Supplementary Material 2 - Model Selection Procedure for Correlates of Burrow Microclimate and Buffering Capacity

Burrows buffer nest temperatures and offer a stable thermal microclimate for threatened seabird chicks during extreme events

31 March, 2024

Contents

PETREL MODEL - correlates of burrow microclimate

Here we show the steps followed to test for correlation between external environmental conditions and petrel burrow thermal environment.

We tested a variety of models including GAM and GAMM. Additionally we tried different methods of accounting for autocorrelation.

Model S2.1, S2.2 and S2.3 - Initial Models

Run three initial models to identify whether the weather variables should be fitted as spline terms, a spline interaction term or linear interaction term.

```
# MODEL S2.1
# Model with spline fits
m1_petrel <- gam(data = lssp,
           Inside~s(scale(Temperature), bs="ts") + # Weather
                  s(scale(Wind.Speed), bs="ts") +  # Weather
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")

# MODEL S2.2
# Explore temp-wind interaction term
m2_petrel <- gam(data = lssp,
           Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts") +
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")

# MODEL S2.3
# Explore Linear interaction
m3_petrel <- gam(data = lssp,
           Inside~scale(Temperature) * scale(Wind.Speed) +
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")
```

Compare the AIC

Spline interaction (`m2_petrel`) has the lowest AIC score.

```
AIC(m1_petrel, m2_petrel, m3_petrel)
```

```
##                 df      AIC
## m1_petrel 64.48478 150509.2
## m2_petrel 75.14165 149706.6
## m3_petrel 50.57213 151031.4
```

Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts") +
##     s(Time, bs = "cc") + s(julian, bs = "ts") + s(Burrow, bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  15.7516     0.1421   110.8   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                            edf Ref.df       F p-value
## s(scale(Temperature),scale(Wind.Speed)) 27.443     29 19357.7  <2e-16 ***
## s(Time)                                  7.548      8   576.3  <2e-16 ***
## s(julian)                                8.971      9  2786.2  <2e-16 ***
## s(Burrow)                               28.987     29  2260.5  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.678   Deviance explained = 67.8%
## -REML =  75047  Scale est. = 0.58166   n = 65170
```

Model S2.4 - Increase the knots for Julian date

From the summary table of `m2_petrel`, the edf is close to the ref.df, indicating that the knots may need to be increased. Here we double the knots to 20.

```
# MODEL S2.4
m4_petrel <- gam(data = lssp,
          Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts") +
                 s(Time, bs="cc") + # Time
                 s(julian, bs="ts", k = 20) + # Date
                 s(Burrow, bs="re"), # random effect
                 method = "REML")
```

Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts") +
##     s(Time, bs = "cc") + s(julian, bs = "ts", k = 20) + s(Burrow,
##     bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  15.7516     0.1418   111.1   <2e-16 ***
```

```
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                           edf Ref.df      F p-value
## s(scale(Temperature),scale(Wind.Speed)) 26.413     29 6258.2  <2e-16 ***
## s(Time)                                  7.343      8  347.8  <2e-16 ***
## s(julian)                               18.977     19 2672.1  <2e-16 ***
## s(Burrow)                               28.990     29 2854.4  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.746   Deviance explained = 74.6%
## -REML =  67371  Scale est. = 0.45894   n = 65170
```

Model S2.5 - Increase the knots again for Julian date

```
# MODEL S2.5
m5_petrel <- gam(data = lssp,
          Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts") +
                 s(Time, bs="cc") + # Time
                 s(julian, bs="ts", k = 40) + # Date
                 s(Burrow, bs="re"), # random effect
                 method = "REML")
```

Model Summary

From the summary of `m5_petrel`, the edf continues to be close to the ref.df value, but we are unable to increase the knots further.

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts") +
##     s(Time, bs = "cc") + s(julian, bs = "ts", k = 40) + s(Burrow,
##     bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  15.7516     0.1418   111.1   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                           edf Ref.df      F p-value
## s(scale(Temperature),scale(Wind.Speed)) 25.984     29 6197.7  <2e-16 ***
## s(Time)                                  7.239      8  297.9  <2e-16 ***
## s(julian)                               38.870     39 1722.0  <2e-16 ***
## s(Burrow)                               28.991     29 3249.9  <2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.777   Deviance explained = 77.7%
## -REML =  63201  Scale est. = 0.40298   n = 65170
```

Compare AIC

Model `m5_petrel` with k = 40 has the lowest AIC score.

```
AIC(m2_petrel, m4_petrel, m5_petrel)
```

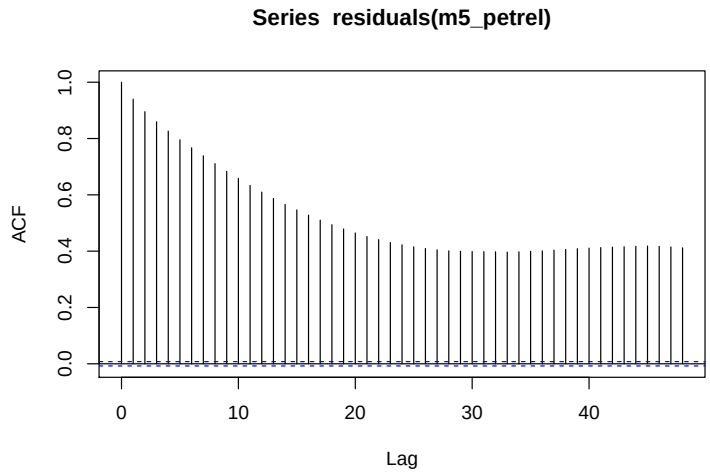
```
##                  df      AIC
## m2_petrel  75.14165 149706.6
## m4_petrel  83.98264 134273.0
## m5_petrel 103.52789 125819.1
```

Explore model fit

Test for temporal autocorrelation

The model `m5_petrel` is highly autocorrelated, therefore, we reject this model.

```
acf(residuals(m5_petrel))
```



Model S2.6 - GAMM with corAR1

We will also explore the GAMM option with burrow as a random effect and include a corAR1 term to account for autocorrelation. We removed the date and time terms because the corAR1 term is accounting for the autocorrelation.

```
# MODEL S2.6
gamm1_petrel <- gamm(data = lssp,
                     Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts"),
                     random = list(Burrow = ~1),# Burrow features
                     corr = corAR1(form = ~ 1|Burrow),
                     method = "REML")
```

Model Summary - gam

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)    15.70       0.14   112.1   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                          edf Ref.df     F  p-value
## s(scale(Temperature),scale(Wind.Speed)) 1.83     29 0.979 3.99e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.00402
##   Scale est. = 1.3542    n = 65170
```

Model Summary - lme

```
## Linear mixed-effects model fit by REML
##   Data: strip.offset(mf)
##         AIC       BIC   logLik
##   -26368.28 -26322.86 13189.14
##
## Random effects:
##  Formula: ~Xr - 1 | g
##  Structure: pdIdnot
##                 Xr1         Xr2         Xr3         Xr4         Xr5         Xr6
## StdDev: 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764
##                 Xr7         Xr8         Xr9        Xr10        Xr11        Xr12
## StdDev: 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764
##                Xr13        Xr14        Xr15        Xr16        Xr17        Xr18
## StdDev: 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764
##                Xr19        Xr20        Xr21        Xr22        Xr23        Xr24
## StdDev: 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764
##                Xr25        Xr26        Xr27        Xr28        Xr29
## StdDev: 0.001724764 0.001724764 0.001724764 0.001724764 0.001724764
##
##  Formula: ~1 | Burrow %in% g
##         (Intercept) Residual
## StdDev:   0.7125722 1.163683
##
## Correlation Structure: AR(1)
##  Formula: ~1 | g/Burrow
##  Parameter estimate(s):
##       Phi
```

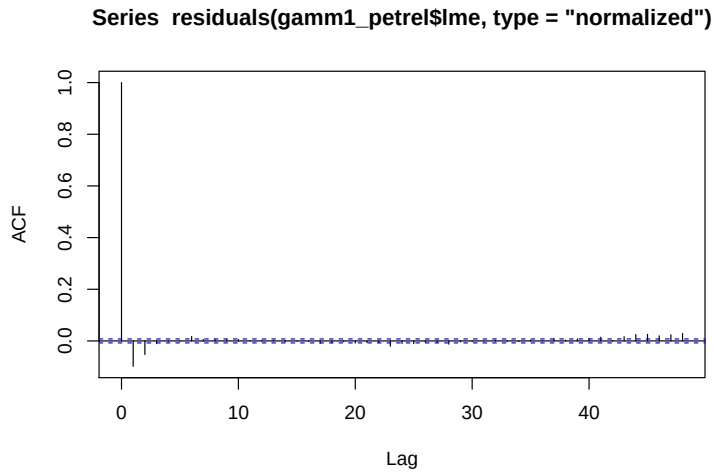
```
## 0.9855106
## Fixed effects:  y ~ X - 1
##   Value Std.Error    DF  t-value p-value
## X  15.7 0.1400175 65140 112.1289       0
##
## Standardized Within-Group Residuals:
##         Min          Q1         Med          Q3         Max
## -4.43842778 -0.46178015  0.05880828  0.61881330  5.09200097
##
## Number of Observations: 65170
## Number of Groups:
##             g Burrow %in% g
##             1            30
```

Explore model fit

Test for temporal autocorrelation

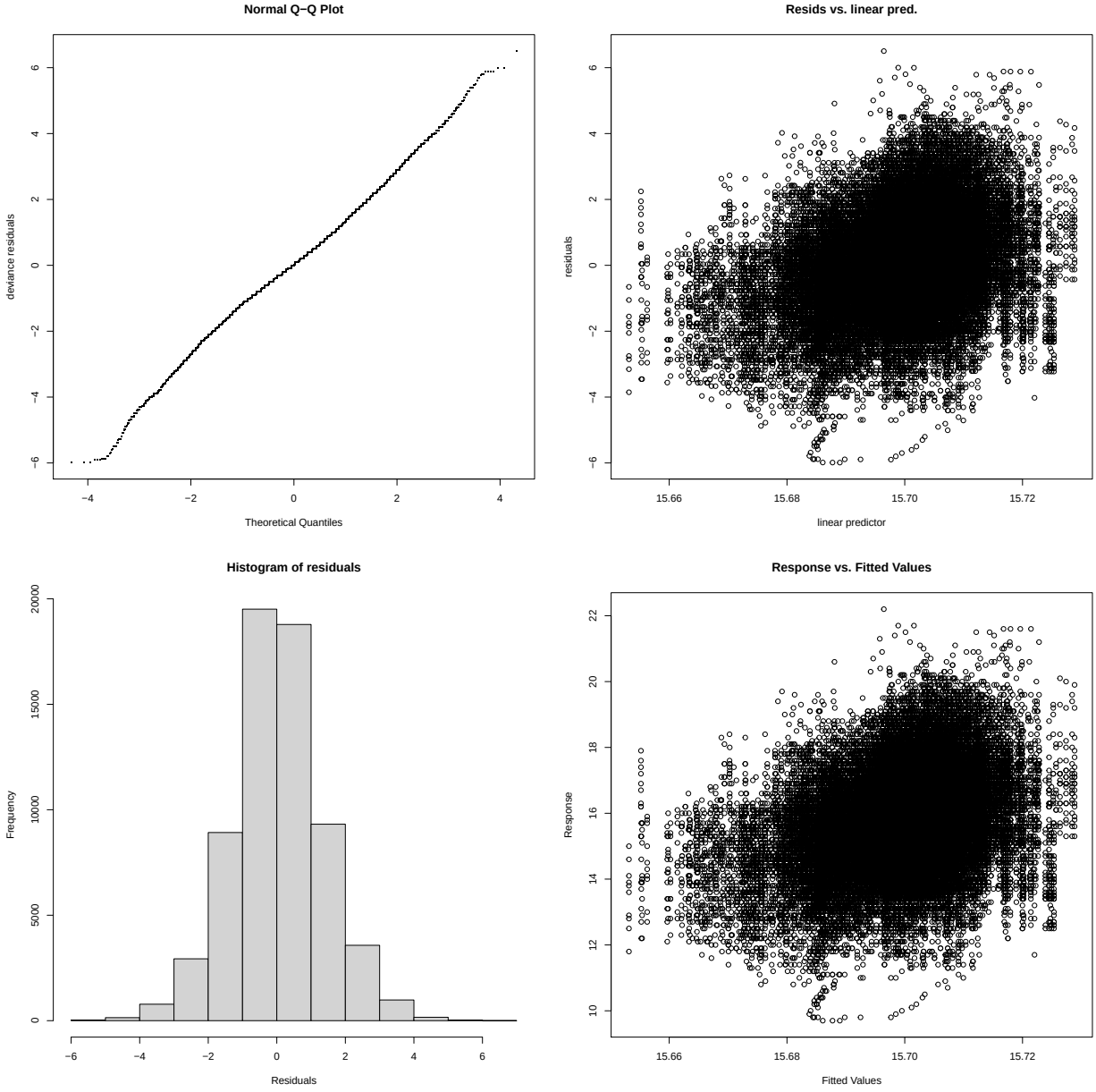
The residual function for gam in R returns the residuals without adjustment for the correlation structure. So must specify type = "normalized"

```
acf(residuals(gamm1_petrel$lme, type = "normalized"))
```



Gam.check

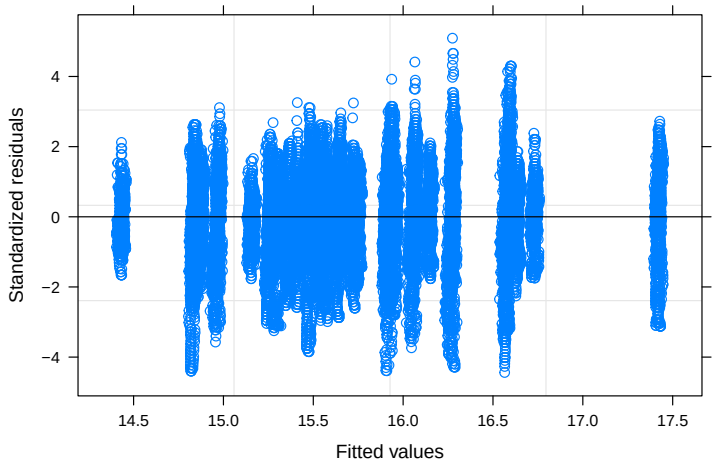
```
gam.check(gamm1_petrel$gam)
```




```
##
## 'gamm' based fit - care required with interpretation.
## Checks based on working residuals may be misleading.
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                          k'   edf k-index p-value
## s(scale(Temperature),scale(Wind.Speed)) 29.00  1.83    0.77  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

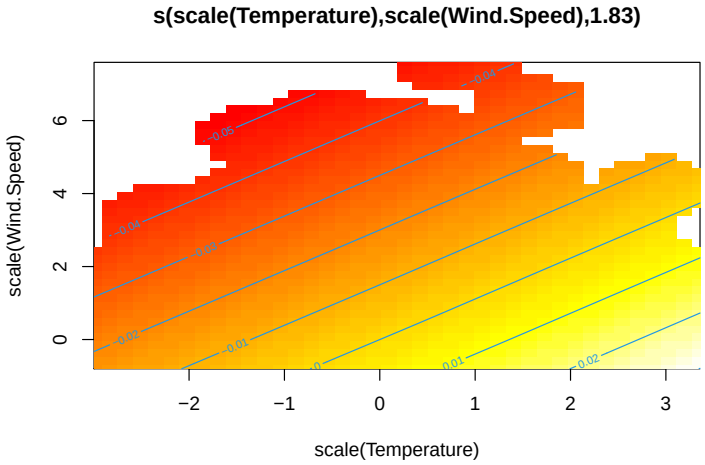
lme plot

```
plot(gamm1_petrel$lme)
```



Visualise the temp-wind interaction in 2D

```
plot(gamm1_petrel$gam, scheme = 2, pages = 1)
```



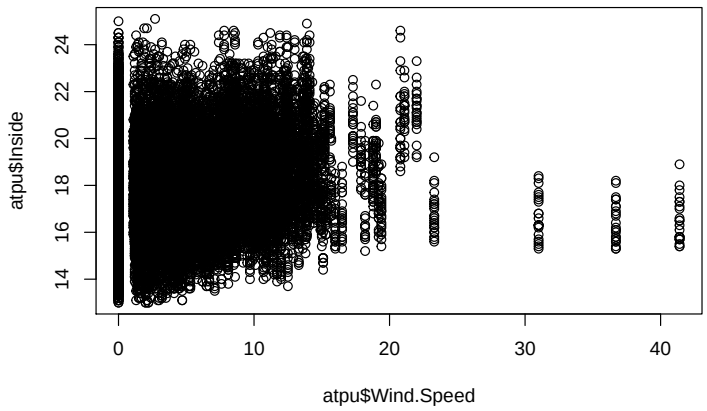
PUFFIN MODEL - correlates of burrow microclimate

Here we show the modelling steps followed to arrive at the final selected model used to test correlates of Atlantic puffin burrow microclimates.

Exploring wind speed

In the plot below, the data for wind speed exceed the speeds recorded during the hurricane, suggesting that there may be issues with data at these three points. They occurred all on the same day over a 1.5 hour period.

```
plot(atpu$Wind.Speed, atpu$Inside)
```

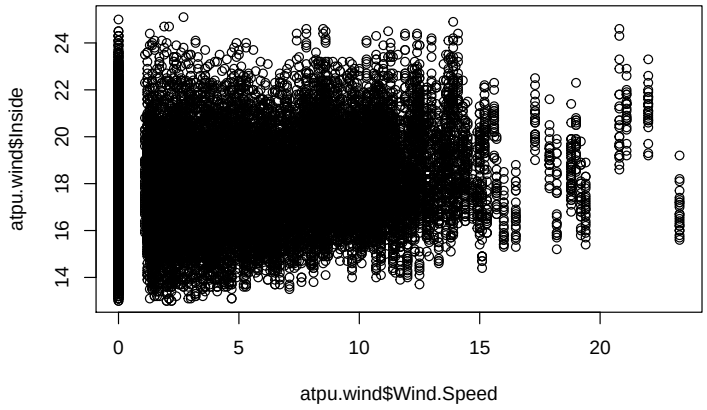


Removing potentially erroneous data

We will remove the high wind speed records for the modelling.

```
# Remove the higher wind speeds
atpu.wind <- atpu %>% filter(Wind.Speed < 30)

# Visualise the data
plot(atpu.wind$Wind.Speed, atpu.wind$Inside)
```



Model S2.7, S2.8, and S2.9 - Initial models

Run three initial models to identify whether the weather variables should be fitted as spline terms, a spline interaction term or linear interaction term.

```
# MODEL S2.7
# Model with spline fits
m1_puffin <- gam(data = atpu.wind,
           Inside~s(scale(Temperature), bs="ts") + # Weather
                  s(scale(Wind.Speed),bs="ts") +  # Weather
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")

# MODEL S2.8
# Explore temp-wind interaction term
m2_puffin <- gam(data = atpu.wind,
           Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts") +
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")

# MODEL S2.9
# Explore Linear interaction
m3_puffin <- gam(data = atpu.wind,
           Inside~scale(Temperature) * scale(Wind.Speed) +
                  s(Time, bs="cc") + # Time
                  s(julian, bs="ts") + # Date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")
```

Compare AIC

Spline interaction (`m2_puffin`) has the lowest AIC score

```
AIC(m1_puffin, m2_puffin, m3_puffin)
```

```
##                  df      AIC
## m1_puffin 58.17853 102887.8
## m2_puffin 68.93652 101397.3
## m3_puffin 43.68667 102512.1
```

Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts") +
##     s(Time, bs = "cc") + s(julian, bs = "ts") + s(Burrow, bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  17.9177     0.2039   87.86   <2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                           edf Ref.df      F p-value
## s(scale(Temperature),scale(Wind.Speed)) 28.184     29  238.7  <2e-16 ***
## s(Time)                                  7.632      8  898.6  <2e-16 ***
## s(julian)                                8.989      9  605.1  <2e-16 ***
## s(Burrow)                               21.985     22 1470.2  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.656   Deviance explained = 65.6%
## -REML =  50876  Scale est. = 1.0081    n = 35604
```

Model S2.10 - Increase the knots for Julian date

From the summary table of `m2_puffin`, the edf is close to the ref.df, indicating that the knots may need to be increased. Here we double the knots to 20.

```
# MODEL S2.10
m4_puffin <- gam(data = atpu.wind,
             Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts") +
                  s(Time, bs="cc") +
                  s(julian, bs="ts", k = 20)+ # Time and date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")
```

Model Summary

The edf continues to be close to the ref.df value, but we are unable to increase the knots further.

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts") +
##     s(Time, bs = "cc") + s(julian, bs = "ts", k = 20) + s(Burrow,
##     bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  17.9177     0.2039   87.87   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                           edf Ref.df      F p-value
## s(scale(Temperature),scale(Wind.Speed)) 27.691     29  158.5  <2e-16 ***
## s(Time)                                  7.657      8  974.6  <2e-16 ***
## s(julian)                               18.966     19  722.2  <2e-16 ***
## s(Burrow)                               21.988     22 1766.3  <2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.713   Deviance explained = 71.4%
## -REML =  47649  Scale est. = 0.83918   n = 35604
```

Compare AIC

Increasing the knots reduces the AIC score.

```
AIC(m2_puffin, m4_puffin)
```

```
##                 df       AIC
## m2_puffin 68.93652 101397.30
## m4_puffin 78.46728  94876.93
```

Model S2.11 - Increase the knots for the interaction term

From the summary table of `m4_puffin`, the edf is close to the ref.df, indicating that the knots may need to be increased. Here we double to knots to 60.

```
# MODEL S2.11
m5_puffin <- gam(data = atpu.wind,
             Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts", k = 60) +
                  s(Time, bs="cc") +
                  s(julian, bs="ts", k = 20)+ # Time and date
                  s(Burrow, bs="re"), # random effect
                  method = "REML")
```

Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts",
##     k = 60) + s(Time, bs = "cc") + s(julian, bs = "ts", k = 20) +
##     s(Burrow, bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  17.9177     0.2041   87.79   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                          edf Ref.df       F p-value
## s(scale(Temperature),scale(Wind.Speed)) 53.701     59   83.48  <2e-16 ***
## s(Time)                                  7.677      8  965.81  <2e-16 ***
## s(julian)                               18.965     19  695.99  <2e-16 ***
## s(Burrow)                               21.988     22 1780.86  <2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.716   Deviance explained = 71.7%
## -REML =  47543  Scale est. = 0.83233   n = 35604
```

Compare AIC

Increasing the knots reduces the AIC score. We will now explore the model fit.

```
AIC(m4_puffin, m5_puffin)
```

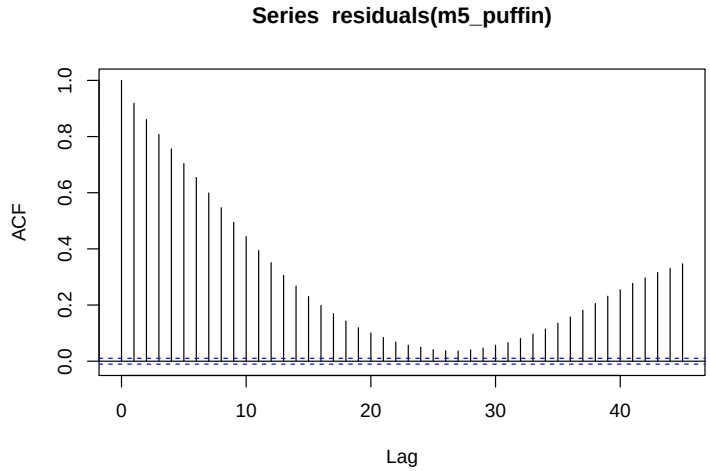
```
##                   df      AIC
## m4_puffin  78.46728 94876.93
## m5_puffin 104.68594 94611.23
```

Explore model fit

Test for temporal autocorrelation

The model `m5_puffin` is highly autocorrelated, therefore, we reject this model.

```
acf(residuals(m5_puffin))
```



Model S2.12 - GAMM with corAR1

We will also explore the GAMM option with burrow as a random effect and include a corAR1 term to account for autocorrelation. We removed the date and time terms because the corAR1 term is accounting for the autocorrelation.

```
## Model S2.12
gamm1_puffin <- gamm(data = atpu.wind,
                     Inside~s(scale(Temperature), scale(Wind.Speed), bs="ts"),
                     random = list(Burrow = ~1),# Burrow features
                     corr = corAR1(form = ~ 1|Burrow),
                     method = "REML")
```

Model Summary - gam

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## Inside ~ s(scale(Temperature), scale(Wind.Speed), bs = "ts")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   17.947      0.205   87.54   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                           edf Ref.df     F p-value
## s(scale(Temperature),scale(Wind.Speed)) 25.31     29 27.78  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0698
##   Scale est. = 1.8759    n = 35604
```

Model Summary - lme

```
## Linear mixed-effects model fit by REML
##   Data: strip.offset(mf)
##        AIC      BIC    logLik
##   18554.43 18596.83 -9272.214
##
## Random effects:
##  Formula: ~Xr - 1 | g
##  Structure: pdIdnot
##               Xr1       Xr2       Xr3       Xr4       Xr5       Xr6       Xr7
## StdDev: 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661
##               Xr8       Xr9      Xr10      Xr11      Xr12      Xr13      Xr14
## StdDev: 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661
##              Xr15      Xr16      Xr17      Xr18      Xr19      Xr20      Xr21
## StdDev: 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661
##              Xr22      Xr23      Xr24      Xr25      Xr26      Xr27      Xr28
## StdDev: 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661 0.2455661
##              Xr29
## StdDev: 0.2455661
##
##  Formula: ~1 | Burrow %in% g
##         (Intercept) Residual
## StdDev:   0.9383819 1.369634
##
## Correlation Structure: AR(1)
##  Formula: ~1 | g/Burrow
##  Parameter estimate(s):
##       Phi
```

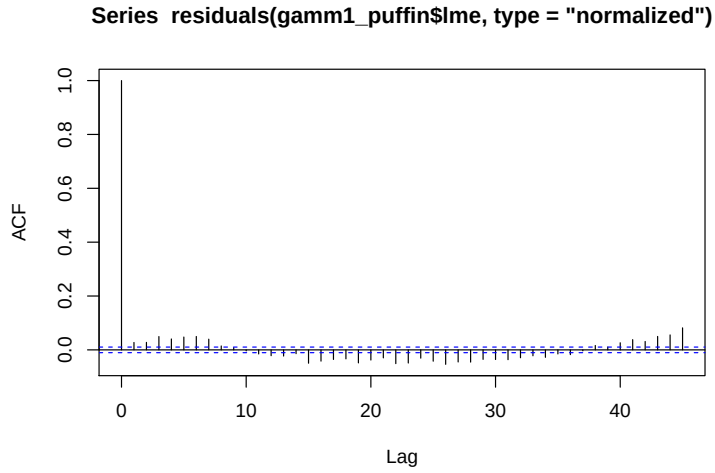
```
## 0.9735332
## Fixed effects:  y ~ X - 1
##      Value Std.Error    DF  t-value p-value
## X 17.94729 0.2050272 35581 87.53616       0
##
## Standardized Within-Group Residuals:
##        Min         Q1        Med         Q3        Max
## -3.2417739 -0.6863952 -0.1010124  0.5454877  4.5341875
##
## Number of Observations: 35604
## Number of Groups:
##             g Burrow %in% g
##             1            23
```

Explore model fit

Test for temporal autocorrelation

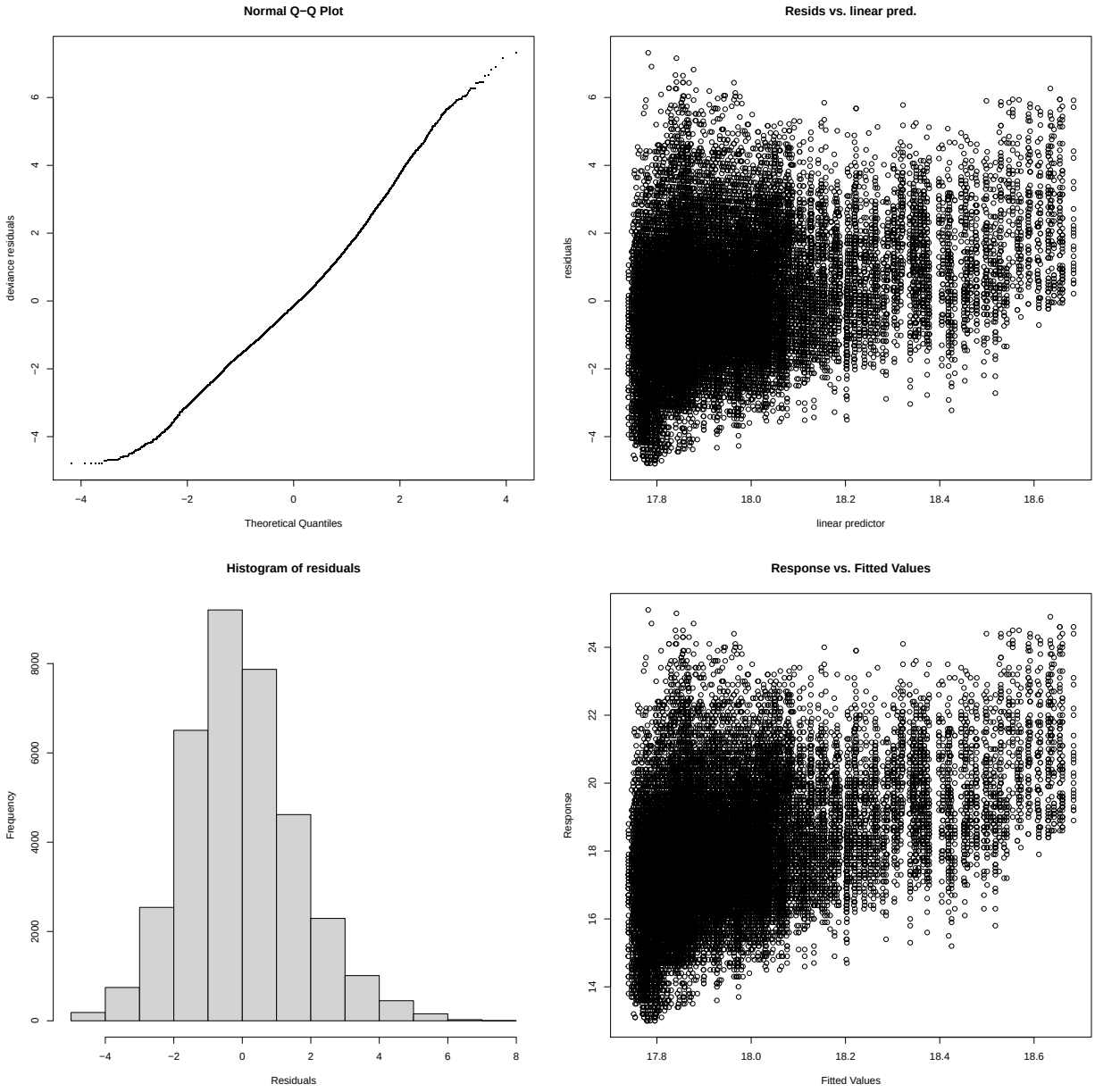
The residual function for gam in R returns the residuals without adjustment for the correlation structure. So must specify type = "normalized"

```
acf(residuals(gamm1_puffin$lme, type = "normalized"))
```



Gam.check

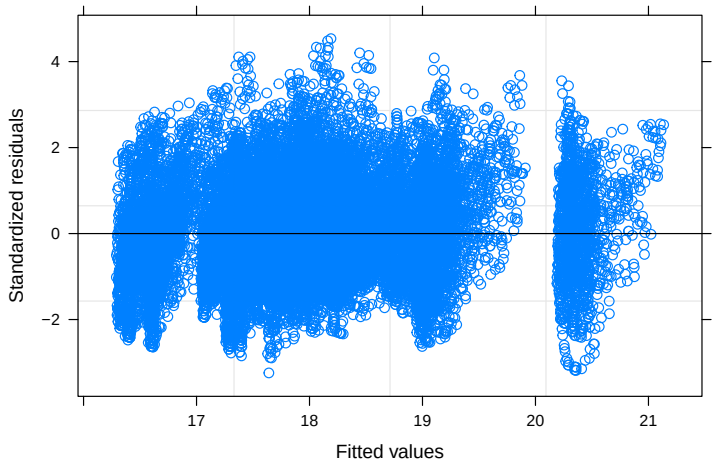
```
gam.check(gamm1_puffin$gam)
```




```
##
## 'gamm' based fit - care required with interpretation.
## Checks based on working residuals may be misleading.
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                                         k'  edf k-index p-value
## s(scale(Temperature),scale(Wind.Speed)) 29.0 25.3     0.7  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

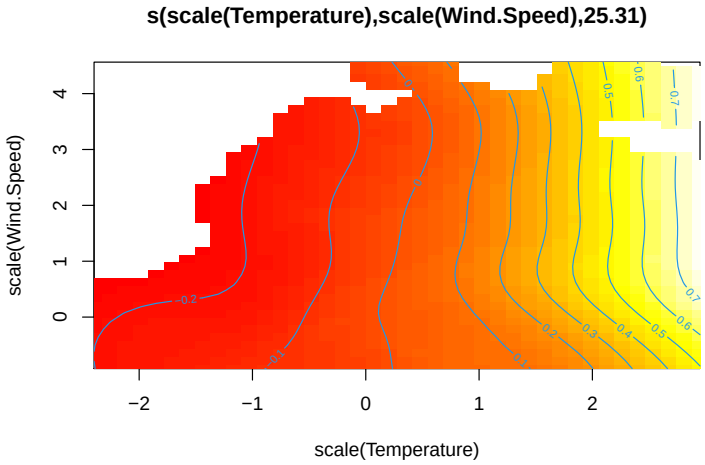
lme plot

```
plot(gamm1_puffin$lme)
```



Visualise the temp-wind interaction in 2D

```
plot(gamm1_puffin$gam, scheme = 2, pages = 1)
```



PETREL MODELS - Favourable burrow features during extreme temperatures

Filter the data in the 99th percentile of external air temperatures recorded at the weather stations. This temperature were identified as 6.5°C.

```
## COLD
extreme_cold_LSSP <- filter(lssp, Temperature <= 6.5 & Species == "Leach's storm-petrel")
extreme_cold_LSSP$Extreme <- "Cold Extreme"
```

Model S2.13 - GAM model - Cold extreme

```
# MODEL S2.13
gam_cold_lssp<- gam(data = extreme_cold_LSSP,
           buffer_kestrel~s(scale(Canopy), bs="ts") + # Weather
                  s(scale(Entrance_Area),bs="ts") +  # Weather
                  s(scale(volume),bs="ts") +  # Weather
                  s(Burrow, bs="re"), # random effect
                  method = "REML")
```

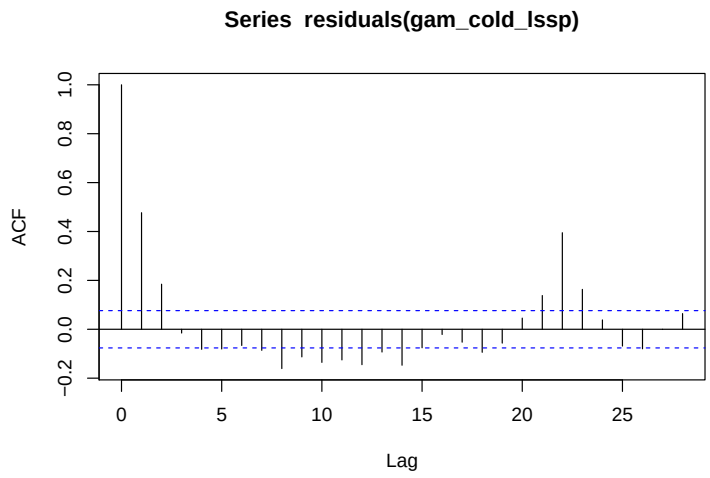
Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## buffer_kestrel ~ s(scale(Canopy), bs = "ts") + s(scale(Entrance_Area),
##     bs = "ts") + s(scale(volume), bs = "ts") + s(Burrow, bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   7.3974     0.2023   36.57   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf Ref.df     F p-value
## s(scale(Canopy))        3.612e-04      9   0.0   0.878
## s(scale(Entrance_Area)) 2.528e-04      9   0.0   0.846
## s(scale(volume))        2.602e-01      9 105.8   0.247
## s(Burrow)               2.848e+01     29 106.3  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.832   Deviance explained = 83.9%
## -REML = 537.71  Scale est. = 0.24075   n = 660
```

Explore model fit

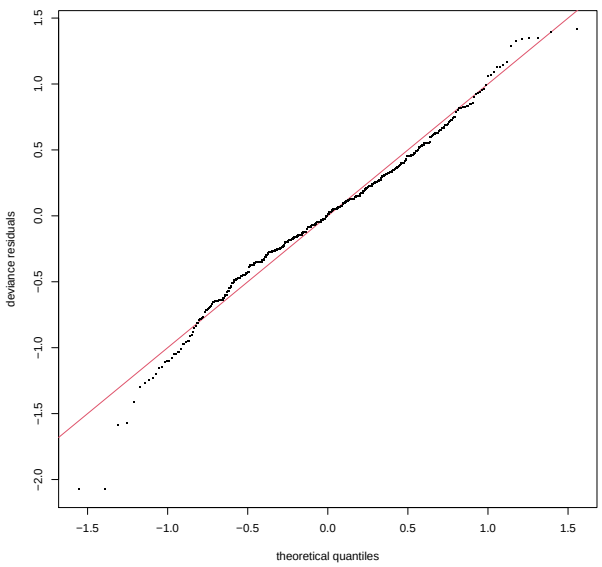
Test for temporal autocorrelation

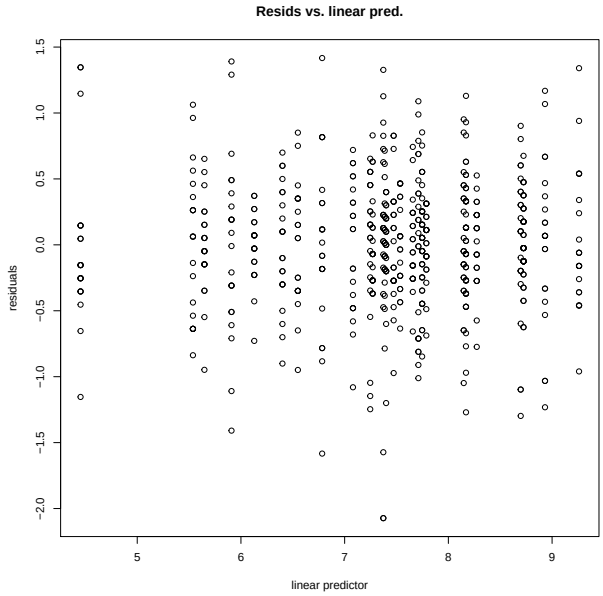
```
acf(residuals(gam_cold_lssp))
```

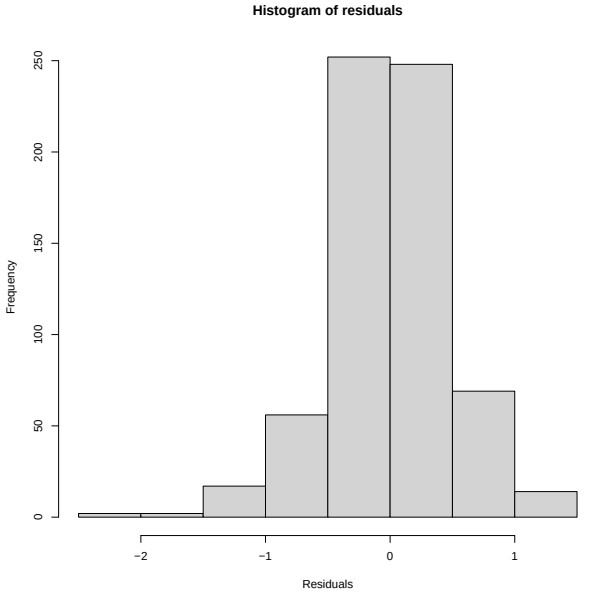


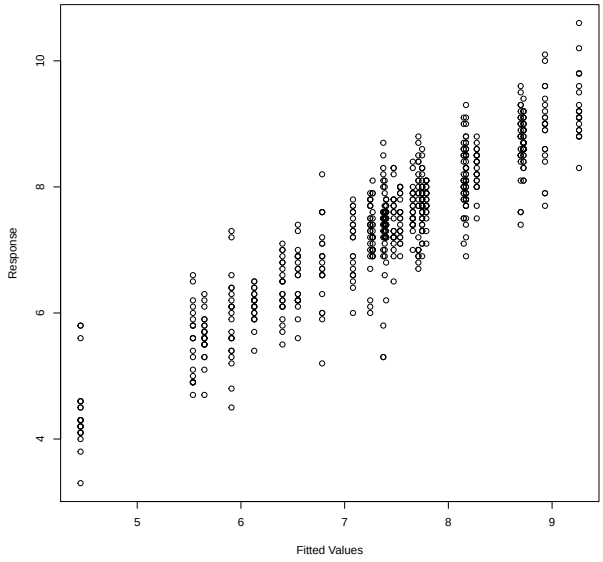
Gam.check

```
gam.check(gam_cold_lssp)
```







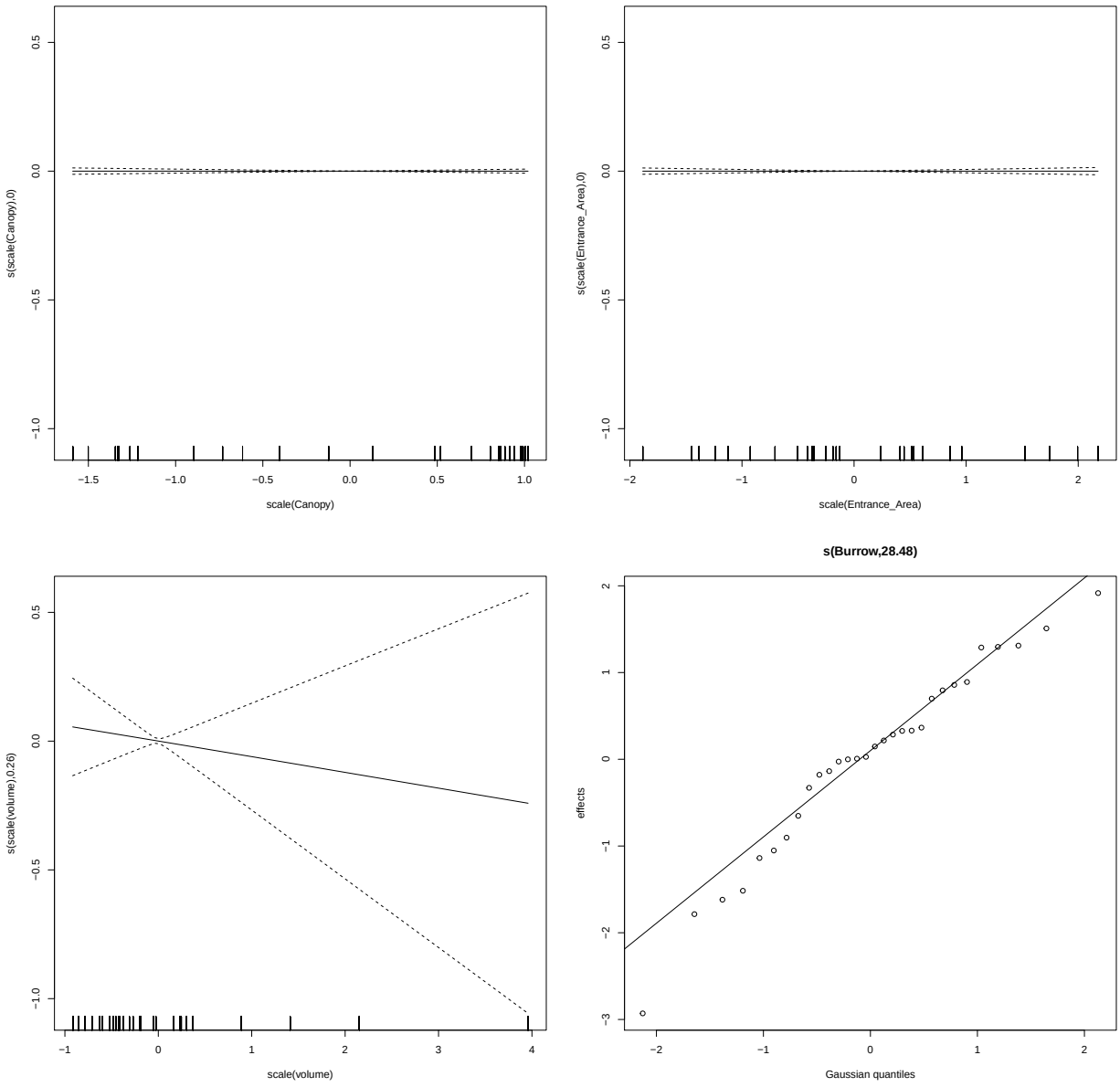



```
##
## Method: REML   Optimizer: outer newton
## full convergence after 10 iterations.
## Gradient range [-0.000176319,0.0002795324]
## (score 537.7096 & scale 0.2407496).
## Hessian positive definite, eigenvalue range [0.0001206716,330.1417].
## Model rank =  58 / 58
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                               k'      edf k-index p-value
## s(scale(Canopy))        9.00e+00 3.61e-04    0.54  <2e-16 ***
## s(scale(Entrance_Area)) 9.00e+00 2.53e-04    0.52  <2e-16 ***
```

```
## s(scale(volume))        9.00e+00 2.60e-01    0.51  <2e-16 ***
## s(Burrow)               3.00e+01 2.85e+01      NA      NA
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Plotting

```
plot(gam_cold_lssp, pages = 1)
```



Model S2.14 - GAMM with corAR1 - cold extreme

```r
# MODEL S2.14
gamm_cold_lssp <- gamm(data = extreme_cold_LSSP,
                   buffer_kestrel~ s(scale(Canopy), bs="ts") +
                   s(scale(Entrance_Area),bs="ts") +  #
                   s(scale(volume),bs="ts"),  # Weather
                   random = list(Burrow = ~1),# Burrow features
                   corr = corAR1(form = ~ 1|Burrow),
                   method = "REML")
```

Model Summary - gam

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## buffer_kestrel ~ s(scale(Canopy), bs = "ts") + s(scale(Entrance_Area),
##     bs = "ts") + s(scale(volume), bs = "ts")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   7.3933     0.2014   36.71   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf Ref.df     F p-value
## s(scale(Canopy))        6.420e-06      9 0.000   0.911
## s(scale(Entrance_Area)) 7.602e-06      9 0.000   0.827
## s(scale(volume))        3.307e-01      9 0.054   0.223
##
## R-sq.(adj) =  0.0216
##   Scale est. = 0.28322   n = 660
```

Model Summary - lme

```
## Linear mixed-effects model fit by REML
##   Data: strip.offset(mf)
##        AIC      BIC    logLik
##   854.2383 885.6733 -420.1191
##
## Random effects:
##  Formula: ~Xr - 1 | g
##  Structure: pdIdnot
##                  Xr1          Xr2          Xr3          Xr4          Xr5
## StdDev: 0.0001069725 0.0001069725 0.0001069725 0.0001069725 0.0001069725
##                  Xr6          Xr7          Xr8          Xr9
## StdDev: 0.0001069725 0.0001069725 0.0001069725 0.0001069725
##
##  Formula: ~Xr.0 - 1 | g.0 %in% g
##  Structure: pdIdnot
##                Xr.01        Xr.02        Xr.03        Xr.04        Xr.05
```

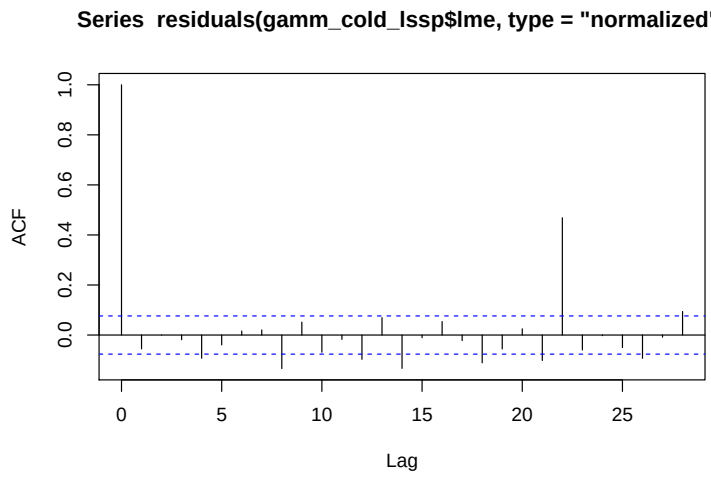
```
## StdDev: 0.0001283057 0.0001283057 0.0001283057 0.0001283057 0.0001283057
##                Xr.06        Xr.07        Xr.08        Xr.09
## StdDev: 0.0001283057 0.0001283057 0.0001283057 0.0001283057
##
##  Formula: ~Xr.1 - 1 | g.1 %in% g.0 %in% g
##  Structure: pdIdnot
##              Xr.11      Xr.12      Xr.13      Xr.14      Xr.15      Xr.16
## StdDev: 0.03351689 0.03351689 0.03351689 0.03351689 0.03351689 0.03351689
##              Xr.17      Xr.18      Xr.19
## StdDev: 0.03351689 0.03351689 0.03351689
##
##  Formula: ~1 | Burrow %in% g.1 %in% g.0 %in% g
##         (Intercept)  Residual
## StdDev:    1.081644 0.5321858
##
## Correlation Structure: AR(1)
##  Formula: ~1 | g/g.0/g.1/Burrow
##  Parameter estimate(s):
##       Phi
## 0.6143071
## Fixed effects:  y ~ X - 1
##      Value Std.Error  DF  t-value p-value
## X 7.393323 0.2014135 630 36.70719       0
##
## Standardized Within-Group Residuals:
##          Min           Q1          Med           Q3          Max
## -3.685602874 -0.524979039 -0.008461842  0.562424838  2.703142724
##
## Number of Observations: 660
## Number of Groups:
##                                g                       g.0 %in% g
##                                1                                 1
##             g.1 %in% g.0 %in% g Burrow %in% g.1 %in% g.0 %in% g
##                                1                                30
```

Explore model fit

Test for temporal autocorrelation

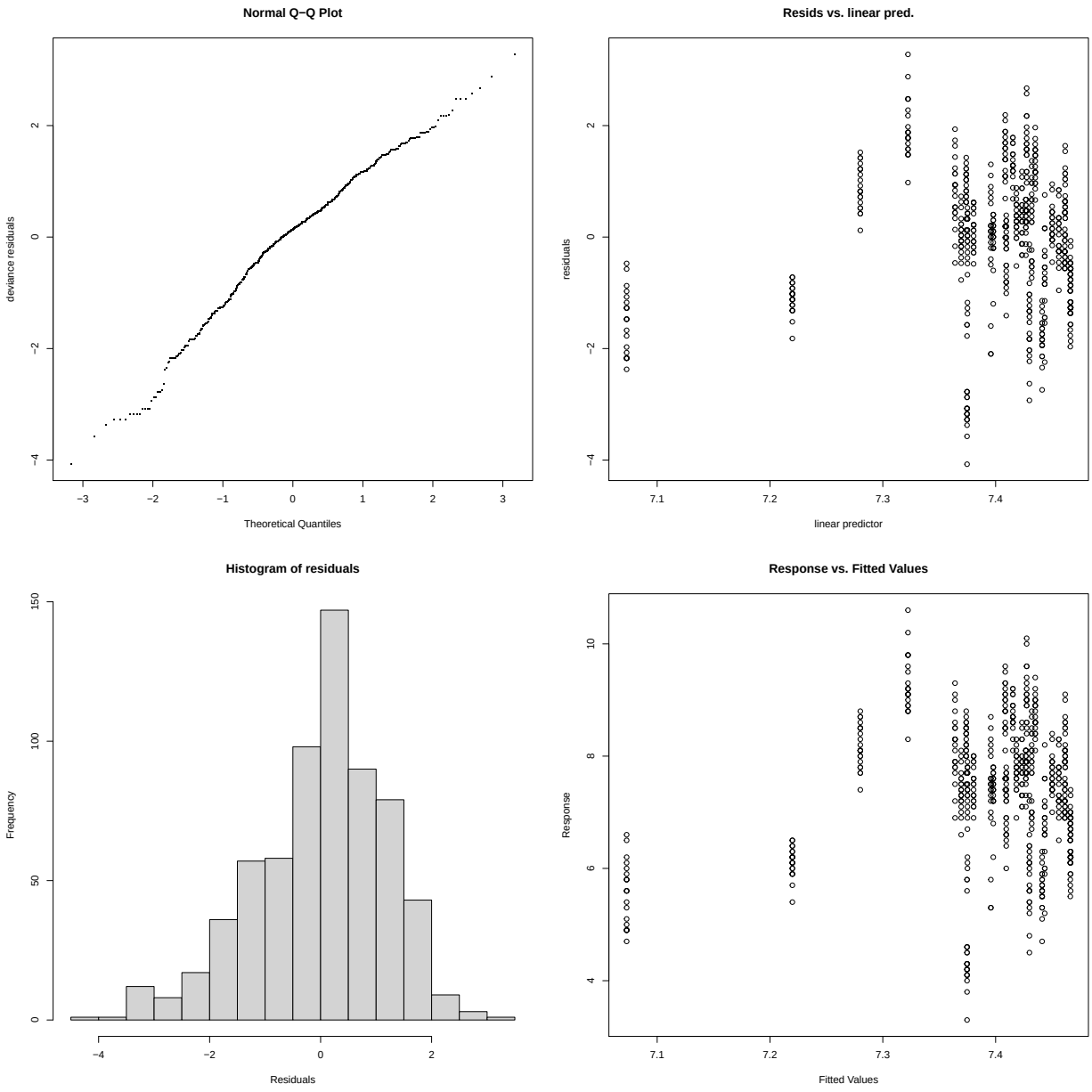
The residual function for gam in R returns the residuals without adjustment for the correlation structure. So must specify type = "normalized"

```
acf(residuals(gamm_cold_lssp$lme, type = "normalized"))
```



Gam.check

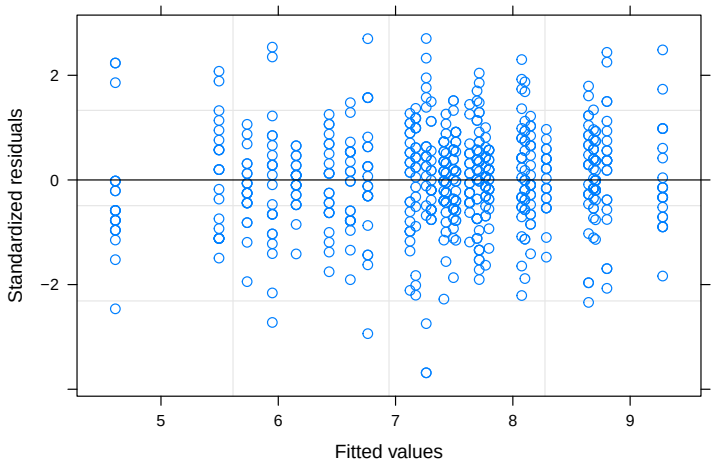
```
gam.check(gamm_cold_lssp$gam)
```




```
##
## 'gamm' based fit - care required with interpretation.
## Checks based on working residuals may be misleading.
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                              k'      edf k-index p-value
## s(scale(Canopy))        9.00e+00 6.42e-06    0.13  <2e-16 ***
## s(scale(Entrance_Area)) 9.00e+00 7.60e-06    0.13  <2e-16 ***
## s(scale(volume))        9.00e+00 3.31e-01    0.12  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

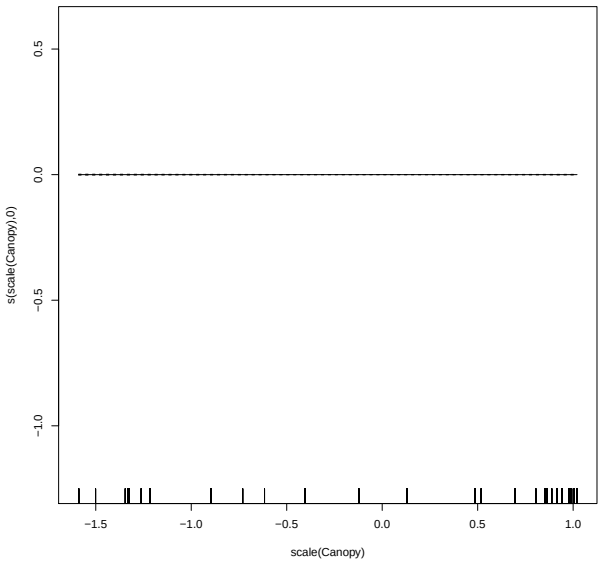
lme plot

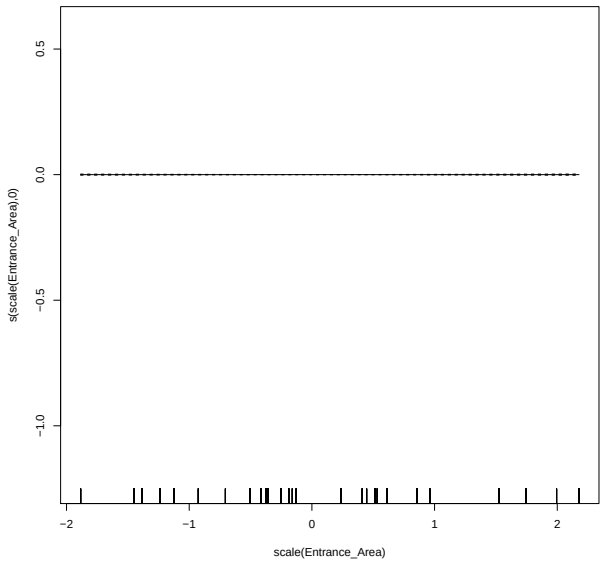
```
plot(gamm_cold_lssp$lme)
```

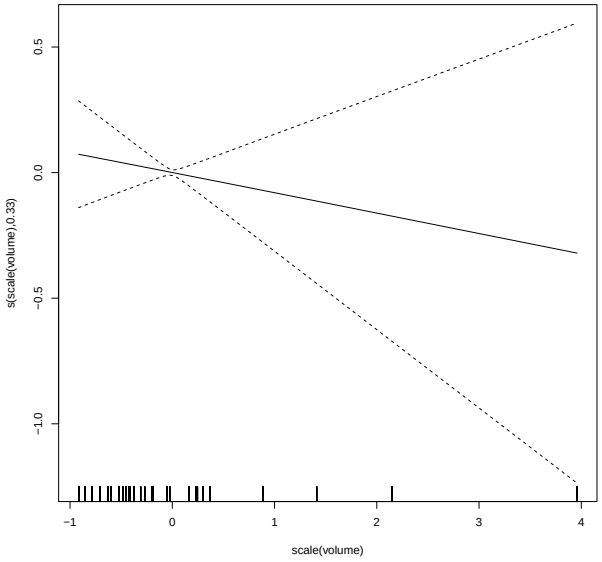


Plot

```
plot(gamm_cold_lssp$gam, pages = 1)
```







PUFFIN MODELS - Favourable burrow features during extreme temperatures

Filter the data in the 99th percentile of external air temperatures recorded at the weather stations. The temperature was identified as 10°C.

```
## COLD
extreme_cold_ATPU <- filter(atpu.wind, Temperature <= 10 & Species == "Atlantic puffin")
extreme_cold_ATPU$Extreme <- "Cold Extreme"
```

Model S2.15 - GAM model - Cold extreme

```
## MODEL S2.15
gam_cold_ATPU<- gam(data = extreme_cold_ATPU,
          buffer_kestrel~s(scale(Entrance_Area),bs="ts") +  # Weather
                 s(scale(volume),bs="ts") +  # Weather
                 s(Burrow, bs="re"), # random effect
                 method = "REML")
```

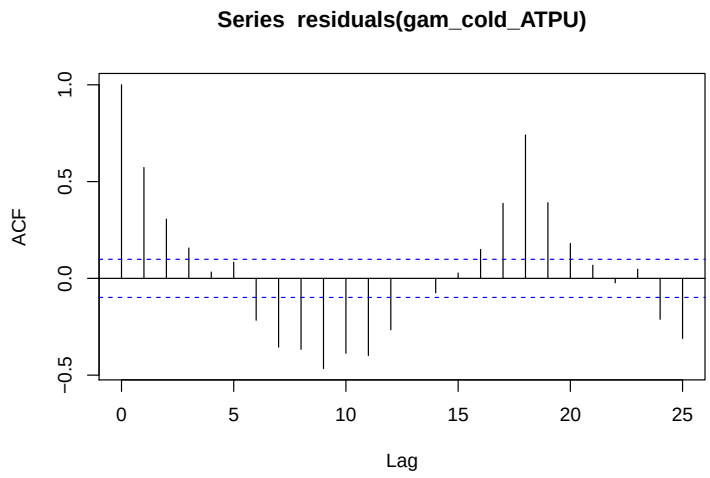
Model Summary

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## buffer_kestrel ~ s(scale(Entrance_Area), bs = "ts") + s(scale(volume),
##     bs = "ts") + s(Burrow, bs = "re")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   8.1187     0.2401   33.81   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf Ref.df     F p-value
## s(scale(Entrance_Area)) 7.472e-04      9   0.0  0.5208
## s(scale(volume))        8.281e-01      9 242.5  0.0214 *
## s(Burrow)               1.937e+01     21  22.8  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.609   Deviance explained = 62.9%
## -REML = 579.43  Scale est. = 0.90959   n = 396
```

Explore model fit

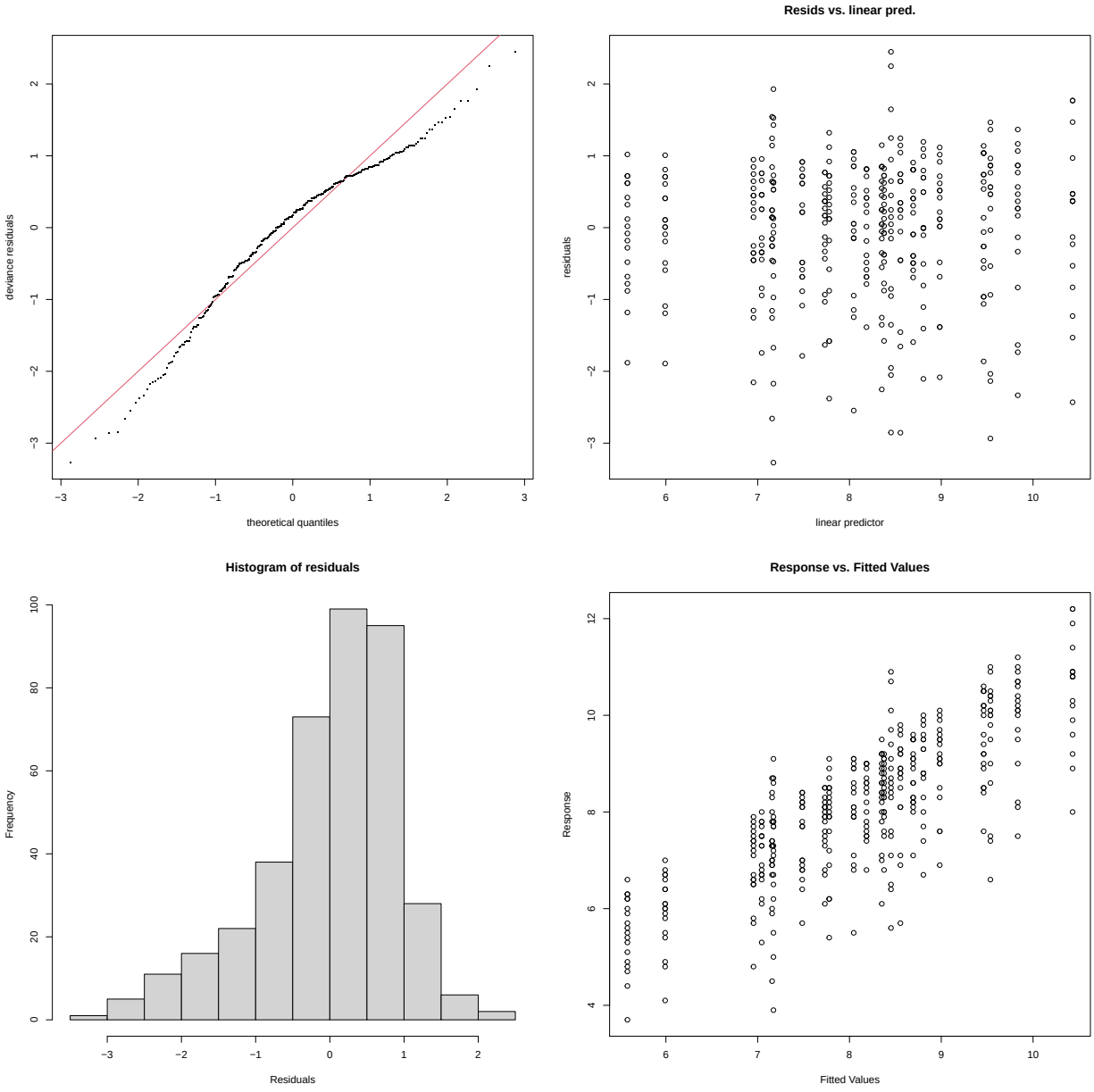
Test for temporal autocorrelation

```
acf(residuals(gam_cold_ATPU))
```



Gam.check

```
gam.check(gam_cold_ATPU)
```

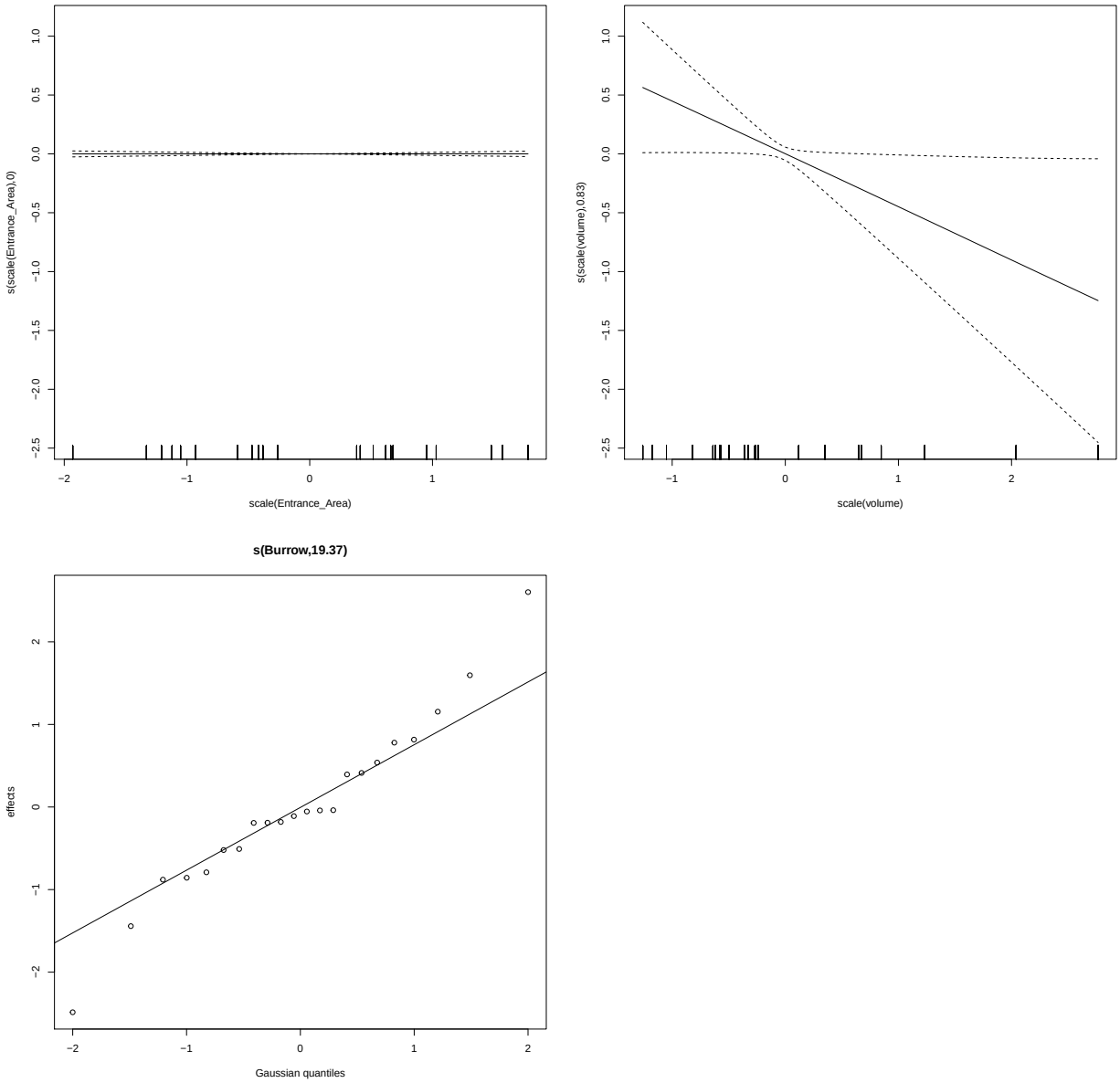



```
##
## Method: REML   Optimizer: outer newton
## full convergence after 9 iterations.
## Gradient range [-0.0002196821,0.000153432]
## (score 579.4342 & scale 0.9095871).
## Hessian positive definite, eigenvalue range [0.0002196303,197.9975].
## Model rank =  41 / 41
##
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                               k'      edf k-index p-value
## s(scale(Entrance_Area)) 9.00e+00 7.47e-04    0.41  <2e-16 ***
## s(scale(volume))        9.00e+00 8.28e-01    0.43  <2e-16 ***
```

```
## s(Burrow)               2.20e+01 1.94e+01      NA      NA
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Plotting

```
plot(gam_cold_ATPU, pages = 1)
```



Model S2.16 - GAMM with corAR1 - cold extreme

```r
# Model S2.16
gamm_cold_ATPU <- gamm(data = extreme_cold_ATPU,
                   buffer_kestrel~ s(scale(Entrance_Area),bs="ts") +  #
                   s(scale(volume),bs="ts"),  # Weather
                   random = list(Burrow = ~1),# Burrow features # random effect
                   corr = corAR1(form = ~ 1|Burrow),
                   method = "REML")
```

Model Summary - gam

```
##
## Family: gaussian
## Link function: identity
##
## Formula:
## buffer_kestrel ~ s(scale(Entrance_Area), bs = "ts") + s(scale(volume),
##     bs = "ts")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)   7.5087     0.3023   24.84   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                                edf Ref.df     F p-value
## s(scale(Entrance_Area)) 7.567e-08      9 0.000  0.6064
## s(scale(volume))        7.358e-01      9 0.296  0.0564 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.123
##   Scale est. = 3.0192    n = 396
```

Model Summary - lme

```
## Linear mixed-effects model fit by REML
##   Data: strip.offset(mf)
##        AIC      BIC    logLik
##   753.0963 776.9696 -370.5482
##
## Random effects:
##  Formula: ~Xr - 1 | g
##  Structure: pdIdnot
##                  Xr1          Xr2          Xr3          Xr4          Xr5
## StdDev: 1.484336e-05 1.484336e-05 1.484336e-05 1.484336e-05 1.484336e-05
##                  Xr6          Xr7          Xr8          Xr9
## StdDev: 1.484336e-05 1.484336e-05 1.484336e-05 1.484336e-05
##
##  Formula: ~Xr.0 - 1 | g.0 %in% g
##  Structure: pdIdnot
##              Xr.01      Xr.02      Xr.03      Xr.04      Xr.05      Xr.06
```

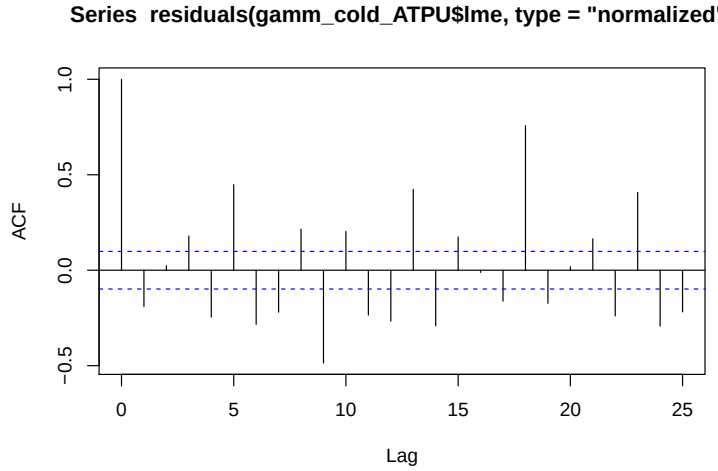
```
## StdDev: 0.04924848 0.04924848 0.04924848 0.04924848 0.04924848 0.04924848
##              Xr.07      Xr.08      Xr.09
## StdDev: 0.04924848 0.04924848 0.04924848
##
##  Formula: ~1 | Burrow %in% g.0 %in% g
##          (Intercept) Residual
## StdDev: 0.0002123481  1.73758
##
## Correlation Structure: AR(1)
##  Formula: ~1 | g/g.0/Burrow
##  Parameter estimate(s):
##       Phi
## 0.9427098
## Fixed effects:  y ~ X - 1
##      Value Std.Error  DF  t-value p-value
## X 7.508655 0.3023402 374 24.83512       0
##
## Standardized Within-Group Residuals:
##        Min         Q1        Med         Q3        Max
## -2.1636641 -0.1517782  0.3399173  0.8381906  2.8564013
##
## Number of Observations: 396
## Number of Groups:
##                       g             g.0 %in% g Burrow %in% g.0 %in% g
##                       1                      1                      22
```

Explore model fit

Test for temporal autocorrelation

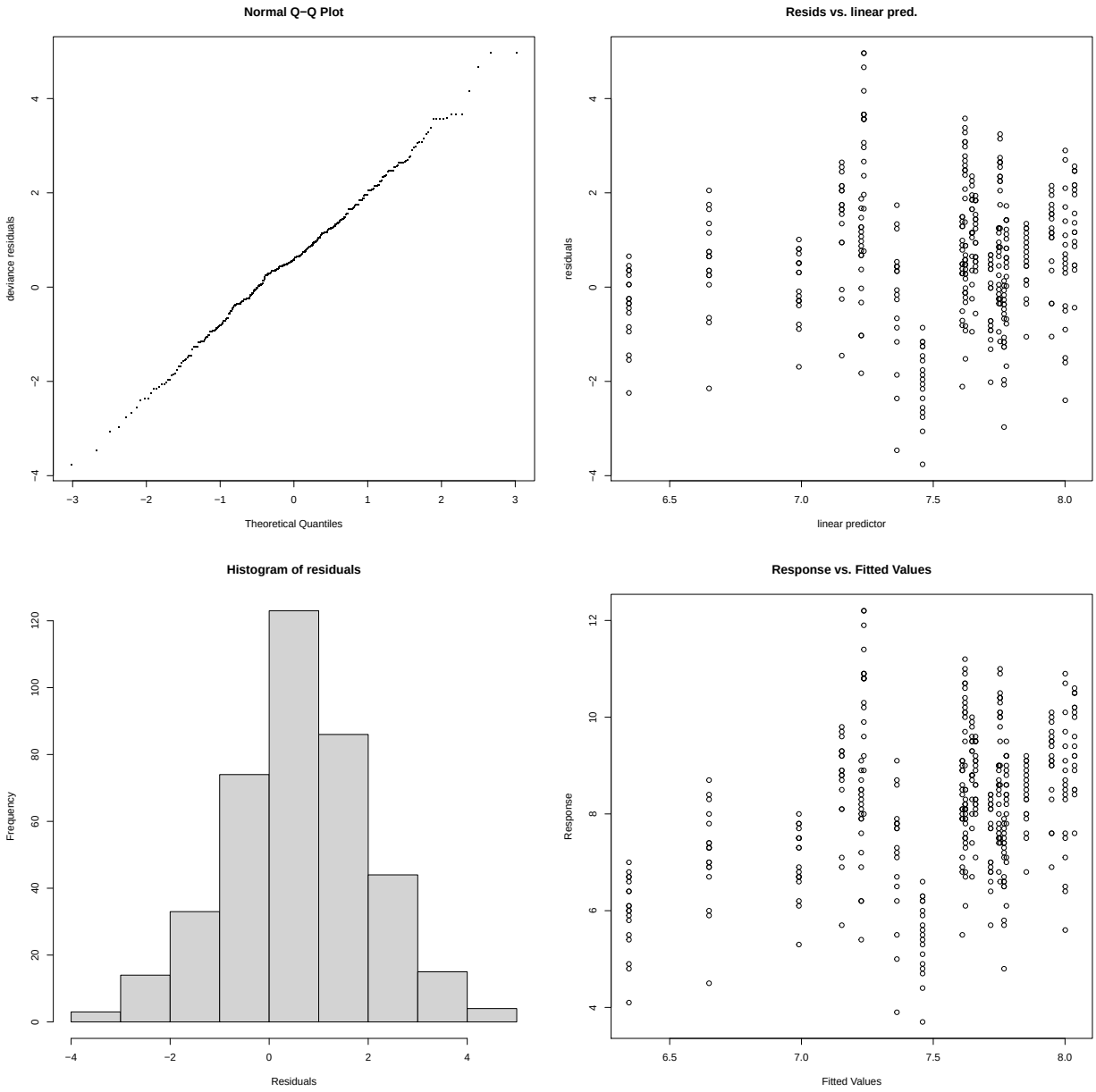
The residual function for gam in R returns the residuals without adjustment for the correlation structure. So must specify type = "normalized"

```
acf(residuals(gamm_cold_ATPU$lme, type = "normalized"))
```



Gam.check

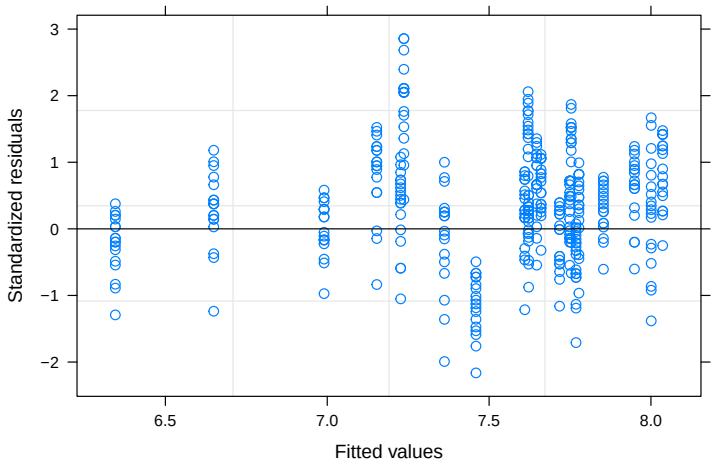
```
gam.check(gamm_cold_ATPU$gam)
```




```
##
## 'gamm' based fit - care required with interpretation.
## Checks based on working residuals may be misleading.
## Basis dimension (k) checking results. Low p-value (k-index<1) may
## indicate that k is too low, especially if edf is close to k'.
##
##                              k'      edf k-index p-value
## s(scale(Entrance_Area)) 9.00e+00 7.57e-08    0.17  <2e-16 ***
## s(scale(volume))        9.00e+00 7.36e-01    0.19  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

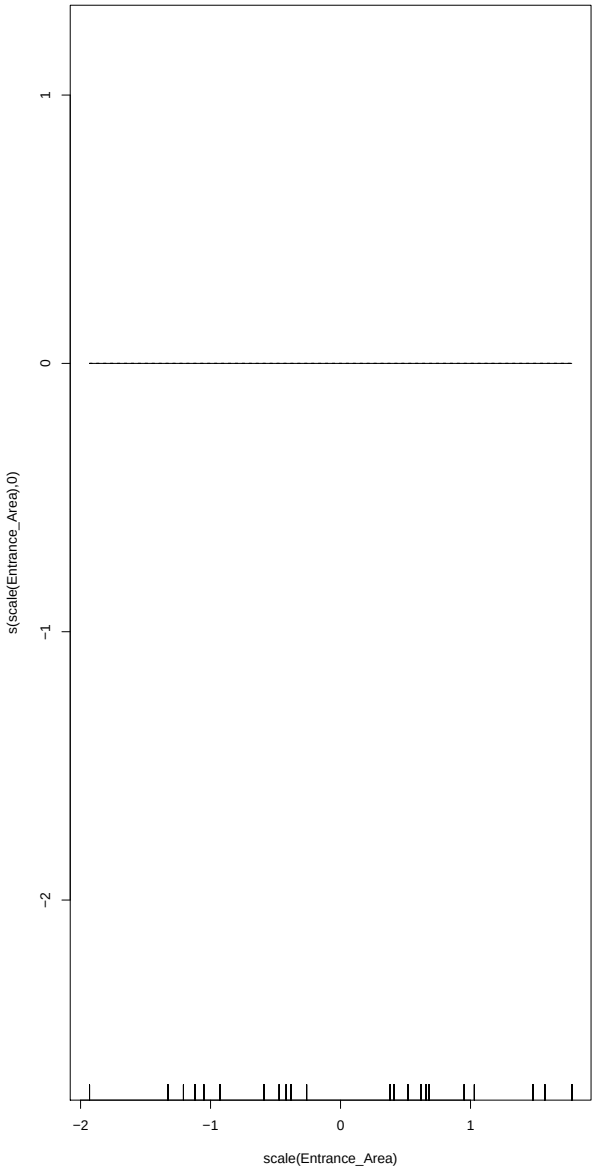
lme plot

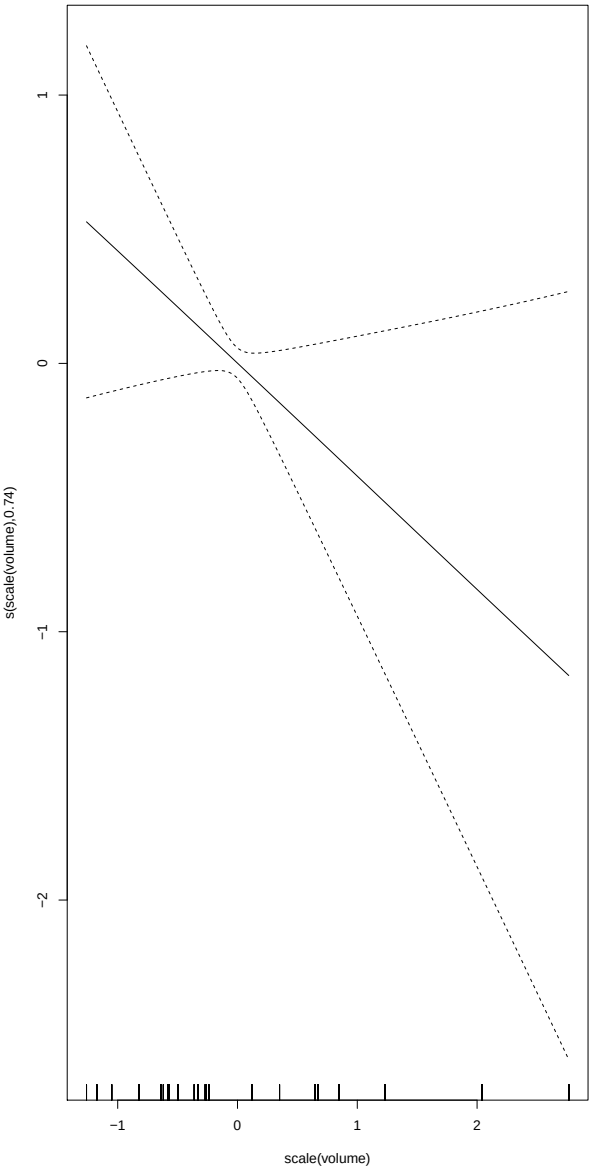
```
plot(gamm_cold_ATPU$lme)
```



Plot

```
plot(gamm_cold_ATPU$gam, pages = 1)
```


s(scale(Entrance_Area),0)
1
0
−1
−2
−2
−1
0
1
scale(Entrance_Area)


s(scale(volume),0.74)
1
0
−1
−2
−1
0
1
2
scale(volume)