Essentially Lagrangian simulation of cloud ensembles

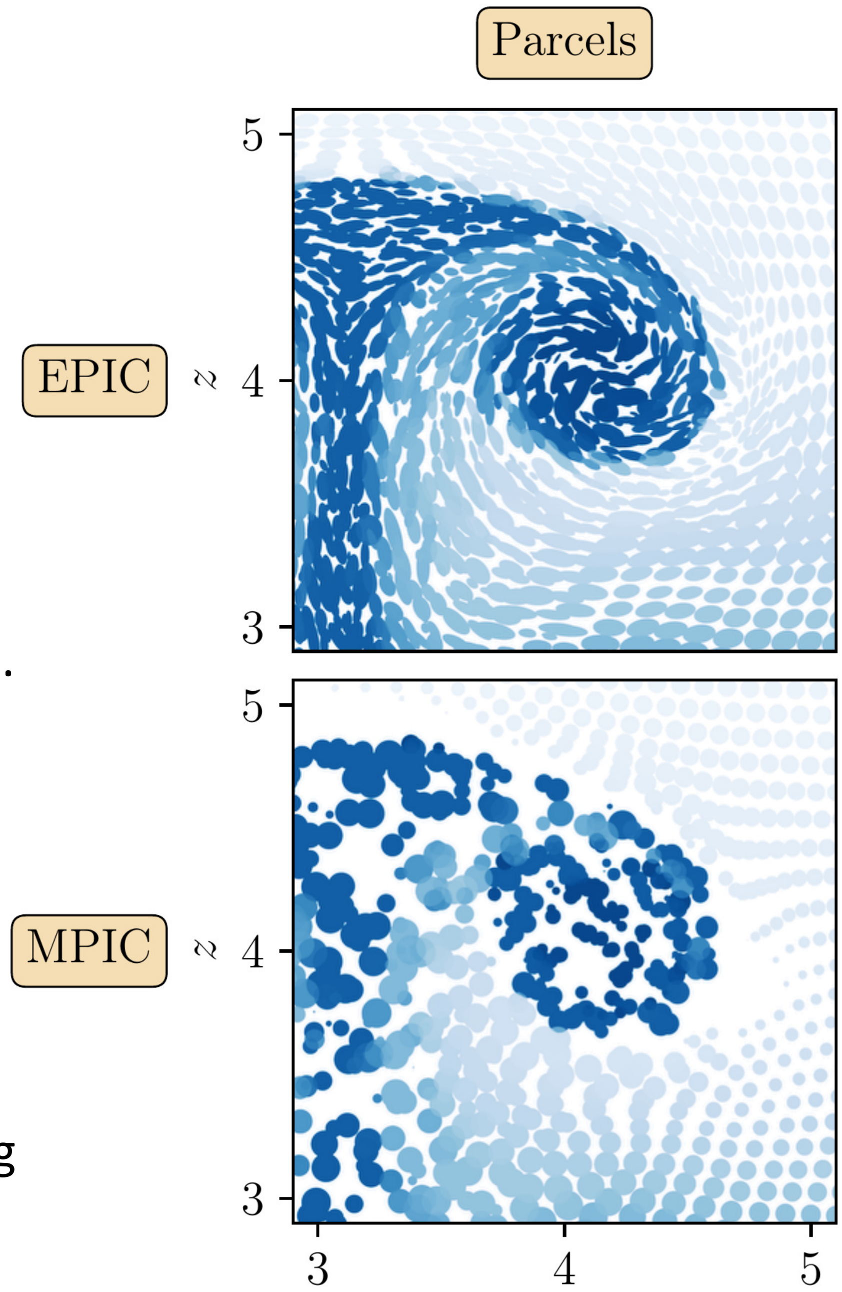
UNIVERSITY OF LEEDS

The EPIC model

The Elliptical Parcel-in-Cell (EPIC) model is a new 2D and 3D geophysical fluid dynamics model based entirely around **Lagrangian parcels**. This goes beyond the semi-Lagrangian approach, which uses a Lagrangian framework for advection but is still largely grid-based.

The parcels in EPIC represent both the **thermodynamic and the dynamical prognostic properties** of the flow. An efficient grid-based solver calculates parcel advection velocities, but diffusive regridding operations are avoided. The Lagrangian approach of EPIC has several advantages that are particularly relevant to moist convection and chemistry: thermodynamic/tracer properties and their correlations are naturally conserved, and the amount of mixing between parcels is explicitly controlled.

EPIC builds on a previous model, the Moist Parcel-in-Cell model, which used spherical parcels instead. It includes several **improvements** to better represent mixing and ensure parcels remain homogeneously distributed.



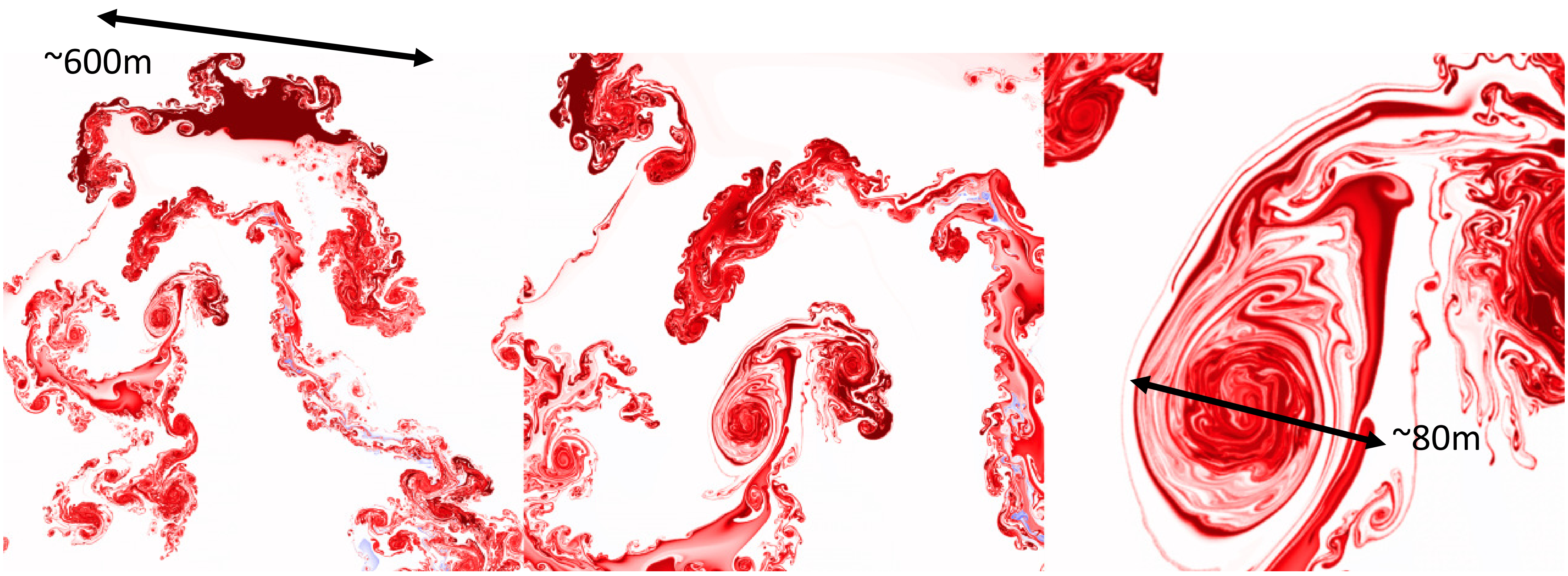
Cross-sections with parcels in 3D EPIC and MPIC coloured by moisture content, showing the homogeneous distribution of EPIC parcels (Frey, Dritschel and Böing, in review).

The **shape** of the parcels in EPIC is given by a matrix **B**, which satisfies $\mathbf{x}^\mathsf{T}\mathbf{B}^{-1}\mathbf{x} = 1$ and evolves under strain as

$$\frac{d\mathbf{B}}{dt} = \mathbf{B}\mathbf{S}^\mathsf{T} + \mathbf{S}\mathbf{B}.$$

Mixing is represented by the stretching of parcels, splitting of very stretched (large aspect-ratio) parcels, and merging of parcels that have become small due to successive splitting.

Progressive zoom into a 2D EPIC buoyancy field (Frey, Dritschel and Böing, JCP-X, 2022).



Steven Boeing: my involvement is largely in making this work for atmospheric flows. Much of the work has been led by Matthias Frey and David Dritschel (St Andrews). Leeds collaborators: Doug Parker, Alan Blyth and Domantas Dilys.

EPIC eye candy: but does it work?

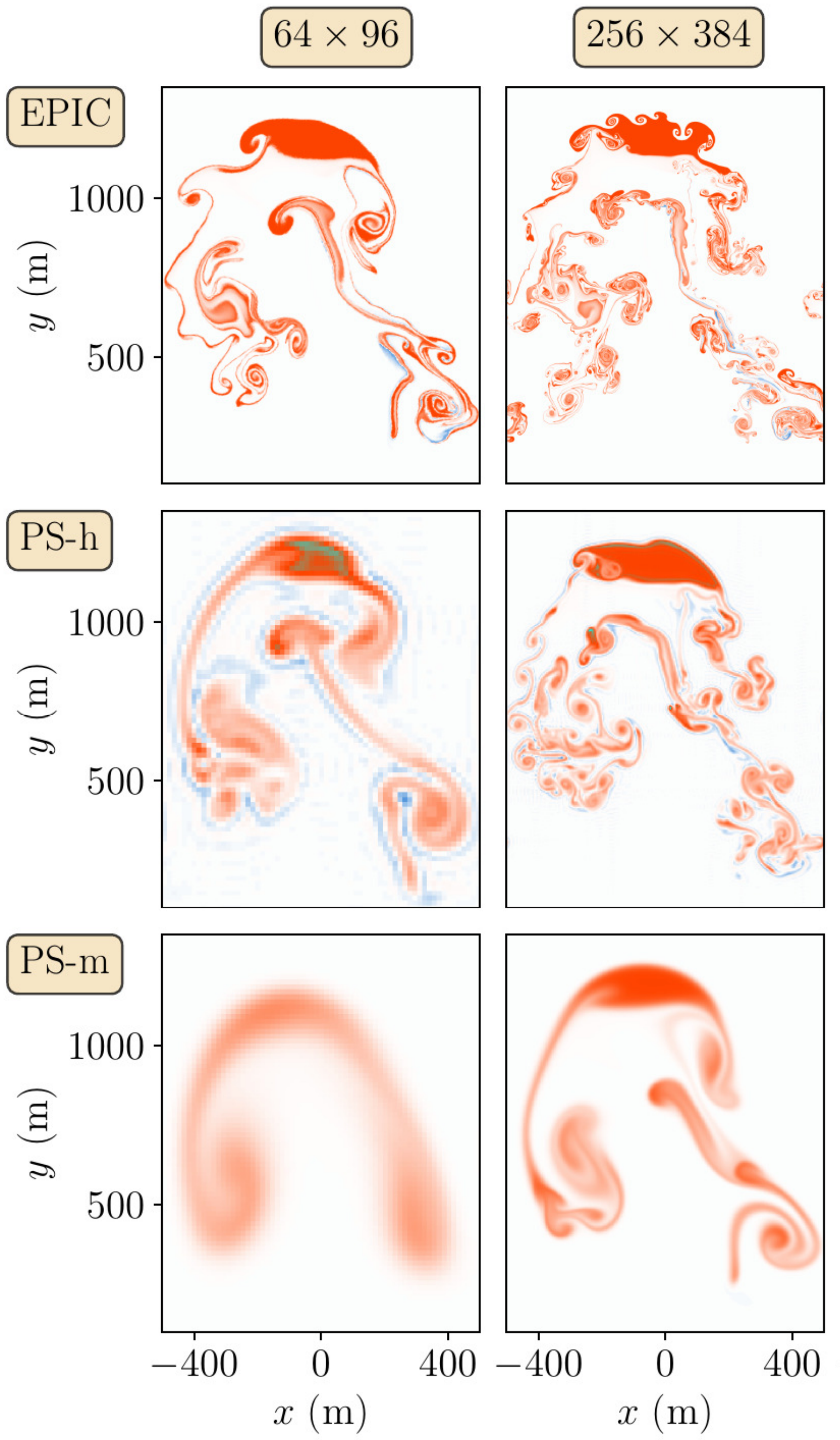
We are keen to apply EPIC to a large number of geophysical fluid dynamics flows, including moist convection (cumulus clouds).

We tested EPIC on several demanding **test cases**:
- A 2D turbulent warm bubble.
- A 2D Taylor-Green flow: this is an analytical solution to the Navier-Stokes equations, which allows us to estimate the effective viscosity of our mixing model.
- A 2D density current, where vortices develop at the gust front.
- A 3D Beltrami flow. This is an unstable analytical solution to the (inviscid) Euler equations, and a good test case for free-slip boundary conditions.
- A 3D flow that is initially unstably stratified (a variation on Rayleigh-Taylor instability with large-scale instabilities).
- An idealised 3D cumulus cloud without precipitation, following up on our MPIC studies.

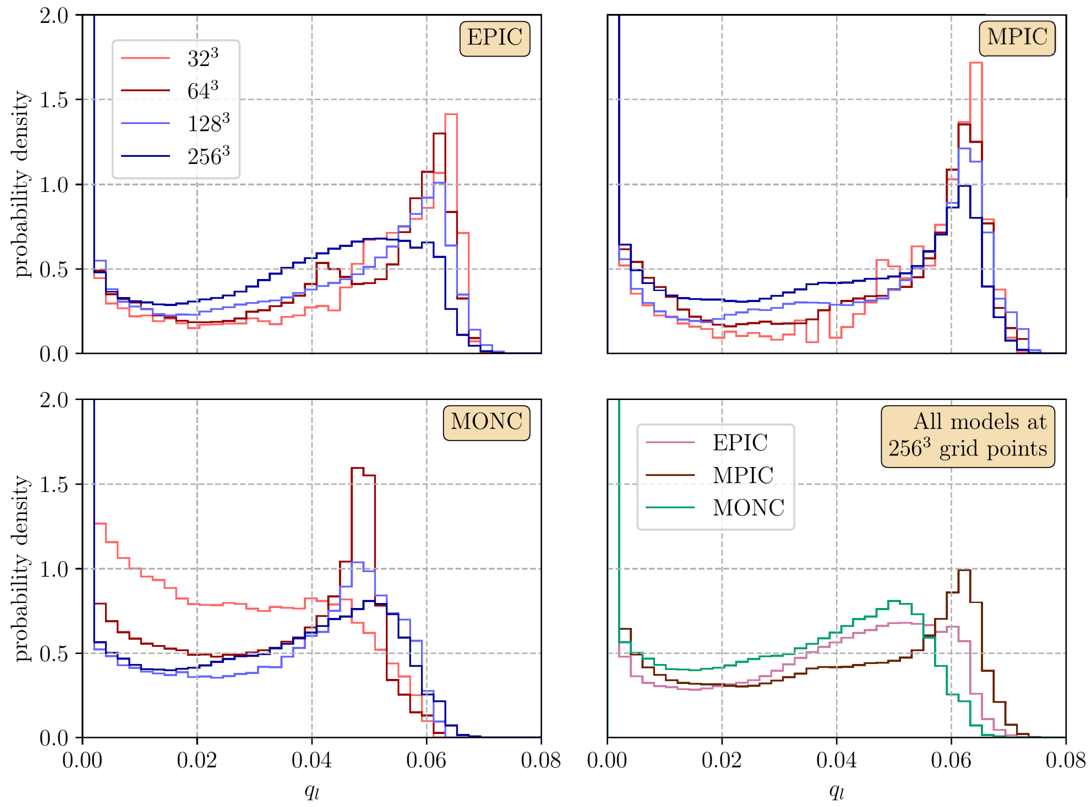
We used both **qualitative** (e.g. cross-sections) **and quantitative** (e.g. histograms, spectra, minima and maxima) **comparisons**, as well as resolution convergence studies to evaluate EPIC.

A key property of EPIC that is beneficial for application to buoyant flows, moist convection, and chemistry is that both advection and mixing are **monotonic** (they do not create larger minima and maxima). EPIC can also resolve much finer-scale structures than LES or pseudo-spectral approaches.

An example of a **convergence study** is given on the right. At high resolution, EPIC's histogram of liquid water content is in between the behaviour of MPIC and MONC (LES). At low resolution, MONC has too many grid cells with low liquid water content, whereas EPIC appears to have too many cells with high liquid water content.



Comparison of a 2D turbulent warm bubble simulation (buoyancy) in EPIC and a pseudo-spectral model (Frey, Dritschel and Böing, JCP-X, 2022).



Liquid water content histograms as a function of grid spacing, for MPIC, EPIC and MONC (Frey, Dritschel and Böing, in review).

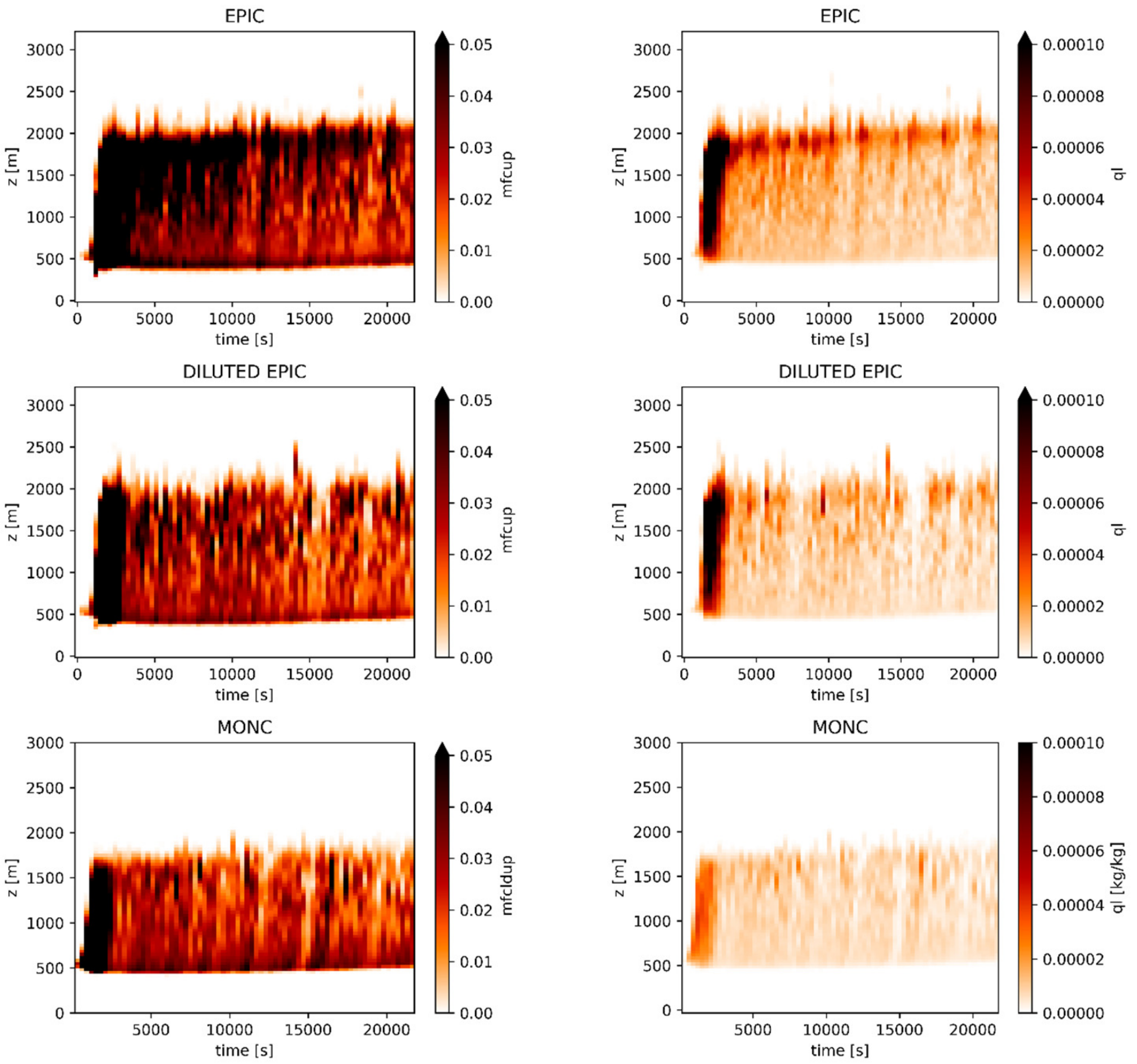
Addressing the convergence issues

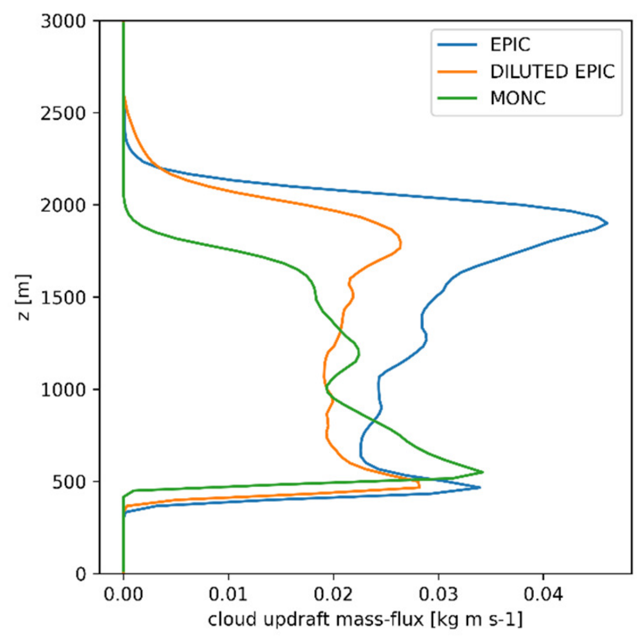
We are looking at a way to represent the effect of **unresolved mixing** in EPIC. The approach is inspired by **Richardson's law** for the growth of a patch of fluid, and a **Smagorinksy model** for dissipation rate (although other models could be used). This results in a simple Lagrangian subgrid model, where parcels grow in volume and dilute. Volume growth depends on strain and grid spacing.

$$dV/dt = P|\tilde{S}|\Delta^{2/3}V^{7/9}$$

Influence of mixing on BOMEX simulations

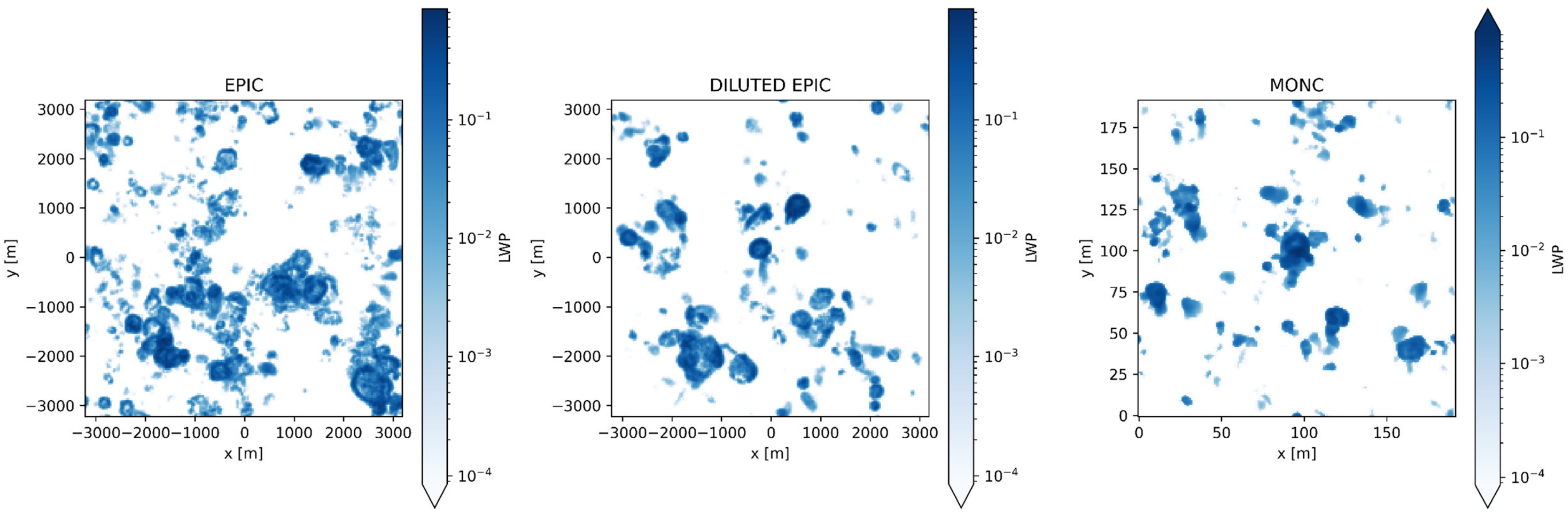
As a first realistic test case, we look at **BOMEX**. In order to perform these simulations, we implemented **realistic thermodynamics, large-scale forcings** and **surface fluxes of heat and moisture.** The mean wind profile is currently set by nudging it to an idealised profile based on the DALES simulations as we haven't yet implemented surface momentum exchange.





Vertical profiles of liquid water and mass-flux in EPIC and MONC BOMEX simulations. The line plot shows averages over the final 150 minutes of the simulation.

The inclusion of a subgrid model influences key properties of the simulated cumulus clouds, including the **mass-flux and liquid water content profiles,** and the **spatial organization of cloud liquid water path.** Vortex rings are clearly visible in EPIC liquid water path.



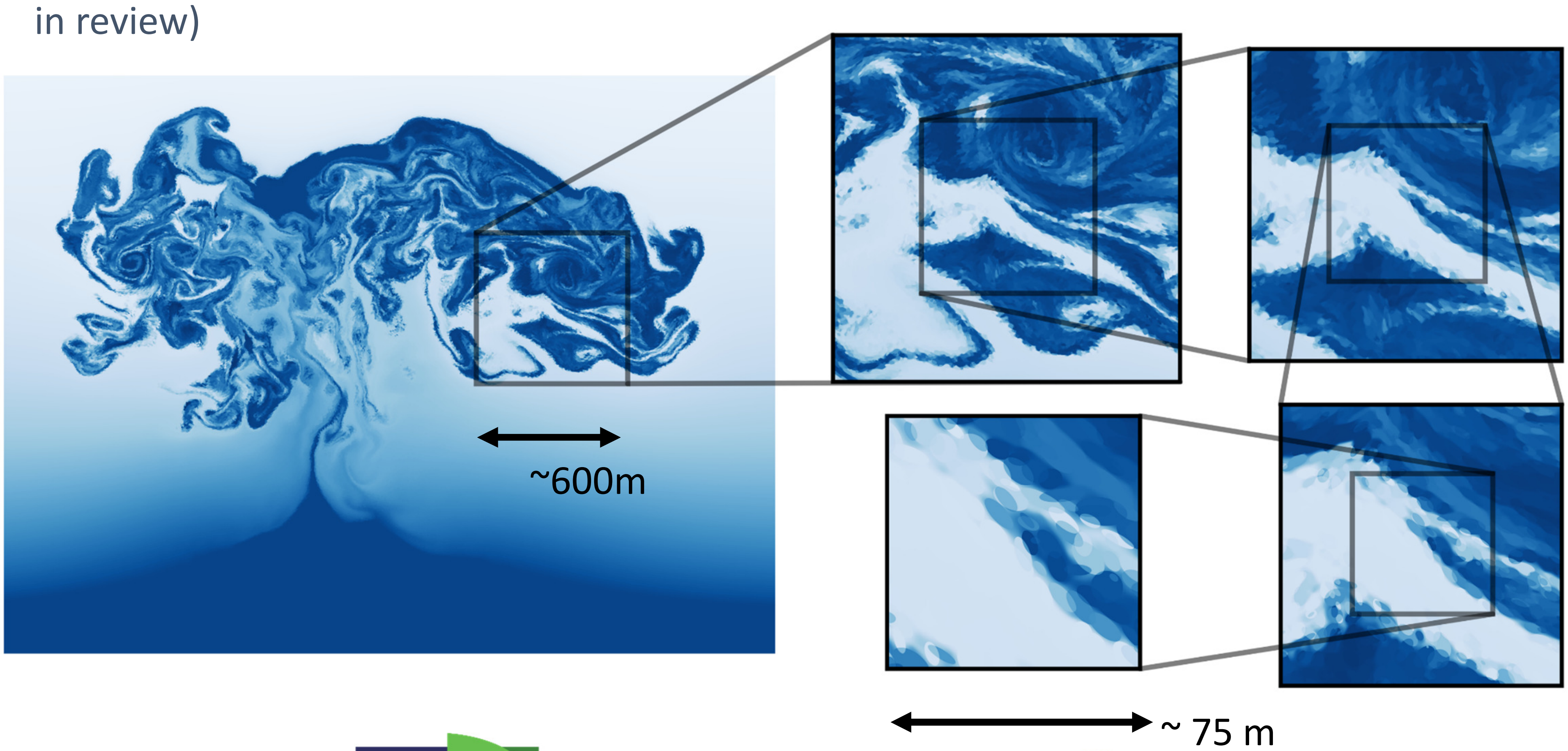
EPIC plans

- Further improve the approach to mixing at low resolution, to address convergence.
  * Add stochastic term to parcel movement?
  * Parcel-parcel interactions?
- We plan to revisit the classical problem of a **growing boundary layer** in a constant stratification. Adding surface momentum exchange would be a next step.
- The main feature missing in EPIC is a treatment of **precipitation**. We want to exploit the Lagrangian nature of the code and the ability to split and merge parcels. The challenge will be to ensure the approach is both computationally affordable and accurate, using a single moment or two-moment approach for each "precipitation parcel".

A cloud simulated with EPIC's predecessor, PMPIC (vis: Domantas Dilys).

- As part of the NERC **CLOUDYTIME** project, we will add a **two-moment cloud droplet scheme** to EPIC. This will allow us to study the coupling between droplet microphysics and dynamics at the cloud edge in a unique way.
- EPIC is ideal for **chemistry**, as different species don't need to be advected separately. We plan to look at a simple test case as part of our current work.
- We would like to apply this model at **every scale**: from lab experiments to the Hadley cell.

Progressive zoom into a 3D EPIC cloud simulation moisture field (Frey, Dritschel and Böing, in review)



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