Simulating clouds using a massively parallel parcel-based framework

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1) An essentially Lagrangian model

- Traditional LES models: numerical diffusion hard to avoid.
- Diffusion erodes high LWC regions which are crucial for precipitation.
- **M**oist **P**arcel-**I**n-**C**ell: moist convection with vortex-in-cell method.
- MPIC uses parcels which carry vorticity, volume, liquid-water potential temperature and moisture.
- Similar approach widely used in computer graphics/movies.
- Simplified moist dynamics and thermodynamics:

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{\nabla p}{\rho_0} + b\hat{\mathbf{e}}_z\,, \qquad \frac{\mathrm{D}b_\ell}{\mathrm{D}t} = 0\,, \qquad \frac{\mathrm{D}q}{\mathrm{D}t} = 0\,, \qquad \nabla\cdot\mathbf{u} = 0$$

$$b = b_\ell + \frac{gL}{c_p\theta_{\ell 0}}\max\left(0, q - q_0 e^{-\lambda z}\right)$$

- Normalisation by volume needed to find buoyancy.
- Allows for a simple setup (Fig. 1). Initial thermal has asymmetry.
- Vorticity formulation, builds on Brackbill and Ruppel (1986), Cottet and Koumoutsakos (2000).
- Parcel splitting and merging used to represent mixing, see detailed description in Dritschel et al. (2018).

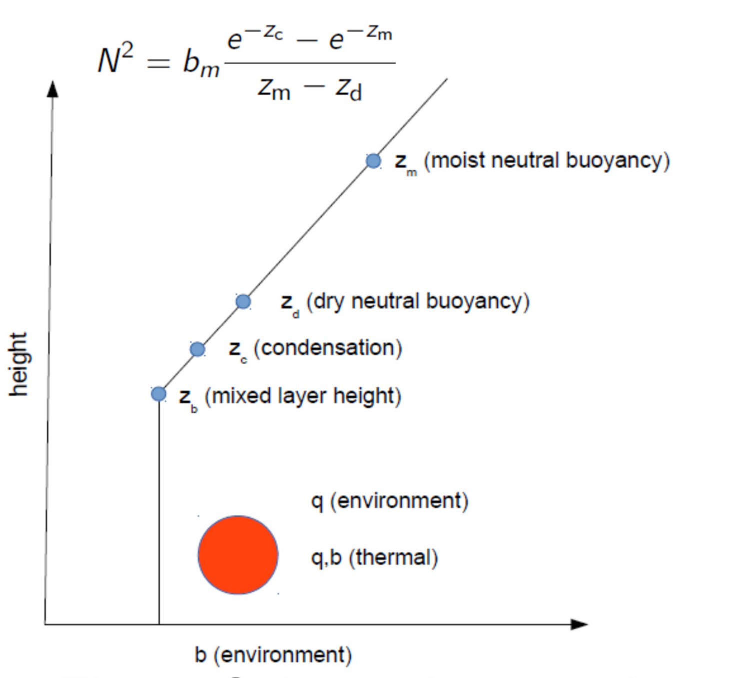


Fig. 1: Schematic setup for simulation of a single thermal.

Key benefits:
- MPIC is an efficient method, simple parcel operations used.
- Exact conservation of parcel properties.
- More physical approach to mixing.
- MPIC provides a high effective resolution compared to the solver grid: subgrid diagnostics available.
- Lagrangian diagnostics can be studied consistently (Fig. 2).

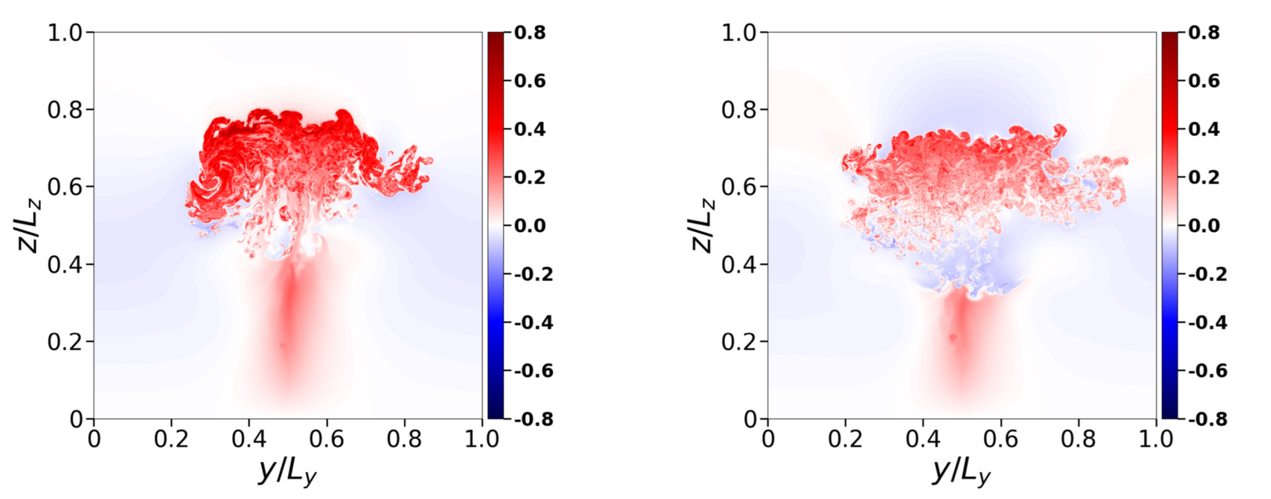


Fig. 2: Example of Lagrangian diagnostics: displacement of parcels from initial position after 6 (left) and 8 (right) time units.

2) MPIC/monc comparison

- MONC: full rewrite of the Met Office Large Eddy Model for use on modern supercomputers (Brown et al. 2015).
- Comparison to MONC with identical dynamics and thermodynamics.
- Good agreement on cross-sections (Fig. 3, Böing et al 2019) and key profiles across resolutions (differences in liquid water content PDF).

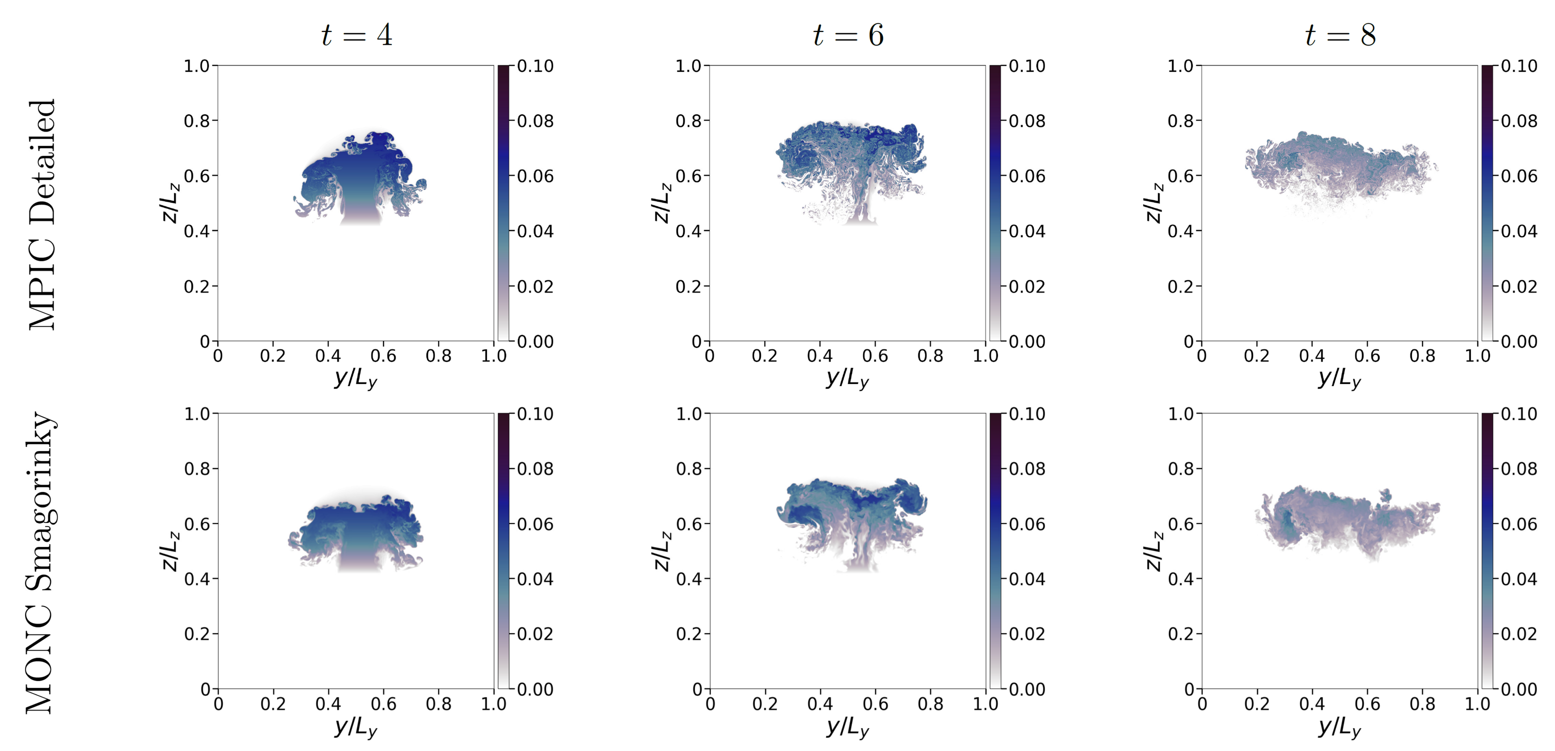


Fig. 3: Development of a cross-section of liquid water in MPIC and MONC simulations (1024^3 grid points in MONC and 384^3 in MPIC).

3) Implementation in MONC's framework

- PMPIC: eCSE grant to implement hybrid openMP/MPI parallelism using MONC's framework (Fig. 4).
- Extension of parallelism to handle parcels. New tridiagonal vorticity solver.
- Scaling influenced by: inhomogeneities in parcel density and scaling of FFT routines. Code scales well going from 5,000 to 20.000 cores (Fig. 5).
- Ability to run much larger domains due to removal of memory constraints.
- Further improvement possible by limiting calls to FFTs. Best scaling achieved with pure MPI. Cause of OpenMP issues needs further investigation (could be due to use of allocatable arrays).

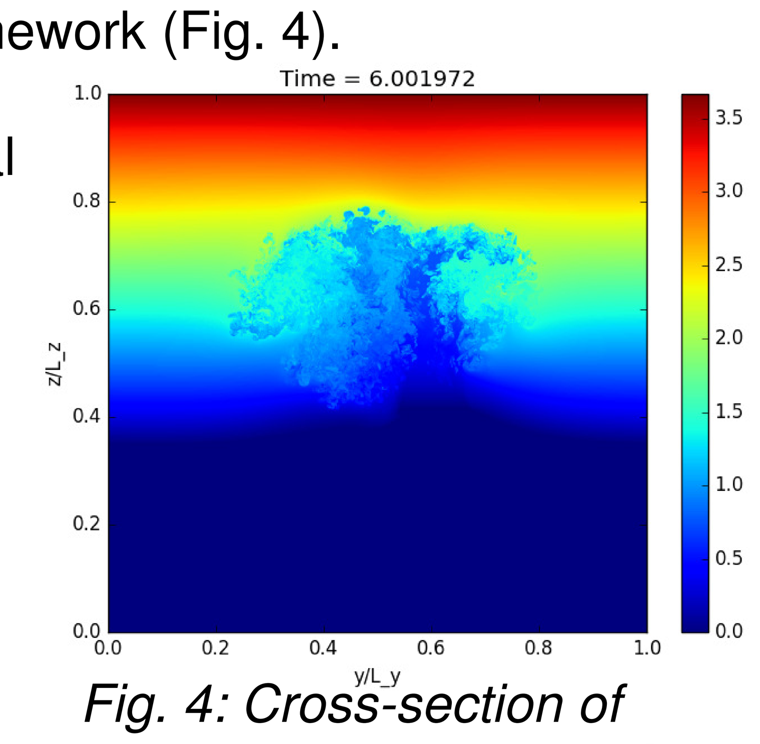


Fig. 4: Cross-section of buoyancy field on a 864^3 grid

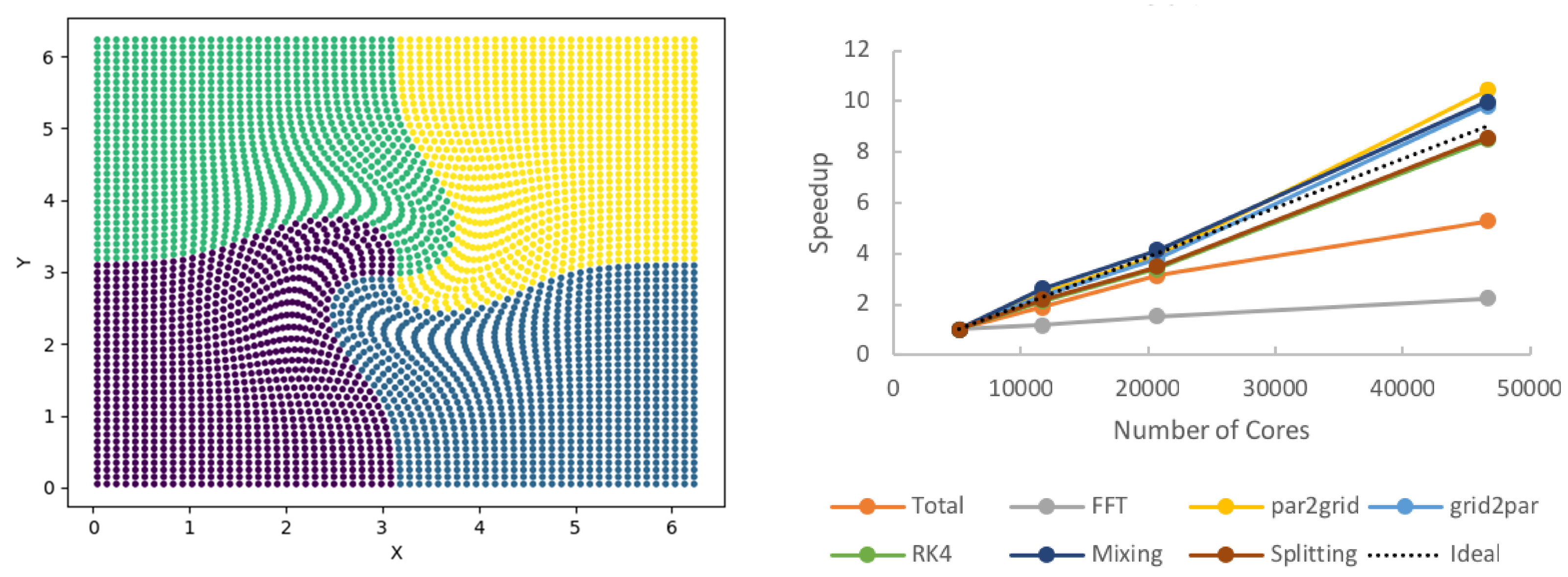


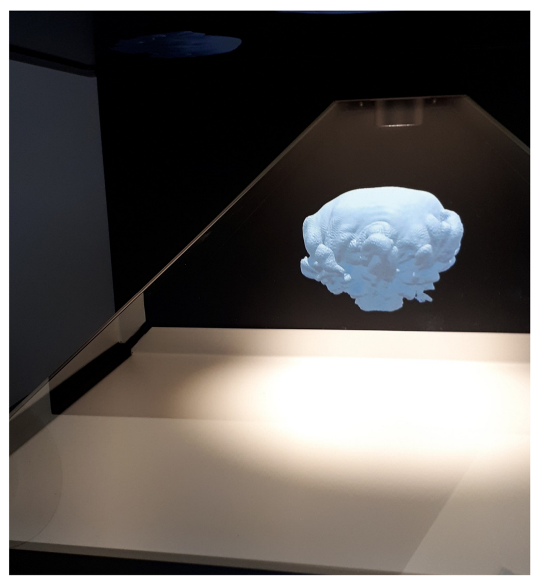
Fig. 5: Illustration of tests for checking parcel parallelism (left) and scaling of the code on a 864^3 domain (~ 12 parcels/cell, right)

4) Future plans

Dynamics and thermodynamics
- Ongoing: surface fluxes, large-scale tendencies, Coriolis force.
- Anelastic version with more realistic saturation adjustment scheme.
- Standard cases (e.g. BOMEX/ARM).

Microphysics and chemistry
- MPIC would be a good match with a superdroplets-based model for microphysics, as MPIC already follows a Lagrangian approach. Water loading could be easily incorporated.
- Advection of many microphysical/chemical/dust species is cheap.
- Looking for collaborations on this topic.

Other
- MPIC could be applied to range of geo/astrophysical problems.
- New pathways to parametrisation using a parcel-based approach (i.e. using parcels to represent clouds)
- Visualisation on pyramid display (photo).



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References: Böing, Dritschel, Parker and Blyth (2019) "Comparison of the Moist Parcel-in-Cell (MPIC) model with large-eddy simulation for an idealized cloud." *Quart. J. Roy. Meteorol. Soc.*
Brackbill and Ruppel (1986) "FLIP: A method for adaptively zoned, particle-in-cell calculations of fluid flows in two dimensions" *J. Comp. Phys.*
Brown, N., Weiland, M., Hill, A., Shipway, B., Maynard, C., Allen, T., and Rezny, M. (2015). "A highly scalable Met Office NERC Cloud model." In: *Proc. 3rd Internat. Conf. on Exascale Applications and Software.*
Cottet and Koumoutsakos (2000) "Vortex methods"
Dritschel, Böing, Parker and Blyth (2018) "The moist parcel-in-cell method for modelling moist convection." *Quart. J. Roy. Meteorol. Soc.*

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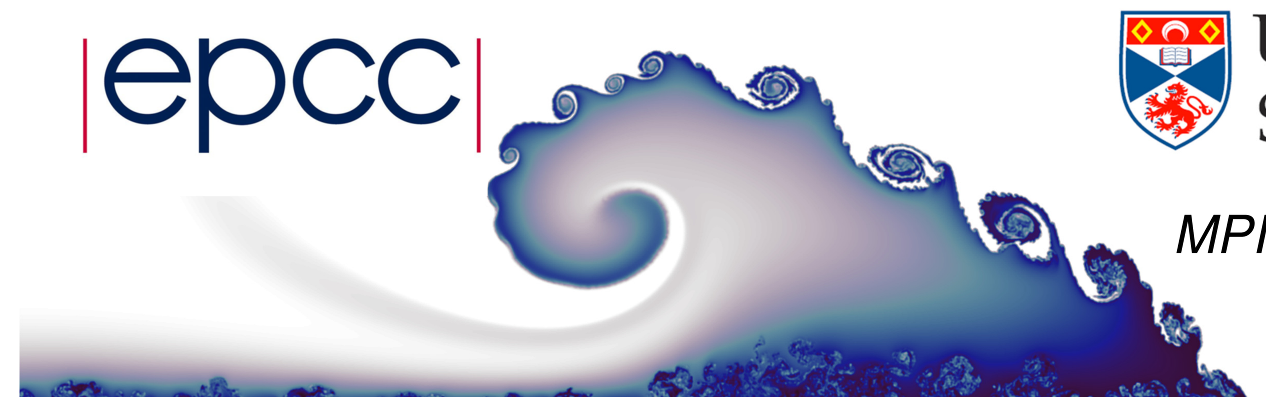

MPIC downdraught simulation

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