Weather generators and phenological models to study climate change impacts on grapevines and apples

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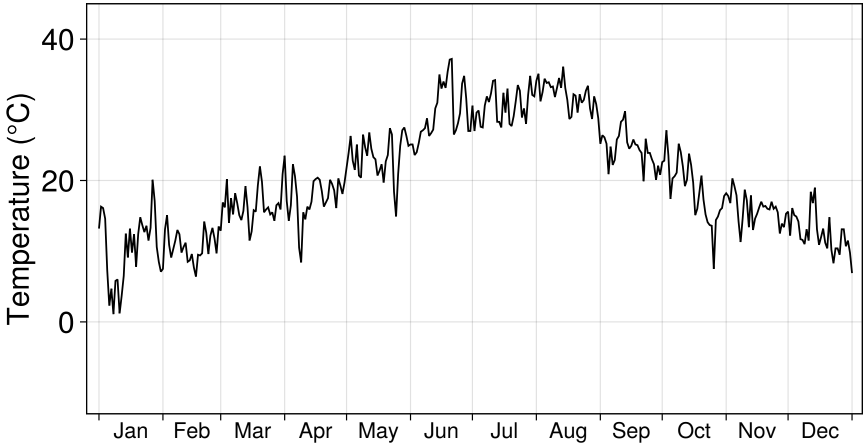
Outline

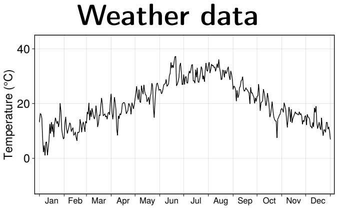
I. Stochastic weather generators

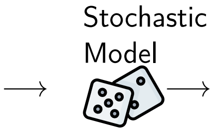
Principle

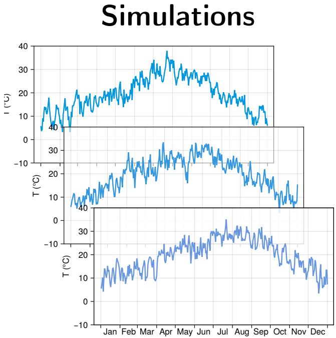


Recorded daily maximum temperature (TX) at Montpellier from 1st May 2003 to 1st November 2003 (source : ECA&D)

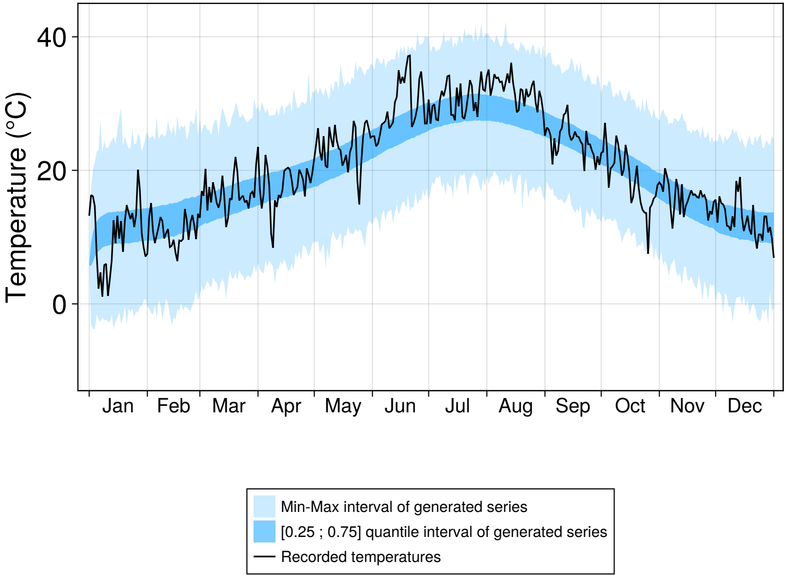
Principle


Weather data
Temperature (°C)
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Stochastic
Model


Simulations
T (°C)
40
30
20
10
0
−10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

With 5000 simulations :



Principle

The SWG can simulate :

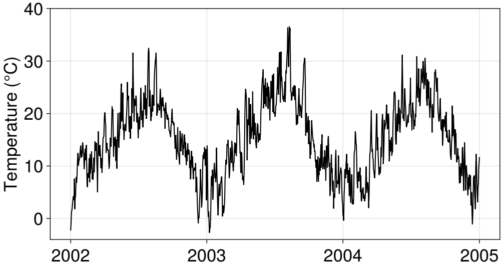
- Daily minimal temperature (TN) series.
- Daily average temperature (TG) series.
- Daily maximal temperature (TX) series.

But for now it can't generate two of these series at the same time because we have to consider a correlation between them.

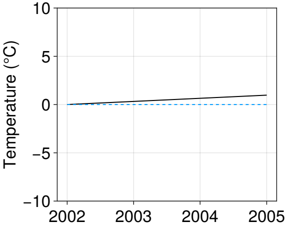
Model

$T_t = M_t + S_t + X_t$ where

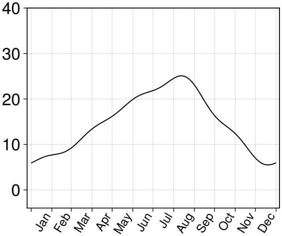
- T_t is the recorded temperature
- M_t is the trend
- S_t is the seasonality
- X_t is the stochastic part



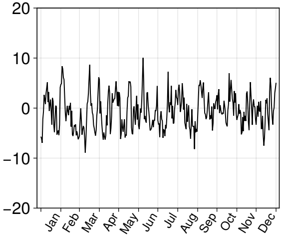
Recorded temperature T_t



Trend M_t



Seasonality S_t

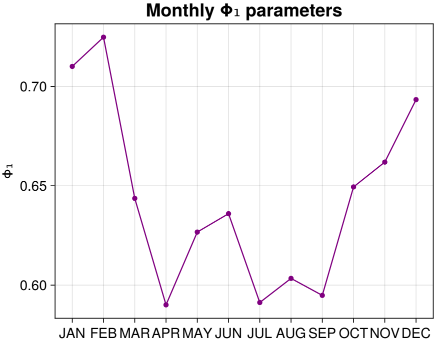


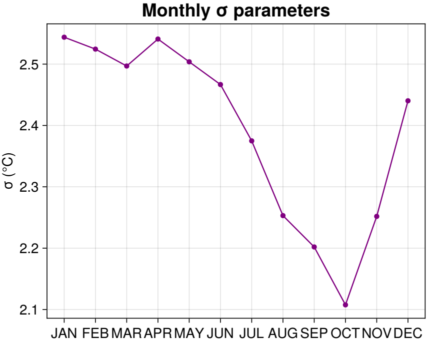
Stochastic part X_t

Model with different parameters for each month :

$$X_t = \phi_{1,m(t)} X_{t-1} + \phi_{2,m(t)} X_{t-2} + ... + \phi_{p,m(t)} X_{t-p} + \sigma_{m(t)} \varepsilon_t$$

With $\varepsilon_t \overset{\text{iid}}{\sim} \mathcal{N}(0,1)$ a noise and $m(t)$ the month of the date t. With $p = 1$, the model trained on the Montpellier TX series (1946-2025) gives :





Algorithm

- Firstly, we estimate the parameters with a **maximum likelihood estimation**.

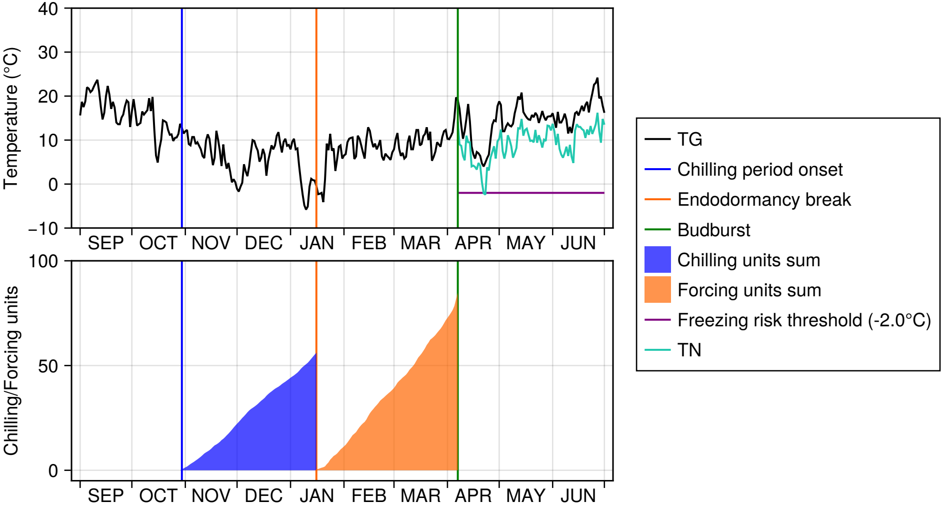
- To simulate a new temperature series $(\hat{T}_t)$:

  1. Initial conditions : $\hat{X}_1 = X_1, \hat{X}_2 = X_2, \ldots, \hat{X}_p = X_p$.
  2. We simulate $\varepsilon_t \sim \mathcal{N}(0,1)$ for $t > p$.
  3. $\hat{X}_t$ calculated with the previous equation, for $t > p$.
  4. $\hat{T}_t = M_t + S_t + \hat{X}_t$.

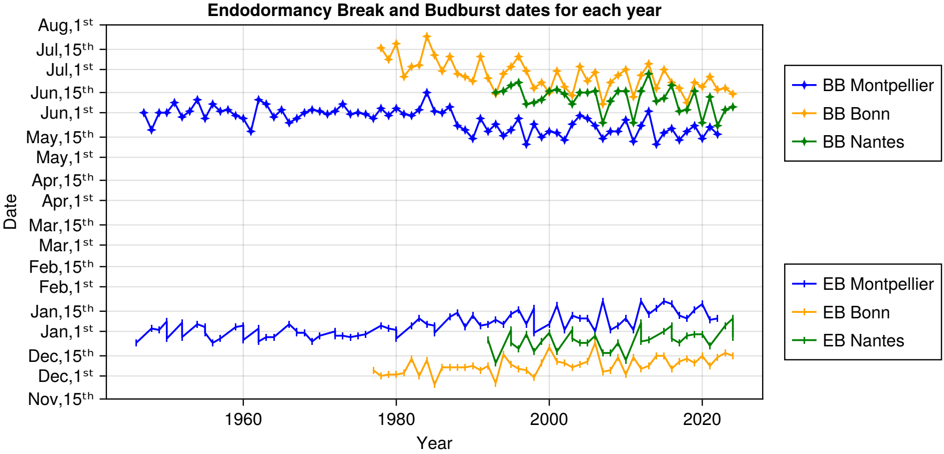
II. Phenological models applied to recorded temperatures

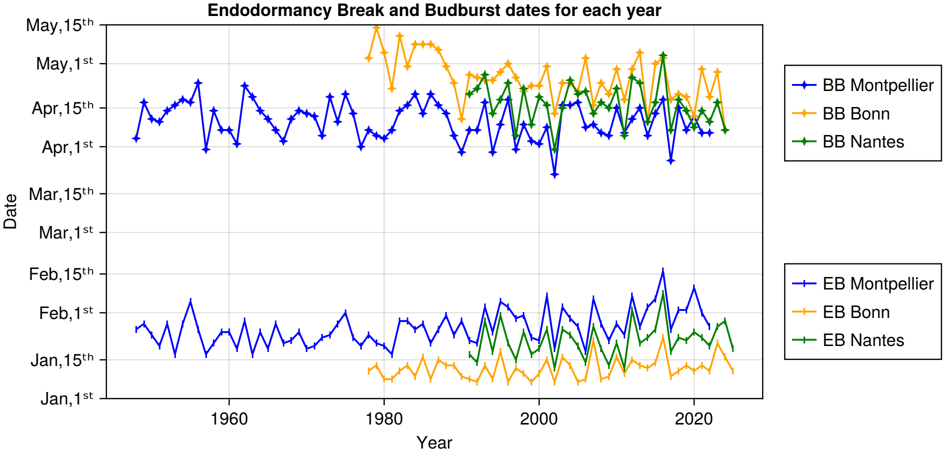
Models used

- For grapevine : **BRIN** (García de Cortázar-Atauri et al. -2009) :
  - Chilling period onset : 1st of August
  - Chilling quantity required C_c : 119.0 (chilling units)
  - Heating quantity required G_{hc} : 13236°C
  - Q_{10c} : 2.17
  - T_{0Bc} : 8.19°C
- For apple (Golden Delicious) : **F 1 Gold 1** (Legave et al. -2013)
  - *CPO* : 30th of October
  - Chilling quantity required C : 56.0 (chilling units)
  - Heating quantity required H : 83.58 (forcing units)
  - Chilling function F_c : Triangular
  - T_c : 1.1°C
  - I_c : 20.°C
  - Forcing function F_h : Exponential
  - T_h : 9.0°C

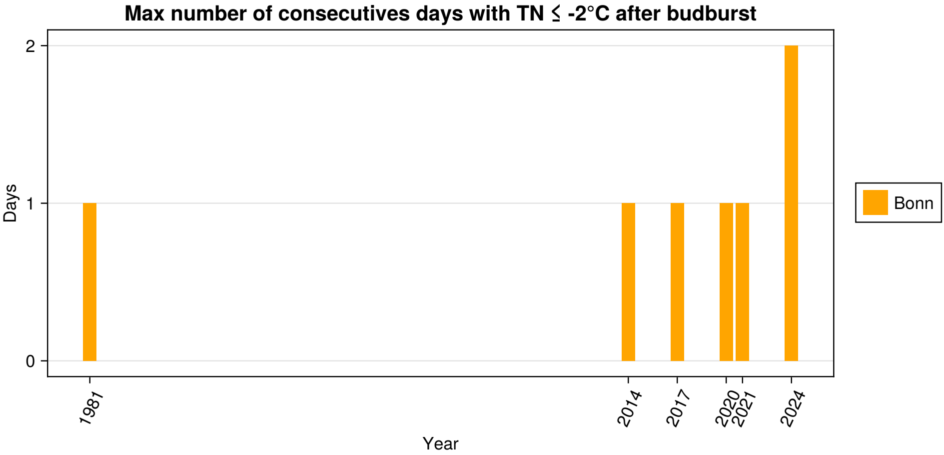


Apple phenology dates predicted for the 2023-2024 period in Bonn.


Endodormancy Break and Budburst dates for each year
Aug,1st
Jul,15th
Jul,1st
Jun,15th
Jun,1st
May,15th
May,1st
Apr,15th
Apr,1st
Mar,15th
Mar,1st
Feb,15th
Feb,1st
Jan,15th
Jan,1st
Dec,15th
Dec,1st
Nov,15th
Date
1960
1980
2000
2020
Year
BB Montpellier
BB Bonn
BB Nantes
EB Montpellier
EB Bonn
EB Nantes

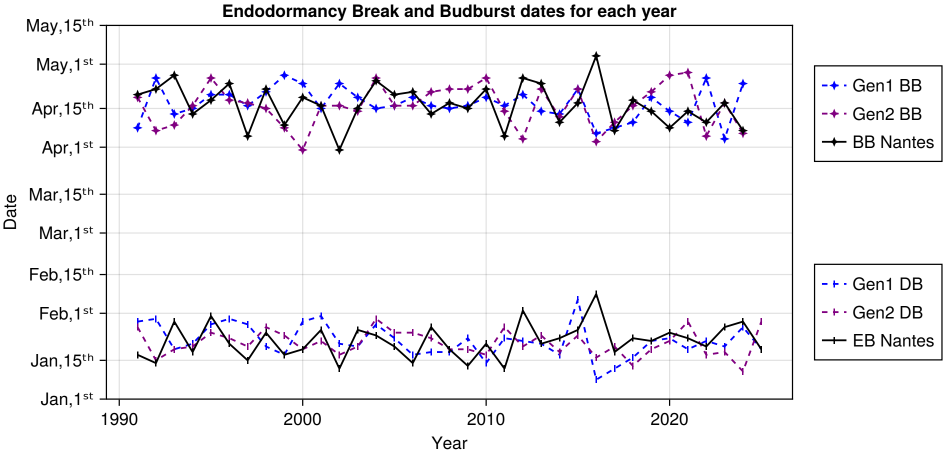

Endodormancy Break and Budburst dates for each year
May,15th
May,1st
Apr,15th
Apr,1st
Mar,15th
Mar,1st
Feb,15th
Feb,1st
Jan,15th
Jan,1st
Date
1960
1980
2000
2020
Year
BB Montpellier
BB Bonn
BB Nantes
EB Montpellier
EB Bonn
EB Nantes

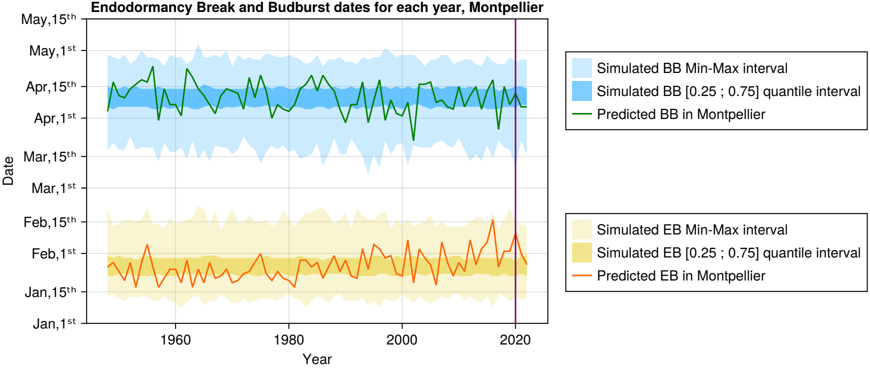
Too early budbursts make the plant vulnerable to a risk of freezing :

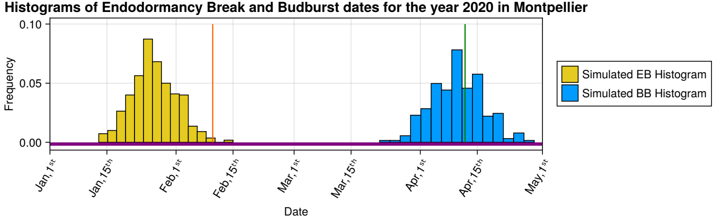


III. Apple phenological model applied to simulated temperatures

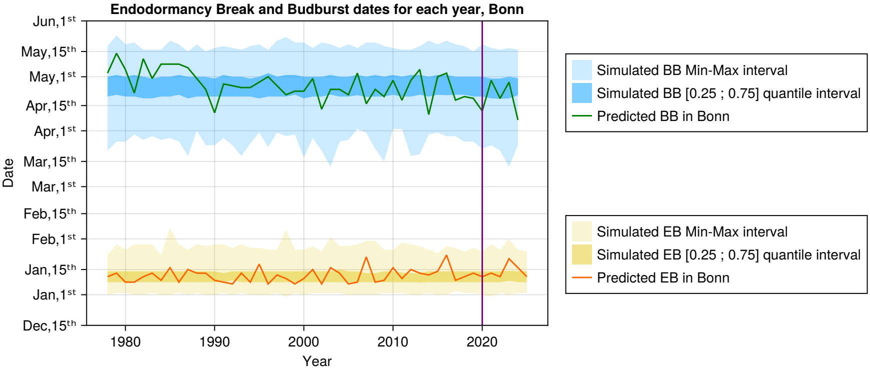
Nantes :

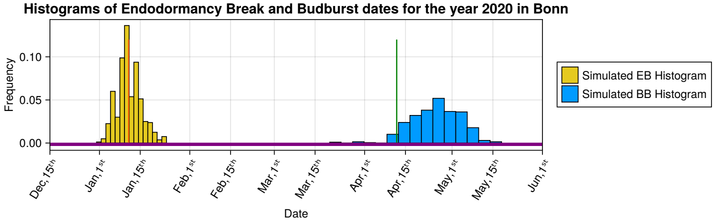

Endodormancy Break and Budburst dates for each year
May,15th
May,1st
Apr,15th
Apr,1st
Mar,15th
Mar,1st
Feb,15th
Feb,1st
Jan,15th
Jan,1st
Date
1990
2000
2010
2020
Year
Gen1 BB
Gen2 BB
BB Nantes
Gen1 DB
Gen2 DB
EB Nantes


Endodormancy Break and Budburst dates for each year, Montpellier
May, 15th
May, 1st
Apr, 15th
Apr, 1st
Mar, 15th
Mar, 1st
Feb, 15th
Feb, 1st
Jan, 15th
Jan, 1st
Date
1960
1980
2000
2020
Year
Simulated BB Min-Max interval
Simulated BB [0.25 ; 0.75] quantile interval
Predicted BB in Montpellier
Simulated EB Min-Max interval
Simulated EB [0.25 ; 0.75] quantile interval
Predicted EB in Montpellier

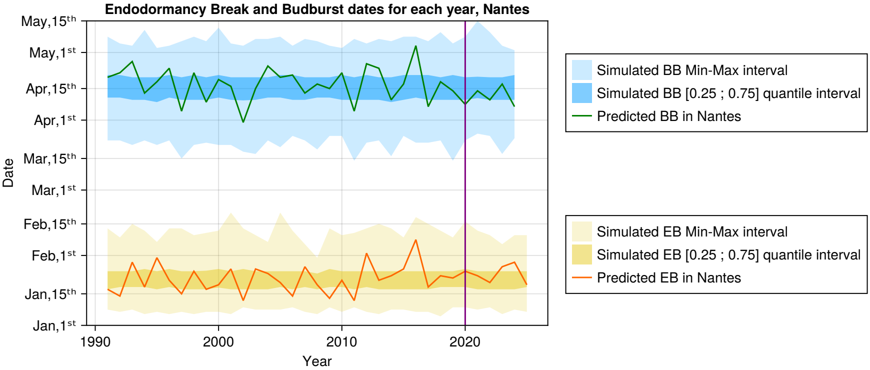

Histograms of Endodormancy Break and Budburst dates for the year 2020 in Montpellier
0.10
0.05
0.00
Frequency
Jan, 1st
Jan, 15th
Feb, 1st
Feb, 15th
Mar, 1st
Mar, 15th
Apr, 1st
Apr, 15th
May, 1st
Date
Simulated EB Histogram
Simulated BB Histogram

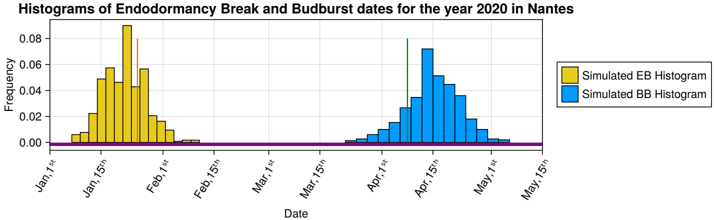
III. Apple phenological model applied to simulated temperatures





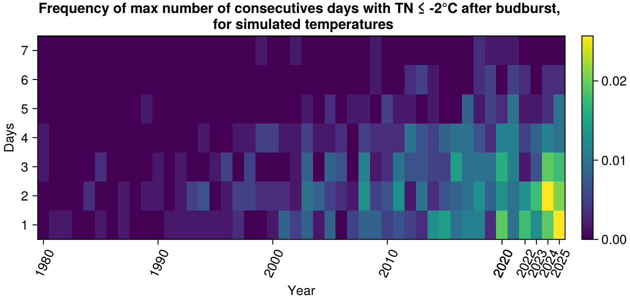
III. Apple phenological model applied to simulated temperatures





Prospects

- Modelising the trend with non-constant values $\longrightarrow$ LOESS regression intended
- Making the SWG able to generate multiple type series correlated (e.g TN and TX or TN and TG) to :
  - Apply grapevine phenology models on generated TN and TX.
  - Model the risk of frost for phenology results from generated series. We can expect results like this :



Thanks you !

Appendix

SWG model details

- Seasonality : Parametric function with a periodicity of 365.25 days :

$$S_t = \mu + \sum_{k=1}^{K} \alpha_k \cos(\omega k t) + \beta_k \sin(\omega k t)$$

With $\omega = 2\pi/365.25$, α_k and β_k coefficients to estimate and K the order ($K = 5$ in our work).

- "Monthly" AR(p) model :

$$X_t = \sum_{i=1}^{p} \phi_{i,m(t)} X_{t-i} + \sigma_{m(t)} \varepsilon_t$$

With $\varepsilon_t \overset{\text{iid}}{\sim} \mathcal{N}(0,1)$ and $m(t)$ the month of the date t.
$\rightarrow (p+1) \times 12$ parameters.

SWG model details

1. **Ordinary Linear Square (OLS) regression** to estimate μ, α_k and β_k for $k = 1, \ldots, K$:

$$T_t = \mu + \sum_{k=1}^{K} (\alpha_k \cos(\omega k t) + \beta_k \sin(\omega k t)) + X_t$$

With X_t the residuals.

2. **Maximum likelihood estimation** on these residuals to estimate $\phi_{i,j}$ and σ_j^2, for $i = 1, 2, \ldots, p$ and $j = 1, 2, \ldots, 12$:

$$X_t = \sum_{i=1}^{p} \phi_{i,m(t)} X_{t-i} + \sigma_{m(t)} \varepsilon_t$$

BRIN model for Grapevine

Endodormancy break date :

$$n_{db} = \min\{N, \sum_{n=CPO}^{N} C_U(n) > C_c\}$$

Budburst date :

$$n_{bb} = \min\{N, \sum_{n=n_{db}}^{N} A_c(n) > G_{hc}\}$$

CPO : Chilling period onset
C_c, G_{hc} : Chilling and heating quantity required
C_U, A_c : Chilling and heating function

Chilling function :

$$C_U(n) = Q_{10c}^{-\frac{TX(n)}{10}} + Q_{10c}^{-\frac{TN(n)}{10}}$$

Heating function :

$$T^*(h,n) = \begin{cases} TN(n) + h\left(\frac{TX(n)-TN(n)}{12}\right) & \text{if } h \leq 12 \\ TX(n) - (h-12)\left(\frac{TX(n)-TN(n+1)}{12}\right) & \text{if } h > 12 \end{cases}$$

$$T(h,n) = \begin{cases} 0 & \text{if } T^*(h,n) < T_{0Bc} \\ T^*(h,n) - T_{0Bc} & \text{if } T_{0Bc} \leq T^*(h,n) \leq T_{MBc} \\ T_{MBc} - T_{0Bc} & \text{if } T_{MBc} < T^*(h,n) \end{cases}$$

$$A_c(n) = \sum_{h=1}^{24} T(h,n)$$

Q_{10c} and T_{0Bc} are parameters and T_{MBc} is fixed at 25°C.

BRIN model for Grapevine

Reminder : parameters considered for our simulation :

- CPO : 1^{st} of August
- C_c : 119.0 (chilling units)
- G_{hc} : 13236°C
- Q_{10c} : 2.17
- T_{0Bc} : 8.19°C

Apple Model

Endodormancy break date :

$$n_{db} = \min\{N, \sum_{n=CPO}^{N} F_c(TG(n)) > C\}$$

Budburst date :

$$n_{bb} = \min\{N, \sum_{n=n_{db}}^{N} F_h(TG(n)) > H\}$$

CPO : Chilling period onset
C, H : Chilling and heating quantity required
F_c, F_h : Chilling and heating function

Reminder : parameters considered for our simulation :

- CPO : 30th of October
- C : 56.0 (chilling units)
- H : 83.58 (forcing units)
- F_c : Triangular chilling

$$F_c(T) = \begin{cases} 1 - (|T - T_c|/I_c) & \text{if } T \in (T_c - I_c, T_c + I_c) \\ 0 & \text{else} \end{cases}$$

With $T_c = 1.1$°C and $I_c = 20.$°C

- F_h : Exponential forcing

$$F_h(T) = \exp(T/T_h)$$

With $T_h = 9.0$°C