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Microphysical time scales and local supersaturation balance at a warm Cloud Top Boundary

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Abstract

Recent results have shown that there is an acceleration in the spread of the size distribution of droplet populations in the region bordering the cloud and undersaturated ambient. We have analyzed the supersaturation balance in this region, which is typically a highly intermittent shearless turbulent mixing layer, under a condition where there is no mean updraft. We have investigated the evolution of the cloud - clear air interface and of the droplets therein via direct numerical simulations. 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 monodispersed 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.

1 Introduction

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 (Eq. (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]).

1.1 Numerical experiment setup

All the numerical experiments have been performed over a 3D $512^2 \times 1024$ cartesian mesh grid. 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).

2 Results

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 (1). 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 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].

3 Conclusions

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 (1) 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

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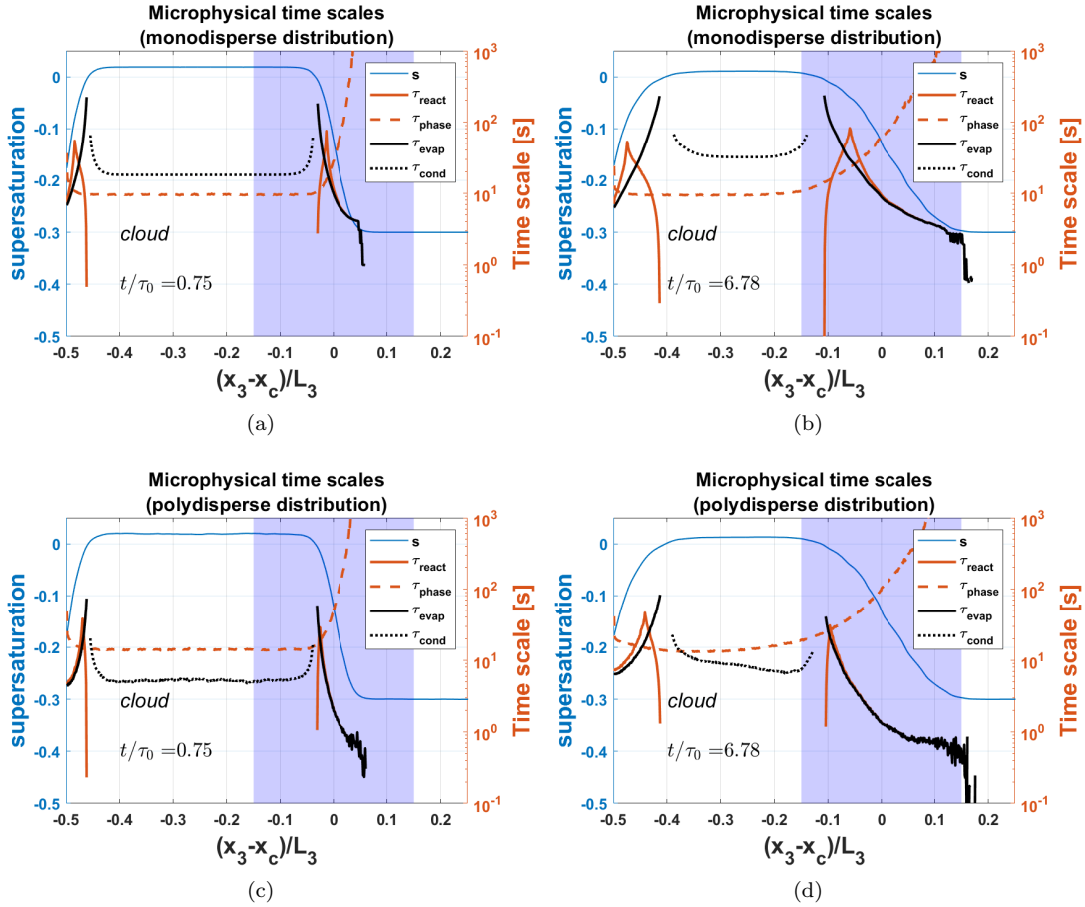

Figure 1: Vertical distribution of the evaporation, $\tau_{evap} = -R_0^2/(2K_sS_0)$, condensation, $\tau_{cond} = 3\,R_0^2/(2\,K_sS_0)$, phase relaxation, $\tau_{phase} = \left(4\pi\kappa_v N\overline{R}\right)^{-1}$, and reaction, τ_{react} - the shortest time that has elapsed since either the droplet 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.

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 (1) oscillates to great extent due to the higher collision rate there.

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