The Effects of Improper Standardization on Modeling Trends in Surface Temperature

Abstract

As the concern surrounding impacts of climate change grows, retrospective analysis of trends in surface temperatures gain importance. Mann, Bradley and Hughes' (1998) highly cited 'hockey stick-shaped' graph showed a drastic increase in surface temperatures post-industrial revolution. We simulated MBH98's technique using the last 40, 79, and 140 years and were able to show false patterns of temperature increases (a hockey stick shape) in random (red noise) time series data. Though not an evidence for the absence of global warming, we hope these findings highlight the importance of proper statistical analyses on sensitive subjects, such as climate change, to avoid the spread of misinformation through platforms like the IPCC.

Introduction

Global warming is defined by a rapid increase in Earth's average temperature, and it is one of the greatest threats to communities and wildlife and has been a major factor in climate change (NASA 2010). Global warming is somewhat natural and has been happening over the centuries, but in recent decades, the accelerating warming of surface temperatures has been attributed to anthropogenic activities, starting from the industrial revolution (Santer et al 1996). To reconstruct surface temperatures of the Northern Hemisphere between 1400 and 1981, Mann, Bradley, and Hughes (MBH98) used proxies such as tree rings, ice cores, and coral skeletons and then conducted principal component analysis (PCA) in their highly credited study. Principal components reduce the dimensionality of large variables into simpler components that are still able to explain the variability in the dataset. Proxies are indirect measures of a variable that is usually difficult to measure directly (in this case, surface temperature). MBH98's analysis produced a graph that showed surface temperatures rapidly increasing after the industrial revolution in the 1900s, resembling a hockey stick shape (Figure 1). MBH98's results were globally accepted as evidence of 20th-century global warming and were even featured in the IPCC's Third Assessment Report, and they were even mentioned on Al Gore's famous climate change documentary 'The Inconvenient Truth'; however, MBH98's method of truncating data was flawed, as first proven by McIntyre and McKitrick in 2003 (MM). The mean of only the last 79 years was used instead of 581, creating a graph that shows a sudden increase in surface temperatures post-industrial revolution (a 'hockey stick' graph), conveniently proving MBH98's claims. In replicating the study with proper standardization, MM found that the tendency of the data to create a hockey stick-shaped graph was much less than was claimed by MBH98. Although MM's correct analysis showed global warming in the last century was not as drastic as found previously, the study did not seek to disprove global warming or climate change but to highlight a flawed methodology in a widely emphasized and accepted study.

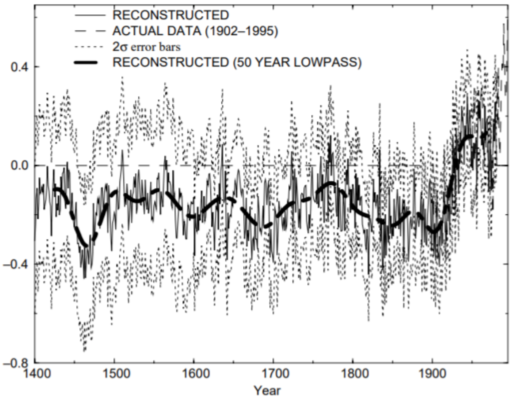

Figure 1. The hockey stick-shaped graph of surface temperature between 1400-1981 from Mann, Bradley and Hughes (1998).

The primary aim of this paper is to replicate McIntyre and McKitrick's 2003 study and analyze the tendency of producing hockey stick shaped graphs when using proper and improper standardization (Figure 2a). Extending beyond MM's study, we seek to explore whether altering the range of years used (40, 79,140) for standardization would impact the tendency of producing hockey stick graphs. We hypothesize that with improper standardization, the likelihood of observing hockey stick graphs will increase as a smaller range of years is used. Proper standardization should produce no such graphs, regardless of the range used (Figure 2b), following MM (2003). Improving retrospective temperature reconstruction techniques allows climate scientists and policy-makers to gain a better insight into the intensity of anthropogenic global warming.

Figure 2(a)

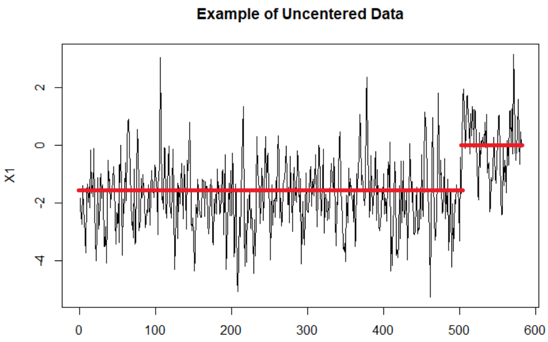

Figure 2(b)

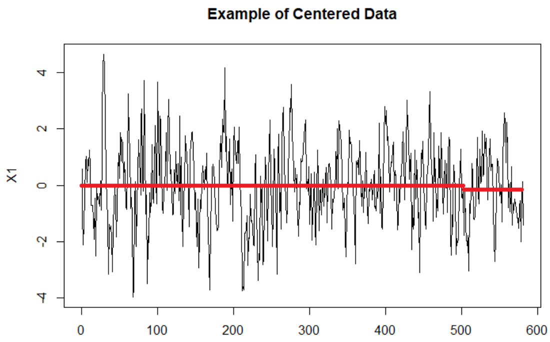

Figure 2 (a). Expected graph if truncated means were used in standardization, **(b)** expected graph with proper standardization using overall means.

Methodology

In this project, we ran a principal component analysis (PCA) simulation, aiming to analyze the likelihood of producing hockey-stick shaped graphs. Following MM, we generated a matrix of 70 series of random/red noise data (columns), with 581 years from 1400 to 1981 (rows). The 70 sets of random red noise data were created using an Autoregressive time series model (Equation 1).

$$x_{i,j} = \beta x_{i,j-1} + \varepsilon_{i,j}$$

Equation 1. A generalized autoregressive time series model equation.

For simplicity, we kept the slope($\boldsymbol{\beta}$) and the standard deviation constant for all the 70 series. The slope ($\boldsymbol{\beta}$) and the standard deviation of the random errors ($\boldsymbol{\varepsilon}$) used in this analysis are the average of the values used by MM(2003) for each of the 70 series and are closely based on MBH98's original data. ($\boldsymbol{\beta}$ = 0.415 ; $\boldsymbol{\varepsilon}$= 0.276) We standardized each series to achieve a mean of 0 and a standard deviation of 1 (Equation 2):

$$Z_1 = \frac{x - \text{series mean}}{\text{series sd}}$$

Equation 2. Method for standardizing each observed value x into a standardized value z.

Similar to MBH98's standardization with truncated means, we standardized using means for the last 79 years, 40 years, and 140 years ('uncentered' data). For each of the series at random, we constructed the principal components, which represent linear combinations of the 70 proxy variables, and ran 10,000 simulations using R programming software. We created a counter which compared the means of the last 40, 79, and 140 years of data to the overall mean, therefore detecting the number of hockey stick shapes. If the absolute value of the difference in means is greater than 1 standard deviation of the data, the graph was considered to have a hockey stick shape. For |*difference*| << *SD,* we consider the graph to be relatively horizontal, similar to Figure 2b.

Results and Discussion

For our centered data using overall means, we observed 0/10000 hockey stick shaped graphs. For our uncentered data, we observed 0/10000 hockey stick shaped graphs when standardizing based on the means of 140 years, 7146/10000 (71±1%) hockey stick shaped graphs when standardizing based on the means of 79 years, and 9998/10000 ($\approx$100%) hockey stick shaped graphs when standardizing based on the means of 40 years (Figure 3). These results produce convincing evidence that reducing the number of years used when improperly standardizing increases the likelihood of observing hockey stick graphs. We expected to get no hockey stick shaped graphs for our properly standardized, centered data. In terms of our uncentered data, we expected the percentage of hockey stick shaped graphs to increase as we decreased the number of years used when standardizing the data; however, our results slightly surprised us, particularly when using 140 years, as we had expected to observe more than 0 hockey stick shaped graphs. The reason we observed none is likely due to our high threshold value in determining whether a graph had the hockey stick shape.

Had we lowered the threshold to one or two standard errors, we would have most likely observed more hockey stick graphs when standardizing using 140 years, as it would increase the sensitivity of the analysis. While using a higher threshold was a limitation of our study, further research could be done using a more sensitive analysis. Another interesting extension could be to graph the percentage change in observed hockey stick graphs per additional year used to standardize the data which would allow to further explore how the range of truncated means affects the number of hockey stick graphs observed. These findings highlight the effects of improperly standardizing data when detecting differences using principal component analysis and also reinforces McIntyre and McKitrick's (2003) findings.

Since its publication in 1998, the ‘hockey stick graph’ has been adopted by many climate scientists, policymakers, and even the IPCC as proof of climate change, and it played a crucial role in the 2005 Kyoto Protocol. The key findings from this study do not disprove global warming or climate change and do not claim that climate change is a narrative climatologists like Mann, Bradley and Hughes use to ‘sell fear to the public’. This study only proves that the standardization in Mann, Bradley and Hughes’ (1998) principal components analysis was flawed. In fact, since the refutation of MBH98, many further studies with more robust methods, expanded proxy data, and better model simulations have been published and were successful in constructing a ‘hockey stick shape’ (Mann et al 2008).

Similar to many other studies, we hope that this paper highlights the importance of robust and sensitive methodology, especially in topic areas as significant as climate change. Bias, especially unconscious, is incredibly easy to introduce when using statistical methods. The impact of bias in statistical analysis, as we can see from MBH98, can be substantial, and proper statistical analyses must be done to avoid any misleading conclusions.

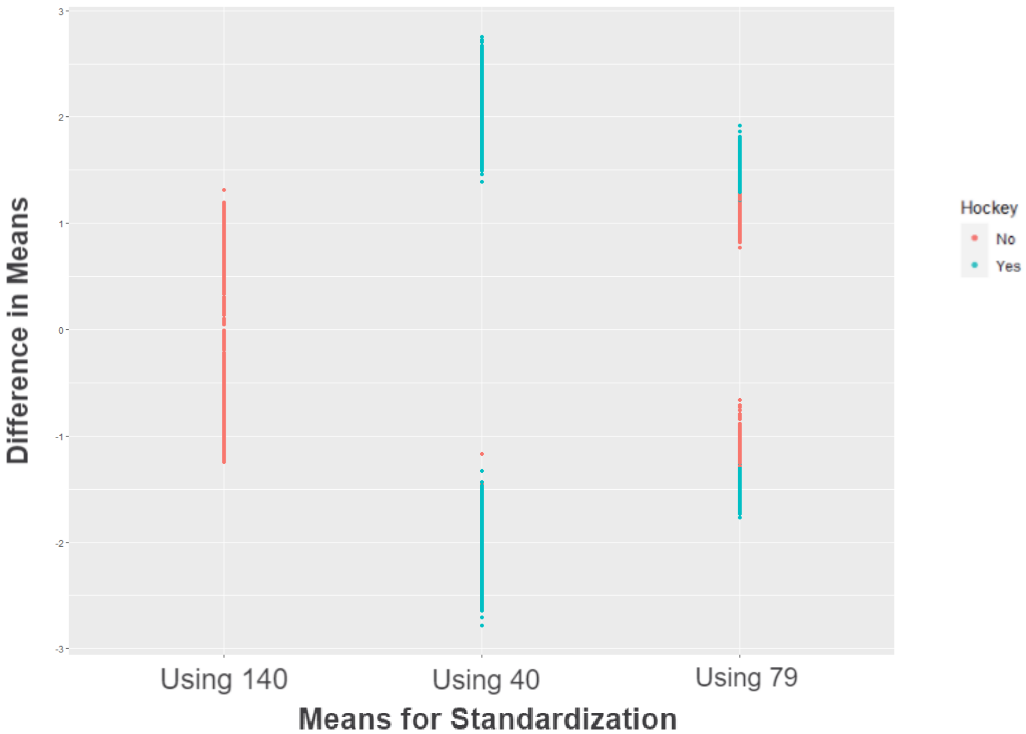

Figure 3. Range of years used to standardize (Standardization Type) versus difference in means graph for 10000 simulations. Points with difference above 1SD produce hockey stick shape graphs, accordingly colored.

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Appendix I

CODE

Define the number of simulations to run.
```
reps <- 10000
```

Centered method

Create a matrix of 0, with 581 rows, and number of columns = number of simulations.
```
centered = matrix(0, nrow =581, ncol= reps)
```
Define a function for generating red noise data and applying PCA to centered data
```
MBHsimm <- function(){
  for (i in 1:reps) {
    X = matrix(0,nrow=581, ncol = 70)
    X[1,] = rnorm(n=70,mean=0,sd=0.276)
    for(k in 2:581) {X[k,] = 0.415*X[k-1,] + rnorm(n=70, mean=0, sd=0.276)}
    X <- data.frame(X)
    c <- apply(X,2,mean)
    s <- apply(X,2,sd)
    centered[,i] = prcomp(X, center = c, scale = s)$x[,1]
  }
  return(data.frame(centered))
}
```
Use the defined function to create a PCA dataframe.
```
centered = MBHsimm()
```
Optional - plot the dataframe as a time-series. This function will only work if reps <= 10.
```
plot.ts(centered)
```

Uncentered method

Create a matrix of 0 with 581 rows, and number of columns = number of simulations.

uncentered = matrix(0,nrow=581,ncol=reps)

Define another function for generating red noise data & applying PCA to uncentered data.
```
MBHsimm2 <- function(){
  for (i in 1:reps) {
    X = matrix(0,nrow=581,ncol=70)
    X[1,] = rnorm(n=70, mean=0, sd=0.276)
    for (k in 2:581) {X[k,] = 0.415 * X[k-1,] + rnorm(n=70,mean=0,sd=0.276)}
    X = data.frame(X)
    filter_x_79 <- X[503:581,]  # Standardized based on last 79. Change range
for other conds.
    c1 <- apply(filter_x_79,2,mean)
    s1 <- apply(filter_x_79,2,sd)
    uncentered[,i] = prcomp(X, center = c1, scale = s1)$x[,1]
  }
  return (data.frame(uncentered))
}
```
Use the second defined function to create a PCA dataframe.
```
uncentered = MBHsimm2()
```
Optional - plot the data frame as a time-series. This function will only work if reps <= 10.
```
plot.ts(uncentered)
```

Counter implementations

This function counts the number of hockey stick shapes in our uncentered dataframe.
```
counthockey <- function() {
```

```
  count <- 0
  for (i in 1:reps) {
    last79 <- uncentered[,i][503:581] # Based on last 79. Change range for
other conds.
    overallmean <- mean(uncentered[,i])
    hockeymean <- mean(last79)
    if ((abs(hockeymean - overallmean)) > (sd(uncentered[,i]))) {
      count <- count + 1
    }
  }
  return(count)
}
```

This function counts the number of hockey stick shapes in our centered dataframe.

```
countcentered <- function() {
  count <- 0
  for (i in 1:reps) {
    last79 <- centered[,i][503:581]
    overallmean <- mean(centered[,i])
    hockeymean <- mean(last79)
    if ((abs(hockeymean - overallmean)) > (sd(centered[,i]))) {
      count <- count + 1
    }
  }
  return(count)
}
```

Difference in means plot

Initialize vectors to hold difference in means and hockey stick indicator value

```
diffs40 <- c()
diffs79 <- c()
diffs140 <- c()

hockey40 <- c()
hockey79 <- c()
hockey140 <- c()
```

Loops to create graph variables. Must run MBHsimm2 with proper indices specified before running a corresponding block:

When standardizing based on last 40

```
  for (i in 1: reps) {
    last40 <- uncentered[,i][542:581]
    overallmean <- mean(uncentered[,i])
    hockeymean40 <- mean(last40)
    diffs40[i] <- hockeymean40 - overallmean
    hockey40[i] <- ifelse(((abs(diffs40[i])) > (sd(uncentered[,i]))), "Yes",
"No")
  }
```

When standardizing based on last 79

```
for (i in 1: reps) {
  last79 <- uncentered[,i][503:581]
  overallmean <- mean(uncentered[,i])
  hockeymean79 <- mean(last79)
  diffs79[i] <- hockeymean79 - overallmean
  hockey79[i] <- ifelse(((abs(diffs79[i])) > (sd(uncentered[,i]))), "Yes",
"No")
}
```

```
# When standardizing based on last 140
for (i in 1: reps) {
  last140 <- uncentered[,i][442:581]
  overallmean <- mean(uncentered[,i])
  hockeymean140 <- mean(last140)
  diffs140[i] <- hockeymean140 - overallmean
  hockey140[i] <- ifelse(((abs(diffs140[i])) > (sd(uncentered[,i]))), “Yes”,
“No”)
}

# Load necessary libraries for following function calls
library(dplyr)
library(ggplot2)

# Creates a data frame with the difference in mean, standardization type, and hockey stick
shape (boolean)
uncentFrame <- data.frame(diffs40, hockey40)
uncentFrame <- mutate(uncentFrame, StandardizationType = "Using 40")
names(uncentFrame)[1] <- "Difference"
names(uncentFrame)[2] <- "Hockey"

uncent79 <- data.frame(diffs79, hockey79)
uncent79 <- mutate(uncent79, StandardizationType = "Using 79")
names(uncent79)[1] <- "Difference"
names(uncent79)[2] <- "Hockey"


uncent140 <- data.frame(diffs140, hockey140)
uncent140 <- mutate(uncent140, StandardizationType = "Using 140")
names(uncent140)[1] <- "Difference"
names(uncent140)[2] <- "Hockey"

uncentFrame <- rbind(uncentFrame, uncent79, uncent140)

# Plots the full data frame
ggplot(uncentFrame, aes(x = StandardizationType, y = Difference, color =
Hockey)) + geom_point()
```