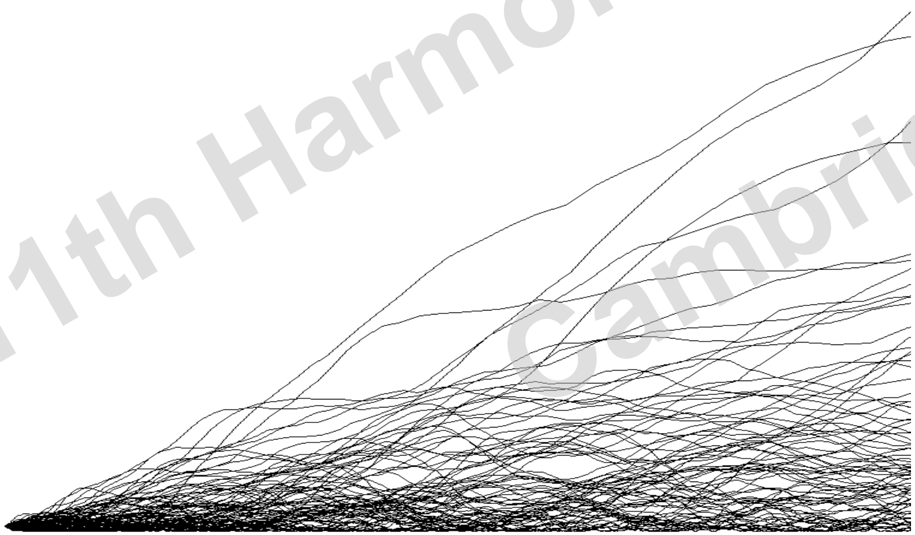
A new puff modelling technique for short range dispersion applications

David Thomson & Andrew Jones, July 2007

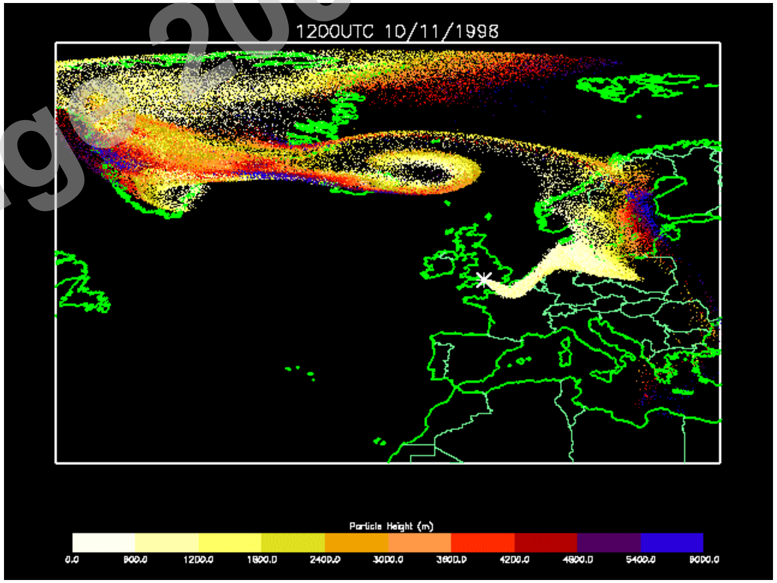
Lagrangian particle models

Met Office

- Knowledge of mean flow and statistics of turbulence is used to construct an ensemble of random trajectories
- Each particle responds to local flow and turbulence



Neutral surface layer

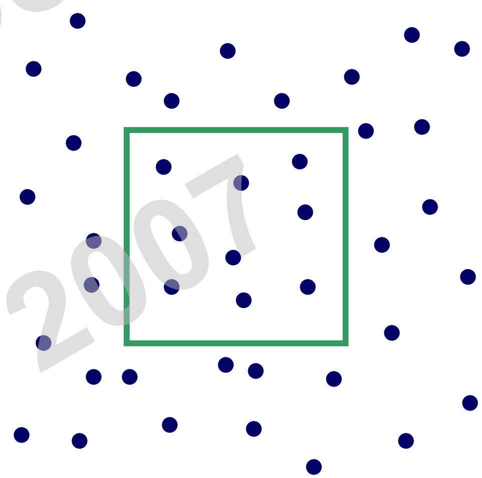


Long range example

The noise problem in Lagrangian particle models

- Particle models calculate concentrations by counting particles in boxes
  - Lots of particles and so expensive

    or
  - Noisy and hard to resolve details



- Various solutions have been proposed:
  - Kernel methods (e.g. de Haan 1999)
  - Hybrid methods using aspects of particle and puff models (e.g. Hurley 1994, de Haan and Rotach, 1998)

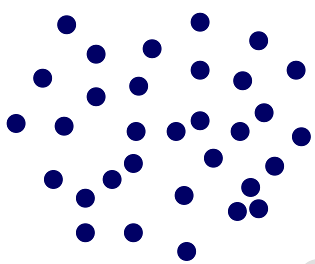
Aim

- To produce a puff model that:
  - – is a good approximation to a given Lagrangian particle model
  - – greatly reduces the noise problem and has a smoothly varying concentration field
  - – includes treatment of skew velocity distributions (e.g. for convective conditions)
  - – can be tuned for accuracy of approximation versus computational cost

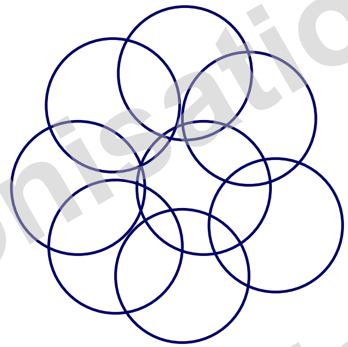
Puff model – basic concept

- Consider an instantaneous source:

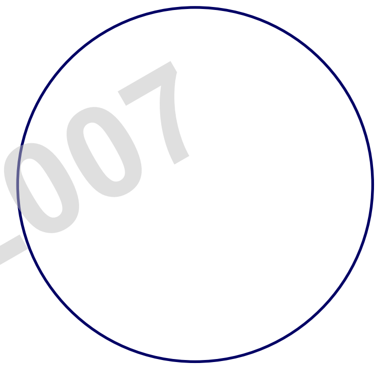
Particle Model



Our puff model



Ensemble mean puff model



- In the puff model we represent
  - some spread by random motion of puff centres
  - some spread by puffs growing
- The division of spread is tunable and we also limit max puff size to ensure flow adequately resolved

Puff model – basic concept

- The "tunability" enables cost-accuracy trade-off:
  - Post accident analysis – best possible accuracy
  - Emergency response – good accuracy but fast model
  - Environmental Impact Assessment – concentration levels of the right magnitude, but model fast enough to run many different met scenarios

Puff model – formulation

- Underlying Lagrangian model:

$$dw = a(z, w, t)\,dt + (2\sigma_w^2/\tau)^{1/2}\,d\xi \qquad dz = w\,dt$$

$(\sigma_w^2 = \text{velocity variance}, \tau = \text{velocity timescale}, d\xi/dt = \text{white noise})$

- A fraction β of the random forcing variance will be treated by the random motion, the rest by the puff spread
- With $z = z_0 + z'$, $w = w_0 + w'$, this leads to

$$dw_0 = \langle a(z_0 + z', w_0 + w', t)\rangle\,dt + (2\beta\sigma_w^2/\tau)^{1/2}\,d\xi$$

$$dw' = [a(z_0 + z', w_0 + w', t) - \langle a(z_0 + z', w_0 + w', t)\rangle]dt + (2(1-\beta)\sigma_w^2/\tau)^{1/2}\,d\xi'$$

- The *‹a›* and *a - ‹a›* terms need to be approximated to obtain a closed model

Puff model – formulation

- Puff growth z', w':
  - Evaluate $a - \langle a \rangle$ by using homogeneous turbulence approximation for a (with time dependence seen by puff):

$$a(z_0 + z', w_0 + w', t) - \langle a(z_0 + z', w_0 + w', t) \rangle = -\frac{w'}{\tau} + \frac{w'}{2\sigma_w^2}\frac{d\sigma_w^2}{dt}$$

  - This leads to a Gaussian puff with moments obeying

$$\frac{d}{dt}\langle z'^2 \rangle = 2\langle z'w' \rangle$$

$$\frac{d}{dt}\frac{\langle z'w' \rangle}{\sigma_w} = \frac{\langle w'^2 \rangle}{\sigma_w} - \frac{\langle z'w' \rangle}{\sigma_w \tau}$$

$$\frac{d}{dt}\frac{\langle w'^2 \rangle}{\sigma_w^2} = \frac{2(1-\beta)}{\tau} - \frac{2\langle w'^2 \rangle}{\sigma_w^2 \tau}$$

Puff model – formulation

- Puff random motion z_0, w_0:
  - Use Gaussian turbulence form of *a*, expand in *z′*, *w′*, and average (with approximations) over puff to get:

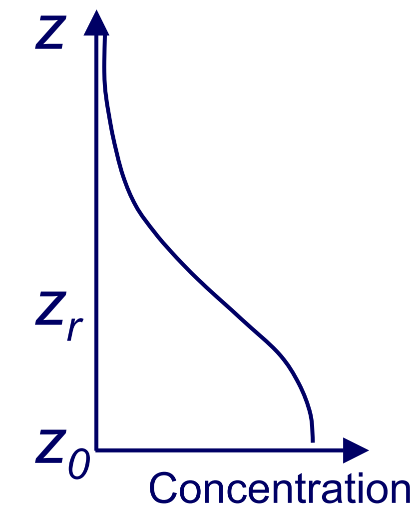
$$\langle a(z_0 + z', w_0 + w', t)\rangle = a(z_0, w_0, t; \beta) + \underbrace{\frac{(1-\beta)}{2}\frac{d\sigma_w^2}{dz} + \frac{\langle w'^2\rangle}{2\sigma_w^2}\frac{d\sigma_w^2}{dz} + \frac{\langle w' z'\rangle}{\tau^2}\frac{d\tau}{dz}}$$

  - The extra drift terms, when added to $a(z_0, w_0, t; \beta)$, reflect the puff drift expected due to gradients in velocity variance and timescale

Puff model – formulation

- Near ground we evaluate 'meteorology' at true centroid of reflected puff and reduce gradients to those 'seen' by the puff:

$$\frac{d\sigma_w^2}{dz} \longrightarrow \frac{d\sigma_w^2(z_r)}{dz_0} = \frac{d\sigma_w^2(z_r)}{dz_r}\frac{dz_r}{dz_0}$$

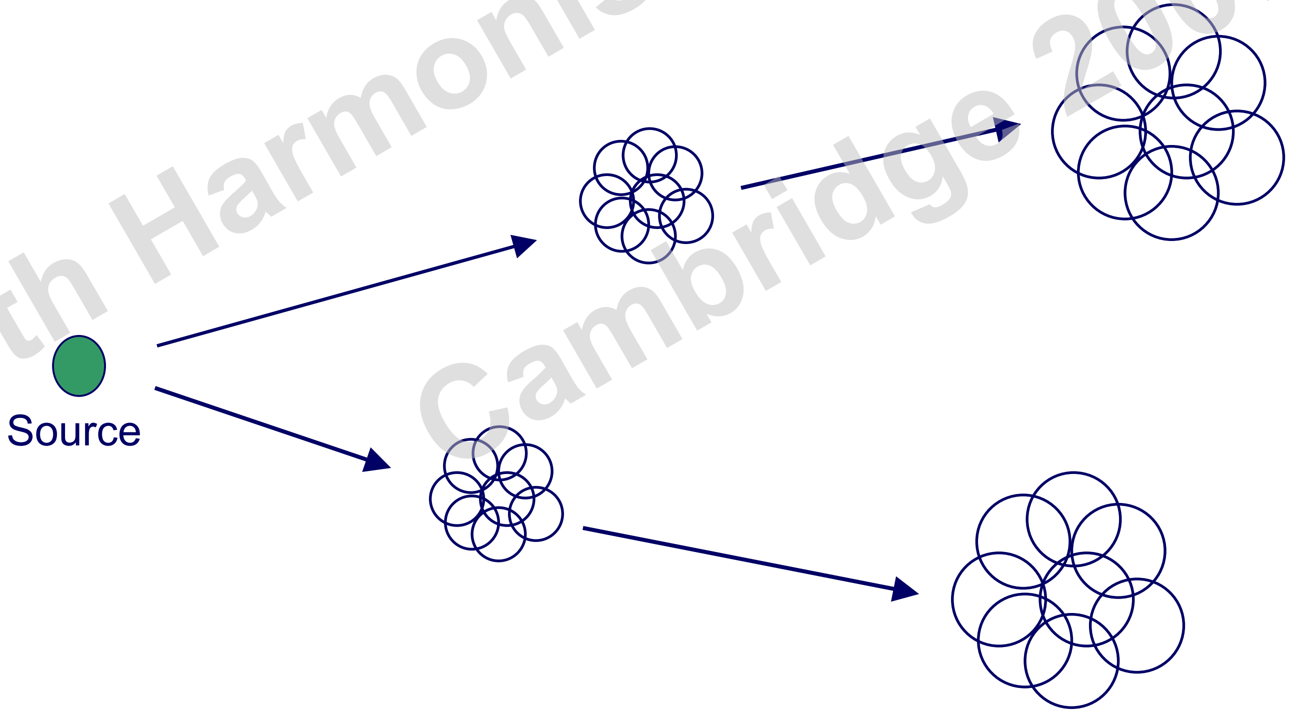


(z_r = centre of mass of reflected puff)

- This ensures a uniform vertical distribution at large times (the model supports the correct well-mixed state once the puffs have stopped growing)

Puff model – formulation

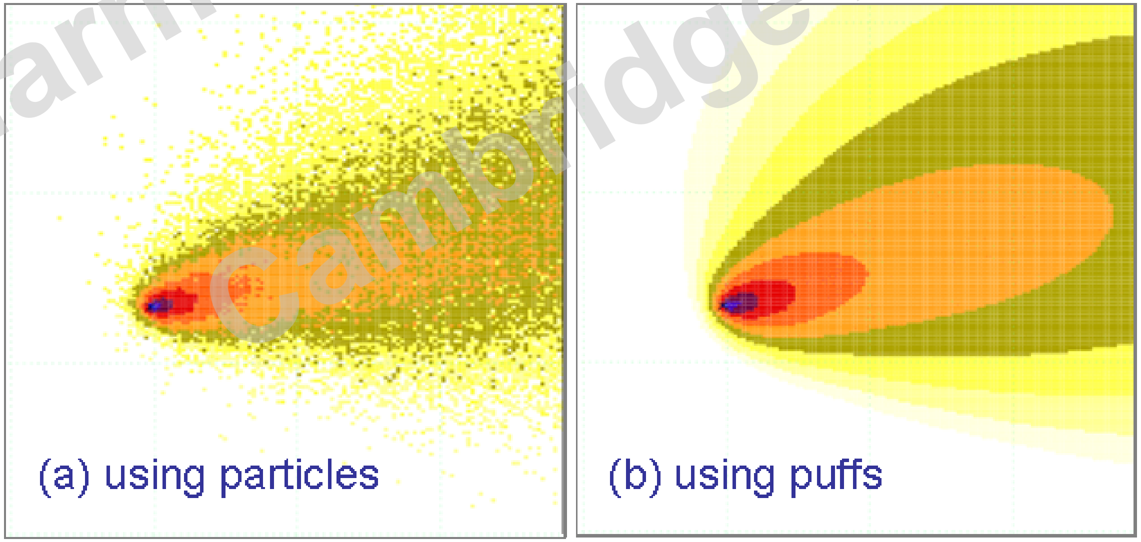
- For continuously emitting sources puffs have a spread in time
- Avoids need to release puffs more often than required to represent changing meteorology



Puff model – results

- Puff model incorporated as an option within "NAME"

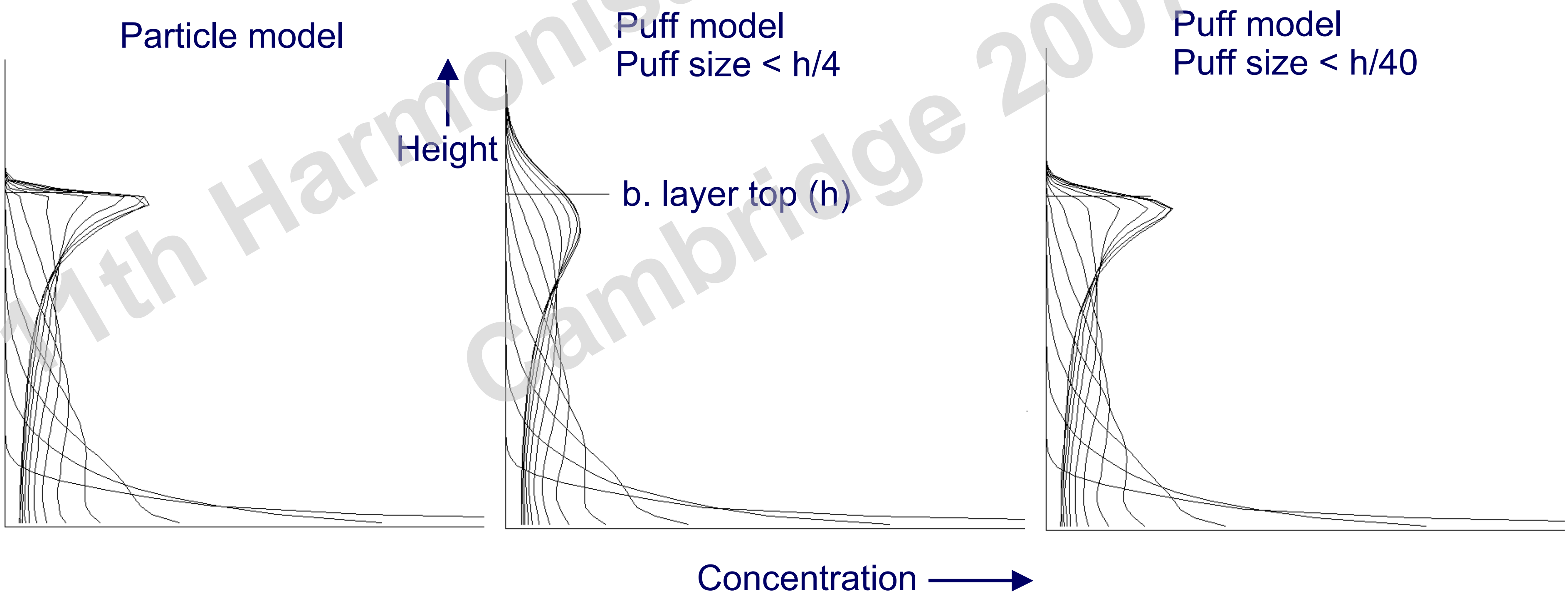
Numerical
Atmospheric Dispersion
Modelling
Environment



Puff model – results

- Near surface source in convective boundary layer (skew velocity distribution)

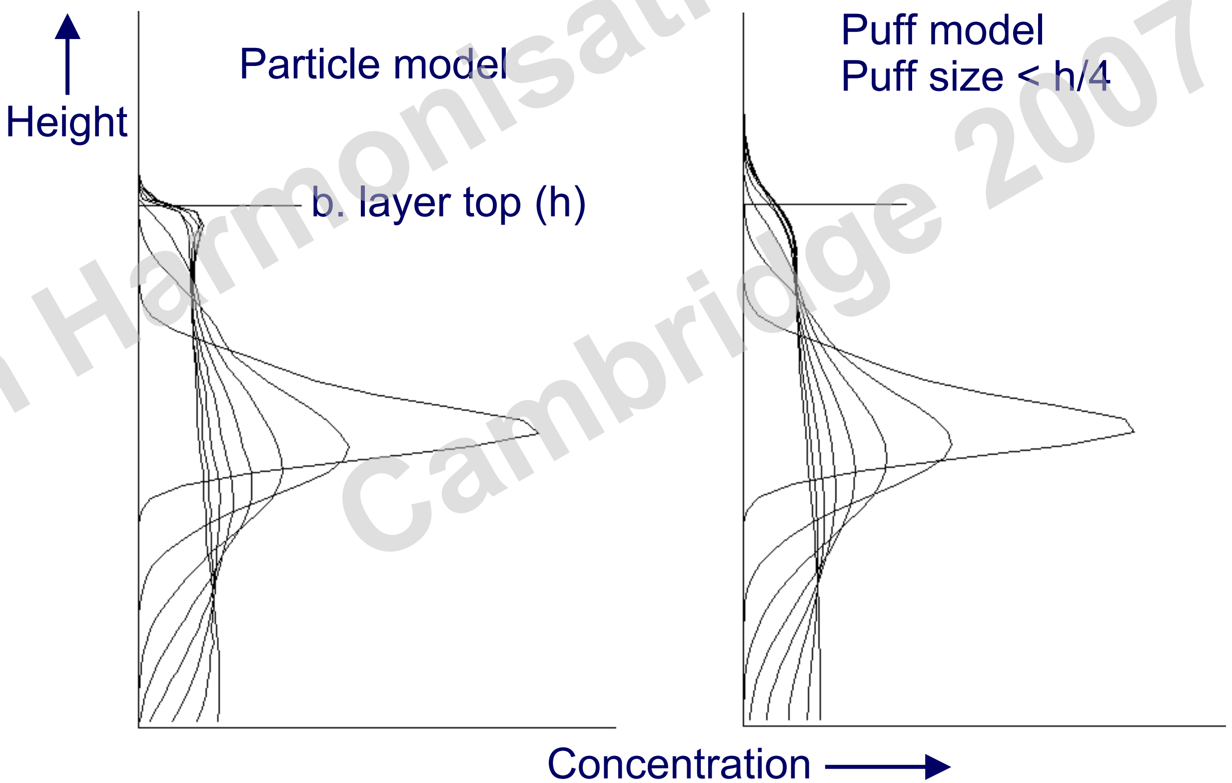
Horizontally integrated concentration at 1 min intervals:



Puff model – results

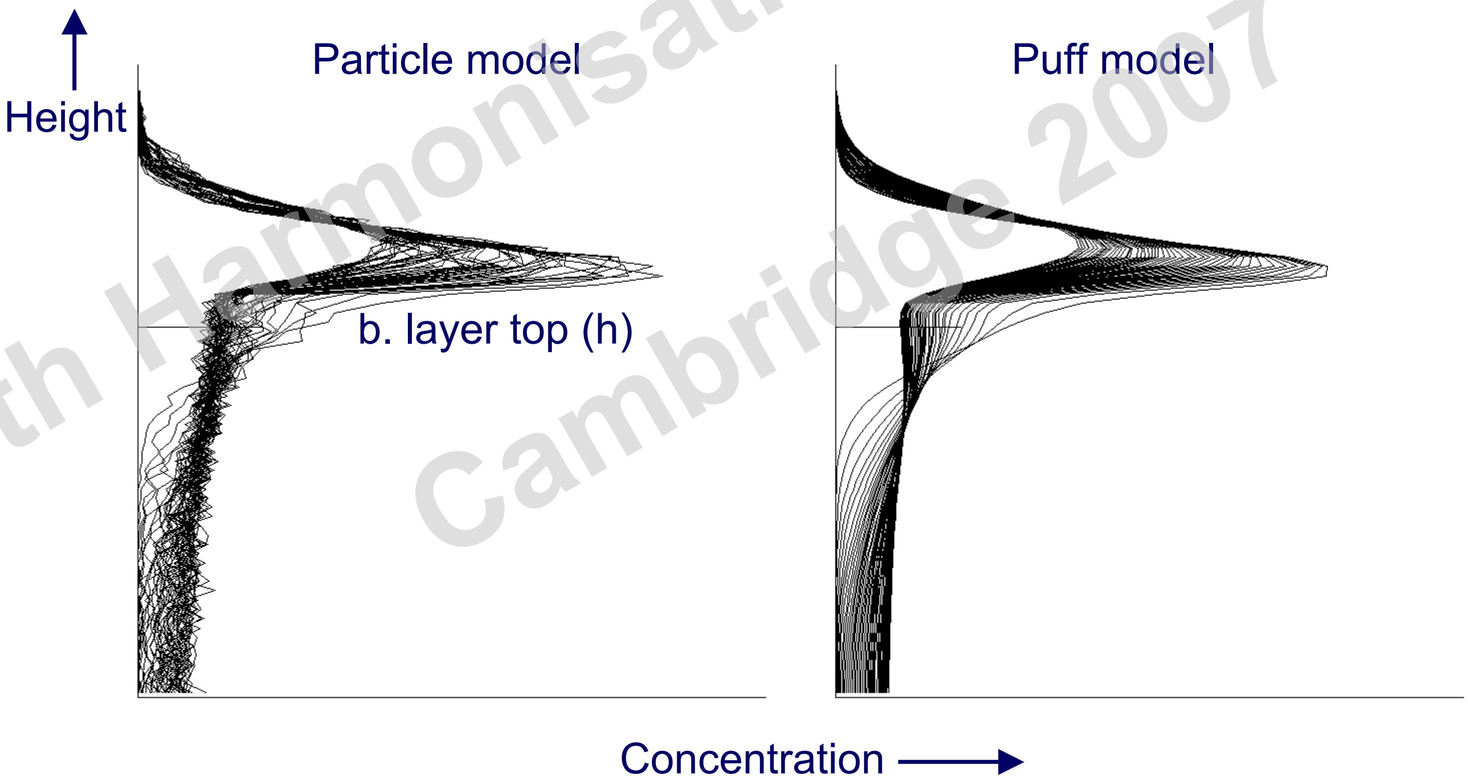
- Mid boundary layer source in convective boundary layer (skew velocity distribution)

Horizontally integrated concentration at 1 min intervals:



Puff model – results

- A fumigation example – source above a turbulent boundary layer (with low level turbulence above b. layer)



Puff model – Comparison with Kincaid

- Comparison with Kincaid experiment
  - Power station stack in the USA
  - Mostly convective met conditions
- Puff model used with Webster and Thomson (2002) plume rise model (within NAME III modelling system)

Normalised mean square error	Fractional bias	Correlation	Fraction within a factor of 2	Fractional bias in std deviation
0.62	–0.025	0.47	0.737	–0.086

(Comparisons of ground-level centre-line concentrations as function of downwind distance – "quality 3" data only)

Summary

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Met Office

- Puff model designed to approximate Lagrangian particle model
- Reduced statistical noise and smoothly varying concentration
- Tunable for accuracy v. cost
- Can accurately reproduce skew CBL behaviour
- Good performance against the Kincaid experiment

- In future we hope to
  - Test against more experiments
  - Extend to longer range