Atmospheric Research 96 (2010) 241–255

Contents lists available at ScienceDirect

Atmospheric Research

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

Investigation into clouds and precipitation over an urban area using micro rain radars, satellite remote sensing and fluorescence spectrophotometry

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ARTICLE INFO

Article history:
Received 7 December 2008
Received in revised form 16 July 2009
Accepted 12 August 2009

Keywords:
Cloud microphysics
Rainfall
Aerosols
Drop size distributions
Organic carbon

ABSTRACT

The observation and modeling of the indirect effects of aerosols on clouds remain an enormous challenge. Aerosols have a significant yet complicated impact on the precipitation processes. They can either enhance or suppress precipitation depending upon type of aerosol, seasonality, climate regime, cloud type or orographic profile of a region, particularly over populated areas. In order to observe and examine both cloud and precipitation processes, a combination of both satellite and ground-based remote sensing techniques can be employed. This paper presents the results from three years of data collection in Birmingham, United Kingdom. It describes and explains the application of a range of complimentary techniques: fluorescence spectrophotometry to examine dissolved organic carbon compounds in rainwater samples; satellite analysis tools are used to assess cloud-top microphysics; and an array of vertically-pointing micro-rain radars (MRRs) are used to assess variations in drop size distribution (DSD) for categorized events. Events are classified as microphysically 'maritime' or 'continental', showing that full development of the ice phase was reached at relatively warm temperatures for microphysically 'maritime' events, but at colder temperatures for microphysically 'continental' events. The importance of updrafts in severe thunderstorms and tornadic events is highlighted. High rainwater content of tyrosine-like substances (TYLIS) and tryptophan-like substances (TRYLIS) is found to be associated mainly with microphysically 'maritime' events, providing evidence for these substances acting as ice nuclei at relatively warm temperatures. High rainwater content of humic-like substances (HULIS) is associated with both microphysically 'maritime' and 'continental' events due to the complexity of such substances. As might be expected, continentally-sourced events had a similar structure to microphysically 'continental' events, whereas maritime-sourced events differed in their microphysical structure, indicating the local impacts on their microstructure. The DSD appears to vary between different events — for example, continentally-sourced, microphysically 'continental', convective events with low rainwater TRYLIS have a DSD containing fewer smaller droplets, whereas maritime-sourced, microphysically 'maritime', stratiform events with high TRYLIS had a DSD containing a greater number of smaller droplets. Satellite observations and vertically-pointing radars were found to be useful for analyzing clouds and precipitation since they provide a wealth of information to allow microphysical parameters to be investigated in detail.

1. Introduction

Aerosols play important roles in the atmosphere, having both direct and indirect effects on climate. The direct aerosol effect is caused by the absorption and scattering of solar radiation, whereas the indirect effect is linked to the action of aerosols as cloud condensation nuclei (CCN), thereby affecting the initial cloud droplet number concentration, albedo,

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doi:10.1016/j.atmosres.2009.08.003

precipitation formation, and lifetime of warm clouds (Pruppacher and Klett, 2000). Evaluating the indirect effects of aerosol on clouds remains an enormous challenge from both the observational and modelling perspectives. This has prompted atmospheric scientists to explore the impact of increasing anthropogenic activities on cloud and precipitation processes.

It is recognised that different aerosols have varying impacts upon precipitation. Theories of precipitation suppression caused by an increase in small CCN have been proposed by Twomey (1974) and Rosenfeld (2000). Small aerosols cause a narrowing of the size distribution of cloud droplets that lead to reduced or suppressed precipitation, since a range of droplet sizes are required for warm rain to develop. Therefore, in polluted clouds it is suggested that there are too many small droplets and too few larger or 'giant' droplets for efficient precipitation to occur. However, it has also been suggested that increasing CCN concentrations prolongs the lifetime of clouds and ultimately acts to increase precipitation (Shepherd, 2005). Due to reduced collection efficiency, such clouds may continue to ascend to altitudes where graupel and ice crystals form — these clouds are deeper and produce heavy rain, lightning and hail. Therefore, under certain conditions, a delay in the onset of warm rain due to aerosols can result in delayed downdraft formation, allowing for more invigorated updrafts which produce deeper and stronger convection. This effect may be experienced 'downwind' of urbanised regions. Furthermore, the presence of 'giant' nuclei can also act to enhance precipitation. Giant aerosols produce large cloud droplets near the cloud base — the effects of such giant CCN are significant when the concentration of small, Aitken nuclei is high, as in urban clouds. Giant CCN also act as a destabilising factor, by accelerating collisions and coalescence between the water drops which causes early development of large drops in lower parts of the cloud. Giant CCN accelerate precipitation formation through the ice phase, due to formation of ice by nucleation. Large droplets formed by the giant CCN produce graupel particles earlier — these have high coagulation efficiency with drops and therefore grow more rapidly as they are lifted in the updraft region, yet they remain close to the cloud base which can also promote ice multiplication processes in supercooled regions (Yin et al., 2000). Aerosols therefore have a significant, yet complicated impact on the precipitation process: they can either enhance or suppress precipitation depending upon type of aerosol, seasonality, climate regime, cloud type or orographic profile of a region, particularly over populated areas. It is also important to note that, in addition to aerosols, there are also other factors which have an impact on precipitation over urban areas, including thermodynamic effects, (Shepherd et al., 2002; Shepherd and Burian, 2003), mechanical effects (Bornstein and Lin, 2000), and bifurcation caused by urban canopies (Loose and Bornstein, 1977; Bornstein and Lin, 2000).

Water-soluble organic compounds (WSOC) are particularly important in heterogeneous nucleation and the formation of clouds and precipitation. A large proportion of rainwater WSOC is still uncharacterized — little is known about the chemical compounds present, their sources, temporal and spatial patterns of variation, and the subsequent impact on climate and the environment (Muller at al., 2008). WSOCs can influence cloud albedo, increase cloud condensation nuclei (CCN) concentrations, contribute to rainwater pH, visibility impairment and photochemical processes, and is a nutrient input to rivers and ecosystems. WSOC can be formed via physical and chemical aging. Sources of WSOC compounds in rain include: primary anthropogenic emissions (motor vehicle exhaust, tyre and asphalt wear, cooking), primary biogenic emissions (biomass burning, soil-derived humic matter resulting from combustion, thermal breakdown of plant ligins and cellulose), marine sources (bubble bursting on ocean surfaces), and secondary organic aerosol formation mechanisms (condensation, evaporation, photochemical reactions, oligomerization and aerosol-phase polymerization). Since a large proportion of WSOC is incorporated into rain droplets within the cloud environment (Barth et al., 2001), analysing rainwater concentrations of such compounds can provide an indication of atmospheric concentrations within the cloud environment. This can then be used to examine the atmospheric conditions under which the precipitation developed — *in situ* data collection at such altitudes would only be possible from balloon or aircraft platforms during the observed event, whilst satellite data would not provide the temporal and spatial resolution required for an investigation into atmospheric conditions during individual precipitation events. Despite the lack of a universal standard for accurate calibration (Muller et al., 2008), rainwater fluorescence intensity can be used as a proxy for the concentrations of substances in the rain samples. This technique provides a non-invasive, rapid method to examine the content of precipitation samples. Humic-like substances (HULIS), tyrosine-like substances (TYLIS) and tryptophan-like substances (TRYLIS) were identified in the rainwater samples (Muller et al., 2008). Atmospheric HULIS are high molecular weight compounds which are similar to terrestrial and aquatic humic substances, but do have substantial differences, such as smaller *average* molecular weight, lower aromatic moiety content, weaker acidic nature, a higher aliphatic component and better surface activity and thus better droplet activation ability compared to terrestrial and aquatic humic substances, due to greater number of solute species in HULIS (Graber and Rudich, 2006). TYLIS and TRYLIS are amino acids: proteins and biogenic matter have recently been found to be effective ice nuclei, especially at relatively warm temperatures (Christner et al., 2008).

In order to observe and examine both cloud and precipitation processes, a combination of satellite and ground-based remote-sensing techniques can be employed. Satellite remote-sensing techniques are increasingly used to examine clouds since aircraft observational tools cannot characterise the true evolution of cloud microphysical, spatial and temporal structure in the cloud droplet scale and relate this to properties of CCN or other environmental factors (Martins et al., 2007). Therefore satellite observations tools, such as temperature-effective radius (T–r_e) relationships and Cloud-Aerosol-Precipitation Satellite Analysis Tool (CAPSAT), are necessary. CAPSAT was developed by Lensky and Rosenfeld (2008) for cloud microphysical characterisation and aerosol–cloud interaction detection. It uses red–green–blue (RGB) composites of selected multispectral channel observations to represent much of the physical information retrieved by the observations from the Meteosat Second Generation (MSG) satellite (Lensky and Rosenfeld, 2008). Combinations of the selected channels can be used to qualitatively examine precipitation forming processes, for example, cloud drop size, which is a major factor in