19th-century atmospheric circulation revealed by old tide gauges

Data Science pour les risques côtiers, November 15th, 2023

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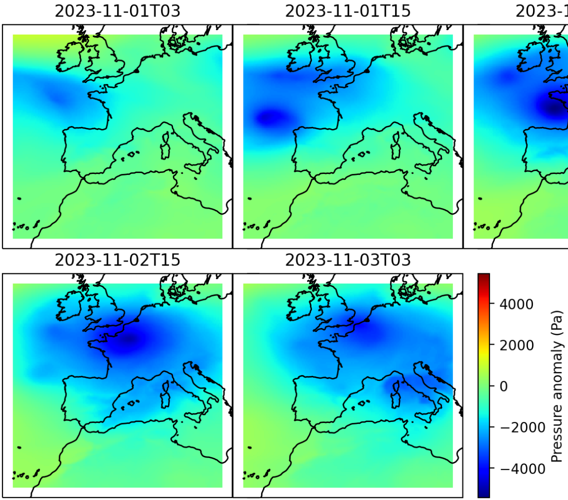
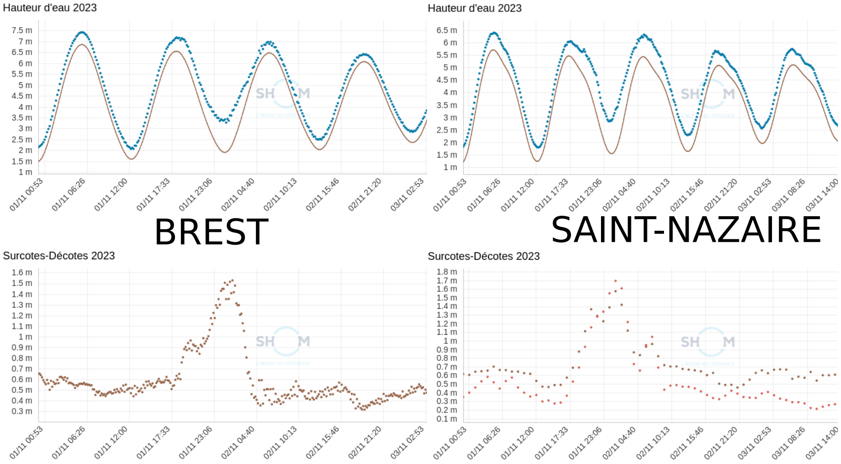
Ciaran : mean-sea-level pressure anomaly



Source : ERA5-reanalysis

Ciaran : sea-level (storm surge) in Brest and Saint-Nazaire



Source : `https://data.shom.fr/donnees/refmar/3`

Inverse problem

Surge forecasting :

$$\text{“storm} \implies \text{surge”}$$

in the future

Inverse problem

Surge forecasting :

"storm $\implies$ surge"
in the future

This presentation :

"surge $\implies$ storm"
in the past

Inverse problem

Surge forecasting :

"storm $\Longrightarrow$ surge"
in the future

This presentation :

"surge $\Longrightarrow$ storm"
in the past

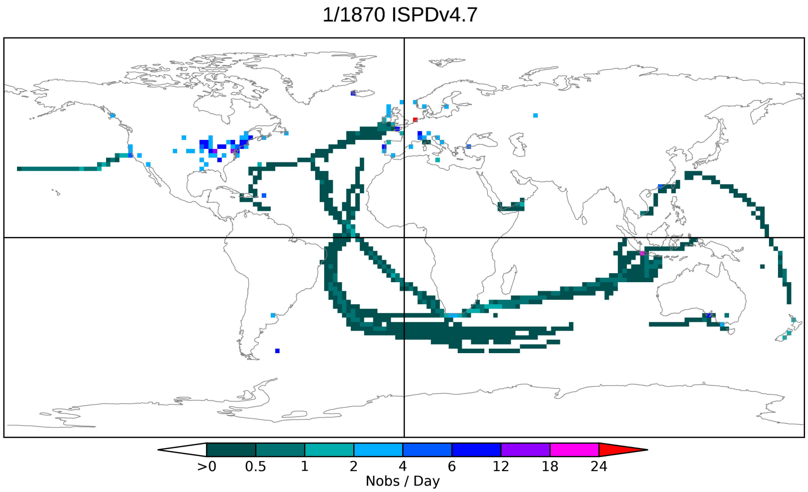
"Can early tide gauges bring new information on the local state of the atmosphere in the 19th century, relative to existing surface pressure records ?"

Surface pressure observations in the 19th century

International Surface Pressure Databank (ISPD) : surface pressure observations (boats, land stations...) assimilated in the Twentieth Century Reanalysis (20CR), 1806-2015.

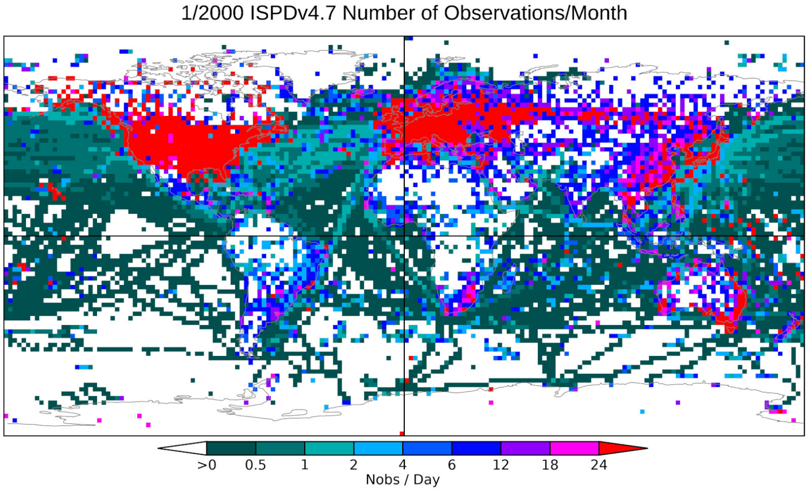
20CR : atmospheric reanalysis (NOAA), assimilates surface pressure, prescribes sea-surface temperature and ice cover, Ensemble Kalman Filter (80 members), 1806-2015, 2° horizontal resolution.

Surface pressure observations in the 19th century

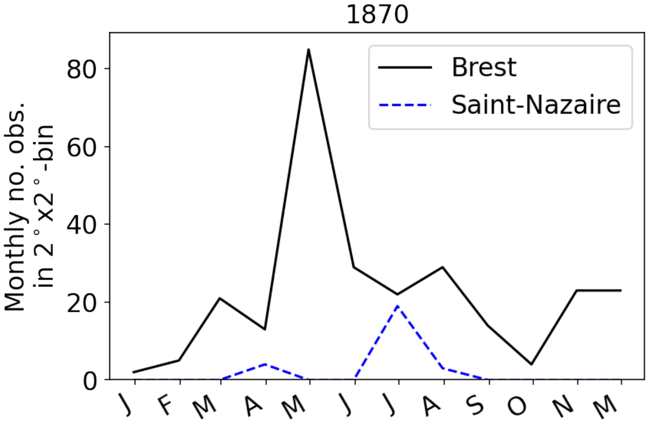


NOAA/PSL & CU/CIRES

Surface pressure observations in the 19th century



Surface pressure observations in the 19th century

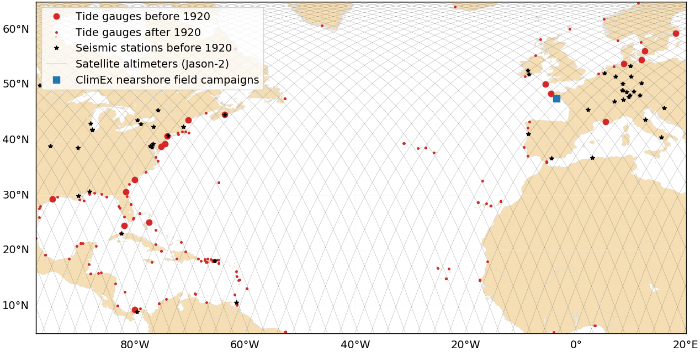


Surface pressure observations in Brest and Saint-Nazaire ?

Saint-Nazaire : none in 19th century ?
Brest : 1861-1881 (Ansell et al., 2006), then Guipavas 1945-now ?

Tide gauge records

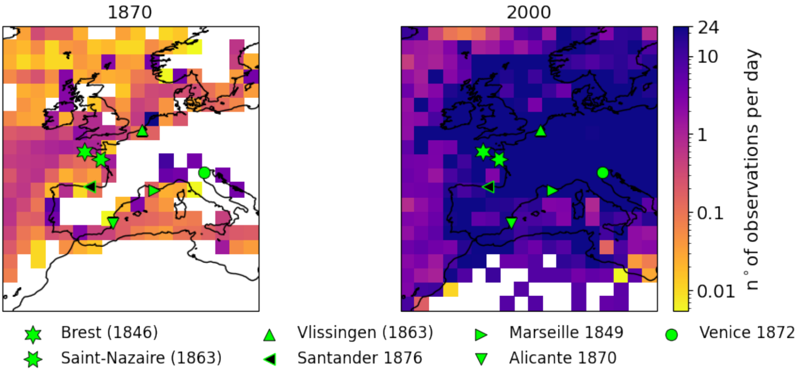
Numerous & often date back to *early-20th* or *mid-19th* centuries.



(Data used in ClimEx project.)

Tide gauge records

Numerous & often date back to *early-20th* or *mid-19th* centuries.



Tide gauge records

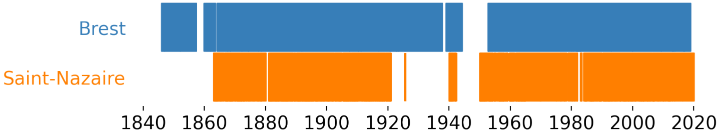
Numerous & often date back to *early-20th* or *mid-19th* centuries.

Sampling : hourly - daily.

Data continuity issues (tide gauge replaced or moved, land movement).

Tide gauge records

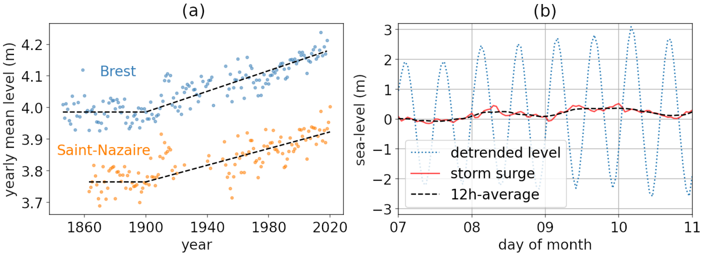
Brest and Saint-Nazaire.
Hourly data.



Tide gauge records

Allow to estimate the **detrended surge**

$$\text{surge} = \text{observed sea level} - (\text{ predicted tide} + \text{linear trend }) \quad (1)$$



which is highly linked to sub-seasonal, regional-scale pressure-system variability (**storms** and **anticyclones**) through *at least* :

- Hydrostatic pressure balance (low atmospheric P → high surge)
- Geostrophic wind (wind towards the coast → high surge)

Scientific question and strategy

"Can early tide gauges bring new information on the local state of the atmosphere in the 19th century, relative to existing surface pressure records ?"

Scientific question and strategy

"Can early tide gauges bring new information on the local state of the atmosphere in the 19th century, relative to existing surface pressure records ?"

- Data :
  1. Tide gauge records of Brest and Saint-Nazaire
  2. 20th century reanalysis (20CR)
- Methods :
  1. Linear regression
  2. Hidden Markov Model
  3. "Analogues"

Sub-question

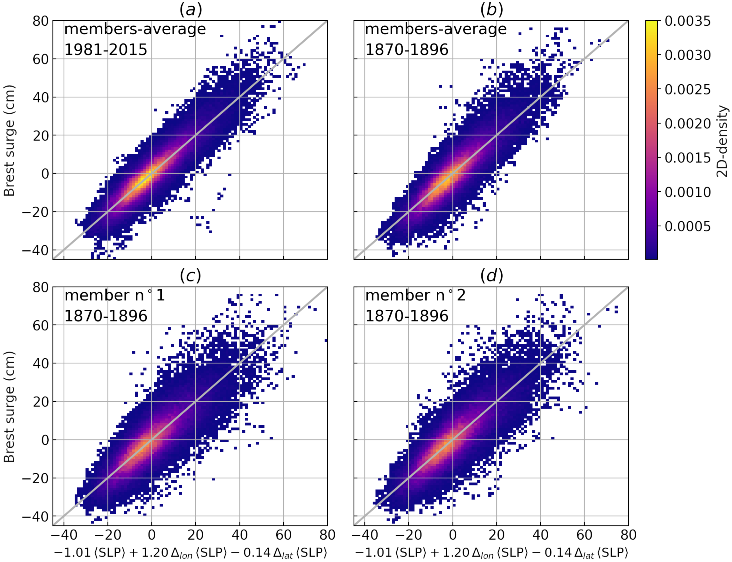
"Is the statistical relationship between observed surges and 20CR sea-level pressure steady ?"

Method = **linear regression**.

- Response variable : *computed using T-Tide and & 12h-averaged*
  - surge(t)

- Explanatory variables :
  - $SLP_{\text{Brest}}(t) := SLP(\text{lon}, \text{lat}, t)$
  - $\Delta_{\text{lon}} SLP(t) := SLP(\text{lon}+2, \text{lat}, t) - SLP(\text{lon}-2, \text{lat}, t)$
  - $\Delta_{\text{lat}} SLP(t) := SLP(\text{lon}, \text{lat}+2, t) - SLP(\text{lon}, \text{lat}-2, t)$

Linear regression : 19th century vs. satellite-era



Sub-conclusion

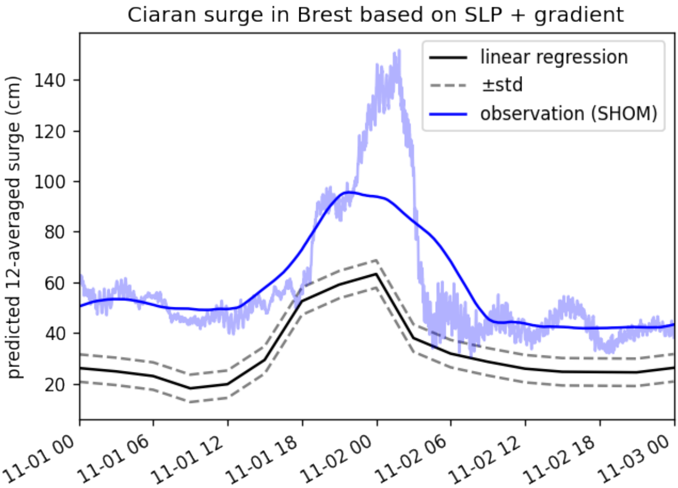
- The linear statistical relationship between the surge and local SLP from 20CRv3 is very similar when comparing periods 1870-1895 and 1981-2015 : physical mechanisms are steady.

  $\rightarrow$ external validation of 20CRv3 from the tide gauges

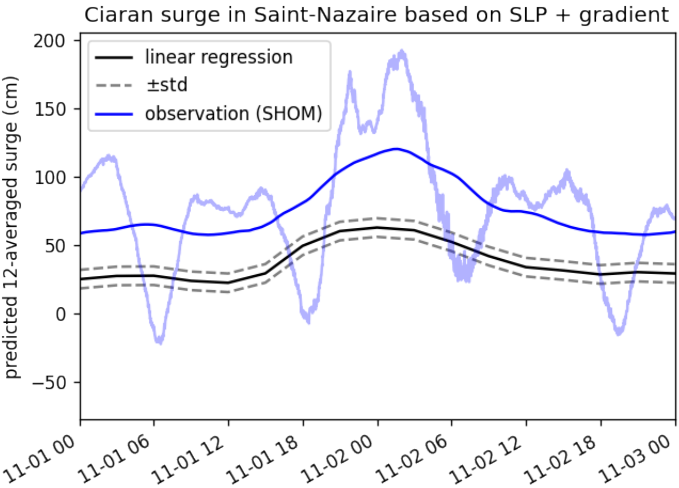
- Differences in the relationship can be explained by the scarcity of surface pressure observations constraining the 20CRv3 ensemble members.

  $\rightarrow$ potential complementary information in the tide gauges !

LR : Ciaran ?


Ciaran surge in Brest based on SLP + gradient
linear regression
±std
observation (SHOM)
predicted 12-averaged surge (cm)
140
120
100
80
60
40
20
11-01 00
11-01 06
11-01 12
11-01 18
11-02 00
11-02 06
11-02 12
11-02 18
11-03 00

LR : Ciaran ?

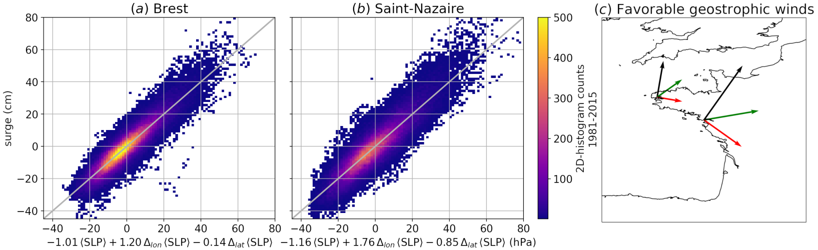

Ciaran surge in Saint-Nazaire based on SLP + gradient
linear regression
±std
observation (SHOM)
predicted 12-averaged surge (cm)
200
150
100
50
0
−50
11-01 00
11-01 06
11-01 12
11-01 18
11-02 00
11-02 06
11-02 12
11-02 18
11-03 00

Sub-question

"Can tide gauge observations help identify (un)likely members ?"

Method = **Hidden Markov Model** (HMM) + linear regression.

Linear Regression



Surge-conditional probabilities for 20CRv3 members

Probabilities can be derived directly from the satellite-era LR :

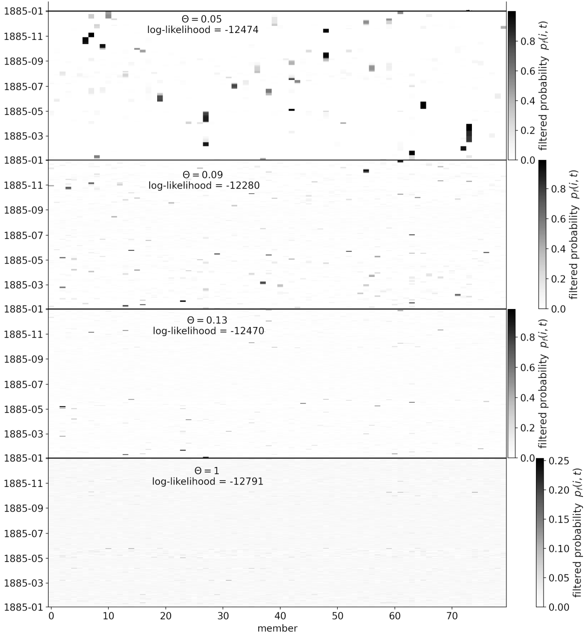
$$
\begin{aligned}
p_{\cancel{\mathrm{HMM}}}(i,t) &= \mathbb{P}\left\{\text{member i } (t) \,|\, \text{surge } (t)\right\} \\
&\overset{\text{hyp}}{=} \mathbb{P}\left\{\, [SLP_{\mathrm{Brest}}, \Delta_{\mathrm{lon}} SLP, \Delta_{\mathrm{lat}} SLP]\,(i,t) \,|\, \text{surge } (t) \,\right\} \\
&\overset{\text{Bayes}}{\propto} \mathbb{P}\left\{\, \text{surge } (t) \,|\, [SLP_{\mathrm{Brest}}, \Delta_{\mathrm{lon}} SLP, \Delta_{\mathrm{lat}} SLP]\,(i,t) \,\right\}
\end{aligned}
$$

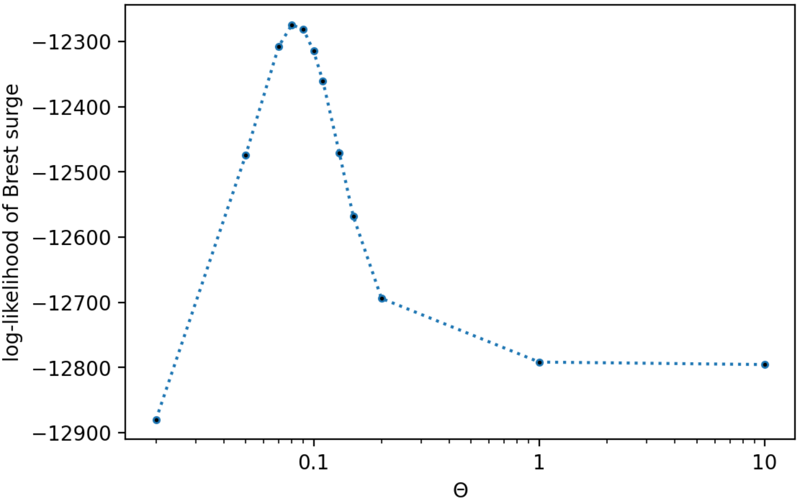
Then, using a Hidden Markov Model.

$$
\mathbb{P}\left\{(i\,, t-1) \to (j\,, t)\right\} \overset{\text{hyp}}{\propto} K_\theta\left(SLP_{\mathrm{map}}(i,t), SLP_{\mathrm{map}}(j,t)\right)
$$

One estimates filtered probabilities using a forward-backward algorithm :

$$
p_{\mathrm{HMM}}(i,t) = \mathbb{P}\left\{\text{member i } (t) \,|\, \text{surge } (0,\ldots,T)\right\}
$$


Θ = 0.05
log-likelihood = -12474
Θ = 0.09
log-likelihood = -12280
Θ = 0.13
log-likelihood = -12470
Θ = 1
log-likelihood = -12791
filtered probability $p_f(i,t)$
member
1885-01
1885-03
1885-05
1885-07
1885-09
1885-11
0
10
20
30
40
50
60
70
0.0
0.2
0.4
0.6
0.8
0.00
0.05
0.10
0.15
0.20
0.25



log-likelihood of Brest surge
−12300
−12400
−12500
−12600
−12700
−12800
−12900
0.1
1
10
Θ

Average differences from surge-conditional probabilities :

$$\delta\mu_{\text{HMM}}(t) = \sum_{i=1}^{80}(p_{\text{HMM}}(i,t) - \frac{1}{80})SLP(i,t)$$

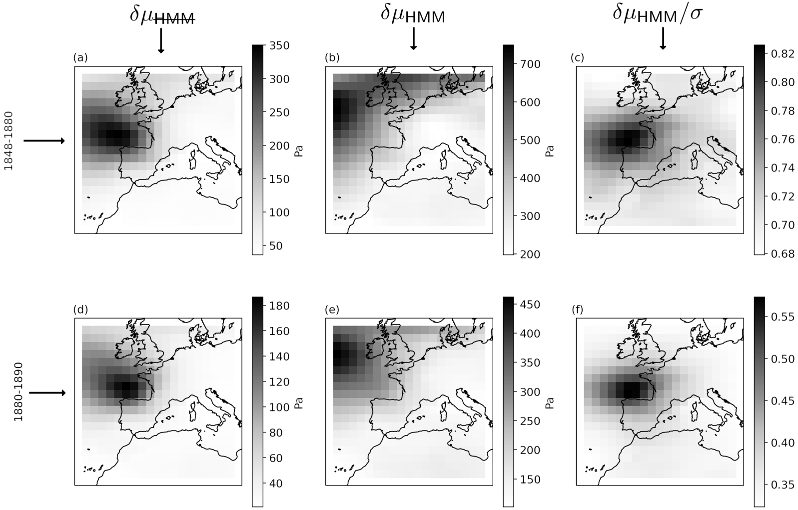
$$\delta\mu_{\text{HMM}}(t) = \sum_{i=1}^{80}(p_{\text{HMM}}(i,t) - \frac{1}{80})SLP(i,t)$$

Standard-deviation of the reanalysis ensemble :

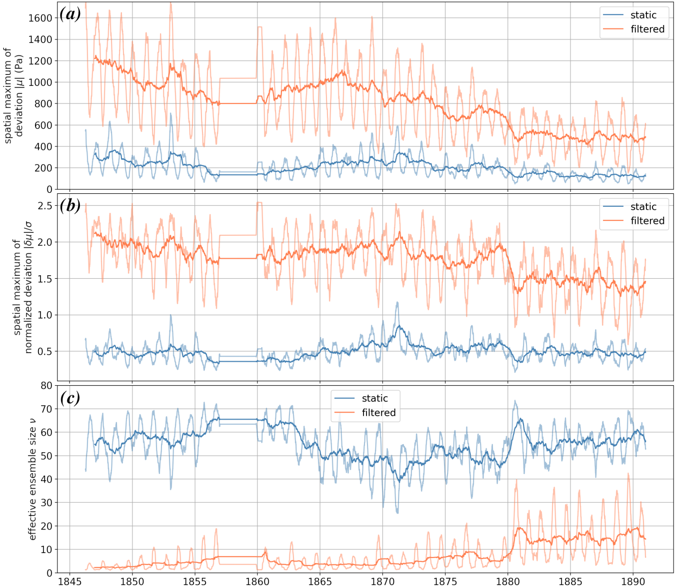
$$\sigma(t) = \left(\frac{1}{80}\sum_{i=1}^{80}\left[SLP(i,t) - \frac{1}{80}\sum_{j=1}^{80}SLP(j,t)\right]^2\right)^{1/2}$$

Effective ensemble size :

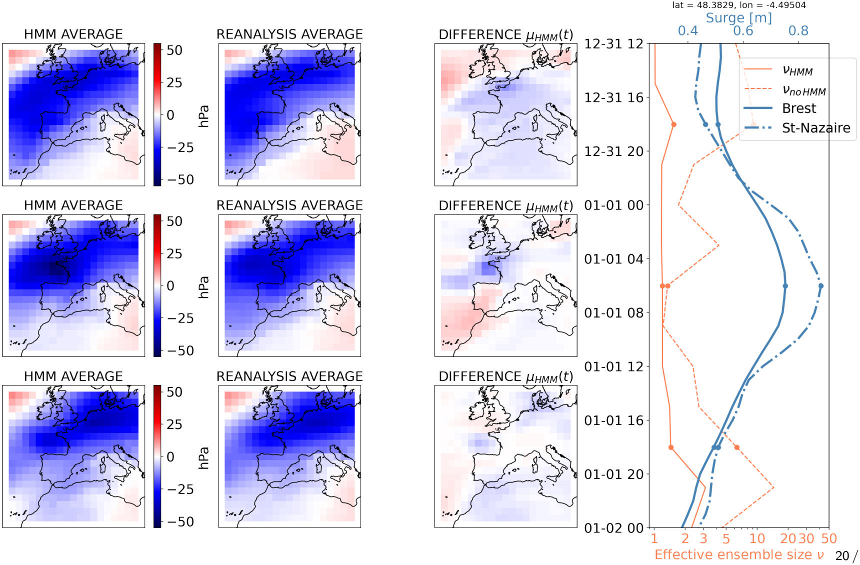
$$\nu_{\text{HMM}}(t) = \frac{1}{\sum_{i=1}^{80} p_{\text{HMM}}(i,t)^2}$$



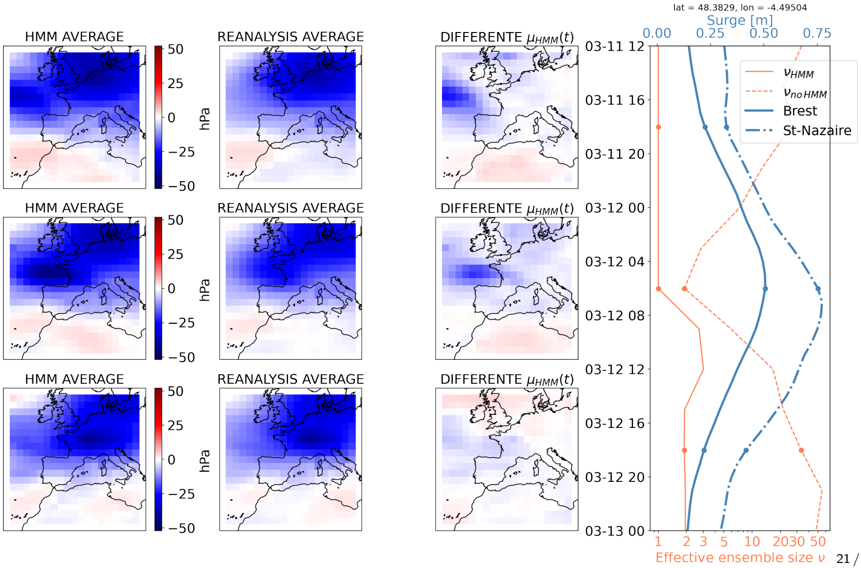
$\delta\mu_{\cancel{\mathrm{HMM}}}$
$\delta\mu_{\mathrm{HMM}}$
$\delta\mu_{\mathrm{HMM}}/\sigma$
1848-1880
1880-1890
(a)
(b)
(c)
(d)
(e)
(f)
Pa


(a)
spatial maximum of deviation |μ| (Pa)
static
filtered
(b)
spatial maximum of normalized deviation |δμ|/σ
static
filtered
(c)
effective ensemble size ν
static
filtered
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890

January 1877



Lothar's big brother (1876)



Sub-question

"Can tide gauge observations *alone* be used to estimate the atmosphere in the 19th century ? How would this compare to 20CRv3 ?"

Method = **Analogue upscaling**.

Analogue upscaling from surge events : framework (1/2)

We estimate the conditional distribution of SLP map :

$$\mathrm{d}\mathbb{P}\left(SLP_{map}(t)\,\middle|\,\text{surges in Brest and Saint-Nazaire }(t)\right), \tag{2}$$

To define the "surge state in Brest and Saint-Nazaire", we define the surge vector :

$$S_v(t) := \begin{pmatrix} s_B(t) \\ s_B(t) - s_B(t-1) \\ s_{SN}(t) \\ s_{SN}(t) - s_{SN}(t-1) \end{pmatrix} \tag{3}$$

We search for analogues of surge vector $S_v(t \in [1870 - 1896])$ using the satellite-era catalog $\mathcal{C}$:

$$\mathcal{C} = \{(S_v(t'), SLP_{map}(t'))\ , t' \in [1981 - 2015]\}\ . \tag{4}$$

Analogue upscaling from surge events : framework (2/2)

We give weight $\omega_k[S_v(t)]$ to analogue number k depending on calendar distance and distance in S_v-space. This allows to estimate a *static* analogue generator :

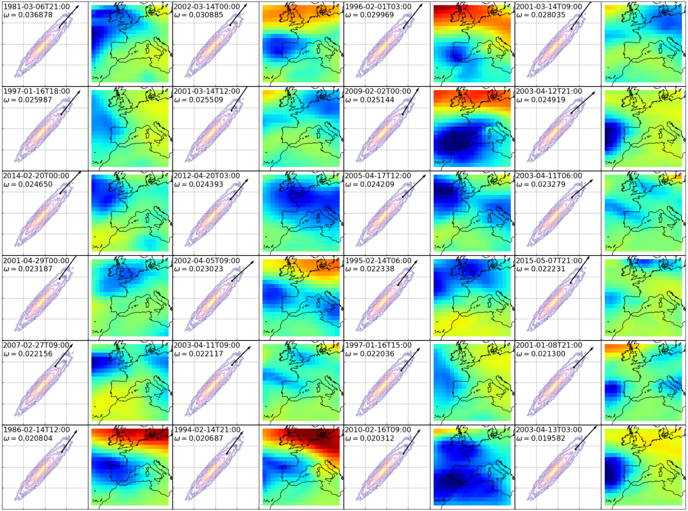
$$\mathrm{d}\mathbb{P}\left(SLP_{map}(t)|S_v(t)\right) \approx \sum_{k=1}^{n} \omega_k[S_v(t)]\, \delta\left\{SLP_{map}(I_k[S_v(t)])\right\}\,, \qquad (5)$$

Using a filtering window $f(\mathrm{d}t)$, we define the *dynamic* analogue generator :

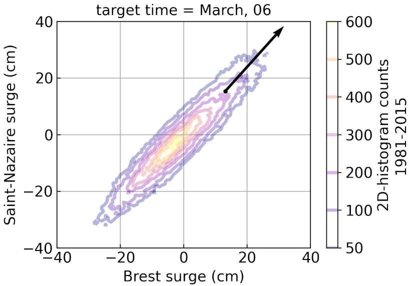
$$\mathrm{d}\mathbb{P}\left(SLP_{map}(t)|S_v(t-\tau)\ldots S_v(t+\tau)\right) \approx$$

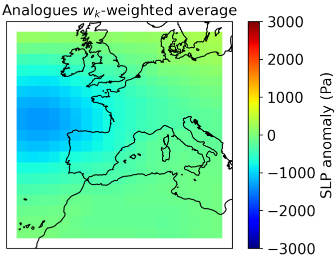
$$\sum_{\mathrm{d}t=-\tau}^{\tau} f(\mathrm{d}t) \sum_{k=1}^{n} \omega_k[S_v(t+\mathrm{d}t)]\ \delta\left\{SLP_{map}(I_k[S_v(t+\mathrm{d}t)]-\mathrm{d}t)\right\}\,. \qquad (6)$$

Ideal example 1



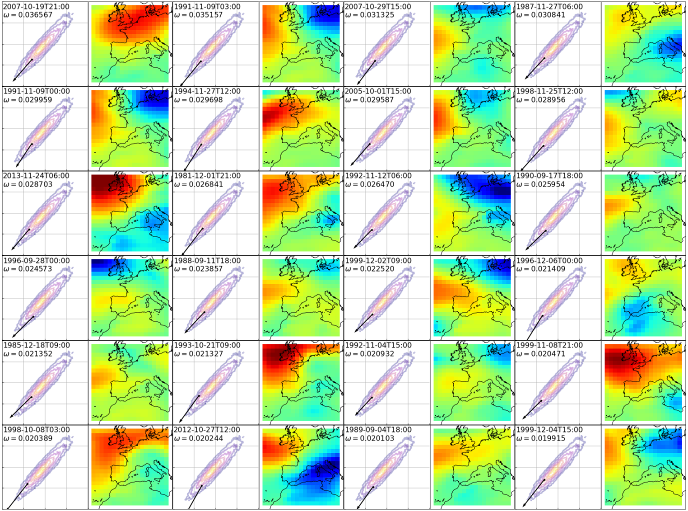
Ideal example 1



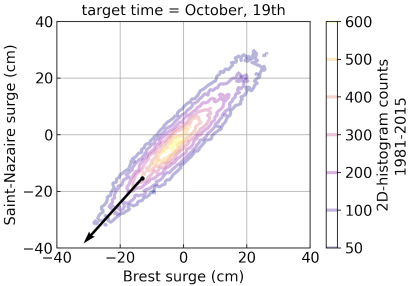


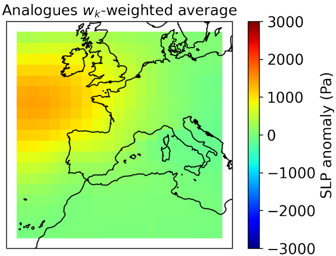
Note : sub-classes of analogues ?

Ideal example 2

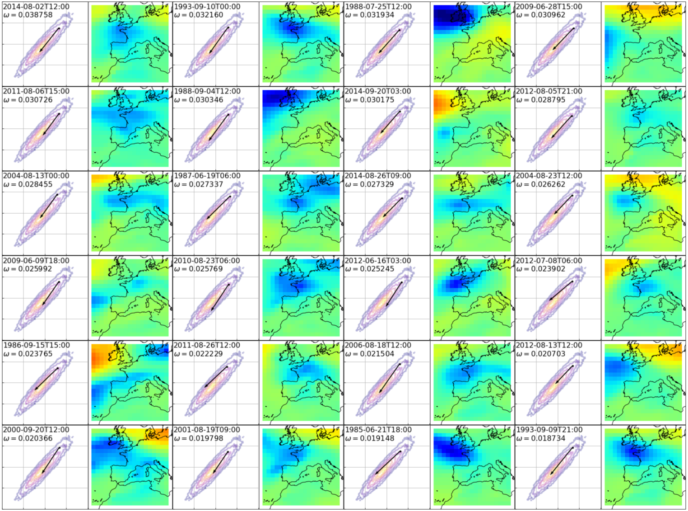


Ideal example 2

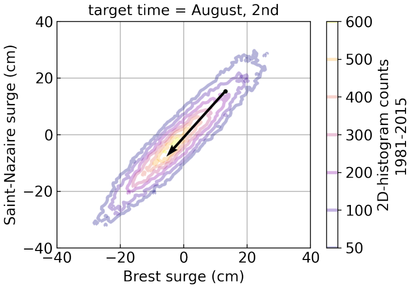


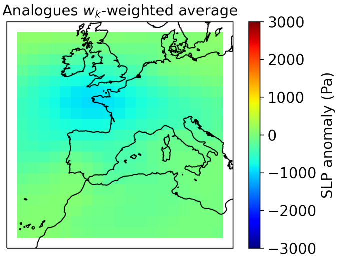


Ideal example 3

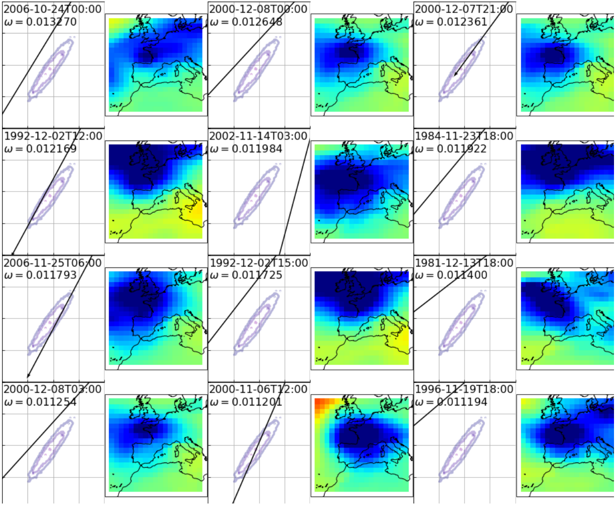


Ideal example 3

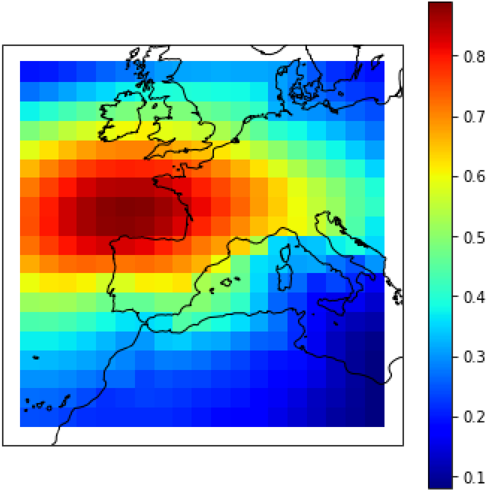




Ciaran !

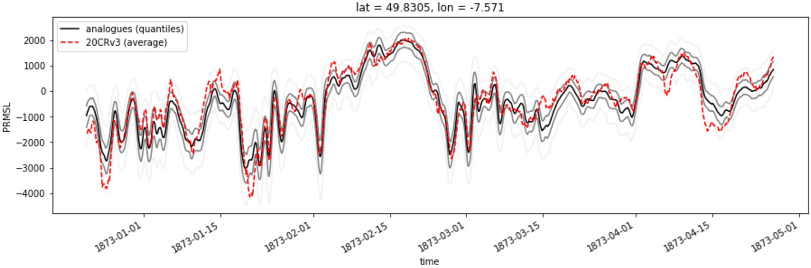

2006-10-24T00:00
ω = 0.013270
2000-12-08T00:00
ω = 0.012648
2000-12-07T21:00
ω = 0.012361
1992-12-02T12:00
ω = 0.012169
2002-11-14T03:00
ω = 0.011984
1984-11-23T18:00
ω = 0.011922
2006-11-25T06:00
ω = 0.011793
1992-12-02T15:00
ω = 0.011725
1981-12-13T18:00
ω = 0.011400
2000-12-08T03:00
ω = 0.011254
2000-11-06T12:00
ω = 0.011201
1996-11-19T18:00
ω = 0.011194

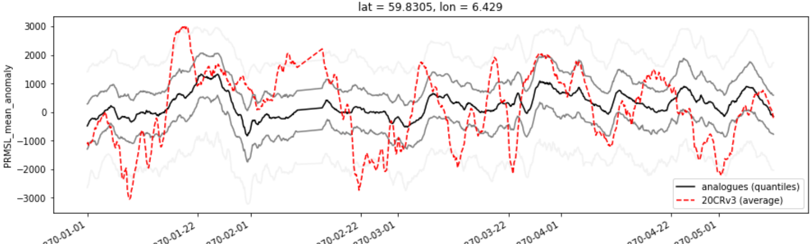
Correlation between analogue's average and 20CRv3 average 1870-1896



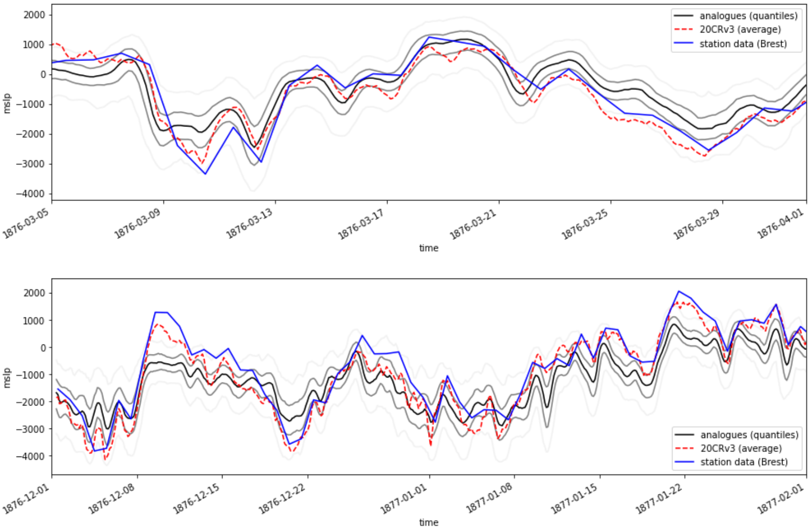
Time series : analogue quantiles vs 20CRv3 average

Quantiles : .05 | .25 | .5 | .75 | .95

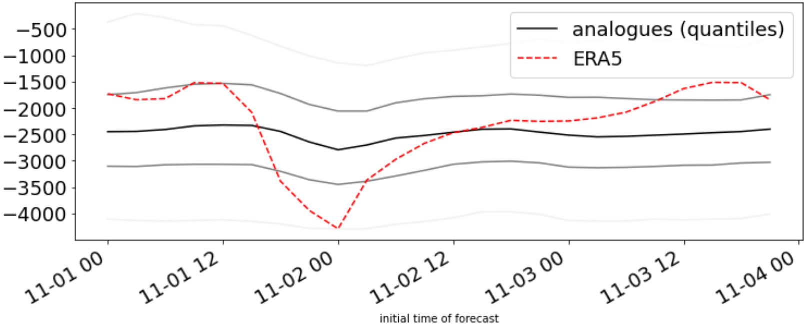




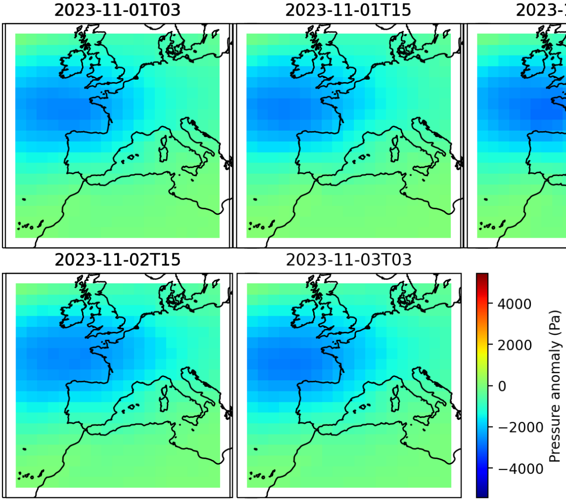
Analogue quantiles vs 20CRv3 and station data



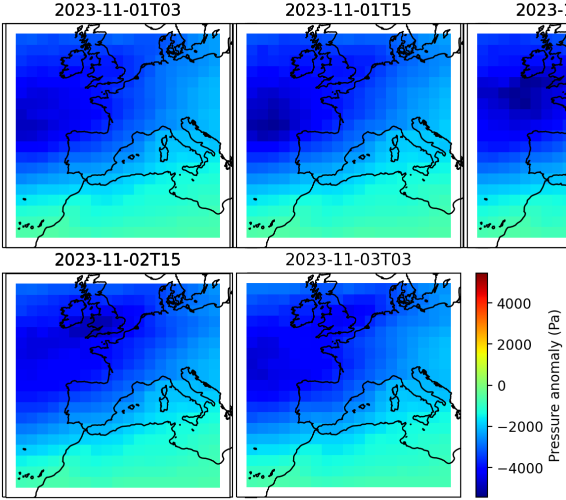
Ciaran


analogues (quantiles)
ERA5
−500
−1000
−1500
−2000
−2500
−3000
−3500
−4000
11-01 00
11-01 12
11-02 00
11-02 12
11-03 00
11-03 12
11-04 00
initial time of forecast

Ciaran : 0.5 quantile of analogues



Ciaran : 0.05 quantile of analogues



Sub-conclusion

1. Using only two tide gauges allows to recover the average 19th century sea-level pressure of 20CRv3 in the area of maximal influence.
2. The analogue method gives meaningful confidence intervals both in high- and low-confidence areas.
3. The analogue method is extremely fast (a few minutes on a laptop).
4. Analogues seem to be a promising method to recover atmospheric variability using indirect sources observations such as tide gauges.
5. Interesting for moderate storms but must be adapted to strongest ones.

Conclusion

1. We have used the tide gauges of Brest and Saint-Nazaire as indirect tracers of 19th-century atmospheric variability, compared with the Twentieth Century Reanalysis 20CRv3.
2. This allows to *validate* 20CRv3 from an external source of observation, and suggests that the tide gauges can help better estimate some specific events that were not well measured with existing pressure sensors.
3. Although indirect sources of observations are harder to use, we have shown that simple statistical methods can be efficient. Data scarcity in the 19th century urges to use all possible sources of observations.

Perspectives

1. Comparison with Brest land station data 1861-1881 :
   - 1st option : validate procedure (analogues or HMM)
   - 2nd option : calibrate method (LR $\rightarrow$ HMM)
2. How often do we have tide gauges without barometers ?
3. Use 10m-wind rather than geostrophic wind to weigh reanalysis members.
4. A better quantification of uncertainties is needed to tackle the case of extreme events (analogue = averaging towards zero ? use non-linear methods ? unobserved events ?).
5. Combine tide gauges, pressure sensors, analogue upscaling to make SLP global dataset (better than pressure observations + optimal interpolation ?)
6. Reconstruct large-scale circulation indices (NAO)

Thank you !

Bibliography (1/2)

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Explaining differences in LR

	std(SLP_{Brest})	std($\Delta_{\mathrm{lon}} SLP_{\mathrm{Brest}}$)	std($\Delta_{\mathrm{lat}} SLP_{\mathrm{Brest}}$)
1981-2015	957.4	266.6	495.6
1870-1896 (ensemble average)	913.3 (-5.6%)	246.6 (-7.5%)	468.7 (-5.4%)
1870-1896 (individual members)	945.4 (-1.3%)	291.3 (+9.3%)	514.3 (+3.8%)

	α	β	γ	R^2	R^2 with "sat.-era" coefs.
1981-2015	-1.105	1.202	-0.137	0.834	0.834
1870-1896 (ensemble average)	-1.142	1.229	-0.178	0.790	0.787
1870-1896 (individual members)	-1.080 $\pm$ 0.006	0.807 $\pm$ 0.017	-0.189 $\pm$ 0.010	0.723 $\pm$ 0.003	0.713 $\pm$ 0.003

Forward-backward algorithm (1/2)

Forward procedure :
Let $\alpha_i(t) := P(Y_1 = y_1, \ldots, Y_t = y_t, X_t = i \mid \theta)$:

$$\alpha_i(1) = \pi_i b_i(y_1)\,, \tag{7}$$

$$\alpha_i(t+1) = b_i(y_{t+1}) \sum_{j=1}^{N} \alpha_j(t) a_{ji}(t)\,. \tag{8}$$

Backward procedure :
Let $\beta_i(t) := P(Y_{t+1} = y_{t+1}, \ldots, Y_T = y_T \mid X_t = i, \theta)$:

$$\beta_i(T) = 1\,, \tag{9}$$

$$\beta_i(t) = \sum_{j=1}^{N} \beta_j(t+1) a_{ij}(t) b_j(y_{t+1})\,. \tag{10}$$

Forward-backward algorithm (2/2)

We can now calculate, according to Bayes' theorem :

$$\gamma_i(t) = P(X_t = i \mid Y, \theta) = \frac{P(X_t = i, Y \mid \theta)}{P(Y \mid \theta)} = \frac{\alpha_i(t)\beta_i(t)}{\sum_{j=1}^{N} \alpha_j(t)\beta_j(t)}, \quad (11)$$

which is the probability of being in state i at time t given the observed sequence Y and the parameters θ.