
```

```
                              nmc = 10000)
sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.68 (p = 0.006)"
```

- Linear trends (in degree Celsius / 100 years) of Arctic2k and NGT-2012 stack over pre-industrial and industrial era:

```
t1 <- 1800 : 1000
t2 <- 2011 : 1800

regressionData <- list(
  data.frame(x = t1, y = subsetData(stackedTemperatureNGT, t1, "stack")),
  data.frame(x = t2, y = subsetData(stackedTemperatureNGT, t2, "stack")),
  data.frame(x = t1, y = subsetData(Arctic2k, t1, "TempAnomaly")),
  data.frame(x = t2, y = subsetData(Arctic2k, t2, "TempAnomaly"))
)

regressionSlopes <- regressionData %>%
  sapply(function(df) {unname(coef(summary(lm(y ~ x, df)))[2, 1 : 2])})
```

```
# NGT 1000-1800 CE:
(regressionSlopes[1, 1] * 100) %>% round(digits = 2)
#> [1] -0.06
# +/-
(regressionSlopes[2, 1] * 100) %>% round(digits = 2)
#> [1] 0.01

# Arctic2k 1000-1800 CE:
(regressionSlopes[1, 3] * 100) %>% round(digits = 2)
#> [1] -0.12
# +/-
(regressionSlopes[2, 3] * 100) %>% round(digits = 2)
#> [1] 0.01

# NGT 1800-2011 CE:
(regressionSlopes[1, 2] * 100) %>% round(digits = 2)
#> [1] 0.73
# +/-
(regressionSlopes[2, 2] * 100) %>% round(digits = 2)
#> [1] 0.11

# Arctic2k 1800-2011 CE:
(regressionSlopes[1, 4] * 100) %>% round(digits = 2)
#> [1] 1.11
# +/-
(regressionSlopes[2, 4] * 100) %>% round(digits = 2)
#> [1] 0.06
```

Comparison of individual NGT firn core records with Arctic2k

We here use those NGT records which are also part of the Arctic2k compilation to assess the extent to which these records contribute to the overall Arctic2k temperature reconstruction. These firn cores are GRIP, GISP2, NGRIP, B16, B18 and B21 and we use the merged versions when redrilled cores are available.

```
mergedFilteredNGT <- processNGT() %>%
  filterData(window = filter.window) %>%
  stackNGT(stack = FALSE)

t <- 2000 : 1000
a2k <- subsetData(filteredArctic2k, t, "TempAnomaly")
grip <- subsetData(mergedFilteredNGT, t, "GRIP")
gisp2 <- subsetData(mergedFilteredNGT, t, "GISP2")
ngrip <- subsetData(mergedFilteredNGT, t, "NGRIP")
b16 <- subsetData(mergedFilteredNGT, t, "B16")
b18 <- subsetData(mergedFilteredNGT, t, "B18")
b21 <- subsetData(mergedFilteredNGT, t, "B21")
```

```
cor(grip, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0

cor(gisp2, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0.29

cor(ngrip, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0.19

cor(b16, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0.39

cor(b18, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0.37

cor(b21, a2k, use = "pairwise") %>%
  round(digits = 2)
#> [1] 0.49
```

Comparison of NGT isotope stack with DMI temperature data

We calculate the correlations of the NGT isotope stack with the temperature data from three coastal Greenland weather stations for the time period 1901–2011.

```
pituffik <- dplyr::select(filteredDMI, "Year", "Pituffik")
upernavik <- dplyr::select(filteredDMI, "Year", "Upernavik")
danmarkshavn <- dplyr::select(filteredDMI, "Year", "Danmarkshavn")
```

- Correlation of NGT isotope stack and Pituffik weather station temperature:

```
res <- estimateCorrelation(stackedNGT, filteredStackedNGT, pituffik,
                           filter.window = filter.window,
                           analysis.period = 2011 : 1901,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.87 (p = 0.002)"
```

- Correlation of NGT isotope stack and Upernavik weather station temperature:

```
res <- estimateCorrelation(stackedNGT, filteredStackedNGT, upernavik,
                           filter.window = filter.window,
                           analysis.period = 2011 : 1901,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.76 (p = 0.001)"
```

- Correlation of NGT isotope stack and Danmarkshavn weather station temperature:

```
res <- estimateCorrelation(stackedNGT, filteredStackedNGT, danmarkshavn,
                           filter.window = filter.window,
                           analysis.period = 2011 : 1901,
                           nmc = 10000)
sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.86 (p = 0.003)"
```

Comparison of NGT-2012 isotope stack with MAR3.5 and GBI data

We calculate the correlation of the NGT isotope stack with data from the regional climate model MAR version 3.5; specifically, with the annual 2m surface air temperature extracted and averaged over the NGT-2012 firn core locations, and with the Greenland-wide melt runoff rate, using 11-yr running mean time series over the common period from 1871 to 2011 CE in both cases. We also analyse how much weaker the correlation is for annual mean data.

- Correlation with MAR temperature:

```
  # filtered data
  res <- estimateCorrelation(stackedNGT, filteredStackedNGT,
                             filteredMAR[, c("Year", "t2m")],
                             filter.window = filter.window,
                             analysis.period = 2011 : 1871,
                             nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.77 (p = 0.000)"

  # annual data
  mar <- readMAR()
  res <- estimateCorrelation(stackedNGT, stackedNGT,
                             mar[, c("Year", "t2m")], filter.window = 1,
                             analysis.period = 2011 : 1871, nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.39 (p = 0.001)"
```

- Correlation with MAR melt runoff:

```
  # filtered data
  res <- estimateCorrelation(stackedNGT, filteredStackedNGT,
                             filteredMAR[, c("Year", "melt")],
                             filter.window = filter.window,
                             analysis.period = 2011 : 1871,
                             nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.63 (p = 0.003)"
```

```
  # annual data
  res <- estimateCorrelation(stackedNGT, stackedNGT,
                             mar[, c("Year", "melt")], filter.window = 1,
                             analysis.period = 2011 : 1871, nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.41 (p = 0.000)"
```

Additionally, we correlate both the NGT isotope data and the MAR melt runoff rate with the Greenland Blocking Index (GBI), where we compare the correlation for melt runoff between annual mean GBI and summer GBI values.

- Correlation between NGT and annual mean GBI:

```
  # filtered data
  res <- estimateCorrelation(stackedNGT, filteredStackedNGT,
                             filteredGBI[, c("Year", "annual")],
                             filter.window = filter.window,
                             analysis.period = 2011 : 1851,
                             nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.63 (p = 0.002)"

  # annual data
  gbi <- readGBI()
  res <- estimateCorrelation(stackedNGT, stackedNGT,
                             gbi[, c("Year", "annual")], filter.window = 1,
                             analysis.period = 2011 : 1851, nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.38 (p = 0.001)"
```

- Correlation between MAR melt runoff and annual mean GBI:

```
  # filtered data
  res <- estimateCorrelation(mar[, c("Year", "melt")],
                             filteredMAR[, c("Year", "melt")],
                             filteredGBI[, c("Year", "annual")],
                             filter.window = filter.window,
                             analysis.period = 2011 : 1871,
                             nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.80 (p = 0.000)"

  # annual data
  res <- estimateCorrelation(mar[, c("Year", "melt")], mar[, c("Year", "melt")],
                             gbi[, c("Year", "annual")], filter.window = 1,
                             analysis.period = 2011 : 1871, nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.56 (p = 0.000)"
```

- Correlation between MAR melt runoff and summer GBI:

```
  # filtered data
  res <- estimateCorrelation(mar[, c("Year", "melt")],
                             filteredMAR[, c("Year", "melt")],
                             filteredGBI[, c("Year", "summer")],
```

```
                              filter.window = filter.window,
                              analysis.period = 2011 : 1871,
                              nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.91 (p = 0.000)"

  # annual data
  res <- estimateCorrelation(mar[, c("Year", "melt")], mar[, c("Year", "melt")],
                              gbi[, c("Year", "summer")], filter.window = 1,
                              analysis.period = 2011 : 1871, nmc = 10000)
  sprintf("r = %1.2f (p = %1.3f)", res$r, res$p)
#> [1] "r = 0.67 (p = 0.000)"
```

Temperature increase of recent 11 years relative to past

We compare the mean temperature over the recent 11 years of the NGT stack with the mean value of the 1961-1990 period and the mean value of the 20th century (1901–2000), including an estimation of the standard error of the difference. We do this assuming the standard spatial isotope–temperature calibration slope for Greenland as well as assuming stronger and weaker values from the temporal slopes derived by Vinther et al. (2009) and Masson-Delmotte et al. (2015).

Set the alternative isotope–temperature calibration slopes:

```
permil2temperature.max <- 2.1     # Vinther et al. (2009)
permil2temperature.min <- 1 / 1.1 # Masson-Delmotte et al. (2015)
```

- Recent 11 years versus 1961-1990 reference period:

```
t1 <- 2011 : 2001
t2 <- 1990 : 1961

recentPeriod <- stackedNGT %>%
  subsetData(t1, var = "stack") %>%
  dplyr::tibble() %>%
  setNames("d18O") %>%
  dplyr::summarise(mean1 = mean(d18O), se1 = sdError(d18O))
referencePeriod <- stackedNGT %>%
  subsetData(t2, var = "stack") %>%
  dplyr::tibble() %>%
  setNames("d18O") %>%
  dplyr::summarise(mean2 = mean(d18O), se2 = sdError(d18O))

difference <- cbind(recentPeriod, referencePeriod)

# mean difference and s.e. for spatial slope
(difference * permil2temperature) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
  round(digits = 1)
#>   deltaT  se
#> 1    1.9 0.5

# mean difference and s.e. for minimum slope
(difference * permil2temperature.min) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
```

```
  round(digits = 1)
#>   deltaT  se
#> 1    1.1 0.3

# mean difference and s.e. for maximum slope
(difference * permil2temperature.max) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
  round(digits = 1)
#>   deltaT  se
#> 1    2.6 0.7
```

- Recent 11 years versus 20th century (1901-2000):

```
t2 <- 2000 : 1901

referencePeriod <- stackedNGT %>%
  subsetData(t2, var = "stack") %>%
  dplyr::tibble() %>%
  setNames("d18O") %>%
  dplyr::summarise(mean2 = mean(d18O), se2 = sdError(d18O))

difference <- cbind(recentPeriod, referencePeriod)

# mean difference and s.e. for spatial slope
(difference * permil2temperature) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
  round(digits = 1)
#>   deltaT  se
#> 1    1.7 0.5

# mean difference and s.e. for minimum slope
(difference * permil2temperature.min) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
  round(digits = 1)
#>   deltaT  se
#> 1      1 0.3

# mean difference and s.e. for maximum slope
(difference * permil2temperature.max) %>%
  dplyr::transmute(deltaT = mean1 - mean2, se = sqrt(se1^2 + se2^2)) %>%
  round(digits = 1)
#>   deltaT  se
#> 1    2.4 0.7
```

References

Masson-Delmotte, V., Steen-Larsen, H. C., Ortega, P., Swingedouw, D., Popp, T., Vinther, B. M., Oerter, H., Sveinbjornsdottir, A. E., Gudlaugsdottir, H., Box, J. E., Falourd, S., Fettweis, X., Gallée, H., Garnier, E., Gkinis, V., Jouzel, J., Landais, A., Minster, B., Paradis, N., Orsi, A., Risi, C., Werner, M. and White, J. W. C., Recent changes in north-west Greenland climate documented by NEEM shallow ice core data and simulations, and implications for past-temperature reconstructions, The Cryosphere, 9(4), 1481–1504, https://doi.org/10.5194/tc-9-1481-2015, 2015.

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R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P. and Svensson, A. M., Holocene thinning of the Greenland ice sheet, Nature, 461(7262), 385–388, https://doi.org/10.1038/nature08355, 2009.