Introduction of low cost sensors (LCSs) in the Belgian climate observation network: a first assessment

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Motivations

- Less than 20 % of the climate stations automated → 115 manual stations equipped with liquid-in-glass thermometers in Stevenson screens

- MINAMATA CONVENTION ON MERCURY → Hg → Rely on alternative technologies

  - Recent advances in electronic and digital technologies provide such a way forward an offer other significant advantages in terms of data storage and real-time data display

  - Installing a sufficient number of AWS to ensure an adequate spacing is difficult to achieve because of economic and geographical limitations

  - Low-cost sensors (LCS) can offer high-resolution spatiotemporal measurements

  - Advances in sensor networks and Internet of Things (IoT) technologies have facilitated the collection of high-resolution spatiotemporal dataset

→ **Use IoT technology and LCS to supplement the measurements from the RMI's AWS**

MeteoHelix IoT pro (BARANI DESIGN TECHNOLOGIES s.r.o)

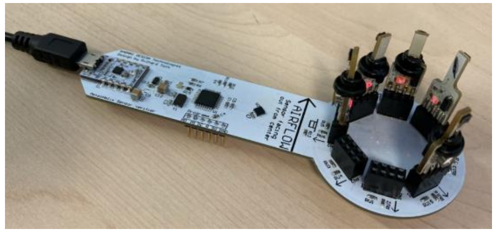
→ Gonzalez et al. (2018). Intercomparison of Shelters in the RMI AWS Network, IOM report, Vol. 132, WMO

→ **All-in-one wireless micro-weather station built into the naturally ventilated Barani's helical MeteoShield**

- Features
  - self-charging with integrated solar panel and internal Li battery
  - comes in two wireless versions: **Sigfox** and LoRaWAN (communication every 10 minutes)
  - 3-in-1 sensor tip

Double-helix shape ventilates better than multi-plates radiation shields (and even fan ventilated shelters) eliminating temperature errors from solar radiations more effectively

- Measures
  - air temperature to WMO accuracy
  - relative humidity to WMO accuracy with dew & frost point output
  - atmospheric pressure
  - (solar irradiation)
- Traceability
  - Removable sensor tip which is interchangeable and can be calibrated with a calibration adapter or replaced



SigFox: Low power wide area network (LPWAN) designed to connect devices at low cost in an energy efficient way

In field inter-comparison
- Air Temperature -

MeteoHelix IoT Pro vs. AWS [JAN 2020 to NOV 2022]*

-> Daily comparisons (at least 130 of the 144 10-min data a day required)

Double lowered wooden Stevenson screen

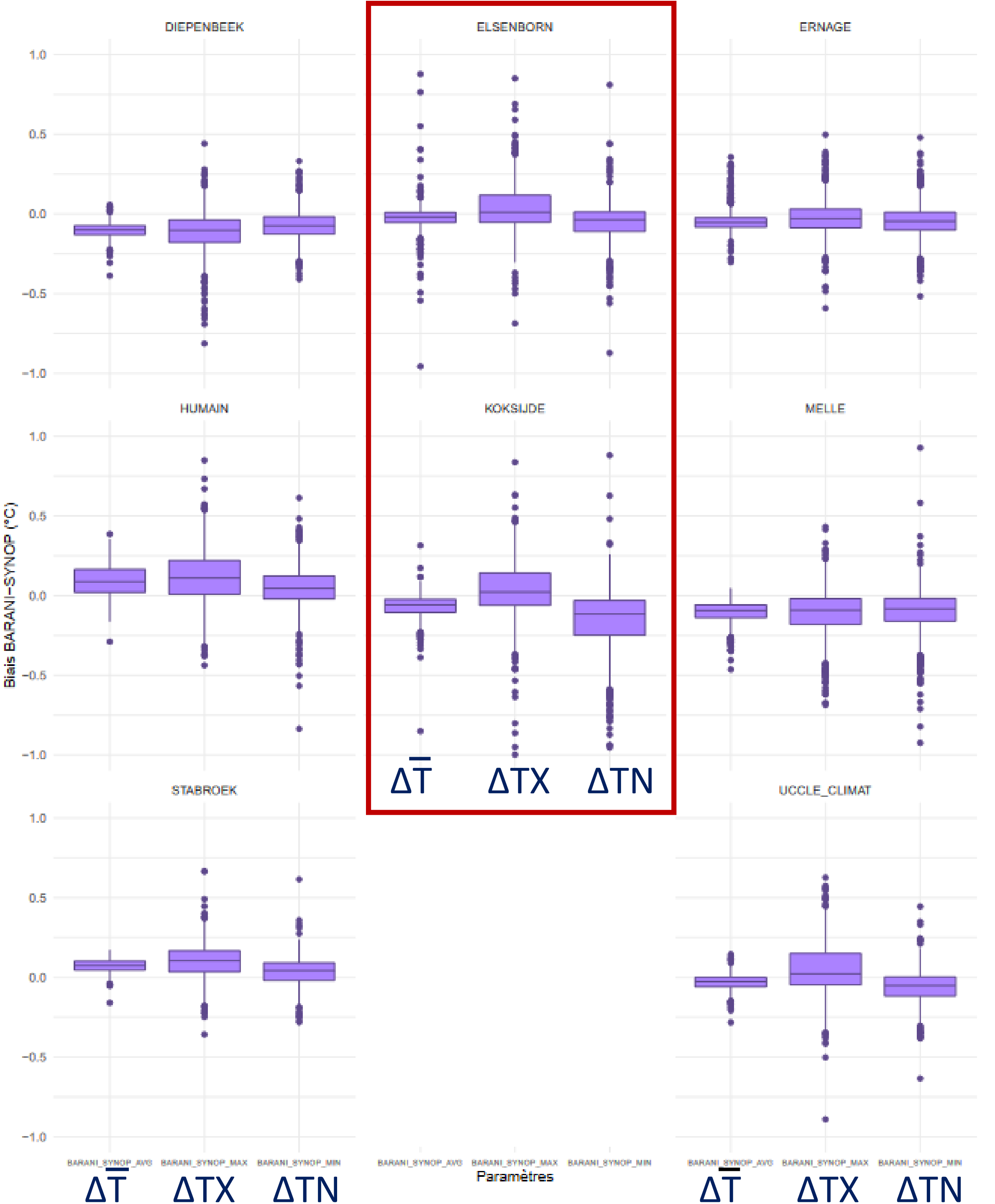
- 5 RMI's SYNOP STATIONS SITES
  - Diepenbeek (50.9155°N, 5.4503°E, 39.3 m, EC: 3)
  - Ernage (50.5819°N, 4.6892°E, 159.2 m, EC: 3)
  - Humain (50.1937°N, 5.2552°E, 295.3 m, EC: 2)
  - Melle (50.9803°N, 3.8160°E, 15 m, EC: 3)
  - Stabroek (51.3248°N, 4.3638°N, 4 m, EC:3)

  [+ Uccle Climat (50.7967°N, 4.3579°E, 101 m, EC:5)]

Artificially ventilated pipe

- 2 MW's SYNOP STATIONS SITES
  - Elsenborn (50.4824°N, 6.1813°E, 565.1 m, EC: na)
  - Koksijde (51.0880°N, 2.6524°E, 4.7 m, EC: na)

Compact fan-ventilated solar shelter



* Excepted Stabroek ended on 20/08/2021 and Diepenbeek ended on 29/04/2022

In field inter-comparison (Uccle – Climat)

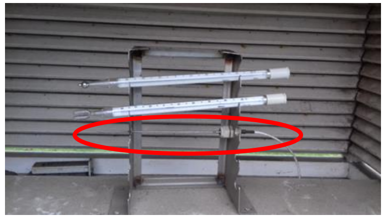
2019/07/13 – 2023/03/25

EC:5

STEVENSON.V.SE

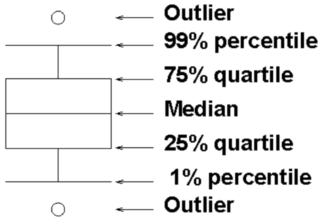
STEVENSON.NV.S

STEVENSON.NV.SW



MeteoHelix

In field inter-comparison (Uccle Climat: 2019/07/13 – 2023/03/25)



1 - Automatic

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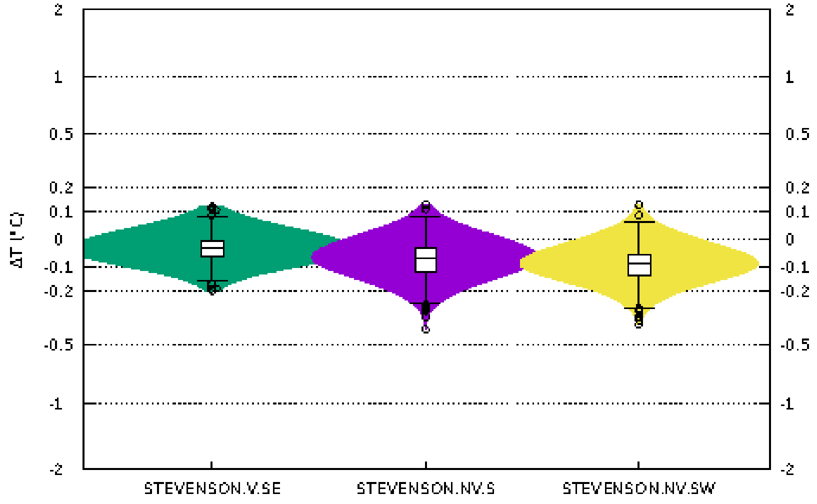
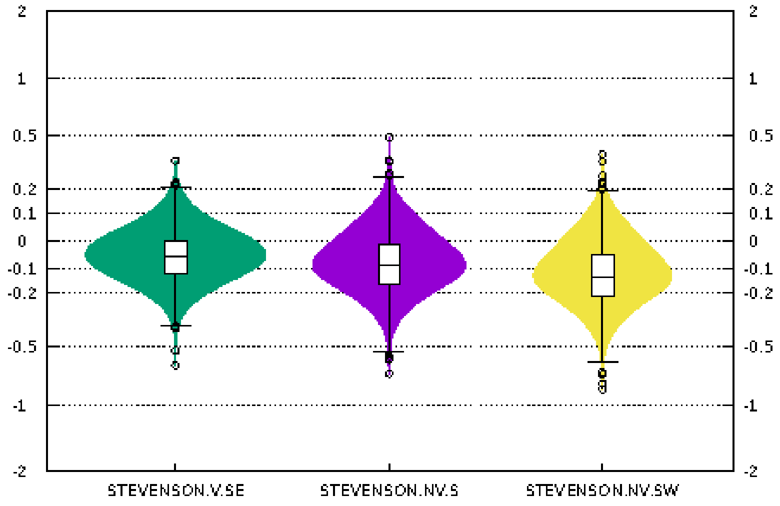
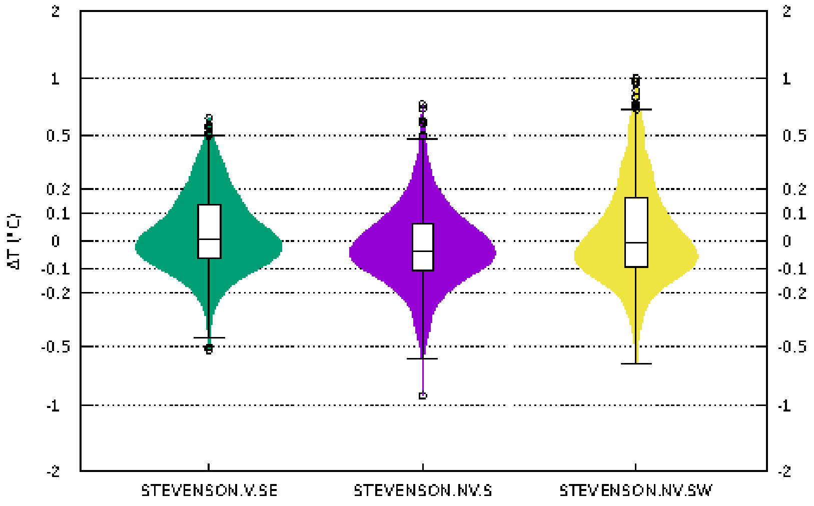


TN

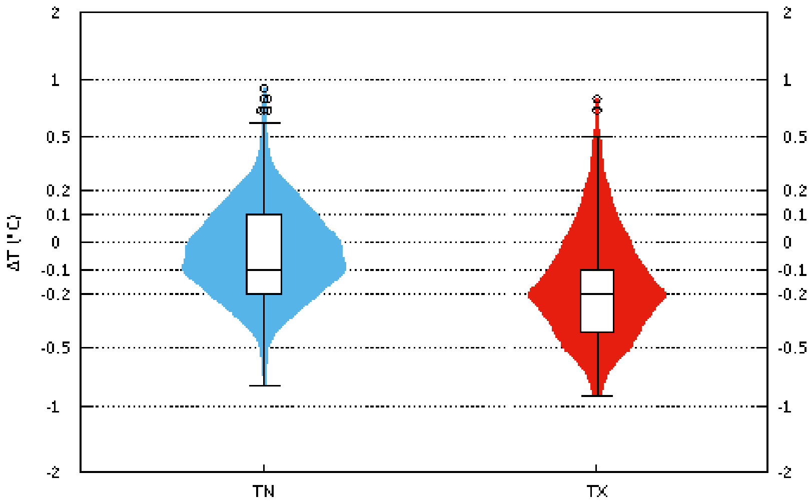


TX

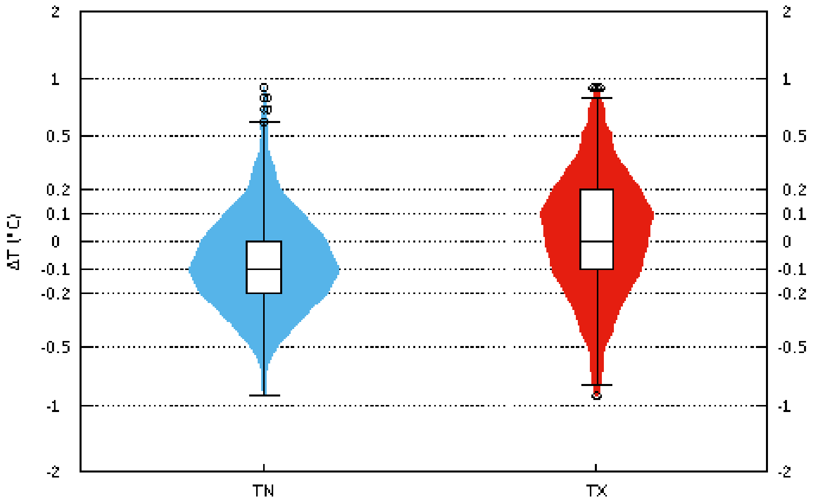


2 - Manual

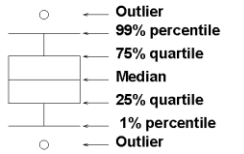
STEVENSON.NV.S



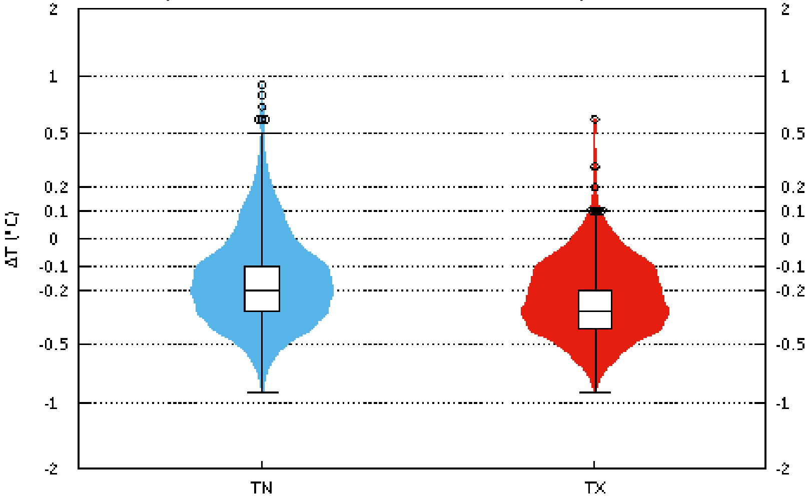
STEVENSON.NV.SW



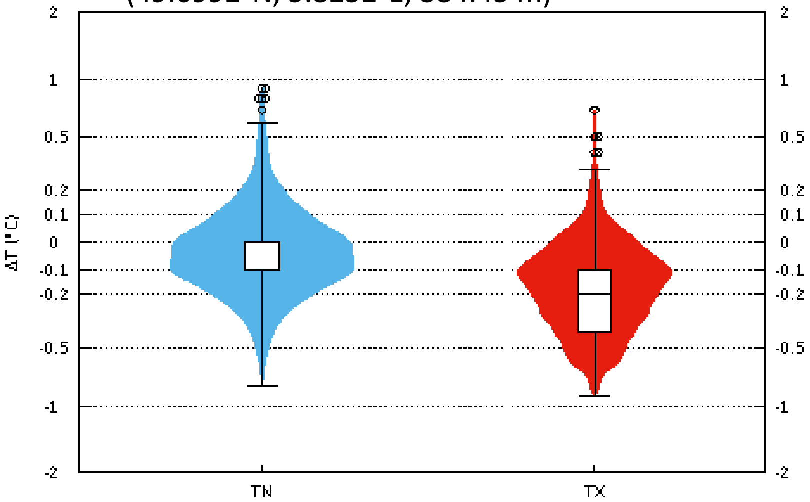
In field inter-comparison (MeteoHelix vs. manual stations)



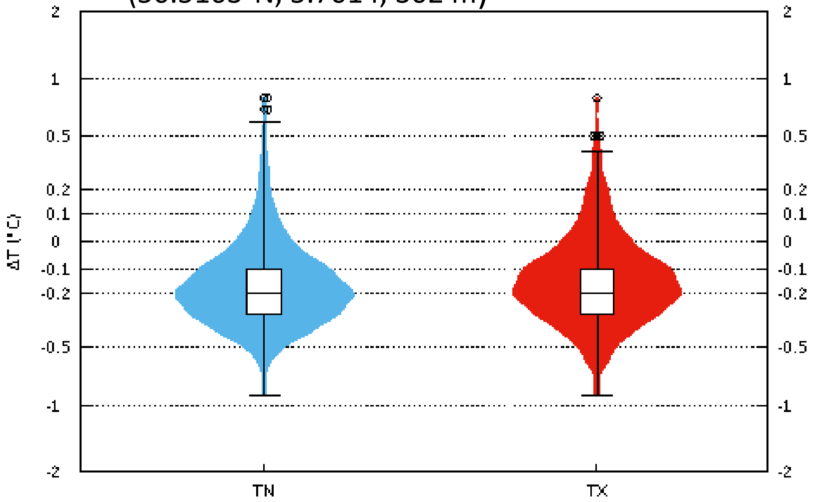
BIEVRE: 2020/02/11 – 2023/03/25
(49.9386°N, 5.0087°E, 384.87 m)



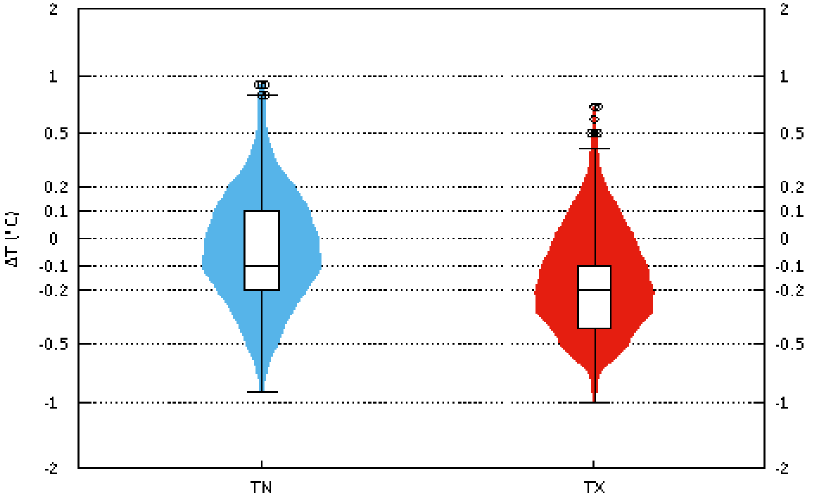
FRASSEM: 2020/06/02 – 2023/03/25
(49.6992°N, 5.8252°E, 384.45 m)



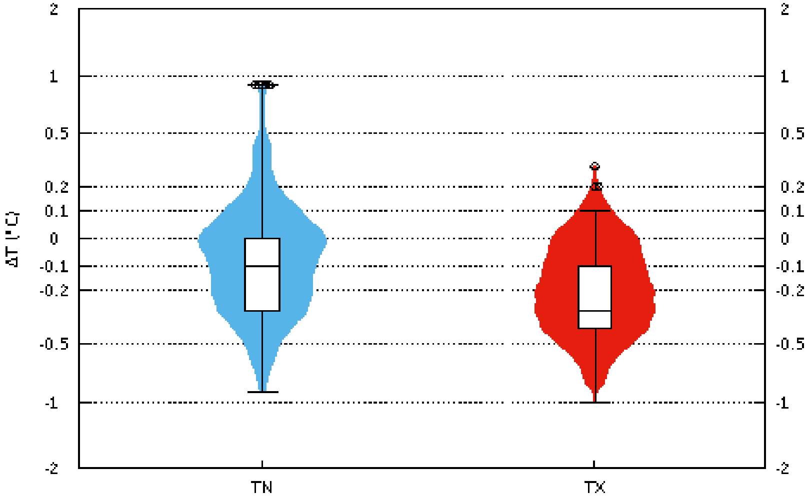
LOUVEIGNE: 2020/01/29 – 2023/03/25
(50.5163°N, 5.7014, 302 m)



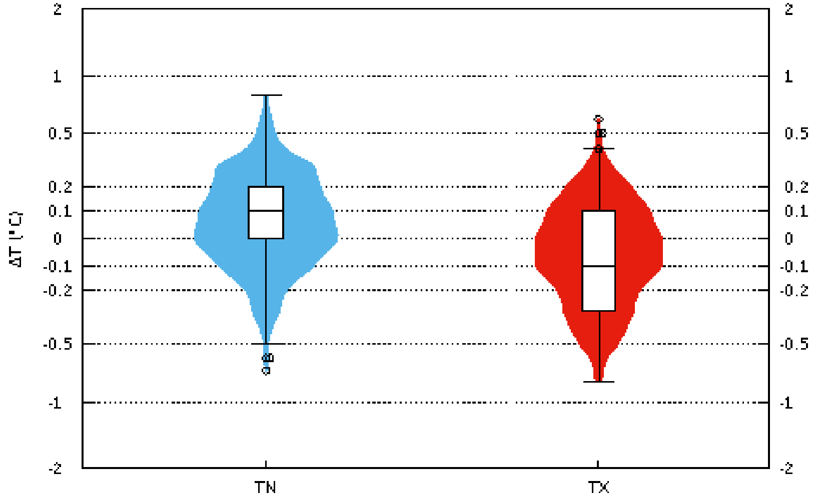
LICHTERVELDE: 2020/01/31 – 2023/03/25
(51.0237°N, 3.1170°E, 24 m)



RANSBERG: 2021/01/13 – 2023/27
(50.8622°N, 5.0317°E, 45.24 m)

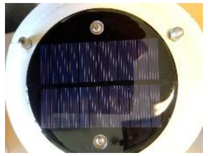


SINT-PIETERS-RODE: 2021/01/14 – 2023/03/25
(50.9128°N, 4.8271°E, 68.29 m)



Identified issues

- MeteoHelix IoT pro (Barani Design Technology s.r.o. new comer in the field of meteorological instrumentations)
  - Sensors failure after a certain period of time: the cause was a poorly applied coating that allowed moisture/condensation to reach the electrical contacts of the sensor (solved: manufacturing defect)
  - Penetration of pests into the housing where the electronics are located. They eat the applied coating and once the coating is gone, the water attacks the station's electronics. (should be solved: the entry holes have been sealed)
  - Station power down due to cracked solar cells (not solved: it is a random issue affecting about 1-2% of the devices. They are working on changing the solar panel construction to reduce this)
    → cause data quality to degrade as towards the end of battery life, sensors tend to produce unstable readings
  - Aging of the photovoltaic panel (still providing electricity but the estimated incident solar radiation could be impacted by some percent)


new

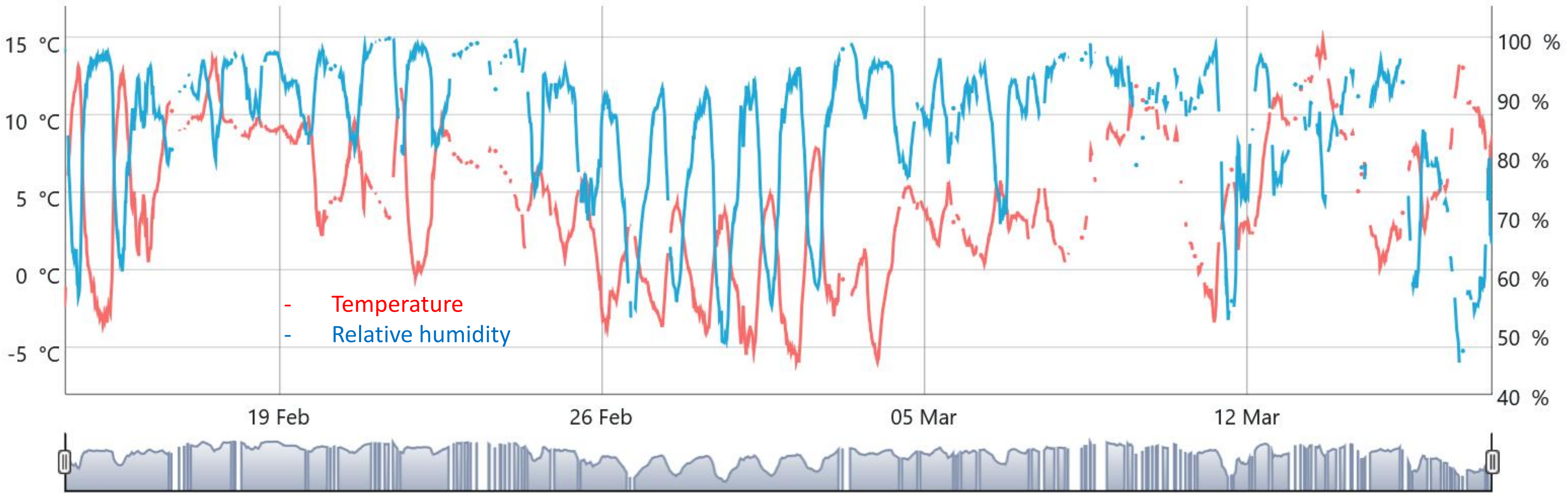

after 1 yr


after 2 yrs

- Poor Sigfox signal coverage in some areas/time

Missing data issue

Gerpinnes. MeteoHelix S/N: 2103SH/011



- ➢ Unstable wireless connection (network congestion)
- ➢ Sensor device outages (limited battery life)
- ➢ Environmental interferences (e.g. human blockage, walls, weather conditions …)

Re-transmitting the data is not an option :

- The computational and energy cost cause it to be inefficient in IoT application (sensors devices limited in terms of battery, memory and computational resources)
- Sigfox limitations in terms of message size (12 bytes) and communication (maximum of 5 wireless transmissions per hour)

Missing data = data definitively lost

→ Gap in time series problematic for end users applications

Automatic completion of gaps: method

1. Data extraction

Stations. All available data from synoptic & Barani stations

Time frame. A running period of 7 days (1008 timestamps)

2. Prefilling of short gaps

Gaps of 1 to 3 timestamps (10 to 30 min) are prefilled by linear interpolation in time.

3. Computation of Principal Components (PCs)

Principal component analysis (PCA) of the subset of complete series.

Threshold to 80% of explained variance.

4. Estimation of linear regression models

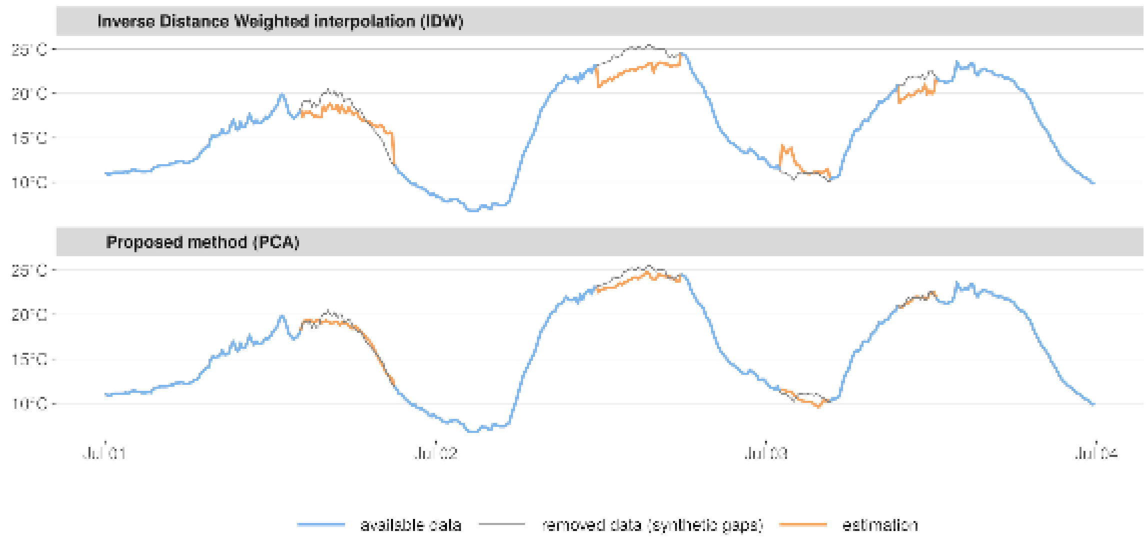
Linear models with the PCs as predictors to estimate each series based on the overlap periods

5. Completion of all gaps by linear regression predictions

Example of gap completion.

→ Proposed method (PCA) compared to IDW

→ Synthetic gaps



→ The proposed method better respects the continuity of the time series.

→ 10-min steps of similar magnitude as between observations

Automatic completion of gaps: validation

100 random experiments.

→ Selection of available data for a random period of 7 days

→ Generation of random synthetic gaps (removal of 10% of the data for durations from 40 min to 8 hours)

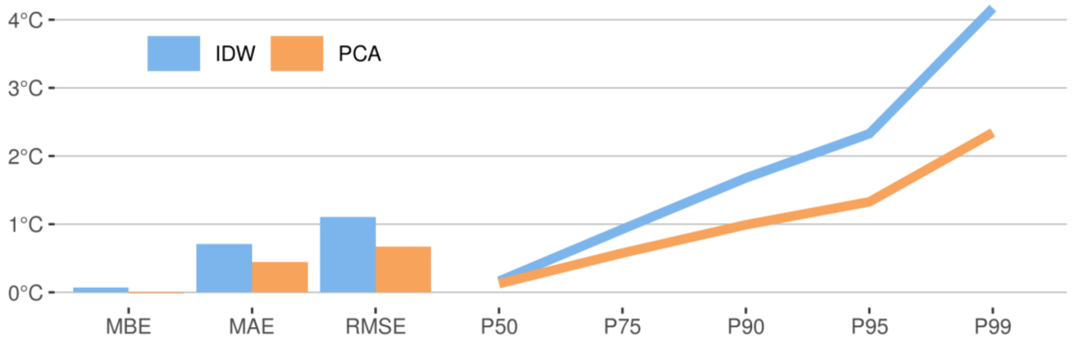
Results.

a. The proposed method (PCA) better estimates the removed data than IDW.

b. PCA estimations generate 10-min steps of similar magnitude as between observations.

a. Validation scores

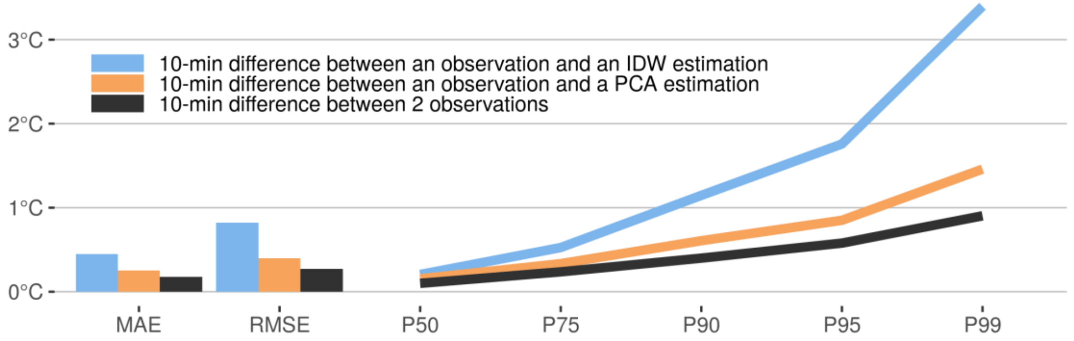
statistics of the deviation between estimations and removed data (synthetic gaps)
average on 100 random experiments



MBE: mean bias error MAE: mean absolute error RMSE: root mean square error
P50, P75, P90, P95 & P99: percentiles of the absolute error

b. Discontinuity scores

statistics of the 10-min difference at the begin and end of the synthetic gaps
average on 100 random experiments



MAE: mean absolute difference RMSE: root mean square difference
P50, P75, P90, P95 & P99: percentiles of the absolute difference

Conclusions

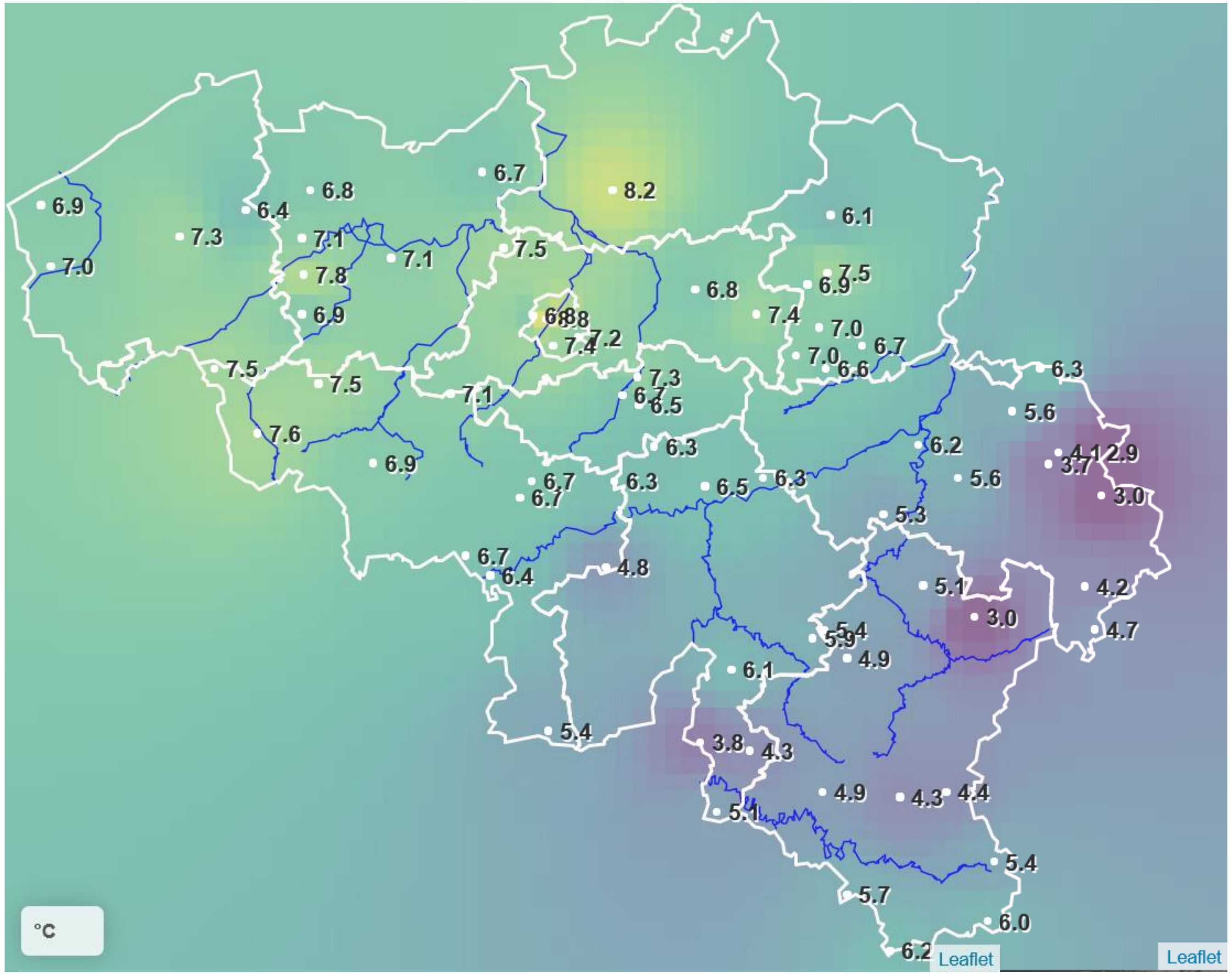
- Much more effort than expected to deploy and maintain the network of MeteoHelix IoT pro stations operational

- Confirmation of the excellent behavior of the Barani double-helix solar radiation Meteo shield while being not artificially ventilated

- Missing data issue is a true problem which seems difficile to overcome in an IoT-based environmental monitoring system + Having only 10 minute averaged values is limiting for data quality control

→ intermediate solution before the completion of an automated climate station (temperature - precipitation) alimented by solar panel and relying on the 4G technology's data transfer

MeteoHelix IoT Pro stations network



- Current situation:
  - 65 operational stations
  - 6 test stations
- Expected for the end of the year:
  - 75 operational stations
  - 6 test stations

Sigfox

- Low power wide area network (LPWAN) dedicated to massive IoT. It is designed to connect devices at low cost in an energy-efficient way
- The 0G Network was created to transmit lightweight message (12 bytes, excluding payload headers)
- The life-cycle of a Sigfox message is always the same:
  - A device wakes up and broadcasts a message using its radio antenna
  - Multiple base stations (local Sigfox OG technology antennas) in the area will receive the message
  - The base stations then sends the message to the Sigfox Cloud, and the Sigfox Cloud eventually sends the message to the customer's end platform
- The Sigfox network is bi-directional
  - from the device to the cloud (uplink)
  - from the cloud to the device (downlink)
- The contractual limit is set at:
  - 6 uplinks per hour
  - 4 downlinks per day

MeteoHelix IoT Pro vs. AWS (Humain synop station)

EC: 2

2020/01/20 – 2022/11/30
→ Hourly data

ΔT (°C)

HOUR (UTC) \ MONTH	J	F	M	A	M	J	J	A	S	O	N	D
(22,23]	0.05	0.12	0.08	0.07	0.09	0.11	0.14	0.11	0.04	0.05	0	0.04
(21,22]	0.05	0.12	0.1	0.09	0.1	0.12	0.15	0.11	0.03	0.05	0	0.02
(20,21]	0.05	0.11	0.09	0.09	0.11	0.13	0.17	0.12	0.06	0.05	0	0.03
(19,20]	0.05	0.12	0.1	0.12	0.12	0.14	0.2	0.14	0.07	0.05	0	0.04
(18,19]	0.05	0.11	0.11	0.16	0.12	0.16	0.19	0.17	0.07	0.05	−0.01	0.03
(17,18]	0.05	0.11	0.13	0.17	0.14	0.22	0.25	0.21	0.08	0.06	0.01	0.03
(16,17]	0.07	0.12	0.14	0.18	0.14	0.24	0.25	0.24	0.15	0.06	0.02	0.03
(15,16]	0.07	0.12	0.14	0.16	0.13	0.24	0.24	0.24	0.16	0.08	0.02	0.04
(14,15]	0.06	0.11	0.12	0.15	0.12	0.23	0.24	0.24	0.17	0.08	0.03	0.04
(13,14]	0.07	0.1	0.09	0.14	0.13	0.22	0.24	0.23	0.15	0.07	0.03	0.05
(12,13]	0.05	0.1	0.09	0.12	0.13	0.22	0.24	0.22	0.17	0.07	0.03	0.04
(11,12]	0.04	0.09	0.09	0.12	0.12	0.21	0.22	0.2	0.14	0.05	0.02	0.04
(10,11]	0.01	0.07	0.07	0.11	0.13	0.19	0.22	0.18	0.13	0.03	0.03	0.03
(9,10]	0.01	0.06	0.06	0.11	0.12	0.2	0.22	0.19	0.12	0.03	−0.01	0.02
(8,9]	0.03	0.07	0.07	0.09	0.12	0.19	0.21	0.18	0.11	0.02	−0.03	0.03
(7,8]	0.05	0.07	0.07	0.1	0.12	0.22	0.21	0.17	0.1	0.02	−0.01	0.03
(6,7]	0.03	0.08	0.05	0.09	0.11	0.19	0.19	0.14	0.1	0.03	0	0.02
(5,6]	0.04	0.09	0.05	0.07	0.08	0.15	0.13	0.11	0.05	0.05	0.01	0.02
(4,5]	0.05	0.1	0.06	0.04	0.04	0.1	0.1	0.08	0.02	0.04	0.01	0.02
(3,4]	0.04	0.1	0.06	0.05	0.05	0.1	0.1	0.08	0.01	0.04	0.02	0.03
(2,3]	0.04	0.1	0.07	0.05	0.04	0.11	0.11	0.1	0.02	0.04	0.02	0.03
(1,2]	0.05	0.1	0.06	0.07	0.05	0.12	0.11	0.1	0.03	0.03	0.01	0.03
[0,1]	0.05	0.12	0.07	0.07	0.06	0.12	0.12	0.1	0.04	0.04	0.01	0.03

ΔT (°C)

WIND SPEED BINS ($m.s^{-1}$) \ GLOBAL SOLAR IRRADIANCE BINS ($W.m^{-2}$)	[0,60]	(60,120]	(120,180]	(180,240]	(240,300]	(300,360]	(360,420]	(420,480]	(480,540]	(540,600]	(600,660]	(660,720]	(720,780]	(780,840]	(840,900]	(900,960]
(10.5,11]	0.2															
(9,9.5]	0.17															
(8.5,9]	0.15															
(8,8.5]	0.16	0.23														
(7.5,8]	0.13			0.09												
(7,7.5]	0.13	0.13	0.1	0.11	0.12	0.04										
(6.5,7]	0.12	0.11	0.1	0.06	0.08	0.06			0.02							
(6,6.5]	0.11	0.11	0.11	0.12	0.05	0.1	0.06	0	0.08	0.05	0.09	0.13				
(5.5,6]	0.1	0.12	0.09	0.1	0.08	0.14	0.07	0.08	0.08	0.14	0.19	0.1	0.15	0.19		
(5,5.5]	0.09	0.09	0.11	0.08	0.09	0.09	0.11	0.09	0.09	0.15	0.13	0.17	0.08	0.12		
(4.5,5]	0.08	0.1	0.1	0.11	0.08	0.08	0.09	0.13	0.1	0.06	0.12	0.15	0.13		0.17	
(4,4.5]	0.09	0.09	0.09	0.09	0.12	0.08	0.07	0.08	0.11	0.11	0.15	0.18	0.15	0.16	0.17	
(3.5,4]	0.08	0.07	0.11	0.1	0.09	0.11	0.11	0.15	0.13	0.13	0.17	0.14	0.17	0.2	0.22	0.19
(3,3.5]	0.08	0.09	0.09	0.12	0.14	0.13	0.13	0.14	0.12	0.17	0.16	0.2	0.18	0.21	0.2	0.18
(2.5,3]	0.08	0.08	0.1	0.13	0.16	0.12	0.15	0.17	0.16	0.16	0.2	0.19	0.22	0.24	0.2	
(2,2.5]	0.07	0.08	0.13	0.12	0.16	0.13	0.14	0.18	0.17	0.19	0.19	0.18	0.26	0.22	0.21	
(1.5,2]	0.06	0.09	0.11	0.11	0.09	0.12	0.16	0.16	0.19	0.18	0.22	0.18	0.21	0.21	0.26	
(1,1.5]	0.06	0.08	0.09	0.11	0.1	0.17	0.13	0.17	0.17	0.18	0.24	0.18	0.13	0.15		
(0.5,1]	0.08	0.08	0.13	0.14	0.09	0.2	0.18	0.13								
(0,0.5]	0.01															