Experimental and Numerical study of a Near-Field Pollutants Dispersion Campaign in a Stratified Surface Layer

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Introduction

- **Pollutants dispersion in a stable atmospheric boundary layer and in complex environment still relatively poorly described by modeling**
- **Stable condition difficult to reproduce in a wind tunnel**
- **Major interest in the field of air pollution from human activities (industrial risks, road transportation, etc.)**

- **Experimental program on the site SIRTA (Site Instrumental de Recherche par Télédétection Atmosphérique) measuring structure of turbulence and associated pollutants dispersion through high temporal and spatial resolution measurements in a stratified surface layer and in near-field**

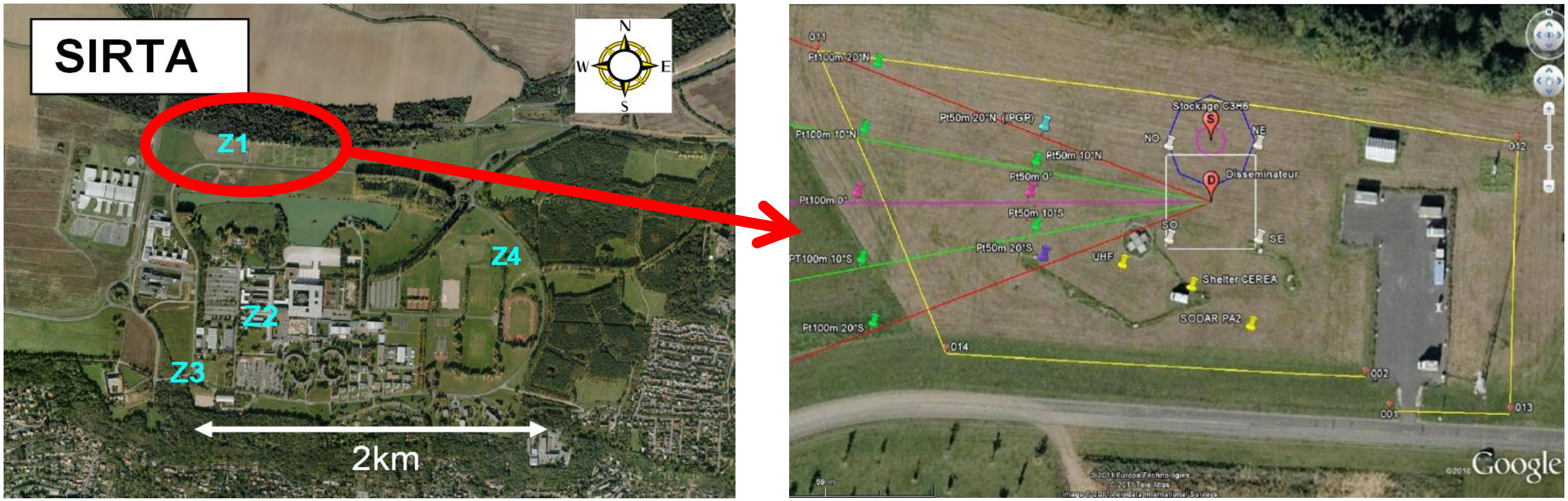
Contents

- SIRTA dispersion experimental program
- Data analysis
- Preliminary numerical simulations
- Conclusion and future works

SIRTA dispersion experimental program: objectives and characteristics

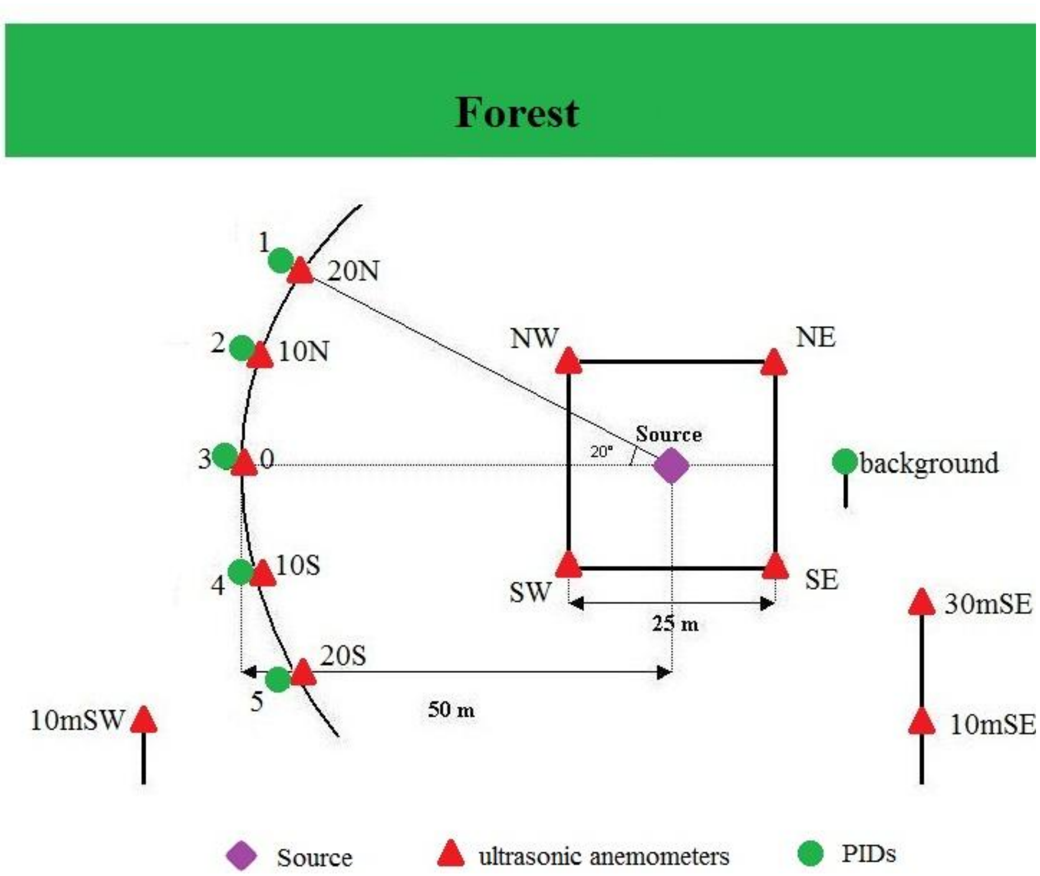
- **Objectives:**
  - Document in high temporal and spatial resolution and in near field, wind fluctuations and concentration fluctuations of a tracer gas
  - Relationships expected between concentration fluctuations and passage of turbulent structure
- **Characteristics:**
  - Experiment in near field (50 to 200 m)
  - Focus on stable thermal stratification, but may include some neutral stratification or slightly convective situations
  - High frequency measurements (about 10Hz) to cover the entire frequency spectrum of fluctuations
  - Large number of sensors measuring turbulence and concentration of tracer gas

SIRTA dispersion experimental program: field and meteorological conditions



- **Meteorological conditions :**
  - Wind direction between 75° and 105°, being as close as possible to 90° (easterly wind)
  - Wind velocity between about 1 and 5 ms^{-1} (at the release height i.e. 3 m) in order to stay in unfavorable dispersion conditions
  - Stable stratification checked both with positive temperature difference *T(30m) - T(10m)* and with positive Monin-Obukhov length

SIRTA dispersion experimental program: devices and sensors position



- **Source (at 3m height)**
- **12 ultrasonic anemometers:**
  - Continuous measurements
  - Measuring at 10 Hz: three components of wind speed and air temperature
  - "Sonic square" (at 3m height): NW, NE, SW, SE
  - "Sonic arc at 50m" (at 3m height): 20N, 10N, 0, 10S, 20S
  - Two masts: 10mSW, 10mSE and 30mSE
- **6 photo ionization detectors (PID):**
  - Measurements during tracer tests
  - Measuring concentration at 50Hz
  - All at 3m height

Sonic data analysis: statistic

- **Intensive Observation Period (IOP) on 5th June 2013 (18:48-20:17): selection of a 60min sub-period (from 19:08 to 20:08) with stationary meteorological conditions**

- ***dd* as mean wind direction**
- ***(a,b,w)* as longitudinal , transverse and vertical component of wind velocity**
- **Vertical stability verified by *T* gradient and L_{MO}**

	NE	NW	SE	SW	20N	20S	10mSW	10mSE	30mSE
dd_{mean} (°)	111.5	106.8	95.0	96.1	108.0	92.4	75.4	71.7	58.2
a_{mean} (ms^{-1})	0.92	1.00	1.63	1.83	1.22	1.68	2.06	2.42	3.54
σ_a^2 (m^2s^{-2})	0.44	0.53	0.54	0.61	0.48	0.56	0.67	0.81	1.29
σ_b^2 (m^2s^{-2})	0.30	0.33	0.50	0.49	0.38	0.48	0.52	0.52	0.77
σ_w^2 (m^2s^{-2})	0.10	0.12	0.13	0.13	0.11	0.14	0.25	0.25	0.32
TKE(m^2s^{-2})	0.42	0.49	0.59	0.61	0.49	0.59	0.72	0.79	1.19
u_* (ms^{-1})	0.21	0.23	0.26	0.25	0.22	0.28	0.36	0.37	0.53
Q_0 (Kms^{-1})	-0.03	-0.06	-0.03	-0.06	-0.03	-0.05	-0.02	-0.03	-0.03
L_{MO} (m)	21	16	40	20	24	34	176	131	416

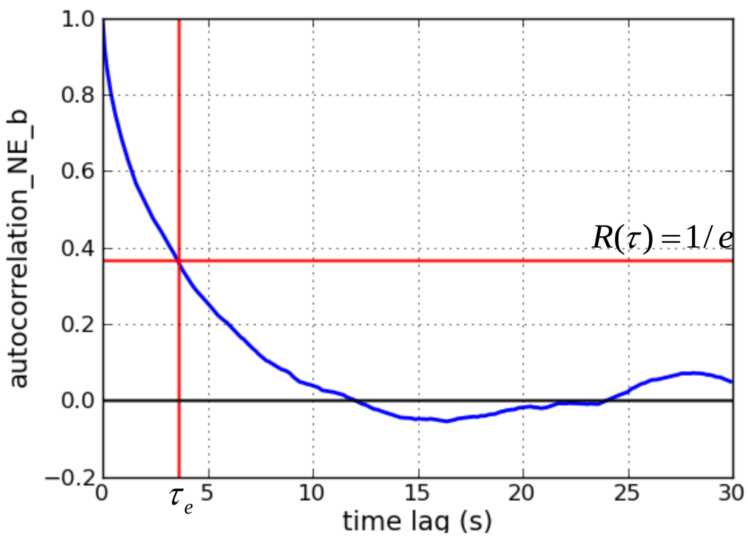
Sonic data analysis: integral length scale

- **Integral length scale : characteristic of the largest scales in a turbulent flow**

$$L = a_{mean} T_e$$

- **Integral time scale approximation**

$$T_i = \int_0^{\infty} R(\tau) d\tau \qquad T_e = \int_0^{\tau_e} R(\tau) d\tau \approx \tau_e$$

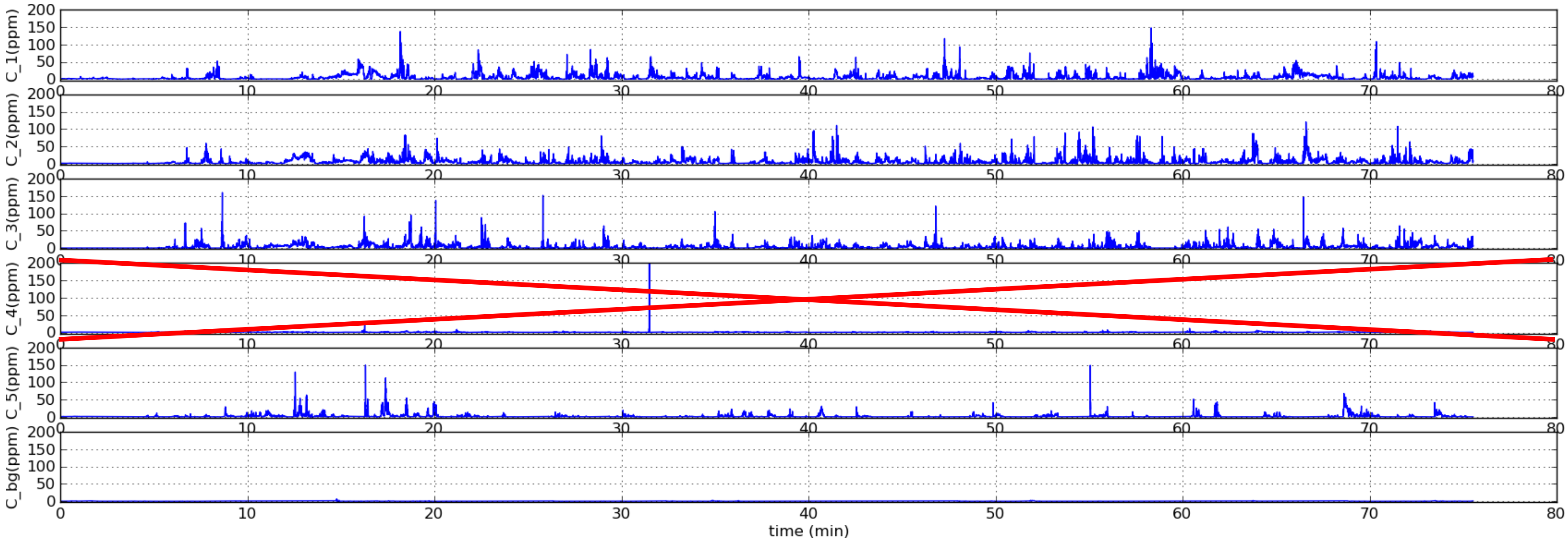


	NE	NW	SE	SW	20N	20S	10mSW	30mSE
L_{aa} (m)	14.82	13.13	14.86	16.69	19.62	14.28	33.31	91.95
L_{bb} (m)	5.67	6.42	11.11	12.47	7.68	12.27	11.51	24.76
L_{ww} (m)	1.83	2.00	1.96	2.02	2.07	2.35	5.96	8.84

- **Quantified anisotropy of turbulence near ground in stable conditions**
- ***L* increasing with altitude**

Concentration data analysis: baseline correction

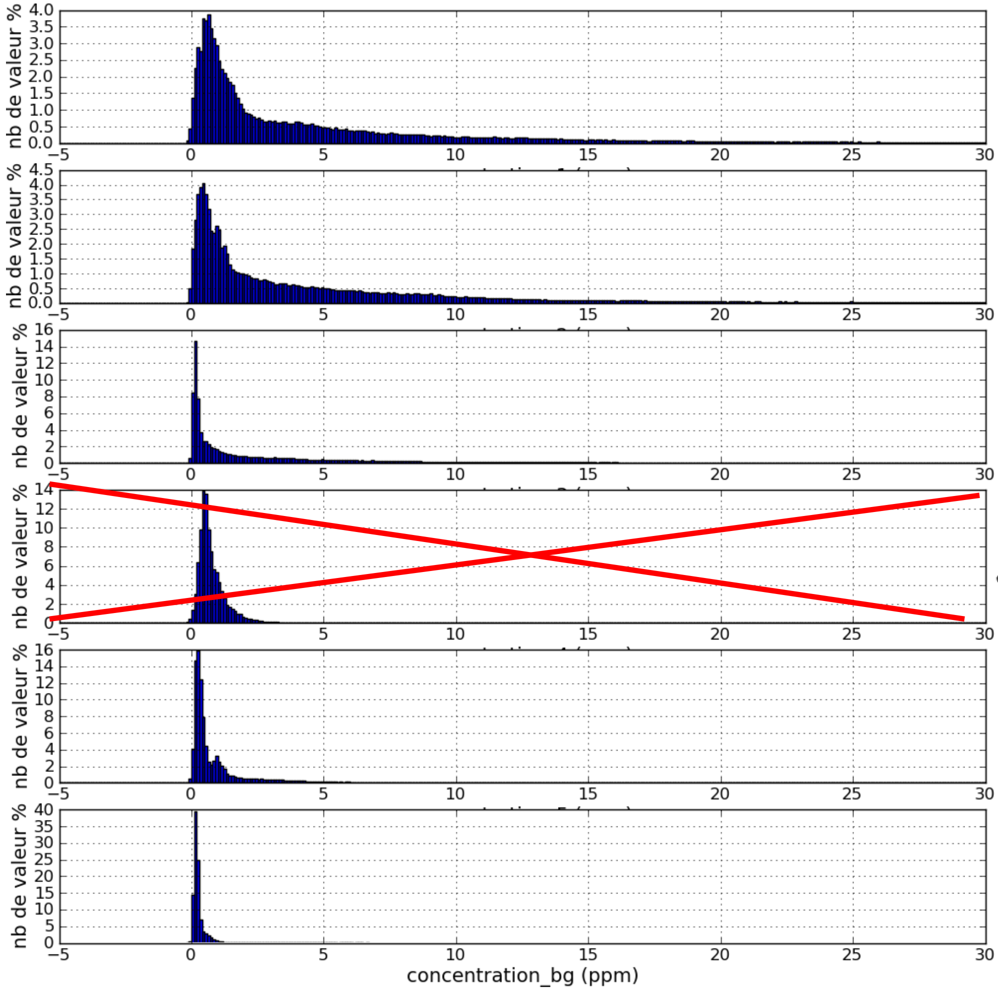
- **IOP on 5th June 2013 : continuous gas release about 70min (18:53 - 20:03)**
- **Raw data: gas concentration in ppm at 50 Hz**
  - Negative values, sensor drift and non zero off-set, background concentration
- **Negative values elimination: linear interpolation of its non-negative neighbors**
- **Baseline method to remove sensors drift and background concentration: average of the 200 smallest values every 5min**



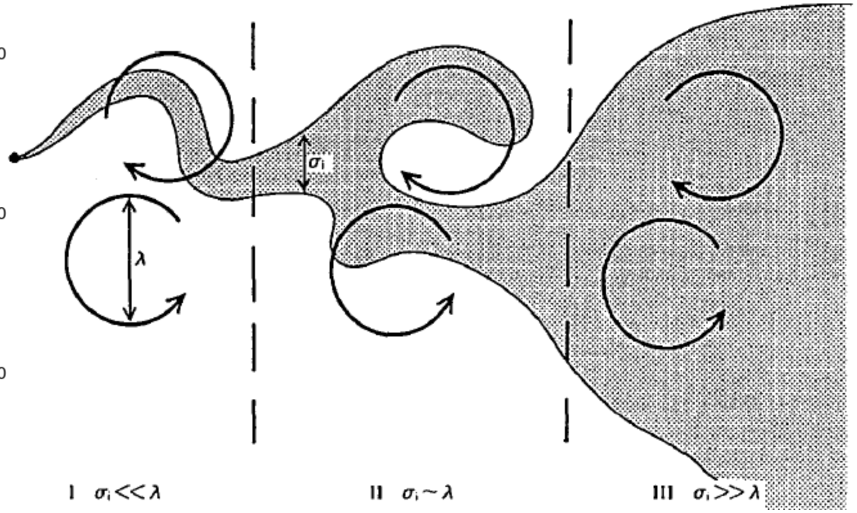
Concentration data after value correction for PIDs (from top to bottom) 1, 2, 3, 4, 5 and background

Concentration data analysis: histogram

- Log-normal distributions
- PIDs at near-source region
- Plume meadering effect



Concentration histogram for PIDs (from top to bottom) 1, 2, 3, 4, 5 and background



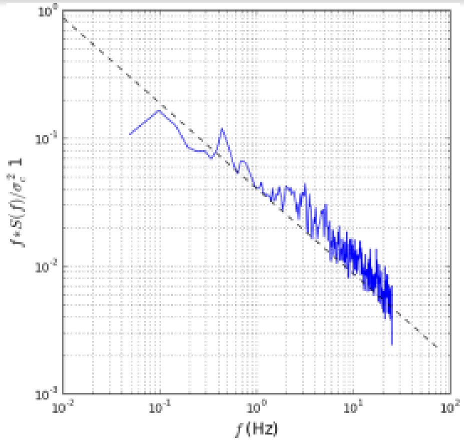
Concentration data analysis: statistic

	PID 1	PID 2	PID 3	PID 5	PID background
Height (m)	3	3	3	3	3
I	0.52	0.54	0.41	0.18	0.00
C (ppm)	5.46	5.58	3.87	1.79	0.25
C_P (ppm)	9.72	9.62	8.68	7.83	-
σ_c (ppm)	7.98	8.19	7.10	5.07	0.25
σ_c/C	1.46	1.47	1.83	2.84	0.98
$(\sigma_c/C)_P$	0.82	0.85	0.82	0.65	-
L_C (m)	6.29	6.52	3.12	12.91	-

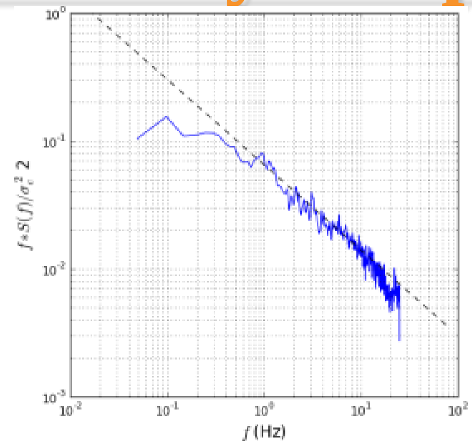
- **Statistical values:**
  - intermittency factor I (probability that the concentration is non-zero)
  - mean concentration C and conditional mean C_P
  - standard deviation σ_c
  - fluctuation intensity σ_c/C and conditional intensity $(\sigma_c/C)_P$
  - threshold value $C_T=2$ ppm

- **Discussion:**
  - I and C have higher values for PID 1 and 2 →coherent with the south-easterly wind
  - great differences found between C and C_P, σ_c/C and $(\sigma_c/C)_P$
  - C_P and $(\sigma_c/C)_P$ almost constants between all the PIDs
  - integral length scales of plume $L_C \sim L_{bb}$
  - plume meandering effect plays probably an important role in concentration measurements

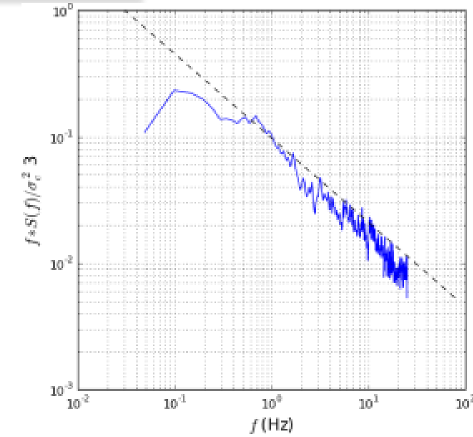
Concentration data analysis: spectra



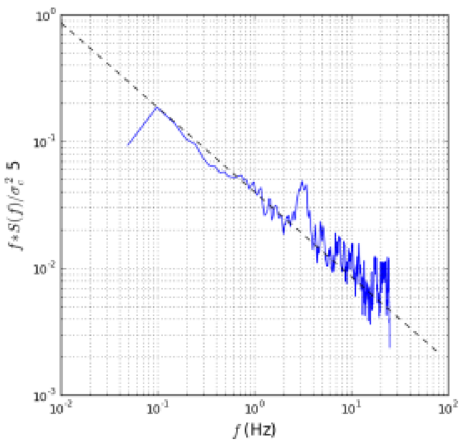
PID 1



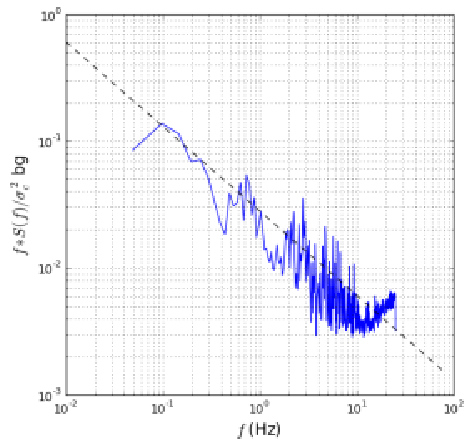
PID 2



PID 3



PID 5

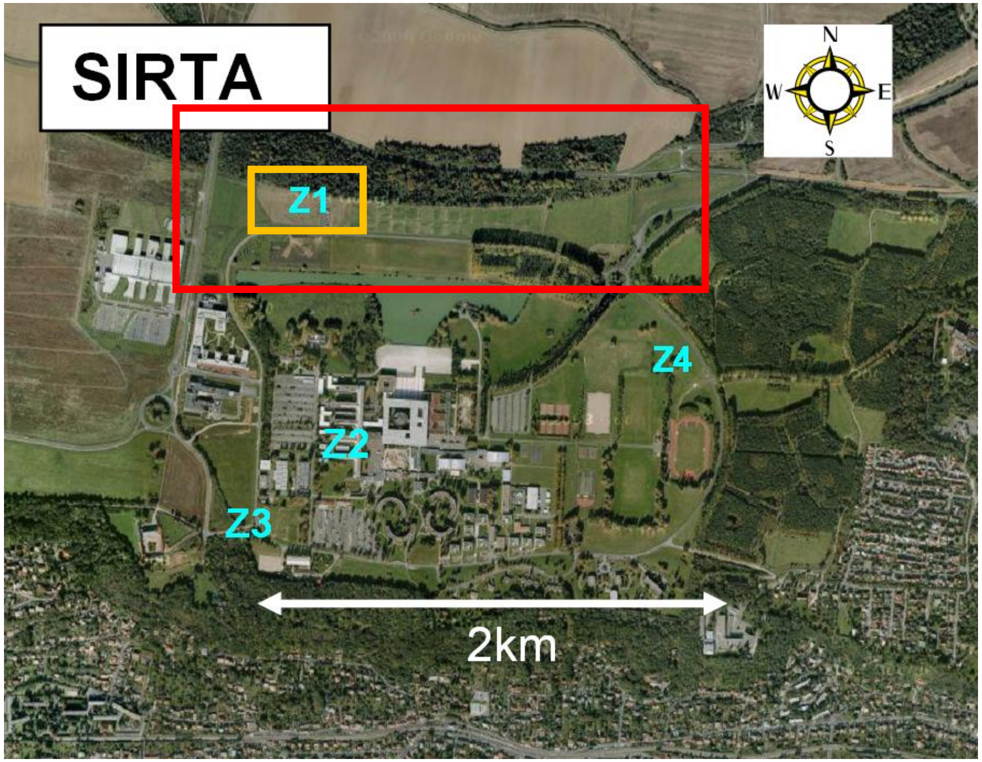


PID background

- Normalized concentration spectra $fS(f)/\sigma_C^2$
- Spectra follow the -2/3 slope → inertial subrange

- **Spectra more fluctuating with a smaller intermittency factor**
- **Inertial subrange found in PID background → might be other source around during the IOP**

Preliminary numerical simulation: modelling



- **Objective: the open source CFD code *Code_Saturne* can reproduce correctly the mean flow on the experiment area**
- **Modelling area**
  - Zone 1(1600m×700 m×200m, red): horizontal resolution 5m
  - Zone 1 instrumented area (180m×100m ×200m , yellow): horizontal resolution 1m
  - Shelters taken into account explicitly in the mesh
- **Boundary conditions**
  - Inlet condition: analytical profiles generated with measurements of anemometers 10mSE and 30mSE in IOP on 5 June 2013
  - Outlet condition: free outflow
  - Ground and shelters surfaces: a constant roughness length z_0=0.1 m

Preliminary numerical simulation: modelling

- **RANS, standard *k-ε* turbulence model , with stable thermal stratification**
- **Identification of different land cover types**
- **Forest modelling:**
  - drag porosity model proposed in Katul et al.(2004)
  - 1 source term in the Navier-Stockes momentum equation

$$S_{u,i} = -\frac{1}{2}\rho\alpha C_D |U| \overline{U_i}$$

  - 2 source terms in the *k-ε* equations

$$S_k = \frac{1}{2}\rho\alpha C_D B_p |U|^3 - \frac{1}{2}\rho\alpha C_D B_d k|U|$$

$$S_\varepsilon = \frac{1}{2}\rho\alpha C_D C_{\varepsilon 4} B_p \frac{\varepsilon}{k}|U|^3 - \frac{1}{2}\rho\alpha C_D C_{\varepsilon 5} B_d \varepsilon |U|$$

with

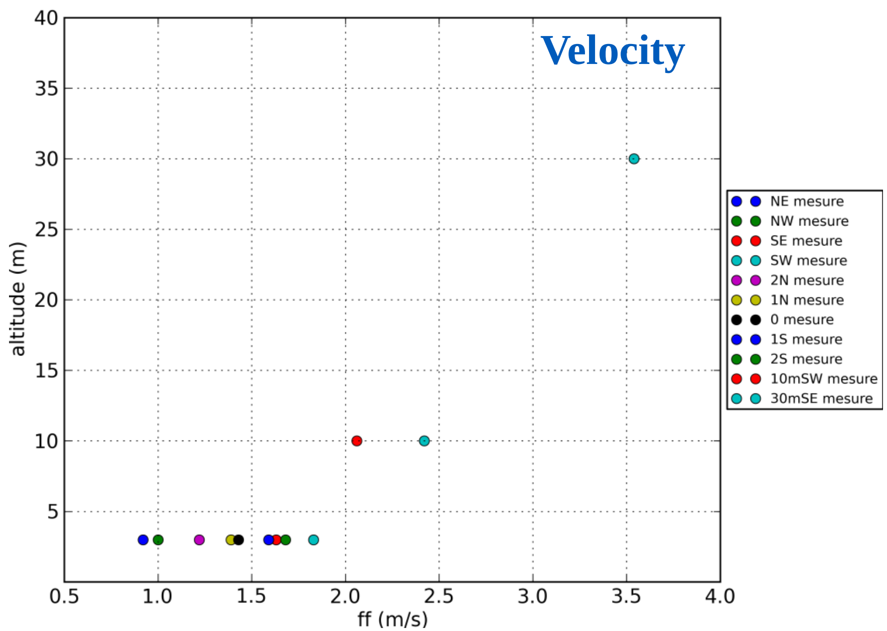
$$B_p = 1, \quad C_\mu = 0.03,$$

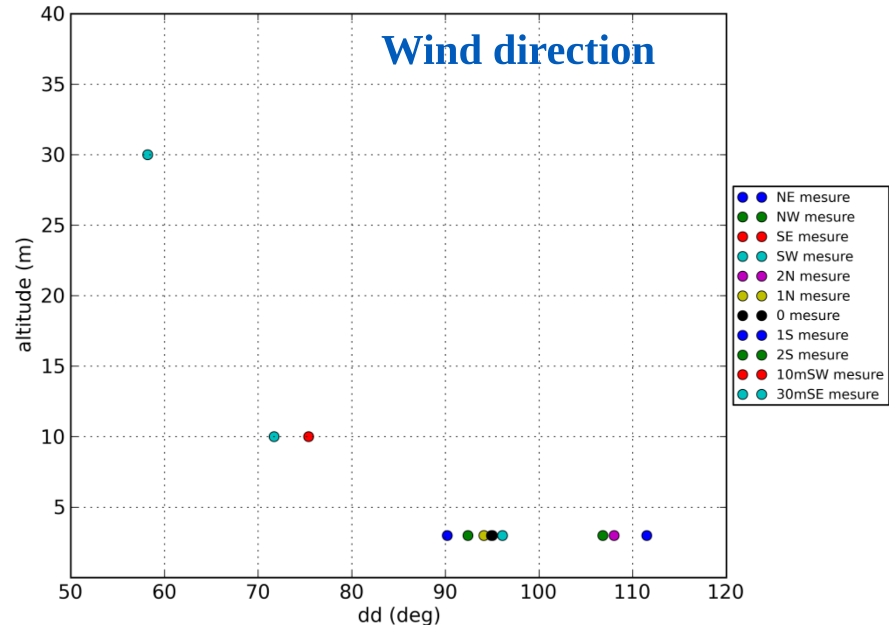
$$B_d = \sqrt{C_\mu}\left(\frac{2}{0.05}\right)^{2/3} B_p + \frac{3}{\sigma_k} = 5.03,$$

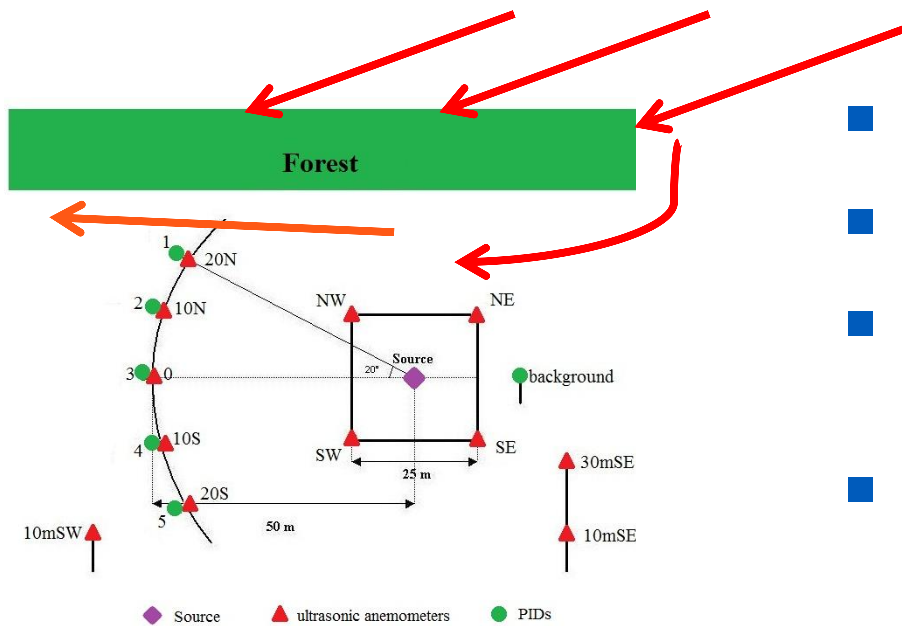
$$C_{\varepsilon 4} = C_{\varepsilon 5} = 0.9$$

α : leaf area density, H: forest height and C_D : drag coeficient

Simulation results: observed effects

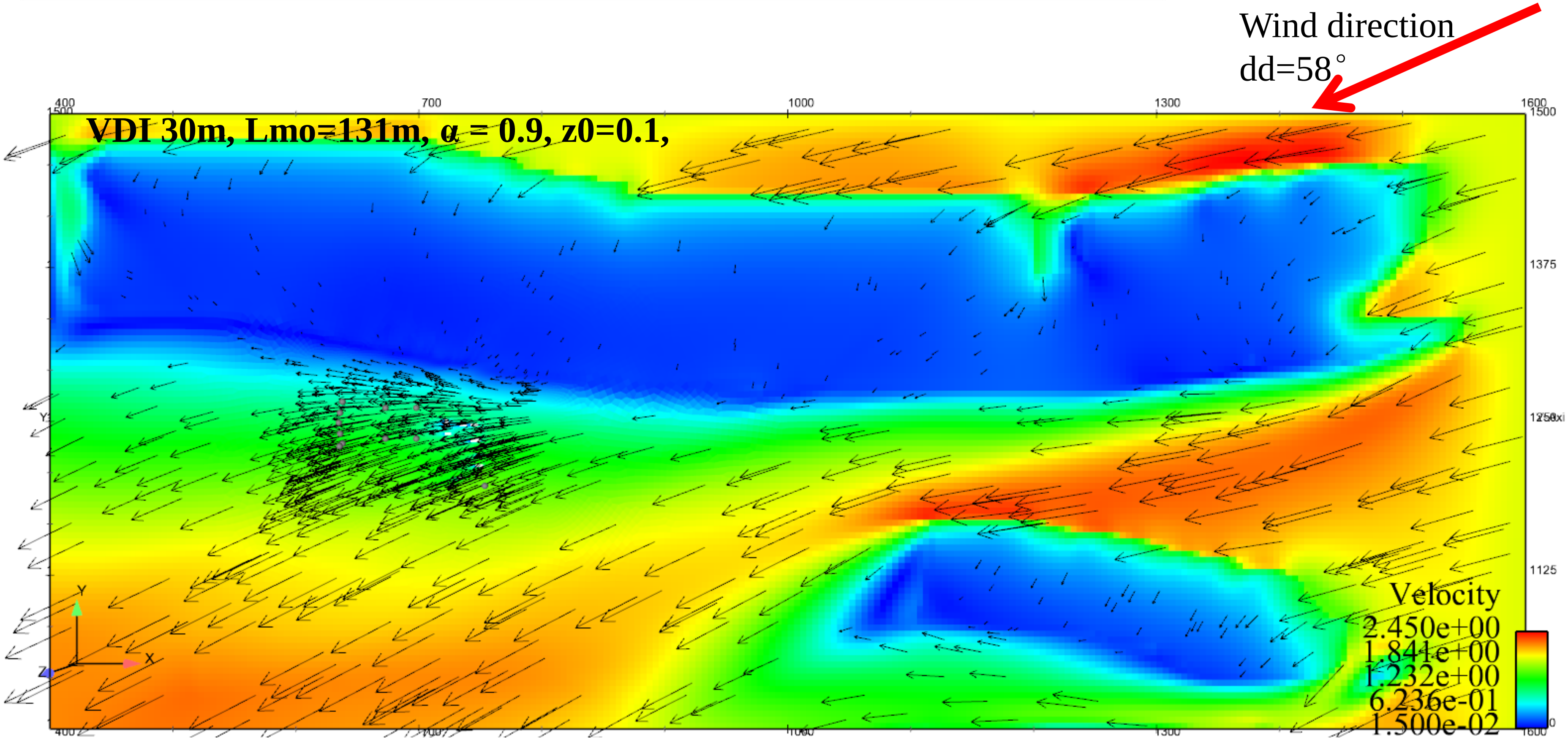






- 3 measurements levels
- Forest height = 15m
- Smaller velocity for anemometers on the north
- Wind rotation at height of 3m

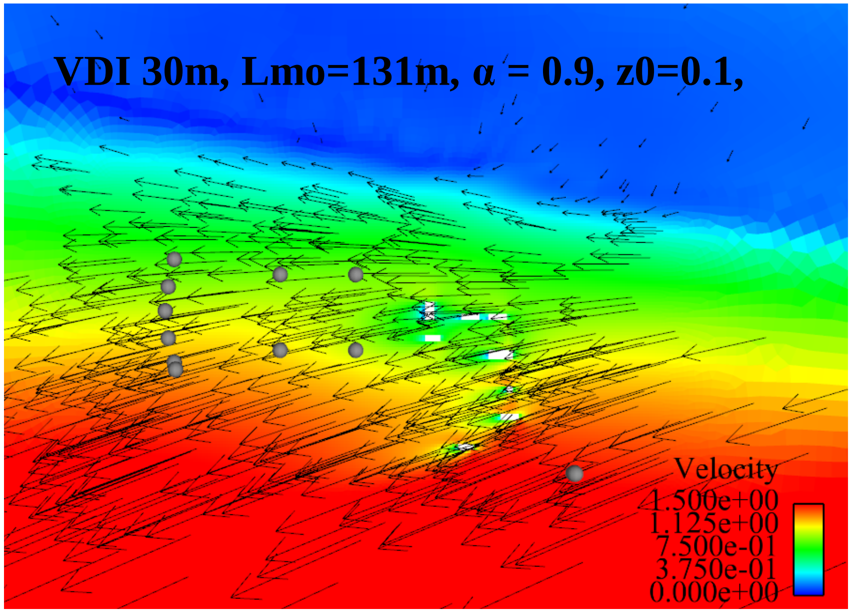
Simulation results: zone 1 whole area



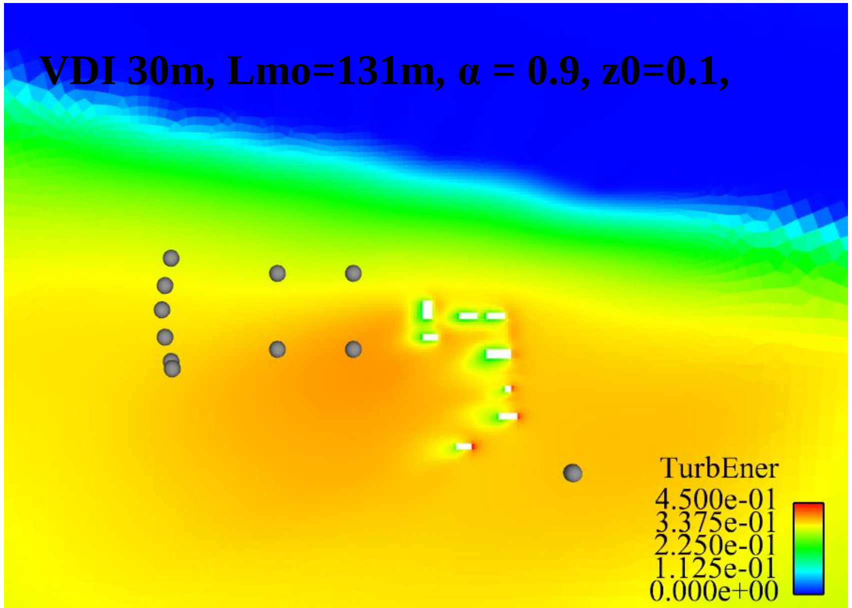
Velocity field at 3m height

- **Wind channelling effect of the forest on the velocity**

Simuation results: zone 1 instrumented area



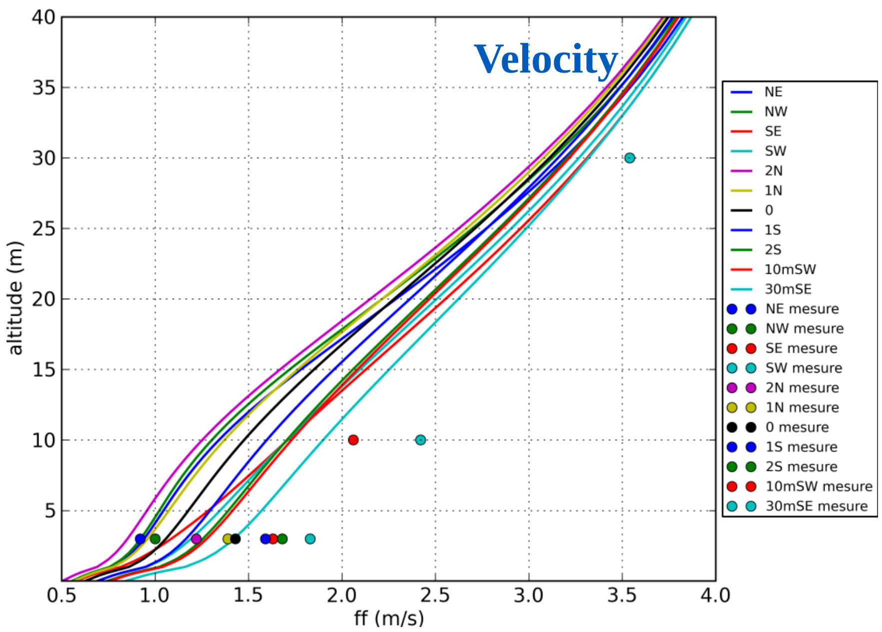
Velocity field at 3m height

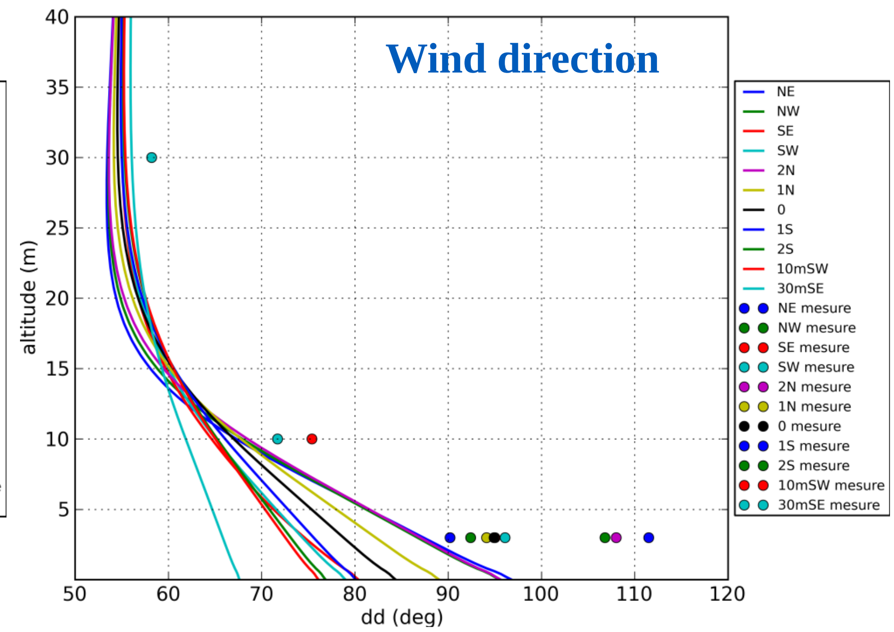


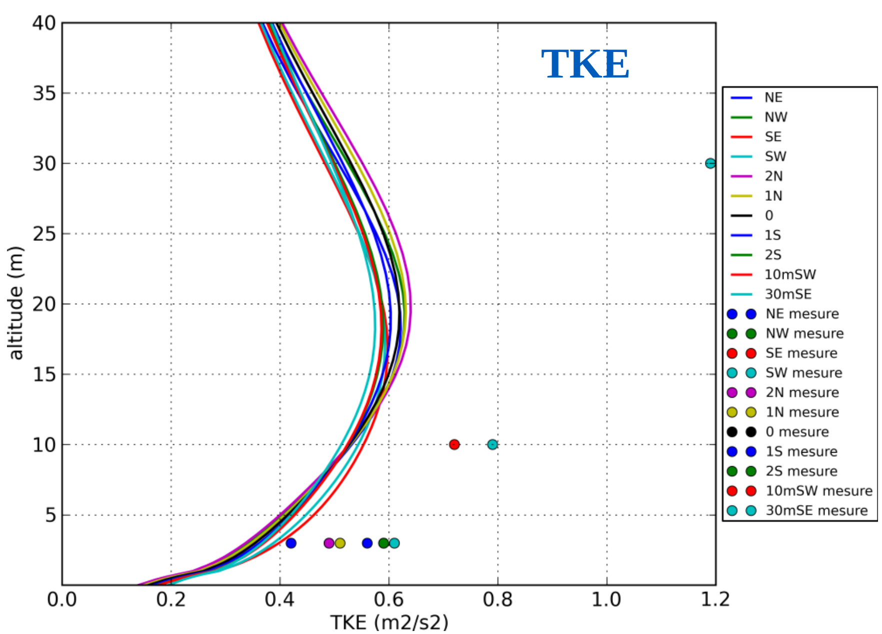
TKE field at 3m height

- Wind velocity slowed down and direction changed by forest
- TKE : lower values close to the forest, higher values behind shelters

Simulation results: comparison







- **Coherent variation trend**
- **Difference in values**
- **No measurement for inlet profile**

Conclusion and future works

Conclusion:

- Characterization of the turbulence strong anisotropy
- Perturbation from the forest : slow down wind velocity and change wind direction
- Evidence of plume meandering effect in stable stratified surface layer
- Numerical simulation reproduced qualitatively wind channelling effect of forest on velocity and impact of shelters on turbulence kinetic energy

Future works:

- Turbulence data analysis for continues measurements over 2 years → turbulence characteristics varied with stability condition
- Additional PIDs allowing to extend the instrumental set-up
- Relationships between turbulence and concentration fluctuations
- Numerical simulations in mode RANS with *Code_Saturne*: using a second-order turbulence model R_{ij}-ε →to model turbulence anisotropy

References

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- Katul G.G., L. Mahrt, D. Poggi, C. Sanz ,2004: One- and two-equation models for canopy turbulence. *Boundary-Layer Meteorol* 113, 81-109
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THANK YOU !

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