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A comparative modeling study of the early electrical development of maritime and continental thunderstorms

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Abstract

Numerical simulations were carried out to investigate differences between the early electrical development of maritime and continental thunderstorms, resulting from the characteristic profound differences between the concentrations of cloud concentration nuclei (CCN) and therefore cloud droplets. It follows that our study relates to the impact of the so-called aerosol hypothesis on thunderstorm electrification.

A bulk-water microphysical model was used. It was assumed that the maritime/continental differences can be represented by employing, for the former case, higher rates of conversion of cloud droplets to raindrops.

The results indicate that in maritime clouds there is an increase (relative to terrestrial clouds) in the amount of precipitation fallout, leading to less cloud water in the mixed phase region and as consequence to fewer ice particles, which reduces significantly the thunderstorm charging. In addition, the cloud top height and updraft velocity decrease. The study demonstrates the importance of cloud dynamics in the formation of charge in the updraft. The calculated significantly smaller value of negative charge density in the updrafts of maritime clouds is a result of reduced charging of the (smaller) graupel in its lower updrafts, and is consistent with reported evidence for the paramount importance of ice in thunderstorm charging, and the reduced electrical activity of oceanic thunderstorms.

Keywords: Non-inductive charging; Maritime and continental clouds; Numerical model; Electrical activity; Aerosol hypothesis

1. Introduction

It is now firmly established (Christian et al., 2003) that areal frequency of lightning over land is about an order of magnitude greater than that over the oceans. The physical reasons for this striking contrast have not been definitively established. One possibility is the thermal hypothesis based on the observation that the land heats up more quickly than ocean water, convection is thus greater over land, which leads to more vigorous thunderclouds and therefore more lightning. Another possibility is the aerosol hypothesis (Rosenfeld, 2000; Williams and Stanfill, 2002; Williams et al., 2004), based on the long-established finding that–largely because of man-made pollution–number concentrations of cloud condensation nuclei (CCN), and therefore cloud droplets concentration are much higher (typically by one or two orders of magnitude) over land than over the oceans. As a result, rainfall production by droplet

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coalescence is more effective over the oceans—because the (fewer) droplets have a wider range of sizes and coalescence is thus more efficient. This leads to smaller amounts of cloud water in the mixed-phase regions of maritime clouds, compared with continental ones. Since, as discussed later, ice development in thunderclouds is intimately related to lightning production and can be influenced in subtle ways by the CCN concentration, it is possible that the ocean/land CCN contrast produces changes in glaciation which cause the pronounced ocean/land lightning frequency contrast.

The principal objective of the modeling work described herein was to examine whether the aerosol hypothesis may explain the significant differences in the rates of early electrical development of thunderstorms formed over land and over the oceans; which would lead to concomitant major differences in lightning activity.

Since the modeling required in order to achieve this goal is concerned only with the early stages of electrical development we deemed it adequate to utilize a one-dimensional multi-thermal parameterised model, of the type employed by Mitzeva et al. (2003), details of which are presented later.

There exists overwhelming field, laboratory and computational evidence (e.g. Latham, 1981) to show that the dominant charging mechanism in most thunderstorms is the non-inductive process (Reynolds et al., 1957; Takahashi, 1978; Jayaratne et al., 1983; Baker et al., 1987; Norville et al., 1991, and a series of papers describing laboratory experiments by Saunders and colleagues at the University of Manchester, UK), which involves rebounding collisions between growing graupel pellets and ice crystals. Accordingly, in our computations, we assume that the separation of charge in our model clouds is solely a consequence of the non-inductive process.

2. Model description

In our model (Mitzeva et al., 2003), convective clouds are assumed to be composed of active and non-active cloud masses (Andreev et al., 1979). The active mass is modeled by successive ascending spherical thermals, while the non-active cloud region consists of thermals that have previously risen and stopped at their zero updraught velocity levels. These stopped thermals diffuse as a spherical source and their characteristics (temperature excess and the presence of water vapour, cloud droplets and ice crystals) vary in time due to turbulent diffusion and evaporation (for more details and equations see Appendix 1).

This multi-thermal treatment simulates the time dependence of the microphysical and thermodynamic characteristics of cumulus development, and has been used in model studies by Mason and Jonas (1974), Blyth and Latham (1997) and others. We assume that the ascending thermals represent the updraft region of convective clouds, while non-active masses represent the environment surrounding the updrafts.

The thermals are driven by the buoyancy force reduced by entrainment and the weight of the hydrometeors contained within them. They entrain air from the cloud-free environment or from a non-active cloud region, depending on their position at a particular moment. The entrainment is parameterised as in Mason and Jonas (1974), with the entrainment rate α inversely proportional to the radius of the ascending thermals: $\alpha = 0.6/R(z)$, where $R(z) = R_0 + 0.2z$ is the thermal radius at height z above cloud base and R_0 is the thermal radius at cloud base.

In order to model the entrainment from the non-active cloud mass, stopped and diffusing spherical thermals are considered as cylinders with the same radius and volume (see Appendix 1). If there is more than one diffusing thermal at a given level, the characteristics of the non-active cloud mass are determined by the superposition of the properties of the diffusing thermals at that level.

Parameterization of the merging of thermals during their ascent is included in the model. As the thermals ascend, their temperature changes due to cooling by expansion of the air, entrainment of environmental air and the release of latent heat. The model uses bulk microphysical parameterizations, with five classes of water substance — water vapor, cloud water S_c, rain S_p, cloud ice S_{cf}, and precipitating ice (graupel) S_{pf}. The cloud droplets and ice crystals are assumed to be monodisperse and have negligible fall velocities. A Marshall–Palmer type size distribution (with fixed intercept values) is assumed for raindrops and graupel.

In the model cloud, droplets are formed by condensation; all the water vapor in excess of the saturation mixing ratio with respect to water is immediately condensed out. Raindrops form by autoconversion of the cloud droplets and grow by collision and coalescence with cloud droplets (Kessler, 1969). Below 0 °C, ice crystals originate by heterogeneous freezing of cloud droplets, the concentration of ice nuclei being given by Fletcher (1962). Homogeneous freezing occurs below −40 °C. Precipitating ice (graupel) forms by the freezing of raindrops (Bigg, 1953), contact nucleation of ice crystals and raindrops (Cotton, 1972), and autoconversion of ice crystals (Hsie