

hurricane_posterior

Yijin Wang

2023-04-17

Model

$$Y_i(t+6) = \beta_{0,i} + \beta_{1,i}Y_i(t) + \beta_{2,i}\Delta_{i,1}(t) + \beta_{3,i}\Delta_{i,2}(t) + \beta_{4,i}\Delta_{i,3}(t) + \mathbf{X}_i\gamma + \epsilon_i(t)$$

$$\begin{bmatrix} \beta_{0,i} \\ \beta_{1,i} \\ \beta_{2,i} \\ \beta_{3,i} \\ \beta_{4,i} \end{bmatrix} \sim MVN\left(\begin{bmatrix} \mu_{0,i} \\ \mu_{1,i} \\ \mu_{2,i} \\ \mu_{3,i} \\ \mu_{4,i} \end{bmatrix}, \Sigma\right)$$

$$\epsilon_i \sim N(0, \sigma^2)$$

Priors

1.

$$\begin{bmatrix} \mu_{0,i} \\ \mu_{1,i} \\ \mu_{2,i} \\ \mu_{3,i} \\ \mu_{4,i} \end{bmatrix} \sim MVN\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, V\right)$$

$$f_{\mu_i}(\mu_i) \propto \det(V)^{\frac{-1}{2}} e^{\frac{-1}{2}\mu_i^T V^{-1} \mu_i} \propto e^{\frac{-1}{2}\mu_i^T V^{-1} \mu_i}$$

2.

$$\Sigma \sim W^{-1}(S, \nu = 5)$$

$$f_{\Sigma^{-1}}(\Sigma) \propto |\Sigma^{-1}|^{n+1} e^{\frac{-1}{2}tr(\Sigma^{-1})}$$

where n is the dimension of dataset... this formula might be wrong meh
determinant n dim of of sigma

Wishart

Due to property of Wishart distribution,

$$\Sigma^{-1} \sim W(S^{-1}, \nu = 5)$$

$$f_{\Sigma^{-1}}(\Sigma^{-1}) = |\Sigma^{-1}|^{\frac{\nu-d-1}{2}} \exp\left(-\frac{tr(S\Sigma^{-1})}{2}\right) \propto |\Sigma^{-1}|^{\frac{\nu-5-1}{2}} \exp\left(-\frac{tr(S\Sigma^{-1})}{2}\right)$$

3.

$$\gamma \sim MVN\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, 0.005^2 I_3\right)$$

$$f_\gamma(\gamma) = (3 * 0.005^2)^{-1/2} \exp\left(-\frac{\gamma^\top 0.005^2 I_3 \gamma}{2}\right) \propto \exp\left(-\frac{400 \gamma^\top \gamma}{2}\right)$$

4.

$$\sigma \sim Half - Cauchy(0, 10)$$

$$f_\sigma(\sigma) = \frac{2 * 10}{\pi(\sigma^2 + 10^2)}$$

By transformation theorem

$$f_{\sigma^2}(\sigma^2) = \frac{2 * 10}{\pi(\sigma^2 + 10^2)} \left| \frac{\sigma}{2} \right|$$

Likelihood

Because random effects coefficients β_i is normal, $Y_i|\beta_i$ also follows a normal distribution by property of normal distribution.

For each hurricane Y_i

$$Y_i|\beta_i, \mu_i, \sigma^2, \Sigma, \gamma \sim MVN(\beta_{0,i} + \beta_{1,i}Y_i(t) + \beta_{2,i}\Delta_{i,1}(t) + \beta_{3,i}\Delta_{i,2}(t) + \beta_{4,i}\Delta_{i,3}(t) + \mathbf{X}_i\gamma, \sigma^2 I_i)$$

$$= MVN(D_i\beta_i + X_i\gamma, \sigma^2 I_{n_i})$$

where

$$Y_i = \begin{bmatrix} Y_i(t=6) \\ Y_i(t=7) \\ \vdots \\ Y_i(t=t_j+6) \\ \vdots \\ Y_i(t=n_i+5) \end{bmatrix}_{n_i \times 1}$$

$$D_i(t) = \begin{bmatrix} 1 & Y_i(t) & \Delta_{i,1}(t) & \Delta_{i,2}(t) & \Delta_{i,3}(t) \end{bmatrix}$$

$$= \begin{bmatrix} 1 & Y_i(t=0) & \Delta_{i,1}(t=0) & \Delta_{i,2}(t=0) & \Delta_{i,3}(t=0) \\ 1 & Y_i(t=1) & \Delta_{i,1}(t=1) & \Delta_{i,2}(t=1) & \Delta_{i,3}(t=1) \\ \cdots & & & & \\ 1 & Y_i(t=t_j) & \Delta_{i,1}(t=t_j) & \Delta_{i,2}(t=t_j) & \Delta_{i,3}(t=t_j) \\ \cdots & & & & \\ 1 & Y_i(t=n_i-1) & \Delta_{i,1}(t=n_i-1) & \Delta_{i,2}(t=n_i-1) & \Delta_{i,3}(t=n_i-1) \end{bmatrix}_{n_i \times 5}$$

$$\beta_i = \begin{bmatrix} \beta_{0,i} \\ \beta_{1,i} \\ \beta_{2,i} \\ \beta_{3,i} \\ \beta_{4,i} \end{bmatrix}$$

$$X_i = \begin{bmatrix} x_{i,1} & x_{i,2} & x_{i,3} \end{bmatrix}_{1 \times 3}$$

$$\gamma = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix}_{3 \times 1}$$

Likelihood for the i th hurricane is

$$f(Y_i|\beta_i, \mu_i, \sigma^2, \Sigma, \gamma) = \det(\sigma^2 I_{n_i})^{-1/2} \exp\left(-\frac{(Y_i - D_i \beta_i - X_i \gamma)^\top (Y_i - D_i \beta_i - X_i \gamma)}{2\sigma^2}\right)$$

To calculate the joint likelihood for $Y = [Y_1 \ Y_2 \dots Y_i \dots Y_H]^\top$, we denote total number of observations for all hurricanes as $N = \sum_{i=1}^H n_i$ where n_i is the total number of observation for the i th hurricane and H is the total number of hurricanes.

All random effects coefficients β_i in

$$B = \begin{bmatrix} \beta_1 & \beta_2 & \dots & \beta_i & \dots & \beta_H \end{bmatrix}$$

$$= \begin{bmatrix} \beta_{0,1} & \beta_{0,2} & \dots & \beta_{0,i} & \dots & \beta_{0,H} \\ \beta_{1,1} & \beta_{1,2} & \dots & \beta_{1,i} & \dots & \beta_{1,H} \\ \beta_{2,1} & \beta_{2,2} & \dots & \beta_{2,i} & \dots & \beta_{2,H} \\ \beta_{3,1} & \beta_{3,2} & \dots & \beta_{3,i} & \dots & \beta_{3,H} \\ \beta_{4,1} & \beta_{4,2} & \dots & \beta_{4,i} & \dots & \beta_{4,H} \end{bmatrix}_{5 \times H}$$

Design matrix for random effects for all hurricanes are in D . $D = \begin{bmatrix} D_1(t) \\ D_2(t) \\ \vdots \\ D_i(t) \\ \vdots \\ D_H(t) \end{bmatrix}_{N \times 5}$

Due to independence of each hurricane, the joint likelihood is

$$\begin{aligned} L_Y(B, \mu, \sigma^2, \Sigma, \gamma) &= \prod_{i=1}^H L_{Y_i}(\beta_i, \mu, \sigma^2, \Sigma, \gamma) \\ &= \prod_{i=1}^H \det(\sigma^2 I_{n_i})^{-1/2} \exp\left(-\frac{(Y_i - D_i \beta_i - X_i \gamma)^\top (Y_i - D_i \beta_i - X_i \gamma)}{2\sigma^2}\right) \\ &= \frac{1}{\sigma^N} \exp\left(-\frac{(Y - DB - X\gamma)^\top (Y - DB - X\gamma)}{2\sigma^2}\right) \end{aligned}$$

Posterior

By Baye's Rule

$$f(B, \mu, \sigma^2, \Sigma, \gamma|Y) \propto f(Y|B, \mu, \sigma^2, \Sigma, \gamma) \times f(B|\mu, \Sigma) \times f(\mu) \times f(\Sigma) \times f(\sigma^2) \times f(\gamma)$$

where

$$\mu = \begin{bmatrix} \mu_1 & \mu_2 & \dots & \mu_i & \dots & \mu_H \end{bmatrix}$$

$$= \begin{bmatrix} \mu_{0,1} & \mu_{0,2} & \dots & \mu_{0,i} & \dots & \mu_{0,H} \\ \mu_{1,1} & \mu_{1,2} & \dots & \mu_{1,i} & \dots & \mu_{1,H} \\ \mu_{2,1} & \mu_{2,2} & \dots & \mu_{2,i} & \dots & \mu_{2,H} \\ \mu_{3,1} & \mu_{3,2} & \dots & \mu_{3,i} & \dots & \mu_{3,H} \\ \mu_{4,1} & \mu_{4,2} & \dots & \mu_{4,i} & \dots & \mu_{4,H} \end{bmatrix}_{5 \times H}$$

$$\begin{aligned}
f(B|\mu, \Sigma) &= \prod_{i=1}^H f(\beta_i|\mu_i, \Sigma) \\
&= \prod_{i=1}^H \det(\Sigma)^{-1/2} \exp\left(-\frac{(\beta_i - \mu_i)^\top \Sigma^{-1} (\beta_i - \mu_i)}{2}\right) \\
&= \det(A)^{H/2} \prod_{i=1}^H \exp\left(-\frac{(\beta_i - \mu_i)^\top A (\beta_i - \mu_i)}{2}\right)
\end{aligned}$$

where $A = \Sigma^{-1}$

$$\begin{aligned}
f(\mu) &= \prod_{i=1}^H f_{\mu_i}(\mu_i) \\
&= \prod_{i=1}^H \det(V)^{-\frac{1}{2}} \exp\left(-\frac{\mu_i^\top V^{-1} \mu_i}{2}\right) \\
&= \det(V)^{-\frac{H}{2}} \prod_{i=1}^H \exp\left(-\frac{\mu_i^\top V^{-1} \mu_i}{2}\right)
\end{aligned}$$

We'll only use $f_{\Sigma^{-1}}$ because only Σ^{-1} shows up in the likelihood equation. We denote $A = \Sigma^{-1}$ in the posterior.

$$\begin{aligned}
f_{\Sigma^{-1}}(\Sigma^{-1}) &\propto |\Sigma^{-1}|^{\frac{\nu-5-1}{2}} \exp\left(-\frac{\text{tr}(S\Sigma^{-1})}{2}\right) \\
f_{\sigma^2}(\sigma^2) &= \frac{2 * 10}{\pi(\sigma^2 + 10^2)} \left|\frac{\sigma}{2}\right| \\
f_{\gamma}(\gamma) &= \exp\left(-\frac{400\gamma^\top \gamma}{2}\right)
\end{aligned}$$

Final posterior

$$\begin{aligned}
f(B, \mu, \sigma^2, \Sigma, \gamma|Y) &\propto f(Y|B, \mu, \sigma^2, \Sigma, \gamma) \times f(B|\mu, \Sigma) \times f(\mu) \times f(\Sigma^{-1}) \times f(\sigma^2) \times f(\gamma) \\
&= f(Y|B, \mu, \sigma^2, \Sigma, \gamma) \times f(B|\mu, A) \times f(\mu) \times f(A) \times f(\sigma^2) \times f(\gamma) \\
&= \frac{1}{\sigma^N} \exp\left(-\frac{(Y - DB - X\gamma)^\top (Y - DB - X\gamma)}{2\sigma^2}\right) \times \\
&\quad \det(A)^{H/2} \prod_{i=1}^n \exp\left(-\frac{(\beta_i - \mu_i)^\top A (\beta_i - \mu_i)}{2}\right) \times \\
&\quad \det(V)^{-\frac{H}{2}} \prod_{i=1}^n \exp\left(-\frac{\mu_i^\top V^{-1} \mu_i}{2}\right) \times \\
&\quad |A|^{\frac{\nu-5-1}{2}} \exp\left(-\frac{\text{tr}(SA)}{2}\right) \times \\
&\quad \frac{2 * 10}{\pi(\sigma^2 + 10^2)} \left|\frac{\sigma}{2}\right| \times \\
&\quad \exp\left(-\frac{400\gamma^\top \gamma}{2}\right)
\end{aligned}$$