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The effect of wind velocity fluctuations on drop spectrum broadening in stratocumulus clouds

Carynelisa Erlick*, Alexander Khain, Mark Pinsky, Yaron Segal

Department of Atmospheric Sciences, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

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Abstract

In this study, a Lagrangian adiabatic parcel model and a trajectory ensemble model (TEM) are used in a sequence of experiments to investigate effects of velocity fluctuations on drop spectrum broadening in stratocumulus clouds. Using the adiabatic parcel model, it is found that even with a weakly buoyant temperature profile, if the initial updraft velocity is low enough, new drop nucleation above the cloud base region can occur via updraft acceleration accompanied by an increase in supersaturation. New nucleation can also occur via parcel recirculation as drops that have not fully evaporated during downdraft reduce the cloud base supersaturation peak in subsequent updrafts. The new nucleation produces new modes in the drop spectrum, broadening the spectrum towards smaller drops. Spectral broadening is also reproduced in the TEM, where an ensemble of 680 parcel trajectories is derived from a large eddy simulation (LES) velocity field. In the TEM, the mechanisms of in-cloud nucleation and growth/evaporation asymmetry caused by updraft acceleration and parcel recirculation promote spectral broadening predominantly in the lower and intermediate levels of the cloud, where parcels with initially low updraft velocities reside.

To explicitly evaluate the effect of subgrid scale turbulent velocity fluctuations on drop spectrum evolution, such fluctuations are added to the mean LES velocity field. The velocity fluctuations are simulated using the Langevin equation, where turbulent diffusion is represented as an autoregression random process of the 1st order. The velocity fluctuations alter parcel trajectories, allowing parcels with initially low vertical velocities to be swept into higher vertical velocity eddies and to penetrate deeper into the cloud. The resulting updraft acceleration and parcel circulation lead to new drop nucleation and to broadening of the upper level drop spectra. The added subgrid turbulent velocity fluctuations also increase the overall number of parcels that exhibit new drop nucleation, bringing the

* Corresponding author. Tel.: +972 2 658 4974; fax: +972 2 566 2581.
E-mail address: caryn@vms.huji.ac.il (C. Erlick).

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fraction to half of the total ensemble under the assumption of strong turbulence. The above mechanisms help explain the existence of quite broad and bimodal stratiform cloud drop spectra, as well as the variation in stratiform drop spectra over short spatial scales. The sensitivity of the above mechanisms to the shape of the CCN spectrum and to variation in the turbulence parameters is investigated.

Keywords: Cloud microphysics; Drop size distribution; Spectral broadening; Parcel model; Trajectory ensemble method

1. Introduction

Simulating the shape of cloud drop spectra in both cumulus and stratiform clouds has historically been a challenge. Drop spectra measured by aircraft are often broader than what is predicted by the equation of diffusional growth. While the classical theory predicts a drop spectrum dispersion of 0.01 near cloud base and a monotonic decrease in dispersion aloft (see, e.g., Pinsky and Khain, 2002), the dispersion measured in cumulus clouds increases with height, reaching about 0.15−0.3 (Politovich, 1993). It should be stressed that the width of a drop spectrum is dictated, not only by the formation of drops with radii exceeding the adiabatic value, but also by drops with radii smaller than the adiabatic value (in the range of, say, 1 μm), which are regularly observed both in cumulus (e.g., Warner, 1969; Brenguier, 1998) and stratiform clouds (e.g., Noonkester, 1984; Nichols, 1984; Korolev, 1995; Gerber, 1996) several hundreds of meters above the cloud base. It is difficult to reproduce wide drop spectra containing both large drops responsible for drizzle formation and the smallest cloud drops even using sophisticated models such as large eddy simulations (LES) (e.g., Khairoutdinov and Kogan, 1999).

The simplest explanation for the broadness, as well as for the bimodality (multimodality) of drop spectra measured in situ, is that the spectra result from spatial averaging of spectra belonging to different parcels. In situ measurements (e.g., Warner, 1969; Korolev, 1994, 1995) indicate that drop spectra vary dramatically in shape over scales as small as tens to a hundred meters, evidence that clouds consist of comparatively small cloud volumes (parcels of a few tens of meters radius) with different drop spectra. However, analysis of spectra within individual parcels also indicates high variability, from narrow to broad and from unimodal to multimodal. Mechanisms other than averaging must be responsible for drop spectrum broadening and bimodal spectra formation in individual cloud parcels of such sizes.

A number of mechanisms for broadening within individual parcels have been suggested (see the reviews by Korolev, 1994, 1995; Brenguier, 1998; Khain et al., 2000; Segal et al., 2003). Among them are (a) entrainment and mixing of cloudy and environmental air (e.g., Mason and Chien, 1962; Baker and Latham, 1982; Jensen and Baker, 1989; Su et al., 1998), (b) fluctuations in cloud drop concentration caused by vertical velocity fluctuations at cloud base (Cooper, 1989), (c) asymmetry between the rates of condensation and evaporation during parcel circulation within clouds (Korolev, 1995), and (d) isobaric mixing (Korolev and Isaac, 2000). Various other mechanisms have been studied in the