High-resolution Dispersion Modelling in the Convective Boundary Layer

Urban Fluid Mechanics SIG Workshop, 29/03/2021

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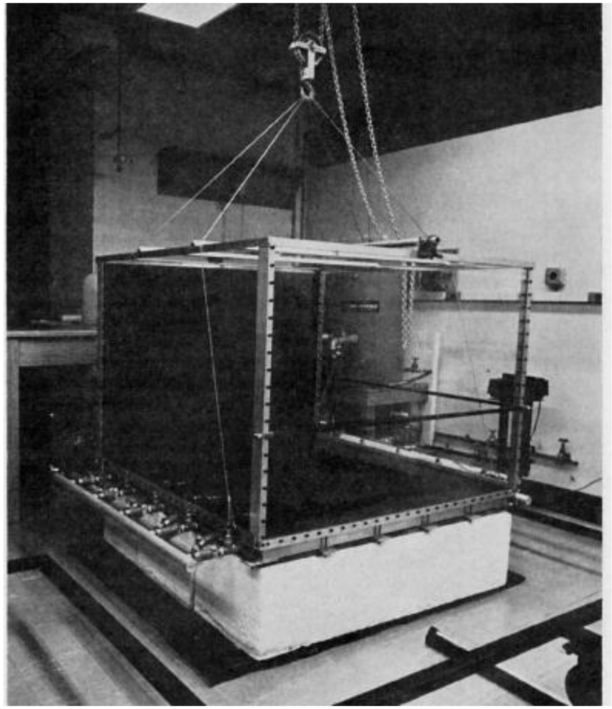
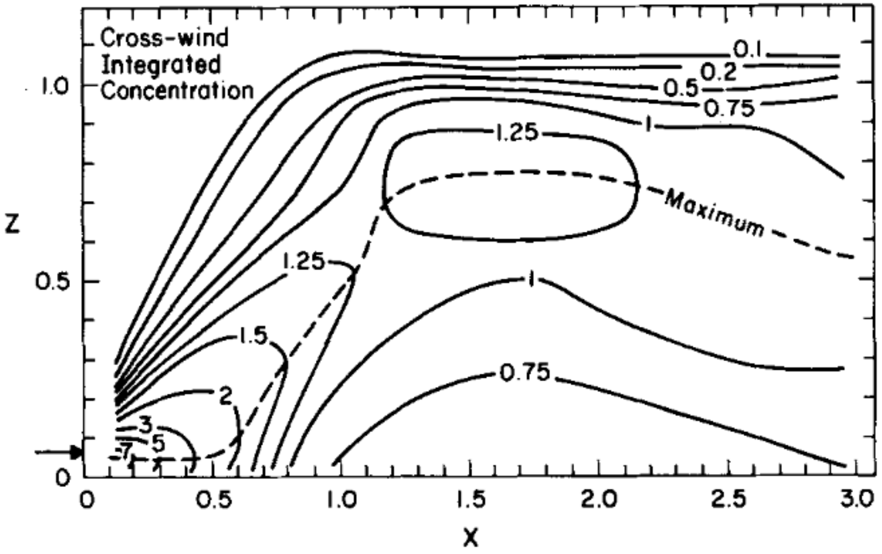
Introduction and Motivation

- Numerical weather prediction (NWP) can now be run at Δ=O(100 m) and air quality models (AQMs) will follow
- Integral scale convective boundary layer (CBL) turbulence becomes largely resolved at Δ=O(100 m)
- Is convective vertical mixing of pollution different at Δ=O(100 m) and Δ=O(1 km)?
- “Lift off” behaviour known to occur -> important for air quality at the city scale?



Willis and Deardorff (1974)

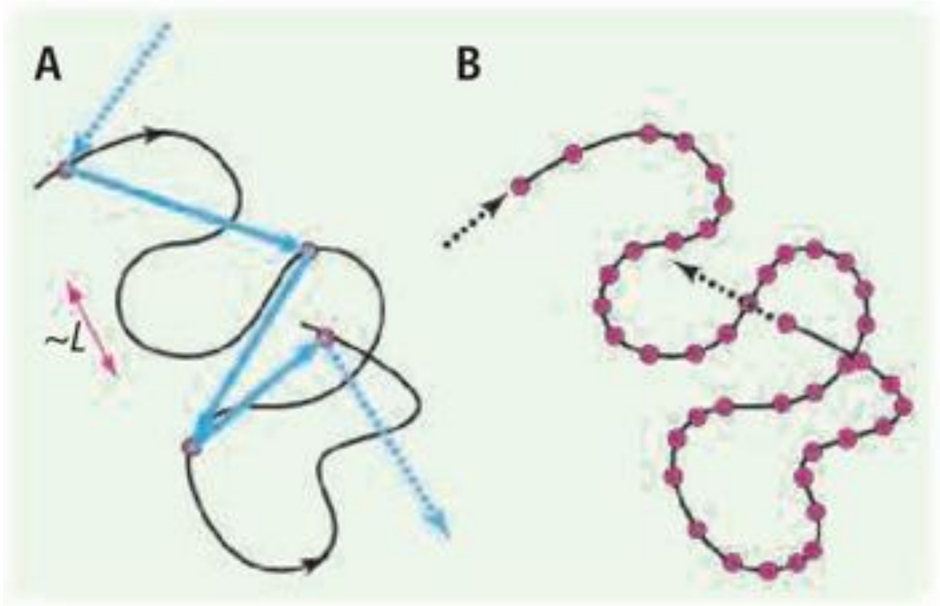


Willis and Deardorff (1976)

Figure 7. Smoothed values of dimensionless cross-wind integrated concentration as a function of height and downstream distance. Arrow denotes source location.

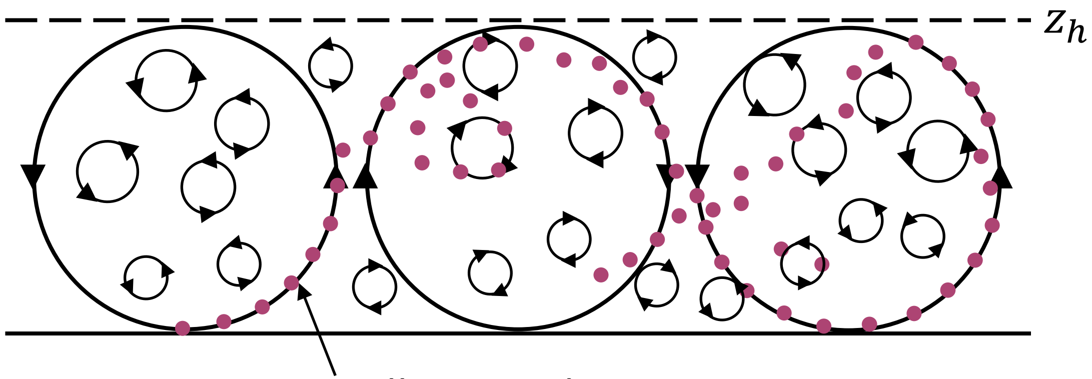
Diffusive and Ballistic Dispersion

Diffusive: $\langle r \rangle \propto t^{1/2}$ Ballistic: $\langle r \rangle \propto t$



Pusey (2011)

A particle released at the surface in a convective boundary layer (CBL):



Ballistic at short times after release

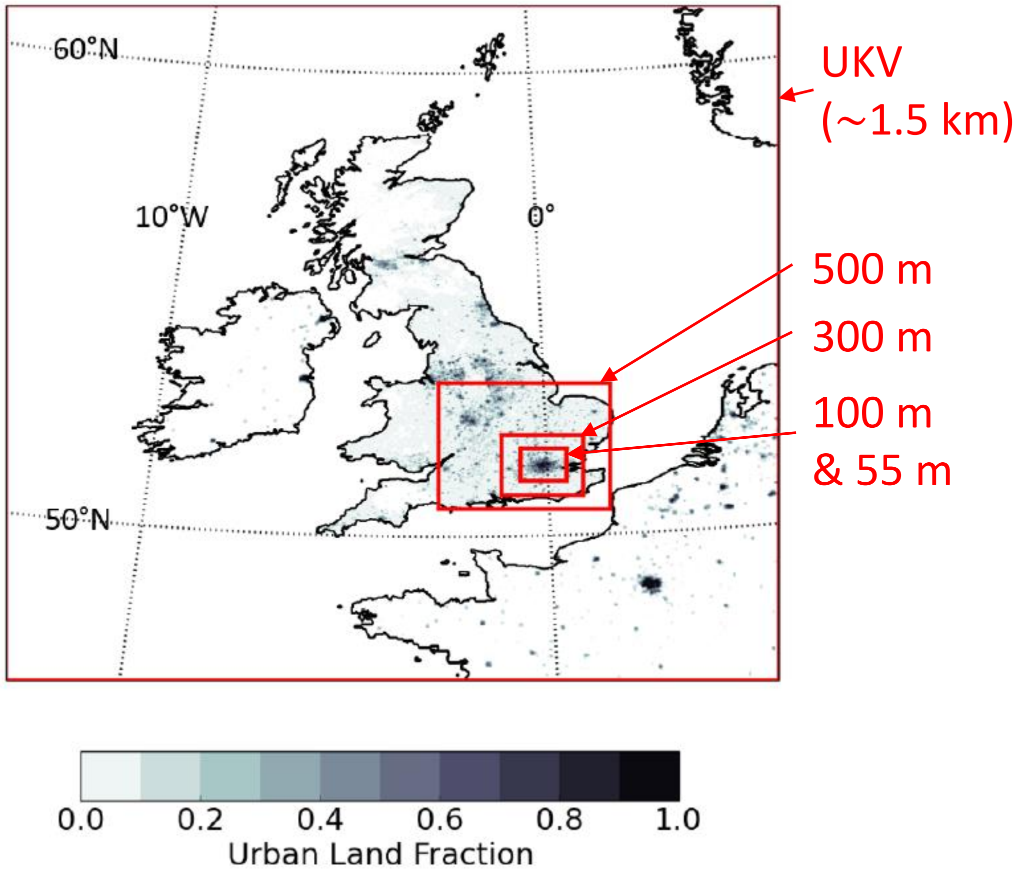
The Met Office Unified Model (UM) parametrises dispersion using K-theory

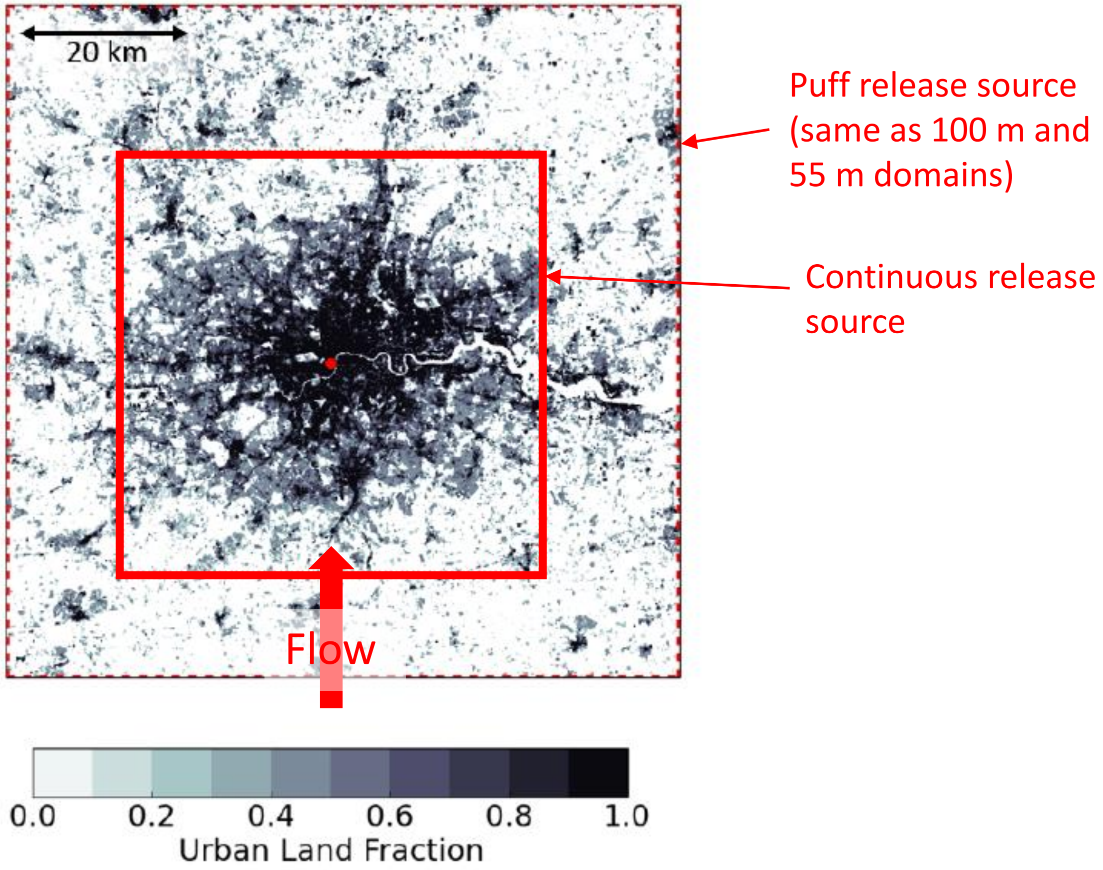
$$F(z) = -K(z)\frac{dc}{dz},$$

so it is treated as being diffusive (Einstein, 1905). It is as if particles are undergoing a random walk (that is more efficient at different heights) with boundaries at the ground and CBL top.

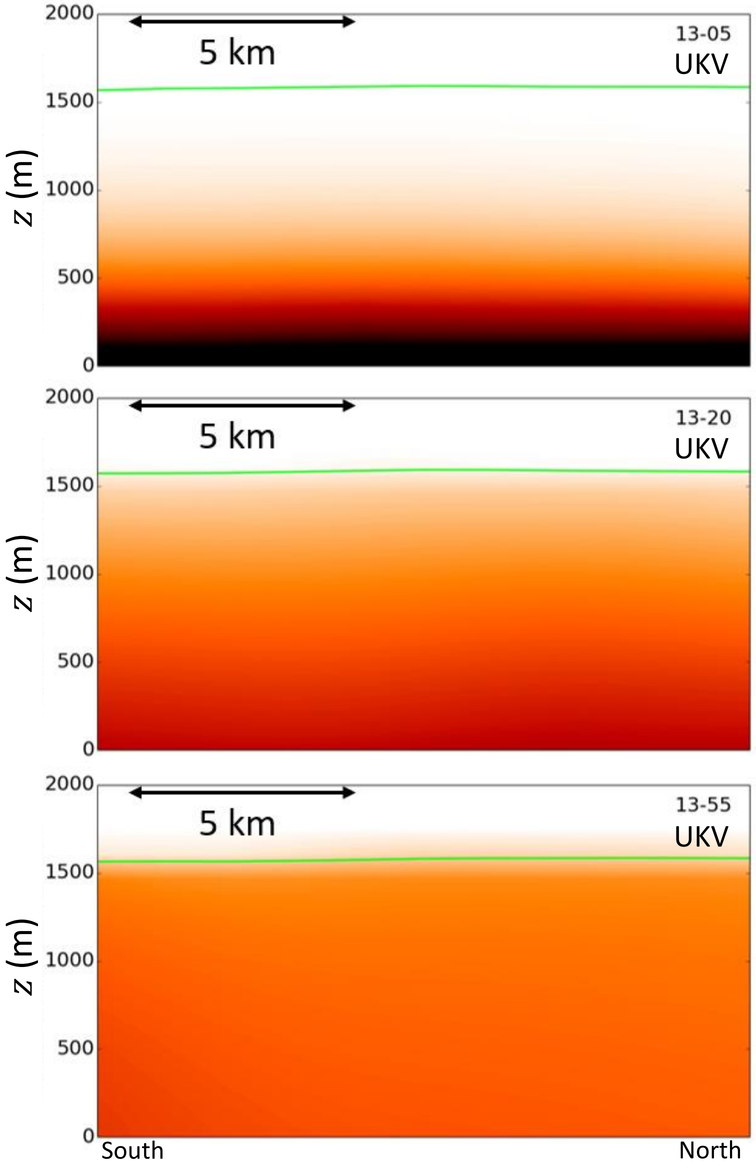
UM Simulations

- Met Office UM nesting suite
- Puff and continuous release, homogeneous, ground source of passive scalar
- Case Study: 04/05/2016 with clear sky convective conditions ($-z_h/L_{MO} \approx 30$ at midday)





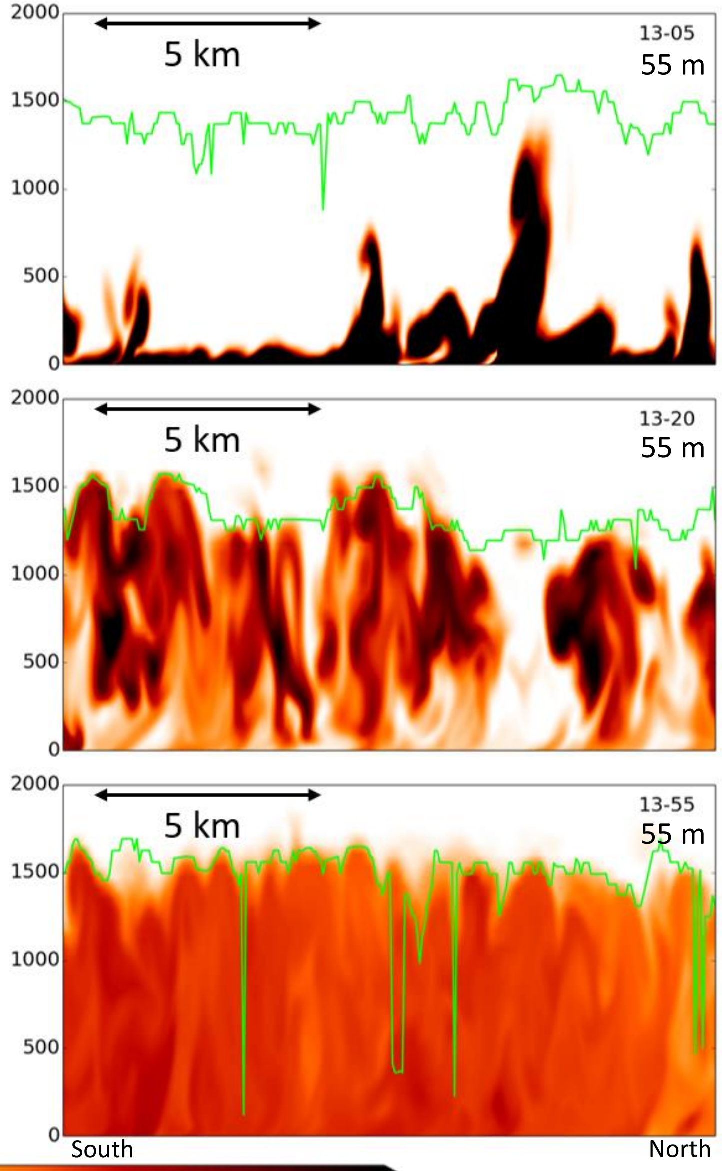
Puff Release Cross-sections



Horizontally homogeneous

Diffusive

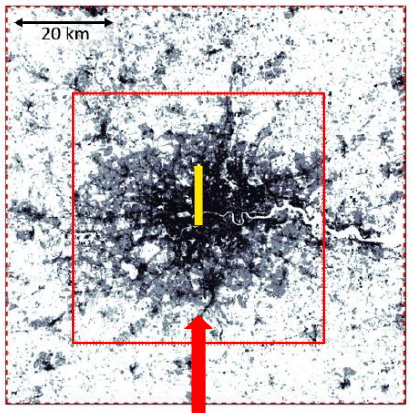
~ Well-mixed



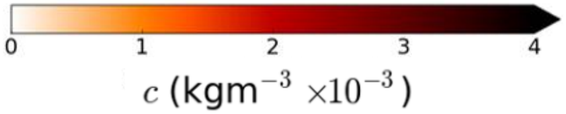
Convergence at surface and localised updrafts

Ballistic -> “lift off”

~ Well-mixed

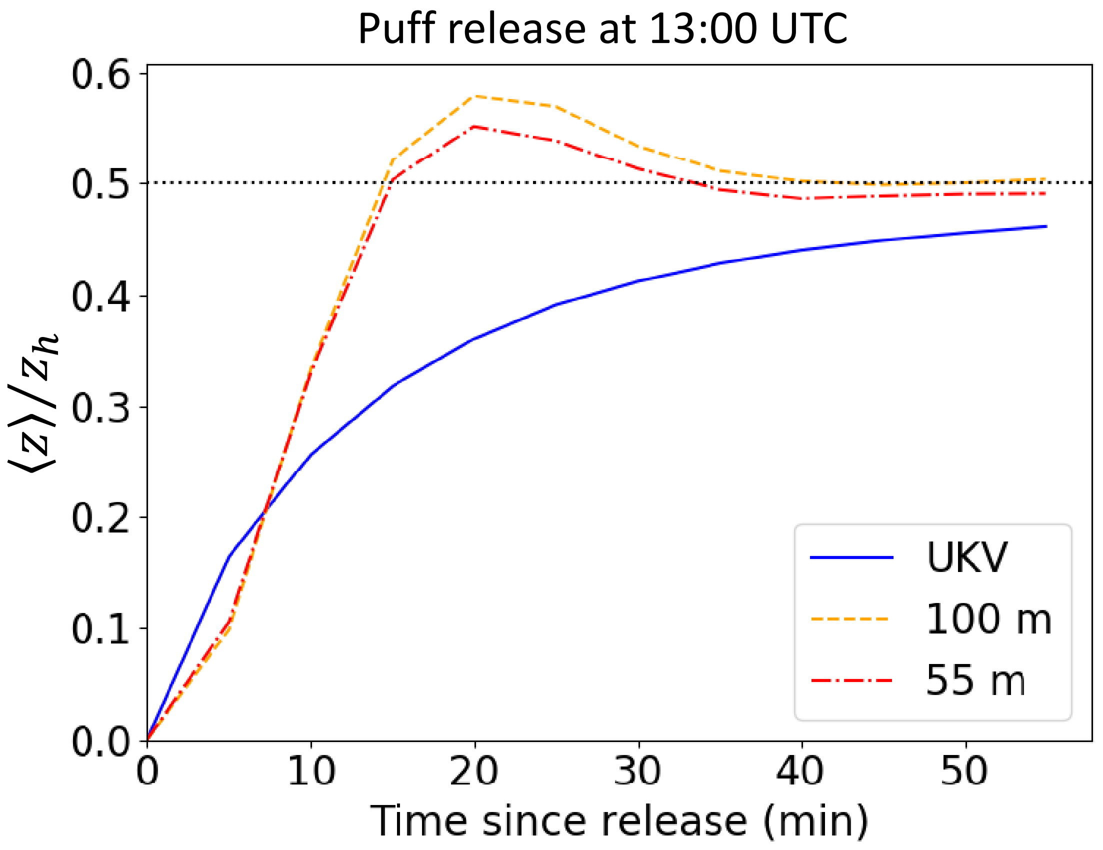


UM diagnosed boundary layer depth



Vertical Mixing Timescales from Centre of Mass (CoM) Trajectories

$$\langle z \rangle / z_h = \frac{\int_A \int_0^\infty c(z) z \, dz dA}{\int_A \int_0^\infty c(z) \, dz dA} \Big/ z_h$$



- Passive scalar undergoes different mixing behaviour with time since release in the 55 m model

- Need more than one timescale to characterise the vertical mixing behaviour

Damped Simple Harmonic Oscillator (DHSO) Model

Langevin equation for a particle in a stationary, horizontally homogeneous flow

$$dw = \left(-\frac{C_0 \epsilon w}{2\sigma_w^2} + \frac{1}{2}\left(1 + \frac{w^2}{\sigma_w^2}\right)\frac{\partial \sigma_w^2}{\partial z}\right)dt + (C_0\epsilon)^{1/2} d\xi,$$

where $w = \dot{z}$ is the vertical velocity of the particle, $\sigma_w^2 = \langle w^2 \rangle$ is the vertical velocity variance of an ensemble of particles, $d\xi$ are Gaussian random velocity increments with zero mean, C_0 is a dispersion parameter and ϵ is the local rate of dissipation of TKE.

Taking the ensemble average

$$\langle \ddot{z} \rangle = \underbrace{-\frac{\langle \dot{z} \rangle}{\tau_{dc}}}_{\text{damping term}} + \underbrace{\frac{\partial \sigma_w^2}{\partial z}}_{\text{drift term}},$$

where $\tau_{dc} = 2\sigma_w^2/(C_0\epsilon)$.

Approximating τ_{dc} as constant and heuristically approximating the drift term

$$\langle \ddot{z} \rangle = -2\gamma\langle \dot{z} \rangle - \omega^2 \langle z \rangle, \qquad \longleftarrow \text{DSHO}$$

where $\gamma = 1/(2\tau_{dc})$ and $\omega = 2\pi/\tau_w$.

DHSO Solutions and Timescales

Overdamped ($\gamma > \omega$) solution:

$$\frac{\langle z \rangle}{z_h} = 0.5 + (\langle z(0) \rangle / z_h - 0.5 - A)e^{-t/\tau_{o1}} + Ae^{-t/\tau_{o2}}$$

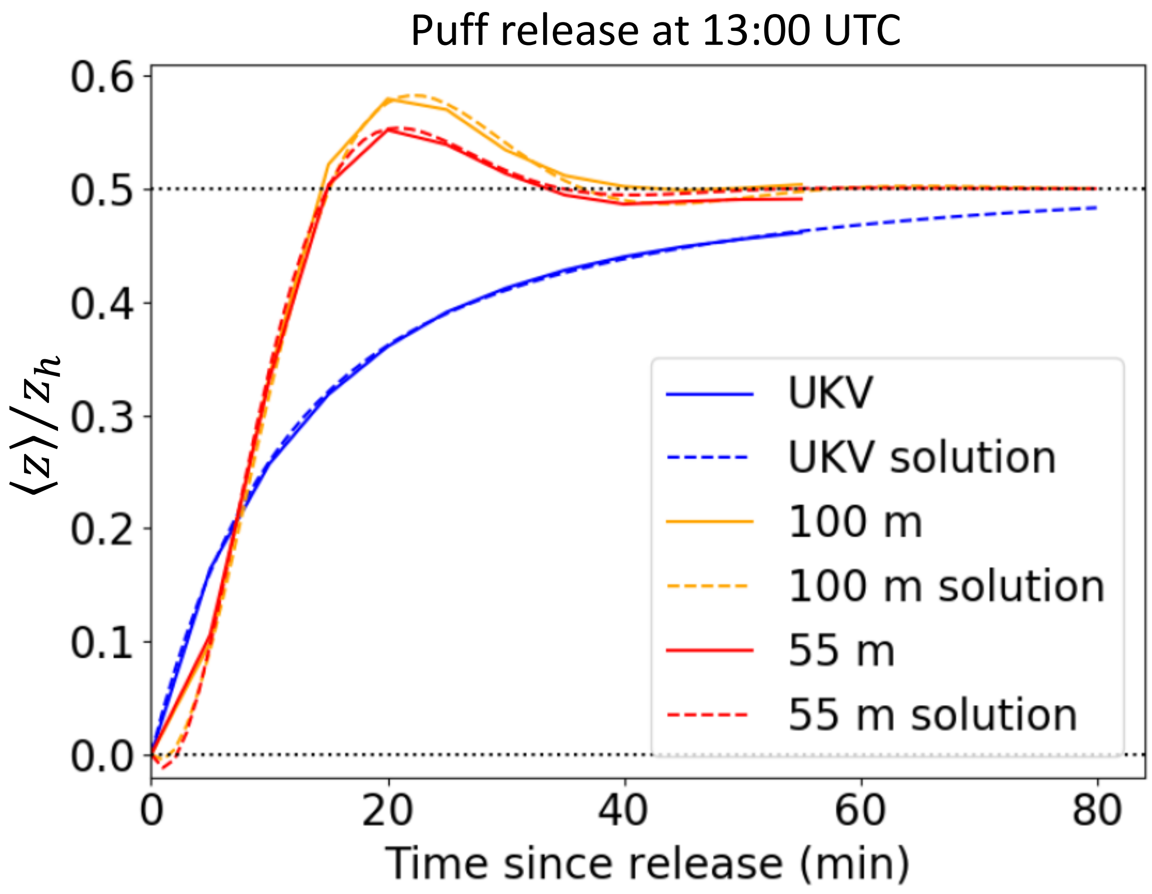
The UKV is overdamped with timescales $\tau_{o1} = 32$ min and $\tau_{o2} = 8$ min.

Underdamped ($\gamma < \omega$) solution:

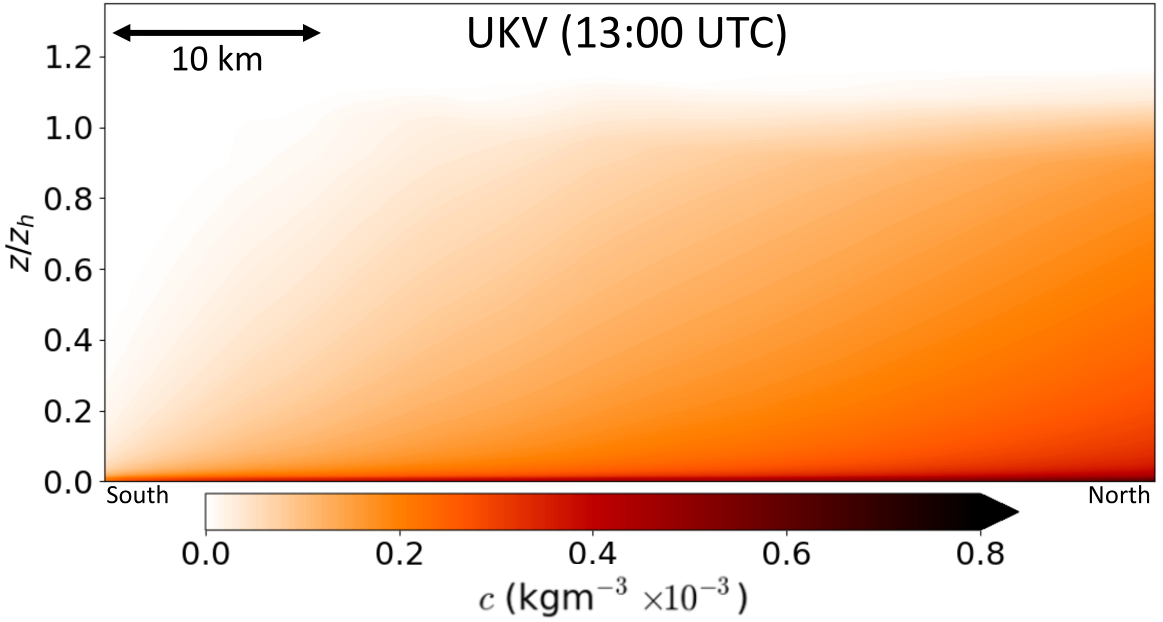
$$\frac{\langle z \rangle}{z_h} = 0.5 + \frac{(\langle z(0) \rangle / z_h - 0.5)e^{-t/\tau_{u1}} \cos(t/\tau_{u2} + \phi)}{\cos(\phi)}$$

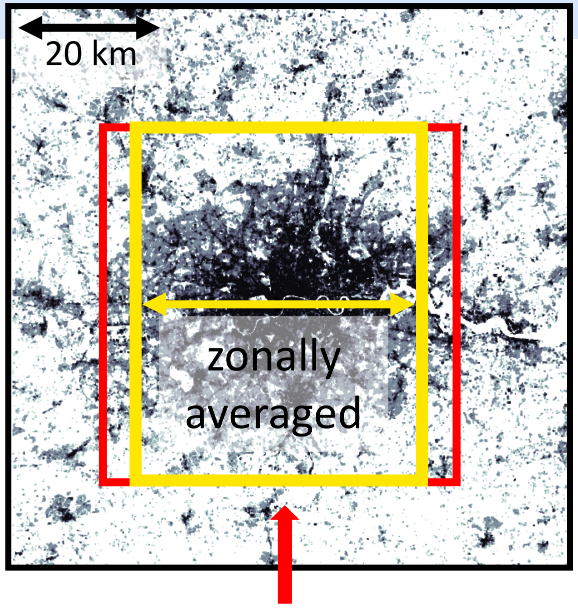
The 55 m model is underdamped with timescales $\tau_{u1} = 9$ min and $\tau_{u2} = 40$ min.

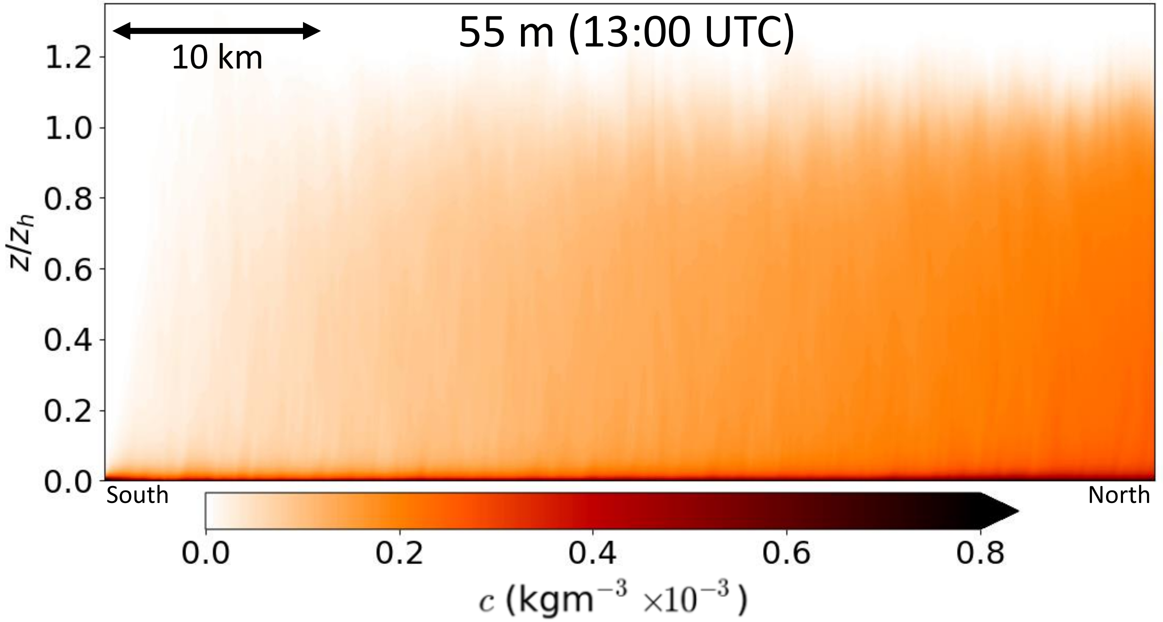
UKV model does not capture the ballistic behaviour and mix efficiently enough at times greater than O(τ_{o2}).

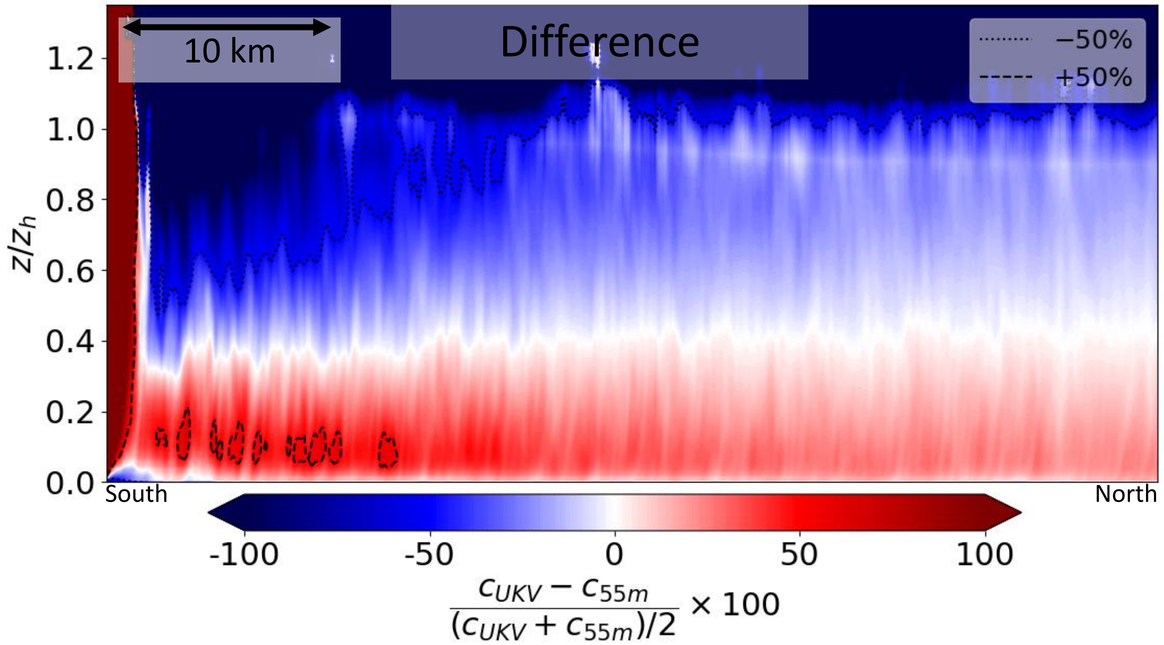


Continuous Release Cross-sections









Conclusions

- $\Delta = O(100\text{ m})$ NWP represents ballistic CBL dispersion unlike $\Delta = O(1\text{ km})$ NWP
- A reduced analytical model (DHSO) was developed that captured the ballistic and diffusive dispersion
- Vertical mixing is much slower at times larger than $\sim$8 min in the UKV model compared to the 55 m model
- This results in near ground level pollution concentrations that are larger in the UKV model compared to the 55 m model by up to 50%. Influence largest when local emissions dominate.

Thank You

Additional Material from Thesis

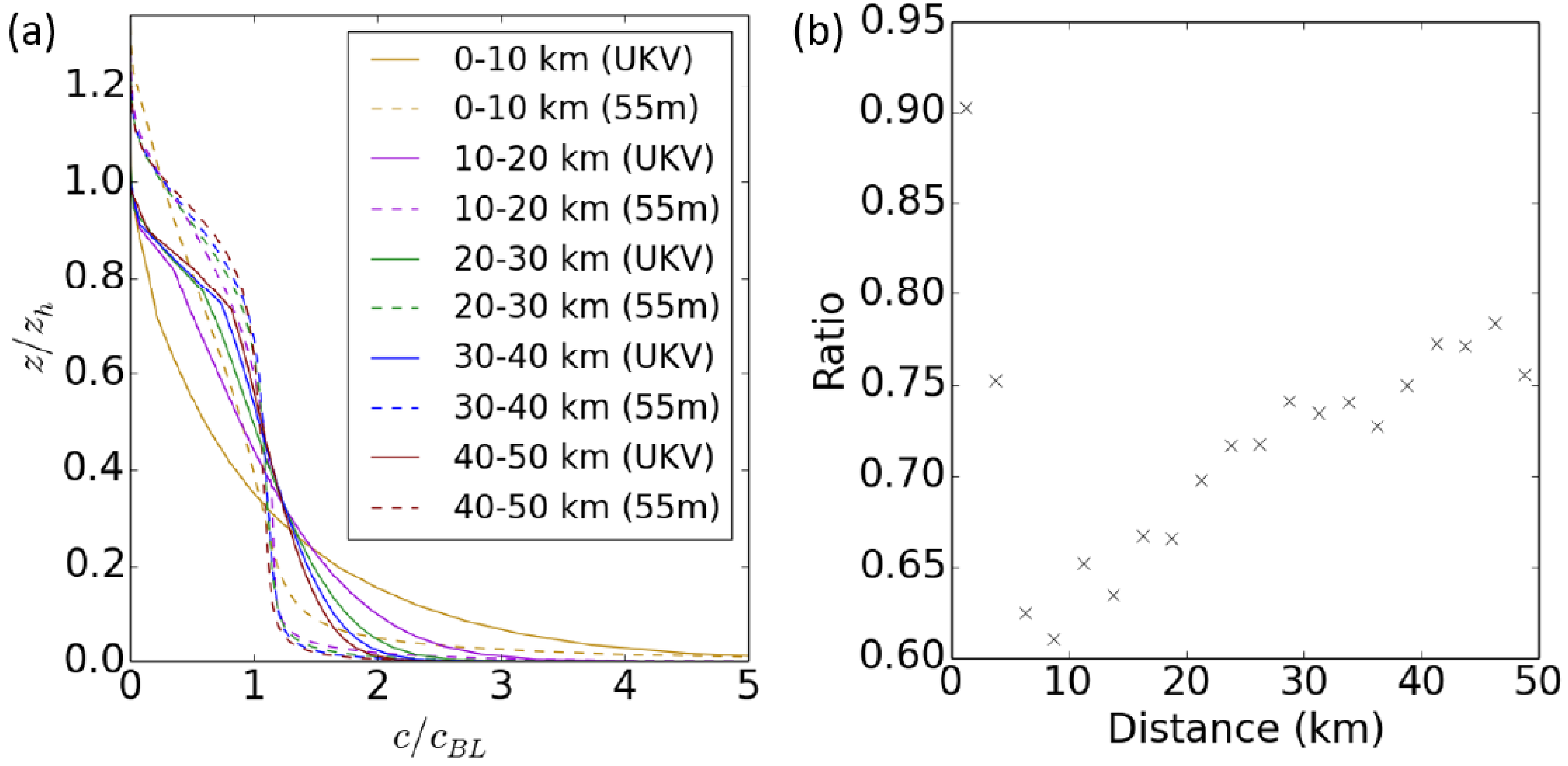


Figure 3.22: (a) UKV and 55 m model continuous release concentration profiles at 13:00 UTC calculated in five regions, 0-10 km, 10-20 km, 20-30 km, 30-40 km and 40-50 km downstream of the southern edge of the continuous source region. (b) Ratio of the 55 m model to the UKV model continuous release concentrations at $z/z_h = 0.02$ normalised by the average concentration in the BL ($c(z/z_h = 0.02)/c_{BL}$) at 13:00 UTC. The ratio was calculated in 2.5 km intervals with increasing distance downstream of the southern edge of the continuous source region. The longitudinal extent of the analysis regions in (a) and (b) was chosen to be the same as the standard analysis region.

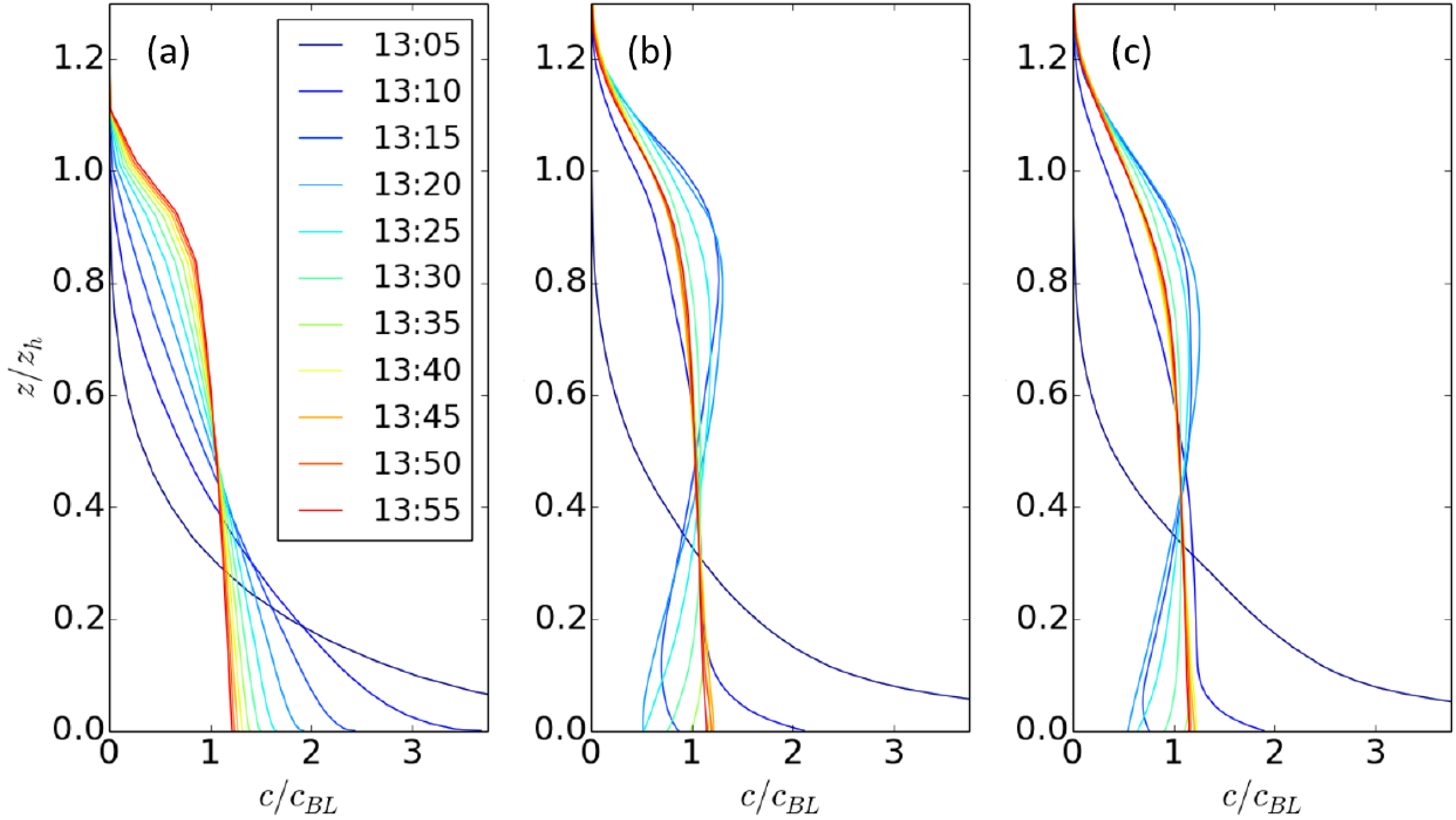


Figure 3.21: Time evolution of the 13:00 UTC puff release concentration profiles for the (a) UKV, (b) 100 m and (c) 55 m models.

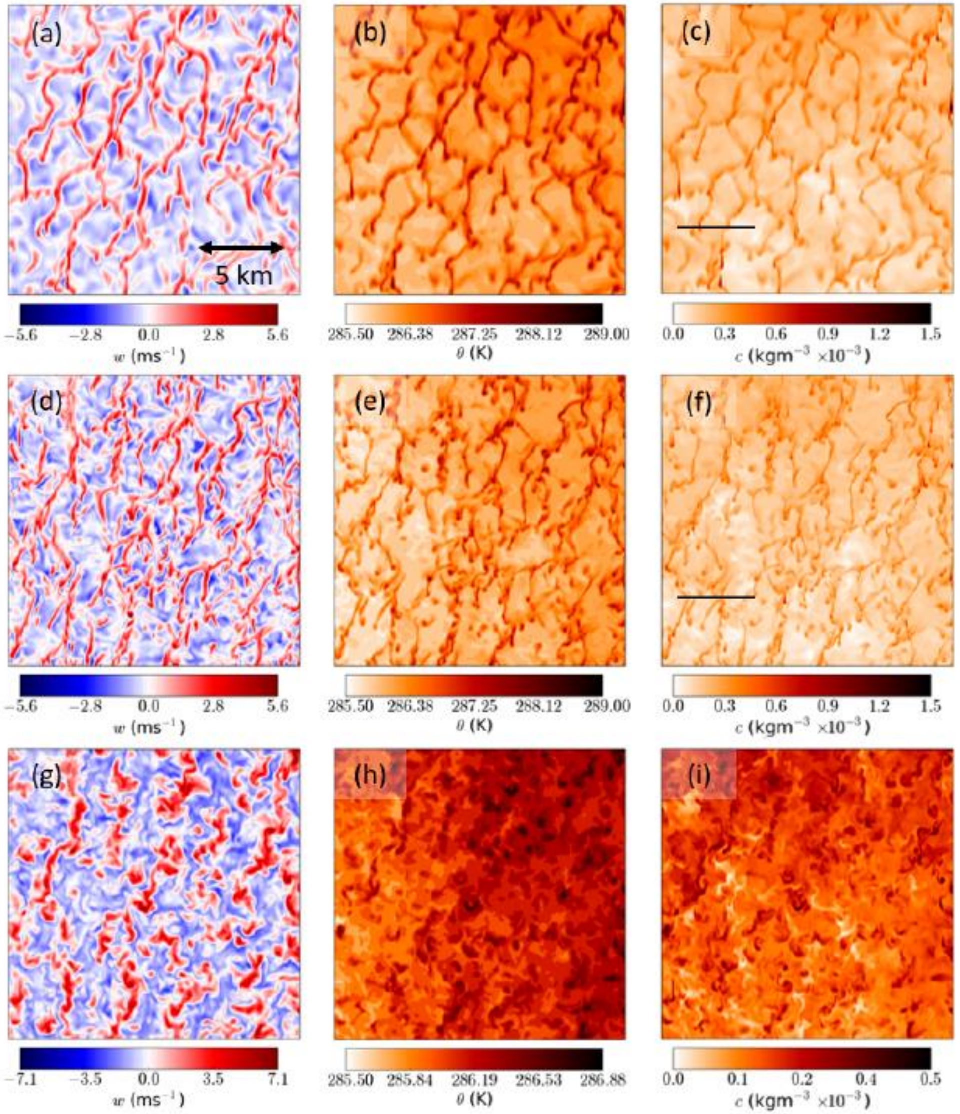


Figure 3.14: Horizontal cross-sections at 13:00 UTC. (a-c) are the 100 m model w, θ and c respectively at $z = 140$ m ($z/z_h \approx 0.1$). (d-f) are the 55 m model w, θ and c respectively at $z = 140$ m ($z/z_h \approx 0.1$). (g-i) are the 55 m model w, θ and c respectively at $z = 700$ m ($z/z_h \approx 0.5$). The cross-sections are centred on the analysis region. The horizontal black lines in (c) and (f) correspond to the locations of the vertical cross-sections in Figs. 3.15a and b respectively.

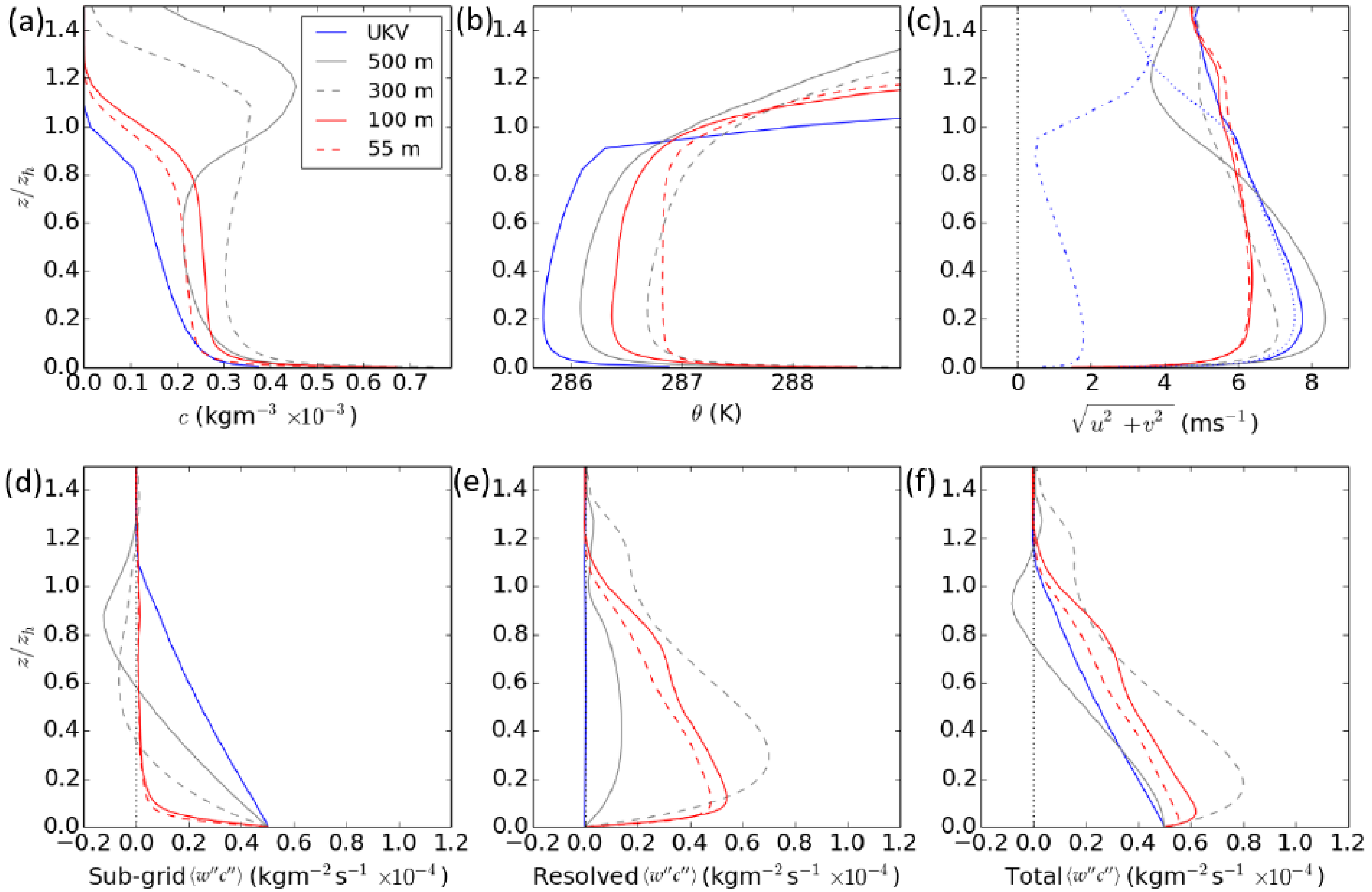


Figure 3.7: Horizontally averaged profiles within the analysis region at 13:00 UTC. (a) Concentration of the continuous release tracer, (b) θ and (c) wind speed. The blue dash-dotted and dotted lines in (c) are the UKV model u and v velocity components respectively. (d), (e) and (f) are the sub-grid, resolved and total tracer vertical turbulent fluxes respectively.

Non-conservation Issues / Grid Point Updrafts in the 300 m Model

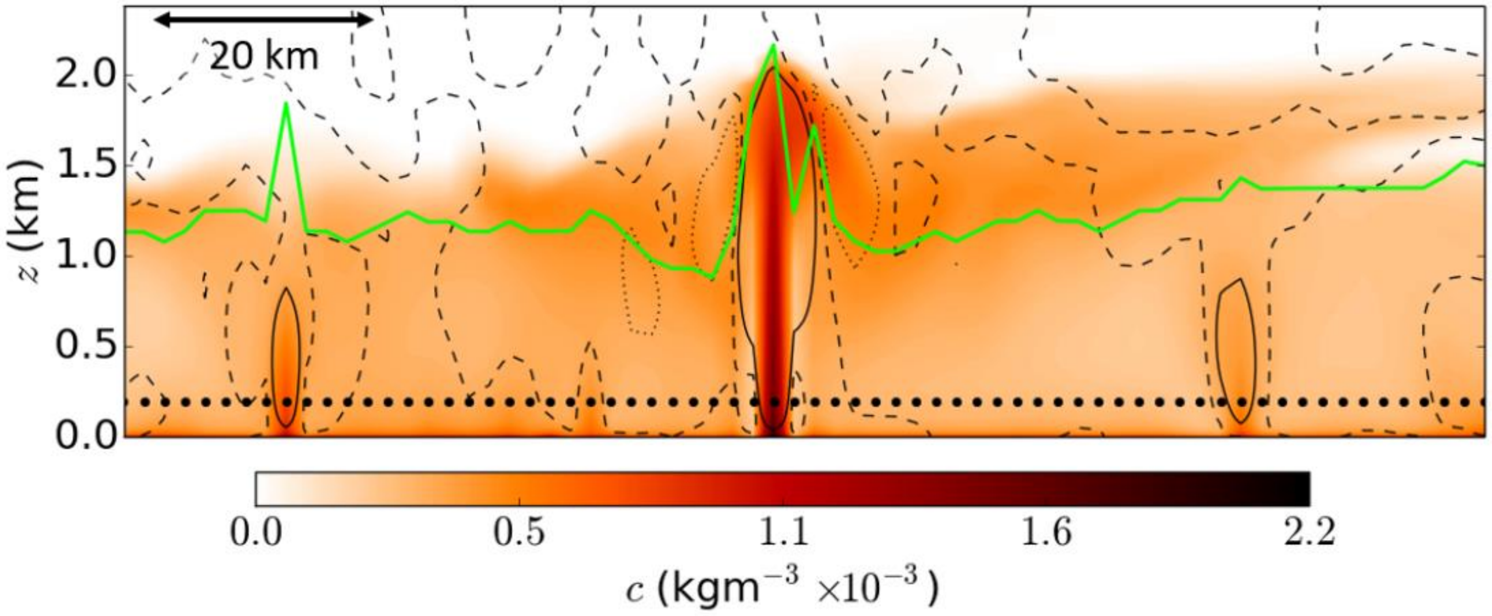


Figure 3.11: 300 m model vertical cross-section of c at 13:00 UTC with location indicated by the solid black line in Fig. 3.10c. Solid black lines, dashed black lines and dotted black lines are −1 , 0 and 1 ms^{-1} vertical velocity contours respectively. Large black dots indicate the horizontal locations of grid points and the solid green line is BL scheme diagnosed z_h.