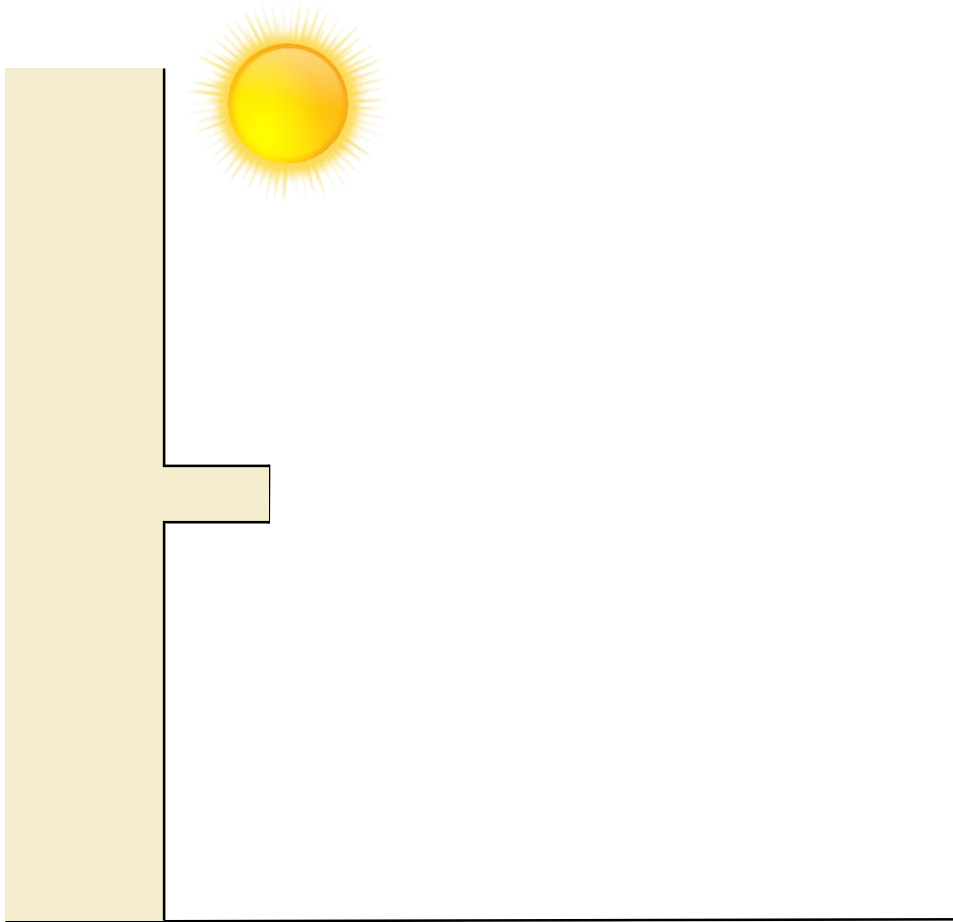


# Micro-climatic monitoring to optimize ageing test methodology: Application on the Saint-Remi Basilica (Rheims, France)

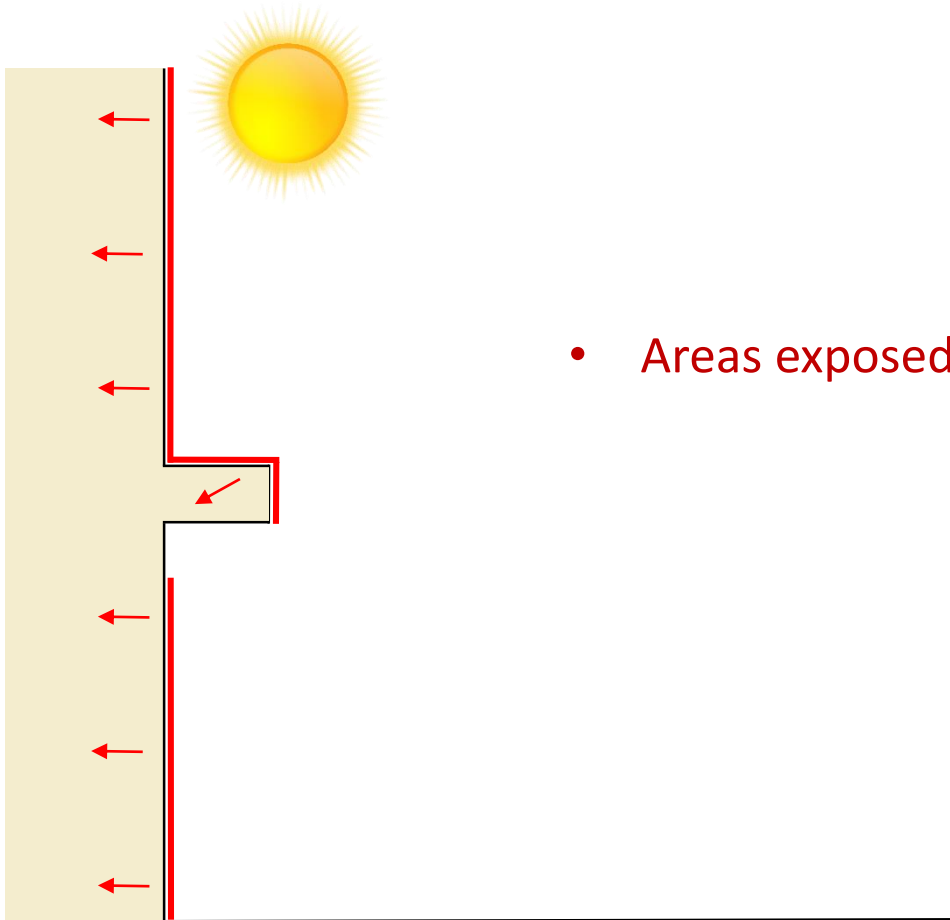
E. HUBY, C. THOMACHOT-SCHNEIDER, P. VAZQUEZ, G. FRONTEAU  
GEGENAA EA 3795, URCA, France



# INTRODUCTION

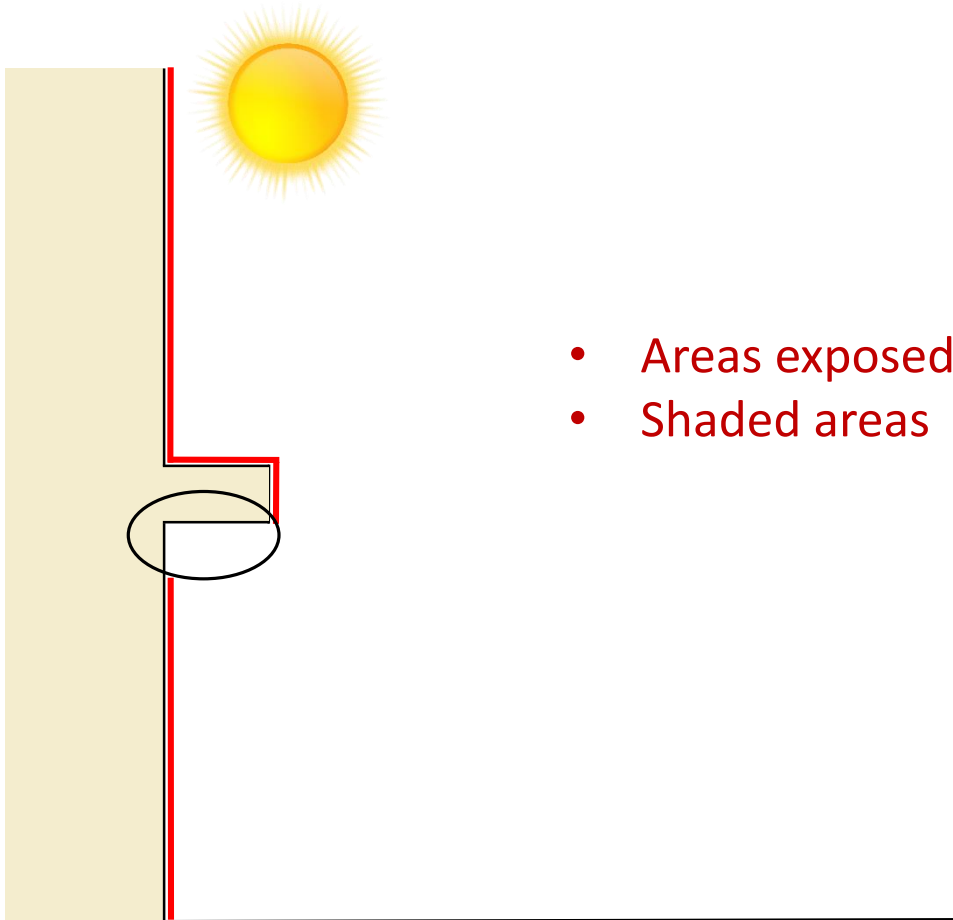


## INTRODUCTION



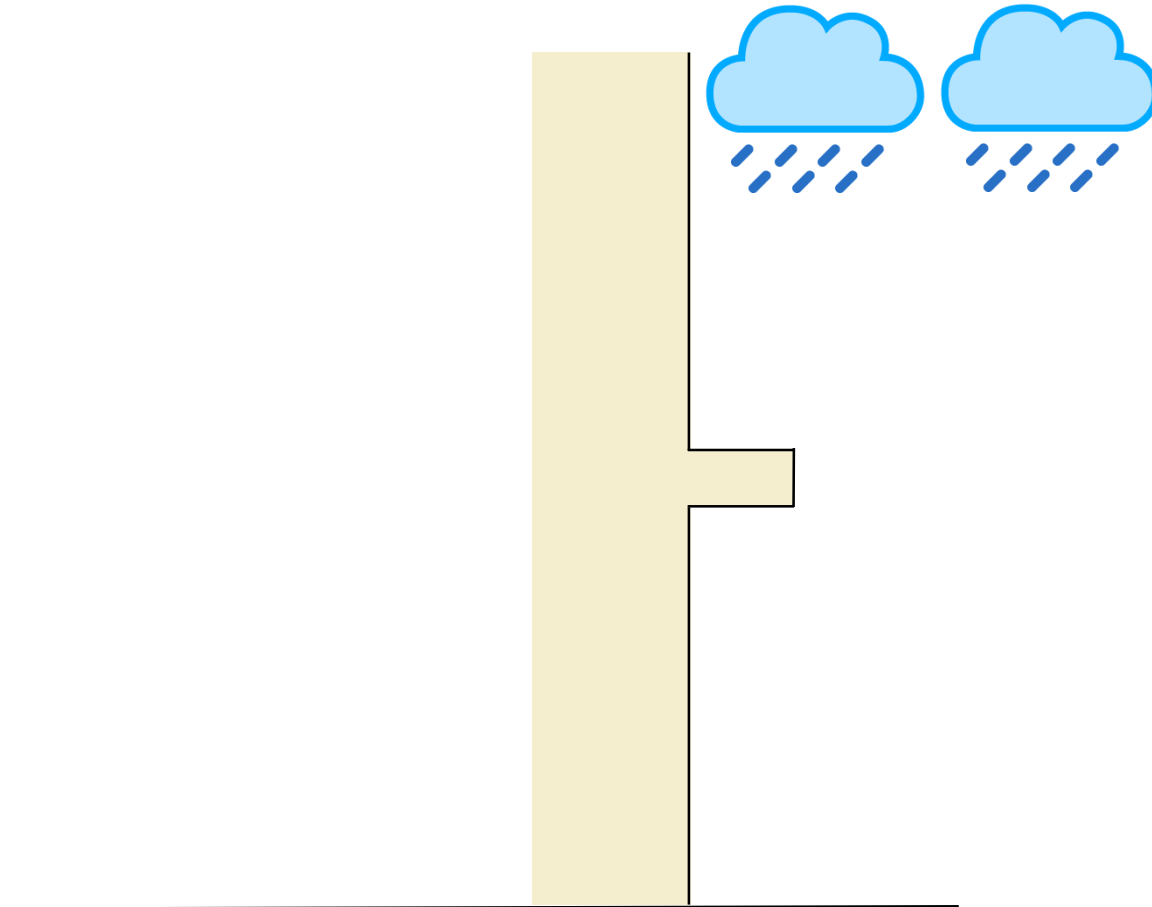
- Areas exposed to solar radiation

## INTRODUCTION

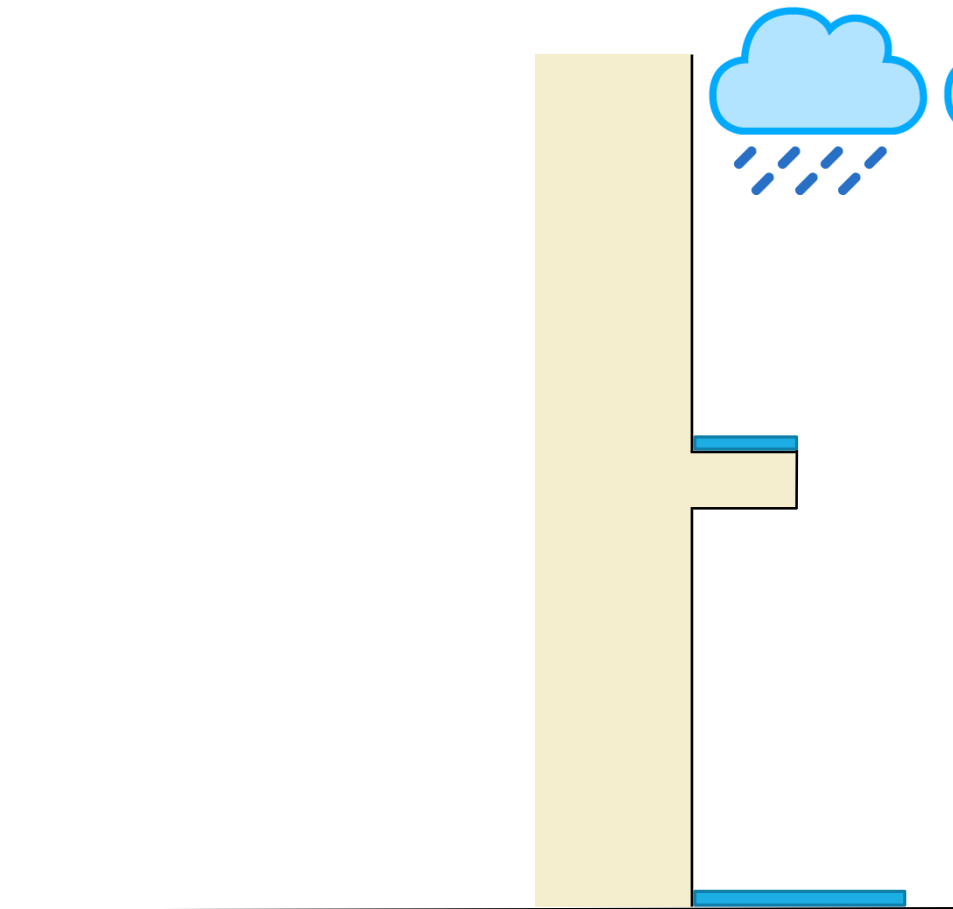


- Areas exposed to solar radiation
- Shaded areas

# INTRODUCTION

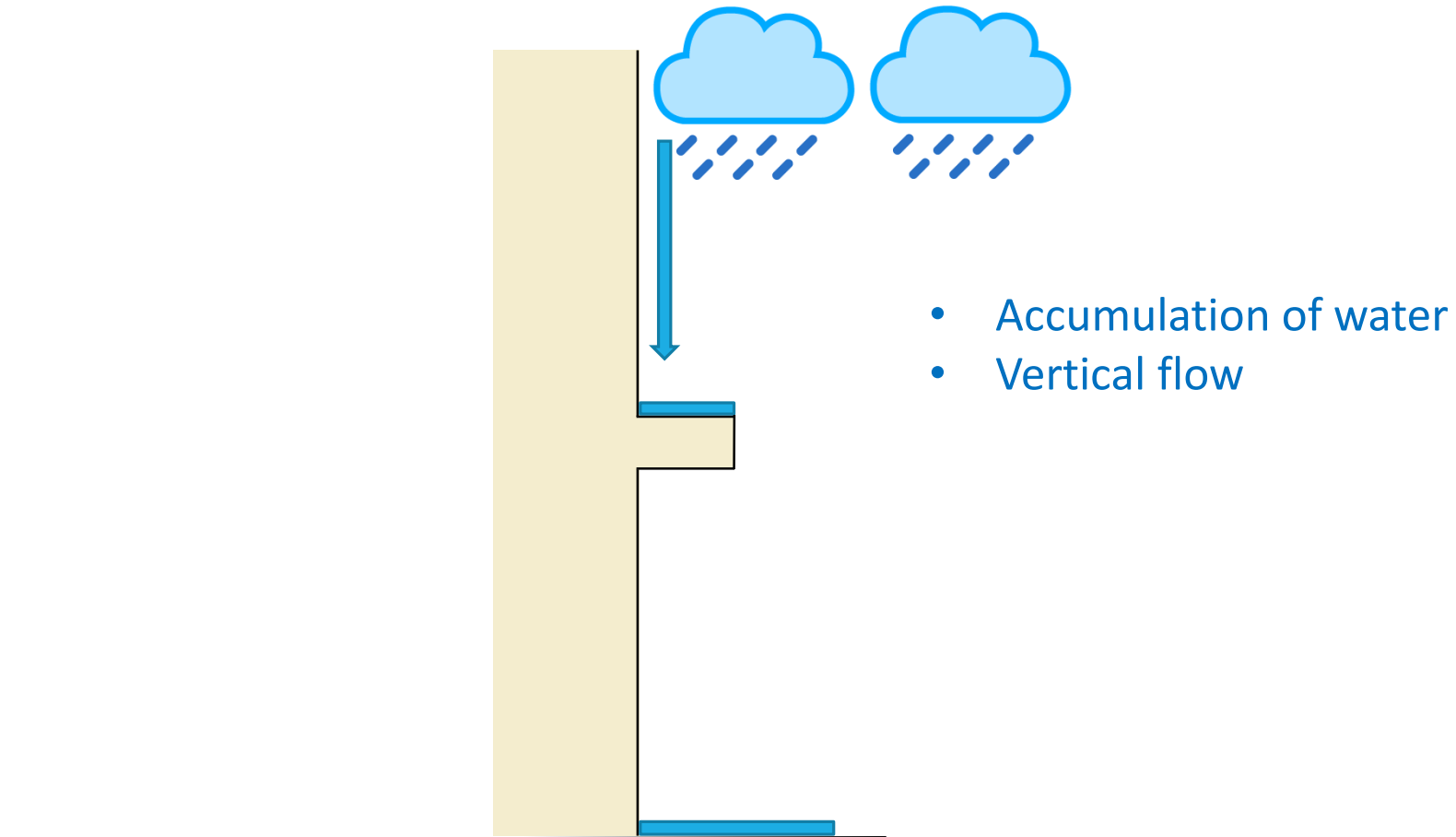


## INTRODUCTION

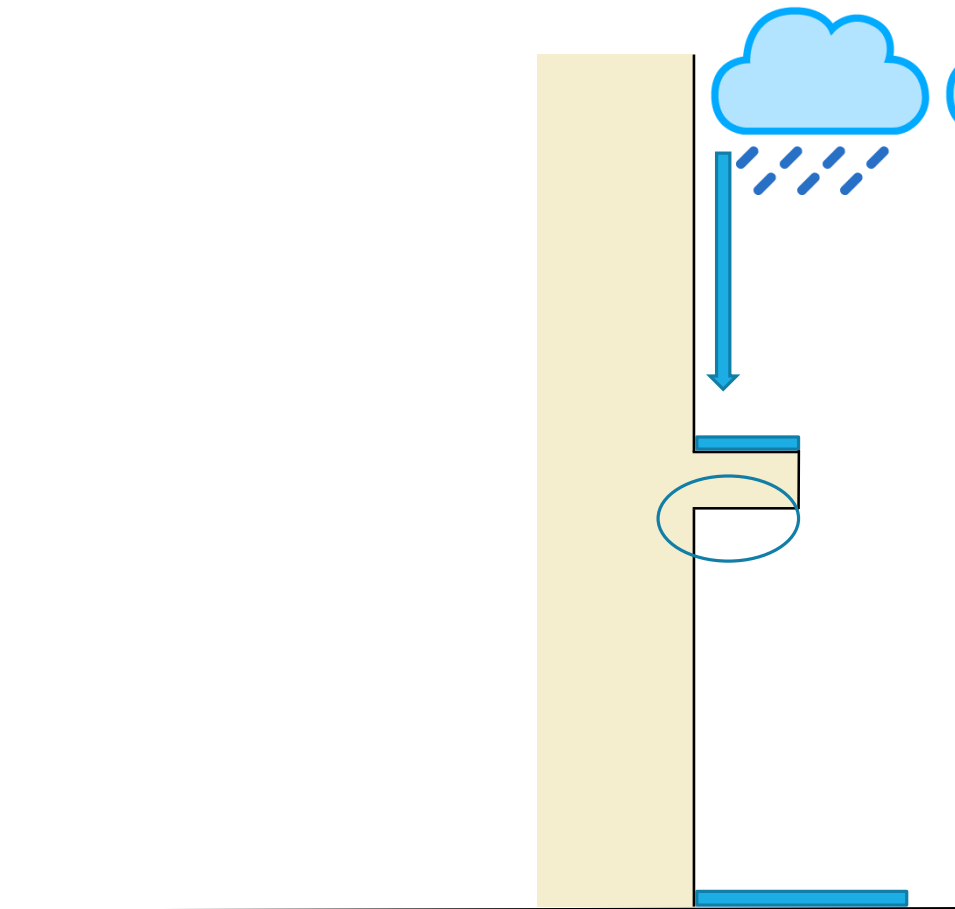


- Accumulation of water

## INTRODUCTION



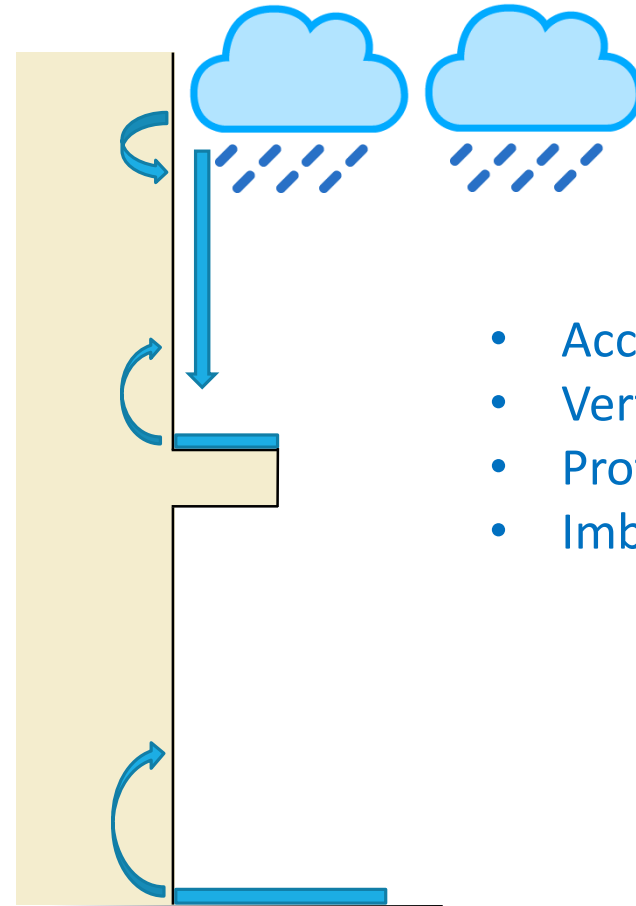
## INTRODUCTION



- Accumulation of water
- Vertical flow
- Protected areas

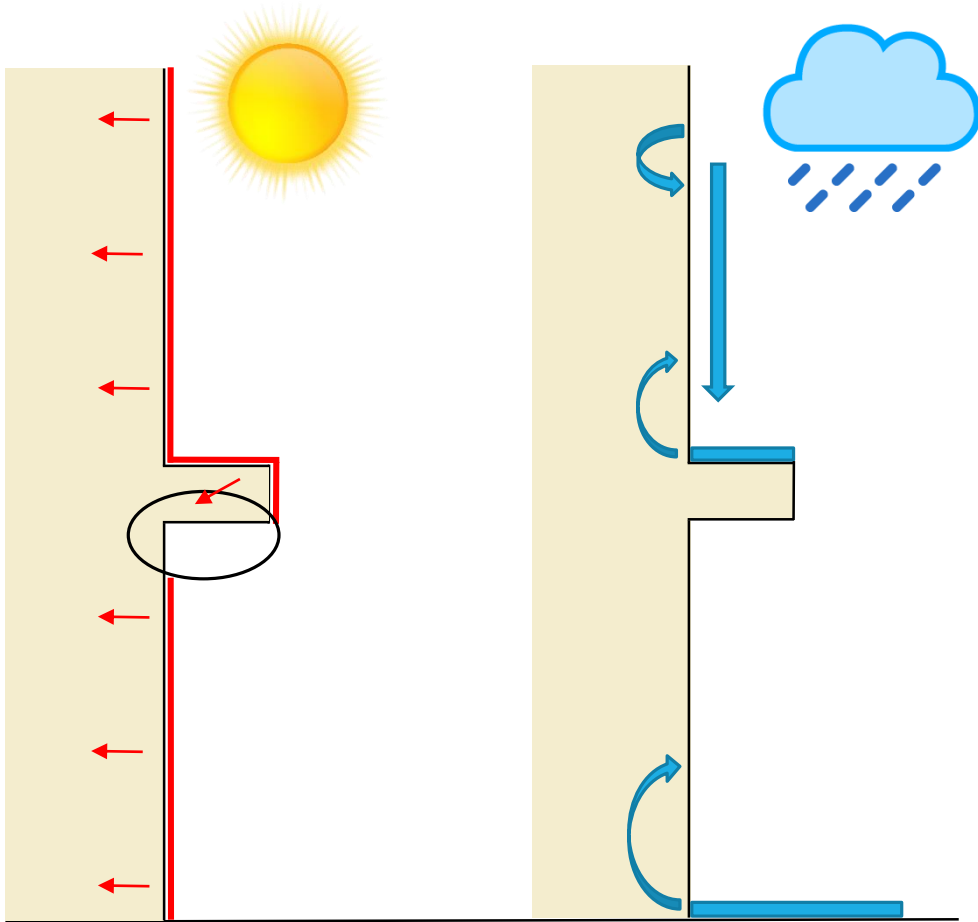


## INTRODUCTION

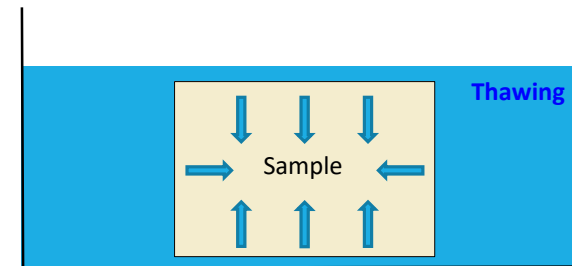
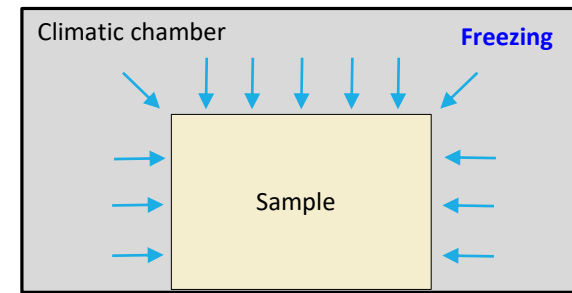


- Accumulation of water
- Vertical flow
- Protected areas
- Imbibition

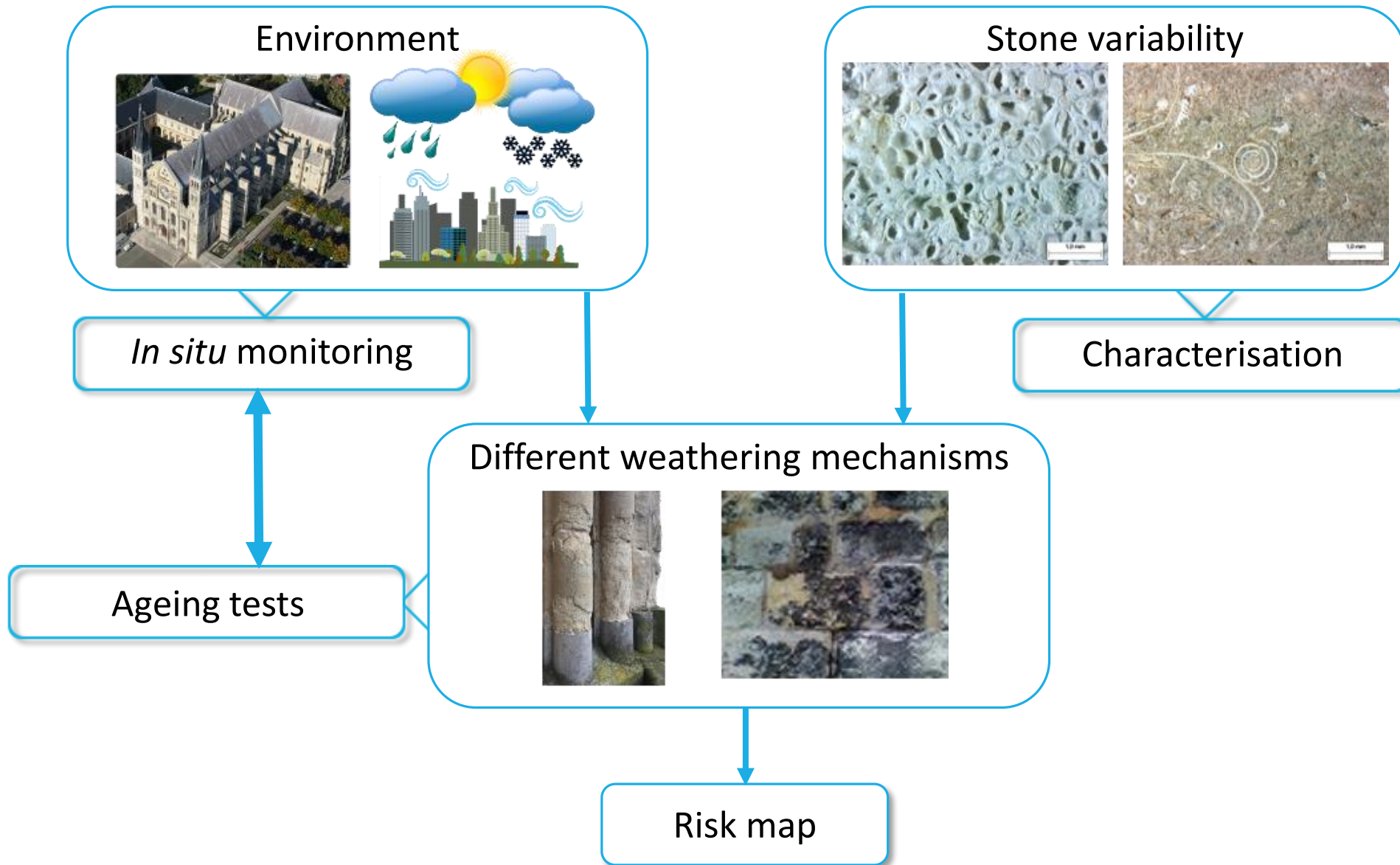
# INTRODUCTION



## Standard test procedure



NF EN 12371  
Natural stone test methods  
Determination of frost resistance



## IN SITU MONITORING

**Saint-Remi Basilica:** inscribed on UNESCO's World Heritage List



*Aerian view of the Saint-Remi Basilica*



*Localization of Reims*



## Two types of limestone:

### “Courville”

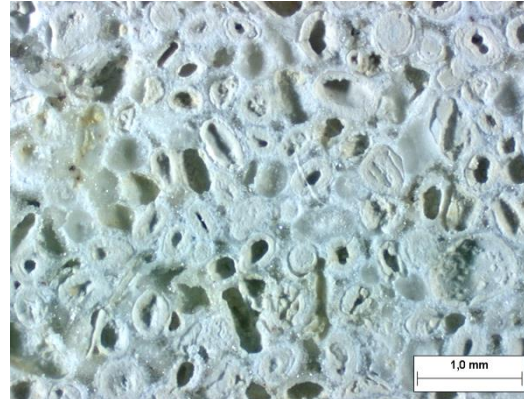
Lutetian limestone  
Original stone



*Courville Gx20*

### “Savonnières”

Jurassic limestone  
Restoration stone

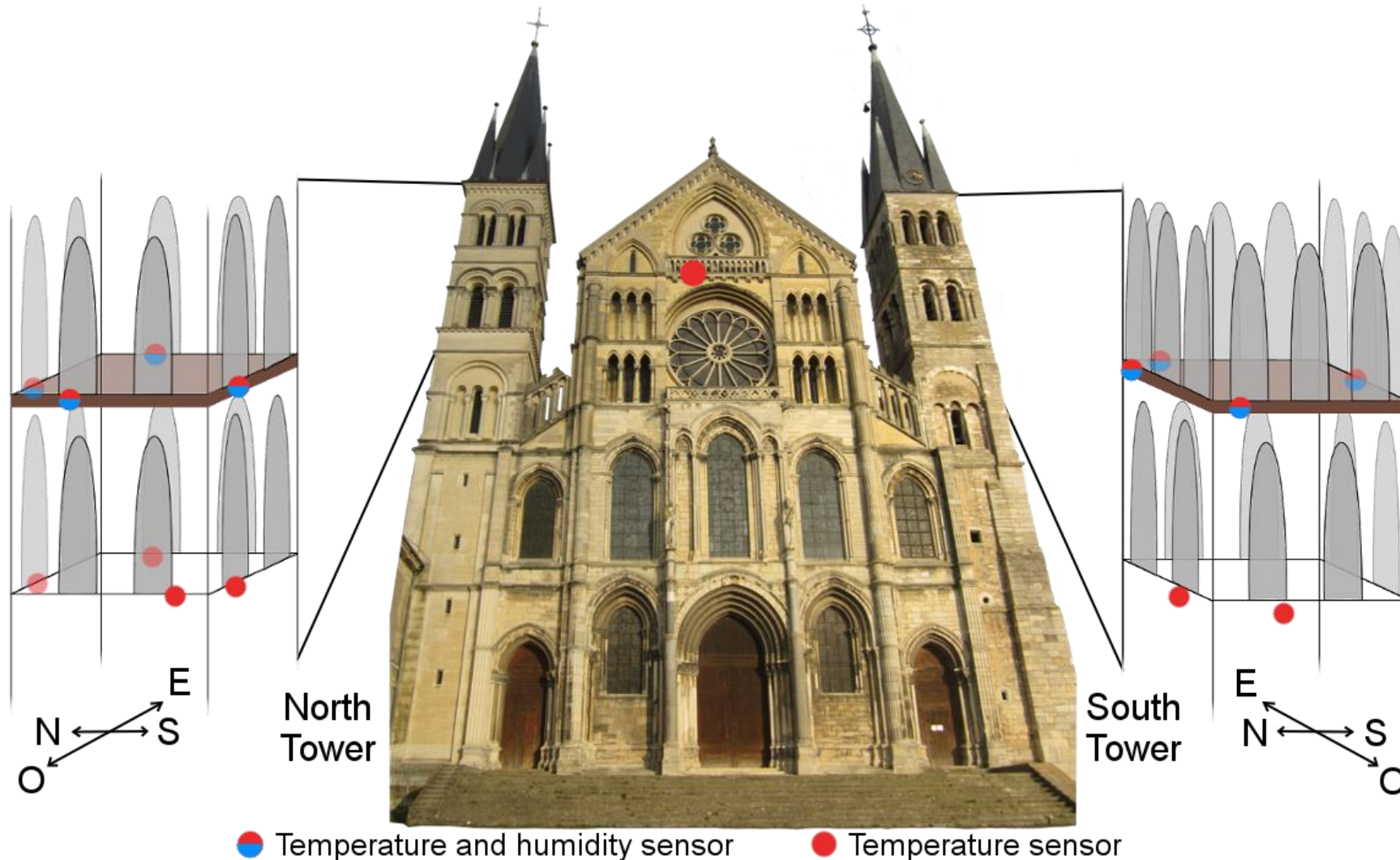


*Savonnières Gx20*



*Picture of weathered stones and restored stones on the Basilica.*

## Monitoring: network of 15 sensors



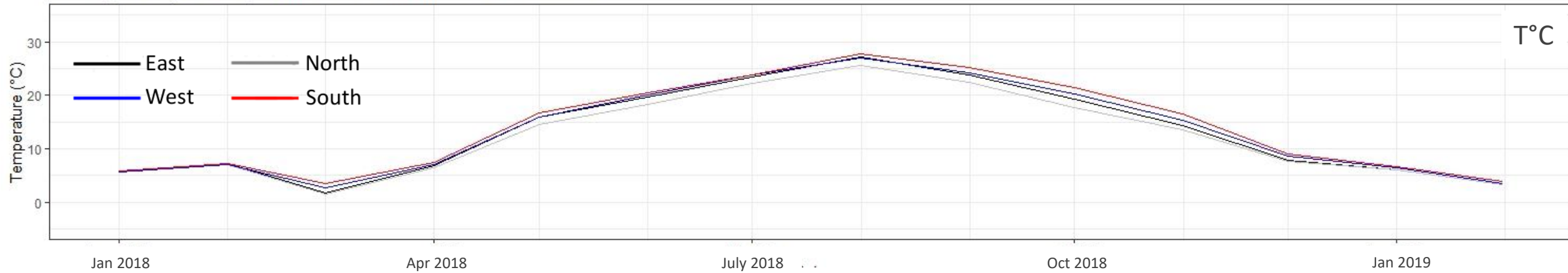
Different **heights**:  
25m and 30m.

Different **orientations**:  
North, South, East and West.

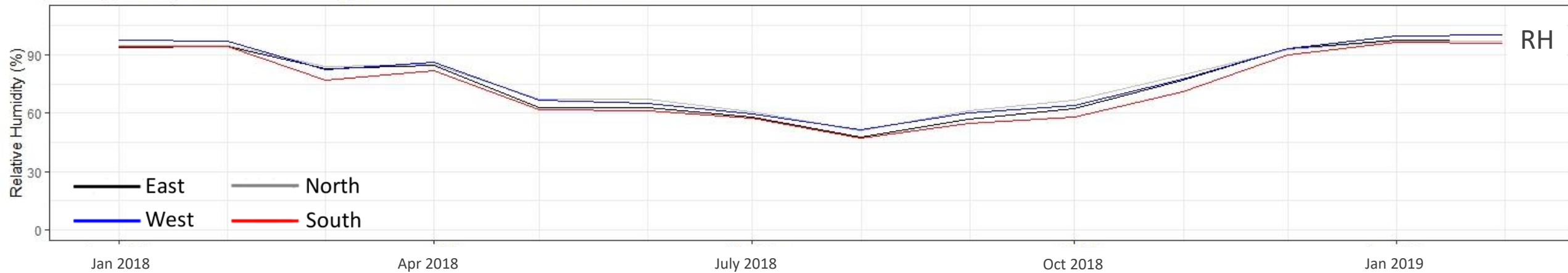


## Monthly average

Monthly average of temperature on the 2nd floor of the south tower

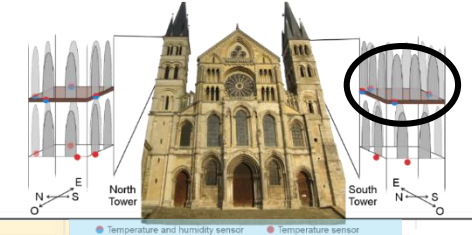


Monthly average of relative humidity on the 2nd floor of the south tower

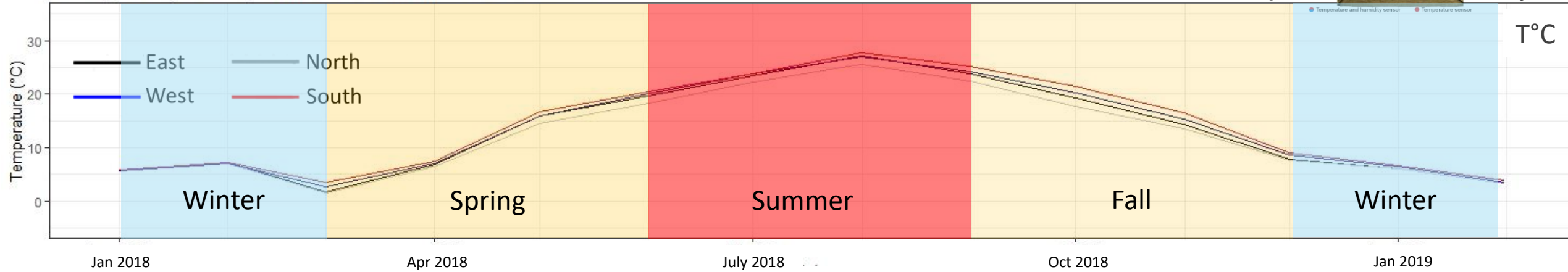




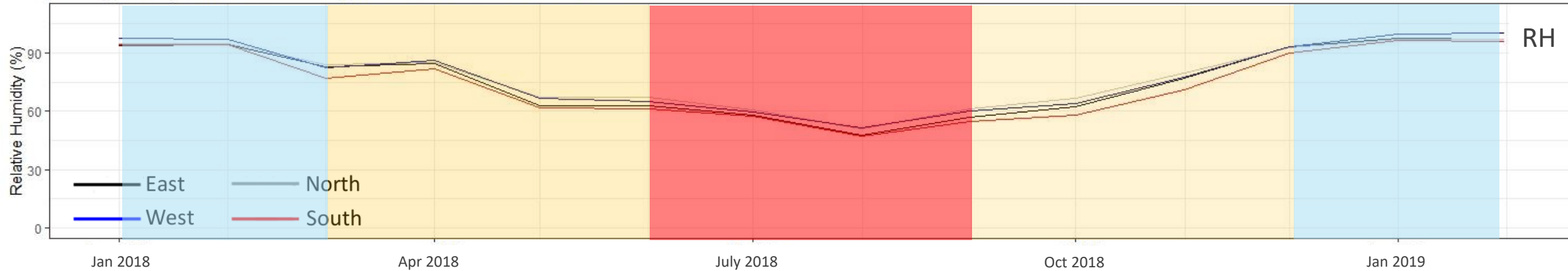
## Monthly average



Monthly average of temperature on the 2nd floor of the south tower



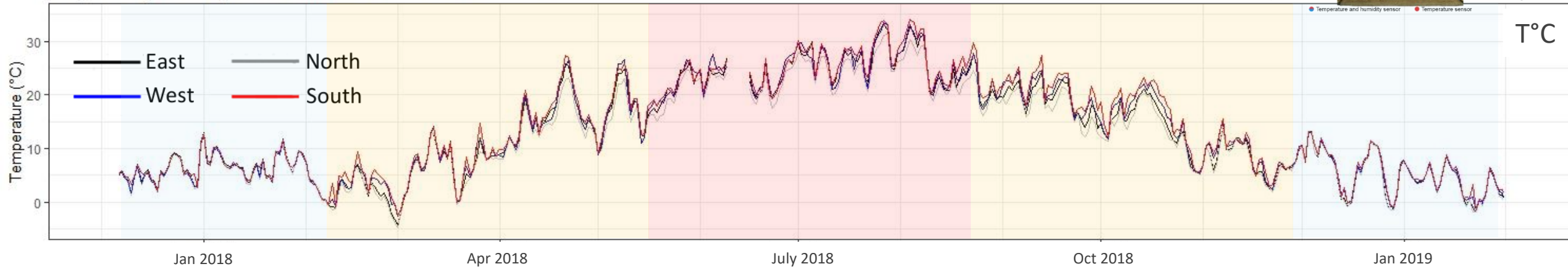
Monthly average of relative humidity on the 2nd floor of the south tower



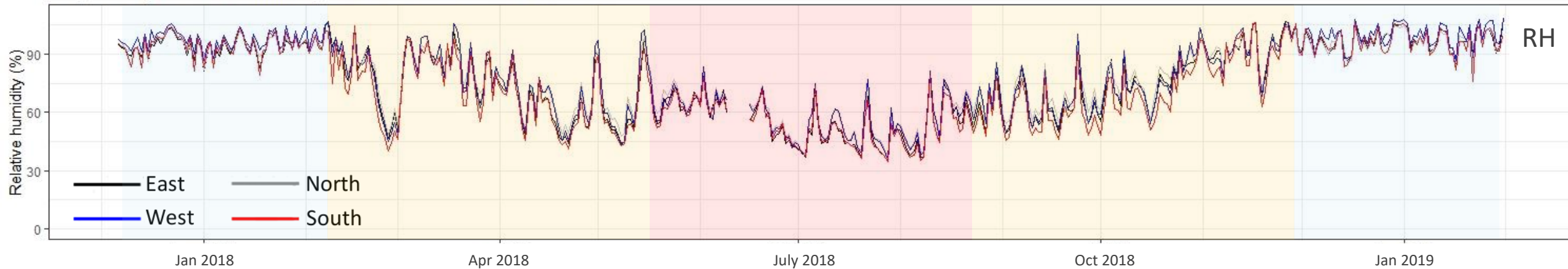


## Daily average

Daily average of temperature on the 2nd floor of the south tower

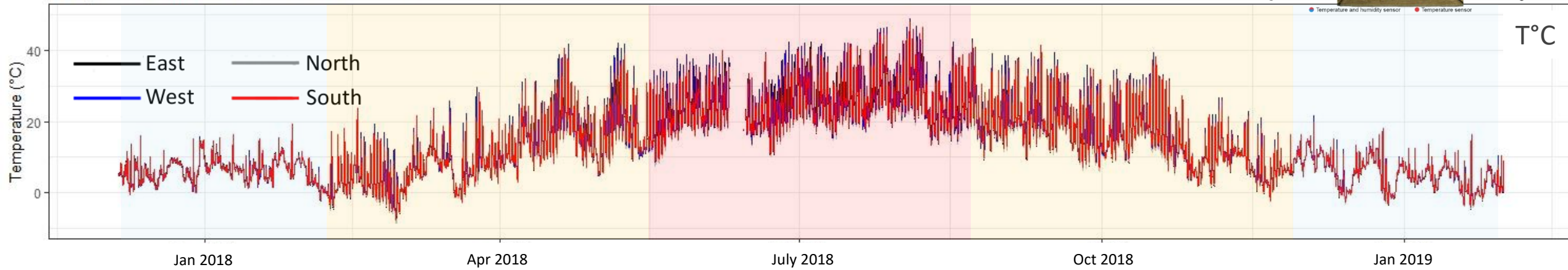


Daily average of relative humidity on the 2nd floor of the south tower

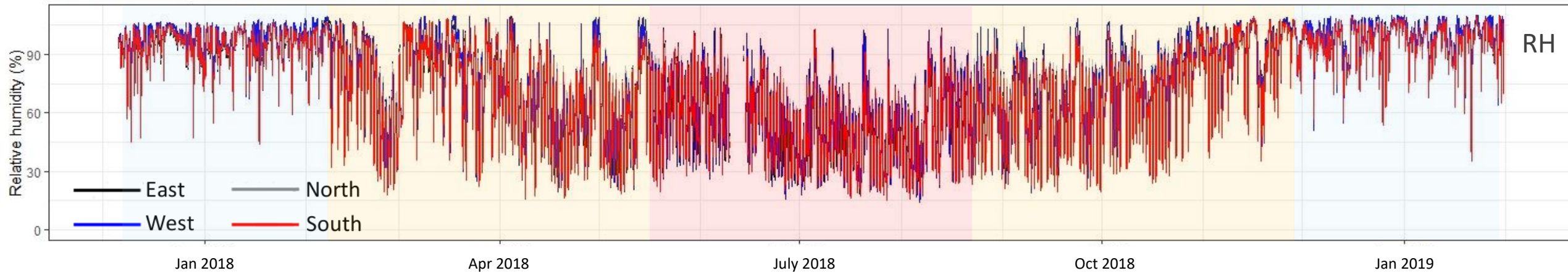


## Daily values – time step of 1 hour.

Temperature on the 2nd floor of the south tower

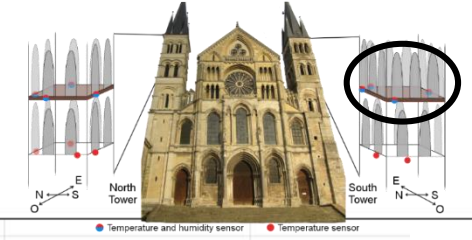


Relative Humidity on the 2nd floor of the south tower

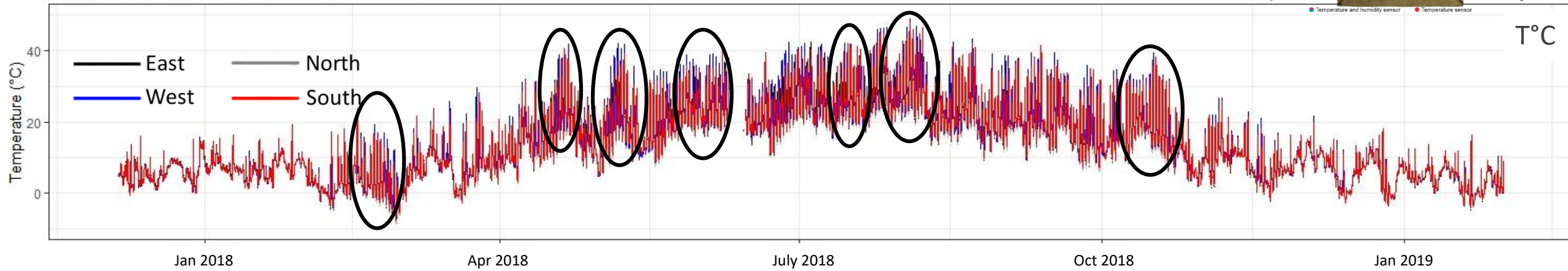




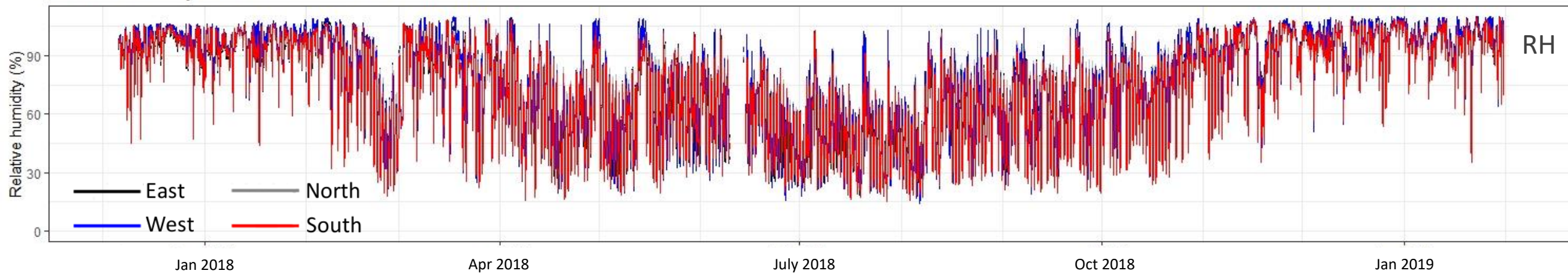
## Identification of typical events: "Sunny day"



Temperature on the 2nd floor of the south tower

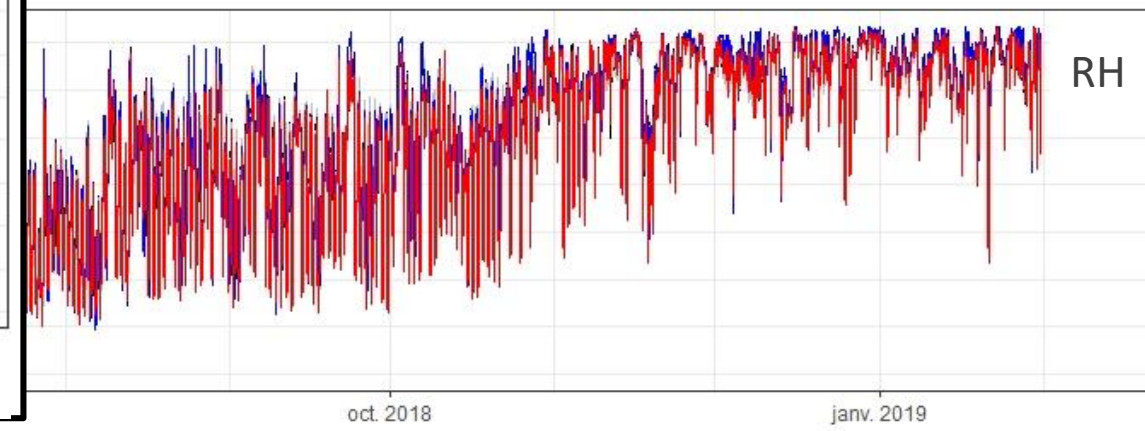
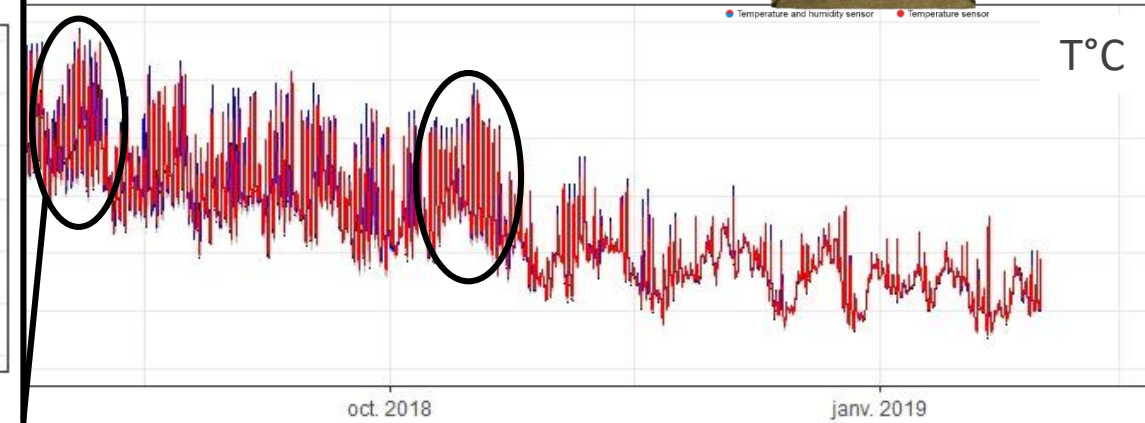
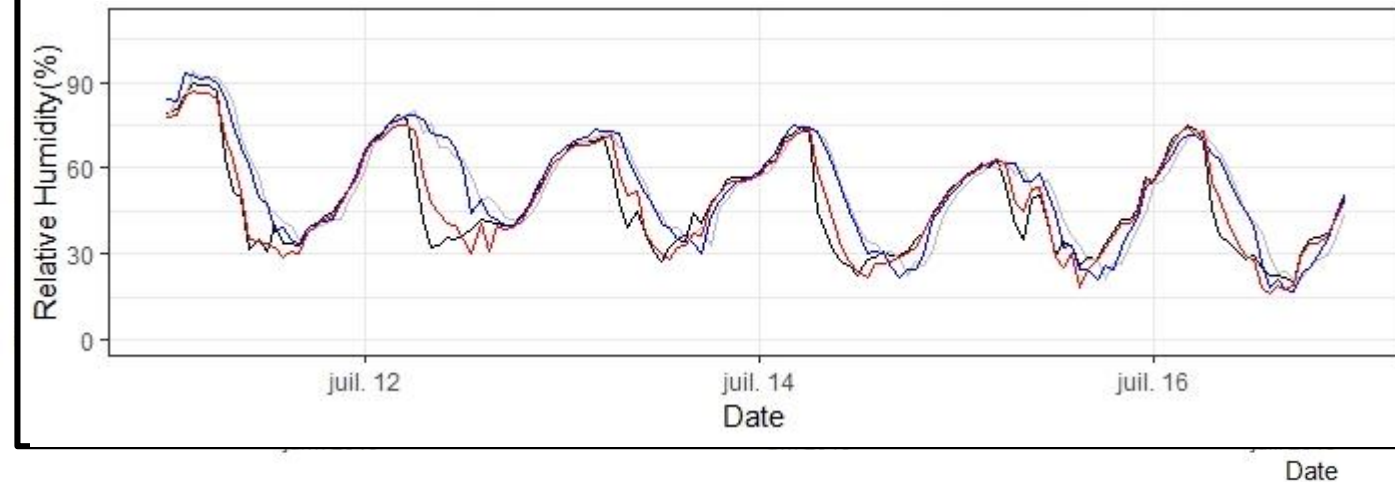
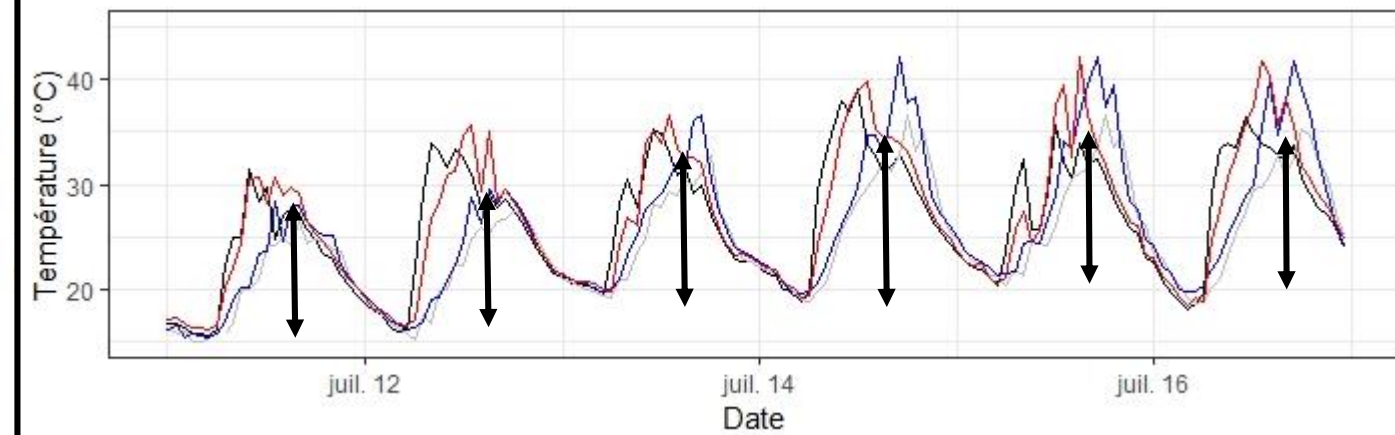
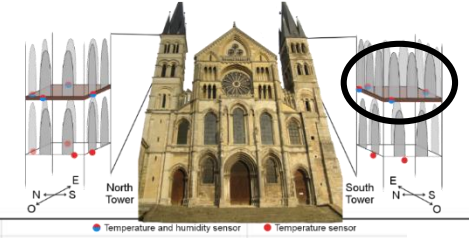


Relative Humidity on the 2nd floor of the south tower



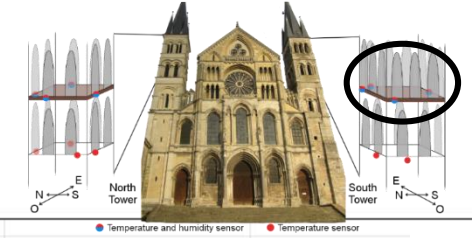
## Identification of typical events

Sunny day:  $\Delta T > 10^\circ\text{C}$

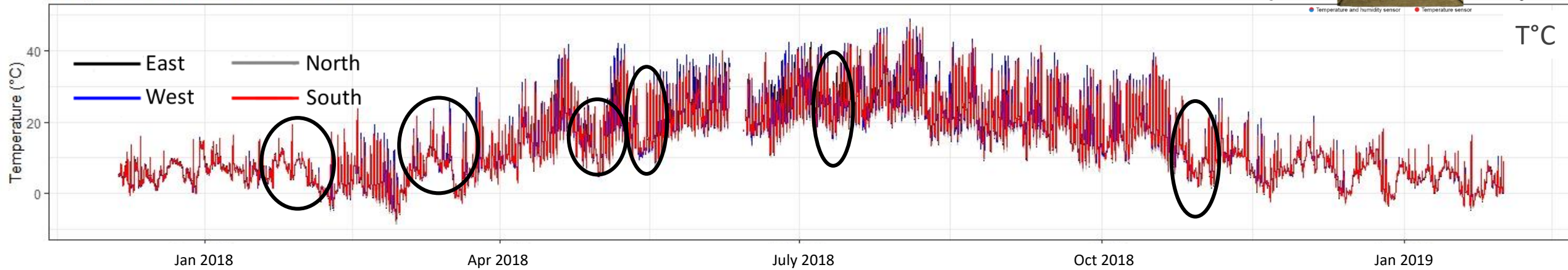




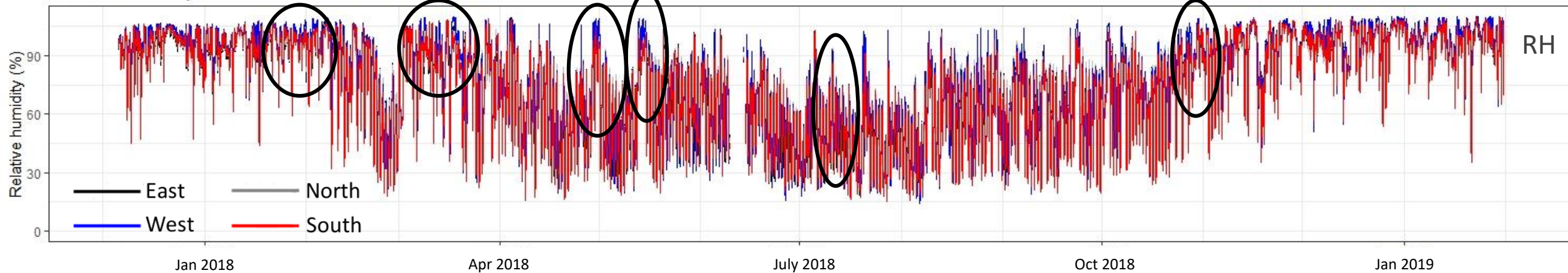
# Identification of typical events: "Rainy day"



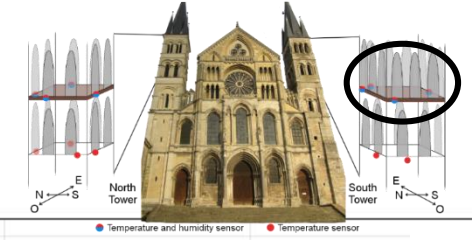
Temperature on the 2nd floor of the south tower



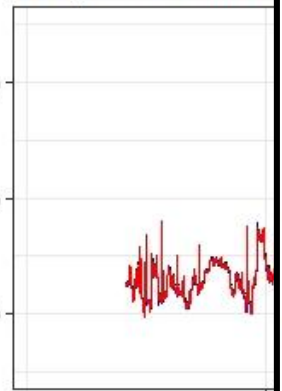
Relative Humidity on the 2nd floor of the south tower



# Identification of typical events: "Rainy day"

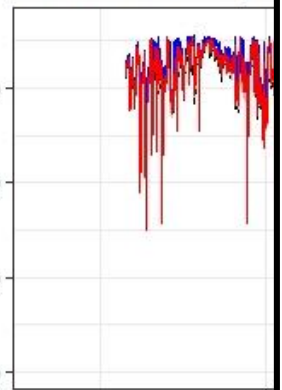


Temperature on the



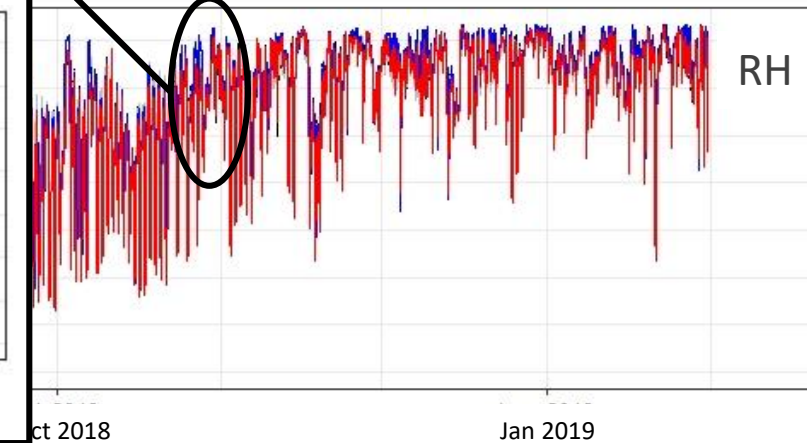
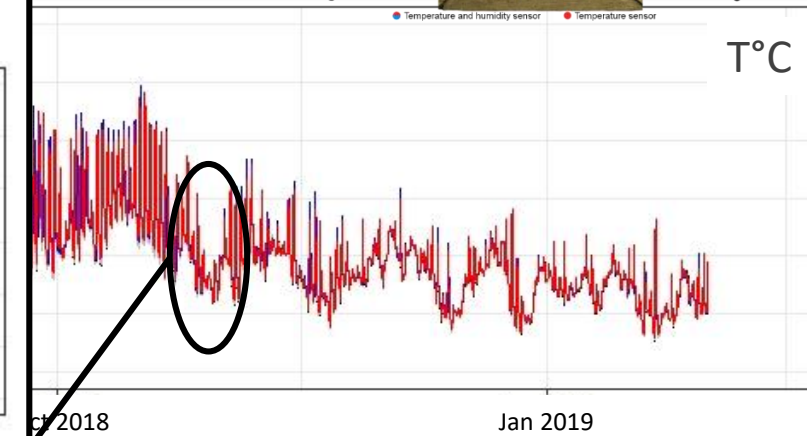
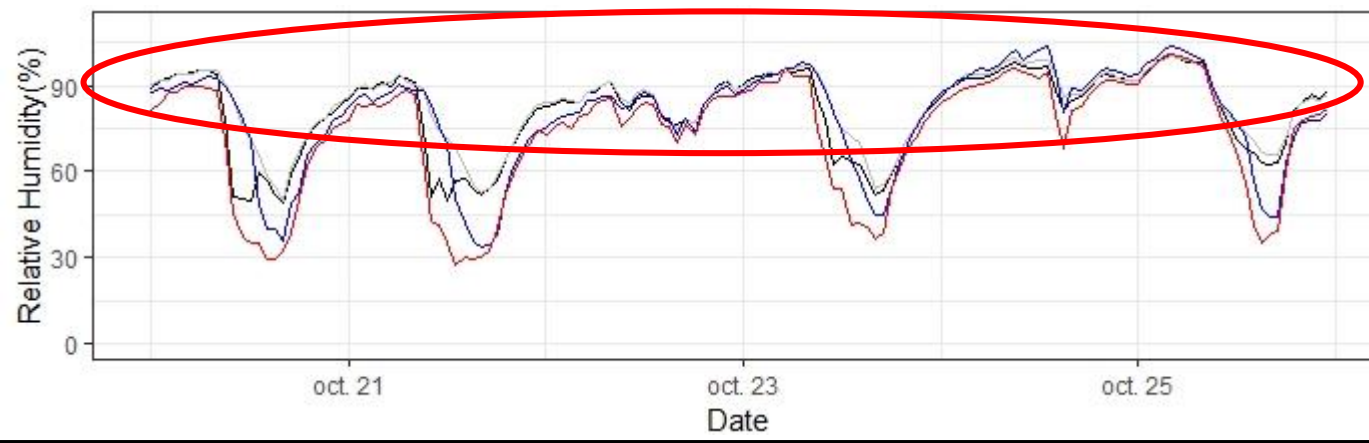
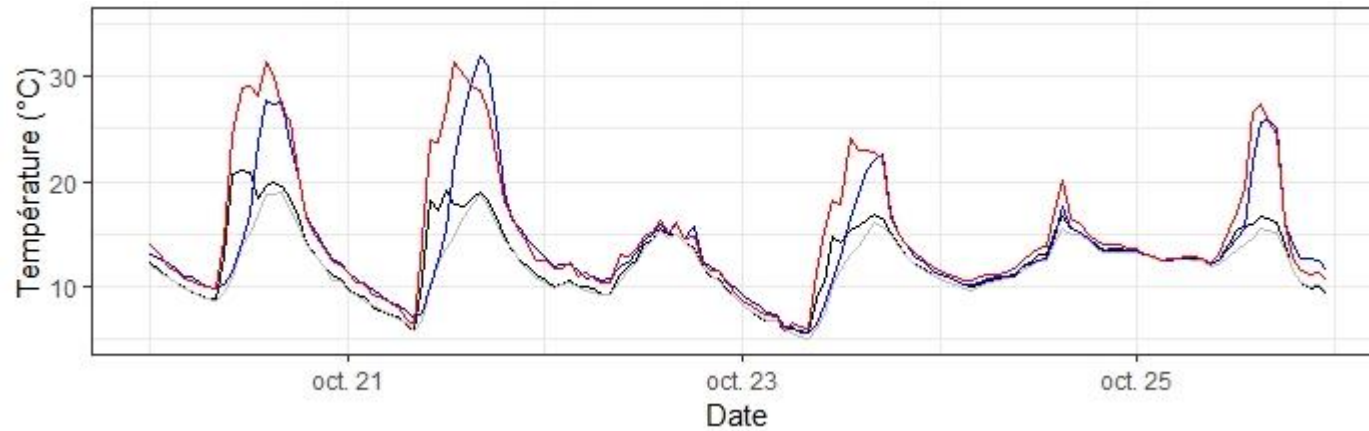
Jan 2

Relative Humidity of



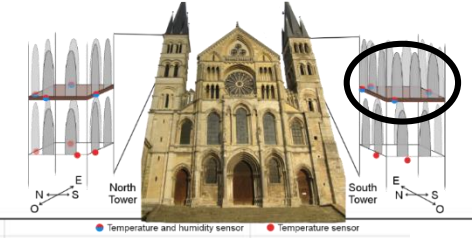
Jan 2

Rainy day: average RH &gt; 90%

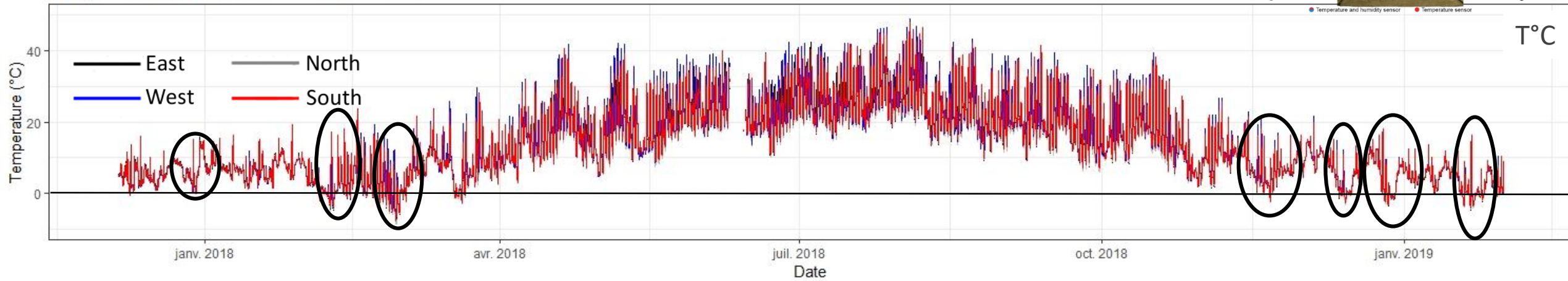




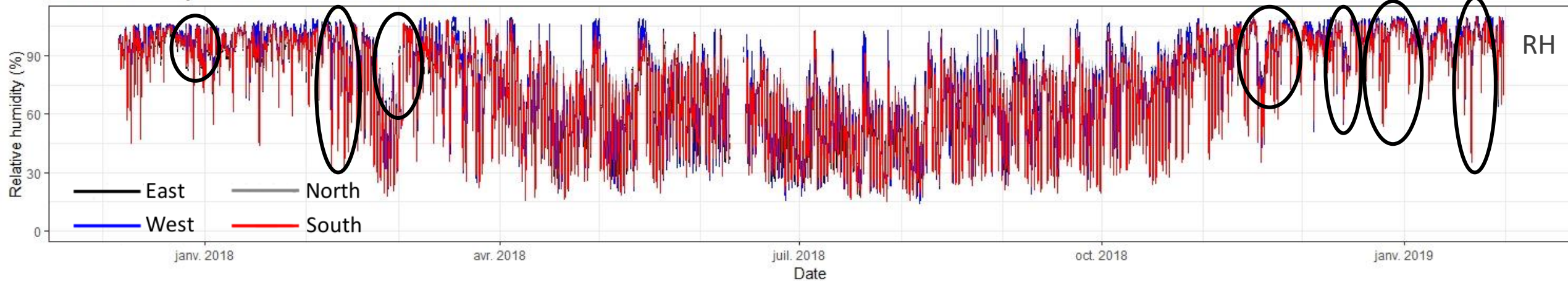
# Identification of typical events: "Frost day"



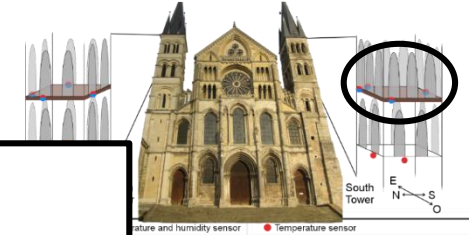
Temperature on the 2nd floor of the south tower



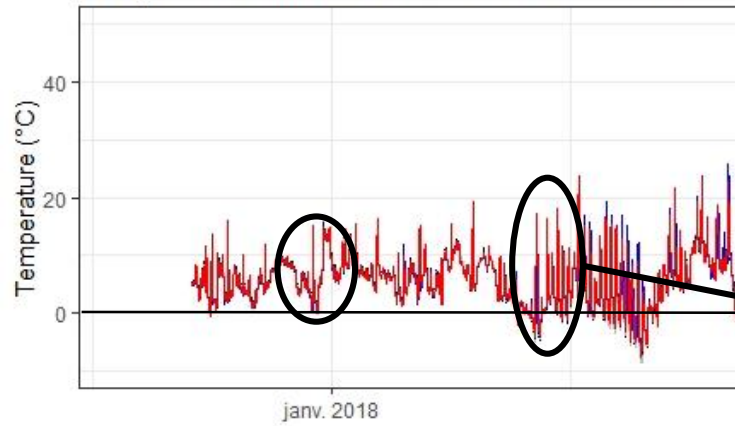
Relative Humidity on the 2nd floor of the south tower



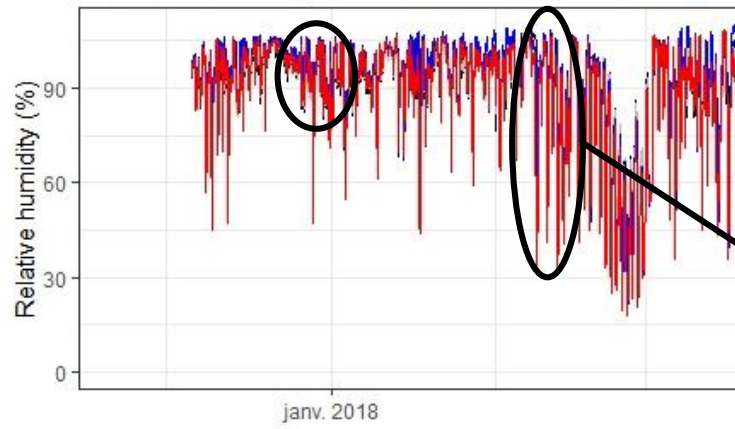
## Identification of typical events: "Frost day"



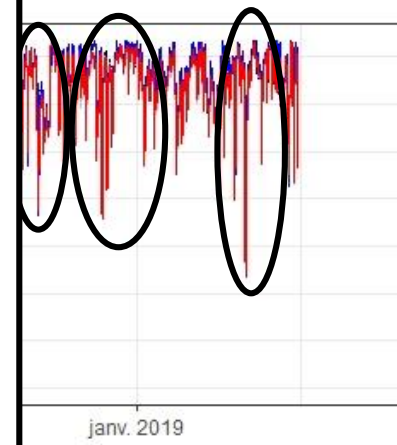
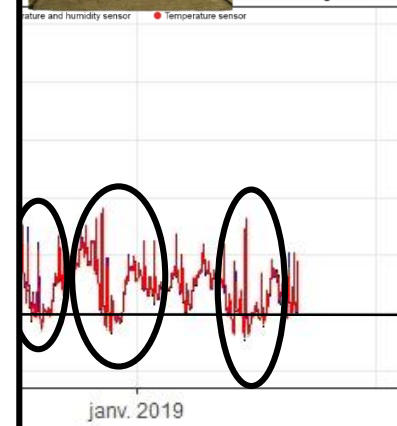
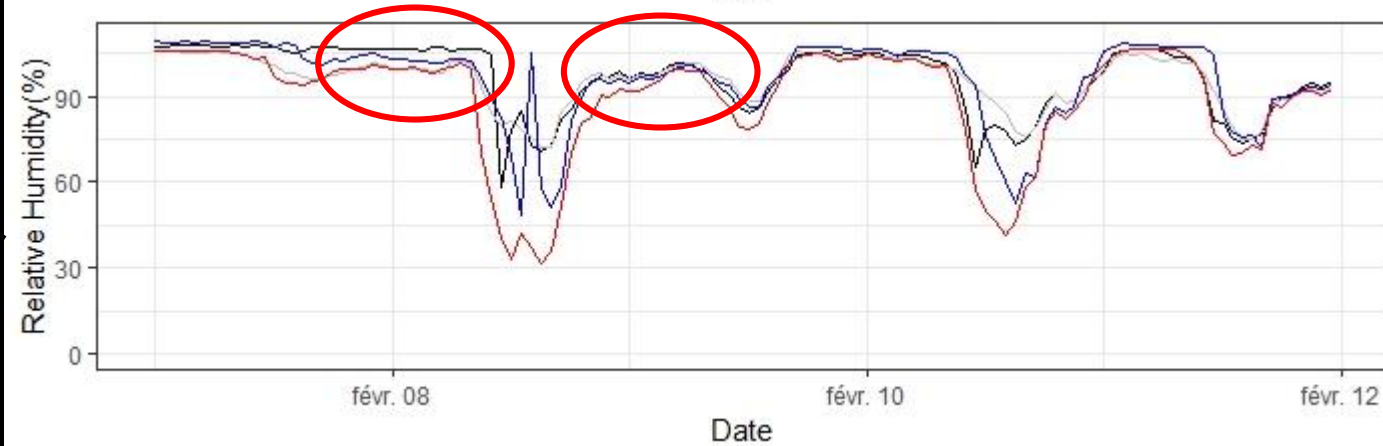
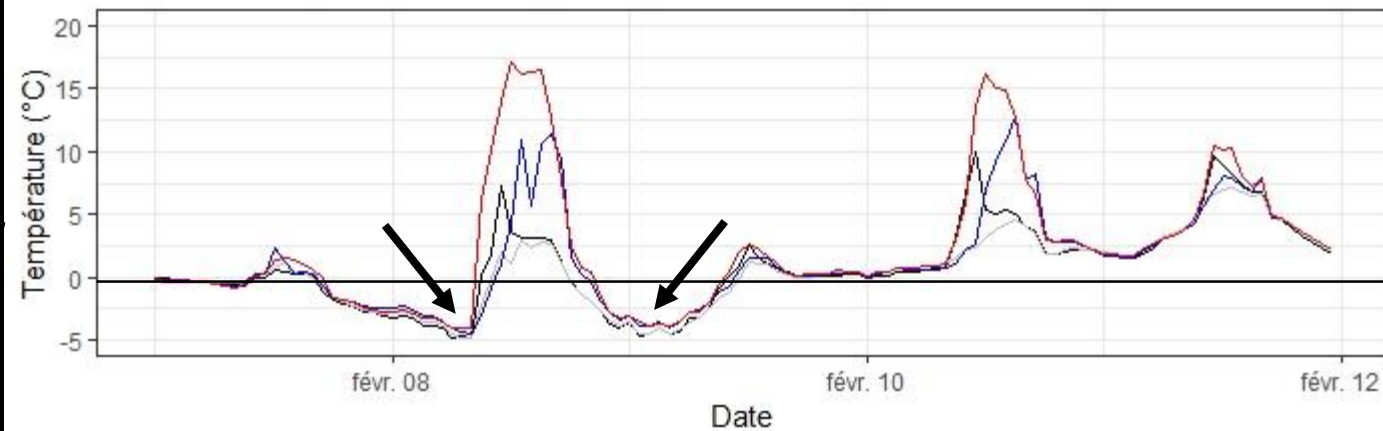
Temperature on the 2nd floor of the south tower



Relative Humidity on the 2nd floor of the south tower



Frost day:  $T < 0^{\circ}\text{C}$  and  $\text{RH} > 90\%$

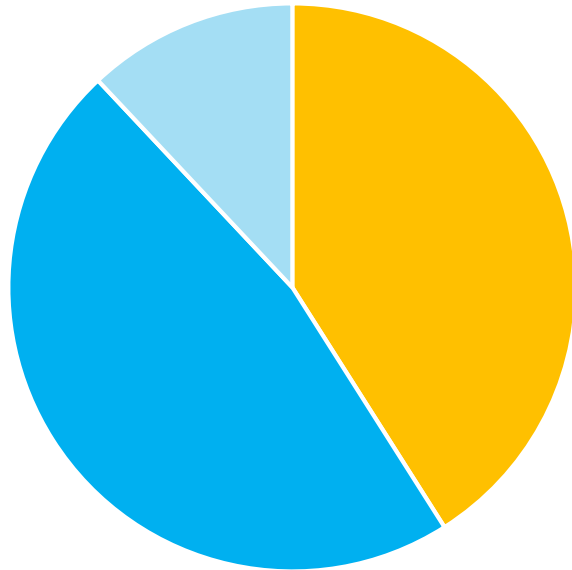




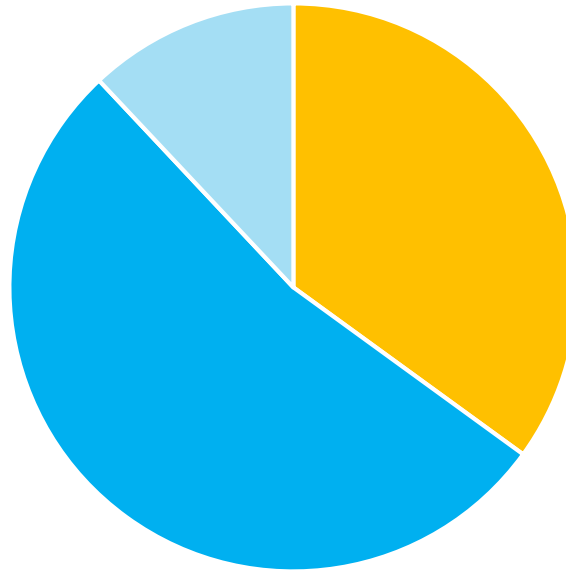
## Identification of typical events:

### Repartition of typical days for the different orientations

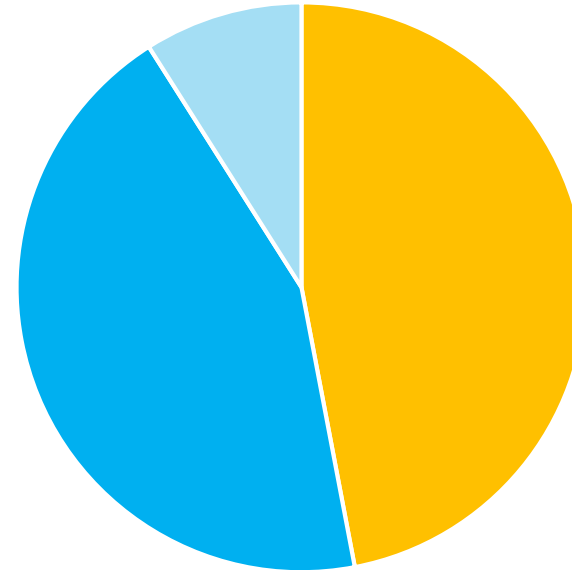
East Façade



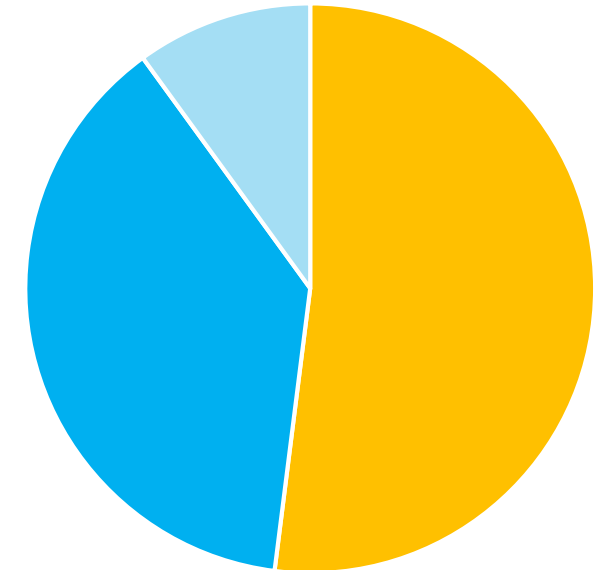
North Façade



West Façade



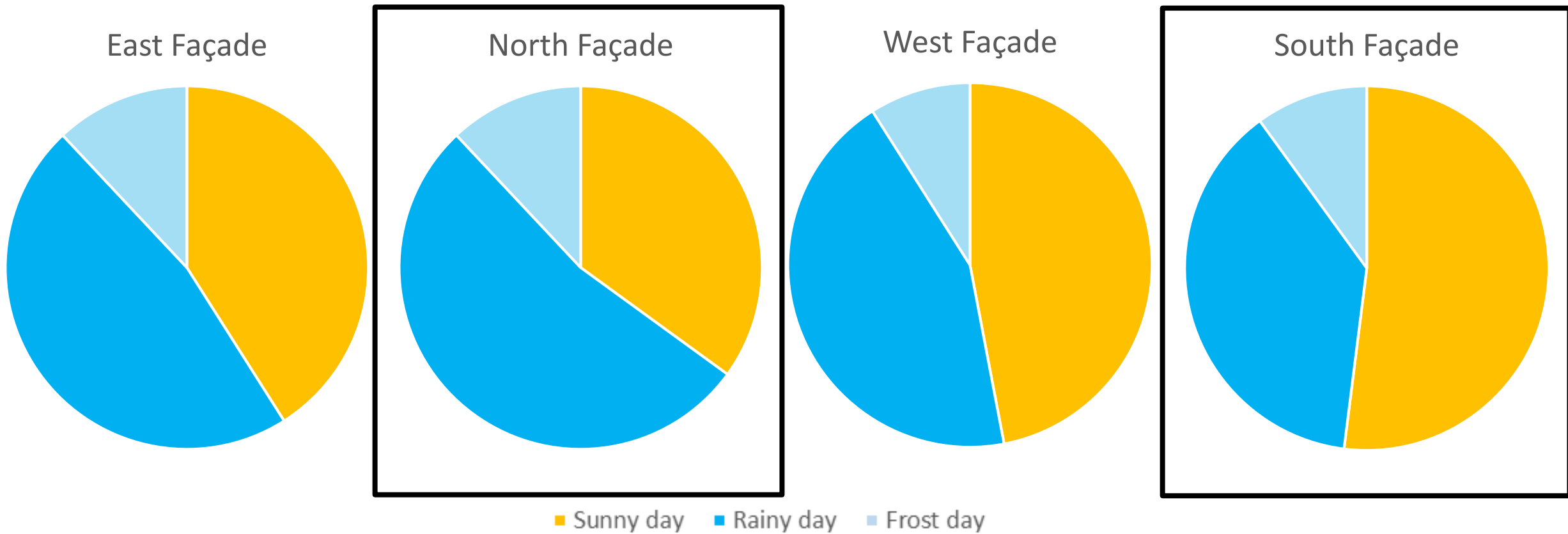
South Façade



■ Sunny day ■ Rainy day ■ Frost day

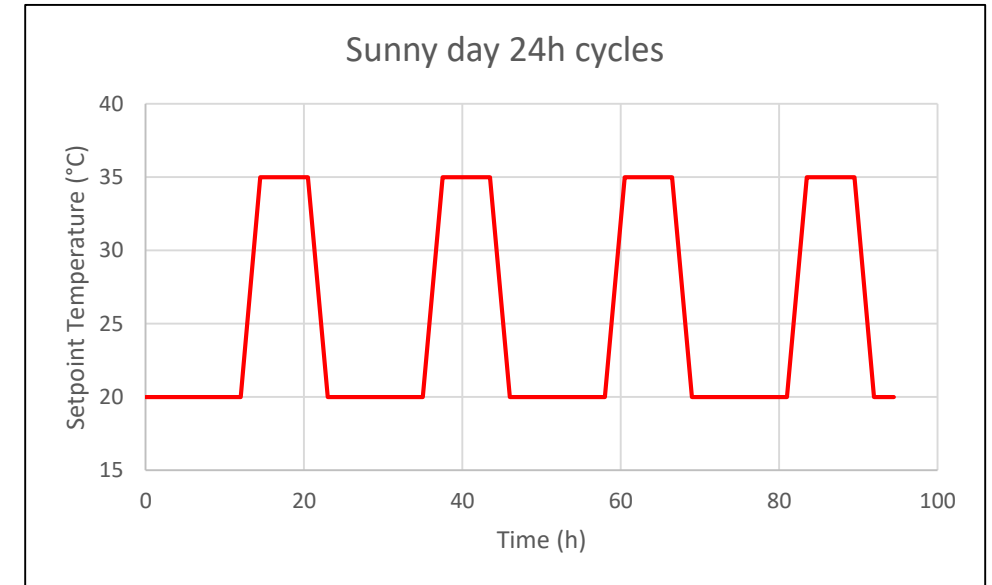
## Identification of typical events:

### Repartition of typical days for the different orientations



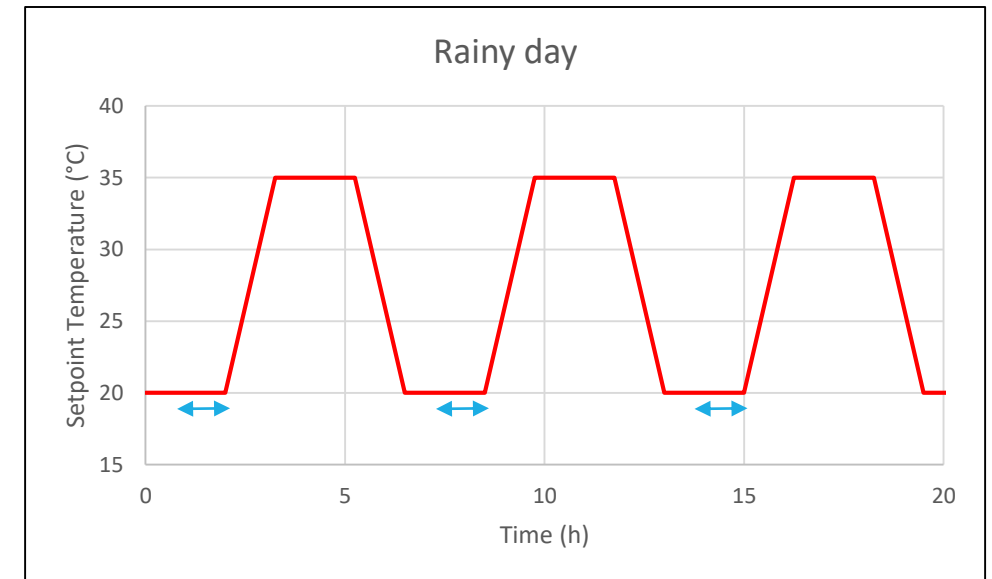
## Identification of typical events

	Temperature variation	Heating/Cooling rate	Humidity
<b>Sunny day</b>	20 – 35°C	0,2 °C/min	Dry



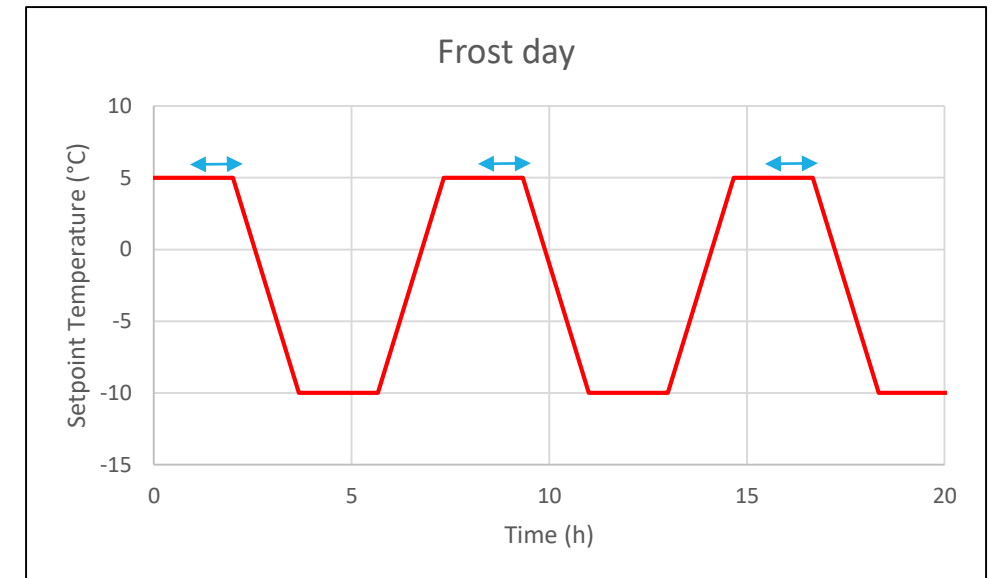
## Identification of typical events

	Temperature variation	Heating/Cooling rate	Humidity
<b>Sunny day</b>	20 – 35°C	0,2 °C/min	Dry
<b>Rainy day</b>	20 – 35°C	0,2 °C/min	1h imbibition



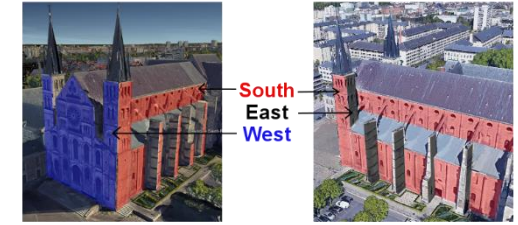
## Identification of typical events

	Temperature variation	Heating/Cooling rate	Humidity
<b>Sunny day</b>	20 – 35°C	0,2 °C/min	Dry
<b>Rainy day</b>	20 – 35°C	0,2 °C/min	1h imbibition
<b>Frost day</b>	-10 – 5°C	0,15 °C/min	1h imbibition

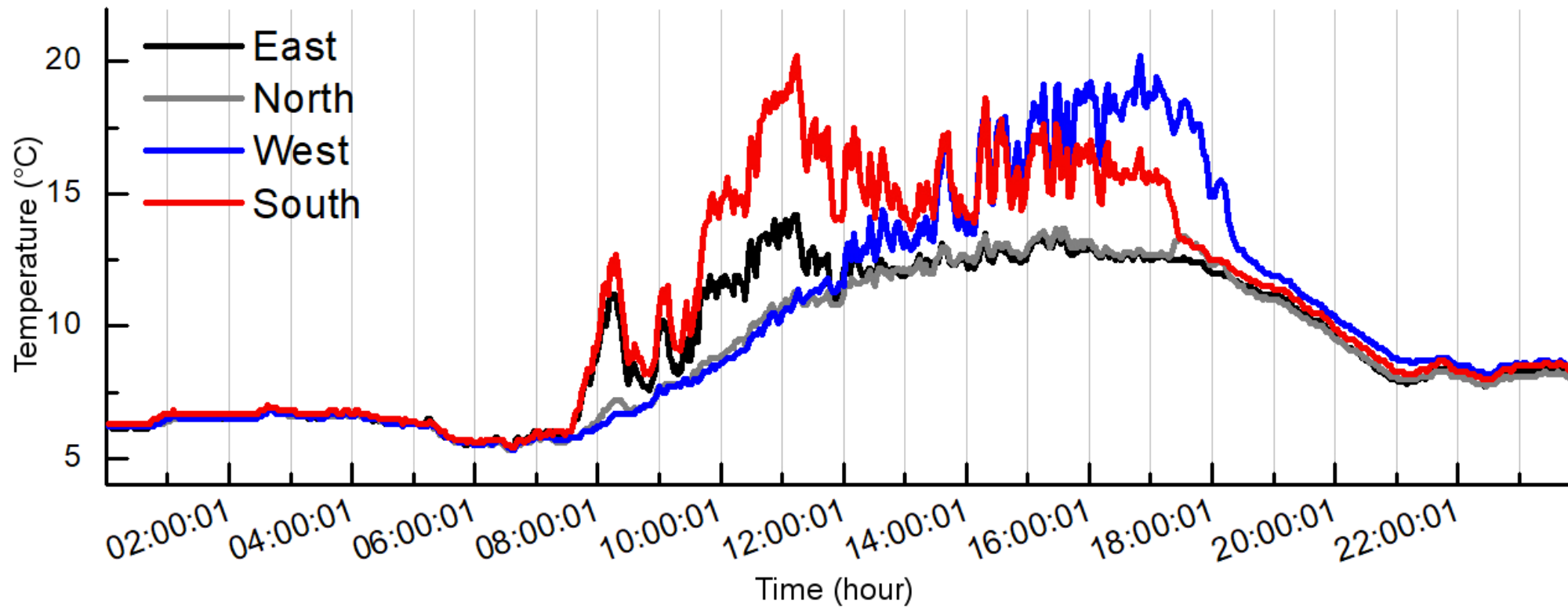


## Identification of typical events

### 1 day observation – time step of 2 minutes.

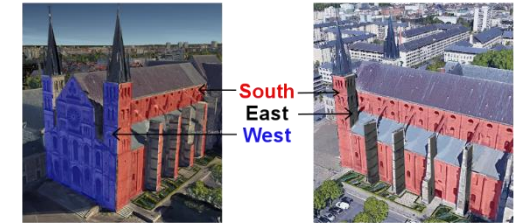


Façades orientation of the Basilica (Google Earth view).

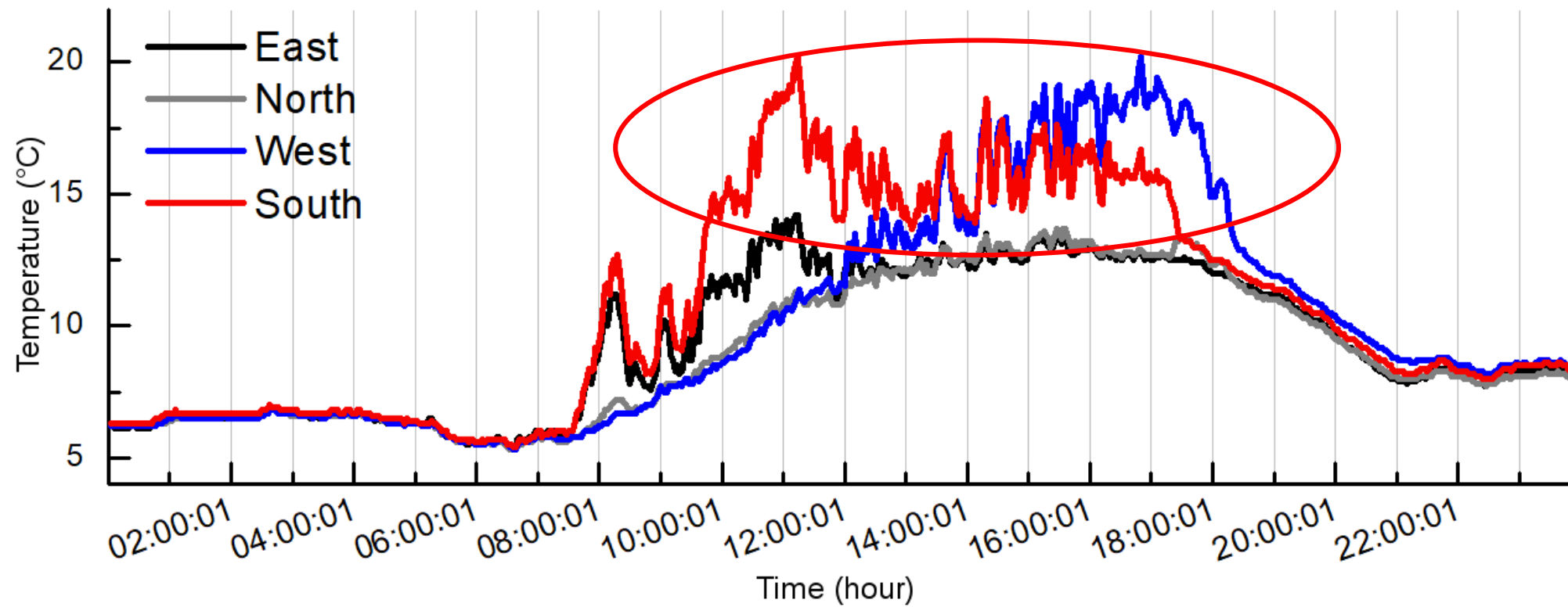


## Identification of typical events

### 1 day observation – time step of 1 hour.

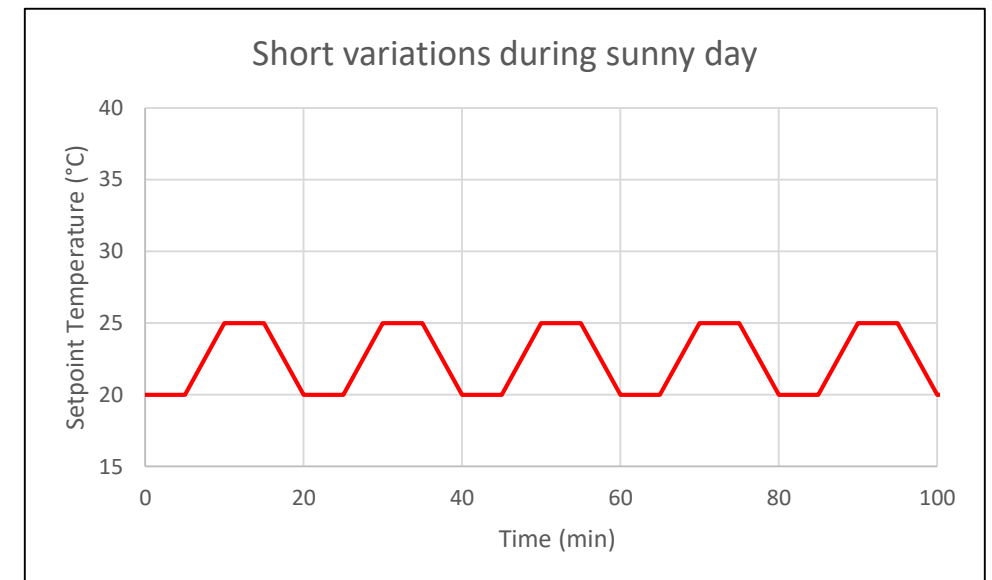


Façades orientation of the Basilica (Google Earth view).



## Identification of typical events

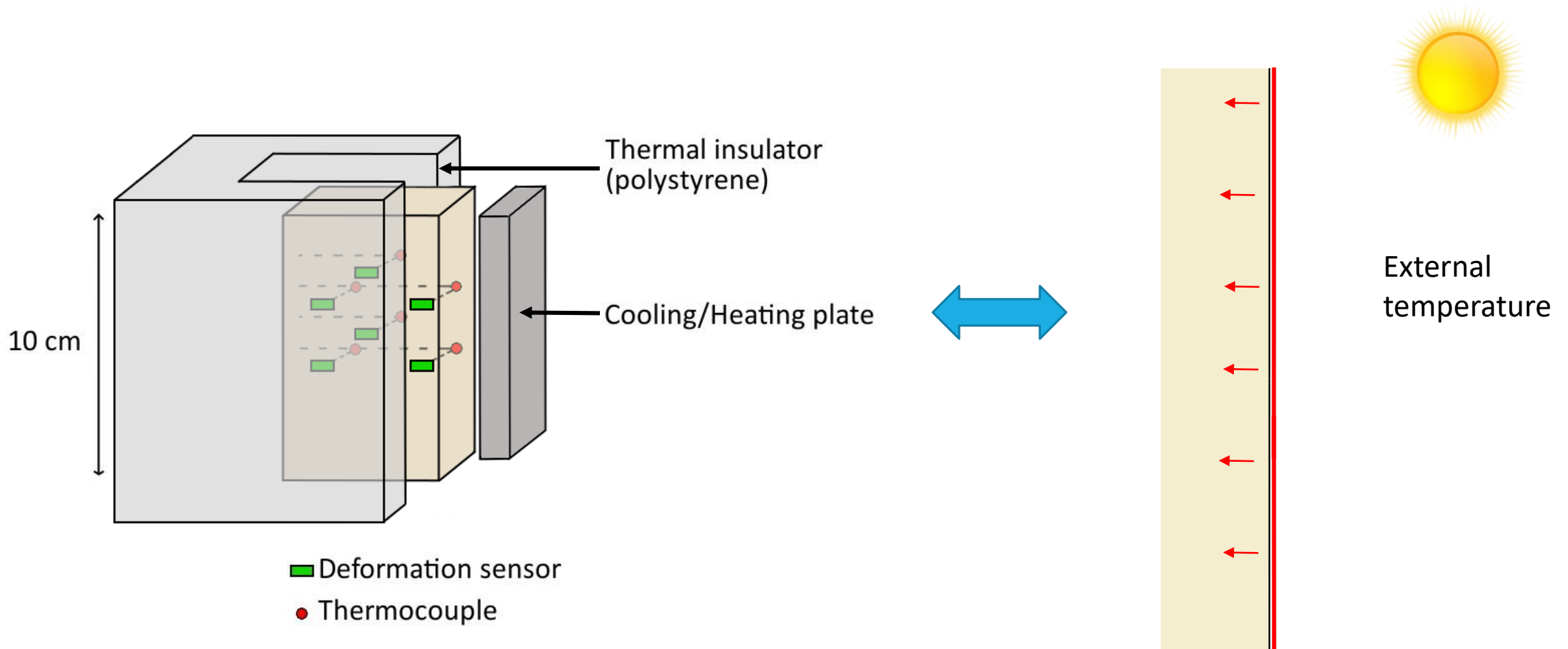
	Temperature variation	Heating/Cooling rate	Humidity
<b>Sunny day</b>	20 – 35°C	0,2 °C/min	Dry
<b>Rainy day</b>	20 – 35°C	0,2 °C/min	1h imbibition
<b>Frost day</b>	-10 – 5°C	0,15 °C/min	1h imbibition day
<b>Short variations</b>	20 – 25°C	1 °C/min	Dry





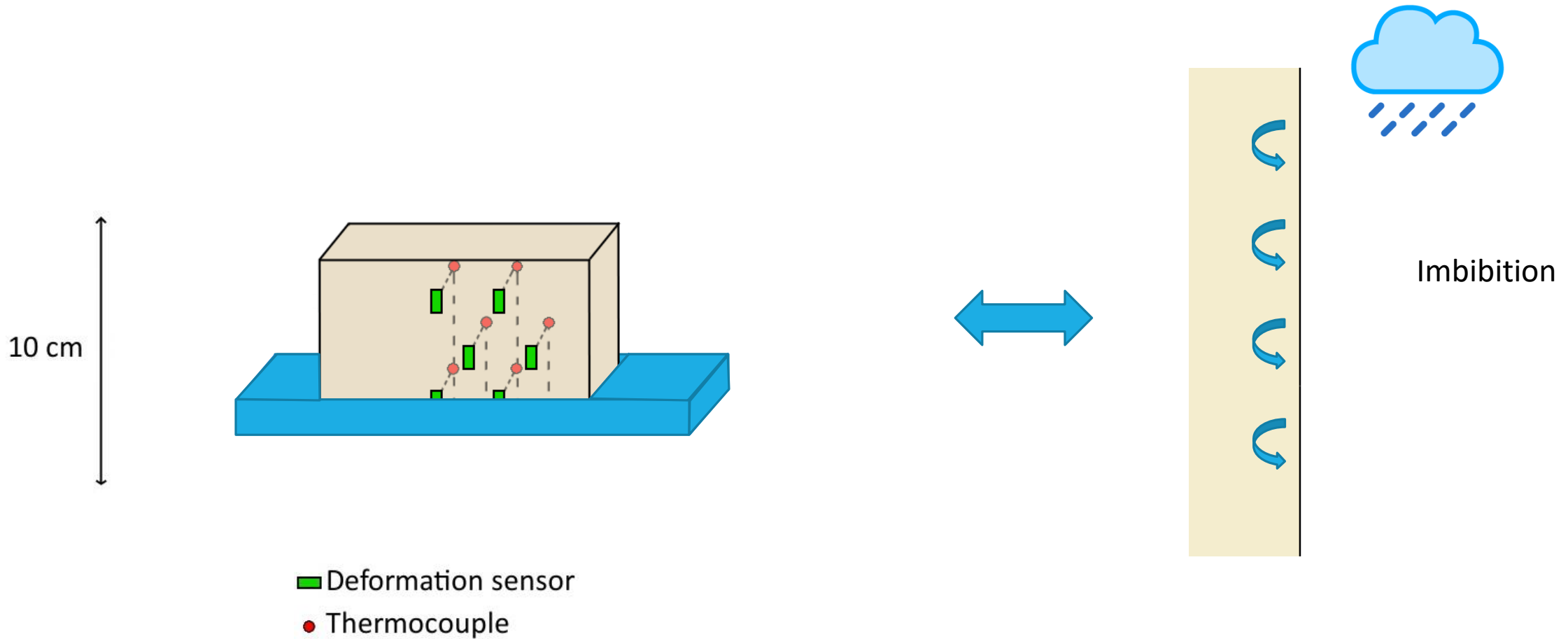
## AGEING TESTS

### Simulation of a vertical surface exposed to **temperature variations**

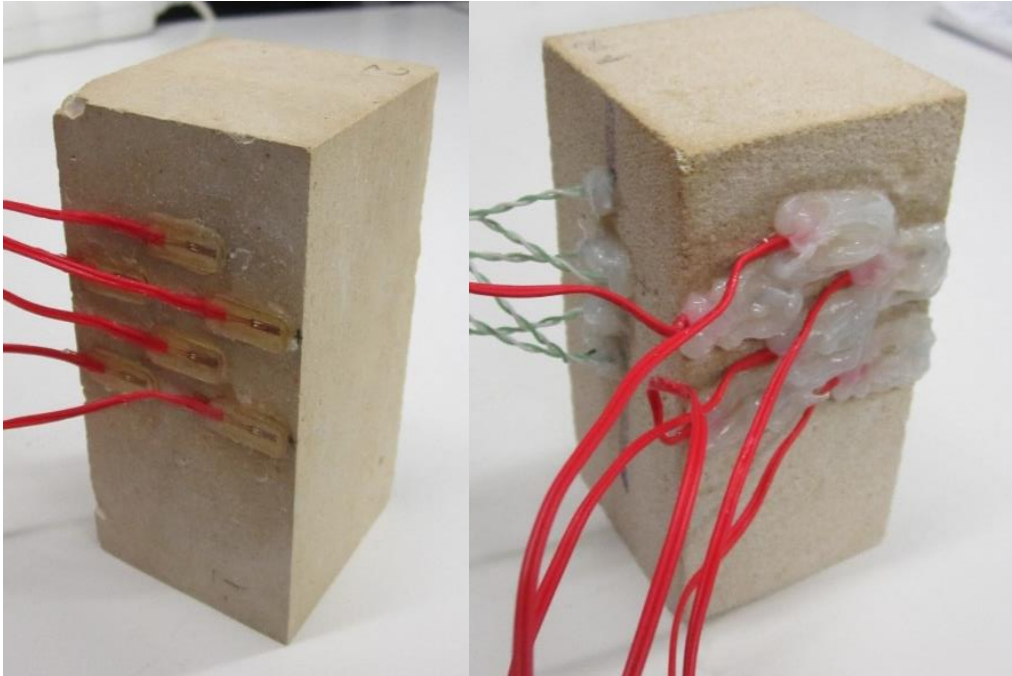


## AGEING TESTS

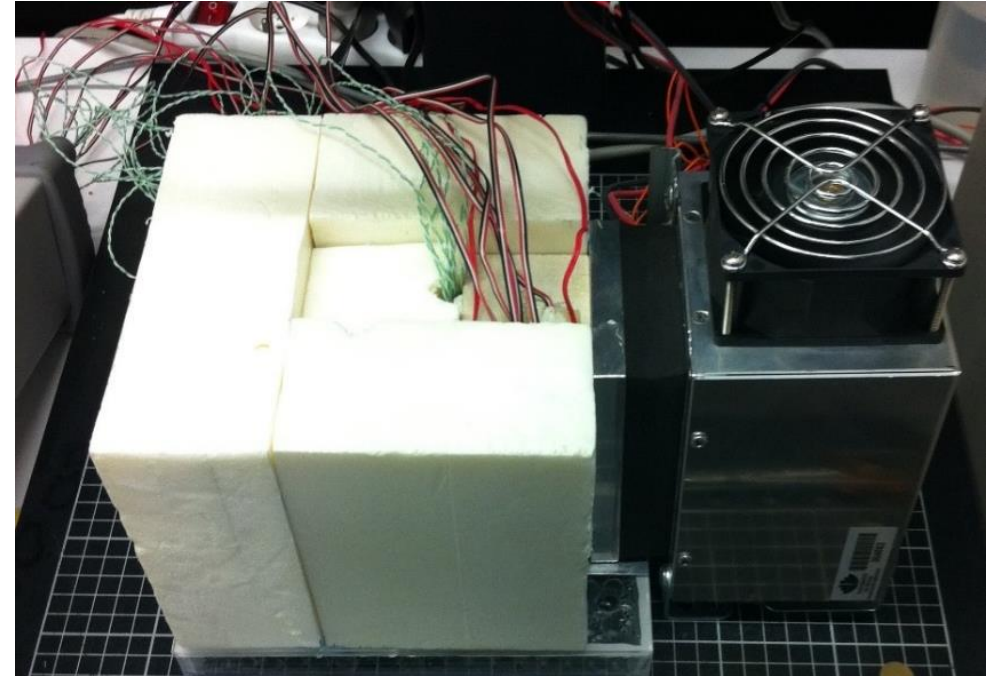
### Simulation of a vertical surface exposed to rain



## Setting

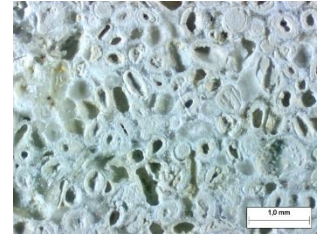


*Sample preparation.*

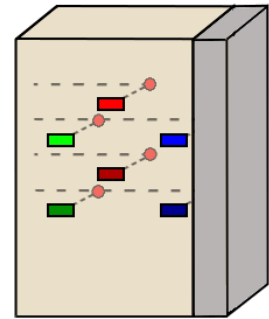
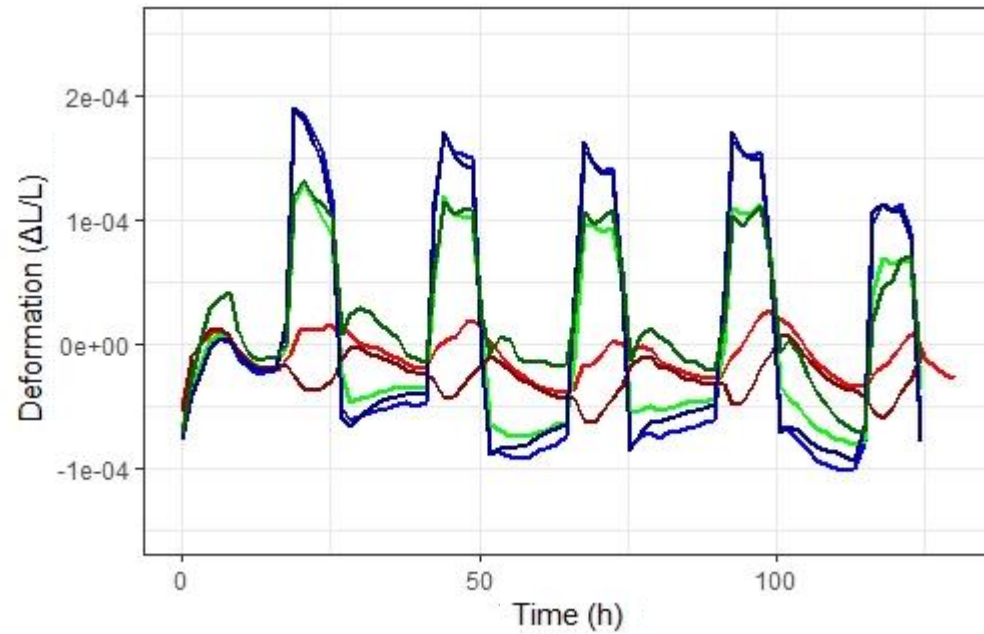
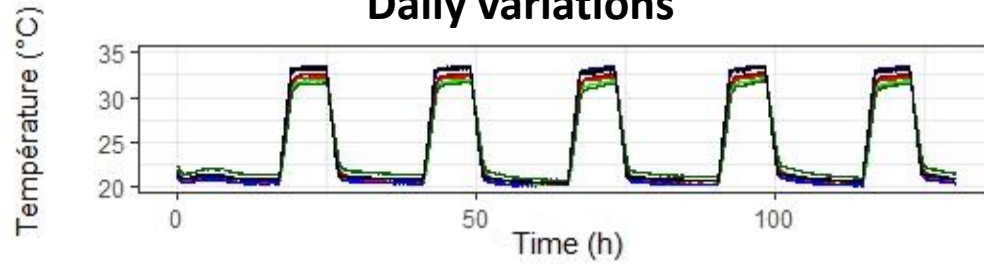


*Experimental setup.*

## Savonnières – Sunny day



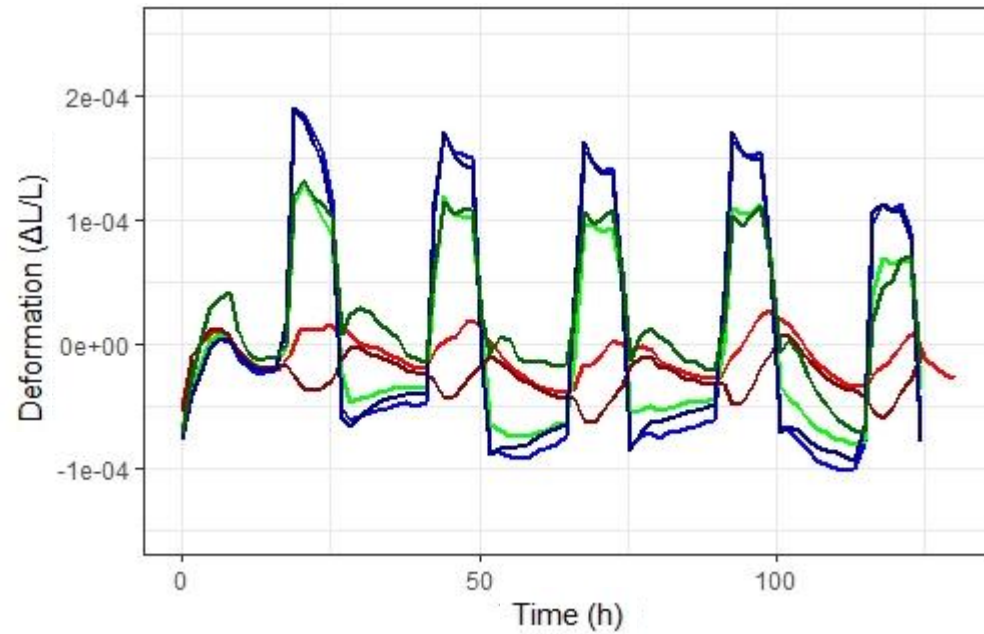
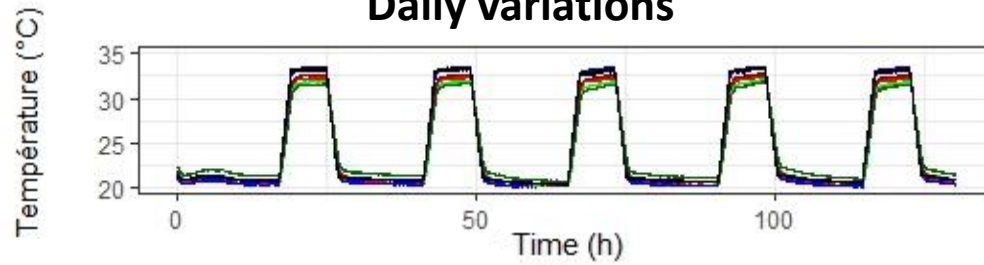
### Daily variations



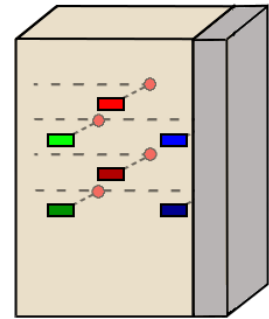
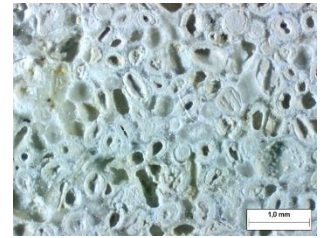
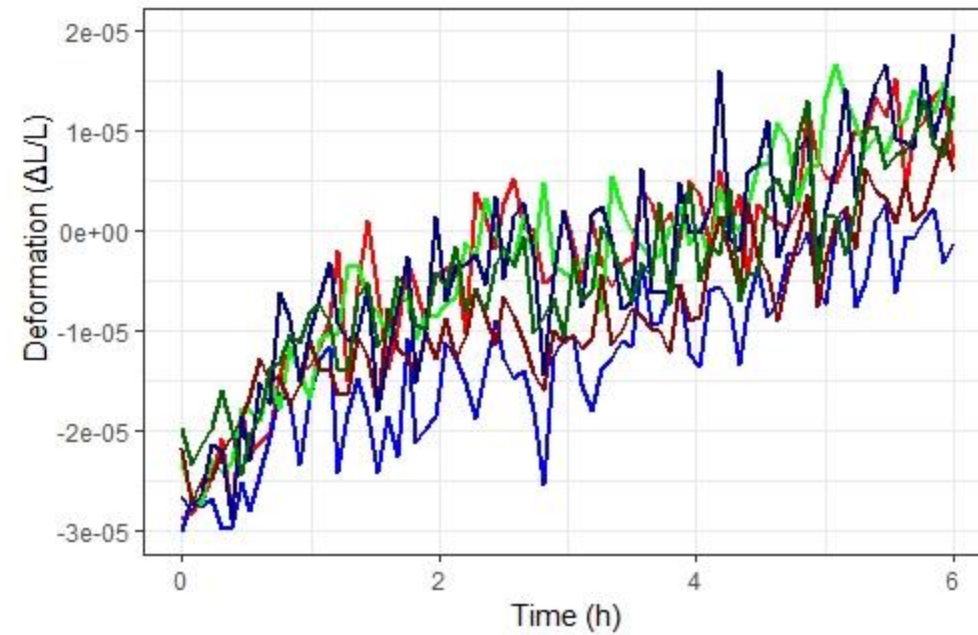
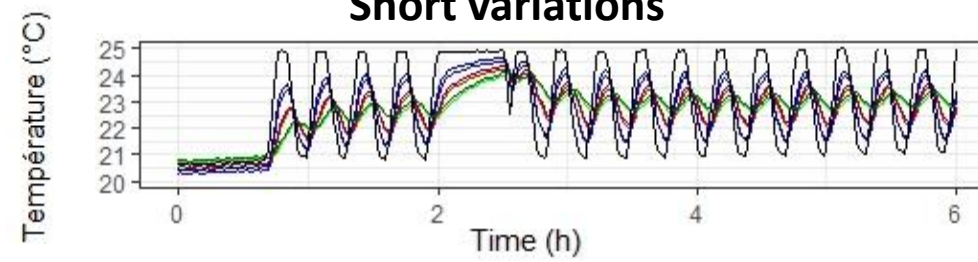
- Plate
- 8cm - 1,3cm
- 7cm - 0,2cm
- 7cm - 2,6cm
- 6cm - 1,3cm
- 5cm - 0,3cm
- 5cm - 2,7cm

## Savonnières – Sunny day

### Daily variations



### Short variations

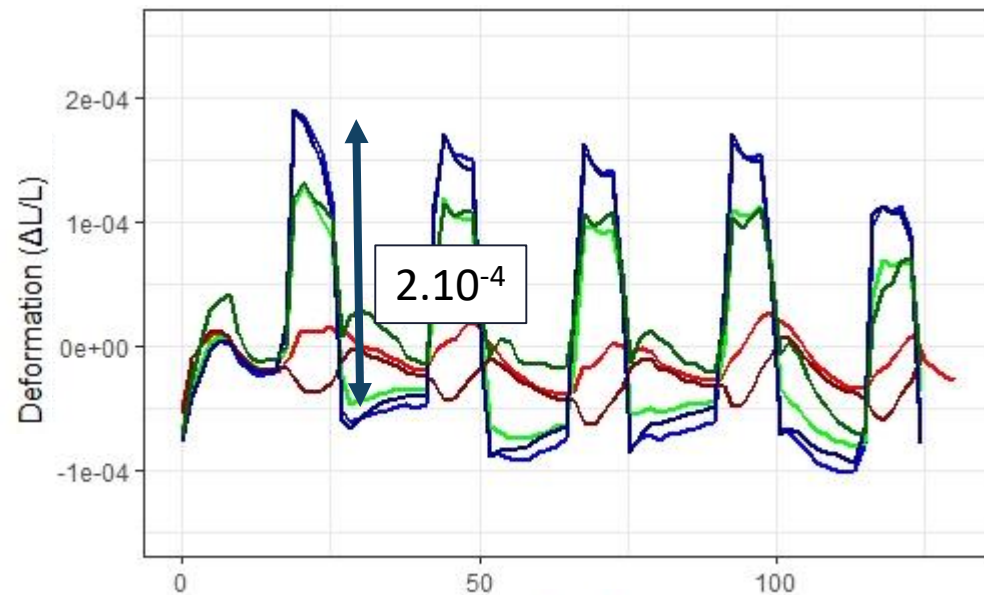
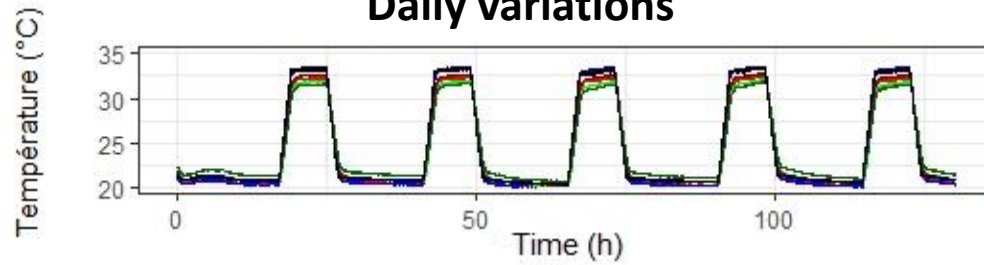


- Plate
- 8cm - 1,3cm
- 7cm - 0,2cm
- 7cm - 2,6cm
- 6cm - 1,3cm
- 5cm - 0,3cm
- 5cm - 2,7cm



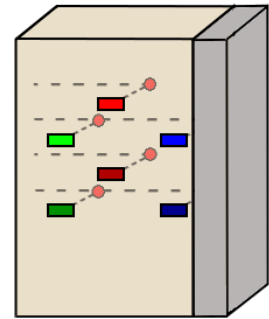
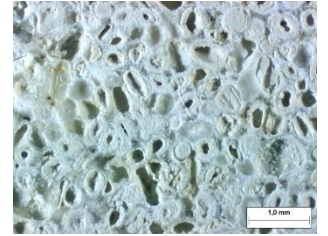
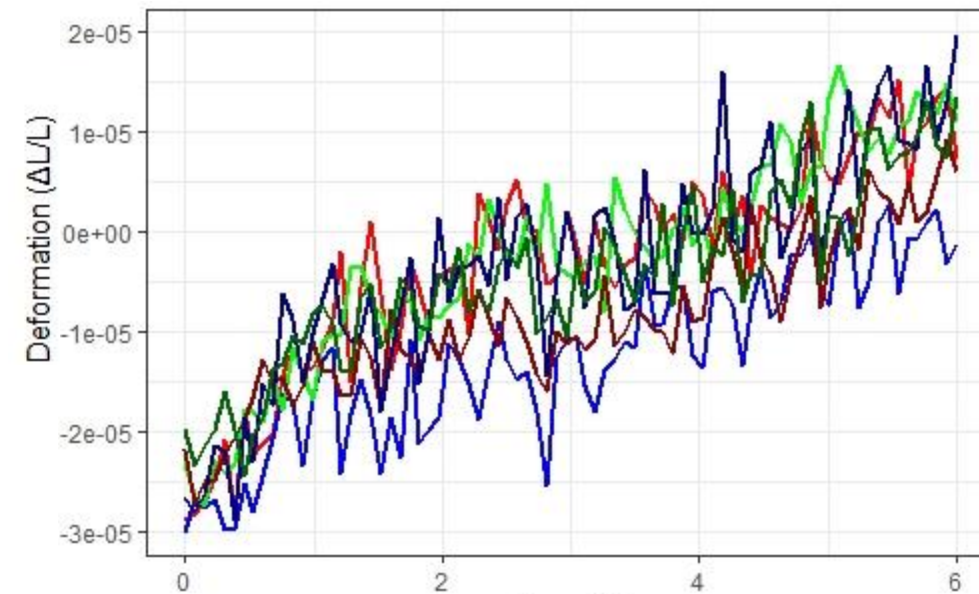
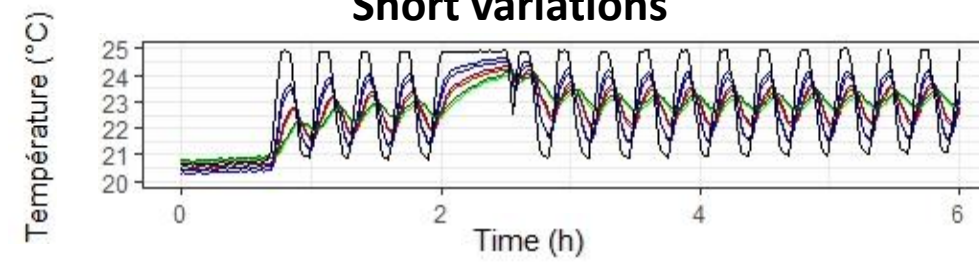
## Savonnières – Sunny day

### Daily variations



For each sunny day:  $2 \cdot 10^{-4}$  deformation near the surface

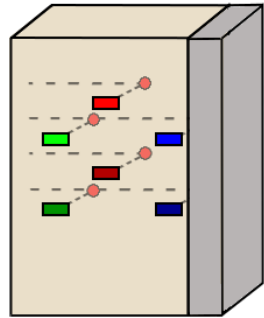
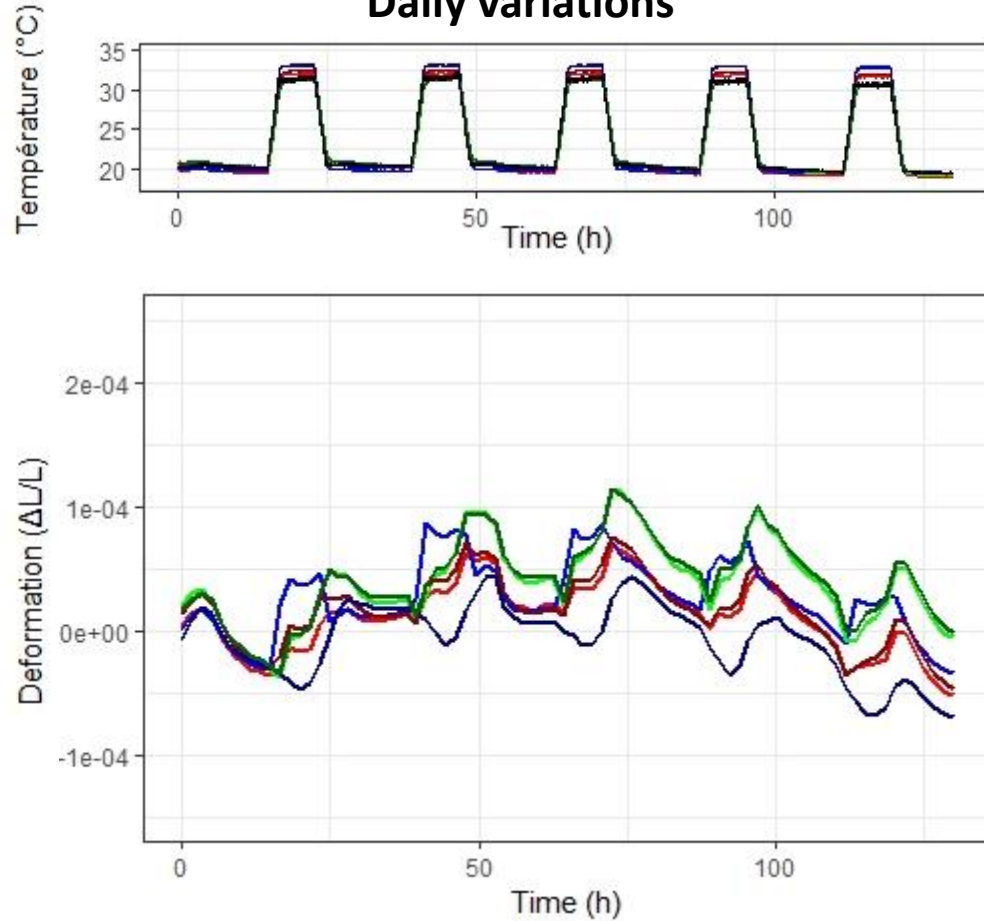
### Short variations



- Plate
- 8cm - 1,3cm
- 7cm - 0,2cm
- 7cm - 2,6cm
- 6cm - 1,3cm
- 5cm - 0,3cm
- 5cm - 2,7cm

## Ageing tests: Courville – Sunny day

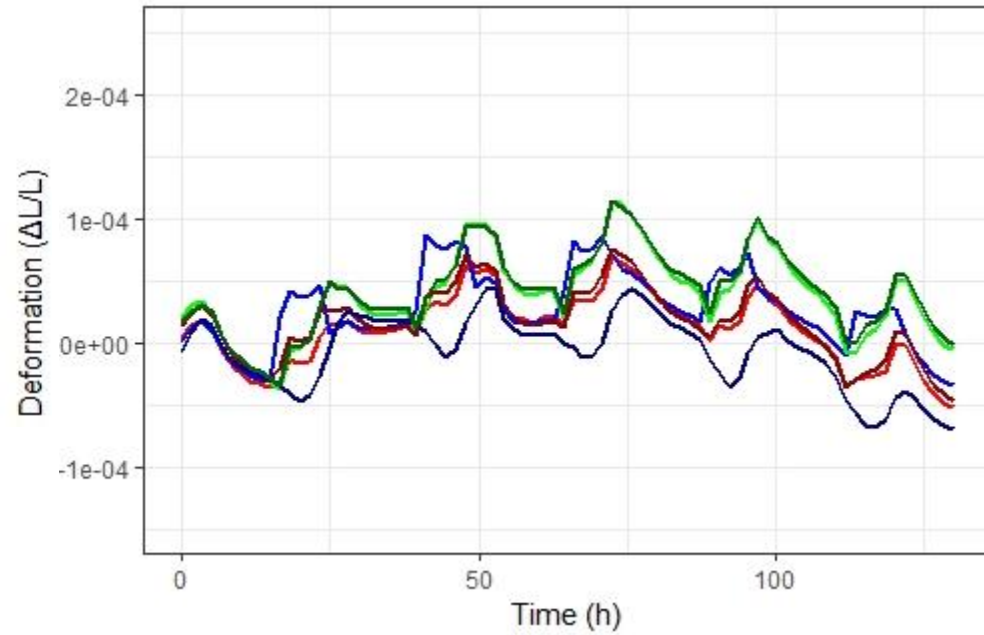
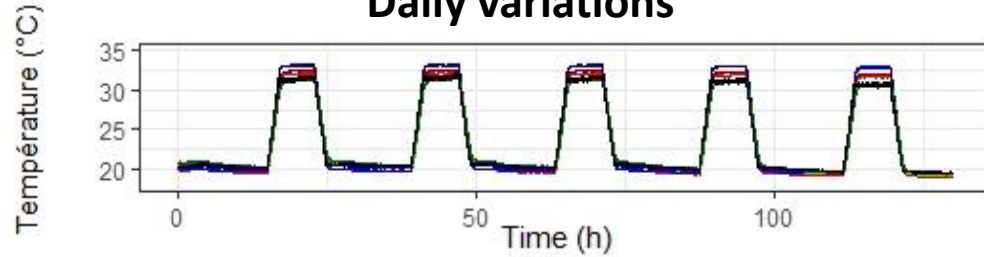
### Daily variations



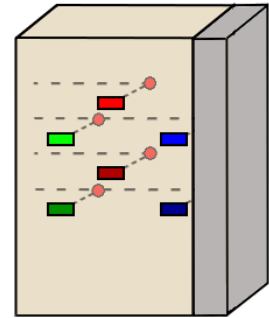
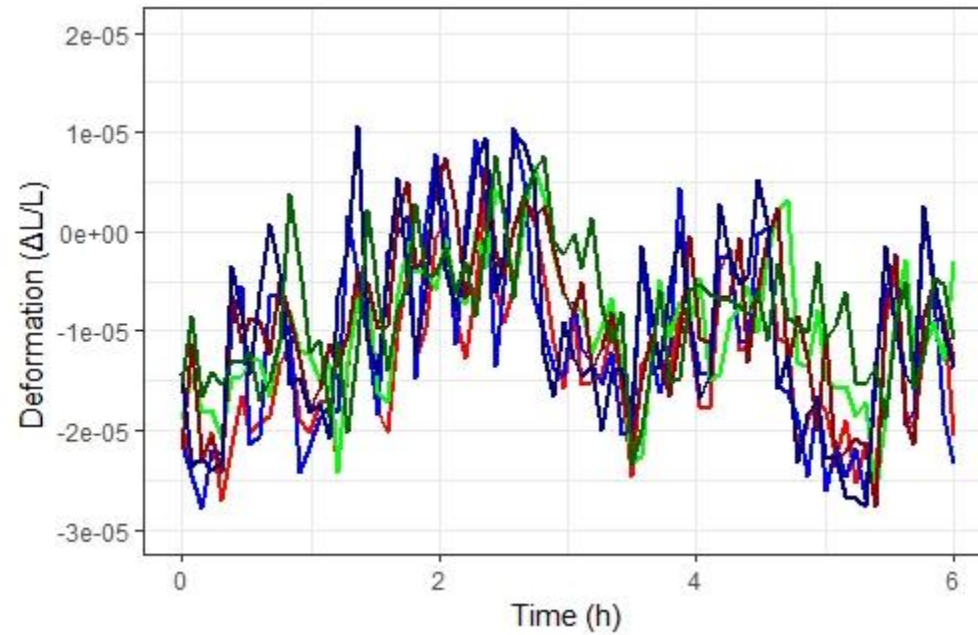
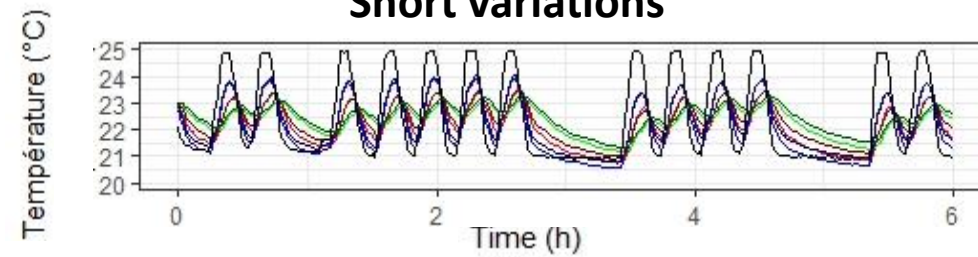
- Plate
- 8cm - 1,3cm
- 7cm - 0,2cm
- 7cm - 2,6cm
- 6cm - 1,3cm
- 5cm - 0,3cm
- 5cm - 2,7cm

## Ageing tests: Courville – Sunny day

### Daily variations



### Short variations

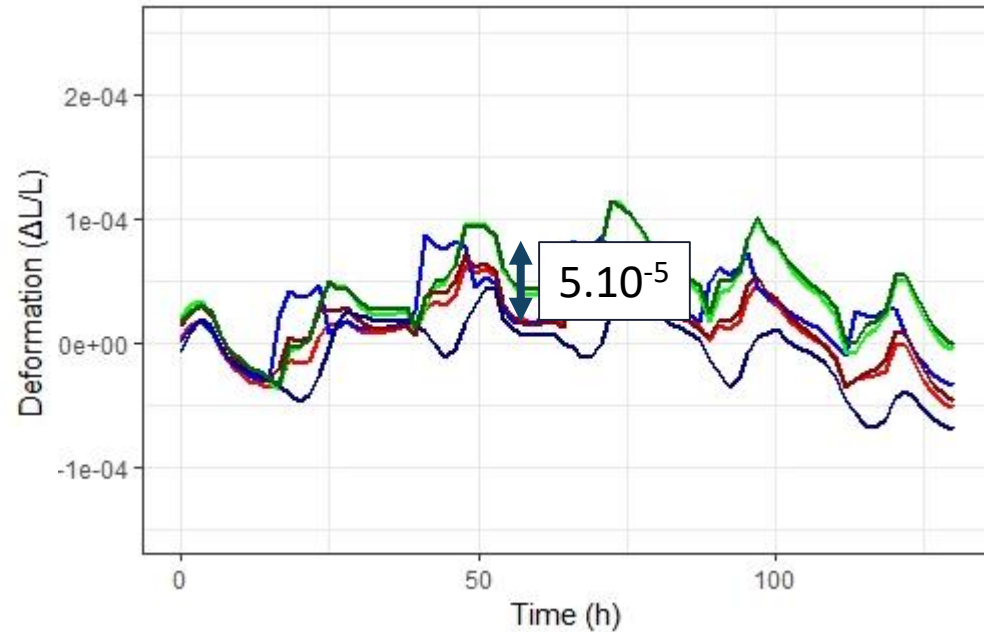
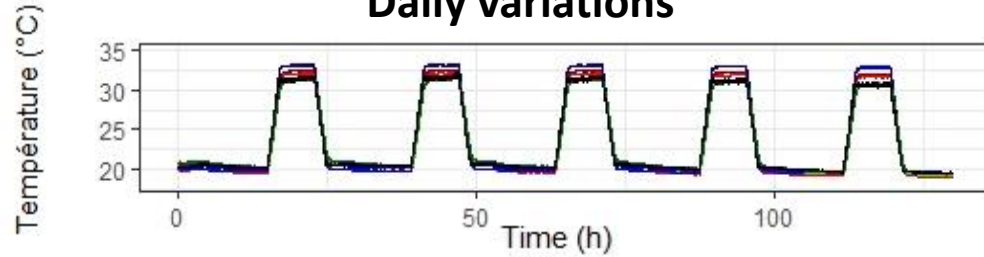


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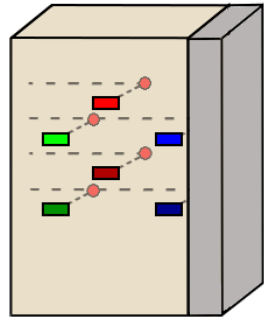
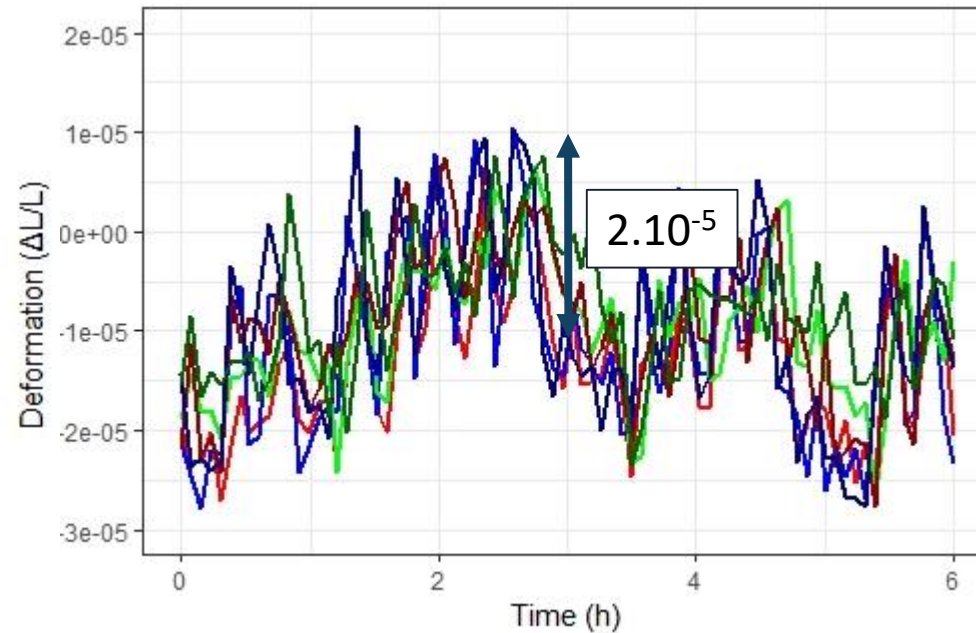
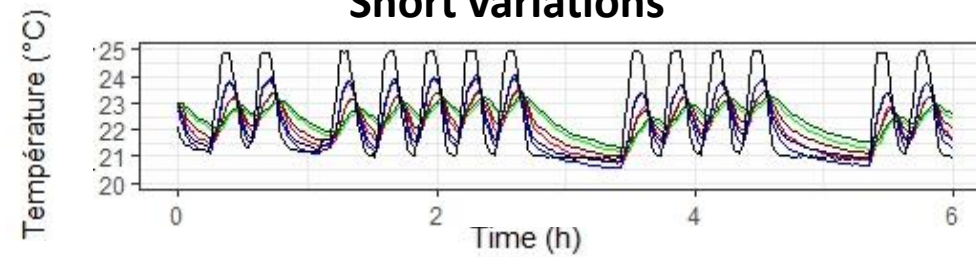


## Ageing tests: Courville – Sunny day

### Daily variations



### Short variations



- Plate
- 8cm - 1,3cm
- 7cm - 0,2cm
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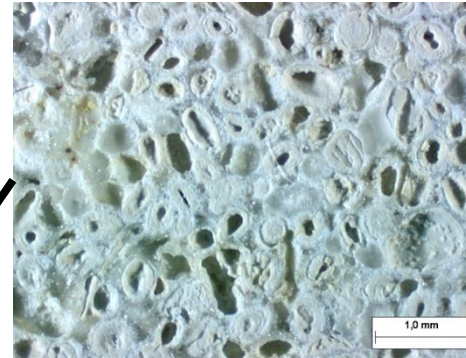
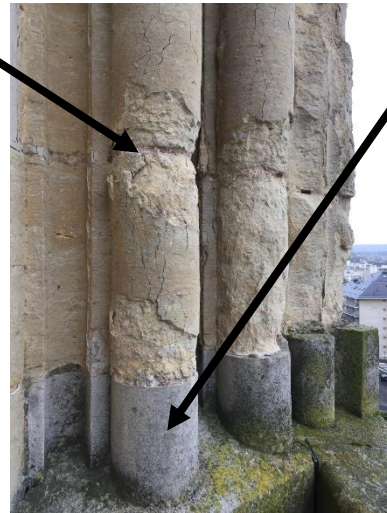
For each sunny day:  $5 \cdot 10^{-5} + 15 \times 2 \cdot 10^{-5}$  deformation near the surface

## Results – Sunny day



### Courville

1 cycle  $5 \cdot 10^{-5}$   
15 cycles  $2 \cdot 10^{-5}$

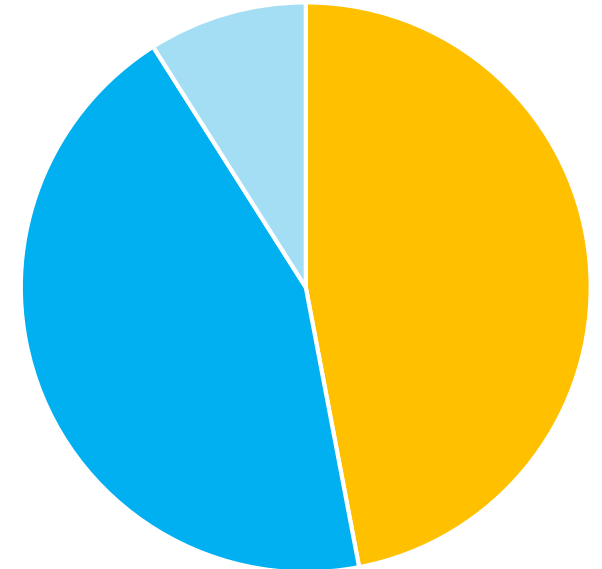


### Savonnières

1 cycle  $2 \cdot 10^{-4}$

*Picture of weathered stones and restored stones on the Basilica (West Façade).*

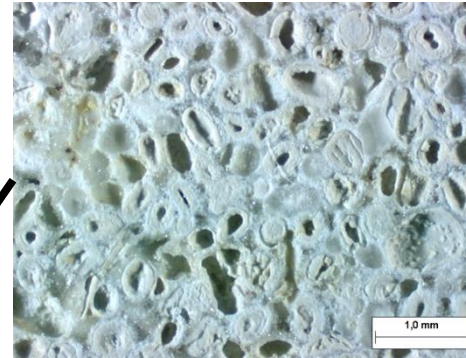
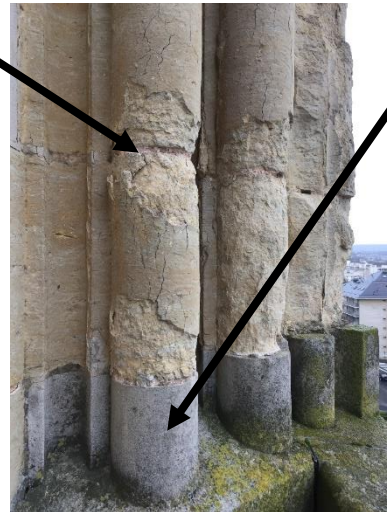
West Façade



## Results – Sunny day



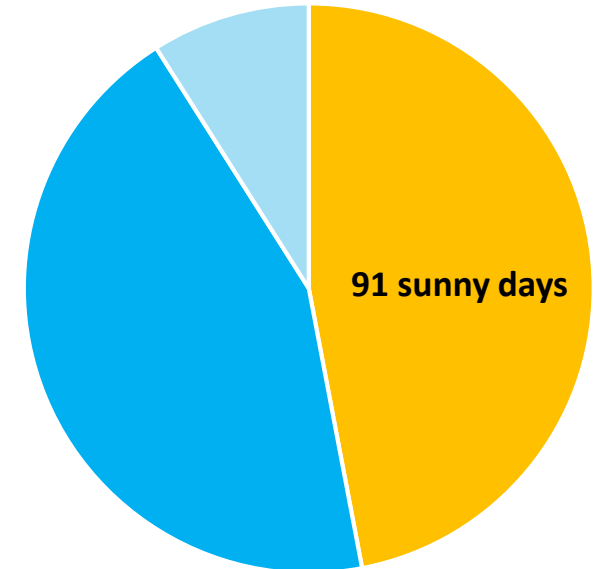
**Courville**  
 1 cycle  $5 \cdot 10^{-5}$   
 15 cycles  $2 \cdot 10^{-5}$



**Savonnières**  
 1 cycle  $2 \cdot 10^{-4}$

*Picture of weathered stones and restored stones on the Basilica (West Façade).*

West Façade



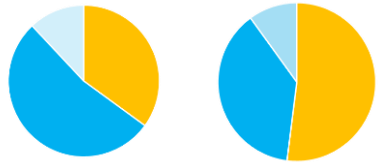
On façades exposed to the sun : more **thermal fatigue** on **Courville** limestone.

## CONCLUSION

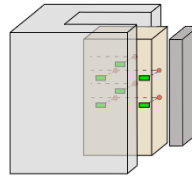
Identification of days



Repartition of typical days



Stone behaviour during the typical days



**Stone behaviour on the monument**

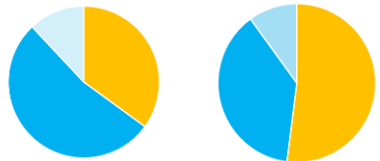


## CONCLUSION

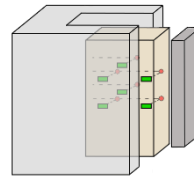
Identification of days



Repartition of typical days



Stone behaviour during the typical days

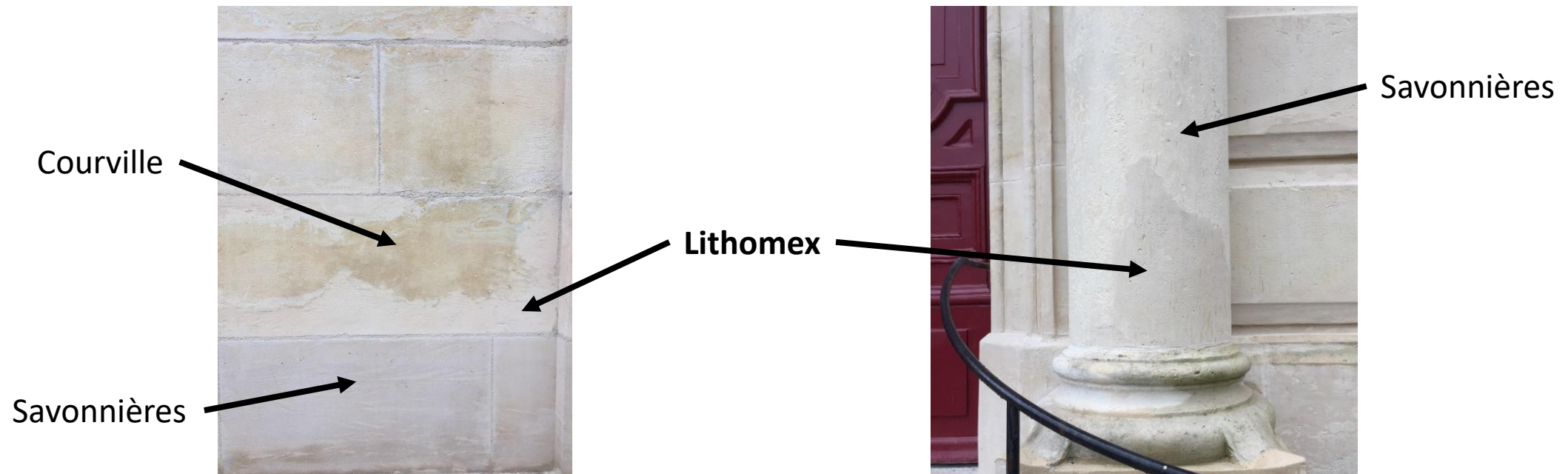


**Stone behaviour on the monument**



## PERSPECTIVES

- Ageing tests simulating frost days according to the *in situ* monitoring
- Mechanical properties & global dilatation measurements
- More intense ageing tests
- Study of a restoration mortar (Lithomex)



Thank you for your attention

