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JULY 8-18 JUILLET 2019 | MONTRÉAL, CANADA

27th/e IUGG General Assembly

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Theoretical and experimental methods for benchmarking turbulent multiphase models of dilute pyroclastic density currents.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823844

Motivation & Outline

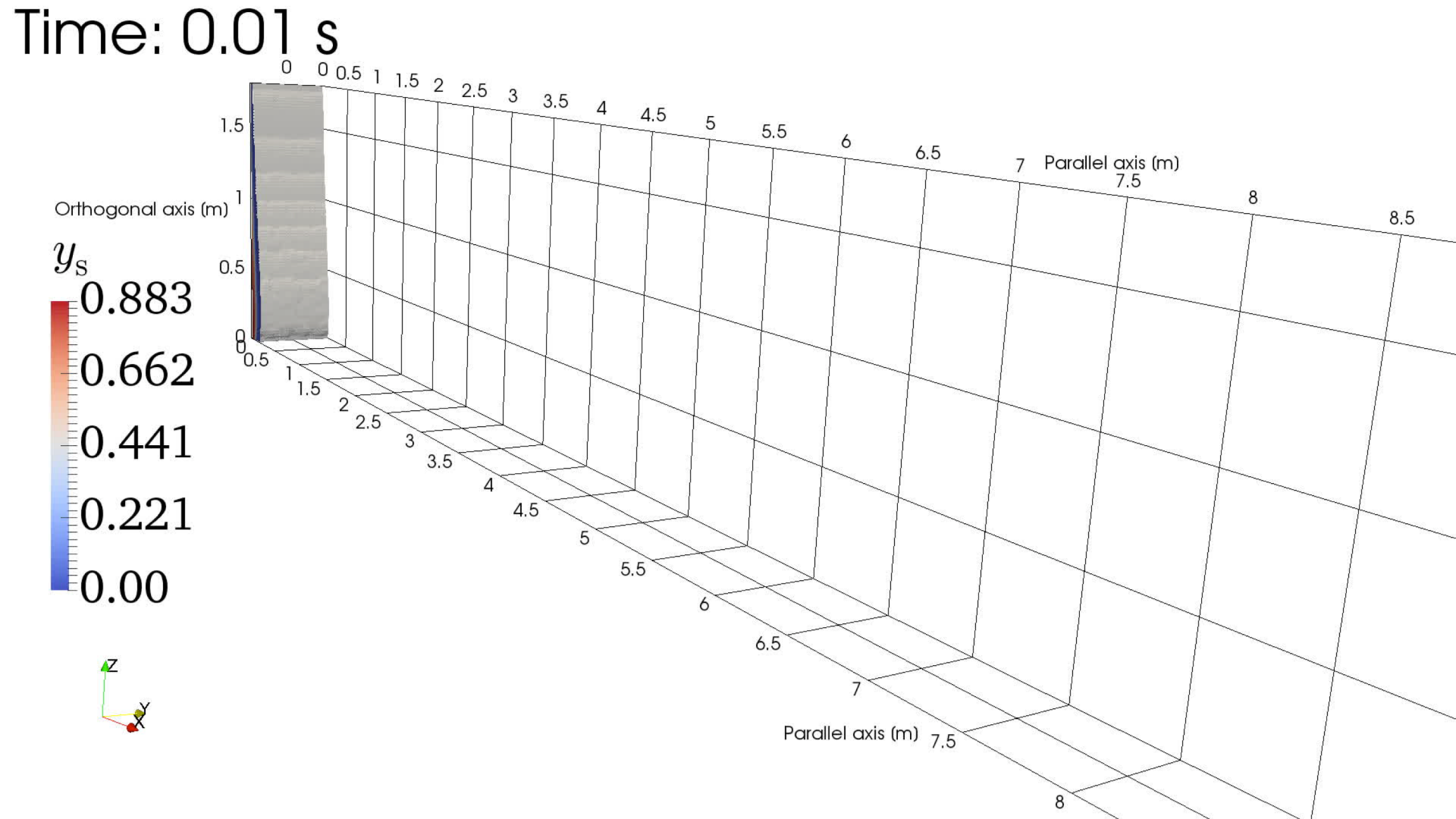
- Definition of a *benchmark* for the study of multiphase gravity currents based on large-scale experiments and numerical models

The experiment

- PELE
- Massey Uni, New Zealand
- 17 m long channel
- Dry and hot ash from Taupo
- Up to 3 tons of material

The numerical model

- ASHEE
- INGV Pisa, Italy
- Eulerian solver for dispersed multiphase turbulence
- Tested both at laboratory and volcanic scale

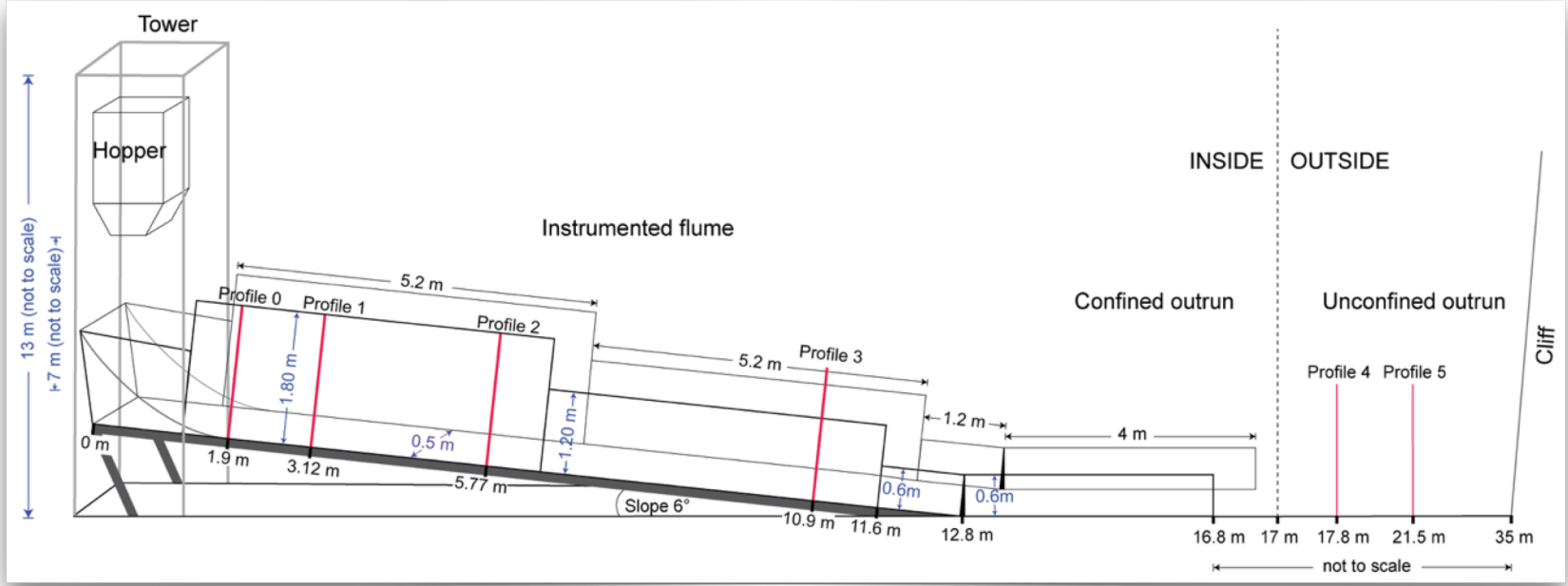

Time: 0.01 s
Orthogonal axis (m)
Parallel axis (m)
Parallel axis (m)
y_S
0.883
0.662
0.441
0.221
0.00
Z
Y
X

1

Benchmark definition

- Experimental data analysis
- Boundary and initial conditions
- Post-processing and data comparison

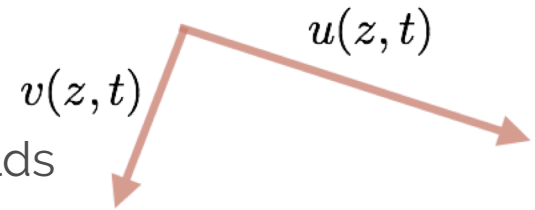
The experiment



Profile 1 will be considered as the inlet condition.
Data will be compared at profile 2 and 3.

The data provided by the experiment

At each profile location, after interpolation:



- PIV: parallel and orthogonal mixture velocity fields
- thermocouples: temperature field of the mixture $T(z,t)$
- concentration and mass fraction of the solid phase $\epsilon_s(z,t)\,, \quad y_s(z,t)$
- grain-size distribution of all the J={1,…, 24} particle classes $y_j(z,t)/y_s(z,t)\,, \quad j \in \mathcal{J}$

Equilibrium assumption at the inlet

Because PIV analysis and thermocouples do not yet allow us to measure the velocity and temperature of each individual particle class, we assume thermal and kinematic equilibrium between gas and particles at the inlet. Specifically, we assume:

- kinematic equilibrium: $u_j = u_\mathrm{g} = u$, $v_j = v_\mathrm{g} = v$
- thermal equilibrium: $T_j = T_\mathrm{g} = T$
- we disregard particle settling velocity with respect to parallel velocity: $|u| \gg |v| \simeq 0$

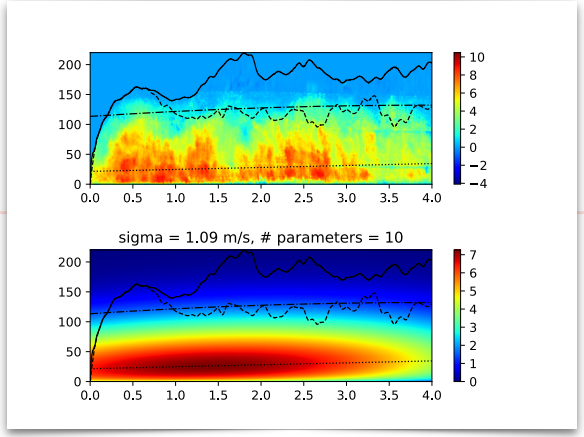
This reduces the number of fields to be input at the inlet.

2

Inlet boundary conditions

- Mean velocity profile (slow temporal fluctuations)
- Velocity fluctuations (turbulence)
- Mean temperature and ash mass fraction profiles
- Grain size distribution

Mean velocity profile



Two regions can be identified in the dilute part of the flow

- the inner region, wall boundary layer: **power law**
- the outer region, free-surface turbulent layer: **semi-gaussian law**

Combining the two and requesting not just continuity but also differentiability:

$$\bar{u}(z,t) = u_{\mathrm{pg}}(z,t) = u_{\mathrm{pg}}(\eta) = U\eta^{\xi}\exp\left[-\left(\frac{\eta-1}{\chi}\right)^2 - \xi(\eta-1)\right]$$

- where **η** is the height normalized with the height of maximum velocity

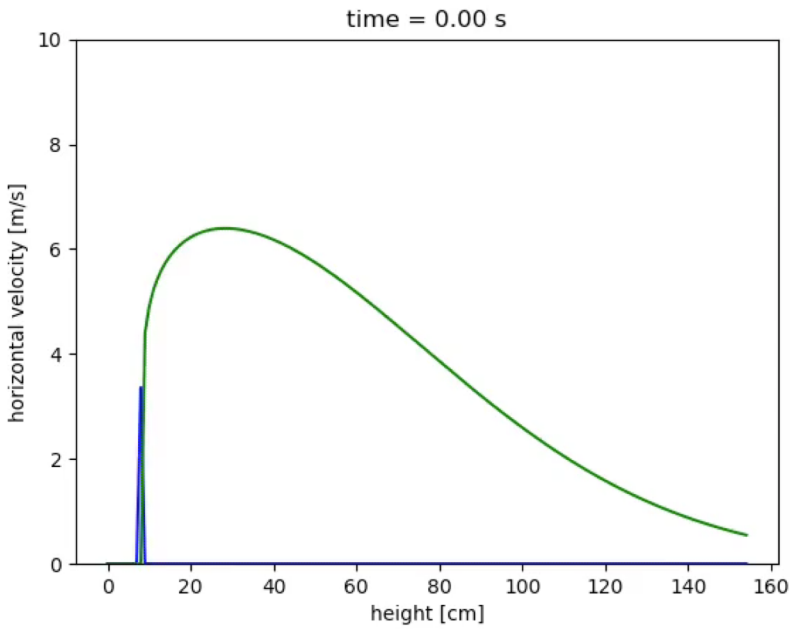
There are 4 parameters defining the profile, each of them function of time:

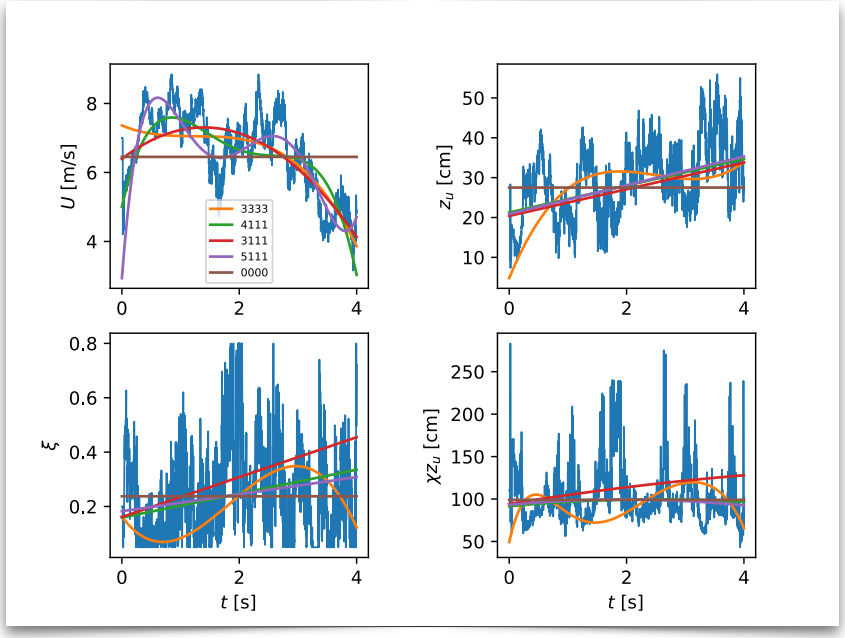
$$U(t)\,, \quad z_u(t)\,, \quad \xi(t)\,, \quad \chi(t)$$

A slow varying function in time should be chosen able to follow the source unsteadiness. We choose polynomials and we compare the result with the fit done without any temporal correlation.

$$\bar{u}(z,t) = u_{\mathrm{pg}}(z,t) = u_{\mathrm{pg}}(\eta) = U\eta^{\xi}\exp\left[-\left(\frac{\eta-1}{\chi}\right)^2 - \xi(\eta-1)\right]$$

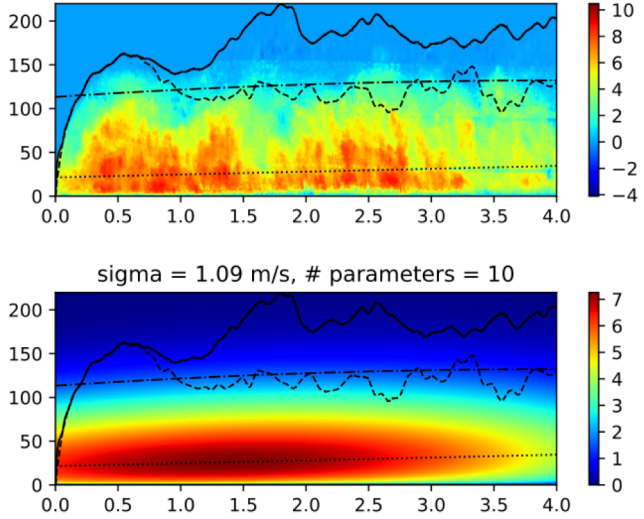
Mean velocity profile





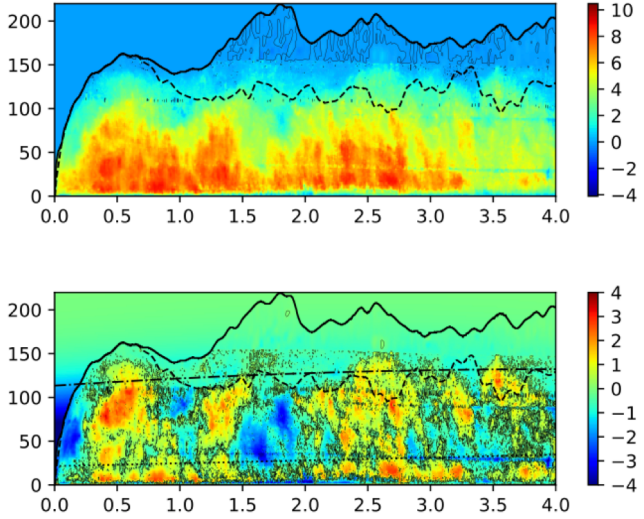
Mean velocity contour plots

Raw data and **mean** parallel velocity



Time [s] vs height [cm] at Profile 1

Raw data and **fluctuations** of velocity

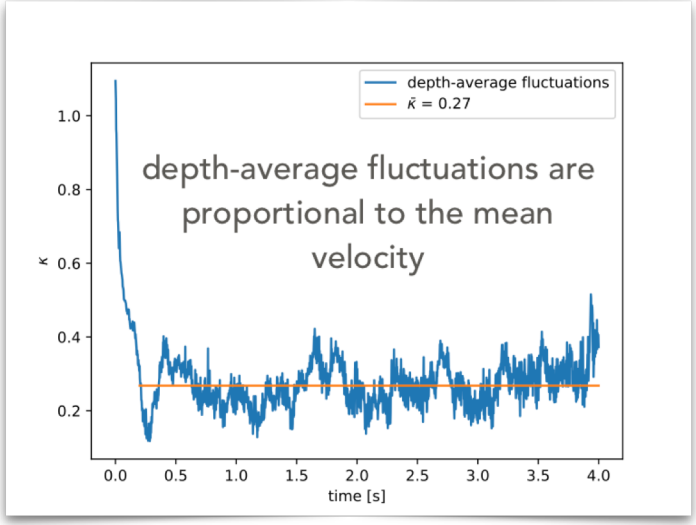


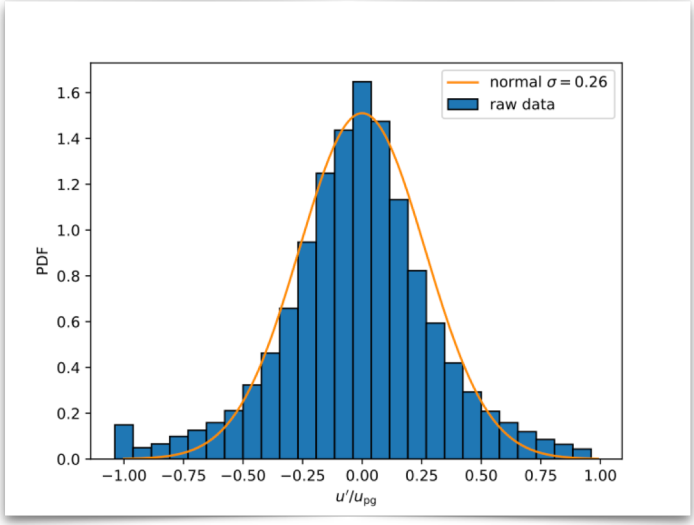
Time [s] vs height [cm] at Profile 1

Velocity fluctuations: distribution

$$u(z,t) = \bar{u}(z,t) + u'(z,t) \qquad \kappa(t) = \frac{\sqrt{\langle (u - u_{\mathrm{pg}})^2 \rangle}}{\langle u_{\mathrm{pg}} \rangle}$$

fluctuations are normally distributed

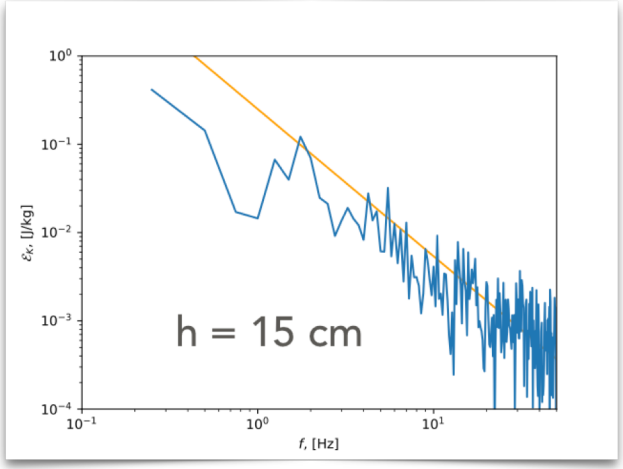


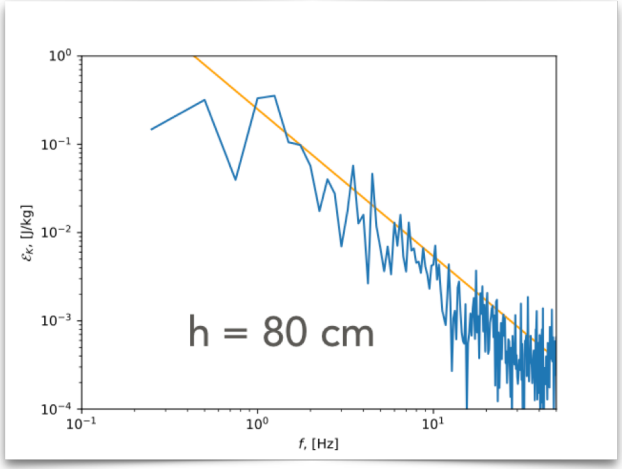


Velocity fluctuations: spectrum

$$E_k \propto f^{-5/3}$$

Fluctuations are normally distributed but they are not white noise.
They are due to **turbulence** and follow the classical Kolmogorov turbulence cascade.
However, for simplicity, we propose to use white noise fluctuations at Profile 1.

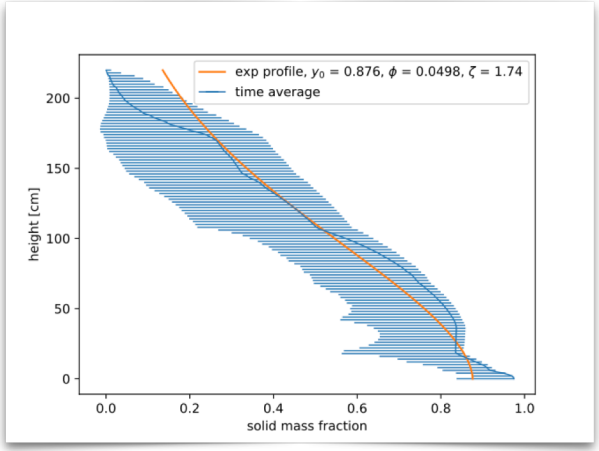




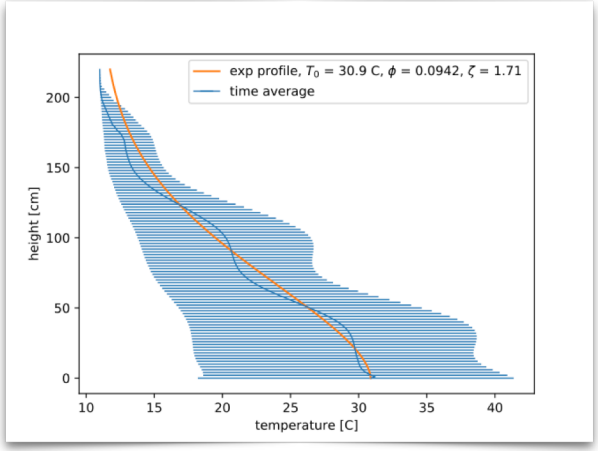
Solid mass fraction and temperature profiles

We simplify both the temperature and mass fraction profiles by neglecting their temporal variability, and give only their time-average profile.
We used the same profiles proposed by Cantero-Chinchilla et al. 2015:

$$y_s(\eta) = y_0 \exp\left(-\phi\eta^\zeta\right)$$

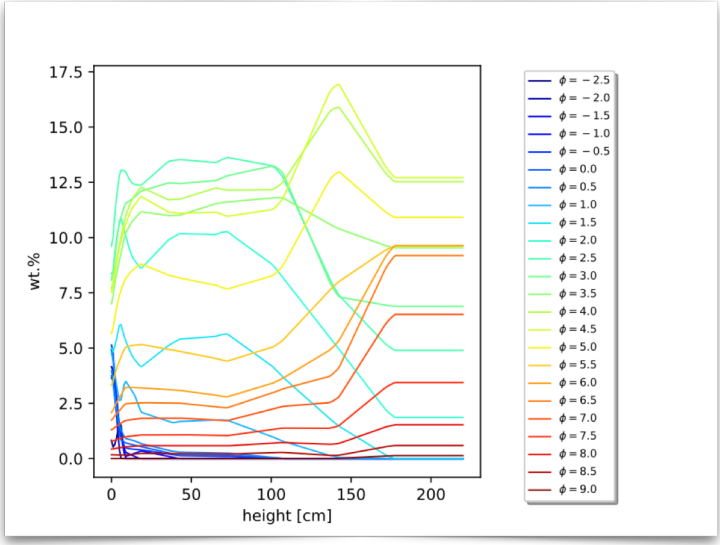


$$T(\eta) = (T_0 - T_a)\exp\left(-\phi\eta^\zeta\right) + T_a$$

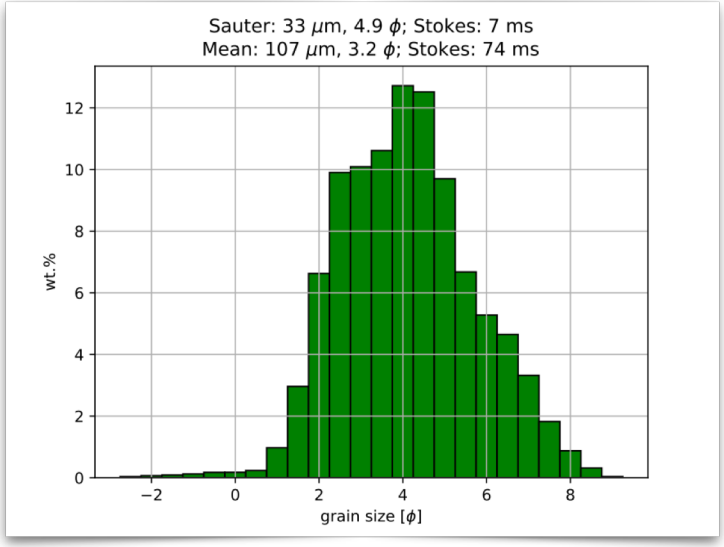


Grain size distribution

Depth average:



Steady, depth average:



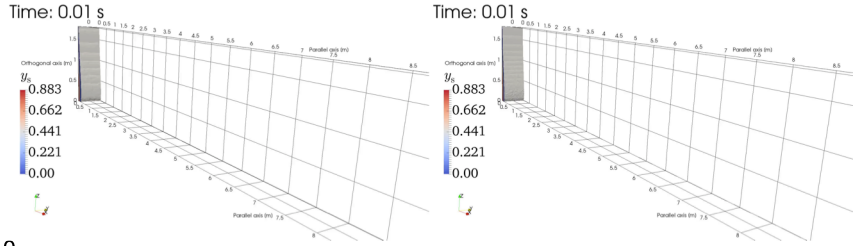
3

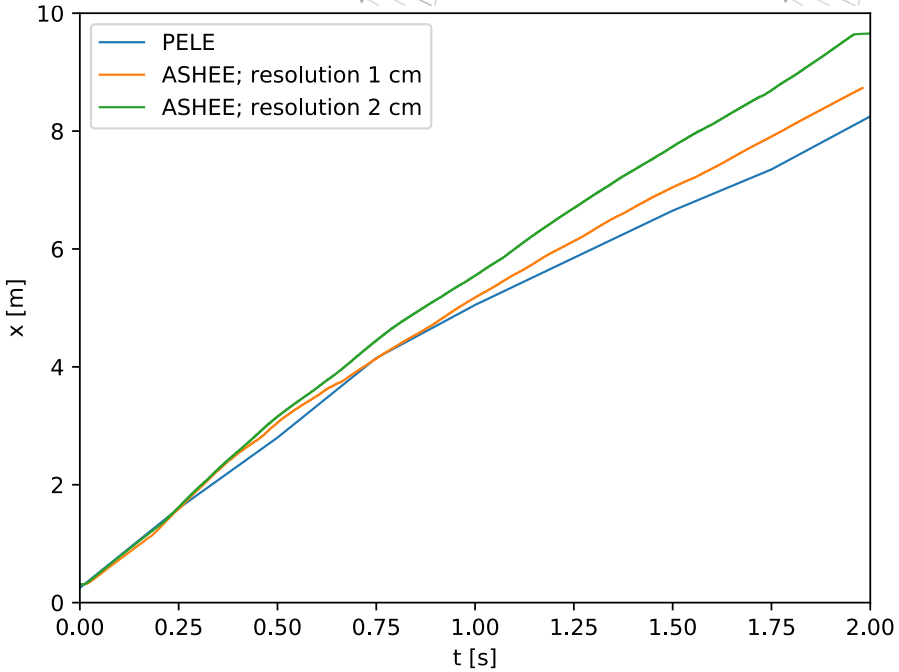
Comparison with ASHEE

- Code features at a glance
- Flow front and deposit characteristics
- Velocity profiles (mean and fluctuations)

ASHEE features at a glance

- **CFD**: 3D Eulerian-Lagrangian plume model for gas-particle two-way coupled turbulent, compressible mixtures
- **Multiphase**: efficient up to ca. 15 gas/ash Eulerian species, Lagrangian approach for lapilli and bombs
- **Decoupling**: Particle settling and clustering
- **Turbulence**: dynamic LES Turbulence model: no empirical parameters for entrainment and mixing
- **Deposit**: one-way from the current to the deposit
- **Boundary layer**: Spalding law with roughness





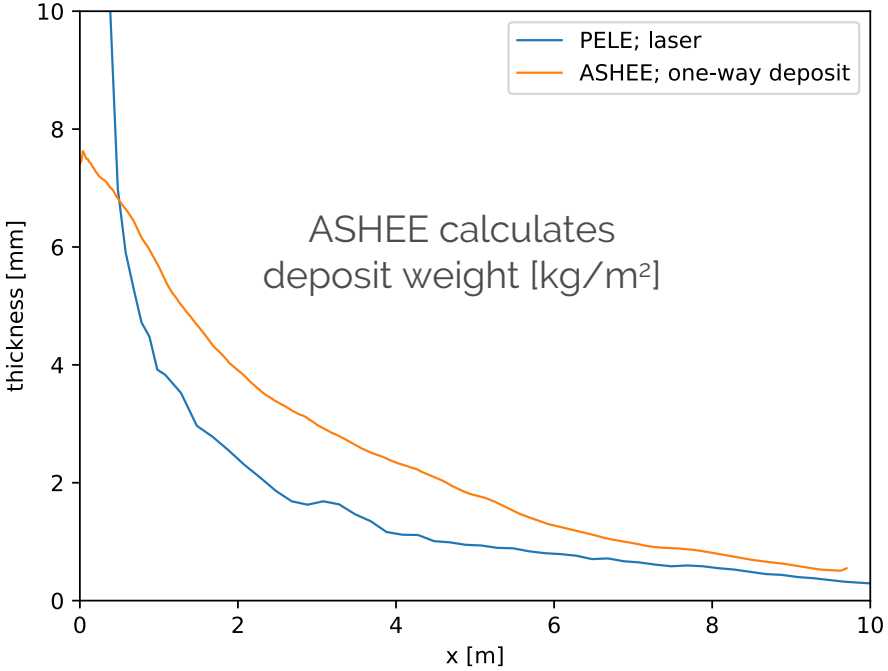
Flow front

The simulated current is slightly faster than the experiment.

This may be due to two reasons:

- Part of the current is exiting the top of the PELE channel
- Numerical issues
  - Resolution
  - Bottom wall boundary condition

Deposit weight/thickness conversion with mean deposit density 1950 kg/m^3



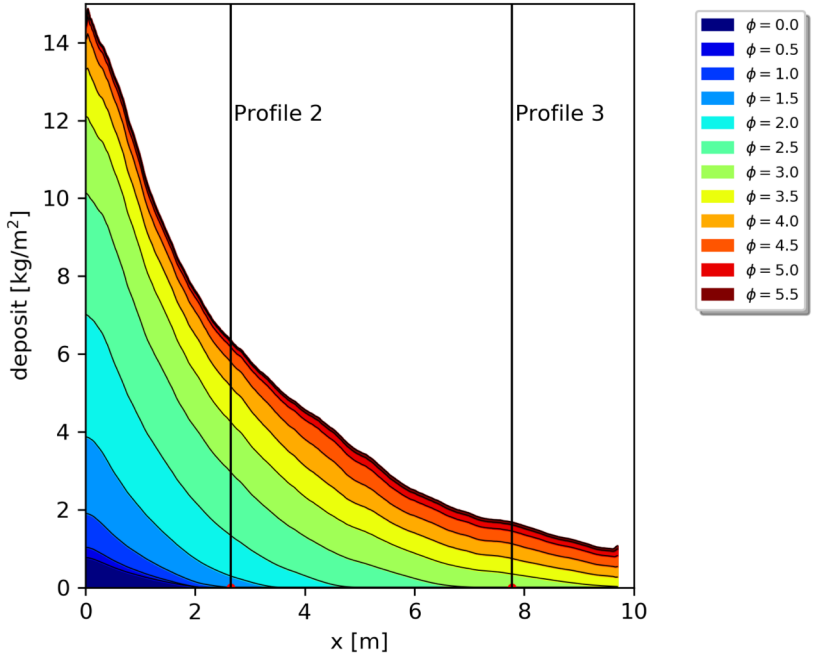
Deposit thickness

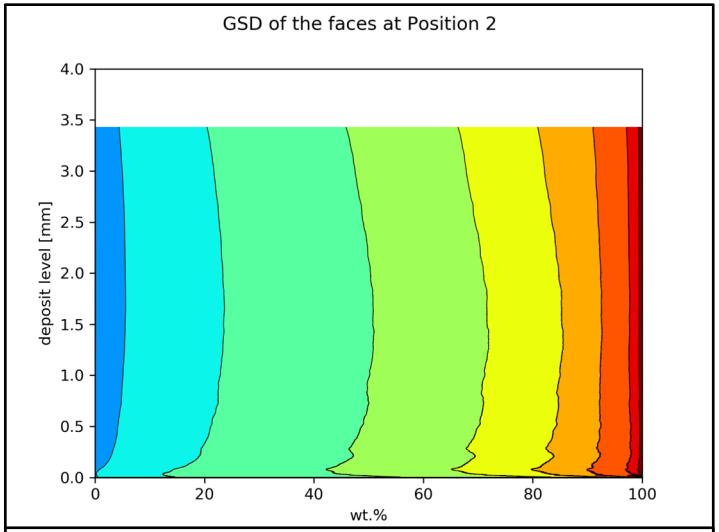
The deposit is underestimated in the proximal region and overestimated in the distal region.

This may be due to two reasons:

- The density of the deposit is not constant with distance
- Numerical issues
  - Particle decoupling model
  - Deposition, resuspension?
  - Initial settling velocity = 0

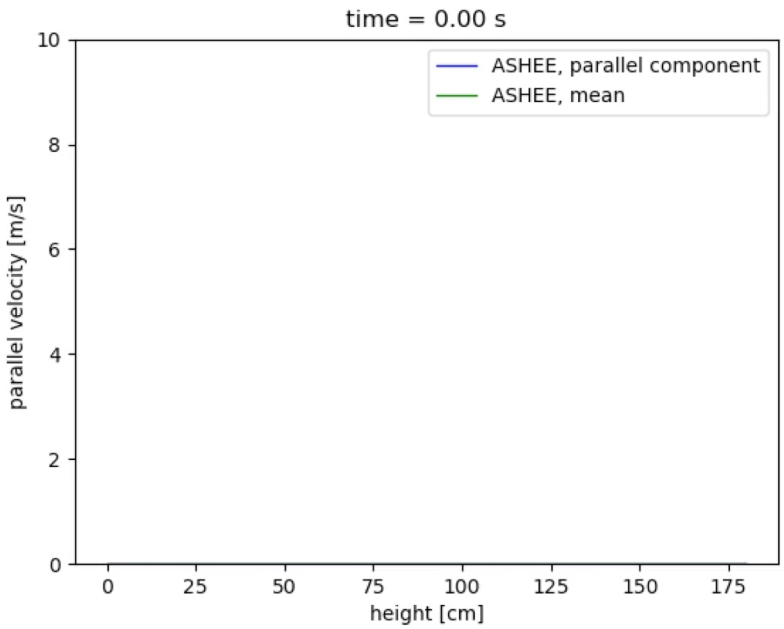
Grain Size Distribution along the channel and of the faces at Position 1 & 2



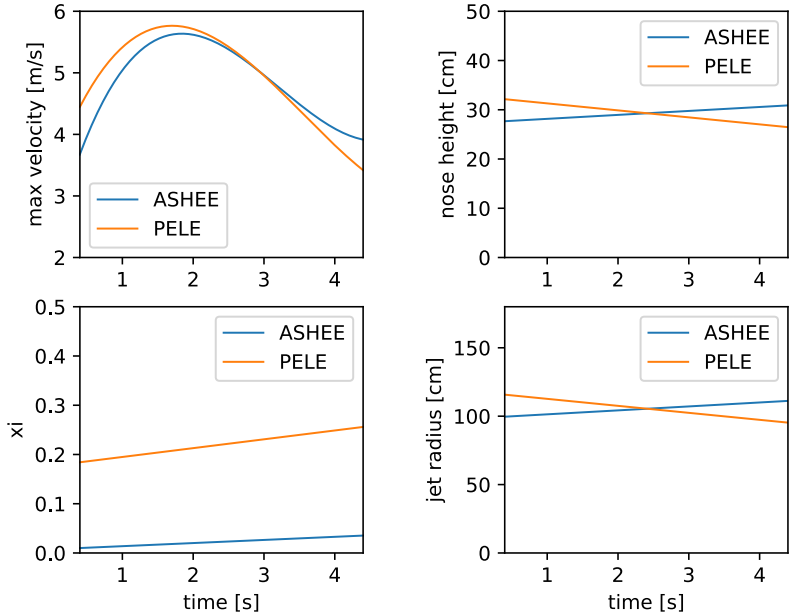


$$\bar{u}(z,t) = u_{\mathrm{pg}}(z,t) = u_{\mathrm{pg}}(\eta) = U\eta^{\xi} \exp\left[-\left(\frac{\eta-1}{\chi}\right)^2 - \xi(\eta-1)\right]$$

Mean velocity: profile 2

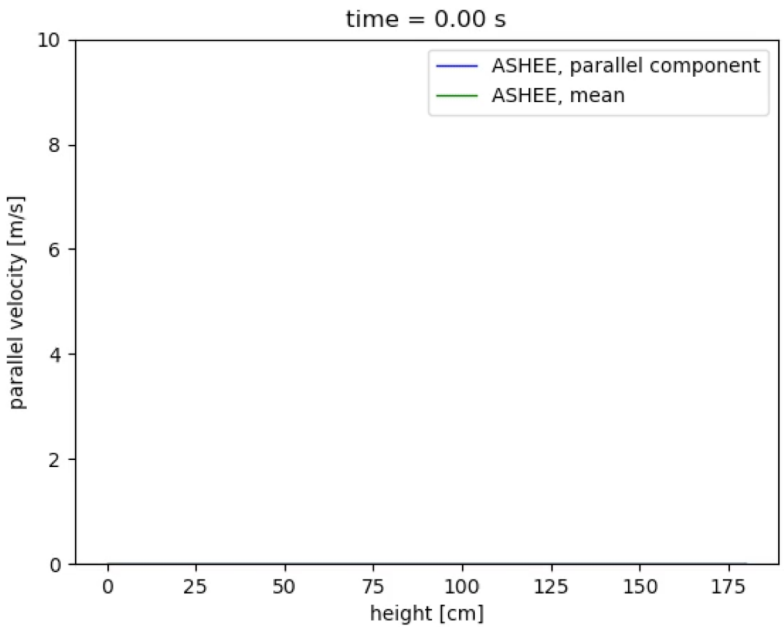


$\sigma_{\mathrm{ASHEE(PELE)}} = 0.723\,(0.971)$ m/s, $R^2_{\mathrm{ASHEE(PELE)}} = 0.839\,(0.53)$

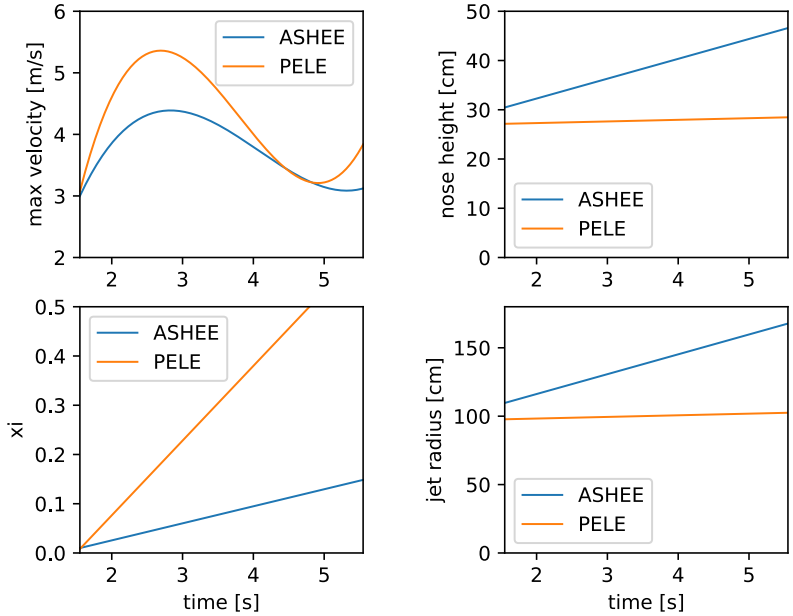


$$\bar{u}(z,t) = u_{\mathrm{pg}}(z,t) = u_{\mathrm{pg}}(\eta) = U\eta^{\xi}\exp\left[-\left(\frac{\eta-1}{\chi}\right)^2 - \xi(\eta-1)\right]$$

Mean velocity: profile 3

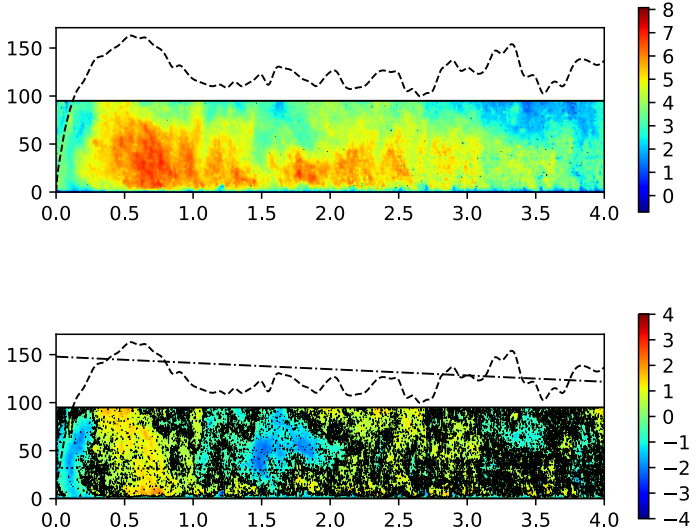


$\sigma_{\mathrm{ASHEE(PELE)}} = 0.855\,(0.874)$ m/s, $R^2_{\mathrm{ASHEE(PELE)}} = 0.583\,(0.573)$



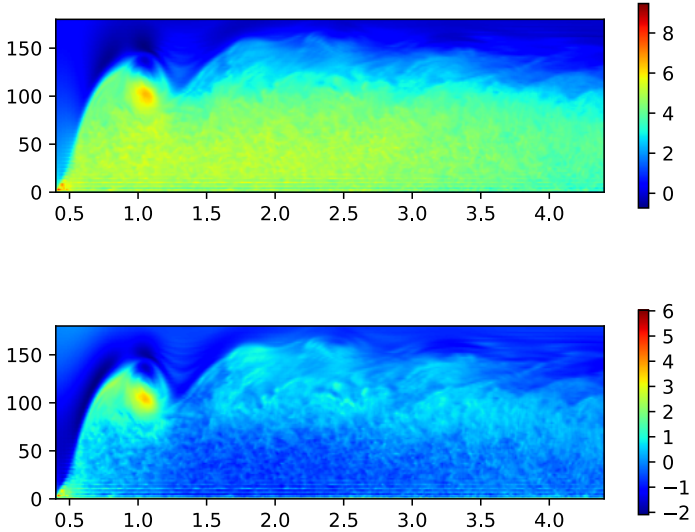
Velocity contours at profile 2

PELE experiment



Time [s] vs height [cm] at Profile 2

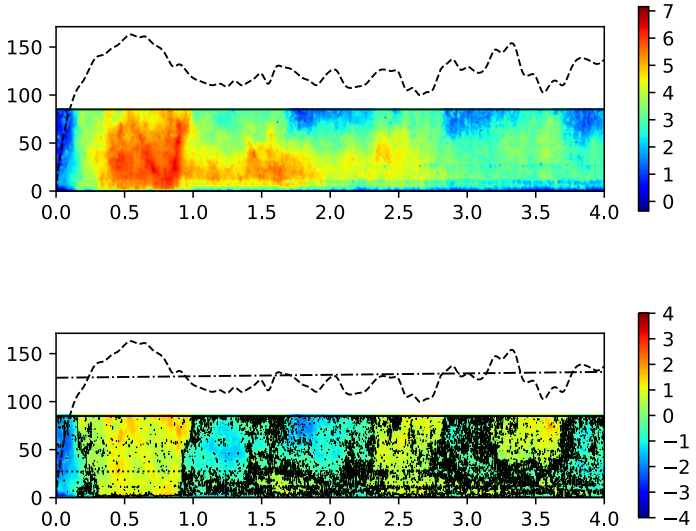
ASHEE simulation



Time [s] vs height [cm] at Profile 2

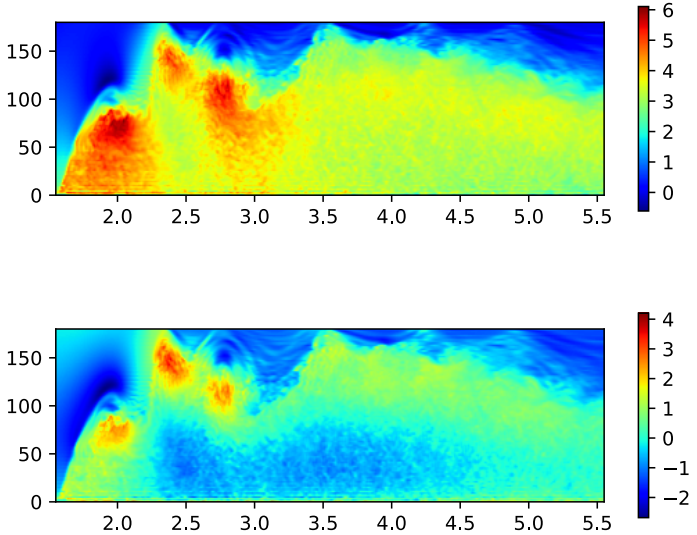
Velocity contours at profile 3

PELE experiment



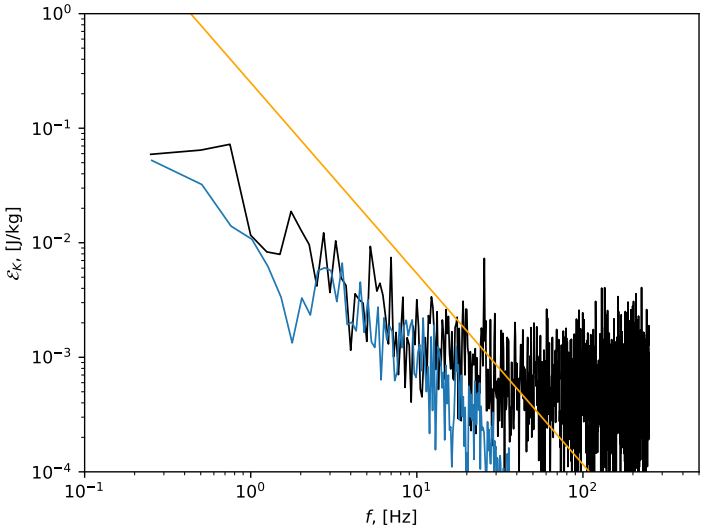
Time [s] vs height [cm] at Profile 3

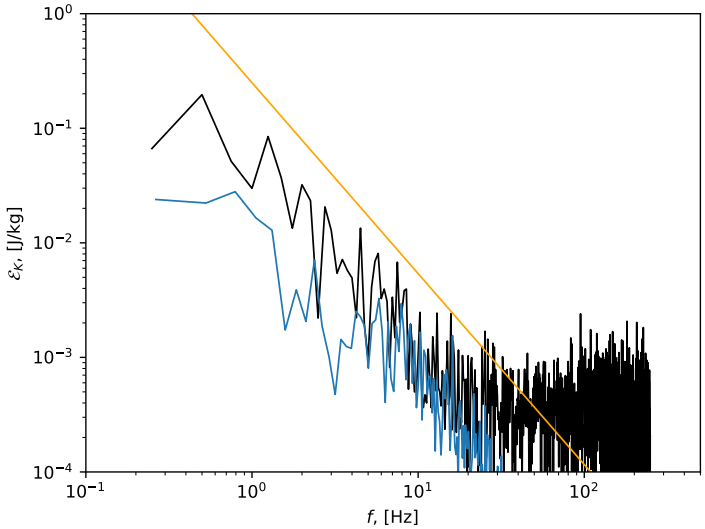
ASHEE simulation



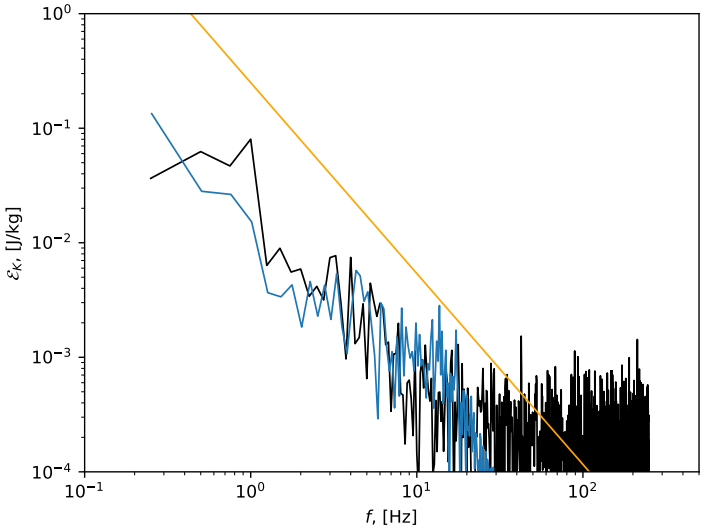
Time [s] vs height [cm] at Profile 3

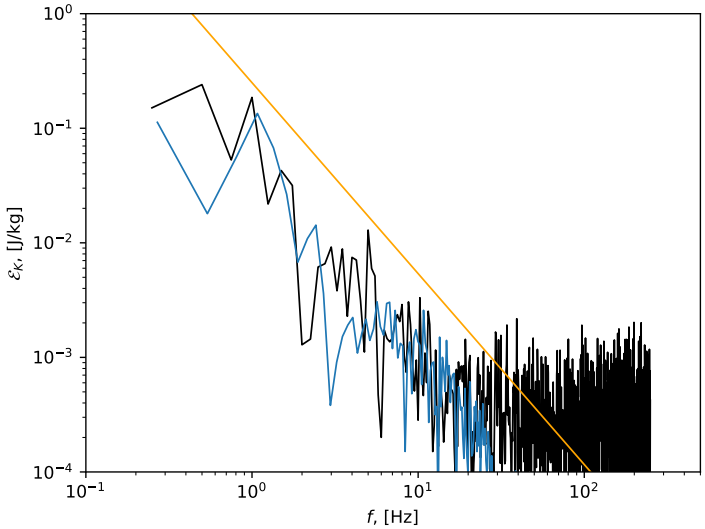
Velocity fluctuations: spectrum at profile 2





Velocity fluctuations: spectrum at profile 3





Conclusions

- **Data analysis**: theoretical fitting of the raw data enables deeper interpretation and comparison between laboratory and numerical experiments
- **Statistics**: not just mean properties but also fluctuations investigated
- **Flow front & deposit**: satisfactory preliminary results. Decoupling and wall boundary condition are crucial.
- **Turbulence**: mean values and turbulent spectra are satisfactorily reproduced. Large-eddy fluctuations need a deeper analysis.
- **Methodology**: a benchmarking example for model *validation* based on large-scale PDC experiment has been proposed to the community.
- We are preparing an international benchmarking study for PDCs.
  Special issue hosted by *Bulletin of Volcanology*.
- Related presentations are at IUGG 2019, e.g. Brosch et al. & Breard et al.

Thanks!

Any questions ?

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 823844