Atmospheric Research 140–141 (2014) 76–84

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Numerical simulations of stratocumulus cloud response to aerosol perturbation

M. Andrejczuk [a,*], A. Gadian [b], A. Blyth [b]

[a] Atmospheric, Oceanic and Planetary Physics, University of Oxford, United Kingdom
[b] School of Earth and Environment, University of Leeds, United Kingdom

ARTICLE INFO

Article history:
Received 8 March 2013
Received in revised form 2 October 2013
Accepted 5 January 2014

Keywords:
Geoengineering
Cloud brightening
LES

ABSTRACT

In this paper results from the 2D numerical model with Lagrangian representation of microphysics are used to investigate the response of the radiative properties of stratocumulus as a result of adding aerosol within the boundary layer. Three different cases characterized by low, moderate and high cloud droplet number and for 3 sizes of additional aerosol 0.01 μm, 0.1 μm and 0.5 μm are discussed. The model setup is an idealization of one of the proposed Solar Radiation Management methods to mitigate global warming by increasing albedo of stratocumulus clouds. Analysis of the model results shows that: the albedo may increase directly in response to additional aerosol in the boundary layer; the magnitude of the increase depends on the microphysical properties of the existing cloud and is larger for cloud characterized by low cloud droplet number; for some cases for clouds characterized by high cloud droplet number seeding may lead to the decrease in albedo when too large radius of seeding aerosol is used.

1. Introduction

Geoengineering of the stratocumulus clouds is proposed as a one of the methods to offset global warming due to a greenhouse gas emission. Various methods are under consideration, aiming to decrease the flux of the solar radiation reaching the Earth surface (Solar Radiation Management, e.g. Shepherd et al. (2009)). One of the proposed methods is cloud brightening (Latham, 1990, 2002; Latham et al., 2008, 2012). In this method reduction of the solar radiation flux is achieved by increasing the cloud albedo — the first indirect effect Twomey (1977), and longevity — the second indirect effect Albrecht (1989), of the low level stratocumulus clouds, by near surface CCN emission.

Climate model simulations (Jones et al., 2009) indicate that stratocumulus cloud seeding may delay global warming by as much as 25 years, giving the time to adopt or to find a better way to deal with the problem. However, the cloud–aerosol interactions and aerosol indirect effect are not fully understood yet, and representation of these processes in climate models are very simplified (e.g. Ghan et al. (2011)). This uncertainty in representation and understanding of the fundamental processes is a source of uncertainty in the climate prediction. In recent years there have been efforts in the scientific community to asses geo-engineering schemes using climate models (Latham et al., 2012, 2008; Korhonen et al., 2010; Jones et al., 2009; Rasch et al., 2009), but relatively little research has been devoted to modelling details of these processes and in particular, the single cloud response to additional aerosols emitted into the boundary layer. Limited studies with simpler models than used in this paper have been conducted in the past to address the effect of the aerosol emission on the cloud in the context of the geo-engineering. Bower et al. (2006) and Latham et al. (2012) assessed validity of cloud modification as a way to offset global warming with parcel model, without taking into account drizzle. This work confirmed an increase of albedo with an increase of cloud droplet number, with the cloud droplet number being the main factor responsible for cloud albedo change. Wang et al. (2011) and Latham et al. (2012) addressed cloud geo-engineering problem in LES (Large Eddy Simulation) framework, resolving aerosol emission from the surface and transport into the cloud, but with less accurate approach to microphysics, with the similar to Bower et al. (2006) conclusions.

---

[*] Corresponding author at: Atmospheric, Oceanic & Planetary Physics, Clarendon Laboratory, Parks Road,Oxford OX1 3PU, United Kingdom.

0169-8095/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.atmosres.2014.01.006

In this study a Lagrangian approach to microphysics (Lagrangian Cloud Model) Andrejczuk et al. (2008, 2010) is used to investigate the stratocumulus cloud response to aerosol perturbation. Lagrangian approach to microphysics is a new development in cloud modelling, aiming to improve representation of microphysics in numerical models. This study does not intend to model all of the details of the aerosol emission from the spray vessels as proposed by Latham (1990, 2002), but rather to look at this problem in an idealized setup. This paper assumes that emitted aerosol forms a well mixed layer below the cloud, with a uniform distribution of aerosol below specified height. Despite this simplification, the process of transport of aerosol from below the cloud into the cloud is represented, and since the boundary layer is typically well mixed there are reasons to believe that aerosol will form such layer with time even when emitted from the surface. We also assume that chemical composition of the aerosol in the boundary layer and that of seeding aerosol is the same ammonium sulphate.

The paper is organized as follows: in Section 2 numerical model is described and initial conditions and model setup are described in Section 3. Model results are discussed in Section 4, and conclusions are in Section 5.

2. Numerical model

Numerical model used to simulate cloud response to aerosol perturbation is the Lagrangian Cloud Model (LCM). Detail of the model formulation can be found in Andrejczuk et al. (2010) (coalescence) and Andrejczuk et al. (2008) (condensation/evaporation). The LCM framework represents the dynamics and thermodynamics in a traditional, Eulerian framework, with the details of the Eulerian model described in Reisner et al. (2005) and Reisner and Jeffery (2009); whilst the microphysics is represented in Lagrangian framework, with two way coupling between Eulerian and Lagrangian parts. The microphysical (Lagrangian) part traces millions of parcels, each representing millions of aerosol particles having the same chemical composition and physical properties (location, aerosol size, velocity). Depending on the environmental conditions i.e. the solution of the Eulerian part of the model water can condense/evaporate on the surface of these aerosols. Corresponding forces are returned to the Eulerian part to progress model forward in time. Since each Lagrangian parcel represents aerosol having the same physical/chemical properties only one additional parameter to the parcel location, velocity, aerosol and droplet size — number of real aerosol particles Lagrangian parcel represents is required to fully describe properties of the parcel. The model used in this paper is one of three of this type of models recently developed, with others reported by Shima et al. (2009) and Riechelmann et al. (2012).

The coalescence algorithm in the Lagrangian microphysics formulation used in simulations reported in this paper maps the collisions between all Lagrangian parcels within the collision grid on a specified two dimensional Eulerian grid (microphysical grid). As a result in coalescence not only droplet sizes but also aerosol sizes are processed, and with time aerosol larger than initially specified can form. New parcels are created only for bins, where number of physical particles is greater than a specified number. Combined with the parcel merging algorithm, this makes problem numerically solvable, by keeping the number of parcels relatively low. Both mapping and merging processes conserve mass of the aerosol and mass of the water. Based on sensitivity study discussed in appendix of Andrejczuk et al. (2012), in the simulations reported in this paper collision is called every 1 s. Additionally each computational grid is split into 4 collision grids.

3. Model set-up and initial conditions

Three 2D idealized cases are considered, with the initial conditions (temperature, qv, horizontal velocity, aerosol distribution) derived from the VOCALS field campaign (Wood et al., 2011). These cases are based on the cloud droplet concentration and for HIGH case— 250 cm^{-3}, MED case— 120 cm^{-3} and for LOW case— 65 cm^{-3} were measured. For all three cases, profiles of potential temperature (θ) and water vapour mixing ratio (q_v) were specified as:

$$\theta(z) = \begin{cases} \theta_B, & z \le z_B; \\ \theta_C + \alpha z, & z_B < z \le z_T; \\ \theta_T + (z - z_T)^{2.8}, & z > z_T; \end{cases} \tag{1}$$

$$q_v(z) = \begin{cases} q_v(\text{or saturation}) & \text{if } z \le z_T; \\ q_{vT} & \text{if } z \le z_T; \end{cases} \tag{2}$$

with the constants for each simulation defined in Table 1. Initial profiles for the θ and q_v and profiles derived from a model for the last 3 h for a model output saved every 6 min are shown in Fig. 1. Additionally, in this figure observed profiles of the LWC and droplet concentration are plotted together with corresponding profiles diagnosed from a model solution.

A 2D assumption means that the flow evolves only in x–y direction; and the variability of the flow in y direction is neglected. Representation of the atmosphere in two dimensions is an approximation, but computational expense of this model prohibits the use of three dimensional domain. A comparison of the solutions between two- and three-dimensional models for a convective planetary boundary layer was discussed by Moeng et al. (2004).

The reference runs use two modal log-normal aerosol distribution fitted to the below cloud Scanning Mobility Particle Sizer (SMPS) observations (Table 2), with the coalescence process active starting from 2nd hour. More details about the setup and comparison of the model results with VOCALS observations can be found in Andrejczuk et al. (2012). Sensitivity runs (Table 3) were initialized from the reference run solutions after 4 h. For the sensitivity runs aerosol of differing concentration and size were added in the area from 300 m below the cloud base to the surface. All sensitivity runs were next run for 6 h with the coalescence process active. The purpose of the sensitivity runs was to determine response of the cloud to the concentration and size of the additional aerosol. Sensitivity runs are identified by the reference run for which additional aerosol

Table 1
Constants used to define profiles of the potential temperature, water vapour mixing ratio and cloud water mixing ratio.

RUN	z_B	z_T	θ_B	θ_C	θ_T	q_{vB}	q_{vT}	α
	[m]	[m]	[K]	[K]	[K]	[g/kg]	[g/kg]	[K/m]
HIGH	800	1380	291.1	293.0	302.5	8.3	0.3	3.3×10^{-3}
MED	1000	1400	289.2	290.4	299.0	7.0	0.7	3.0×10^{-3}
LOW	900	1260	290.1	291.1	301.0	7.8	0.7	2.8×10^{-3}