Odour Source Identification in a Complex Flow Environment using a Particle Trajectory Model

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Introduction

- The need has arisen to identify potential odour emission sources from boundary monitoring.
- More often than not, airflow in industrial situations is subject to interference from structures.
- Popular trajectory models used (e.g. HySplit) cannot accurately depict particle motion in complex flow situations.
- In addition, the temporal resolution of the data often used in the trajectory model is too coarse to resolve the flow in these situations.
- A new pseudo 3D model based on the Navier Stokes equations, is presented here.

Navier Stokes Equations

- These are equations which can be used to determine the velocity vector and pressure field that applies to a fluid, given some initial conditions.

- Developed from Newton's second law.

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{\nabla P}{\rho} + \nu \nabla^2 \boldsymbol{u}$$

- The above equation is too difficult to solve analytically.

- Approximations and simplifications to the equation set have been made until they had a group of equations that they could solve using a variety of techniques like finite differencing.

Navier Stokes Equations

- The flows are characterised by a system of non-linear PDEs (in 2D component form):

Momentum equations:

$$\frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} = \frac{1}{R_e}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\partial (u^2)}{\partial x} - \frac{\partial (uv)}{\partial y} + g_x$$

$$\frac{\partial v}{\partial t} + \frac{\partial p}{\partial y} = \frac{1}{R_e}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\partial (uv)}{\partial x} - \frac{\partial (v^2)}{\partial y} + g_y$$

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Numerical Treatment (time stepping)

$$u^{(n+1)} = F^n - \delta t \frac{\partial p^{(n+1)}}{\partial x} \qquad (1a)$$

$$v^{(n+1)} = G^n - \delta t \frac{\partial p^{(n+1)}}{\partial y} \qquad (1b)$$

where

$$F = u^n + \delta t \left[\frac{1}{Re} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\partial (u^2)}{\partial x} - \frac{\partial (uv)}{\partial y} + g_x \right] \qquad (2a)$$

$$G = v^n + \delta t \left[\frac{1}{Re} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{\partial (uv)}{\partial x} - \frac{\partial (v^2)}{\partial y} + g_y \right] \qquad (2b)$$

Discretization

- The derivatives in Eq^n. 2a and 2b are discretised in two dimensions using finite differencing:

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}=\frac{u(x_{i+1,j})-2u(x_{i,j})+u(x_{i-1,j})+u(x_{i,j+1})-2u(x_{i,j})+u(x_{1,j-1})}{\delta y^2}$$

$$\frac{\partial(uv)}{\partial y}=\frac{1}{\delta y}\left(\frac{(v_{i,j}+v_{i+1,j})}{2}\frac{(u_{i,j}+u_{i,j+1})}{2}-\frac{(v_{i,j-1}+v_{i+1,j-1})}{2}\frac{(u_{i,j-1}+u_{i,j})}{2}\right)$$

$$\frac{\partial(u)^2}{\partial x}=\frac{1}{\delta x}\left(\left(\frac{u_{i,j}+u_{i+1,j}}{2}\right)^2-\left(\frac{u_{i-1,j}+u_{i,j}}{2}\right)^2\right)$$

Discretization

- Pressure is determined by solving:

$$\frac{\partial^2 p^{(n+1)}}{\partial x^2} + \frac{\partial^2 p^{(n+1)}}{\partial y^2} = \frac{1}{\delta t}\left(\frac{\partial F^{(n)}}{\partial x} + \frac{G^{(n)}}{\partial y}\right) \qquad (3)$$

Boundary Conditions

- Fluid flows freely in the horizontal direction in from the boundary and out of the opposite boundary

- The vertical velocity approaches zero at the boundaries.

- Apply no-slip boundary conditions to cells that are adjacent to internal obstacle cells. This forces the u and v velocity to tend towards zero in these cells.

Calculation Methodology

$$F = u^n + \delta t\left[\frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\partial(u^2)}{\partial x} - \frac{\partial(uv)}{\partial y} + g_x\right]$$

$$G = v^n + \delta t\left[\frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\partial(uv)}{\partial x} - \frac{\partial(v^2)}{\partial y} + g_y\right]$$

Determine building locations/heights. Apply no-slip boundary conditions

Define inflow conditions (u and v components)

Compute $F^{(n)}$ and $G^{(n)}$ from $u^{(n)}$ and $v^{(n)}$ using eq^n 2a and 2b

(Multiple iterations)

Solve the Poisson equation for pressure $p^{(n+1)}$ using eq^n 3

$$\frac{\partial^2 p^{(n+1)}}{\partial x^2} + \frac{\partial^2 p^{(n+1)}}{\partial y^2} = \frac{1}{\delta t}\left(\frac{\partial F^{(n)}}{\partial x} + \frac{G^{(n)}}{\partial y}\right)$$

Compute new velocity field $u^{(n+1)}$ and $v^{(n+1)}$ from $p^{(n+1)}$ using eq^n 1a and 1b

$$u^{(n+1)} = F^n - \delta t\frac{\partial p^{(n+1)}}{\partial x}$$

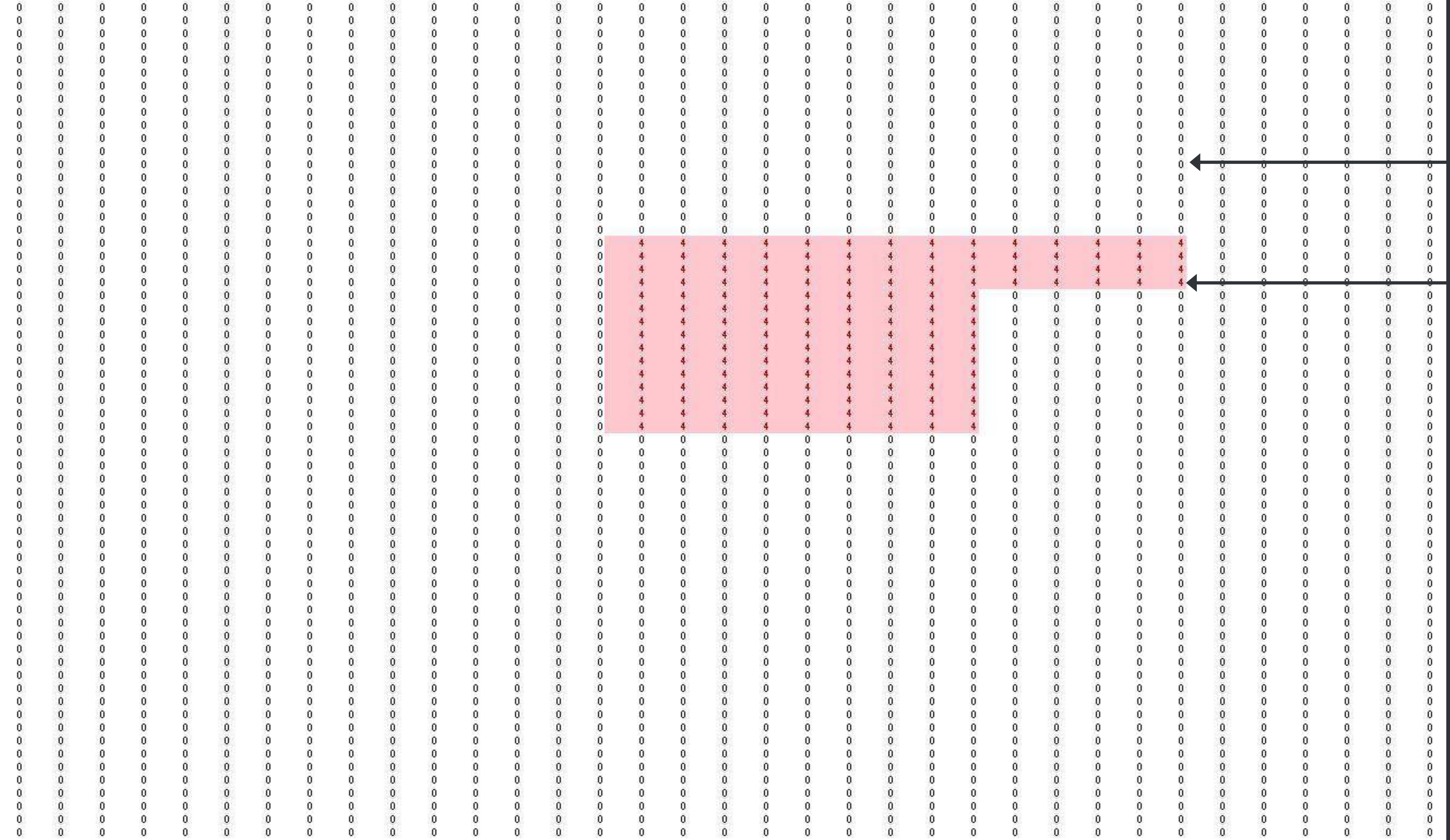
$$v^{(n+1)} = G^n - \delta t\frac{\partial p^{(n+1)}}{\partial y}$$

(If solution converges then)

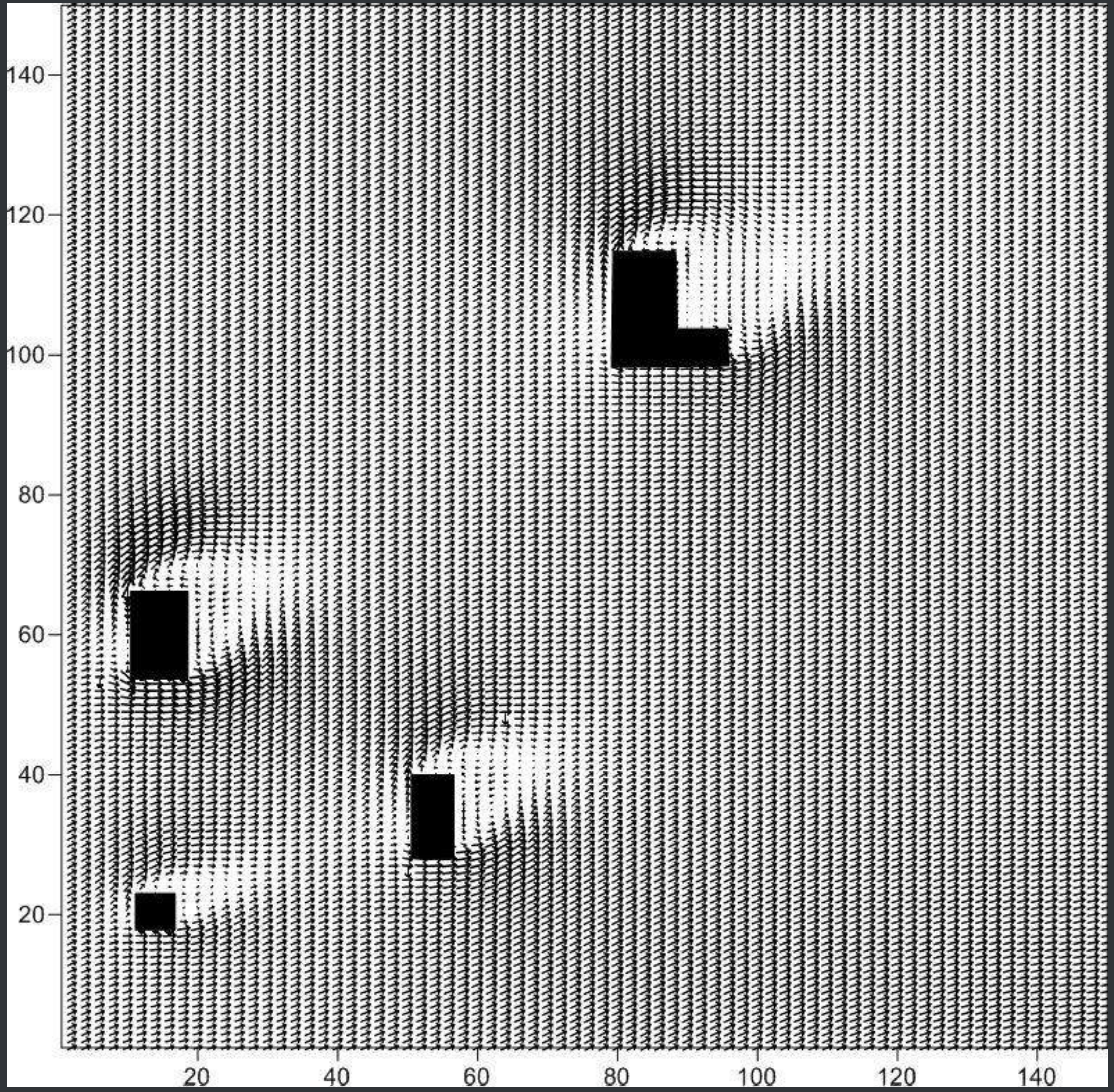
Write u,v and w fields for level

(Next level)

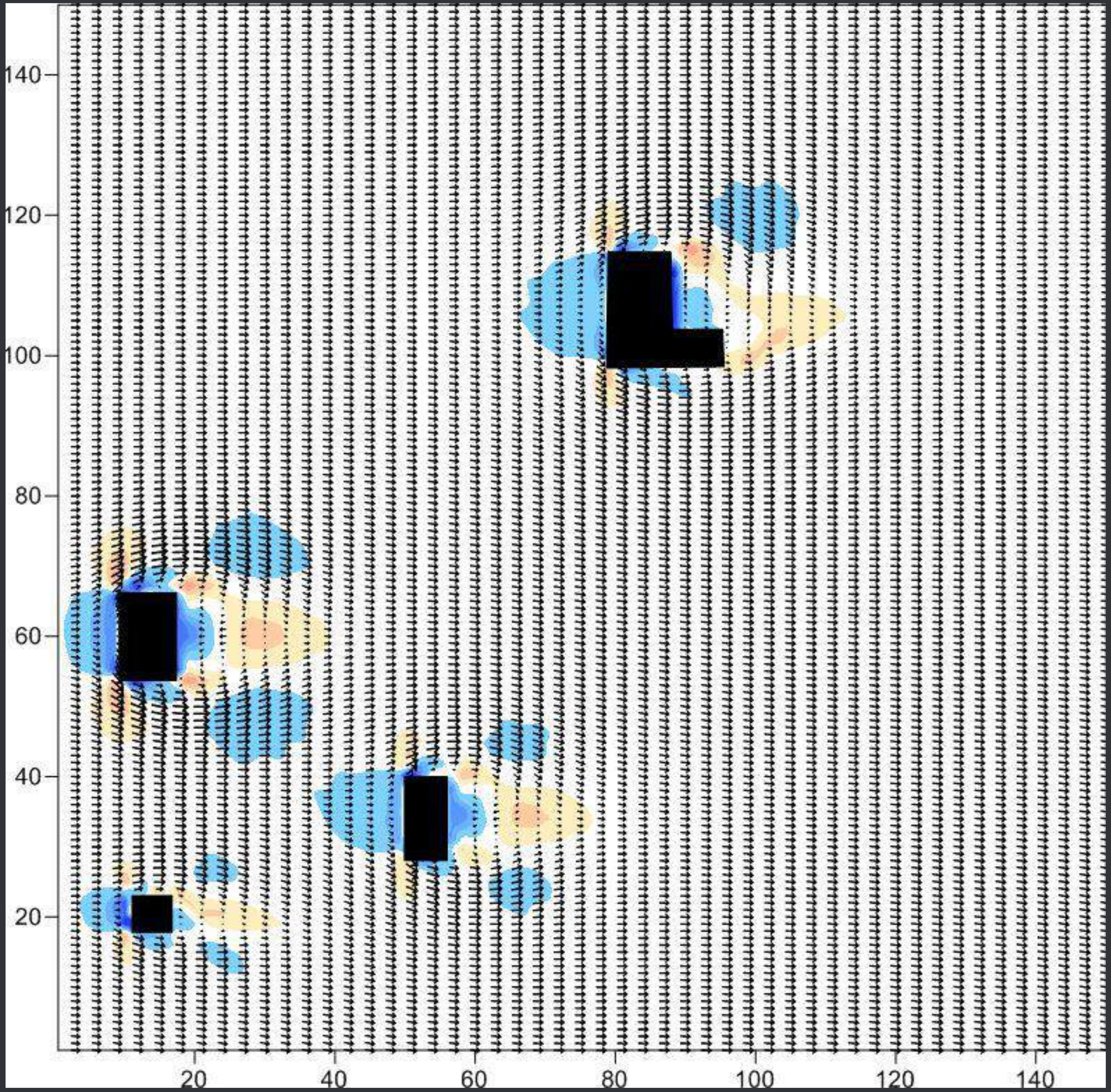
Defining Buildings



Wind Vectors



Vertical Velocity



Particle Trajectories

- 3D kinematic trajectory model (D'Abreton, 1996; D'Abreton and Tyson; 1996).
- The model is Lagrangian, with motion being described in terms of air parcels moving with air streams.
- The model uses the explicit method of integration:

$$x(t+dt)=x(t)+V[x(t)]dt$$

- The parcel velocity vector V=(u,v,w) is the sum of the mean and turbulent component

$$V=\bar{V}+V'$$

Particle Trajectories

- Spatial fields of flow (u-, v- and w-components) are used to drive the particle trajectory model

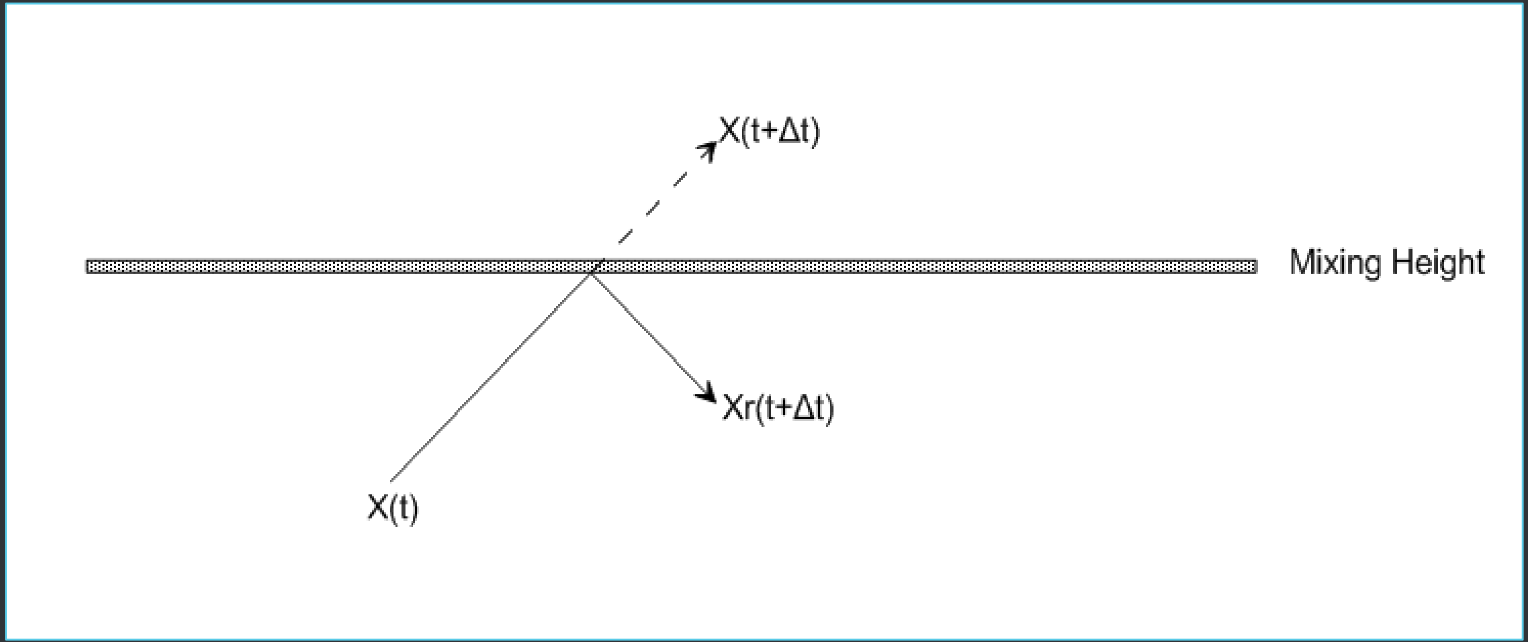
- For the dispersion calculations the turbulence components are derived from the definition of the TKE

- The relationship between the horizontal and vertical components is explicitly defined through the turbulence anisotropy factor:

$$\frac{W'^2}{U'^2 + V'^2}$$

Particle Trajectories

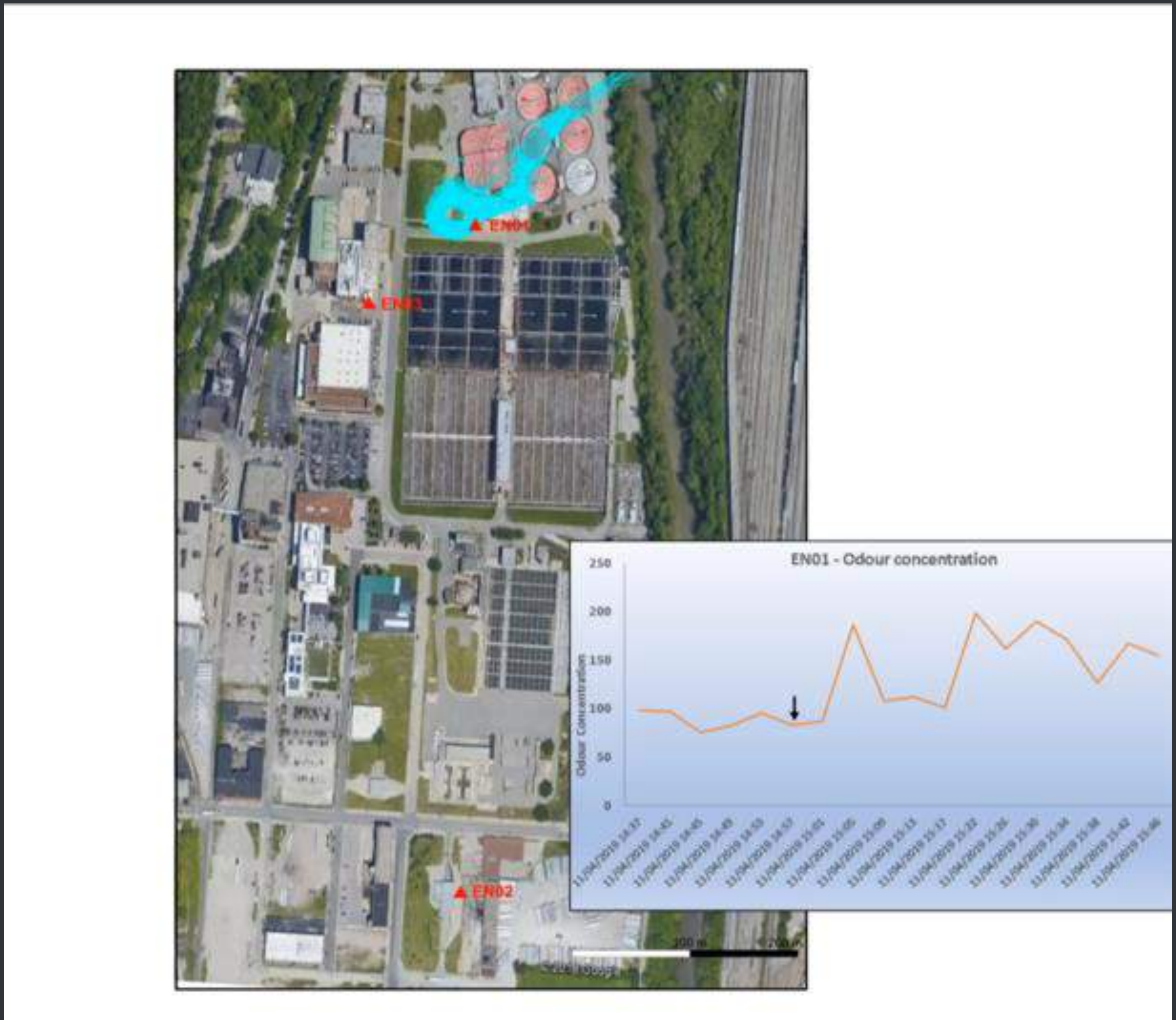
- Particles transported upward higher than the mixing height at that location are reflected downward from the mixing height.



- Particles impacting on buildings are also reflected.

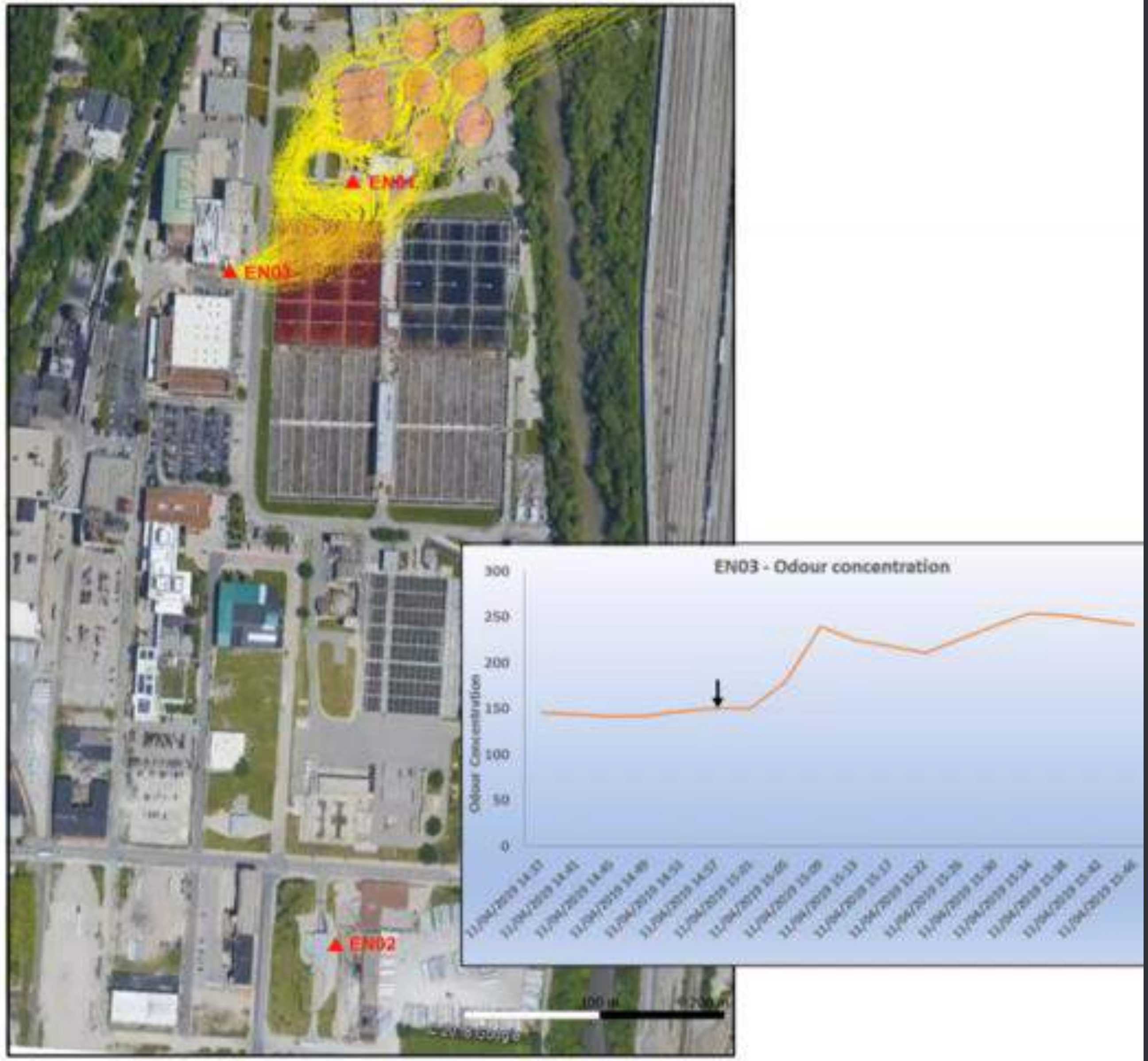
Examples

Examples



EN02
EN01 - Odour concentration
Odour Concentration
250
200
150
100
50
0

Examples


EN03
EN02
EN03 - Odour concentration
Odour Concentration
300
250
200
150
100
50
0
100 m

Conclusions

- This model allows near real-time solution of complex flow from a single onsite weather station.

- The complex flow model can be used the drive a particle trajectory model to determine near-field transport in disturbed flow.

- The example shows that in most cases, odour sources can be identified from a combination of trajectories. In particular, offsite odour sources can be identified, thereby averting the need for mitigatory actions and even potential legal issues.