ParCFD2022
33^{rd} International Conference on Parallel Computational Fluid Dynamics
May 25-27 2022, Alba Italy

MICROPHYSICAL TIME SCALES AT A WARM CLOUD TOP BOUNDARY

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Key words: DNS, Cloud microphysics, Mixing, Supersaturation, Microphysical timescales

Abstract. We have analyzed the supersaturation balance in the region bordering the cloud and undersaturated ambient, which is typically a highly intermittent shearless turbulent mixing layer, under a condition where there is no mean updraft. We have compared horizontal averages of the phase relaxation, evaporation, reaction and condensation times within the cloud-clear air interface for the size distributions of the initial monodisperse and polydisperse droplets. For the monodisperse population, a clustering of the values of the reaction, phase and evaporation times, that is around 20-30 seconds, is observed in the central area of the mixing layer, just before the location where the maximum value of the supersaturation turbulent flux occurs. This clustering of values is similar for the polydisperse population but also includes the condensation time. The mismatch between the time derivative of the supersaturation and the condensation term in the interfacial mixing layer is correlated with the planar covariance of the horizontal longitudinal velocity derivatives of the carrier air flow and the supersaturation field, thus suggesting that a quasi-linear relationship may exist between these quantities.

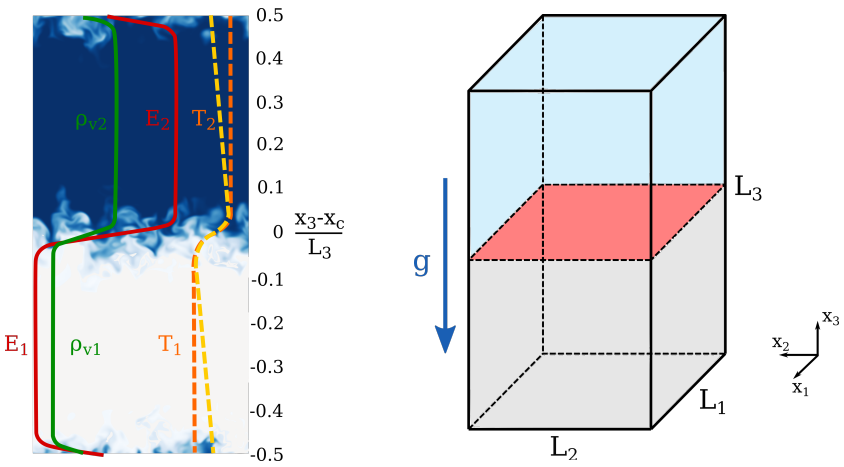
DISCUSSION

The supersaturation balance within a cloud is often described by means of a production-condensation model of the type proposed by [1], where the mean updraft velocity w and the mean radius of the droplet population $\overline{R}$ are the main contributors to the time derivative of S

$$\frac{dS}{dt} \cong c_1 w - \frac{S}{\tau_{phase}} \tag{1}$$

where $\tau_{phase} = (c_2 n_d \overline{R})^{-1}$ is the phase relaxation timescale, n_d is the droplet number density and c_1, c_2 are coefficients that depend, albeit only slightly, on the temperature, c_1 and temperature/pressure, c_2 [2]. Cooper (1989)[3] described a theoretical framework in which the variability of S.

The aim of the present work is twofold: i) to compute and compare the various microphysical time scales in the cloudy - clear air interfacial layer; ii) to infer a possible source term for Twomey's equation (1) that accounts for the small-scale statistics of the carrier flow at a cloud-top boundary where the updraft is null. We have used the dataset from the direct numerical simulations by Golshan et. al (2021)[4], where we adopted a high-resolution pseudospectral method (see Tordella et. al (2011)[5]).



(a) (b)

Figure 1: (a) Initial distributions of kinetic energy E, water vapor density ρ_v and temperature T in the vertical direction across the interfacial mixing layer. The temperature fluctuation is plotted with yellow the dash-dotted line, while the non-periodic physical temperature T is plotted with the orange dash-dotted line. (b) The computational domain is a parallelepiped composed of two adjacent cubes, where $L_3 = 1.024\,m$ and $L_{1,2} = 0.512\,m$.

All the numerical experiments have been performed over a 3D $512^2 \times 1024$ cartesian mesh grid, see Figure 1. The governing equations are the incompressible Navier-Stokes equations, with the Boussinesq approximation for both temperature and vapour density, and active scalar transport equations for the water vapour and the thermal energy. The inertial cloud water drops are represented via a Lagrangian approach, including Stokes drag and gravitational settling. This representation is coupled to the vapor and temperature equations through their respective evaporation-condensation source terms (see Fossa et. al (2022)[6] and Golshan et. al (2021)[4] for the complete description of the physical system).

The condensation-evaporation rate of the spherical k-th droplet can be estimated according to [3]

$$\frac{dR_k}{dt} = \frac{K_s}{R_k} S \tag{2}$$

where $S = \rho_v/\rho_{sv} - 1$ is the supersaturation and K_s is the droplet growth coefficient equal to $8.6 \cdot 10^{-11}$ m^2/s.

The horizontal planar average values of microphysical time scales are plotted for two different time instants and the initial droplet size distribution type in the cloud and mixing regions, see Figure 2. The condensation and evaporation times diverge toward values of the order of 10^3 seconds at the saturation location, $S = 0$, where they are not defined. The phase relaxation time, τ_{phase}, elongates across the mixing layer as the mean radius and the droplet concentration decrease. In time, the τ_{phase} growth rate smoothes out as

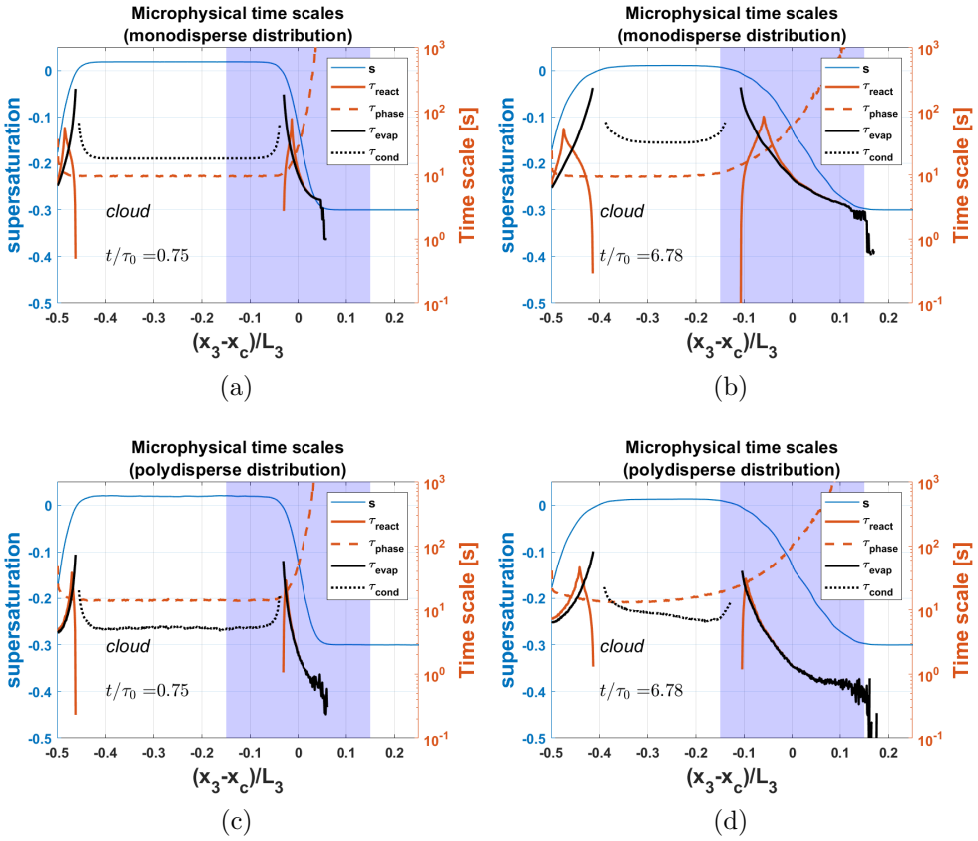


Figure 2: **Microphysical time scales and mean supersaturation in the cloud and interfacial mixing regions**. Vertical distribution of the evaporation, $\tau_{evap} = -R_0^2/(2K_sS_0)$, condensation, $\tau_{cond} = 3\,R_0^2/(2\,K_sS_0)$, phase relaxation, $\tau_{phase} = \left(4\pi\kappa_v N\overline{R}\right)^{-1}$, and reaction, τ_{react} - the shortest time that has elapsed since either the droplet has evaporated completely or the parcel has become saturated, time scales computed inside each grid cell and then averaged on horinzontal planes. The data are displayed for the monodisperse (a, b) and the polydisperse (c, d) cases for two different time instances. The planar average of supersaturation $\overline{S}$ is also given for comparison.

the layer widens. The fact that τ_{phase} grows indefinitely in the diluted interfacial region is not surprising and was also observed during the in-situ measurements of shallow cumulus clouds by Siebert and Shaw (2017)[7].

The most interesting observation is that there is a location inside the mixing layer where the phase relaxation, the reaction time and the evaporation time cluster together. This location precedes the location where the turbulent fluxes maximize. By comparing the distributions in Figure 2 with the distribution of the turbulent supersaturation flux, see Fig.2 in [6], it is possible to see that the clustering of the microphysical times takes place at almost the same location, where the flux rate is close to a maximum. The microphysical times separate before and after this location. In particular, the reaction

time is much shorter than the evaporation and phase relaxation times before this location. The reaction time then collapses to the evaporation time, which is much shorter that the phase relaxation time. In the polydisperse case, the clustering of the microphysical times also includes the condensation time, as expected, since condensation often occurs rapidly in the spectral range of the drops with a small radius for these populations. The evaporation time on the right hand side of the panels in Figure 2 oscillates to great extent due to the higher collision rate there.

We hypothesize that the small-scale turbulent fluctuations may contribute to the overall local supersaturation balance. In order to assess this hypothesis, we looked for the proportionality relation between: i) the difference in the planar averages of the supersaturation time derivative and the condensation term, and ii) the covariance of the supersaturation and the intermittency of the small-scale, as represented by the fluctuations of the longitudinal derivatives of the velocities:

$$\overline{\frac{dS}{dt}} + \overline{\frac{S}{\tau_{phase}}} = \overline{\mathcal{P}_t} \sim \mathrm{cov}_{S,\partial u_i/\partial x_i} \tag{3}$$

This is conceptually equivalent to modeling supersaturation production as the product of the supersaturation fluctuations and the characteristic frequency of small-scale turbulent structures, $\sim \tau_\eta^{-1}$.

The relatively large absolute values of the correlation coefficients in Figure 3 confirm that a quasi-linear relation should hold between the source term $\overline{\mathcal{P}_t}$ and $\mathrm{cov}_{S\partial u_i/\partial x_i}$. An alternative way of estimating the proportionality constant, C, relevant to the dimensional quantities, along the transient is to integrate across the mixing layer of $\overline{\mathcal{P}_t}$ and $\mathrm{cov}_{S\partial u_i/\partial x_i}, i = 1, 2$:

$$\int_\Delta \left| \frac{d\overline{S}}{dt} + \frac{\overline{S}}{\tau_{phase}} \right| dx_3 \cong C \int_\Delta \left| \mathrm{cov}_{S\partial u_i/\partial x_i} \right| dx_3$$

The estimated values of the non-dimensional constant C are reported in Figure 3.

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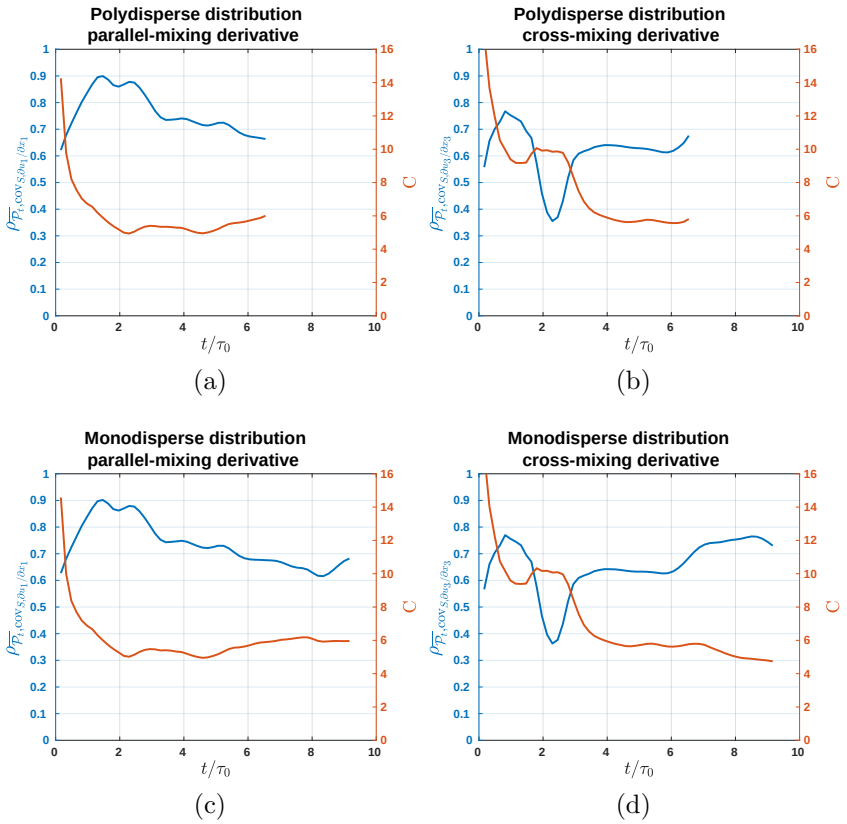

Figure 3: **Time evolution of the estimated production-planar covariance correlation coefficient and the proportionality constant**. The Pearson correlation coefficient between the turbulence production term $\mathcal{P}_t$, see equation(3), and the supersaturation-velocity longitudinal derivative covariance plotted for the horizontal (left) and vertical (right) longitudinal derivatives during the transient. The correlation coefficient peaks around the first initial eddy turnover time and slowly decreases in magnitude to an asymptote ~ 0.7 as the transient progresses.

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