Turbulence Measurements for a Near-Field Pollutants Dispersion Campaign in a Stratified Surface Layer

Xiao Wei, Eric Dupont, Bertrand Carissimo, Eric Gilbert and Luc Musson-Genon

21 BLT, 9-13 June 2014, Leeds, UK

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**

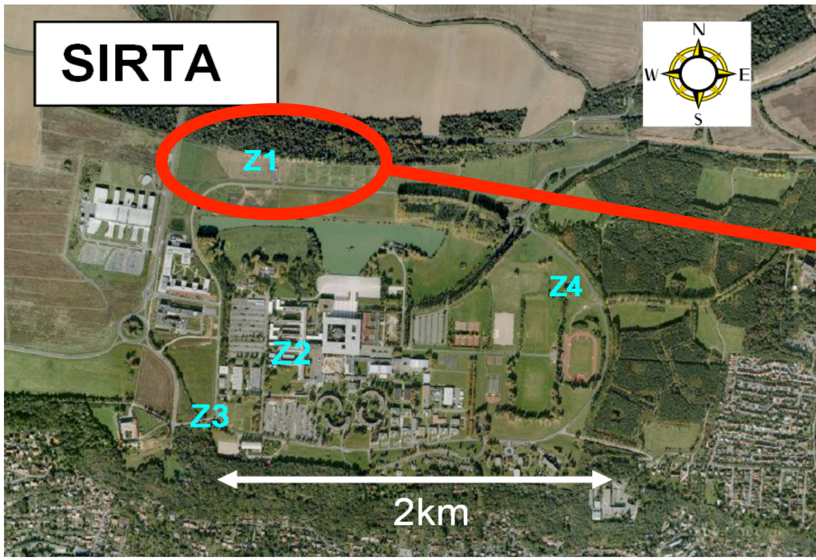
Contents

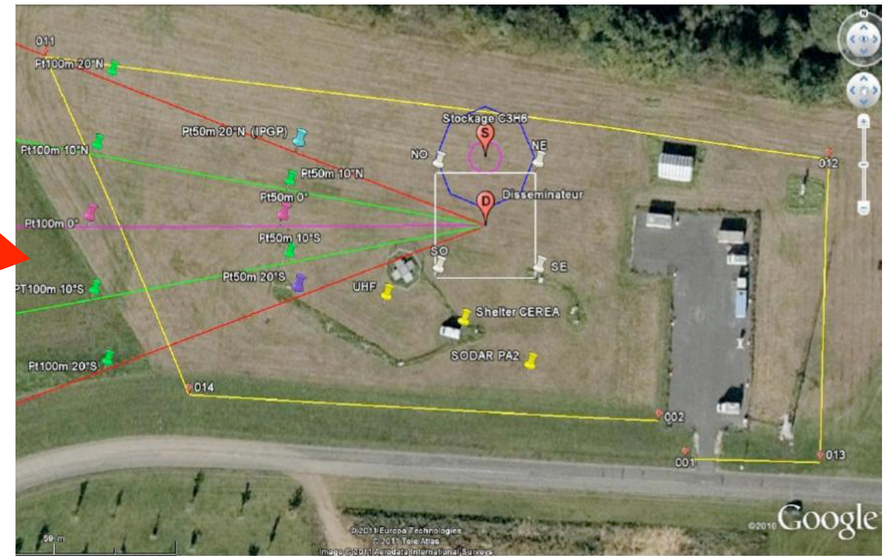
Contents

SIRTA experimental program: objectives and characteristics

- **Objectives:**
  - To characterize the fine structure of turbulence and associated dispersion through high temporal and spatial resolution measurements in a real site
  - To find expected relationships 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 to document spatial inhomogeneities

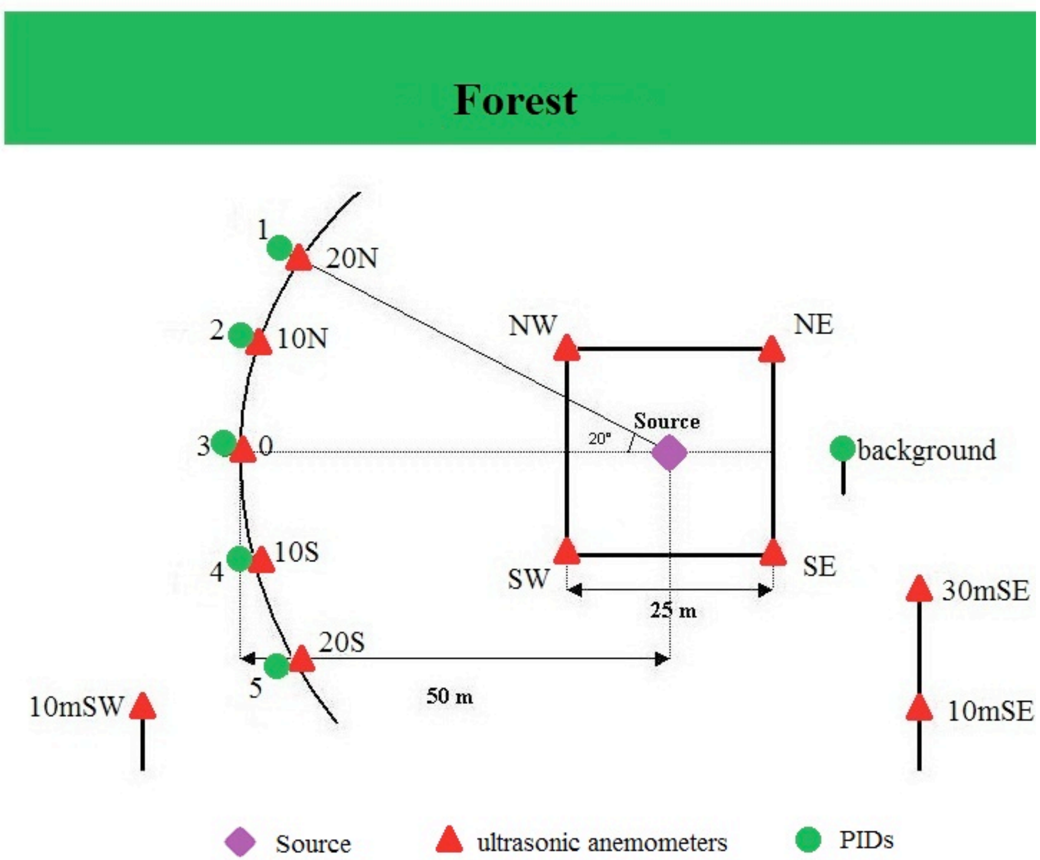
SIRTA experimental program: field and meteorological conditions





- **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 experimental program: devices and sensors position

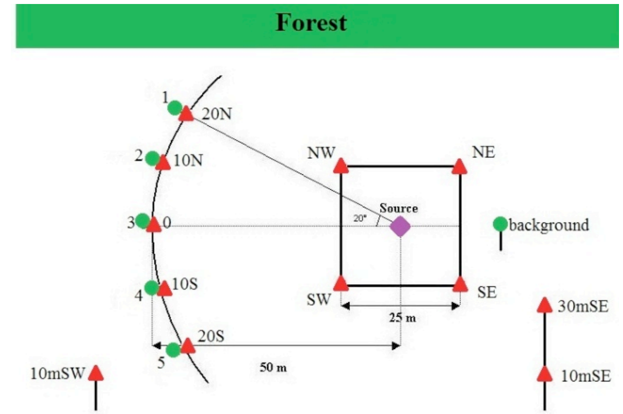


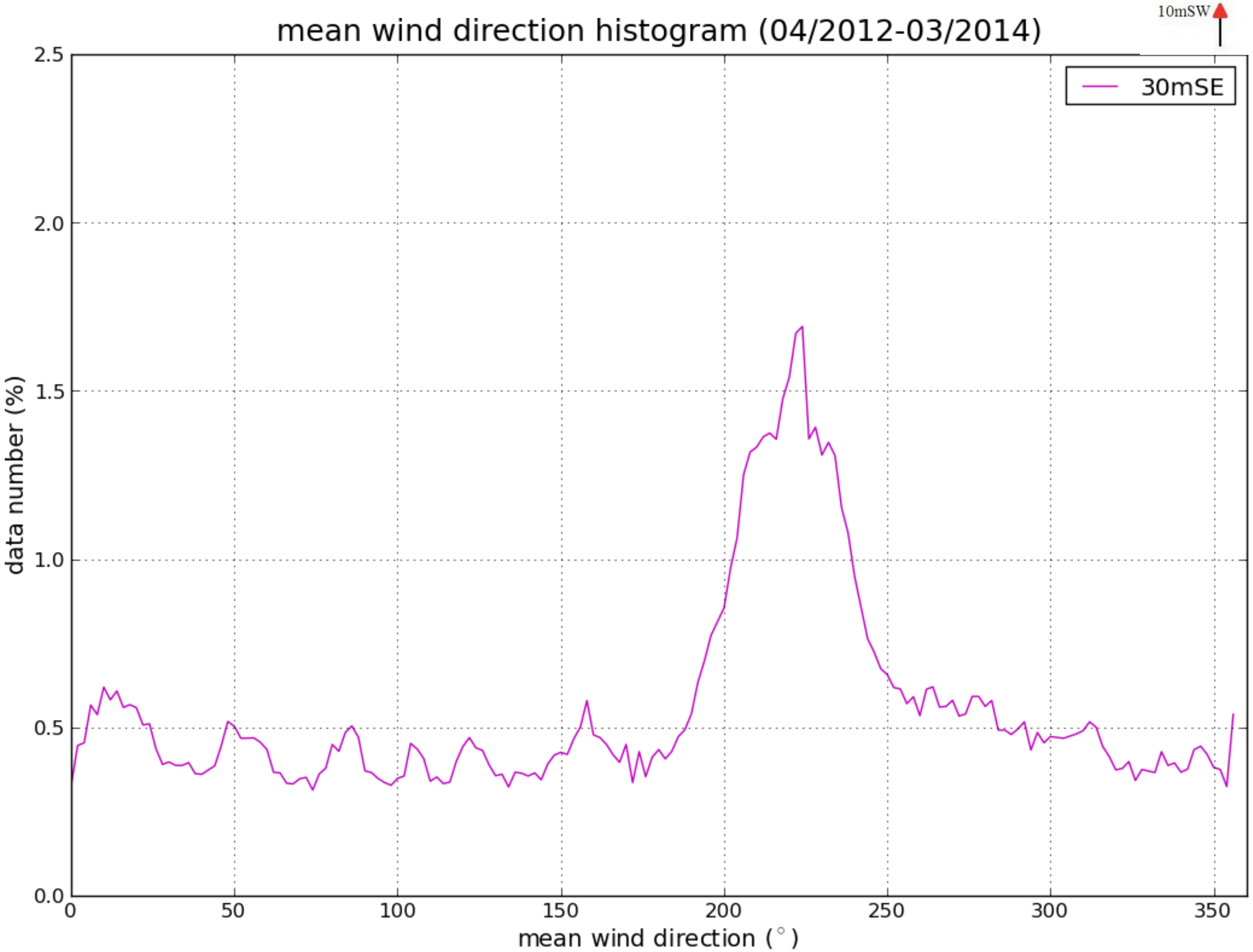
- Source (at 3m height)
- 12 ultrasonic anemometers:
  - Continuous measurements
  - Measuring at 10 Hz: three components of wind speed and air temperature
  - "Sonic square" (at 3m height): NW, NE, SW, SE
  - "Sonic arc at 50m" (at 3m height): 20N, 10N, 0, 10S, 20S
  - Two masts: 10mSW, 10mSE and 30mSE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

Contents

Wind direction

- Terrain heterogeneity in zone 1
- Wind channeling by the forest to the north

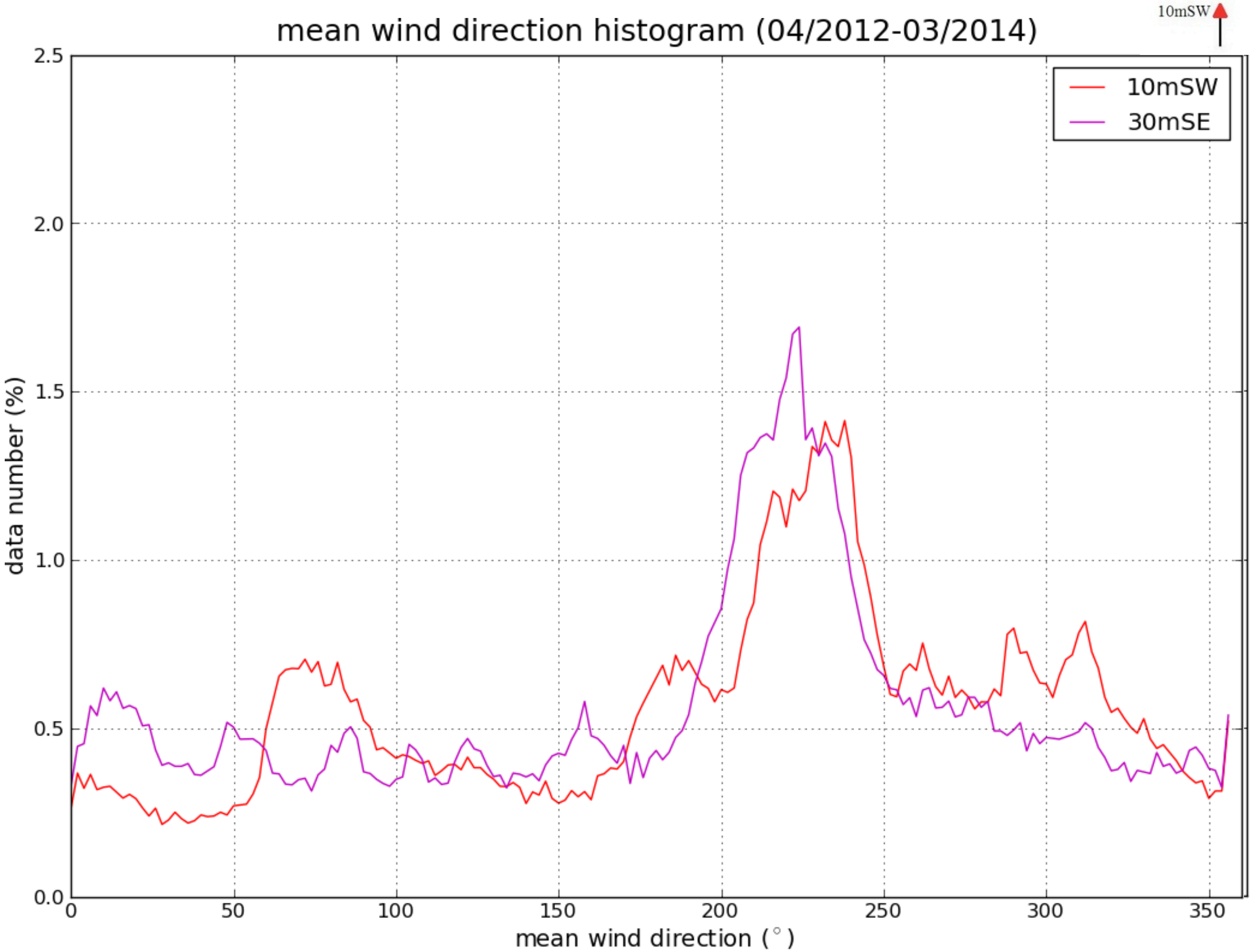


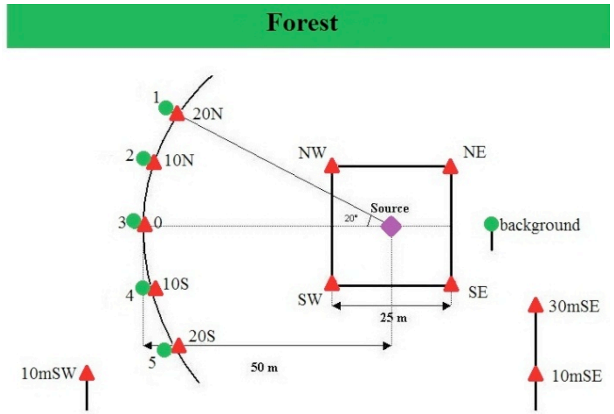


- Forest height: 15 m
- At 30m: prevailing wind direction South-West

Wind direction

- Terrain heterogeneity in zone 1
- Wind channeling by the forest to the north

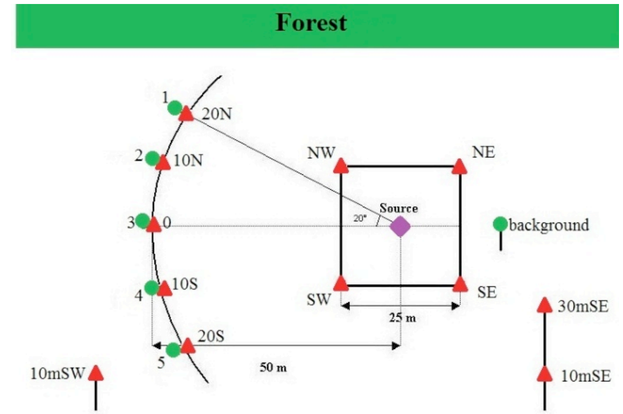


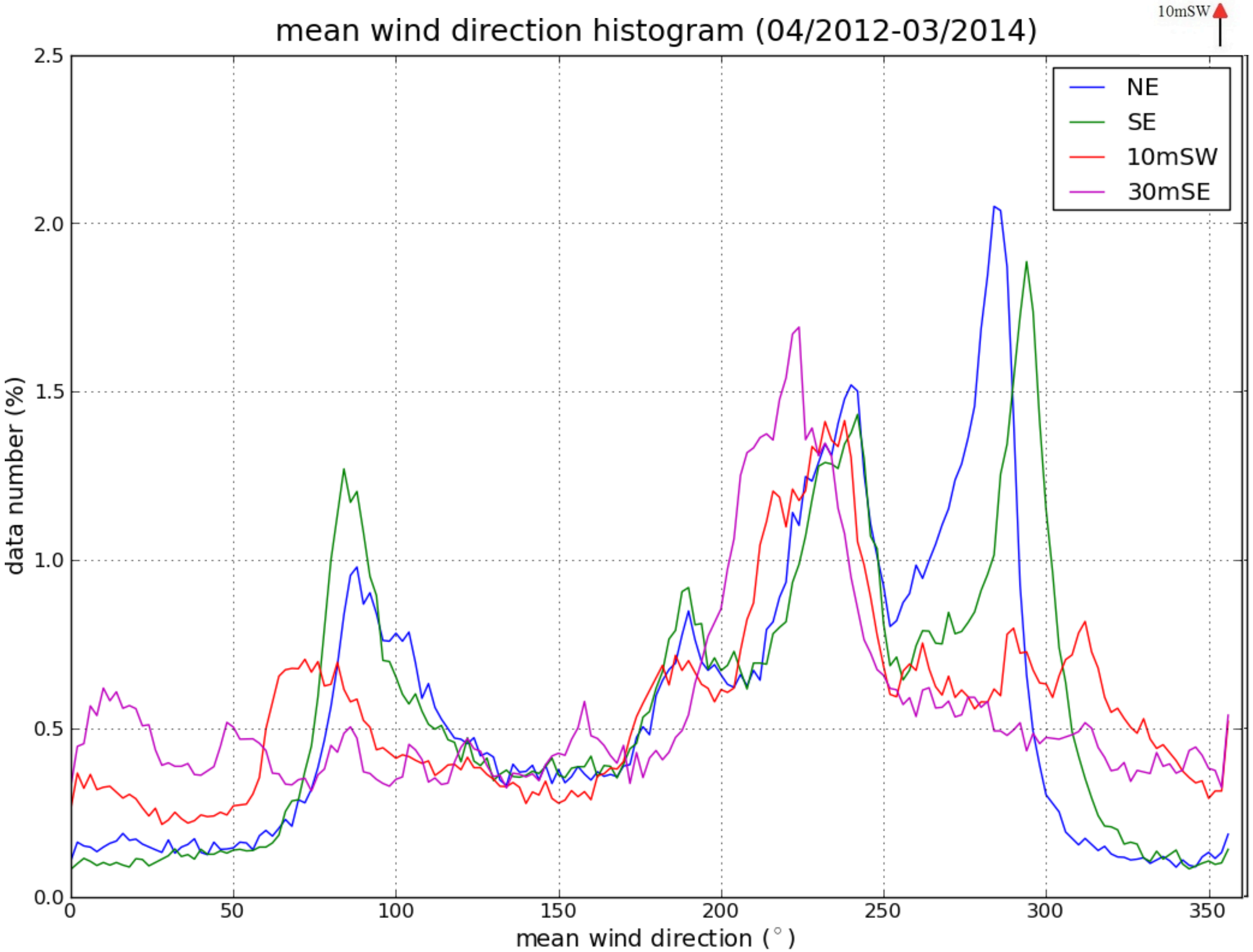


- Forest height: 15 m
- At 30m: prevailing wind direction South-West
- At 10m: more easterly and westerly wind

Wind direction

- Terrain heterogeneity in zone 1
- Wind channeling by the forest to the north

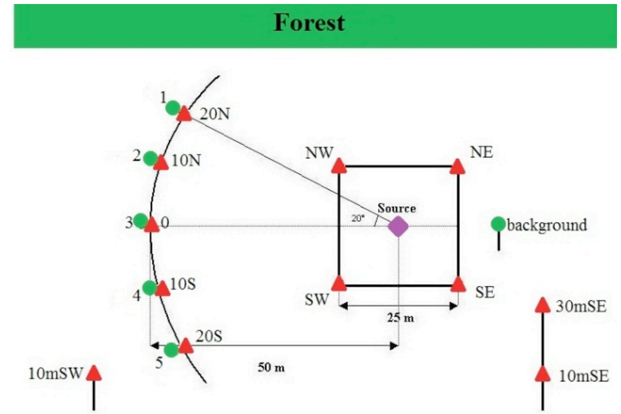


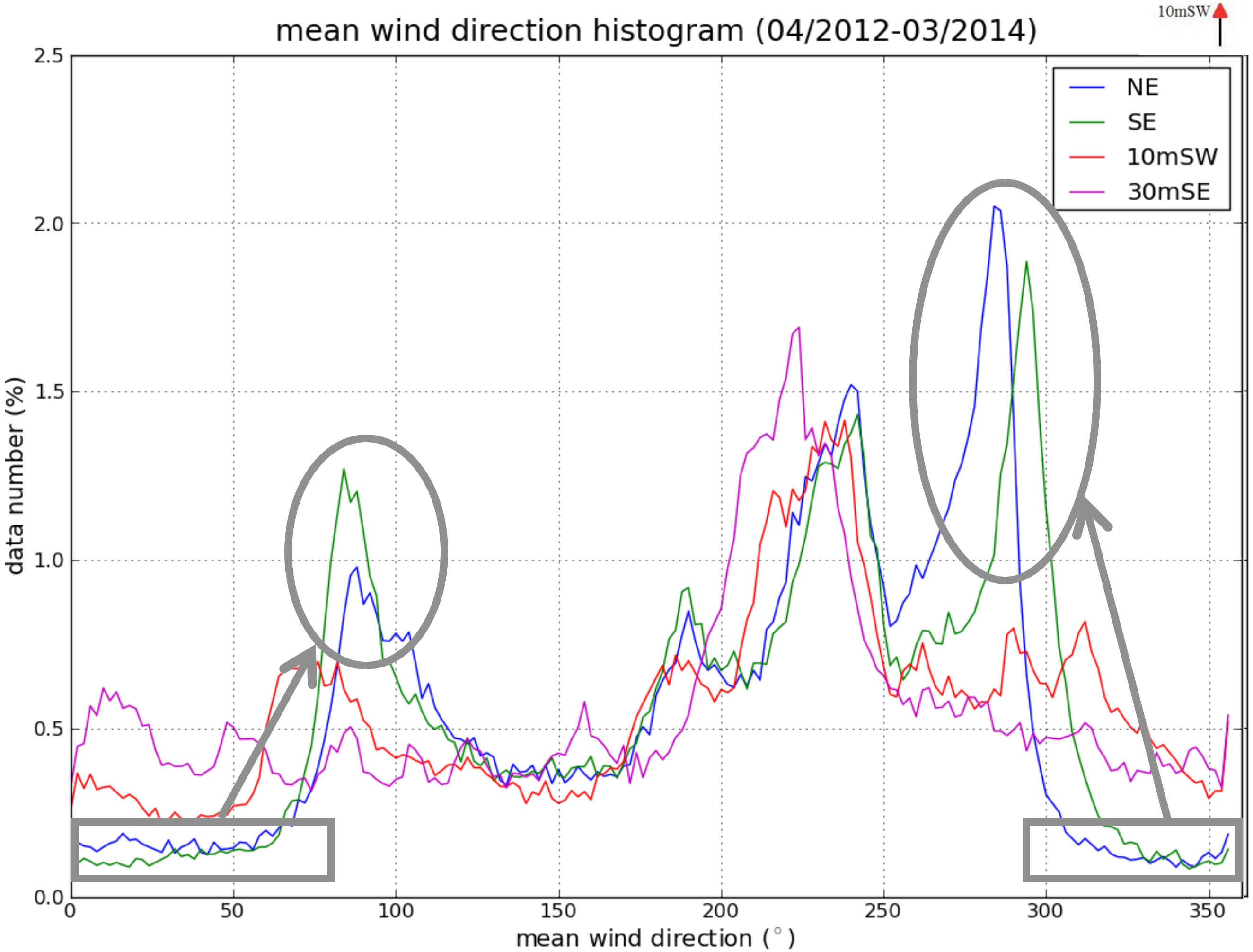


- Forest height: 15 m
- At 30m: prevailing wind direction South-West
- At 10m: more easterly and westerly wind
- At 3m:
  - Picks around 90°and 270°
  - Few wind for northerly sector

Wind direction

- Terrain heterogeneity in zone 1
- Wind channeling by the forest to the north





- Forest height: 15 m
- At 30m: prevailing wind direction South-West
- At 10m: more easterly and westerly wind
- At 3m:
  - Picks around 90°and 270°
  - Few wind for northerly sector

Contents

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by T gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by *T* gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by *T* gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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 (m²s^{-2})	0.44	0.53	0.54	0.61	0.48	0.56	0.67	0.81	1.29
σ_b^2 (m²s^{-2})	0.30	0.33	0.50	0.49	0.38	0.48	0.52	0.52	0.77
σ_w^2 (m²s^{-2})	0.10	0.12	0.13	0.13	0.11	0.14	0.25	0.25	0.32
TKE(m²s^{-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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by *T* gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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^{2}s^{-2})	0.44	0.53	0.54	0.61	0.48	0.56	0.67	0.81	1.29
σ_b^2 (m^{2}s^{-2})	0.30	0.33	0.50	0.49	0.38	0.48	0.52	0.52	0.77
σ_w^2 (m^{2}s^{-2})	0.10	0.12	0.13	0.13	0.11	0.14	0.25	0.25	0.32
TKE(m^{2}s^{-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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by T gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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^{2}s^{-2})	0.44	0.53	0.54	0.61	0.48	0.56	0.67	0.81	1.29
σ_b^2 (m^{2}s^{-2})	0.30	0.33	0.50	0.49	0.38	0.48	0.52	0.52	0.77
σ_w^2 (m^{2}s^{-2})	0.10	0.12	0.13	0.13	0.11	0.14	0.25	0.25	0.32
TKE(m^{2}s^{-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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by *T* gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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

Turbulence study for measurements during IOP: statistics from ultrasonic anemometers

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

- **Vertical stability verified by *T* gradient and L_{MO}**
- ***(u, v, w)* in meteorological reference and *(a,b,w)* in rotated frame**
- ***dd* as mean wind direction**

	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

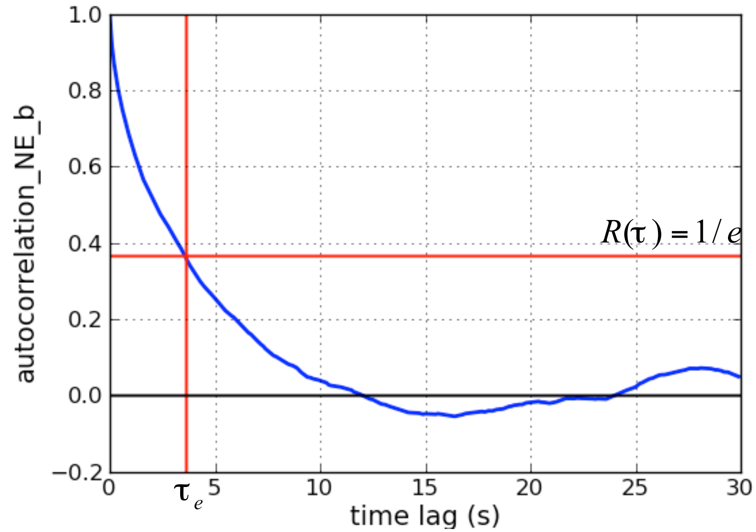
Turbulence study for measurements during IOP: integral length scale

- **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**

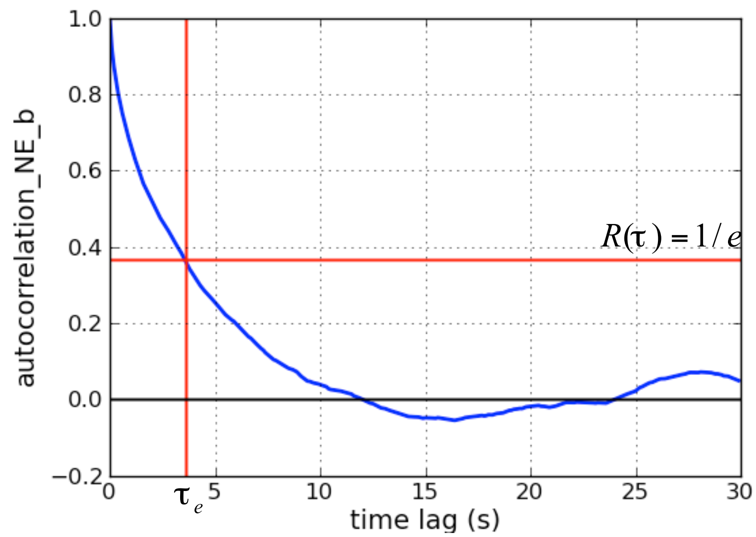
Turbulence study for measurements during IOP: integral length scale

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

$$L = a_{mean} T_e$$

- **Integral time scale approximation**

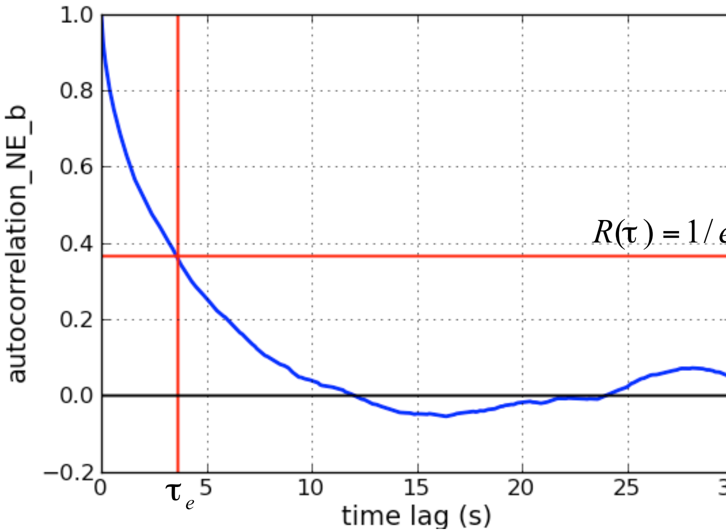
$$T_i = \int_0^{\infty} R(\tau)\,d\tau \qquad T_e = \int_0^{\tau_e} R(\tau)\,d\tau \approx \tau_e$$



	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**

Turbulence study for measurements during IOP: integral length scale



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

$$L = a_{mean} T_e$$

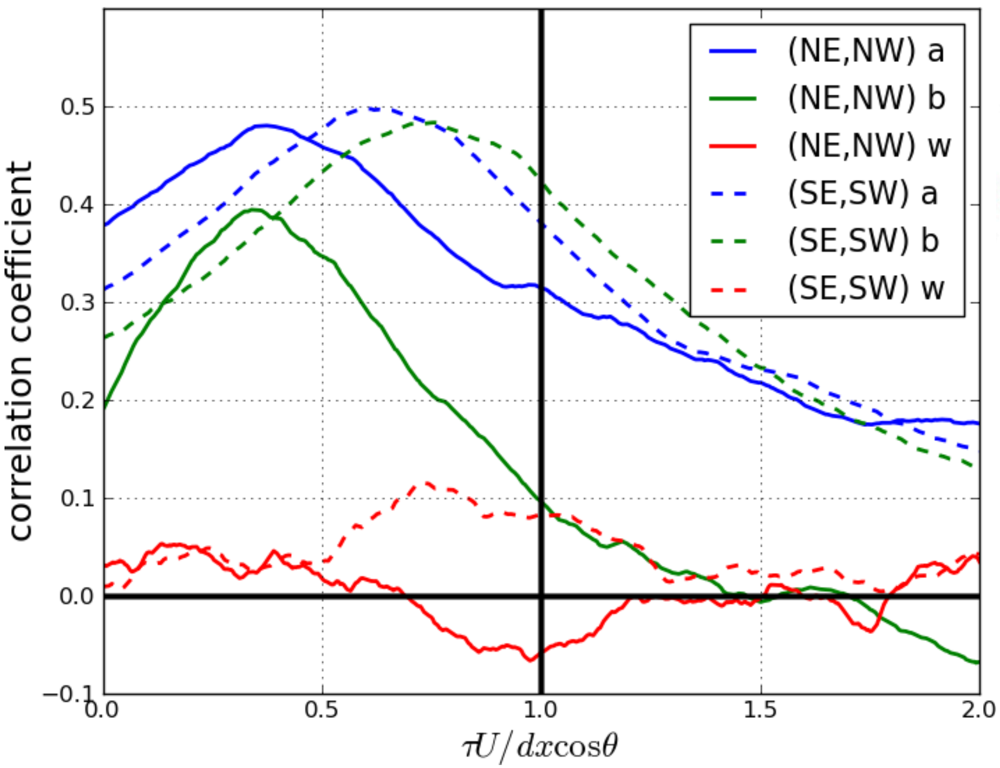
- **Integral time scale approximation**

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

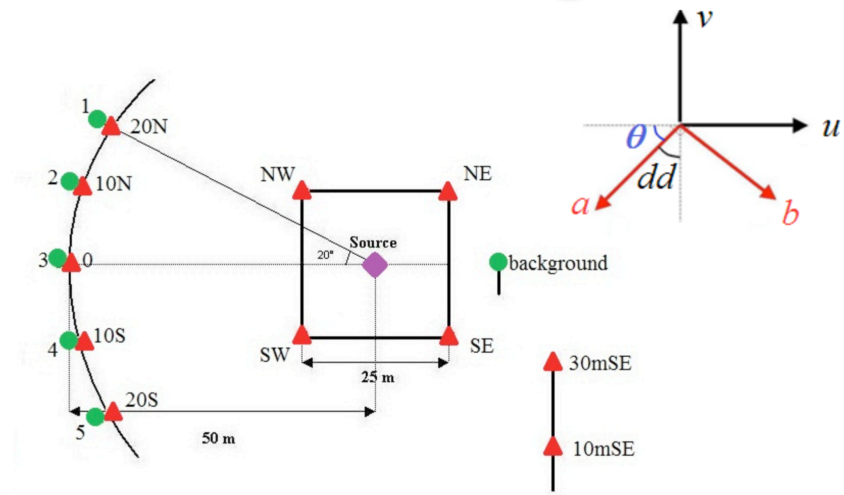
	NE	NW	SE	SW	20N	20S	10mSW	30mSE
L_{aa} (m)	14.82	13.13	14.86	16.69	19.62	14.28	33.31	91.95
L_{bb} (m)	5.67	6.42	11.11	12.47	7.68	12.27	11.51	24.76
L_{ww} (m)	1.83	2.00	1.96	2.02	2.07	2.35	5.96	8.84

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

Turbulence study for measurements during IOP: velocity cross-correlation



Spatial cross-correlation of anemometers (NE,NW) and (SE,SW) as a function of a normalized time lag



- **Normalized time lag :**

$$\tau_{norm} = \frac{\tau}{t_{th}} \quad \text{with} \quad t_{th} = \frac{dx_{eff}}{U} = \frac{dx\cos(\theta)}{U}$$

- **Cross-correlation peaks reaching up to 0.5 for streamwise component**
- **Peaks on the left of the vertical line at $\tau U/dx\cos\theta=1$**

Turbulence study for measurements during IOP: velocity cross-correlation

- **Eddy advection velocity deduced from cross-correlation**

$$U_{adv} = dx_{eff} / \tau_{\max}$$

- **Ratio of the eddy advection velocity to the mean wind speed at instrument level**

$$r = U_{adv} / U$$

	θ (°)	U (ms^{-1})	$U_{adv\ a}$ (ms^{-1})	$U_{adv\ b}$ (ms^{-1})	$U_{adv\ w}$ (ms^{-1})	r_a	r_b	r_w
(NE, NW)	19.1	0.96	2.53	2.71	-	2.64	2.82	-
(SE, SW)	5.6	1.73	2.82	2.28	2.37	1.63	1.32	1.37

- **Discussion:**
  - U_{adv} much greater than U
  - Similar results found in HATS field program (Horst T.W. *et al.* 2004)
  - Strong vertical velocity gradient in the surface layer near the ground and eddy advection affected by the flow at higher level
  - Taylor's hypothesis not valid during the experiment

T.W. Horst, J. Klessl, and D.H. Lenshow. HATS : Field Observations to Obtain Spatially Filtered Turbulence Fields from Crosswind Arrays of Sonic Anemometers in the Atmospheric Surface Layer. Journal of the Atmospheric Sciences, 61, 2003.

Turbulence study for measurements during IOP: power spectra

- **TKE power spectra**
  - Comparison with Kolmogorov's theory
  - Existence of an inertial subrange
  - Slope between -1 and -5/3
- **Eddy surface layer very close to ground (Drobinski *et al.* 2004) :**
  - Eddies coming from upper layers stretched along wind direction and lose their isotropy
  - Three regions found in velocity spectra (in near-neutral stratification)

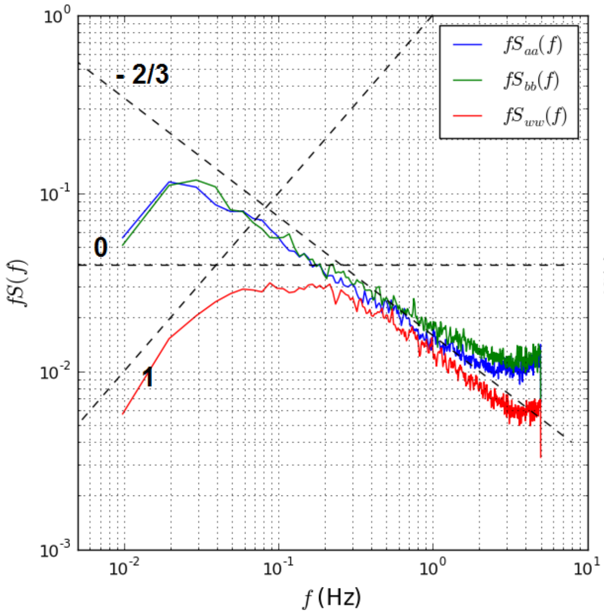
$$\begin{cases} S_{ii}(k) \propto k^{-5/3} & \text{for} \quad k \geq k_u \\ S_{ii}(k) \propto k^{-1} & \text{for} \quad k_u \geq k \geq k_l \\ S_{ii}(k) \propto k^{0} & \text{for} \quad k_l \geq k \end{cases} \qquad i = (a, b)$$

$$\begin{cases} S_{ww}(k) \propto k^{-5/3} & \text{for} \quad k \geq k_u \\ S_{ww}(k) \propto k^{0} & \text{for} \quad k_l \geq k \end{cases}$$

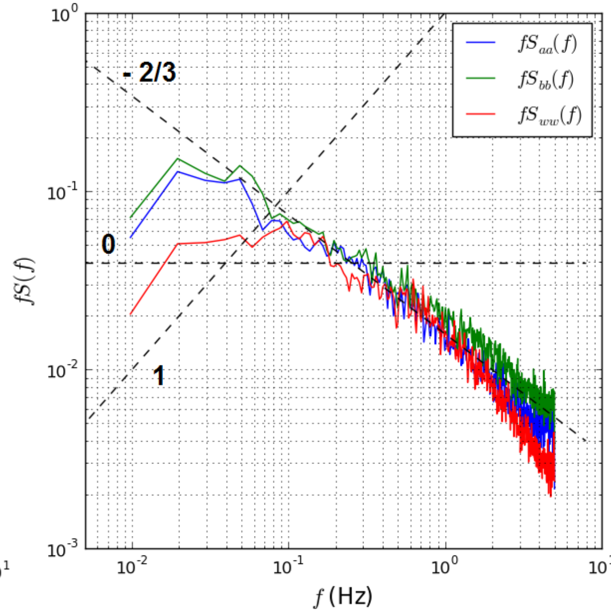
Drobinski, P., P. Carlotti, R.K. Newsom, R.M. Banta, R.C. Foster, J. Redelsperger, 2004: The Structure of the Near-Neutral Atmospheric Surface Layer. *J. Atmos. Sci.*, **61**, 699–714.

Turbulence study for measurements during IOP: power spectra

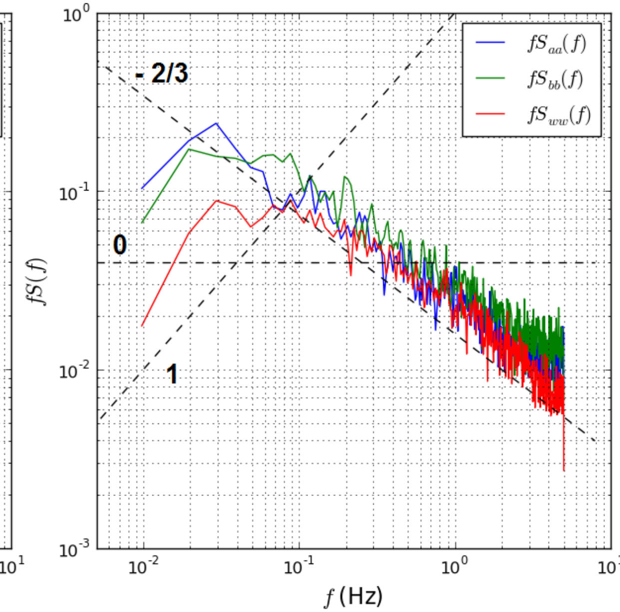
3m



10m



30m



- **Discussion:**
  - Average spectra of anemometers at the same level
  - Different spectrum form between vertical and horizontal velocity components
  - Vertical velocity spectrum increasingly closed to the others with increasing heights → less anisotropic turbulence at higher level
  - Some evidence of k^{-1} subrange found in spectra (slope 0 in figures)

Contents

- SIRTA experimental program
- Impact of terrain heterogeneity
- Turbulence study for measurements during IOP
- Conclusion and perspective

Conclusion and perspective

Conclusion for turbulence study

- Heterogeneity: impact of the forest on wind direction and velocity
- Characterization of the turbulence by integral length scale showing strong anisotropy: $L_{aa} > L_{bb} >> L_{ww}$
- Spatial velocity cross-correlation: $U_{adv} > U$
- Velocity spectra: evidence of -1 power law at intermediate frequency subrange

Perspective:

- Turbulence data analysis for continues measurements over 2 years → turbulence characteristics varied with stability condition
- Relationships between turbulence and concentration fluctuations
- Additional PIDs allowing to extend the instrumental set-up
- Numerical simulations with the open source CFD code Code_Saturne co-developed at CEREA using different turbulence models (k-ε, R_{ij}-ε)

<u>THANK YOU FOR YOUR ATTENTION</u>

Email : xiao.wei@edf.fr

21 BLT, 9-13 June 2014, Leeds, UK