

# **Financial instruments to mitigate the risk of climate change: rainfall and temperature**

Silvana Stefani

Università Milano Bicocca

[silvana.stefani@unimib.it](mailto:silvana.stefani@unimib.it)

Coauthored with Enrico Moretto, Simone Cambiaghi, Matteo Parravicini and Adeyemi Sonubi

# Outline

- **PART 1: THE CLIMATE CHANGE ISSUE**

Is there any climate change issue? Is there an agreement in the scientific community? What are the latest decisions taken at the international community level? Evidence about climate change

- **PART 2: PRICING AND EVALUATING FINANCIAL INSTRUMENTS** against risk of temperature and rainfall

A suitable model for the underlying; the financial instrument and its pricing; simulations

# Climate research\_1

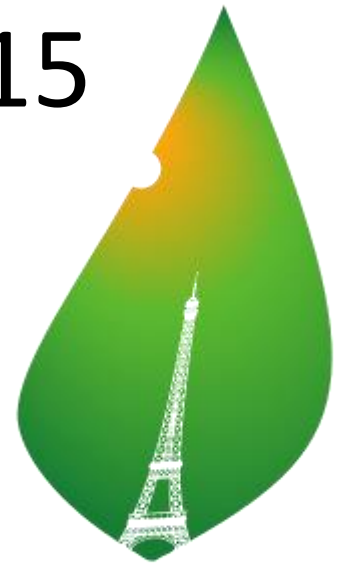
- The climate system, like so many other large and complex systems, cannot be studied in a traditional laboratory research setting.
- This is what is called *post-normal science*, that is the phenomena to be studied are complex, stakes are high and the available time for research is insufficient. However, waiting until it is clear how the climate system works before making decisions will probably be «too late».

# The climate change issue\_1

- Climate change can be caused either by natural phenomena (i.e. glacial ages or volcanic eruptions) or human-driven action (i.e. emissions of greenhouse gases in the atmosphere, mainly CO<sub>2</sub>).
- There is a strong scientific consensus (IPCC, 2013) that the ongoing climate change is entirely due to humanity (Barnosky et al, 2012)

# The Paris conference 2015

The agreement calls for zero net anthropogenic GHG emissions to be reached during the second half of the 21st century. In the adopted version of the Paris Agreement, the parties will also "pursue efforts to" limit the temperature increase to 1.5 °C. The 1.5 °C goal is somehow ambitious, since it would require zero emissions sometime between 2030 and 2050.



PARIS2015  
UN CLIMATE CHANGE CONFERENCE  
COP21·CMP11

# Some obstacles..

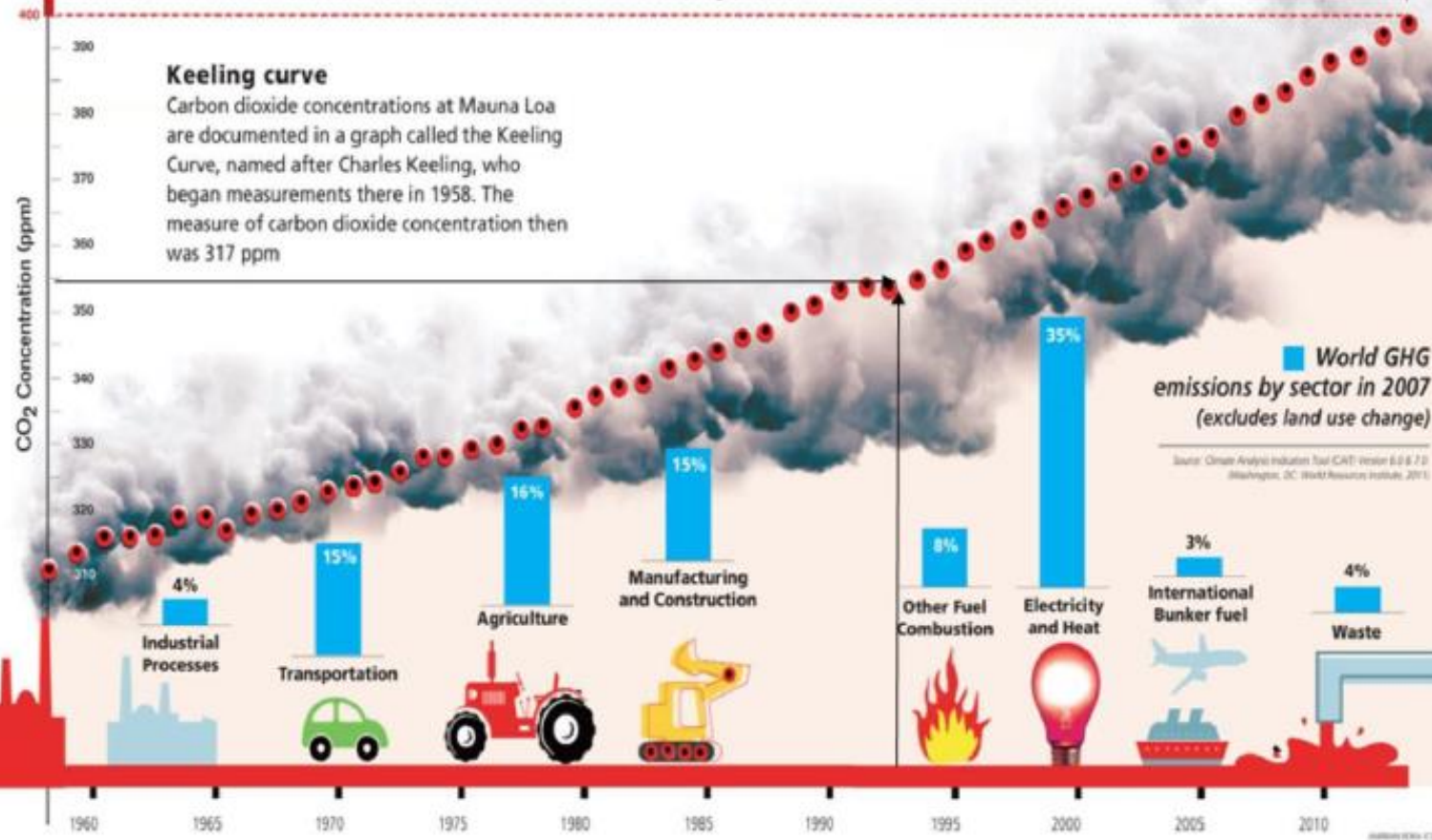
At political level, the attempts of managing the climatic changes at a global level, i.e. the decisions taken in the 2016 Paris conference, have been recently counterbalanced by a not clearcut US policy.

# A first in human history

Carbon dioxide levels have crossed 400 ppm. This means the impacts of climate change will be even more pronounced—droughts, floods and sea level rise, for instance. If the world does not act to limit carbon dioxide emissions, climate change will cause devastation worldwide, and more so in South Asia. The poor will end up with a raw deal

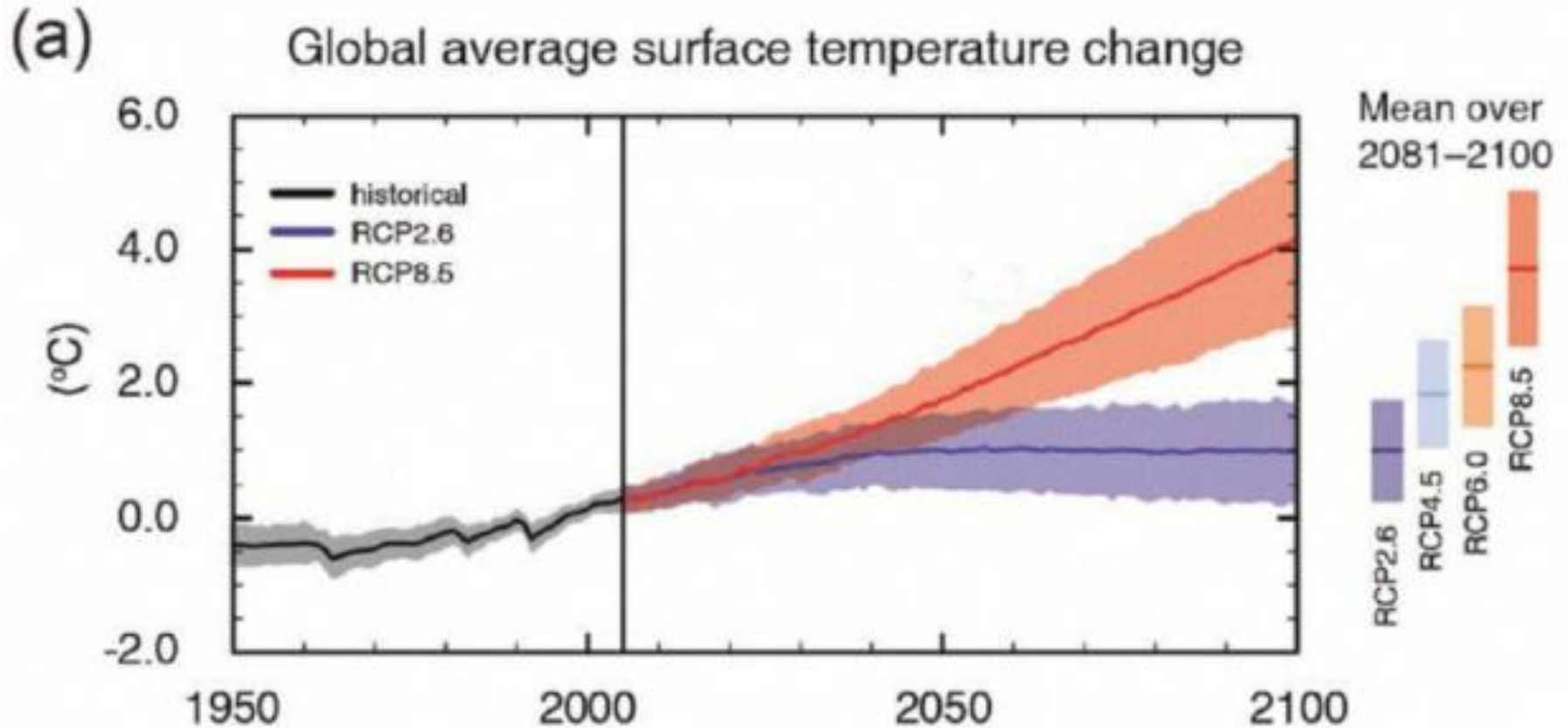
BREACHES  
**400**  
PPM ON  
MAY 9, 2013

Carbon dioxide concentration at Mauna Loa Observatory, Hawaii



- For the past several years, CO<sub>2</sub> concentrations have hovered close to 390 ppm. The 400 ppm daily average is a first in human history
- In the last 50 ppm increase, the Arctic melted. Imagine what another 50 ppm increase will do
- Diversity of even common species found in most parts of the world will be badly hit. Animal species in particular may decline more as a result of loss of food from plants
- Some environmentalists are of the view that to return to the 350 ppm level, use of conventional energy sources has to be re-examined. But this is easier said than done. Any alternative measure will require finance and technological assistance from industrialised countries to developing countries. Even though institutions for financial transfer exist under UNFCCC, there is no money and the industrialised world has not provided exclusive climate finance to developing countries yet

# The future of global warming according to IPCC AR5



# 2014: WAS THE HOTTEST YEAR IN RECORDED HISTORY



## NORTHERN HEMISPHERE:

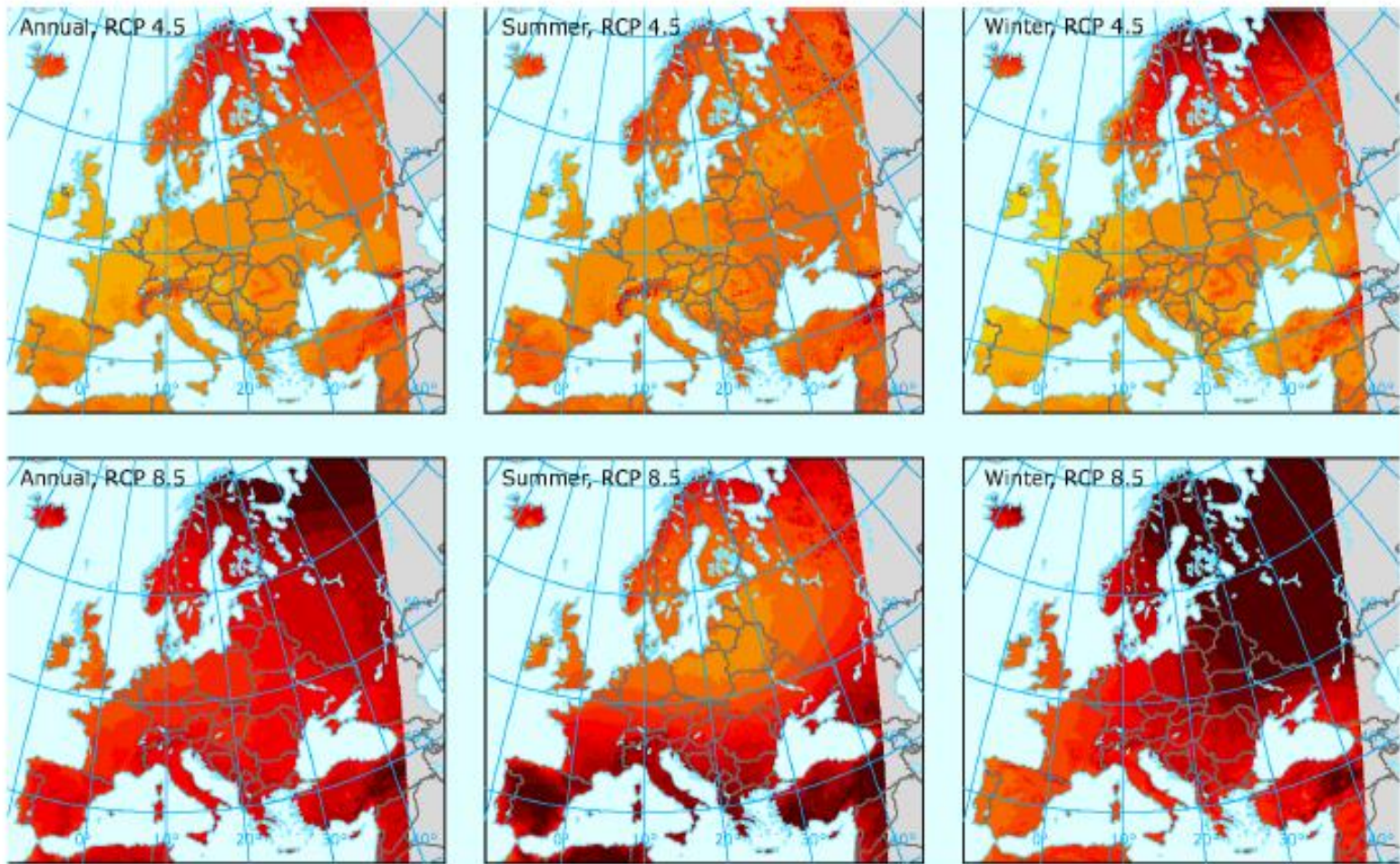
hottest Northern Hemisphere sea surface temperature (outside the tropics) for February. Hottest May on record globally.

## SOUTHERN HEMISPHERE:

highest January Southern Hemisphere land temperature on record



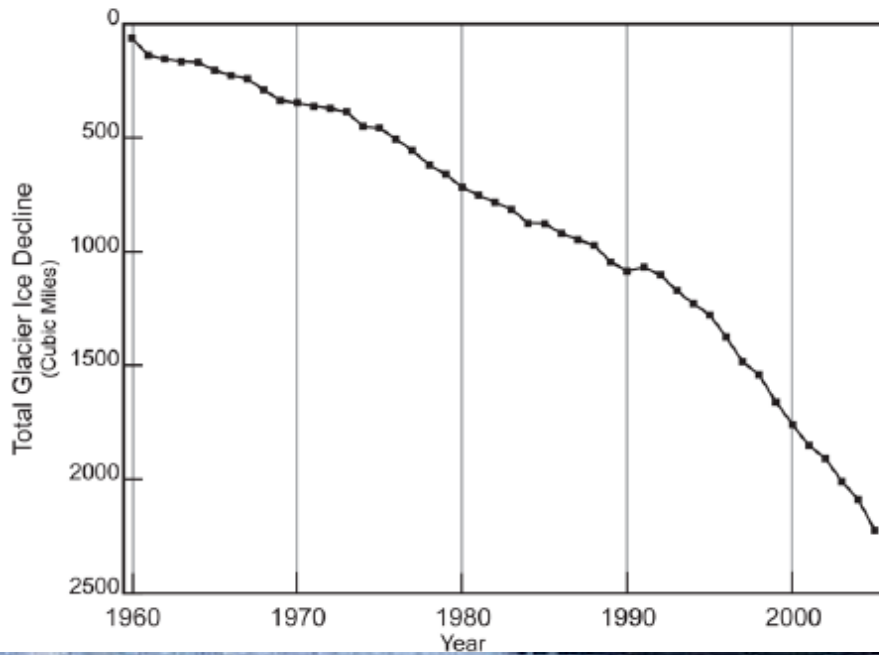
CLIMATE CHANGE IS DRIVING MORE EXTREME WEATHER AND IMPACTING PEOPLE AROUND THE WORLD. THIS IS THE CRITICAL DECADE FOR ACTION.



Source: IPCC, 2013.

Figure 1.4.3: Projected changes in temperature for Europe. In the upper side the lower emission scenario is displayed, while in the lower side the high emission scenario. Dark red means higher temperature than current average.

# Trend of total mass of glaciers



# The effect of climate changes\_1

Climate scientists (IPCC, 2013) agree that if greenhouse gases emissions will continue in the future at current path, the predicted impacts will be:

- ▶ Longer and more intense heat waves;
- ▶ More frequent damaging storms;
- ▶ Major damages to coastal cities as sea level rises;
- ▶ Water shortages in populated parts of the world
- ▶ Local reduction of crop yields;
- ▶ Economic losses, social strife and political unrest;
- ▶ Spread of infectious disease;
- ▶ Major damages to unique ecosystem;
- ▶ Extinction of species.

# The effect of climate changes\_2

*At least a trillion dollars\* of the world economy is sensible to weather variations. It is estimated that at least 20% of the world economy is affected by weather conditions and at least 80% of public service companies consider climatic conditions as a key factor for their operating revenues»*

*US secretary of commerce William Daley, 1998*

\* Un miliardo di miliardi!  $10^{18}$

# The effect of climate changes\_3

The climatic change affects the most diverse economic sectors among which:

- Agriculture
- Building activities
- Electricity generation (through change of wind, modified solar and precipitation patterns, change of demand, ...)
- Tourism (seaside resorts, skiing, ...)
- ... up to the financial sector

# PART 2: PRICING AND EVALUATING A FINANCIAL INSTRUMENT

Pricing and evaluating a financial instrument against risk of temperature and rainfall

A suitable model for the underlying

The financial instrument and its pricing

Simulations

# WEATHER RISK

## **WEATHER RISK**

Risk due to uncertainty in cash flow and revenues deriving from climate volatility

## **WEATHER DERIVATIVES**

Financial derivatives where the underlying is a meteorological variable

# TEMPERATURE DERIVATIVES: The underlying variables

Temperature derivatives are a special typology of financial derivatives, where the underlying is given by temperatures; those contracts are typically OTC contracts.

The three main indices underlying of temperature derivatives are:

- **CDD** (*Cooling-degree days*):  $CDD(t) = \max(T(t) - threshold; 0)$
- **HDD** (*Heating-degree days*):  $HDD(t) = \max(threshold - T(t); 0)$
- **CAT** (*Cumulative Average Temperature*):  $CAT(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} T(t)$

# HOW TO PRICE A DERIVATIVE?

1. MODELLING THE UNDERLYING

2. THE PRICING MODEL

# 1. MODELLING THE UNDERLYING

$$T(t) = \mu(t) + \varepsilon(t) \quad \text{with} \quad \varepsilon(t) = \sigma(t)\varepsilon(t)$$

**RESIDUALS**

$$\mu(t) = \Lambda(t) + \sum_{i=1}^p \alpha_i (T(t-i) - \Lambda(t-i))$$

**AR  
PROCESS**

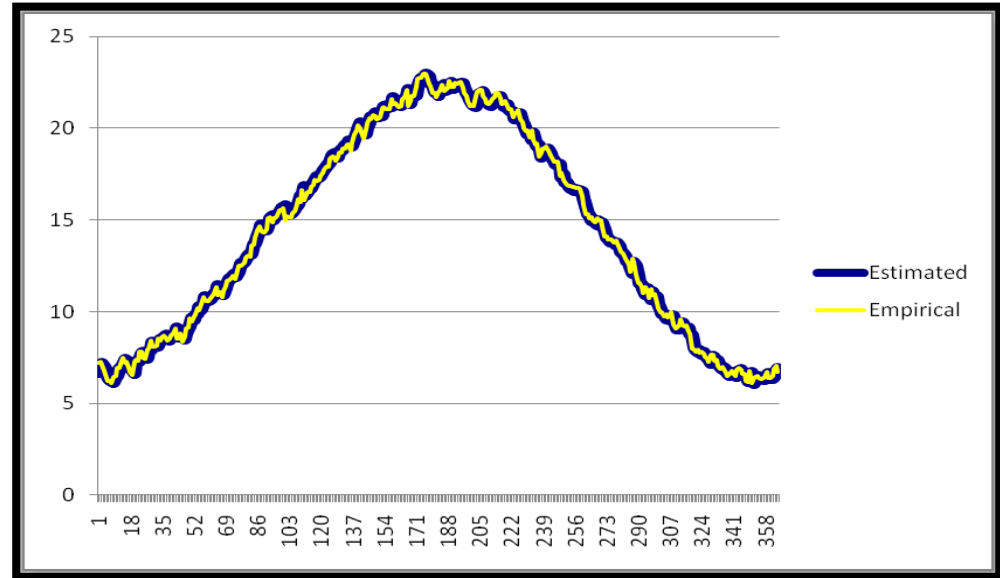
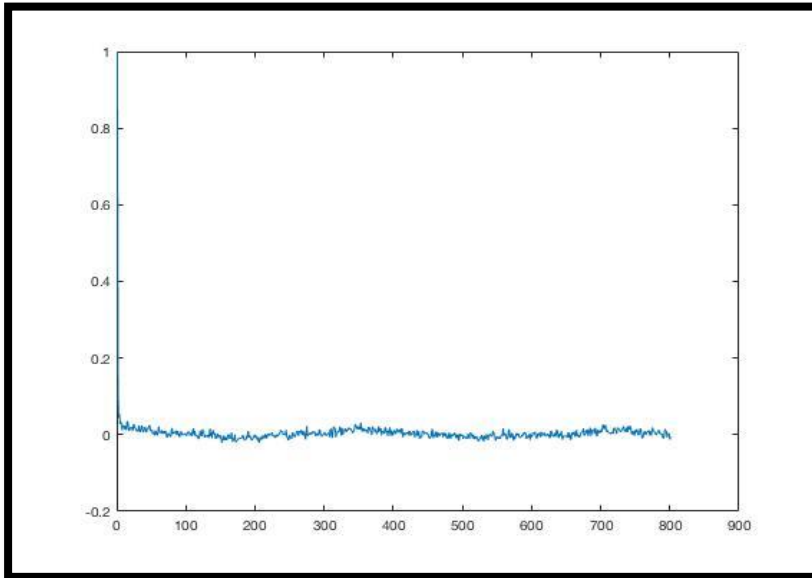
$$\Lambda(t) = a_0 + a_1 t + a_2 \cos(2\pi t/365) + a_3 \sin(2\pi t/365)$$

**TREND**

**SEASONALITY**

# VALIDATION

- To verify the goodness of fit:



- To the left: in the residuals autocorrelation function, the seasonality has been removed and captured by the model
- To the right: observed daily mean temperatures (in yellow) and estimated (in blu)

# 2. THE PRICING MODEL

Generally speaking, a contract payoff valid for the period from  $\tau_1$  to  $\tau_2$  is given by:

$$X(\tau_1, \tau_2) = k \times \textit{indice}$$

where for *index* we mean HDD, CDD or CAT and  $k$  is the *tick size*, that is a fixed value that converts Celsius degrees in Euros

- The standard approach is the *burn analysis* (F.E.Benth, Papazian and Skiadopoulos), based on the expected payoff  $[X(\tau_1, \tau_2)]$ , discounted at a given interest rate in order to obtain the present value of it:

$$P(t, \tau_1, \tau_2) = \exp(-r(\tau_2 - t))[X(\tau_1, \tau_2)]$$

## ASSUMPTIONS

1. The *tick size* is set as 20 euros.
2. All contracts last one month
3. The discount rate is set as 0

# BURN ANALYSIS: OUR PROPOSAL\_2

- For each day we simulate 1000 values of the stochastic component of the model through the formula

$$\varepsilon(t) = \sigma(t)\epsilon(t)$$

- The residuals are added to the components of the model.
- From the simulated 1000 temperature values for each day of the month, we have calculated the corresponding index. From those 1000 values we have got the arithmetic mean to add to the values obtained from the time series.

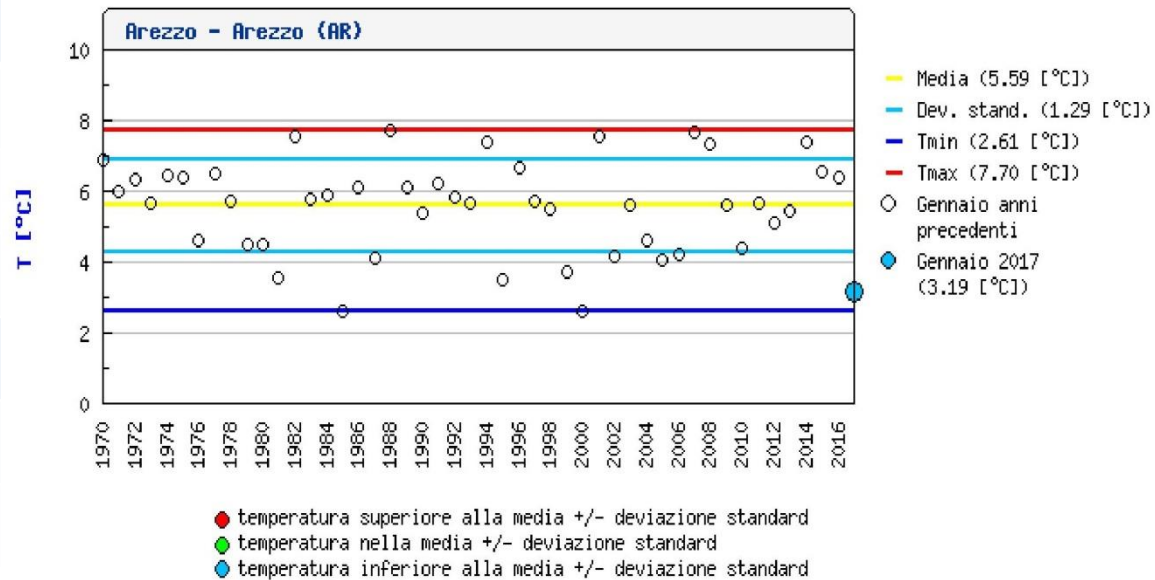
We remind that for an OTC contract directly negotiated with a counterpart (bank or insurance), the bank or insurance may apply a component to be added to the price, called *risk loading*, generally set as the 5% of the 95° percentile of the payoff distribution.

# APPLICATION

## ❖ CASE I: JANUARY 2017 (HDD)

- **Underlying Index:**  $HDD(t) = \max(\text{soglia} - T(t); 0)$
- **Fixed threshold:** 2.43 °C (the tenth percentile of the time series)
- **The meteorological station of reference:** Arezzo

JANUARY 2017 – HDD with threshold 2.43 °C	
Price	139.58 €
Risk loading	34.74 €
Final price	174.32 €
Payoff	451.60 €
Gain (loss)	277.28 €



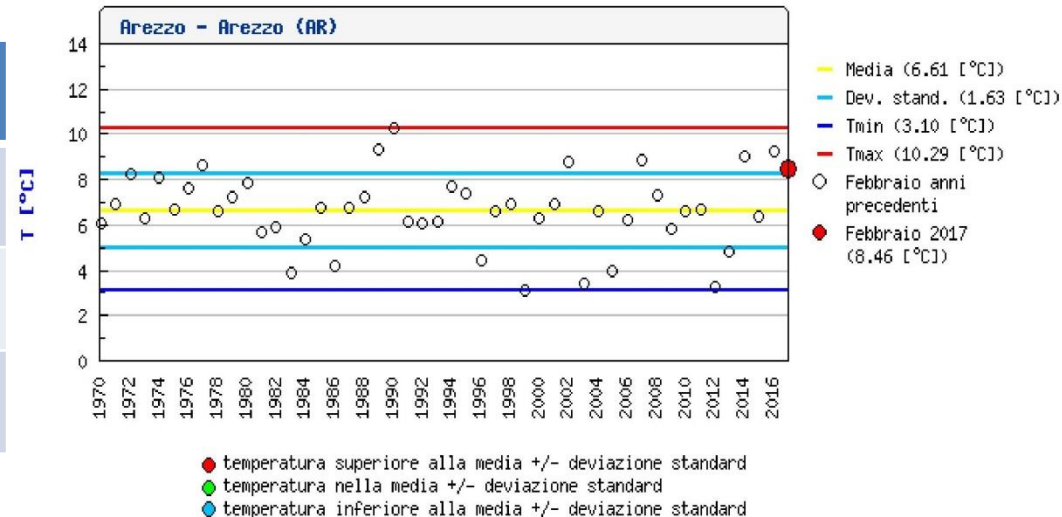
## CASE II: February 2017 (HDD)

- **Fixed threshold:** 3.5 °C (tenth percentile of the time series)

We have remarked that until 1989 all monthly HDD resulted positive, while on the contrary since 1989 on they are almost always null

- **New threshold:** 7.5 °C (the tenth percentile of the time series of the last twenty years)

FEBRUARY – HDD with threshold 7.5 °C	
Final price	664.47 € *
Payoff	167 €
Gain (loss)	(497.47 €)



\* Comprehensive of *risk loading* of 98.86 €.

# Precipitation derivatives

## The Rainfall Index

**Precipitation derivatives** (*rainfall derivatives*): the underlying is given by an index (*the CME Rainfall Index*) based on the quantity of rain fallen down in a given period.

The **CME Rainfall Index**, on a given time range  $(\tau_1, \tau_2)$ , is defined as the aggregated quantity of rain fallen daily (in mm.) in the given time range.

If  $P(t)$  is the quantity of rain fallen in day  $t$ , the index is

$$RF(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} P(t)$$

# 1. Modelling the underlying

- $P(t)$ ,  $t=1,2,\dots,T$  ( $t = \text{days}$ ), is a time series related to the precipitations in a given locality
- A multiplicative models is considered, composed of three variables

$$P(t) = g(t)J(t)\varepsilon(t)$$

**$g(t)$**

**Daily seasonal  
mean**

**$J(t)$**

**Noise  
component**

**$\varepsilon(t)$**

**Variable indicator**

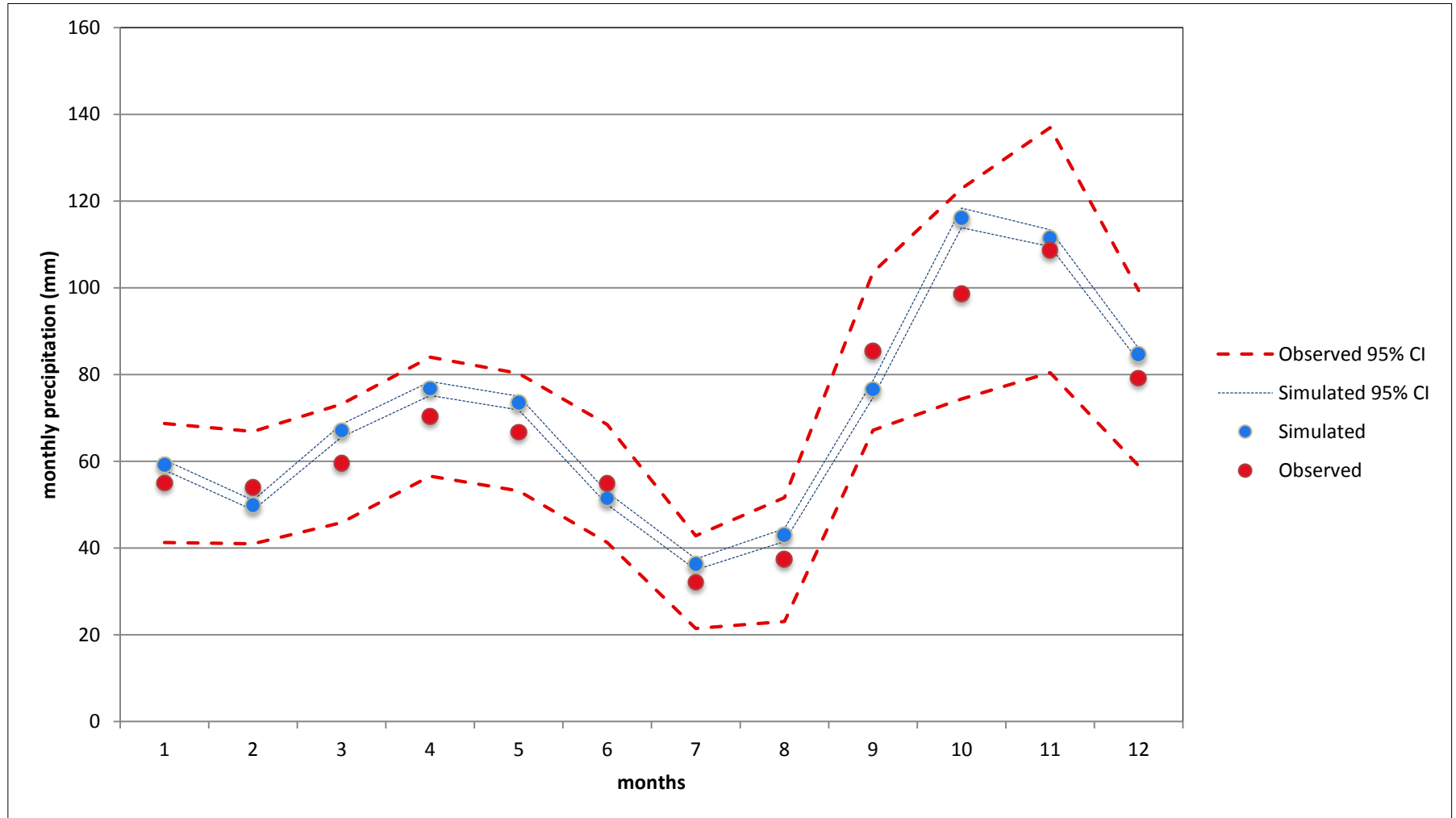
$$\varepsilon(t) = \begin{cases} 1 & \text{prob.} = \lambda(t) \\ 0 & \text{prob.} = 1 - \lambda(t) \end{cases}$$

- $\varepsilon(t)$  takes value 1 in case of rain, otherwise 0.
- The product  $g(t)J(t)$  describes the amount of precipitations in a given day
- $g(t)$  and  $\lambda(t)$  are seasonal functions and are modelled as truncated Fourier series :

$$\delta(t) = c_0^\delta + \sum_{l=1}^2 (c_{2l}^\delta \cos(2l\pi t/365) + c_{2l+1}^\delta \sin(2l\pi t/365))$$

where  $\delta(t)$  can be  $\lambda(t)$  or  $g(t)$ .

# Comparison between observed and estimated data



## 2. The pricing model

- The contract has a monthly duration and its underlying is

$$RF(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} P(t)$$

- The contract, at maturity, pays to the subscriber

$$X(\tau_1, \tau_2) = k \times RF(\tau_1, \tau_2)$$

where  $k$  is the *tick size* (conversion mmm/Euros), fixed at 20 euros.

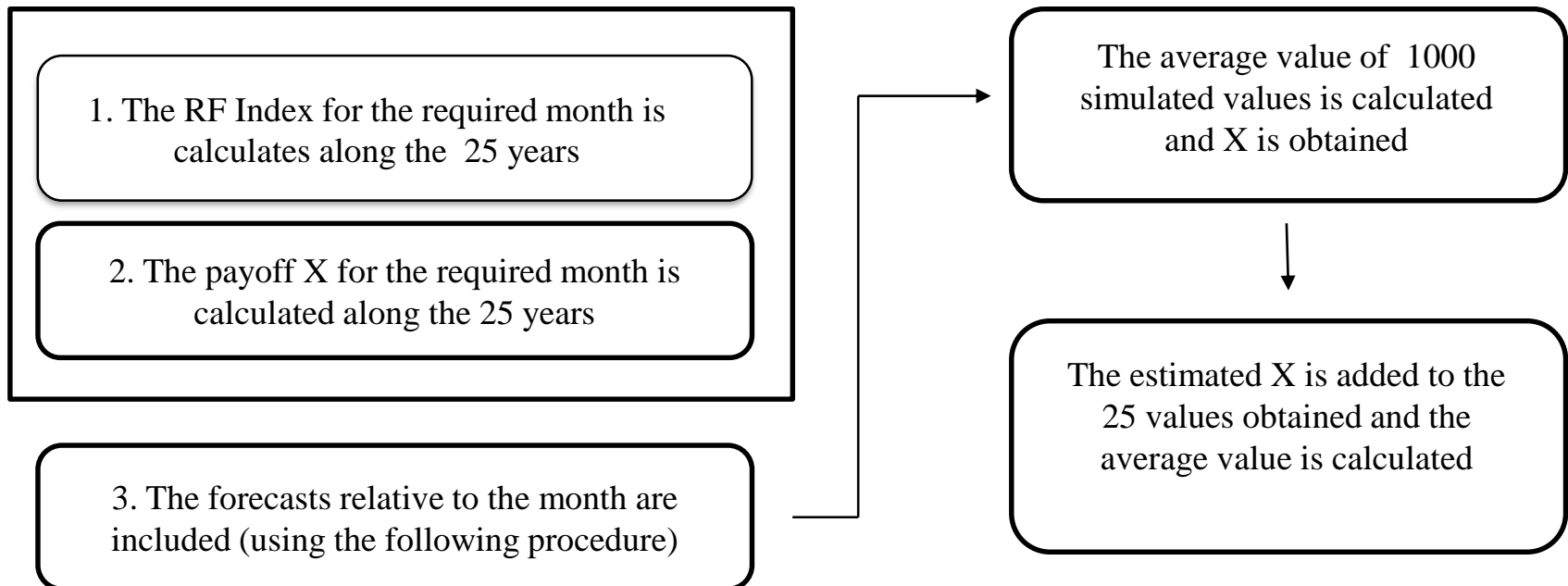
We will price this contract

# *The Burn Analysis (our proposal)*

- The price is so obtained

$$P(t, \tau_1, \tau_2) = \exp(-r(\tau_2 - t))[X(\tau_1, \tau_2)]$$

where  $X(\tau_1, \tau_2)$  represents the average value of the considered payoffs



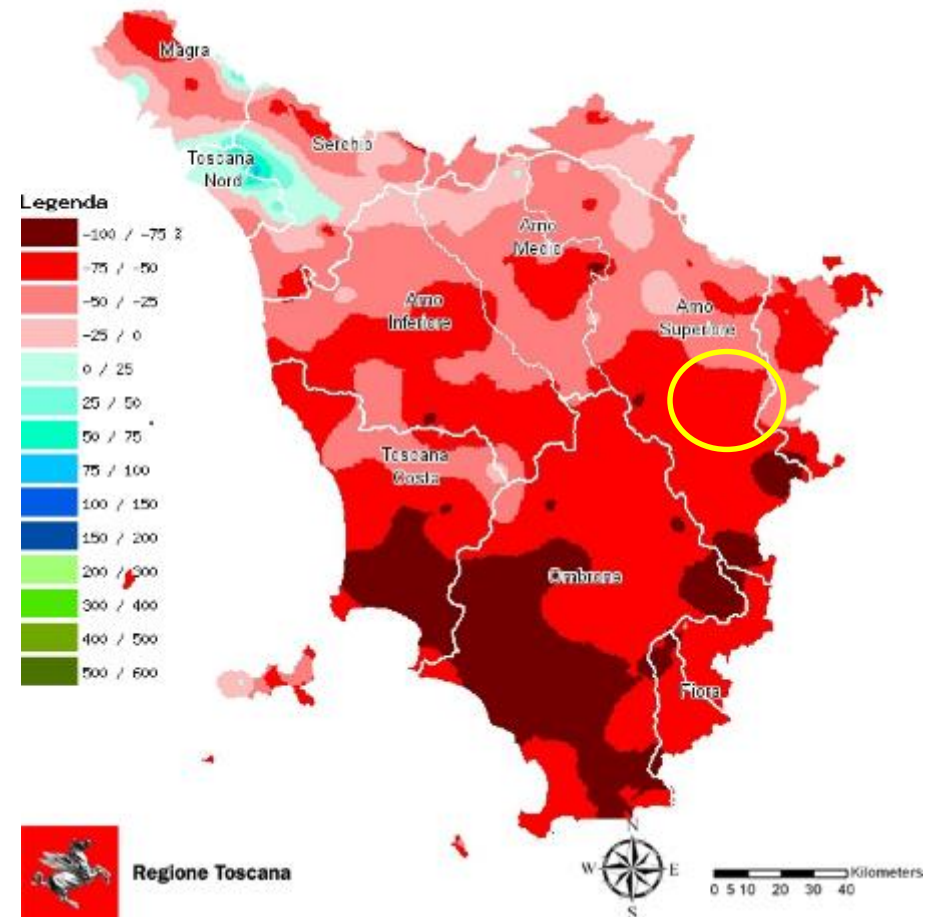
# CASE 1: *January 2017*

- **Duration** :Monthly
- **Underlying**: RF
- **Meteorological station**: Arezzo
- January 2017 has been characterized by quite low monthly rains, so justifying the contract loss.

January 2017 - RF Index	
<b>Price</b>	1.103 €
<b>Risk loading*</b>	106 €
<b>Final price</b>	1.209 €
<b>Payoff</b>	416 €
<b>Gain/(Loss)</b>	(793 €)

\* 5% of 95° percentile of payoff distribution

Fig. 2 - Confronto tra le precipitazioni (Σ) di gennaio 2017 con le medie di gennaio del periodo 1987-2016

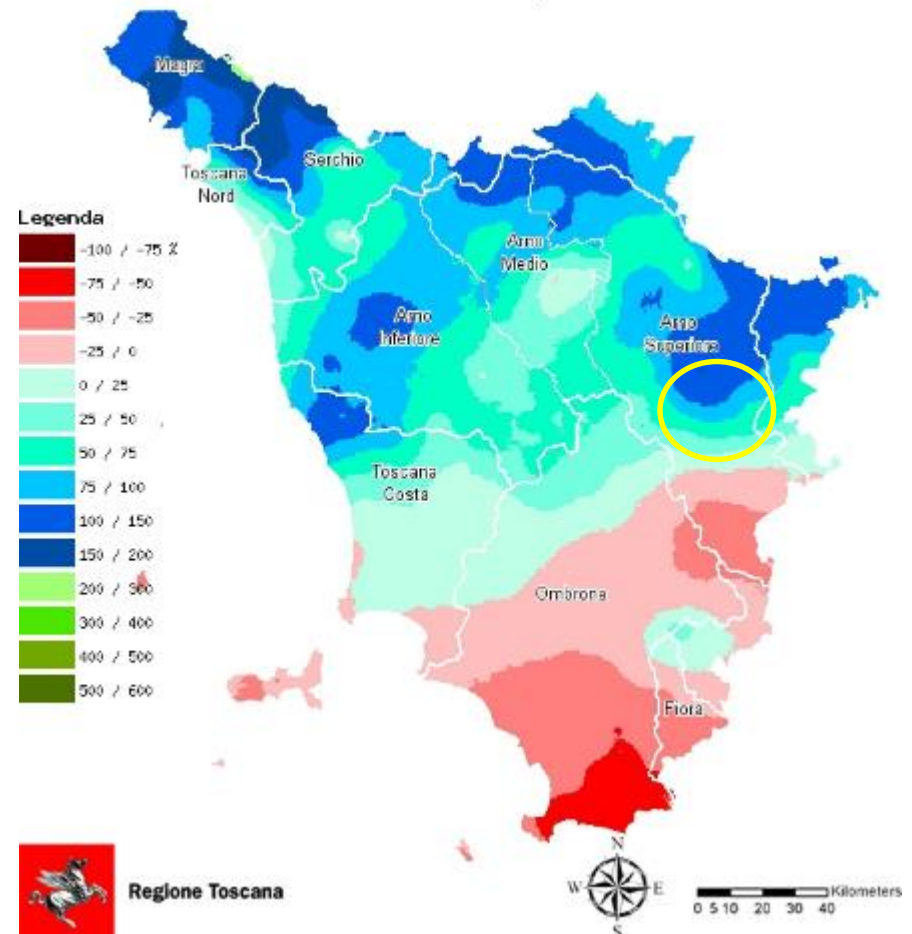


# CASE 2: February 2017

- **Duration** :Monthly
- **Underlying**: RF
- **Meteorological station**: Arezzo
- Precipitations in Feb 2017 have been quite higher (about 70 mm) than the historical average (50 mm) .

February 2017 – RF Index	
<b>Price</b>	1.075 €
<b>Risk loading</b>	108 €
<b>Final price</b>	1.183 €
<b>Payoff</b>	1.408 €
<b>Gain/(Loss)</b>	225 €

Fig. 2 - Confronto tra le precipitazioni (%) di febbraio 2017 con le medie di febbraio del periodo 1987-2016



# CONCLUSIONS

**MITIGATION OF  
CLIMATIC RISK**

**TAILORED  
CONTRACTS**

**TICK SIZE AND  
THRESHOLD**

# References

- Barnosky A.D. *et al* (2012) Approaching a state shift in Earth's biosphere, doi:10.1038/nature11018
- Baum S.D., Haqq-Misra J. D. and C. Karmosky : "Climate change: evidence of human causes and arguments for emission reduction" *Sci Eng Ethics* (2012) 18: 309-410
- Benestad, R.E. and Schmidt, G.A. (2008) , Solar trend and global warming, *JGR-atmospheres*, 114, D14101, doi:10.1029/2008JD011639.
- Benth F.E., Jurate Saltyte Bent, (2013) *Modeling and pricing in financial markets for weather derivatives*, Advanced Series on Statistical Science & Applied Probability, World Scientific
- Bhattacharya S., A.Gupta, Koushik Kar and Abena Owusu "Hedging strategies for risk reduction through weather derivatives in renewable energy markets" doi: 10.1109/ICRERA.2015.7418597
- Chandramowli S.N. and Felder F.A. (2014), Impact of climate change on electricity systems and markets . A review of models and forecasts, *Sustainable Energy Technologies and Assessments*, 5: 62-74
- Fankhauser S. (1994). The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach. *The Energy Journal*, 15: 157-184
- IPCC AR5 (2013), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change
- Laffoley D. and Baxter J.M. (eds) (2016) Explaining Ocean Warming: Causes, scale, effects and consequences, IUCN [https://portals.iucn.org/library/sites/library/files/documents/2016-046\\_0.pdf](https://portals.iucn.org/library/sites/library/files/documents/2016-046_0.pdf)
- Papazian and Skiadopoulos (2010), Modeling the Dynamics of Temperature with a View to Weather Derivatives, SSRN-id1517293.pdf
- Riahi K. et al (2011) RCP 8.5—A scenario of comparatively high greenhouse gas emissions, *Climatic Change* 109:33

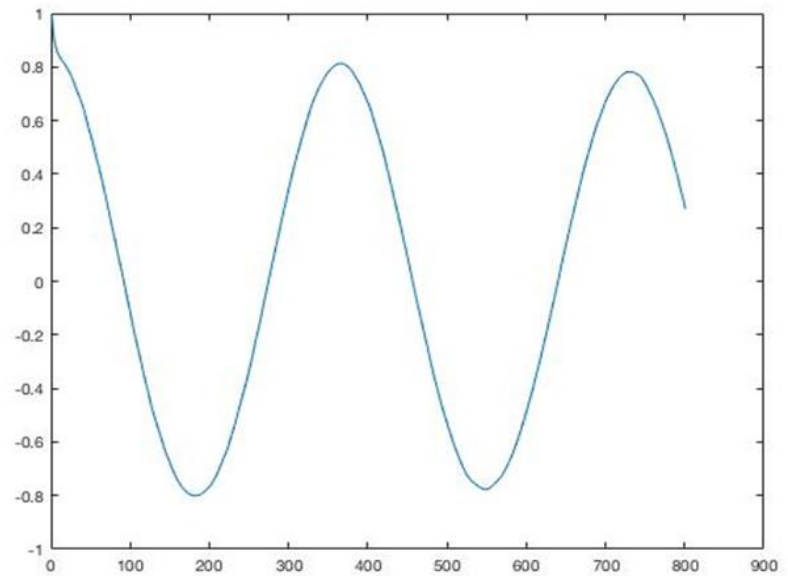
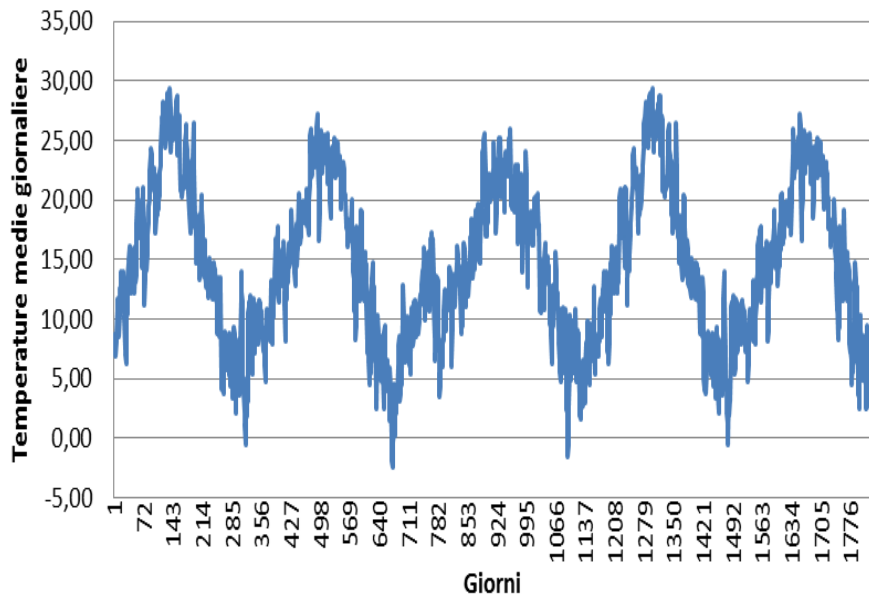
**THANKS FOR YOUR ATTENTION!**  
**silvana.stefani@unimib.it**

# TEMPERATURE

# THE EMPIRICAL ANALYSIS

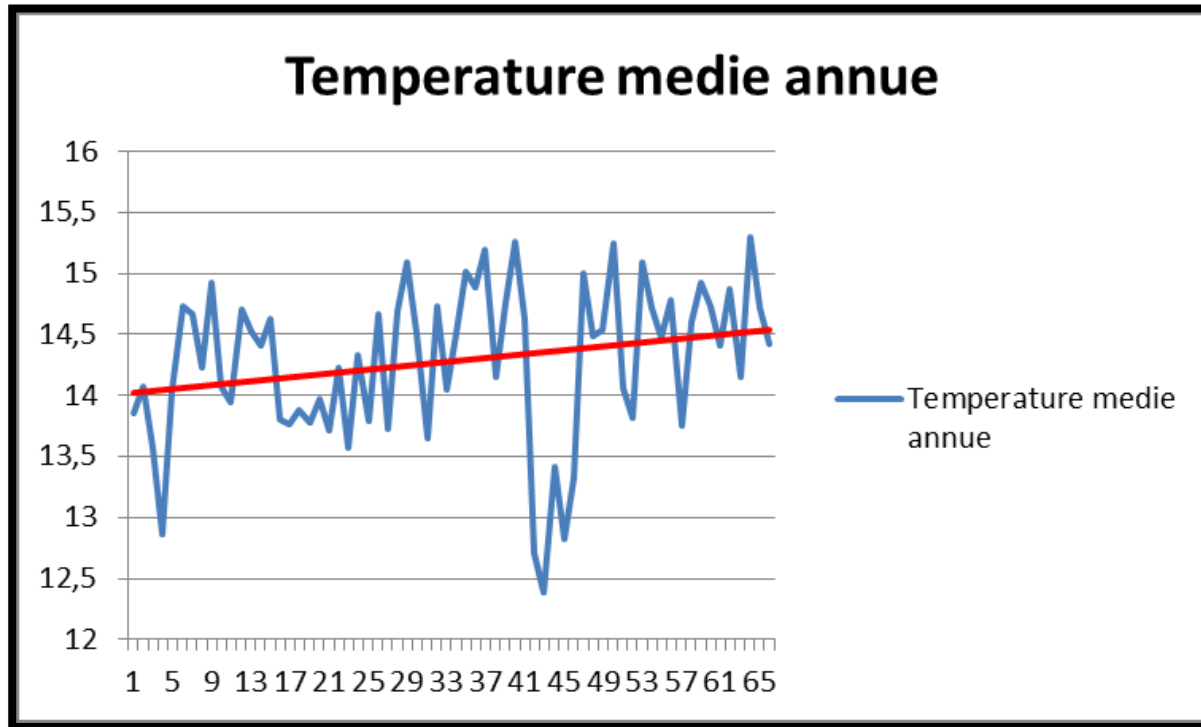
## ❖ THE DATA

- Max and min daily temperatures ( $^{\circ}\text{C}$ ) municipality of Arezzo in Tuscany in the time range of 66 years (1951 - 2016), SIR Internet site.
- Average daily temperatures are calculated as the average daily mean of max and min.



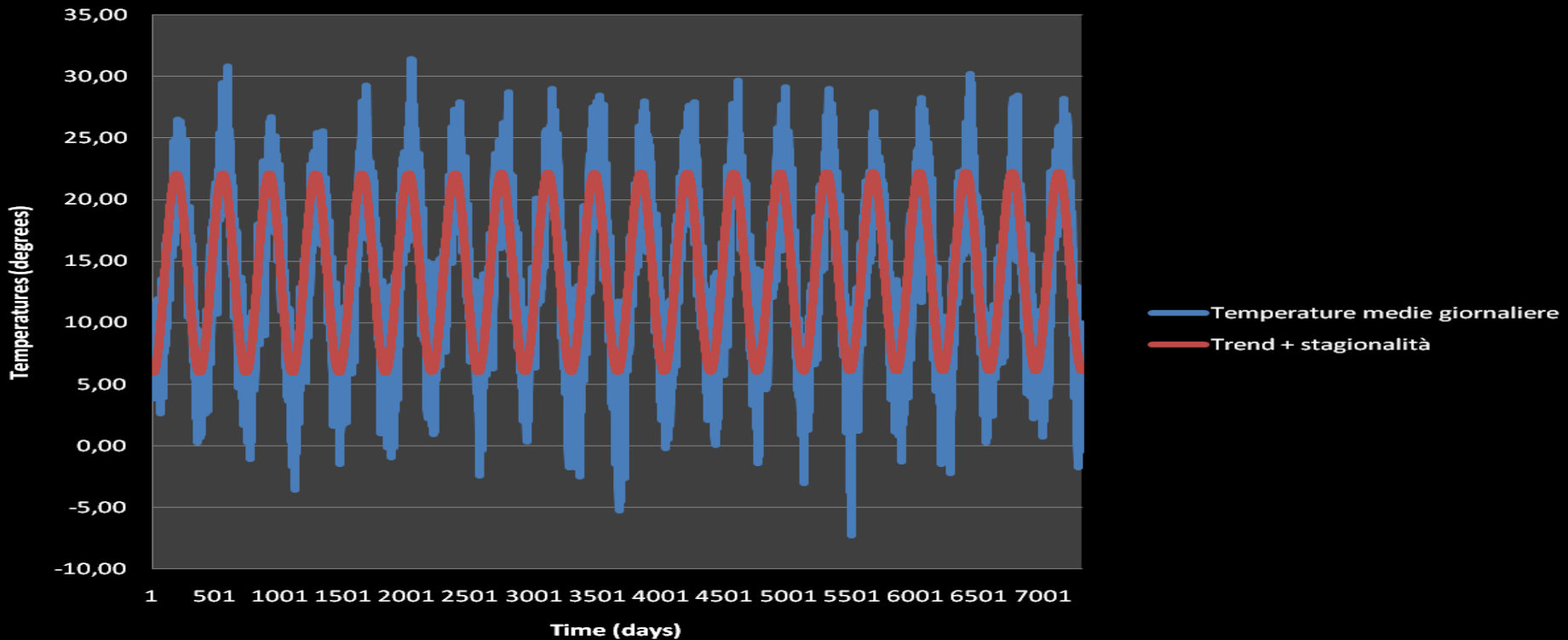
# THE ESTIMATES

## ❖ THE TREND



- A linear trend
- 0.52 °C increase of average temperatures in 66 years

## Fitted trend and seasonality



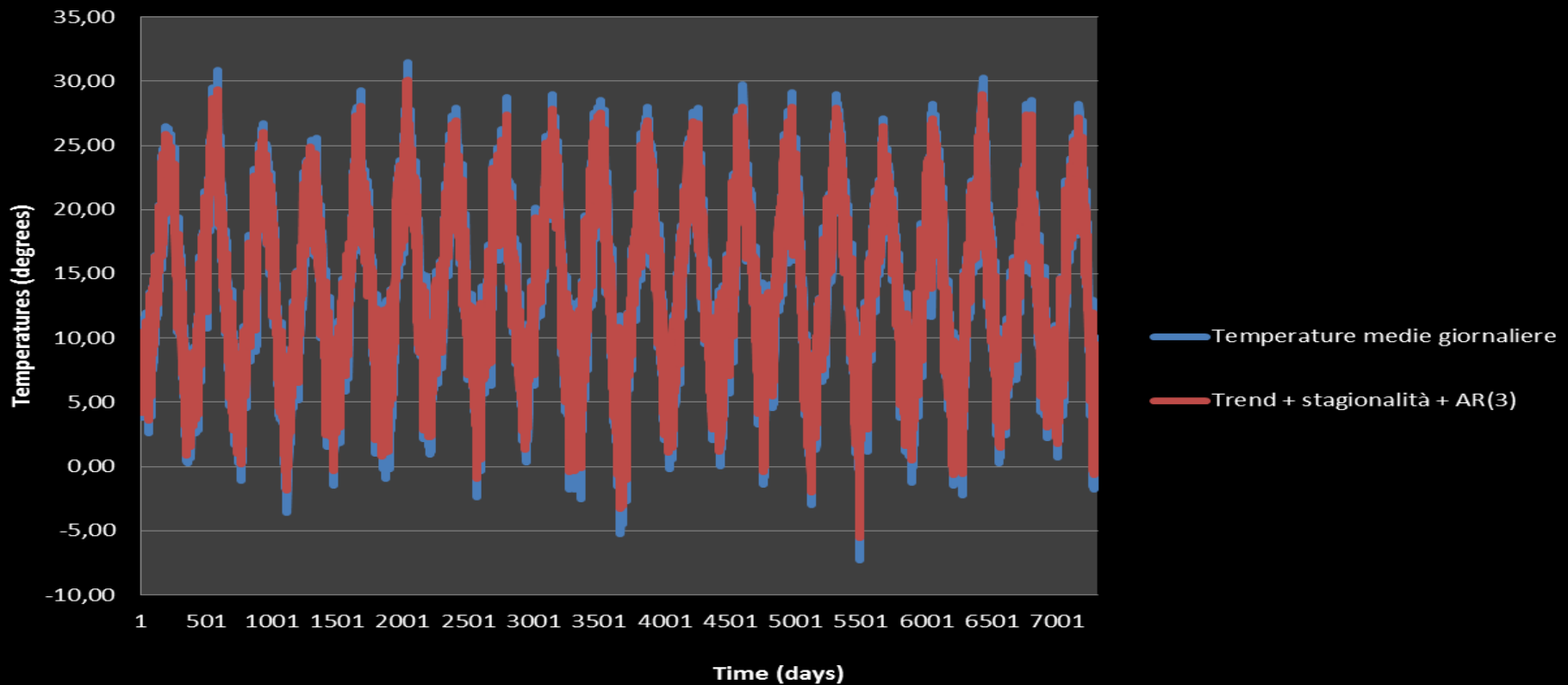
## ❖ THE SEASONALITY

- Seasonality is modelled through a truncated Fourier series

$$\Lambda(t) = a_0 + a_1 t + a_2 \cos(2\pi t/365) + a_3 \sin(2\pi t/365)$$

- The calibration of  $a_0, a_1, a_2, a_3$  parameters is done with a OLS technique

## Fitted trend and seasonality



## ❖ THE AUTOREGRESSIVE PROCESS

$$\mu(t) = \Lambda(t) + \sum_{i=1}^p \alpha_i (Z(t-i) - \Lambda(t-i))$$

- We have chosen a AR(3). The temperatures of day  $t$  are correlated with the days  $t-1$ ,  $t-2$ ,  $t-3$ .

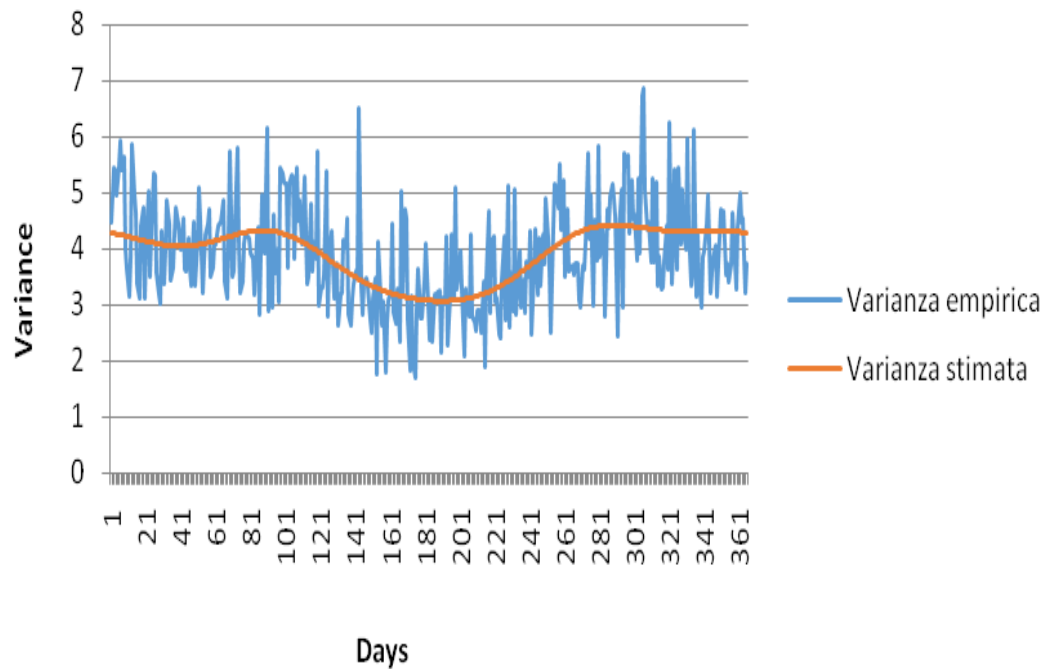
## ❖ THE RESIDUALS

$$\varepsilon(t) = \sigma(t)\epsilon(t)$$

where  $\sigma(t)$  is a volatility function dependent on time and  $\epsilon(t)$  is a random process of Gaussian type with average zero and std dev. The variance  $\sigma^2(t)$  is modelled through the usual truncated Fourier series:

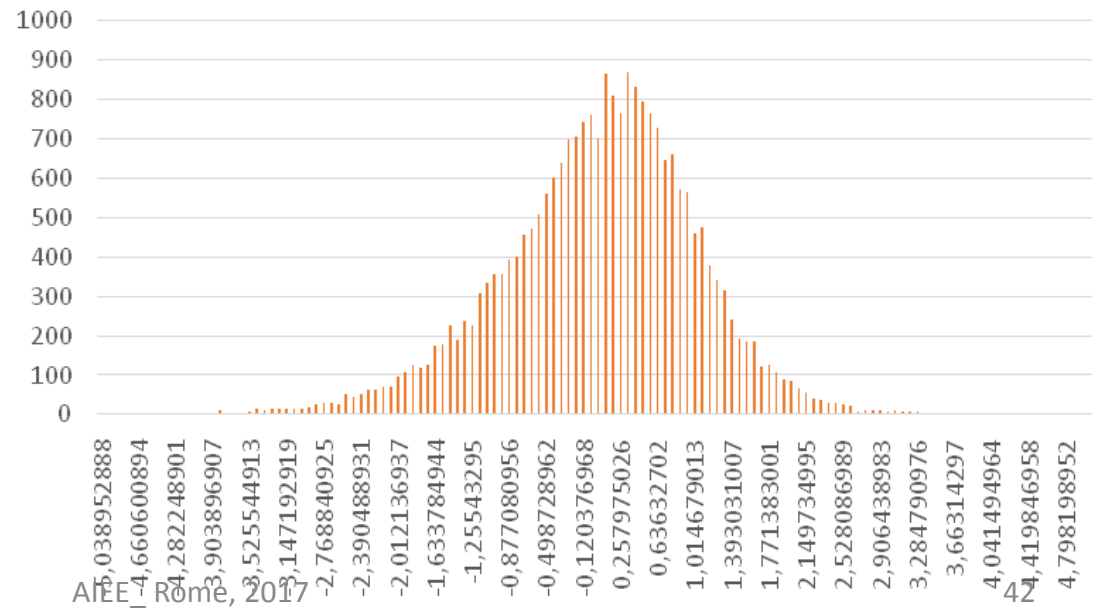
$$\sigma^2(t) = b_1 + \sum_{l=1}^4 (b_{2l}\cos(2l\pi t/365) + b_{2l+1}\sin(2l\pi t/365))$$

- We calculate the daily variance of observed residuals, considering for each day of the year the 66 values, then the OLS technique is applied.



To the left, we note that the temperature variations increase in the passage from cold to warm.

To the right, histogram of residuals  $\epsilon(t)$ , where the normal standard behavior is confirmed.



# BURN ANALYSIS: OUR PROPOSAL\_1

- We do have 66 values of the considered monthly index. We then multiply them by the tick size and get the 66 payoffs.
- To those 66 values we add the payoff value of 2017, obtained through the temperature model
- In practice, this predicted value is given by the last available temperatures (December 29,30,31, 2016) following then the formula

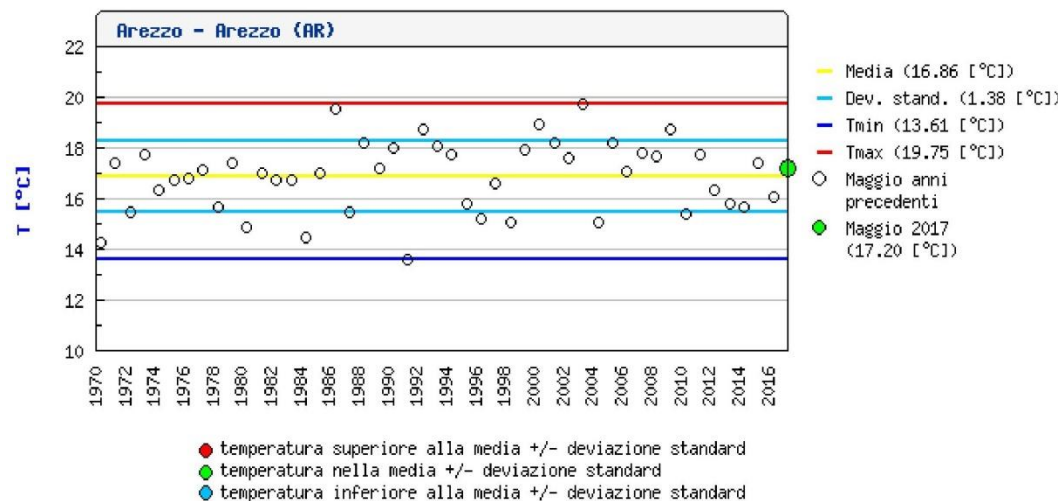
$$\mu(t) = \Lambda(t) + \sum_{i=1}^3 \alpha_i (Z(t-i) - \Lambda(t-i))$$

## CASE III: MAY 2017 (CDD)

- **Underlying Index:**  $CDD(t) = \max(T(t) - soglia; 0)$
- **Fixed threshold:** 25.5 °C (the 90° percentile of the time series)

We have remarked that until 1989 all monthly CDDs were null, while on the contrary since 1989 they have always been positive

MAY – CDD with threshold 25.5 °C	
Final price	101.02 € *
Payoff	0 €
Gain (loss)	(101.02 €)

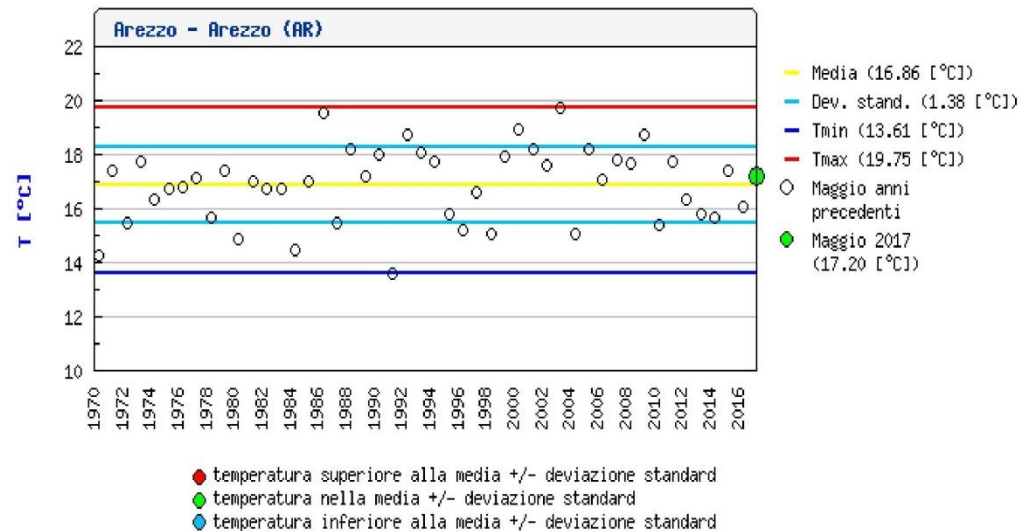


\* Comprehensive of *risk loading* of 20.53 €.

## ❖ CASE IV: May 2017 (CAT)

- **Underlying Index:**  $CAT(\tau_1, \tau_2) = \sum_{t=\tau_1}^{\tau_2} T(t)$
- **Fixed threshold:** No threshold for this Index
- **Meteorological station of reference:** Arezzo

MAY – CAT	
Price	11951.88 €
Risk loading	781.88 €
Final price	12733.76 €
Payoff	10661 €
Gain (loss)	(2072.76 €)



# RAINFALL

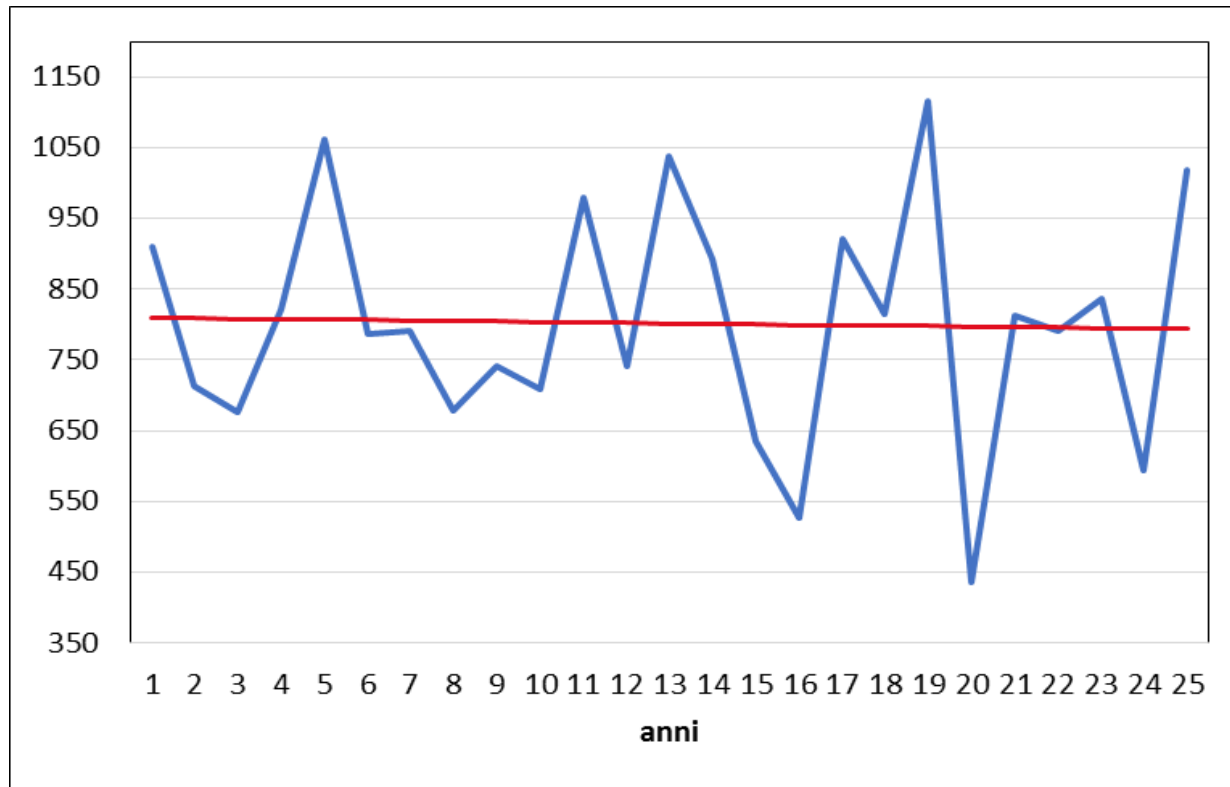
# Model validation

- 1.000 realizations of the model are obtained for each day along the year (we will obtain 1000 realizations for Jan 1, 1000 for Jan 2, ...).
- Two sequences of random numbers are generated, one to simulate  $J(t)$  (*Exponential*) and one for  $\varepsilon(t)$  (*Bernoulli*).
- A series of values  $P(t)$  is calculated.
- Simulations are finally aggregated at monthly level through the formula

$$\sum_{i=1}^m P(t_i)$$

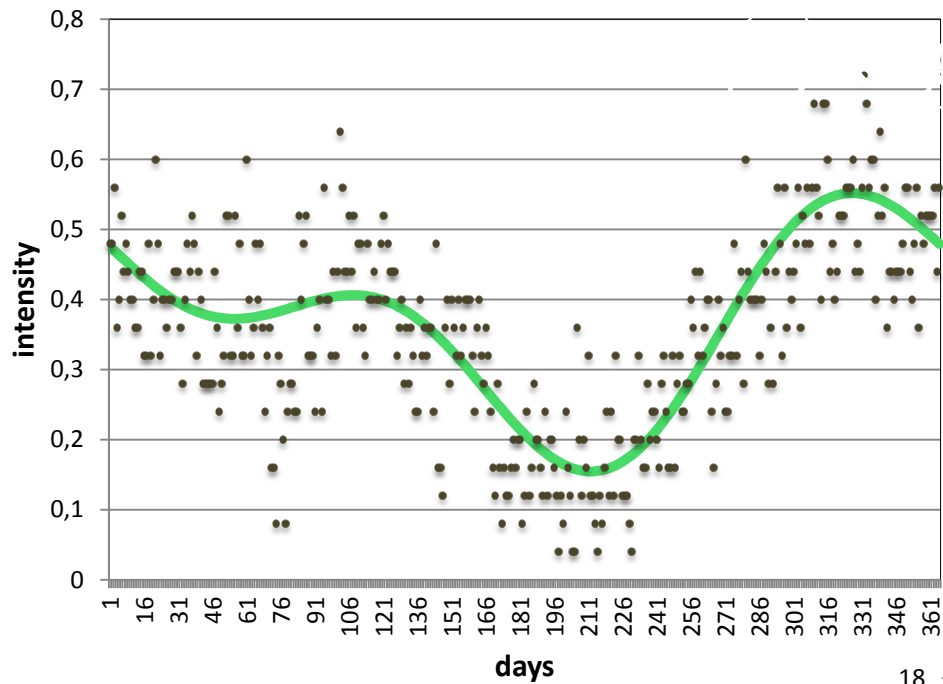
# The trend

- The trend is calculated on the yearly precipitation
- No noticeable trend in the considered time range
- The climate change impacts on the intensity and frequency of rain, not on the total volume



# The model

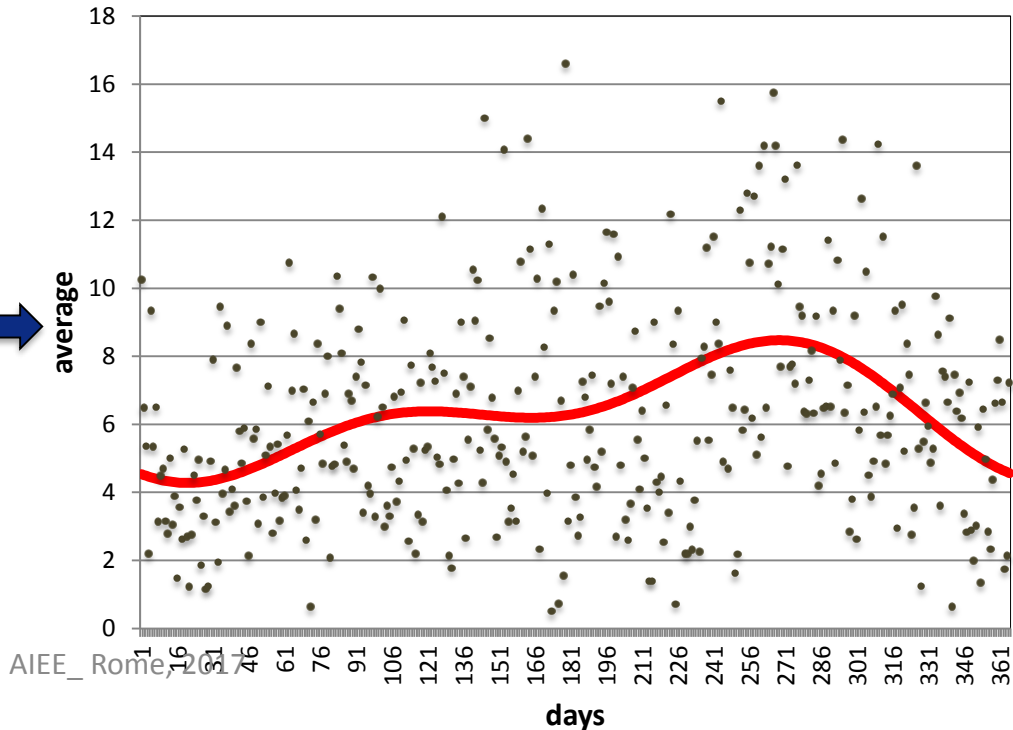
- Each component has been estimated separately
- The observed daily intensity and the observed average daily precipitation is calculated for every day in the year.
- The **observed daily intensity** is the proportion of precipitations observed in one given day
- The **observed seasonal daily average** is the average of daily precipitations in a given day along the 25 years
- Based on those measures, the functions  $g(t)$  and  $\lambda(t)$  have been estimated



**Daily intensity  $\lambda(t)$**   
 in blu the observed values, in  
 green  $\lambda(t)$

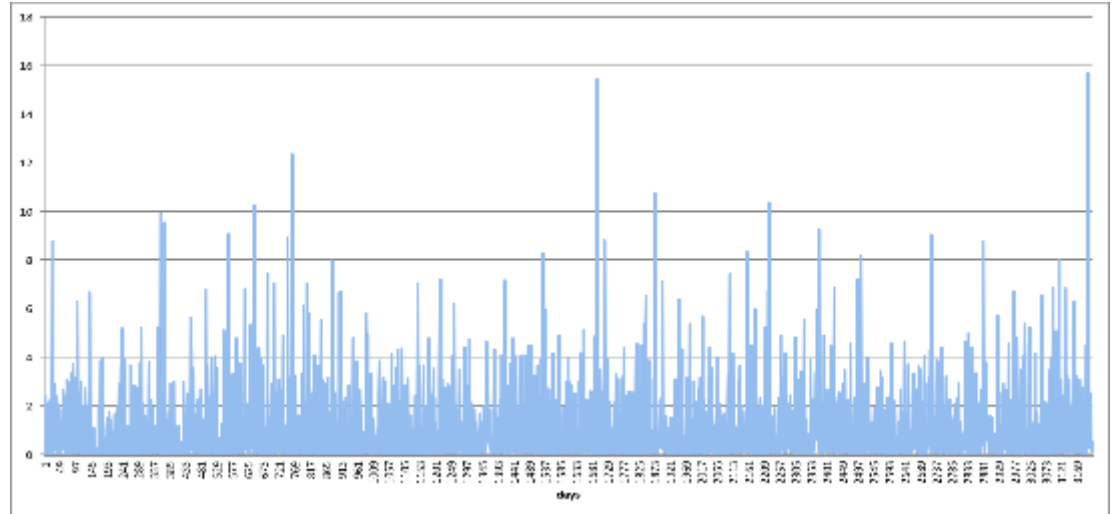


**Daily seasonal average  $g(t)$**   
 In blu the observed values, in  
 red  $g(t)$



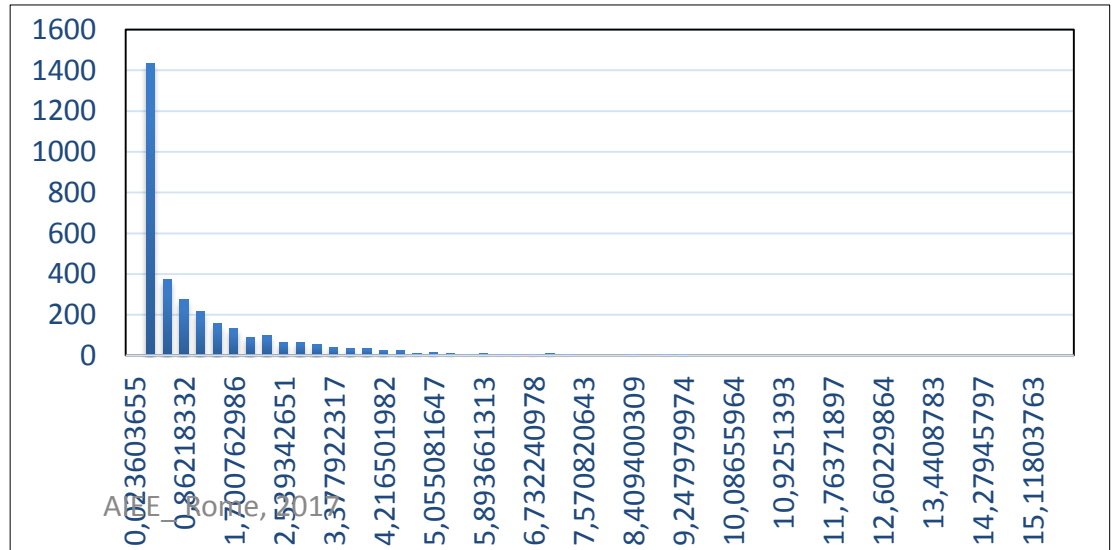
# The noise Component J(t)

Dividing the quantity of rain observed in one given day by the estimated daily average the noise component J(t) is obtained



The exponential distribution is chosen to model noise

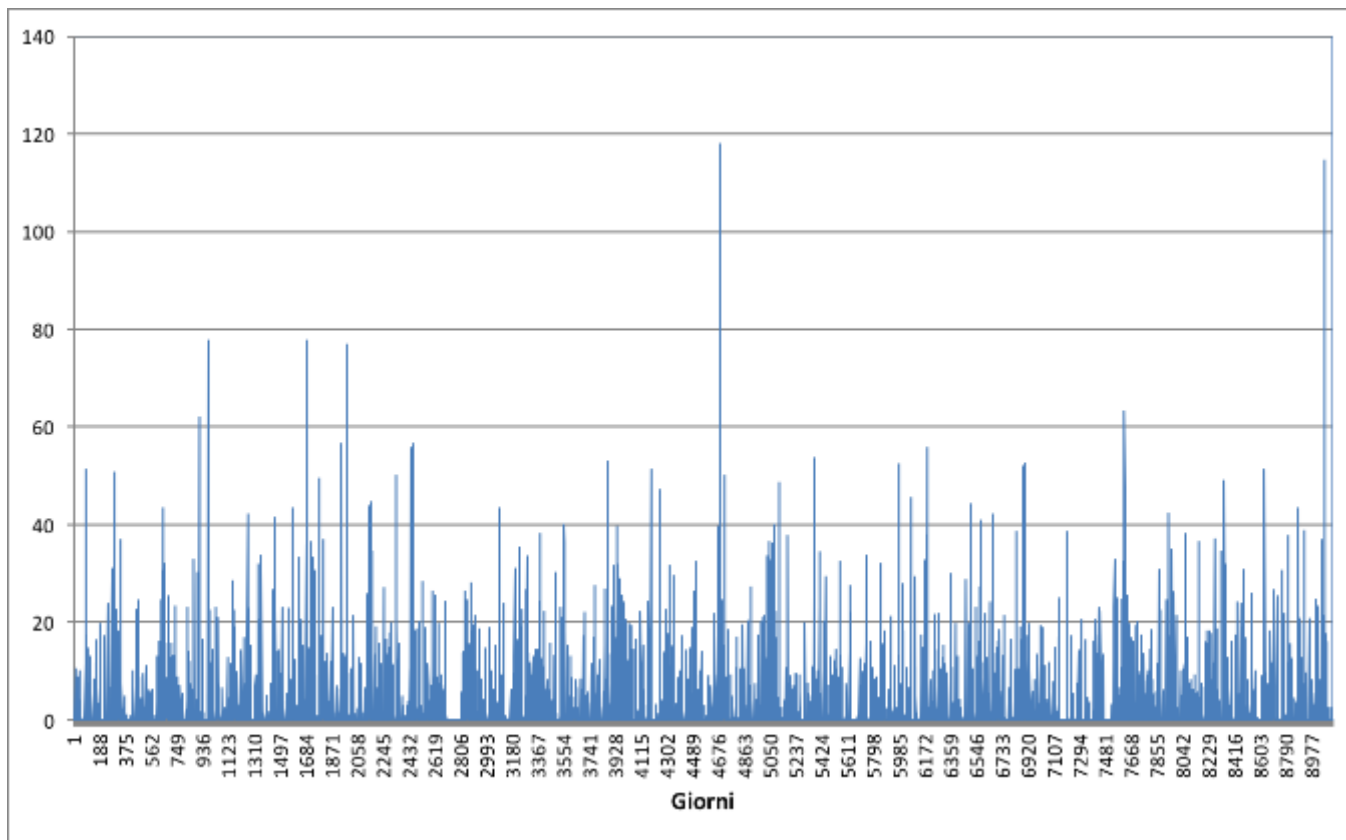
$$f(x; \mu) = \frac{1}{\mu} \exp\left(-\frac{x}{\mu}\right)$$



ArE, Sorle, 2015

# The application – The data

- Daily precipitations (mm) of Arezzo municipality (Tuscany), recorded in a time range of 25 years (1992 - 2016), taken from the **SIR (Settore Idrologico Regionale)** site <http://www.sir.toscana.it/>



AIEE\_ Rome, 2017

# Precipitation derivative with threshold

- Index based on the deviation of daily precipitations from a critical threshold
- The contract will pay if precipitations are above the critical threshold. The payoff is the following:

$$X(\tau_1, \tau_2) = k \times \sum_{s=\tau_1}^{\tau_2} \max(P(t) - c, 0)$$

- Where again  $k$  is the *tick size* (20 €),  $P(t)$  the level of precipitations expressed in mm registered in the time range and  $c$  is the threshold level chosen
- The threshold value can be taken as the 90<sup>th</sup> percentile of the distribution of the precipitations for the considered month: for January, it is calculated as **5.44 mm**, for February is **7.22 mm**.

# CASES 3 and 4: *January and February (with threshold)*

**Duration** : Momthly

**Underlying**: Index with threshold (5,44 mm)

**Meteorological station**: Arezzo

The loos corresponds to less precipitations in January 2017 than usual

<b>January 2017 – Theshold 5,44 mm</b>	
<b>Price</b>	497,76 €
<b>Risk loading</b>	65,48 €
<b>Final price</b>	563,24 €
<b>Payoff</b>	223,2 €
<b>Gain/(Loss)</b>	(340,04 €)

**Duration** : Monthly

**Underlying**: Index with threshold (7,22 mm)

**Meteorological station**: Arezzo

The gain corresponds to more precipitations in Feb 2017 than usual

<b>February 2017 – Threshold 7,22 mm</b>	
<b>Price</b>	364,73 €
<b>Risk loading</b>	35,41 €
<b>Final price</b>	400,14 €
<b>Payoff</b>	846,8 €
<b>Gain/(Loss)</b>	446,66 €