

Concentration fluctuations and risk estimation on industrial sites

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Context and methods

Risks linked to industrial activities

Knowledge on both the mean field and fluctuations of concentration is necessary to estimate risks linked to pollutant exposure on industrial sites. While time-averaged concentrations provide meaningful information for chronic risk exposure, local exceedance of high concentration values potentially trigger chemical reactions or exceed harmful limits for living organisms. Information on temporal variations of the one-point concentration signal and peak to mean ratios is thus a key parameter for toxicity assessment and accident management, hence the focus of this work on concentration fluctuations.

While the latter are better understood in academic configurations, there is a lack of knowledge on the effect of obstacles and geometrical elements on the statistical distribution followed by the concentration signal. Hence, we focus on the effect of the site geometry on the dispersion of a passive scalar emitted by a continuous localised source.

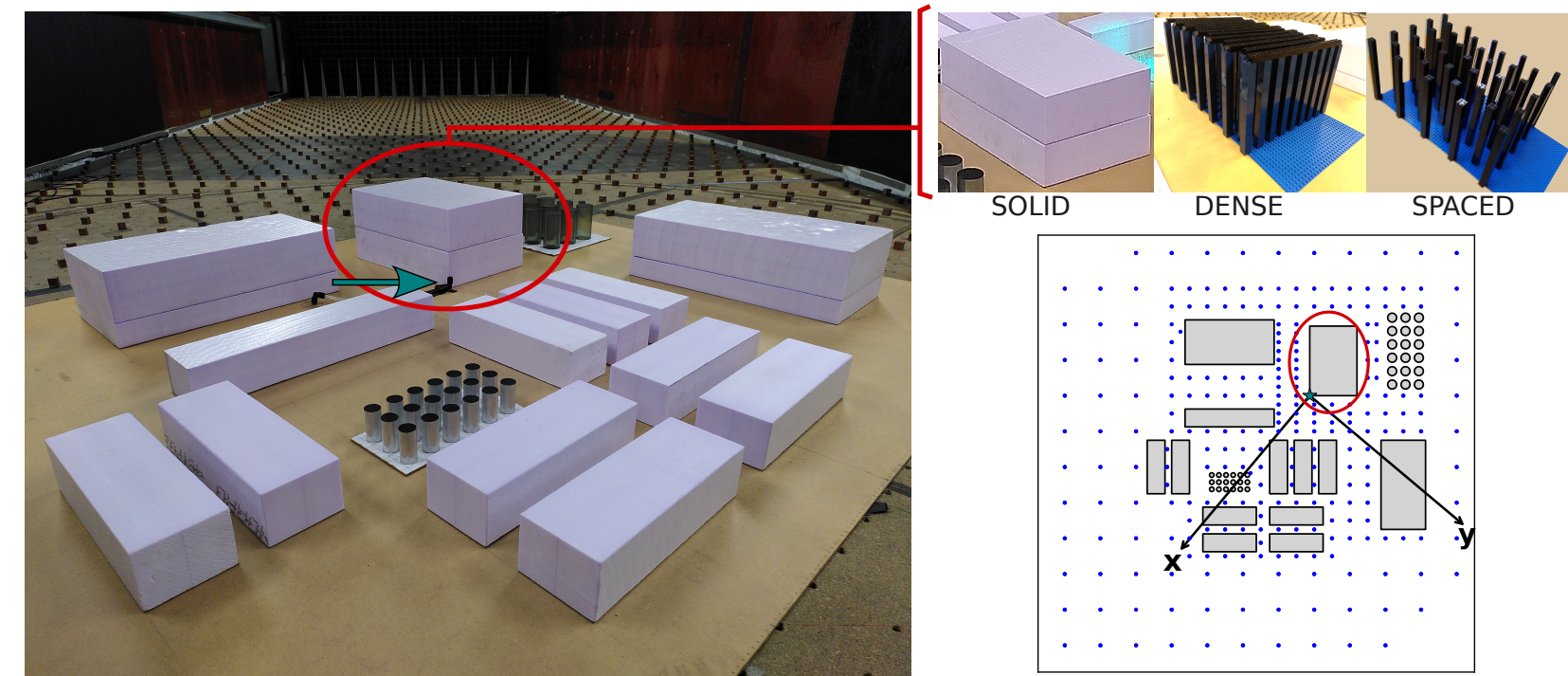


Figure 1: Idealised industrial site inside the wind tunnel that reproduces the atmospheric boundary layer (thanks to a grid, Irwin spires and roughness elements). Effect of porosity is studied by replacing the circled building by column versions.

Site definition:

We defined an idealised industrial site that contains typical elements such as tanks in a basin, a porous structure, buildings of various sizes and shapes... However, the geometry was kept simple enough to maintain a general description and avoid site specificity. The boundary layer was already described by [2].

Wind tunnel measurements

We built a small-scale model of the idealised industrial site and placed it in the wind tunnel within a neutral incident boundary layer of 80cm with a top velocity of 5 m s^{-1} . A source of ethane is placed at the corner of the tallest building (which is replaced by porous versions depending on the configuration).

Point concentration measurements were performed with a fast flame ionisation detector (FFID). We obtain time series of concentration from which statistical moments (mean, variance...) up to the order 4 are computed to characterise the distribution of concentration.

Velocity measurements were performed with a laser Doppler anemometer (LDA). This method provides the velocity magnitude along two directions. We thus performed point measurements on horizontal planes (UV) and on vertical planes (UW).

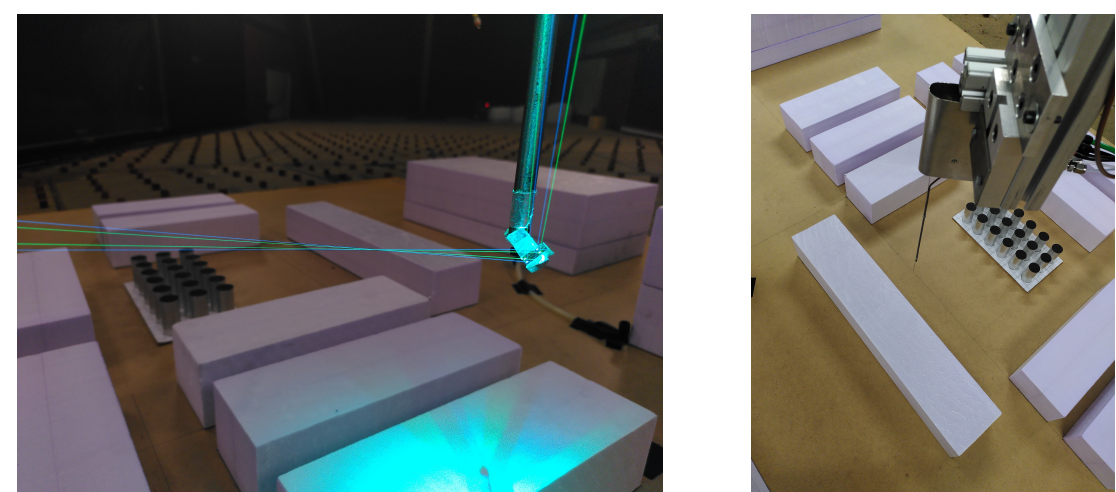


Figure 2: We used a Laser Doppler Anemometer (LDA) for velocity measurements and a fast flame ionisation detector (FFID) for concentration.

Conclusions

High concentration levels are more easily modeled by the tested distributions than the lower range. High percentiles, namely the 95th and 99th, are more accurately predicted than high order statistical moments (skewness and kurtosis). This is due to the complex behaviour of the experimental concentration distribution at lower concentration levels. Such hardly predictable distributions are encountered in locations where geometry strongly impacts the flow and the dispersion.

Velocity fields

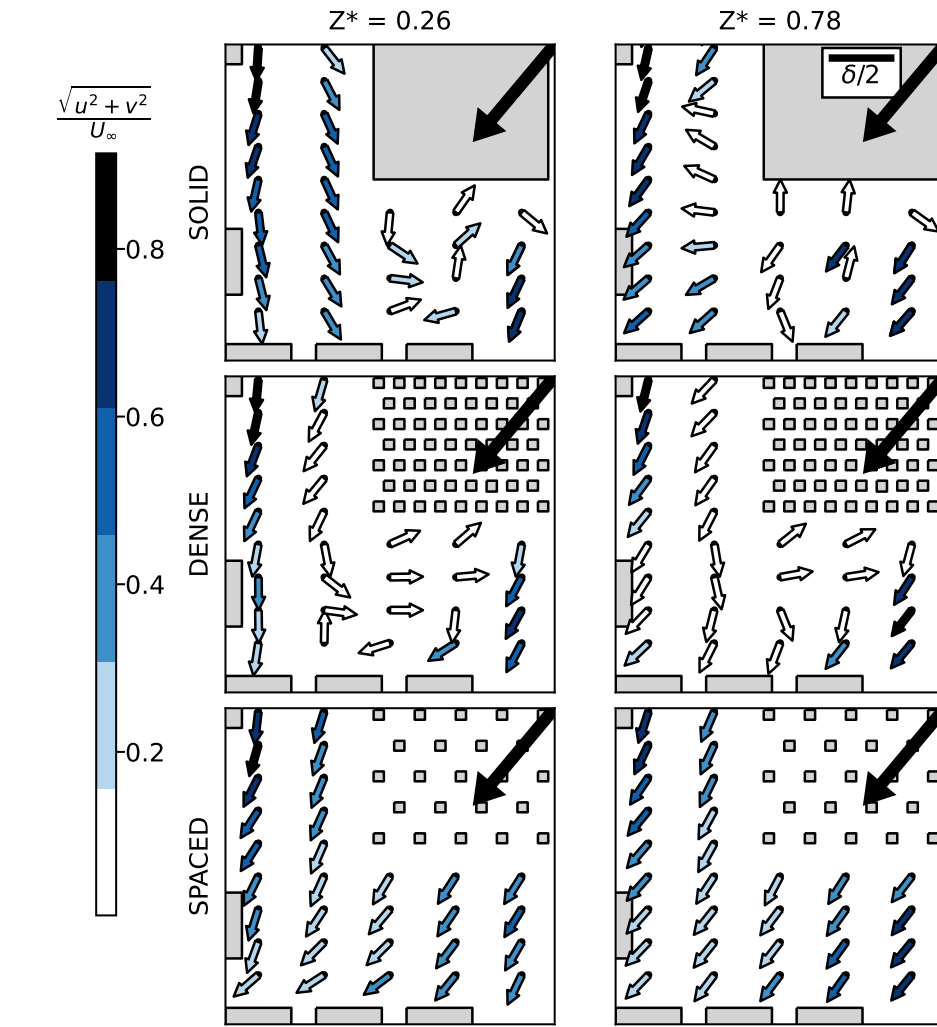


Figure 3: Velocity field on 2 horizontal slices for all configurations. Distances are rendered dimensionless by division by the height of the tallest element δ (which is replaced by the porous versions in the dense and spaced cases).

The main differences between the velocity fields of the different configurations lie in the position and intensity of the wake of the tallest building of the site. Turbulence and mixing capacities are thus affected by the porosity of the main obstacle. The forcing wind direction stays prevailing in the spaced configuration, while mixing is enhanced in the solid and dense cases.

Time-averaged concentration

Pointwise time-averaged concentration is analysed on several horizontal slices on the site. We show here maps of mean concentration at 2 heights and vertical profiles at specific locations indicated by corresponding markers. The figure for fluctuation intensity ($i_C = \sigma_C / \bar{C}$ with σ_C the standard deviation of the temporal concentration signal and $\bar{C}$ the time-averaged dimensionless concentration) follows the same structure. The building porosity mainly impacts the plume shape and extent due to the velocity field that drags the tracer inside the wake of the major obstacle. Mixing is enhanced in the dense configuration and is lowest in the spaced case. In the latter, the effect of columns is low and the plume shape resembles the most to a plume that spreads over a flat terrain.

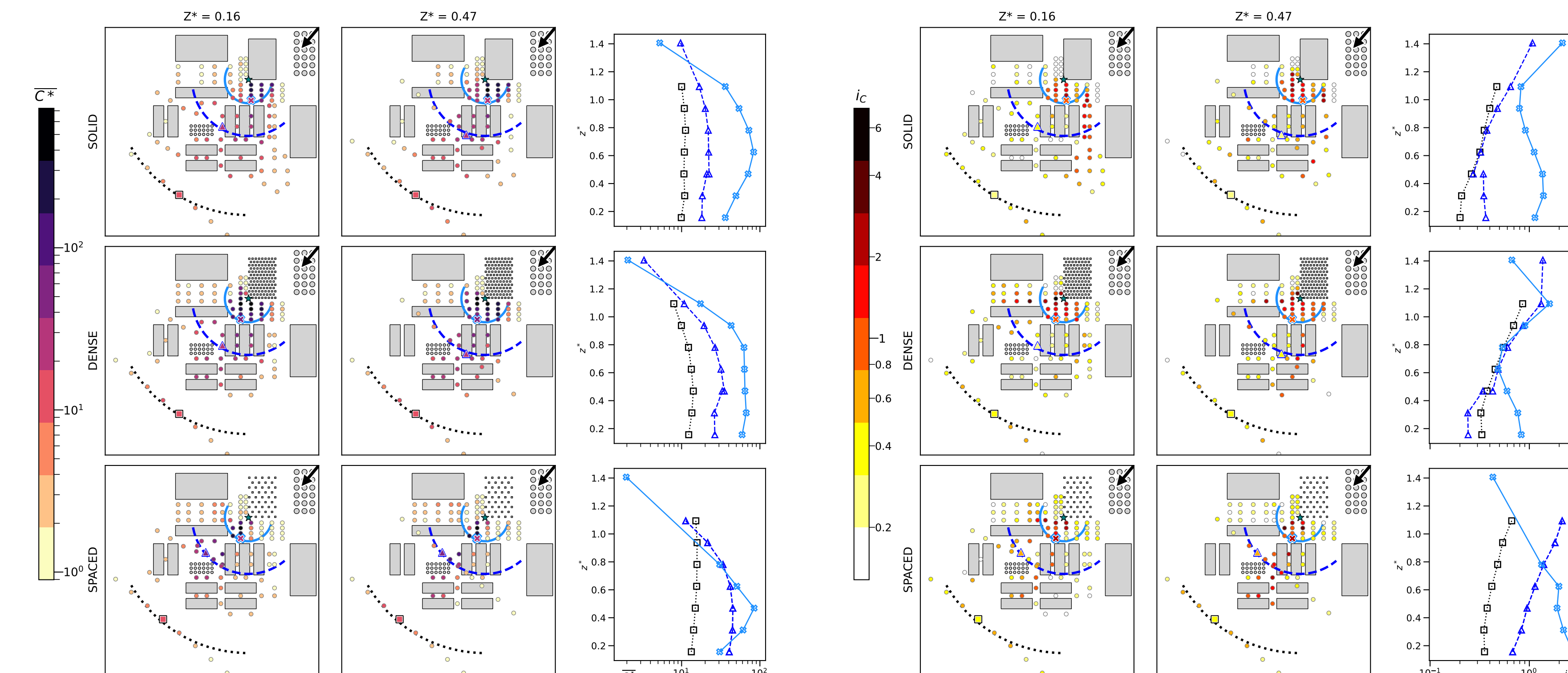


Figure 4: Mean concentration field and fluctuation intensity $i_C = \sigma_C / \bar{C}$ at 2 horizontal slices with vertical profiles at specific locations.

Differences are major in the close and mid fields but diminish in the far field where the main difference still visible lies in the position of the plume centerline.

Model distributions

Several 2-parameter distributions are tested against the experimental distribution of one-point concentration values.

- Gamma distribution

$$PDF_{\Gamma}(c) = \frac{c^{k-1} \exp(-c/\theta)}{\Gamma(k)\theta^k}$$

with $k = \frac{1}{i_C}$ and $\theta = \frac{\bar{C}}{k}$ the shape and scale parameters.

- 2-parameter Weibull distribution

$$PDF_W(c) = \beta \alpha (\beta c)^{\alpha-1} \exp(-(\beta c)^\alpha)$$

with α approximated by $\alpha \simeq (1/i_C)^{1.086}$ the shape parameter, and $\beta = \Gamma(1 + \frac{1}{\alpha}) / \bar{C}$ the scale parameter.

- Lognormal distribution

$$PDF_L(c) = \frac{1}{c\lambda\sqrt{2\pi}} \exp\left(-\frac{(\ln(c - \mu))^2}{2\lambda^2}\right)$$

with $\lambda = \ln(i_C^2 + 1)^{1/2}$ and $\mu = \ln(\bar{C}) - \frac{\lambda^2}{2}$ corresponding to the standard deviation and average of the logarithm of concentration.

Statistical moments and peak to mean ratios

The Kullback Leibler divergence (KL) provides information on the quality of agreement between the tested model distributions and experimental distributions of concentration values. The lower the KL value, the better the fit. The agreement between model and experimental distributions at the lowest measurement layer on the site is reached in the mid and far fields. Complex shapes of distributions obtained in the wake of the main obstacle are more hardly reproduced by model distributions. We found the lognormal, gamma and 2-parameter Weibull models to be the most accurate respectively in the close, mid and far fields.

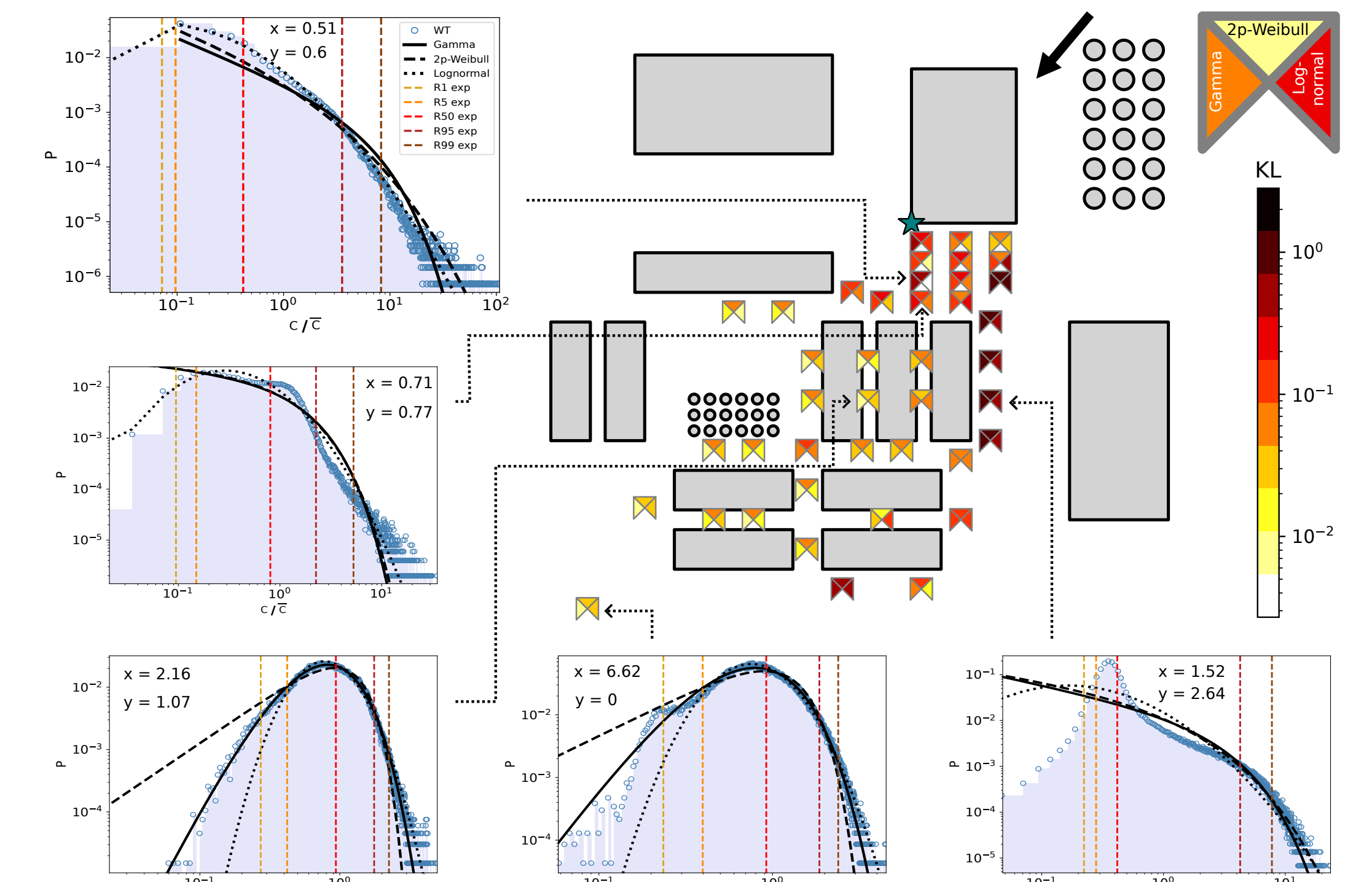


Figure 5: Concentration distribution at specific locations and ratios of 1st, 5th, 50th, 95th and 99th percentiles to the mean concentration.

In locations where geometrical elements have a strong impact, distributions correspond better for high concentration values. This effect translates in a poor agreement between modeled and experimental high order statistics (skewness and kurtosis). On the contrary, peak to mean ratios obtained from the 95th and 99th percentiles of concentration are accurately reproduced by all models.

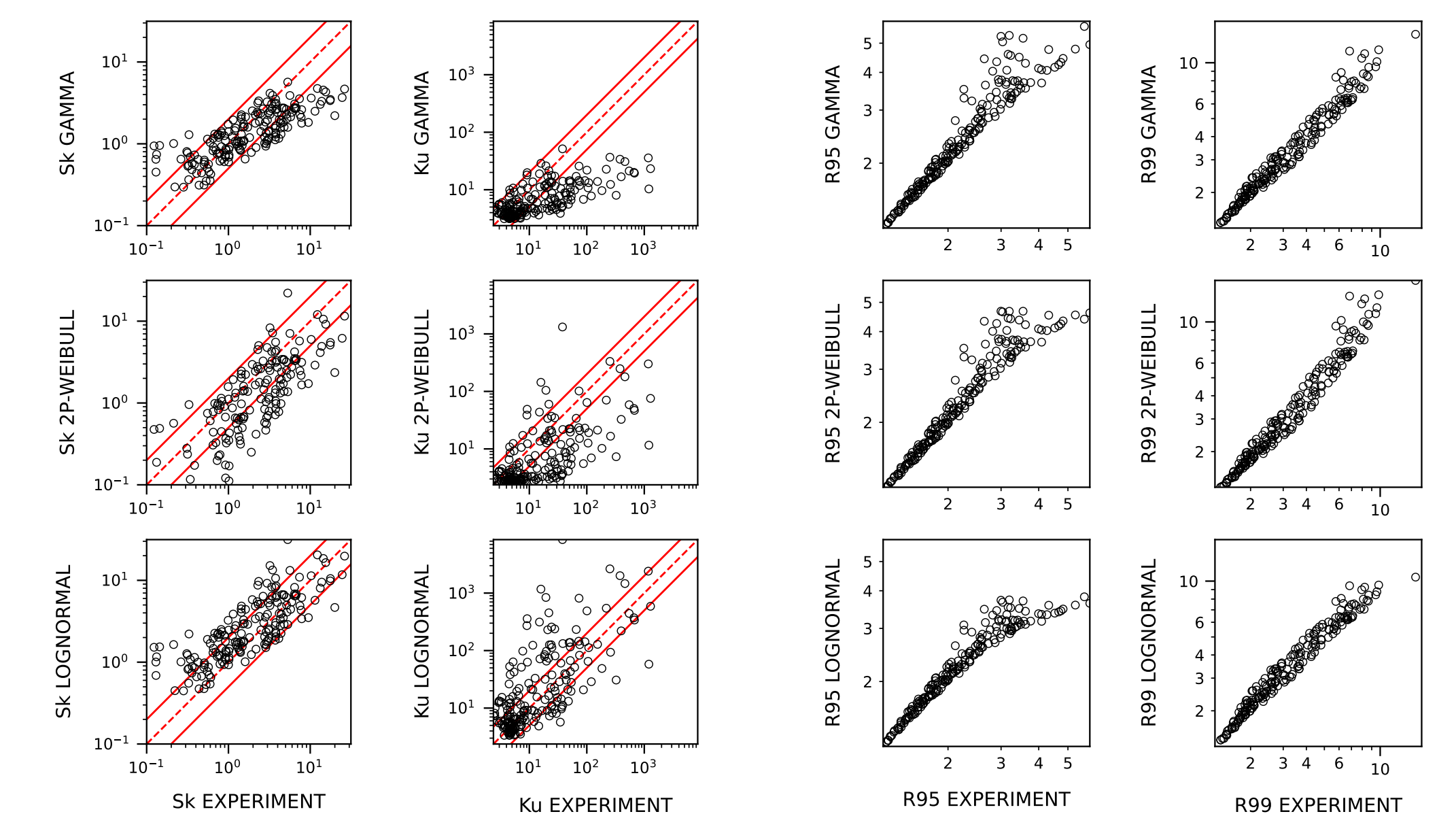


Figure 6: Comparison of modeled and experimental skewness and kurtosis (left) and ratios of 99th and 95th percentiles to the mean (right). Red lines surround values within a factor of 2 of the observations.

References

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