Atmospheric Research 140–141 (2014) 38–60

Contents lists available at ScienceDirect

Atmospheric Research

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

# Review: Cloud invigoration by aerosols—Coupling between microphysics and dynamics

O. Altaratz [a,*], I. Koren [a], L.A. Remer [b], E. Hirsch [a]

[a] Department of Earth and Planetary Sciences, The Weizmann Institute of Science, Rehovot, Israel
[b] Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD, USA

ARTICLE INFO

*Article history:*
Received 2 April 2013
Received in revised form 19 November 2013
Accepted 5 January 2014

*Keywords:*
Aerosol and cloud
Cloud and precipitation
Climate

ABSTRACT

The cloud invigoration effect refers here to the link between an increase in aerosol loading and deepening of convective clouds. The effect can be reflected also in a larger cloud fraction and an increase in the condensate mass that is distributed higher in the atmospheric column. Identifying the invigoration effect by aerosols requires attributing certain changes in cloud dynamics to changes in cloud microphysics. More than 10 years of extensive research using data collected in field experiments, analysis of satellite measurements and the employment of state-of-the-art numerical models have been used in an attempt to study this elusive phenomenon. Despite these intensive efforts, the validity of the invigoration effect and the possibility of climate responses to this effect are still considered to be open questions. In this review observational evidence and modeling results for cloud invigoration are discussed. Studies that indicate convective cloud invigoration effects, as well as studies that suggest no or even opposite effects are summarized. A coherent physical mechanism that describes a chain of processes that takes place under the proper conditions in the core of a convective cloud provides explanation for the "ideal" case of invigoration reported by observations and numerical modeling, while the competition between core-based vs. margin-based processes explains the cases that deviate from the "ideal". Because convective clouds play a key role in the Earth's radiation balance, in the water cycle and atmospheric circulations, invigoration implies possible consequences at scales ranging from a single cloud up to the global.



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* Corresponding author at: Department of Earth and Planetary Sciences. The Weizmann Institute of Science, Rehovot 76100, Israel. Tel.: +972 8 9344228.
*E-mail address:* orit.altaratz@weizmann.ac.il (O. Altaratz).

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http://dx.doi.org/10.1016/j.atmosres.2014.01.009

## 1. Introduction

Processes that shape cloud and cloud field properties can be divided into three classes: microphysical (including chemistry), dynamical and radiative. Microphysical processes are related to the formation, evolution and properties of cloud and precipitation particles (Pruppacher and Klett, 1978). Dynamical processes describe the movement of air in clouds and their immediate environments (Houze, 1993). Dynamics span a large range of scales of motion, from turbulence to synoptic scales. Atmospheric radiation processes describe the interactions between atmospheric compounds (gases, clouds and aerosol) and electromagnetic radiation (Petty, 2006). Processes discussed in this review are related to the microphysical and dynamical domains.

The main source of complexity in understanding clouds is the tight coupling between scales and processes. One of the main questions leading today's cloud-climate research is: “How tightly are microphysical and dynamic processes coupled?” This is a two-way question. In one direction, the question of how do dynamics affect microphysics? is well-appreciated, emerging from the basic droplet diffusional growth equations (Pruppacher and Klett, 1978). The major uncertainty of the coupling resides in the reverse question: “How do microphysics affect dynamical processes” (Khain et al., 2005; van den Heever et al., 2006; Levin and Cotton, 2009). Embedded in this question is the need to define the role, if any, of aerosol effects on clouds of all types, including aerosol invigoration of these clouds and cloud systems.

Aerosol properties serve as the initial conditions for droplet activation in the cloud. Therefore, changes in aerosol properties inherently produce changes in the cloud microphysical processes. There is a growing body of work, to be discussed below, that shows how changes in aerosol size-distribution affect the timing of the onset of rain and its vertical location within the cloud. This by itself suggests that microphysics affect the water distribution within the cloud. Moreover, rain is the end result of a long chain of linear and non-linear processes, starting from activation and droplet growth by diffusion and continuing to collision-coalescence related processes. Therefore, aerosol effects on the initiation of rain reflect earlier influences on condensation and evaporation, drag-forces, latent heat fluxes, droplet terminal velocities, drop collection and entrainment. It is through these processes that microphysical changes affect the dynamics.

Studies that address cloud invigoration by aerosols link changes in aerosol properties to changes in the cloud dimensions, condensate spatial distribution and rain patterns. Such associations suggest significant coupling between cloud microphysics and cloud or cloud system dynamics. A cloud system is a group of organized clouds. It is this coupling that leads to invigoration, the enhanced development of the clouds. This paper reviews attempts to answer where, when and in what way, convective clouds are affected by the microphysical impact on the dynamics branch of the coupling, covering observation-based and cloud resolving modeling studies.

### 1.1. Clouds and climate

Clouds are key players in the climate system, significantly affecting Earth's energy balance and providing a fundamental link in the water cycle. At the same time, clouds are the least understood climate process (Forster et al., 2007). The radiation budget, water cycle and energy balance of the Earth's system depend on cloud microphysical and macrophysical properties, such as, coverage, vertical extent and internal properties. Therefore, a better understanding of the role of clouds in the climate system requires a good understanding of the processes that affect cloud properties.

Specifically, clouds serve as atmospheric radiation modulators in both the short wave and long wave portions of the spectrum (Baker and Peter, 2008; Trenberth et al., 2009). Clouds cool the atmosphere by reflecting solar radiation to space, and account for approximately 2/3's of the Earth's albedo (Trenberth et al., 2009). In the long-wave infrared (LWIR) range, clouds act like a greenhouse gas and warm the atmosphere by absorbing the Earth's outgoing LWIR radiation. The net radiative effect of a single cloud or a cloud system (organized structures of dynamically related clouds) depends on the cloud type, size and location within the atmospheric column. For example, low-altitude stratiform clouds (like Marine-Stratocumulus, MSc) cool the Earth–atmosphere system by reflecting sunlight back to space and do not significantly disturb the outgoing LWIR radiation that continues to radiate at a similar blackbody temperature as the ocean (Hartmann and Doelling, 1991; Wood, 2012). On the other hand the net radiative effect of high-altitude cirrus clouds is warming, driven by their cold temperature compared to the earth's surface and relative low reflectance in the visible (Stephens and Webster, 1981; Fusina et al., 2007).

Equally important is the effect of cloud processes and properties on precipitation. Rain rate patterns and the total amount of precipitation affect the amount of water available for human use. Also, cloud processes that affect precipitation likewise contribute to the energy balance of the atmosphere. Cloud internal thermodynamic processes, such as condensation, evaporation, freezing, deposition, sublimation, melting and precipitation fallout provide a significant component of energy input and output from the atmosphere, through latent heat related processes (Trenberth et al., 2009). Furthermore,