# Draft - Night warming treatments

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Historical temperatures recorded every 15 minutes from 1998 to 2020 were downloaded from the Data Archives webpage (http://weather.uwaterloo.ca/data.html) maintained by the University of Waterloo Weather Station (43°28'27.5"N 80°33'24.4"W), Ontario, Canada. Date and temperature formatting was standardized and data cleaning was performed to remove any incorrect entries caused by technical errors (such as unrealistic temperature entries of 100 °C) using R Studio software. This dataset was then subset to the period of June 1-10, which represents late Spring in temperate regions. This period has been chosen because it occurs in the growing season, where any effects to performance can be more readily observed. In addition, other night warming experiments were conducted using this same timeframe (e.g., Zhao et al., 2014; Barton & Schmitz, 2017; Higashi, Barton, & Oliver, 2020). To simulate night warming treatments, the clean file saved on GitHub was then downloaded to R.

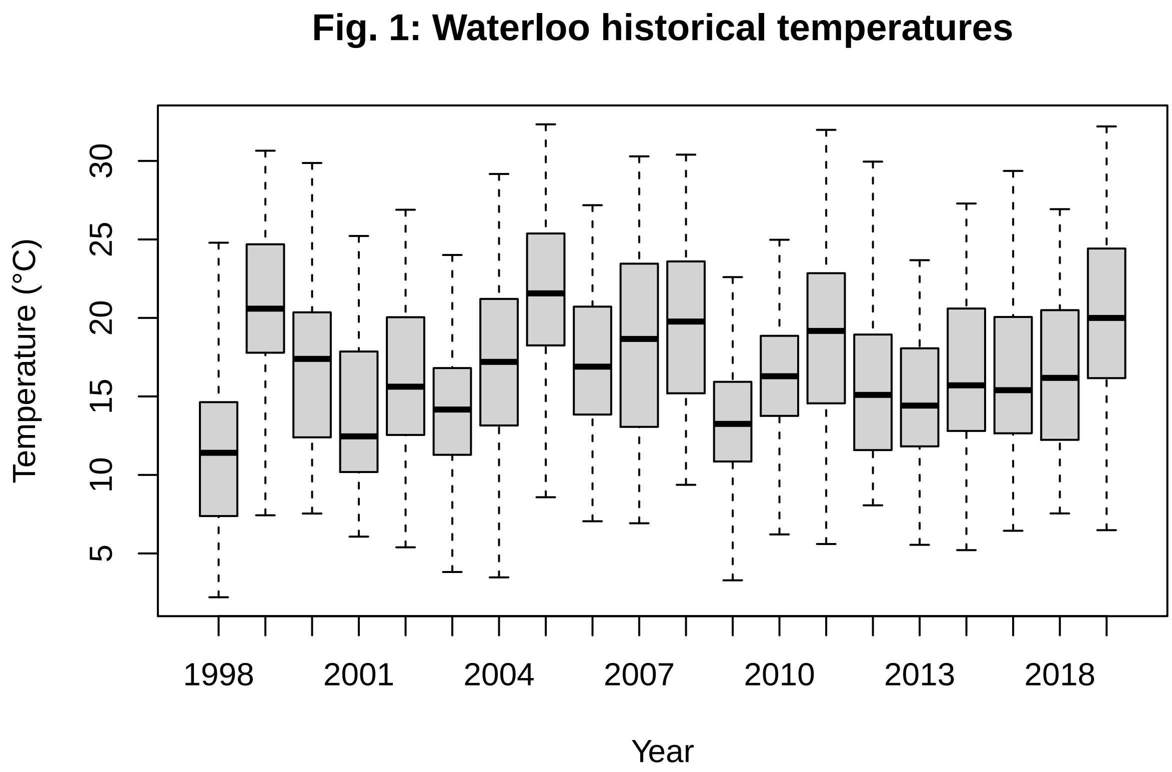
```
refjune <- read.csv("https://raw.githubusercontent.com/Cuddington-Lab/thermal-experiments/main/historica

head(refjune)
```

```
##       Date    Time Temperature      DateTime month year hour day
## 1 6/1/1998 0:00:00       6.823 6/1/1998 0:00     6 1998    0   1
## 2 6/1/1998 0:15:00       6.547 6/1/1998 0:15     6 1998    0   1
## 3 6/1/1998 0:30:00       6.213 6/1/1998 0:30     6 1998    0   1
## 4 6/1/1998 0:45:00       5.994 6/1/1998 0:45     6 1998    0   1
## 5 6/1/1998 1:00:00       5.803 6/1/1998 1:00     6 1998    1   1
## 6 6/1/1998 1:15:00       5.737 6/1/1998 1:15     6 1998    1   1
```

Next, very cold and very hot years, such as 1998 and 2020, have been excluded from the dataset so that it contains mostly years representative of average current conditions.

```
boxplot(Temperature~year, data=refjune, main="Fig. 1: Waterloo historical temperatures",
        outline=FALSE, xlab="Year", ylab="Temperature (°C)",
        names = levels(as.factor(refjune$year)))
```




```r
refjune<-subset(refjune, !(year==1998 | year==1999 | year== 2005
                           | year== 2009| year== 2020))
```

Mean hourly temperatures were then obtained across years. This composed a reference 24-hour temperature sequence which is named "control", as it is the basis for the control treatment.

```r
refjune <- aggregate(list(control=refjune$Temperature),
                     by = list(time=refjune$hour), mean)
head(refjune)
```

```
##   time  control
## 1    0 13.67270
## 2    1 13.26294
## 3    2 12.96297
## 4    3 12.67259
## 5    4 12.44668
## 6    5 12.37298
```

Minimum and maximum temperatures were extracted from this reference temperature sequence (note: "time2" column represents fictitious hours from 1-15, as it would be hard to fit a linear model using actual hours which are not in a crescent order, ie. start at 3pm and end at 5am).

```r
reftemps <- data.frame(cbind(time2 = c(15,1),
                             subset(refjune,
                                    control == max(refjune$control)
                                    | control == min(refjune$control))))
```

Temperature regimes were based on Higashi, Barton, & Oliver (2020). The control group is characterized by maximum and minimum temperatures equivalent to local conditions. In the night warming regime (nw), minimum temperatures are increased by 5°C, while in the daytime warming (dw), maximum temperatures are increased by 5°C. Finally, a whole day warming regime (ww) was created with all hourly temperatures being increased by 2.5°C. Across all treatments, maximum temperatures occurred at 3pm, while minimum temperatures occurred at 5am, which corresponds to historical data and results in 14 hours from minima to maxima and 10 hours from maxima to minima. The photoperiod consisted of 16 hours of light and 8 hours of darkness, which is also close to local conditions in the growing season (National Research Council, 2022).

```
reftemps$nw <- ifelse(reftemps$control==min(reftemps$control),
                      reftemps$control+5, reftemps$control)
reftemps$dw <- ifelse(reftemps$control==max(reftemps$control),
                      reftemps$control+5, reftemps$control)
reftemps$ww <- reftemps$control+2.5

head(reftemps)
```

```
##    time2 time  control       nw       dw       ww
## 6     15    5 12.37298 17.37298 12.37298 14.87298
## 16     1   15 20.52177 20.52177 25.52177 23.02177
```

Next, linear models were created based on maximum and minimum temperatures, along with the respective hours in which they occurred.

```
lm_func <- function(y) lm(y ~ time, data = reftemps)

lapply(reftemps[,3:6], lm_func)
```

```
## $control
##
## Call:
## lm(formula = y ~ time, data = reftemps)
##
## Coefficients:
## (Intercept)         time
##      8.2986       0.8149
##
##
## $nw
##
## Call:
## lm(formula = y ~ time, data = reftemps)
##
## Coefficients:
## (Intercept)         time
##     15.7986       0.3149
##
##
## $dw
##
## Call:
## lm(formula = y ~ time, data = reftemps)
##
## Coefficients:
## (Intercept)         time
##       5.799        1.315
##
```

```
##
## $ww
##
## Call:
## lm(formula = y ~ time, data = reftemps)
##
## Coefficients:
## (Intercept)         time
##     10.7986       0.8149
```

```
fit <- lm(cbind(control, nw, dw, ww) ~ time, data = reftemps)

thermalseq <- data.frame(time=c(5:15))
thermalseq <- data.frame(cbind(time=thermalseq$time,(predict(fit,thermalseq))))

head(thermalseq)
```

```
##   time  control       nw       dw       ww
## 1    5 12.37298 17.37298 12.37298 14.87298
## 2    6 13.18786 17.68786 13.68786 15.68786
## 3    7 14.00274 18.00274 15.00274 16.50274
## 4    8 14.81762 18.31762 16.31762 17.31762
## 5    9 15.63250 18.63250 17.63250 18.13250
## 6   10 16.44738 18.94738 18.94738 18.94738
```

A linear function was applied to allow for an even ramp-up from minimum to maximum temperatures based on the "time" column (actual hours in which temperatures occurred) (control and whole day warming: 0.814879 °C/hour; daytime warming: 1.314879 °C/hour; night warming: 0.314879 °C/hour).

```
lm_func2 <- function(y) lm(y ~ time2, data = reftemps)

lapply(reftemps[,3:6], lm_func2)
```

```
## $control
##
## Call:
## lm(formula = y ~ time2, data = reftemps)
##
## Coefficients:
## (Intercept)        time2
##     21.1038      -0.5821
##
##
## $nw
##
## Call:
## lm(formula = y ~ time2, data = reftemps)
##
## Coefficients:
## (Intercept)        time2
##     20.7467      -0.2249
##
##
## $dw
##
## Call:
```

```
## lm(formula = y ~ time2, data = reftemps)
##
## Coefficients:
## (Intercept)        time2
##     26.4610      -0.9392
##
##
## $ww
##
## Call:
## lm(formula = y ~ time2, data = reftemps)
##
## Coefficients:
## (Intercept)        time2
##     23.6038      -0.5821
```

```
fit2 <- lm(cbind(control, nw, dw, ww) ~ time2, data = reftemps)

thermalseq2 <- data.frame(time2=c(1:15))
thermalseq2 <- data.frame(cbind(time2=thermalseq2$time2,
                                (predict(fit2,thermalseq2))))

head(thermalseq2)
```

```
##   time2  control       nw       dw       ww
## 1     1 20.52177 20.52177 25.52177 23.02177
## 2     2 19.93972 20.29686 24.58257 22.43972
## 3     3 19.35766 20.07194 23.64337 21.85766
## 4     4 18.77560 19.84703 22.70417 21.27560
## 5     5 18.19355 19.62212 21.76497 20.69355
## 6     6 17.61149 19.39720 20.82578 20.11149
```

A second linear function was applied from maximum to minimum temperatures based on the "time2" column (fictitious hours to provide a crescent ordering for model fitting) (control and whole day warming: -0.5820564 °C/hour; daytime warming: -0.9391993 °C/hour; night warming: -0.2249136 °C/hour). Predicted temperatures based on these linear models were then obtained for a 24-hour period.

Fictitious hours were replaced by actual hours and predictions from the 2 linear models were bound together.

```
thermalseq2$time2 <- c(15:23,0:5)
colnames(thermalseq2)[1] <- "time"

thermalseq3 <- rbind(thermalseq,thermalseq2)
thermalseq3 <- thermalseq3[order(thermalseq3$time),]
thermalseq3 <- thermalseq3[!duplicated(thermalseq3$time), ]
rownames(thermalseq3) <- NULL

head(thermalseq3)
```

```
##   time  control       nw       dw       ww
## 1    0 15.28326 18.49755 17.06898 17.78326
## 2    1 14.70121 18.27264 16.12978 17.20121
## 3    2 14.11915 18.04772 15.19058 16.61915
## 4    3 13.53709 17.82281 14.25138 16.03709
## 5    4 12.95504 17.59790 13.31218 15.45504
## 6    5 12.37298 17.37298 12.37298 14.87298
```

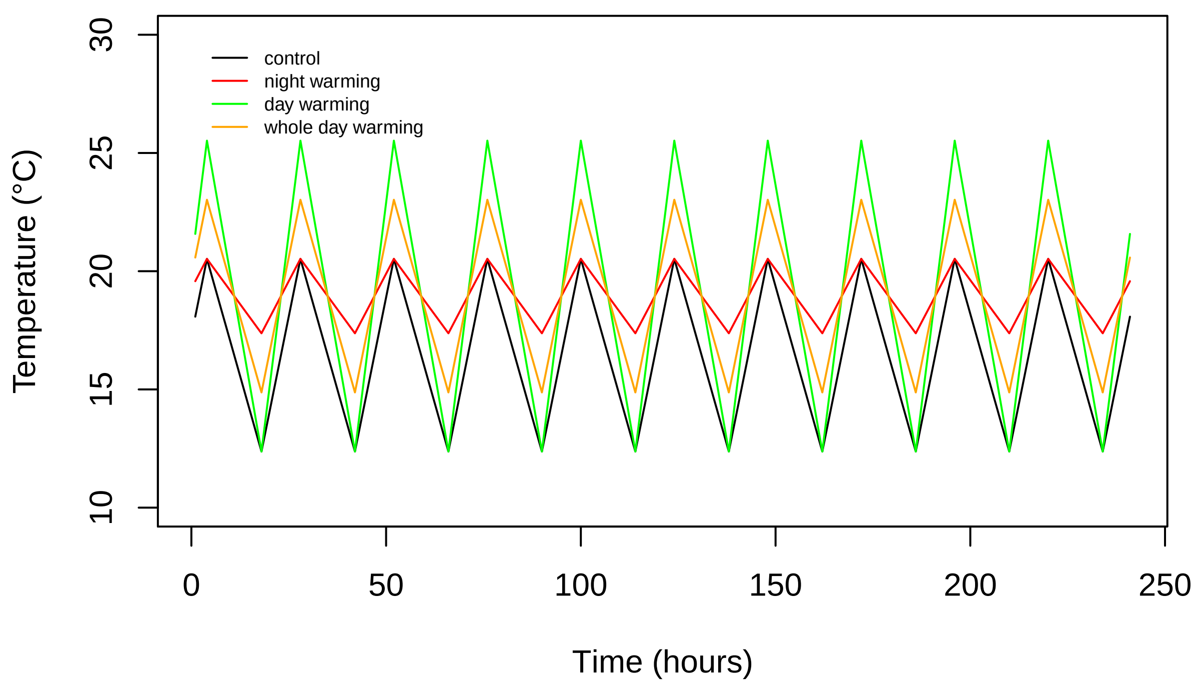
The obtained daily sequence was multiplied in order to obtain a thermal sequence of 10 days in total, ensuring that the start and the end of the experiment are at 12pm.

```
rows= c(1:nrow(thermalseq3))
times = 11
thermalseq3 <- thermalseq3[rep(rows, times),]
thermalseq3 <- thermalseq3[-(1:12),]
thermalseq3 <- thermalseq3[-(242:252),]
```

Each thermal sequence can be visualized in Fig. 2.

```
plot(thermalseq3[,2],type="l",col="black",ylim=c(10,30),
     main="Fig. 2: Night warming experiment treatments",
     xlab="Time (hours)", ylab="Temperature (°C)")
lines(thermalseq3[,3],type="l",col="red")
lines(thermalseq3[,4],type="l",col="green")
lines(thermalseq3[,5],type="l",col="orange")
legend(1, 30, legend=c("control", "night warming",
                       "day warming", "whole day warming"),
       col=c("black", "red", "green", "orange"), lty=1, cex=0.6,bty = "n")
```

**Fig. 2: Night warming experiment treatments**




All of the warming treatments (nighttime, daytime, and whole day) treatments have daily average temperatures which are 2.5 °C higher than the ambient conditions represented by the control group. This increase is within IPCC projections for this region (IPCC, 2018). The night warming treatment allows for testing the effect of increased minimum temperatures and a consequent reduction in daily temperature variation (as observed below in the reduced standard deviation values for this group on the summary statistics below). While daily maxima are the same in the night warming and control groups, daily maxima are increased in the daytime warming treatment proportionally to nighttime the minimum temperature reduction, to test for potential differential effects following warmer days vs warmer nights. Finally the importance of symmetry in terms of warming can be tested by comparing a symmetrical, whole day warming treatment with the two asymmetrical treatments (night and daytime warming).

```
colnames(thermalseq3) <- c("time","control","night_warming",
                           "day_warming","whole_day_warming")

library(pastecs)
stats <- stat.desc(thermalseq3[,c(2:5)])
round(stats, 2)
```

```
##              control night_warming day_warming whole_day_warming
## nbr.val       241.00        241.00      241.00            241.00
## nbr.null        0.00          0.00        0.00              0.00
## nbr.na          0.00          0.00        0.00              0.00
## min            12.37         17.37       12.37             14.87
## max            20.52         20.52       25.52             23.02
## range           8.15          3.15       13.15              8.15
## sum          3965.45       4566.95     4568.95           4567.95
## median         16.45         18.95       18.95             18.95
## mean           16.45         18.95       18.96             18.95
## SE.mean         0.15          0.06        0.25              0.15
## CI.mean.0.95    0.30          0.12        0.49              0.30
## var             5.62          0.84       14.64              5.62
## std.dev         2.37          0.92        3.83              2.37
## coef.var        0.14          0.05        0.20              0.13
```

References

Higashi, C., Barton, B., & Oliver, K. (2020). Warmer nights offer no respite for a defensive mutualism. Journal of animal ecology, 89(8), 1895-1905.

Intergovernmental Panel on Climate Change (IPCC). (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

National Research Council (Canada). Sun Calculator. https://nrc.canada.ca/en/research-development/products-services/software-applications/sun-calculator/