Atmospheric Research 101 (2011) 327–340

Contents lists available at ScienceDirect

Atmospheric Research

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

The effect of aerosol layers on convective cloud microphysics and precipitation

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ARTICLE INFO

Article history:
Received 21 August 2010
Received in revised form 24 March 2011
Accepted 24 March 2011

Keywords:
Aerosol
Transport
Continental
Maritime

ABSTRACT

The effects of aerosols transported at different altitudes on the microphysical and dynamic processes of clouds formed on different background aerosol concentrations have been investigated using a dynamic cloud model with spectra-resolved microphysics. Two scenarios are conducted to represent the continental and maritime aerosol types. Under the same initial thermodynamic conditions, the continental case generates larger number of liquid drops compared to the maritime case due to the enhancement of background aerosol load, whereas the consumption of water vapor weakens the deposition nucleation and growth of ice particles, leading to reduced number and mass concentration of ice crystals and graupel particles. Aerosols transported either in the boundary layer (0–2 km) or mid-troposphere (2–6 km) can change the characteristics of cloud and precipitation. For continental cases, these transported aerosol particles lead to an increase in the drop number concentration, but decrease in the updraft velocity during cloud development stage, the maximum effective radius of drops, the maximum number concentration of ice crystals and graupel particles, and suppress the ground rainfall. The rainfall shows high sensitivity to changes in microphysics due to enhanced aerosol load. Aerosols transported in the boundary layer have more significant effect on the cloud microphysics and precipitation than that at mid-troposphere. For maritime cases, the transported aerosol particles show similar enhancement effect on number concentration of drops with longer cloud lifetime and hence delayed and suppressed precipitation occurring when aerosol concentration is enhanced in boundary layer, whereas the precipitation increases when aerosols transport in mid-troposphere due to larger maximum effective radius of drops, contributed by melting of larger graupel particles with efficient accretion growth. The results from marine cases and different initial aerosol concentration of continental cases show that the effect of transport of aerosols exhibits more notable effects for lower initial aerosol concentrations. The influence of the environmental wind shear has not been included in the present study.

1. Introduction

Aerosol particles play an important role in the troposphere and climate system, they could scatter and absorb solar radiation, contribute to the chemical reaction, and exist as condensation nuclei during cloud formation. Long-range transport of aerosol particles and precursors is one of the prominent approaches for geochemical cycle, which affects radiation budget of the earth's surface as well as cloud and precipitation processes, and further influences global climate directly or indirectly (Pongkiatkul and Kim Oanh, 2007; Duarte et al., 2008; Stith et al., 2009; Chang et al., 2010; Dumka et al., 2010).

Several studies indicated that pollutants can be transported from the Asian continent across the Pacific Ocean (Tu et al., 2004; Heald et al., 2006; Yu et al., 2008; Wang et al., 2009). Heald et al. (2006) found that the strongest transpacific

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doi:10.1016/j.atmosres.2011.03.007

transport occurs in spring at 40–55°N, and concentrations during the days of model-predicted maximum Asian influence (1.04 μg/m^3) are much higher than the seasonal mean values (0.69 μg/m^3). Yu et al. (2008) estimated that about 18 Tg/a aerosol pollutants could be exported from east Asia to the northwestern Pacific Ocean, of which about 25% reached the west coast of North America. The importing flux of 4.4 Tg/a to North America is equivalent to about 15% of the local emissions from the United States and Canada. Wang et al. (2009) suggested that the background concentrations of sulfate in the western United States increased by 0.4 μg/m^3 in monthly average due to the Asian emissions.

Episodic long-range transport of pollutants occurs on different altitudes under varied weather systems (Andreae et al., 1988; Bertschi and Jaffe, 2005; Verma et al., 2006). Andreae et al. (1988) carried out first detailed airborne observations of long-range transport of Eurasian emissions to the remote northeast Pacific troposphere in 1985. Their results showed that long-range transport at mid-tropospheric levels plays an important role in determining the chemical composition of the atmosphere even in remote northern hemispheric regions. Bertschi et al. (2004) and Bertschi and Jaffe (2005) provided a detailed study of long-range transport to the northeast (NE) Pacific on the basis of aircraft flights, and observed air masses containing highly correlated and well-defined layers of O_3, CO, and aerosol enhancements within the 0–6 km column. Verma et al. (2006) investigated that lofting of air as high as 800 hPa (approximately 2 km above sea level) could lead to entrainment of aerosols into the free troposphere and long-range transport. Liang et al. (2004) found that transport in the warm conveyor belt of midlatitude cyclones is the dominant export mechanism throughout the year, export induced by deep convection becomes important during summer and fall, and episodic long-range transport of pollutants from Asia to the NE Pacific occurs throughout the year every 10, 15, and 30 days in the upper, middle, and lower troposphere, respectively.

Aerosol size distributions may be modified due to scavenging by cloud and precipitation during the intercontinental transport. Brock et al. (2004) considered that the midlatitude cyclonic system appeared to effectively scavenge most pre-existing particle mass, but could allow transport of gas-phase precursors which substantially alter downstream particle microphysical and chemical properties, and led to substantially enhanced particulate sulfate mass and gas-phase H_2SO_4. Observations of Dunlea et al. (2009) confirmed the conceptual model proposed by Brock et al. (2004) for transpacific transport from Asia. Roberts et al.'s (2006) measurements showed that new particle formation frequently occurs in layers between 1000 and 7000 m above sea level.

Like the aerosols emitted from local sources, the transported aerosols can intervene in native cloud processes as cloud condensation nuclei (CCN) or ice nuclei (IN) (Pueschel et al., 1986; Fridlind et al., 2004; Stith et al., 2009), which affect the formation and development of cloud and precipitation. The study of Pueschel et al. (1986) demonstrated that the anthropogenic sources hundreds of kilometers upwind caused the small-particle (accumulation) mode number to increase from hundreds to thousands per cubic centimeter and the mass load to increase from a few to several tens of micrograms per cubic meter, mostly in the form of sulfur aerosols, which appeared to act as CCN to affect the cloud drop concentration. Fridlind et al. (2004) argued that most anvil crystals form on mid-tropospheric rather than boundary-layer aerosols, and suggested that distant pollution sources may have a greater effect on anvil clouds than do local sources. Simulation results of Yin et al. (2005) also suggested that the occurrence of mid-tropospheric aerosol layers that have been advected through transport could strongly affect cloud microphysical processes and precipitation formation. The accumulated surface precipitation, the amount of liquid water and ice as well as the strength of the updrafts and downdrafts can be influenced with the transported aerosol layer (van den Heever et al., 2006; van den Heever and Cotton, 2007).

Many previous studies have examined transpacific transport of Asian pollution and their effect on air quality (e.g. VanCuren, 2003; Bates et al., 2004; Nowak et al., 2004; Chin et al., 2007; Dickerson et al., 2007; Hadley et al., 2007; van Donkelaar et al., 2008; Pfister et al., 2009). In the meantime, a great many simulation studies have primarily dealt with the indirect effect of aerosols from local emissions in recent years. Aerosols can either suppress precipitation due to the pronounced increase in number concentration and decrease in effective radius of cloud droplet (Jacobson et al., 2007; Lerach et al., 2008; Martins et al., 2009; Muhlbauer and Lohmann, 2009; Teller and Levin, 2008), or enhance rainfall on account of the impaction on ice phase processes indirectly via changes in liquid phase processes (Lee et al., 2008; Tao et al., 2007). Effect of aerosols on cloud and precipitation depends crucially on type (i.e., maritime or continental) and number concentration of background aerosols (Khain et al., 2008), as well as dynamical properties, i.e., atmospheric thermodynamic conditions, wind shear, etc. (Fan et al., 2007; Lynn et al., 2007). When background aerosol concentration exceeds a critical value, characteristics of cloud turn to insensitive to the variation of aerosol number concentration (Li et al., 2008). Aerosols affect clouds more significantly over ocean than over land (Jin and Shepherd, 2008). A few papers investigated the effect of aerosols from distant areas on convective clouds (van den Heever et al., 2006; van den Heever and Cotton, 2007). In this study, a two-dimensional axisymmetric convective cloud model (Yin et al., 2005) with detailed description of warm and cold cloud microphysics is used to investigate the effects on cloud development due to changes in the CCN size distribution that occur with transport of pollution aerosols. Here the influence of environmental wind shear is not included.

2. Description Of model and numerical experiments

The model dynamics and microphysics are based on the axisymmetric non-hydrostatic convective cloud model of Reisin et al. (1996), which is an updated version of the one put forth by Tzivion et al. (1994), and was improved by Yin et al. (2005).

A set of prognostic equations is solved for the vertical and radial velocity, the pressure perturbation, the virtual potential-temperature perturbation, the specific humidity perturbation, the specific number concentration and mass of aerosol in a spectral bin, the specific number concentration and mass for each type of cloud particles in a size bin, and the concentration of activated ice nuclei. Four species of hydrometeors are