Literature Review: Aerosols and Hydrologic cycle

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Physical Climatology Course, 387H

December, 2006

The University of Texas at Austin, Austin, TX

Abstract

Tiny airborn particles including those released by human activities and the secondary organic aerosols have potential impacts on the hydrologic cycle. This review briefly introduces the aerosols formation, potential feedback between the aerosols and hydrologic cycle. Recent progress in aerosols, cloud and precipitation is described. The current status using model tools to investigate the interaction between the aerosols and hydrologic cycle are introduced. This review also outlines the satellite view of aerosols and their possible impacts on the cloud formation. Through the literature review, the future challenges in this area are addressed.

1. Introduction

The land – atmosphere interaction through exchanges of energy, water, momentum between the land surface and atmosphere is well understood. The land surface characteristics such as the albeo, roughness, and land cover/land use can have an impact on the water cycle. However in the water cycle, the role of aerosols is not taken into account. Aerosols play an important role in many areas including human health, atmospheric reactions, the radiation and precipitation. Increases in aerosol concentration and changes in their composition may affect the Earth’s climate and water supply. Aerosols have direct and indirect effects on the Earth’s climate system by reducing the amount of solar radiation that reaches the surface and changing the properties of clouds. On the one hand, as aerosols increase, the surface temperature may cool due to its direct effect. On the other hand, owing to the indirect effect, as aerosols concentration increases, it may decrease the rainfall through increasing the small CCN which can reduce the collision rate. In this way, changing aerosols in the atmosphere can change the frequency of cloud occurrence, cloud thickness, and rainfall amounts.

Barth et al. (2005) discussed the coupling between the land ecosystems and the atmospheric hydrologic cycle through biogenic aerosol pathways. In their paper, the schematic of this coupling system (shown in Figure 1) describes the aerosols and hydrologic cycle via the water and energy exchange between the land and atmosphere. Considering the aerosols effects is necessary for understanding the interaction in the atmosphere such as the feedback between the radiation, and hydrologic cycle. The increase of aerosols will increase cloud condensation nuclei (CCN) which is a necessary condition for the formation of clouds. The increase of cloud will further affect precipitation in some regions. In some sense, the increase of aerosols can change the frequency of heavy rainfall. Likewise, in the hydrologic cycle, the land surface features especially the soil moisture and vegetation variation can affect the aerosols formation through changing the secondary organic aerosols. Conceptually, these potential feedbacks are well known; however, the processes controlling each step in this coupled system are highly uncertain. The importance of these processes to the hydrologic cycle is unknown.

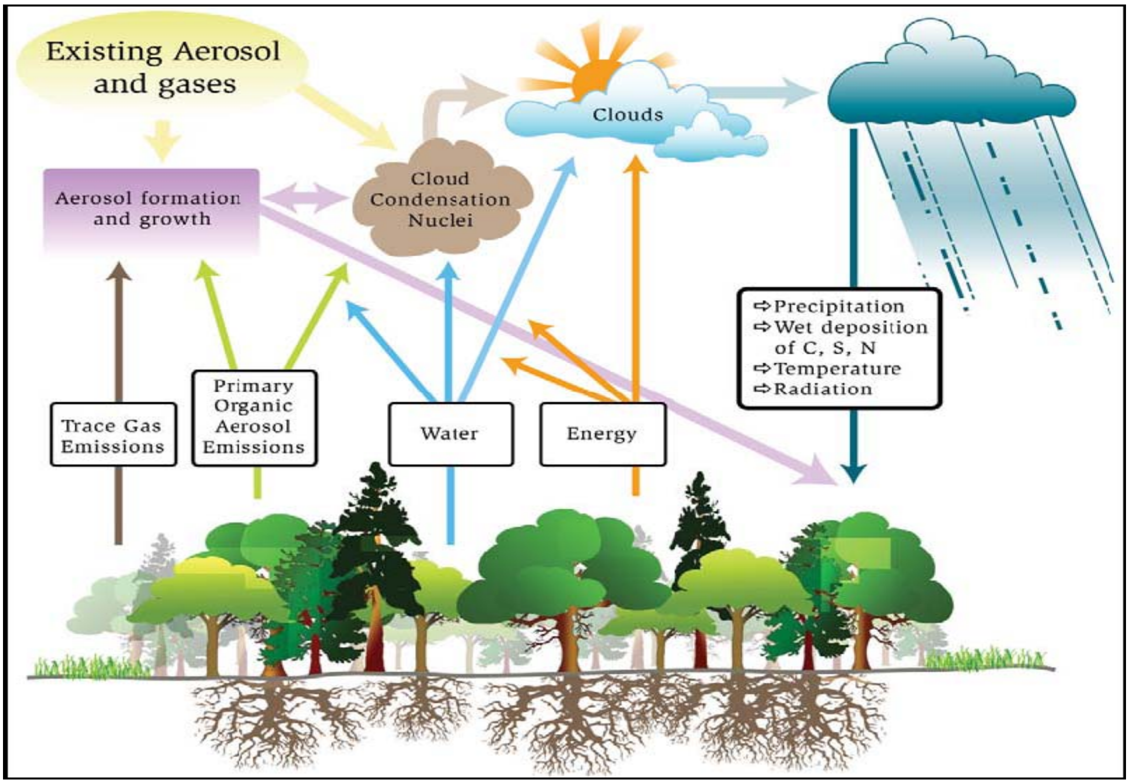

Figure 1 Schematic of the coupling of terrestrial ecosystems and the hydrologic cycle via energy and water exchange and aerosol processing (Barth et al., 2005)

2. Aerosols formation

Aerosols are tiny particles suspended in the air ranging in size from a few nanometers to a few hundred micrometers in diameter. Some occur naturally, originating from volcanoes, dust storms, forest and grassland fires, and living vegetation. Human activities, such as the burning of fossil fuels, automobiles, power plants, wood burning, and the alteration of natural surface cover, also can generate aerosols. Averaged global aerosols made by human activities currently account for about 10% of the total amount of aerosols in the atmosphere. Most of that 10% is concentrated in the Northern Hemisphere, especially downwind of industrial sites, and overgrazed grasslands.

Much work has been done to understand the formation of anthropogenic aerosols including the measurements, the laboratory experiments and model simulations. While progress has been made in understanding the direct input for aerosols, the contribution of secondary organic aerosols is also very important for understanding the aerosols and hydrologic cycle. It is known that organic material makes up a major mass fraction of ambient aerosols and a significant fraction of them is secondary organic. For instance, the secondary organic aerosols are formed in the atmosphere from volatile organic precursors. First, a large parent organic is oxidized to produce products with vapor pressures significantly lower than that of the parent. These products can partition between the gas and aerosol phases via condensation and nucleation (Griffin et al., 2002). The secondary aerosols are formed by the reaction of volatile organic compounds with the principle atmospheric oxidizing agents (i.e. ozone, no3 radicals). So the volatile organic compounds (VOCs) including anthropogenic and biogenic types are important for the formation of secondary organic aerosols. Greenberg et al. (1999) found over 90% of the total VOCs entering the atmosphere are biogenic. Biogenic VOCs (BVOCs) from the vegetation can regulate the atmosphere trace gas composition, in which, isoprene is the primary VOC emitted from trees in different locations. The total flux of biogenic nonmethane volatile organic compounds (NMVOCs) in North America is comprised primarily of isoprene (35%) (Guenther et al., 2000). And there are 98% of the total annual natural NMVOCs emissions are emitted by vegetation. The emission inventories are very important in determining the flux of BVOCs. Not only different vegetations can emit different fractions of BVOCs, but also the same vegetation in different locations can emit different fractions of BVOCs due to different climate conditions and soil types. The aerosols from the oxidization of BVOCs have been investigated showing their importance for the formation of secondary organic aerosols (Koch et al. , 2000). But estimates of the biogenic aerosols from the oxidization of BVOCs are not well understood due to the large potential sources and complex processes. Understanding the secondary organic aerosols is one of most important questions to understand water cycle in the atmosphere and land surface. The feedback mechanism between the anthropogenic and secondary organic aerosols and hydrologic cycle is an important issue for climate prediction and air forecasting.

3. Aerosols, cloud and precipitation feedback

Aerosols exert the control over the formation of cloud and precipitation through their direct effects on the nuclei which is the carrier of cloud droplets. Each cloud drop requires an aerosol particle to condense on. So the biogenic and anthropogenic aerosols can become the cloud condensation nuclei (CCN) to affect the cloud formation. The number of CCN is a critical link between aerosols, clouds and precipitation. On the one hand, the concentration, size and composition of aerosols can determine the cloud properties, which control the evolution and development of precipitation. On the other hand, the higher number of CCN can lead to the higher number of cloud drops which will increase the albedo of cloud, prolong the lifetime of cloud and reduce the precipitation. Likewise, the properties of clouds can have an effect on the formation of aerosols due to the change of cloudiness, cloud optical properties, precipitation and other meteorological variables by altering the radiation, temperature and vapor pressure.

The net effect of aerosols is to cool the earth's surface by reflecting sunlight (Huang et al. 2006). Depending on their composition, aerosols can also absorb sunlight in the atmosphere, cooling the surface but warming the atmosphere in the process. Huang et al. used a coupled regional climate-chemistry-aerosol model including sulfur module, a carbonaceous aerosol module and the algorithms which can simulate direct and indirect aerosol effects. The aerosol-cloud interaction is estimated by using CCM3 radiation package, which calculates cloud radiation in terms of cloud liquid water content and cloud effective radius. But the radius of anthropogenic aerosols is treated as a constant value. The parameterization of this interaction is represented by the empirical relationship between the cloud droplet number concentration and the aerosol concentration. The cloud droplet number concentration is related to the cloud effective radius. They also considered the possible effects which is the increase of cloud lifetime through the reduction of cloud droplet size. Their model results indicated that the aerosols have impacts on surface temperature by changing the clouds and radiation. The aerosols can reduce the day-time solar heating at the surface and increase the long-wave radiation at night with increasing surface temperature. But this work just depends on the empirical relationship, the physical description in the model about the link between the cloud droplet concentration and aerosols concentration is not considered.

These effects of aerosols on the temperature profile, along with the role of aerosols in cloud formation, may impact the hydrologic cycle through changes in cloud cover, cloud properties and precipitation.

The role of aerosols in precipitation is not very well understood. Recently a new paper written by Khaih et al. (2005) addressed the aerosol impacts on the dynamics and microphysics of deep convective clouds. They used a spectral microphysics two-dimensional cloud model to study the mechanisms through which how the aerosols affect cloud microphysics, dynamics and precipitation are presented. They found there is significant impact of aerosols on cloud microphysics and dynamics, Maritime aerosols can lead to the formation of raindrops that falls to the ground when the upward motion is increasing. Their simulations also show the increase of aerosols does increase the CCN which causes the formation of a large small number of droplets which can decrease the collision rate. So it results in a time delay in the formation of raindrop. Then this delay prevents the decrease of vertical motion and increase the duration of the diffusion droplet growth stage. At the same time, the more latent heat is released by condensation. They also reveal that the aerosol effect on precipitation can be understood only in combination with the dynamical effect of aerosols. Aerosols can decrease the precipitation efficiency of most single clouds and lead to the formation of intensive convective clouds and thunderstorms accompanied by high precipitation rates. So the aerosols in atmosphere can influence atmospheric motions and radiation balance at different scales from local to global scales.

Besides the human produced aerosols, the secondary organic aerosols play a possible role in the hydrologic cycle. Because the main sources producing the SOA, BVOCs emissions depend on the vegetation density and species distribution, solar radiation, temperature and other climate conditions. It links the aerosols and the hydrologic cycle through the land-atmosphere interaction. Description of seasonal variations of vegetation for studying this feedback is critical in the coupled model. The growth is controlled by the climate conditions such as precipitation, temperature, radiation. So the precipitation which represents the water cycle has a potential to affect the aerosol formation which can further influence the water cycle.

5. Investigation of this interaction using numerical models

The development of numerical models offers a good tool to study the interaction between the aerosols and hydrologic cycle. Much progress has been made to model the formation and distribution of trace gases. But the chemical processes in air quality modeling systems were treated independently of the meteorological model. The treatment of aerosols in the models is hindered by the lack of measurements and poor understanding of physically mechanism between the aerosols and cloud microphysics. A better representation of the aerosol in the climate model is required by treating the interaction between the multiple aerosol types for water and cloud updrafts. Through the model tool, the possible feedback between these two cycles can be addressed. Lau et al. (2005) did a simulation using NASA finite-volume GCM with microphysics of clouds in relaxed Arakawa Schubert cumulus parameterization scheme. They used three-dimensional aerosol forcing functions for five major aerosol types derived from outputs of the Goddard Chemistry Aerosol Radiation Transport model. Their results suggest that the impacts of aerosols on the monsoon are testable. But the further study needs the climate model coupled with aerosol-cloud interaction processes. The direct and indirect impacts of aerosols may exist in the monsoon system. It demonstrates the need of coupled chemistry-atmosphere model. Their work also shows the observation of aerosol emissions datasets is necessary for evaluating this interaction.

The Weather Research and Forecasting (WRF) model is a next generation mesoscale meteorological model being developed collaboratively among several agencies. The WRF-chem (Grell et al., 2005) is a version of WRF that can simulate trace gases and particulates simultaneously with the meteorological fields. The meteorological and air quality components use the same time transport schemes, vertical mixing parameterization and time step for transport and vertical mixing. The different gas-phase and aerosol modules are added to this model allowing the investigation of feedback between the meteorological conditions and aerosols through different chemical mechanisms. It will also allow the cloud-aerosol interaction processes in the model. Additionally, the secondary organic aerosols model (SORGAM) is already coupled in this model system allowing the study of interaction between the secondary organic aerosols meteorological variables.

6. Satellite view of aerosols

Understanding these feedbacks is particularly difficult because aerosols take a multitude of shapes and forms, ranging from desert dust to urban pollution, and because aerosol concentrations vary strongly over time and space. To accurately study aerosol distribution and composition therefore requires continuous observations from satellites, networks of ground-based instruments and dedicated field experiments.

Due to the short lifetime, most aerosols are regional, but the aerosols in high atmospheric layer will be transported by winds. During the transportation, the properties of aerosols will be modified owing to different atmospheric conditions. It is not easy to measure the aerosols using routine measurements. With the development of remote sensing techniques, satellite can measure the aerosols concentration depending on the aerosol optical thickness (AOT) which describes attenuation of the sunlight by a column of aerosol. The first instrument designed for aerosol measurements, Polarization and Directionality of the Earth's Reflectances (POLDER) is the first instrument designed for aerosol measurements. The MODIS and MISR of NASA's EOS system can measure the global distribution of aerosol concentration since 2000 (Kaufman et al. 2002 figure 1).

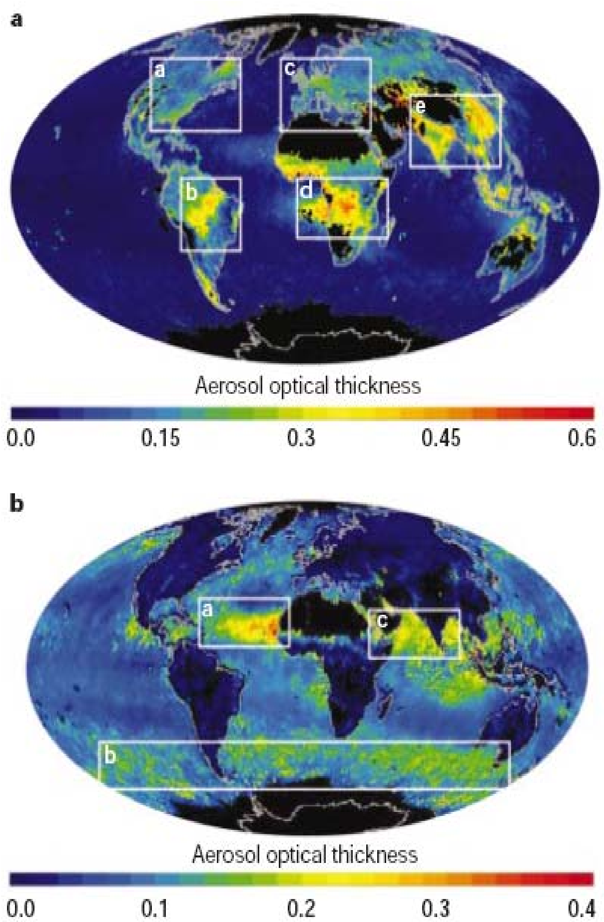

Figure 2 Global distribution of fine and coarse AOT derived from MODIS measurement (Kaufman et al. 2002 figure 1)

Knowledge of the vertical distribution of aerosols and clouds is therefore needed to calculate the impact of aerosol radiative effects. Through the satellite data, the anthropogenic aerosols seem to reduce formation of precipitation and affect cloud radiative properties at the same time (Kaufman et al. 2002, figure 6). This figure shows the schematic diagram of cloud formation in a clean and polluted atmosphere. In a clean atmosphere, the cloud droplet size increases with cloud development until precipitation takes place. However, in a polluted day, the availability of cloud condensation nuclei decreases cloud droplet development.

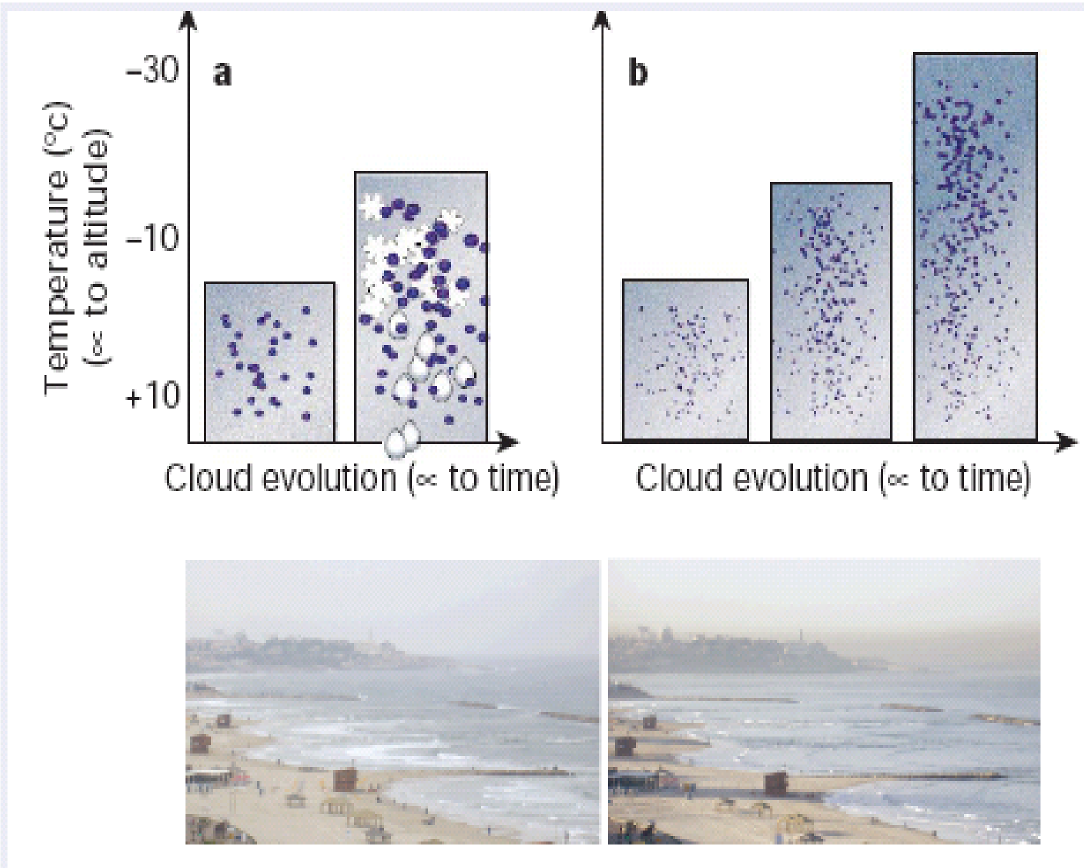

Figure 3 a. clean atmosphere, b. polluted atmosphere

(Kaufman et al. 2002, figure 6)

Additionally, the global satellite data shows there are 10-25% smaller cloud droplets corresponding to the increase of aerosol concentration. These results will help us understand the possible roles of aerosols in direct way and indirect way.

7. Future challenges

Studying the feedback requires advanced measurements such as satellite. The more precise satellite derived AOT is needed to compare observed air quality dataset and serves as a continuous monitoring air quality from space.

The land surface effects on the formation of aerosols should be investigated, which include the dynamic vegetation model, high resolution land cover/use data. The more realistic biogenic emissions can be modeled by a biogenic emissions model.

The coupling physics mechanism should be incorporated in the current climate model. The understanding of the cloud microphysical processes is important for us to understand the feedback between the aerosols and hydrologic cycles, including the field campaign and numerical models. Model evaluation and uncertainty assessment tools are needed to qualify this feedback through model aspect. The data assimilation techniques for air quality module in the coupled model system are needed using the existing datasets.

Future research will focus on revealing the magnitude of the aerosol effects on cloud formation and precipitation on regional and global scales and its sensitivity to cloud dynamics. To understand this link, we need to distinguish natural from anthropogenic aerosols. Especially the role of secondary organic aerosols in the hydrologic cycle needs to be well addressed due to the importance of water and energy cycle. To achieve this objective, the satellite measurement, coupled numerical models, ground-based measurements and laboratory and field experiments are the most important tools.

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