

Modeling particle growth by condensation and deposition in turbulent mixed-phase cloud volumes

A doctoral dissertation by
Daniel G. Albuquerque 

Supervisor: **Prof. Dr. Hab. Hanna Pawłowska** 
Institute of Geophysics, Faculty of Physics, University of Warsaw

Co-supervisor: **Dr. Gustavo C. Abade** 
Institute of Geophysics, Faculty of Physics, University of Warsaw



UNIVERSITY
OF WARSAW

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Abstract

Mixed-phase clouds play a central role in the Earth’s radiation budget and hydrological cycle, yet their microphysical evolution remains one of the largest sources of uncertainty in atmospheric modelling. A key difficulty arises from the interaction of turbulent fluctuations with nonlinear phase-change processes, such as the Wegener–Bergeron–Findeisen (WBF) mechanism, which are typically parameterised in large-scale models under the assumption of spatial homogeneity. A series of numerical and experimental studies suggest that neglecting subgrid fluctuations can lead to systematic biases, most notably an artificially rapid depletion of supercooled liquid water by the WBF process. At the same time, cloud measurement campaigns provide abundant observations of long-lived mixed-phase clouds that are rich in liquid water content.

This thesis develops and applies a stochastic Lagrangian parcel model to investigate the limitations of the mean-field assumption and to quantify the impact of turbulence on mixed-phase microphysics. In this framework, individual cloud droplets and ice crystals are embedded in a modelled turbulent environment, represented by Gaussian stochastic velocity fluctuations combined with a deterministic mixing model. For the purpose of representing the intrinsic heterogeneities of turbulent environments, each cloud particle carries forward its own independent history of velocity fluctuations, and is assumed to interact – growing by condensation and evaporating, while providing microphysical feedback – primarily with its immediate vicinity, with their thermodynamic and microphysical properties evolving according to fundamental conservation laws. Interactions with other particles are mediated through a modelled mixing mechanism characterised by a single timescale, tuned in accordance with inertial-range turbulence scaling laws.

Our model bridges the gap between overly simplified bulk schemes and computationally prohibitive direct numerical simulations, providing a framework of intermediate complexity within the cloud model hierarchy. By explicitly resolving subgrid-scale variability, the stochastic approach reveals extended persistence of liquid water, modified growth rates and activation of ice crystals, and a distinct supersaturation dynamics that traditional homogeneous parcel models are unable to reproduce. Although observed in an idealised framework, these effects prove robust across a range of initial conditions and turbulence intensities, indicating

that unresolved-scale turbulence might play an important role in the development of the microphysical state in mixed-phase clouds.

These results open clear opportunities for further model refinement and integration into larger-scale frameworks. Our approach allows for the replacement of the turbulent mixing model by more elaborate ones, while keeping the rest of the formulation unchanged. Most importantly, its ability to capture the impact of fluctuations on phase-change processes makes it a promising candidate for subgrid parameterisation in large-eddy simulations, where the representation of mixed-phase microphysics remains a major source of uncertainty. In this role, the present work provides both a physically grounded and computationally tractable route toward improving the fidelity of cloud models across scales.