1.4 EAST ASIA SOURCE REGION AEROSOLS (EASRA): AN IDEAL TESTBED FOR STUDYING THE DIRECT AND INDIRECT CLIMATE EFFECTS OF NATURAL AND ANTHROPOGENIC AEROSOLS

Z. Li[1], M. King[2], S. Tsay[2], B. Holben[2], Y. Kaufman[2], R. R. Dickerson[1]
[1]Department of Meteorology and ESSIC, University of Maryland, College Park, MD
[2]NASA Goddard Space Flight Center, Greenbelt, MD

1. INTRODUCTION

The importance of aerosols in the Earth's climate system is becoming increasingly apparent, but fully understanding and unraveling the complex effects of aerosols remains a daunting task (Ramanathan et al. 2001). To tackle this problem, we shall direct a major effort to special regions where not only are aerosols abundant and unique, but also the climate is exceptionally sensitive to their presence. An ideal region is East Asia, with its heart in China, where aerosol characteristics and effects are poorly known, but could be the strongest in terms of both direct and indirect effects. The physical properties and chemical composition of aerosols in this region differ considerably from those found elsewhere. As a result, not only is the magnitude of aerosol forcing large, the mechanisms by which aerosols interact with energy and water cycles may differ from those identified in relatively clean environments elsewhere. China is thus an ideal testbed for examining both existing aerosol-climate paradigms and exploring new ones. So far, little international attention has been paid to this important region except for the ACE/Asia experiment that was conducted primarily outside the major source regions. This paper is intended to provide a state of knowledge concerning the major types of aerosols near the source regions in China, following a literature review of both English and Chinese journals. The latter publications are largely unknown to the international community outside China.

2. AEROSOL STATUS IN CHINA

China is one of the world's major aerosol sources, mean aerosol optical depth in China being about twice the global continental mean value (Fig. 1). Heavy loadings and a quick pace of change allow one to isolate aerosol climatic effects relatively easily.

Since China strived to modernize the nation in the 1980s, aerosol loading experienced rapid escalation due to sharp increase in the emission of aerosol particles into the atmosphere, accompanied by discernible trends of an increasing "northern drought and southern flood" in precipitation pattern, and general cooling over some densely populated regions. It is plausible that these trends have something to do with the changes in aerosol.

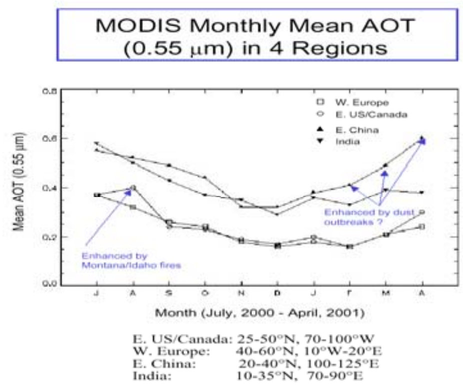

Fig. 1. Comparison of aerosol optical depth in Asia, Europe and America derived from MODIS.

Three major types of aerosols coexist in China, namely, sulfate and carbonaceous aerosols and dust aerosol, some of which (e. g. dust) can travel a long distance (e. g. to the US) and affect a much larger area.

2.1 Dust Aerosols

The primary natural aerosol in China is mineral dust generated from dust storms arising in desert regions, as well as from agriculture fields, barren land, and semi-arid regions (Fig. 2). Dust emitted from China's nine deserts and semi-arid regions may affect the environment and climate of the Northern Hemisphere mid-latitudes. The annual mean dust emission from China is estimated to be around 800 Tg. Dust outbreaks in China appear to have intensified in recent years in terms of frequency, duration, and area of occurrence, as revealed by numerous satellite observations such as TOMS, AVHRR, SeaWIFS and MODIS. During the major dust episodes observed in spring 1998, dust storms swept from the Takamoukou desert across the Pacific to the US. In 2001, there were 3 major, 10 medium, and 5 light dust outbreaks in northern China. On average, dusty weather was recorded every other day from the beginning of Spring 2001. The total number of dusty days recorded in 2001 was 41. The drought in northern China has played an important role in dust outbreaks. It remains a

Corresponding author address: Z. Li, Dept. of Meteorology and ESSIC, 2207 CSS Bldg., University of Maryland, College Park, MD 20742-2465; e-mail: zli@atmos.umd.edu

critical question, though, whether the aerosol indirect effect has anything to do with the drought trend. The direct cause of dust storms is vegetation cover lost in farming and ranching activities. 27% of the total land area of China is desert or is undergoing desertification, the economical impact of which is approximately $0.6 billion annually. Dust storms tend to intensify during daytime and weaken at night (Xu et al., 1979). To probe the vertical concentration of dust aerosol, a handful of lidar instruments were deployed in China (Qiu, 1984). Dust aerosol was found to reach an altitude of over 6 km. According to a model (MM5) study by Liu and Zhou (1998), dust is lifted to the upper atmosphere by cold fronts in the lower atmosphere (below 4 km) and by the westerly wind at higher altitudes. The radiative forcing of dust aerosol was evaluated using AVHRR and ground observations made during the HEIFE experiment (Shen and Wei, 1999a, 1999b; We and Shen, 1998). In Beijing, solar radiative heating is larger on dust storm days than on dust-free days by 80-318% Yi and Han, 1989). Major dust storm tracks have been identified (Sun et al., 2001). There are two major sources of dust outbreaks in China: the western Xinjiang territory that includes the Taklamakan Desert, and northwestern Inner Mongolia that includes the Gobi Desert. In Xinjiang, desertification has increased by 400 km^2 every year. Dusty weather can reduce visibility to less than 50 m, increase local top-of-atmosphere albedo by 50-100%, and reduce total solar radiation by 10-40% (Zhou et al., 1994).

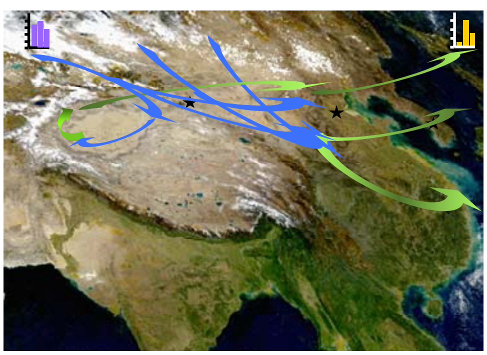

Fig. 2. Major dust storm tracks in China (based on Sun et al. 2001)

2.2 Anthropogenic Aerosols

As the most populated and fastest developing country in the world, China emits a large amount of anthropogenic aerosols. The primary energy sources in China comprise coal (74.8%, or 1.36 billion tons per year in 1997), oil (17.9%), natural gas (1.77%), hydroelectric (0.09%), and nuclear (5.44%). The dominance of coal consumption, combined with relatively low burning efficiency result in severe air pollution. Major pollutants include sulfur dioxide, nitrogen oxides, soot, and suspended particles. The total annual emission of SO_2 amounts to 20.9 Tg (76.2% industrial and 23.8% domestic) and the countrywide average atmospheric concentration of SO_2 is 0.056 mg m^{-3}, and to 0.037 mg m^{-3} for nitrogen oxides. Note that nitrogen oxide concentrations in Chinese cities may increase rapidly with a drastic increase in private vehicles. Heavy pollution has taken a severe toll on the environment, human life, and the economy. For example, the large concentration of SO_2 has caused widespread acid rain. The total area affected by acid rain is approximately equal to one third of China's total territory, including more than half of Chinese cities, mostly in southern China. In the foreseeable future, the composition of energy infrastructure in China will not change significantly, but the demand for energy will continue to grow, likely leading to more pollution and more anthropogenic aerosols. The problem is exacerbated because of increasing numbers of small, inefficient power plants owned privately or by local governments. Such small enterprises usually do not have coal-cleaning and sulfate-removal facilities essential to produce "clean energy." Yet, given the overall very low consumption of energy per capita in China, only about 1/48 the level of the US, this increasing trend may last a considerable period of time.

Due to air pollution, the imaginary part of the aerosol refractive index is generally high, and decreases from cities to the countryside (Hu et al., 1991). The single scattering albedo is generally low, as is shown in a comparison between Beijing and Washington DC (Fig. 3). The chemical composition of urban aerosols in China differs considerably from that in North America and Europe, with significantly higher concentrations of sulfate and black carbon (Wang, 1981; Ren et al., 1982). The highly hygroscopic nature of the pollutants compounds its climate effect due to the influence of humidity (Li et al., 1996, 2000). Because of their high soot content, these aerosols have a warming effect (over 1 °C per day) in the upper boundary layer and a cooling effect in the lower boundary layer, leading to a more stable atmosphere during the daytime. At night, the effect is just the opposite. Zhao et al. (1983) monitored aerosols in Beijing with a 7-band sunphotometer, from which the aerosol size distribution was retrieved. The radii of dust aerosols were found to be generally larger than 2.1 μm, while the radii of pollutant aerosols were generally less than 2.1 μm (Yang, 1995). The average refractive index in Beijing was found to be 1.517–0.034i during heating periods and 1.533–0.016i during non-heating periods. Note that these values are very crude estimates from solar direct and sky diffuse radiance measurements using shadowband radiometers for simultaneous retrieval of aerosol optical thickness, size distribution, refractive index, and surface albedo (Lu et al., 1981; Qiu, 1983, 1986; Li, 1989). Long-term lidar observations of aerosol profiles have been obtained in Beijing and Hefei (Zhu et al., 1998), supplemented by some short-term campaigns (Bai et al., 2000). A unique and seemingly ubiquitous local aerosol maximum between 5 and 8 km was found that has yet to be explained.

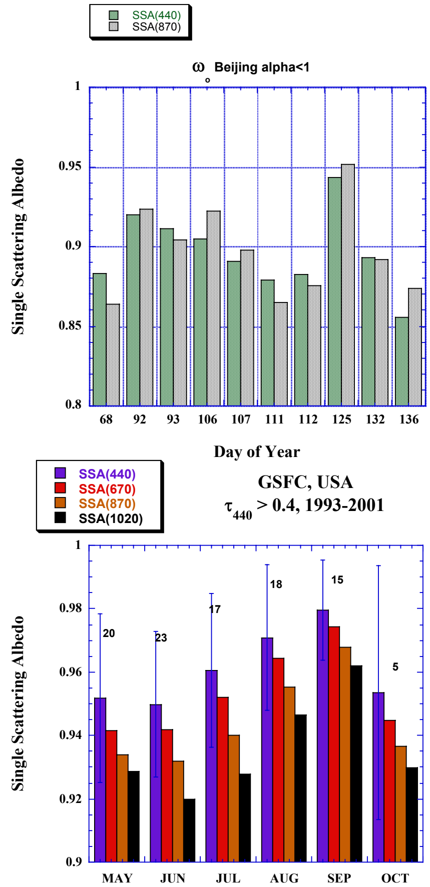

Fig.3. Comparison of single scattering albedos in Beijing and Washington as retrieved from AERONET measurements.

2.3 Climatic Effects

The climatic effect of anthropogenic aerosols produced in China is certainly significant but poorly quantified. One apparent effect of the aerosol increase is a reduction in direct solar radiation at the surface (Xu, 1990). According to Luo [2001], the reduction from the 1960s to 1980s is larger than 20% in all cities, with the largest decrease of 29.2% occurring in Guangzhou, where visibility has diminished by more than 50% during the last two decades!

Using aerosol optical thickness data estimated from surface radiation measurements (Fig. 3), Luo (1998) computed aerosol radiative forcing across China and found that the largest forcing (-13 Wm^{-2}) occurred in spring and the smallest (-8 Wm^{-2}) in winter. Note that these estimates are subject to considerable uncertainties due to errors in the retrieval of optical thickness and lack of observations for other aerosol attributes. The distribution and radiative forcing of anthropogenic aerosols was also modeled, based on an inventory of emission sources and strength (Hu and Shi, 1998a, 1998b; Zhang and Gao, 1987). The strong radiative forcing resulting from large aerosol loading impinges substantially on regional climate (Zhou et al., 1998; Hu and Shi, 1998). One direct effect is surface cooling that can exceed the warming effect of increased greenhouse gases. For example, a generally decreasing trend of surface temperature observed in the heavily industrialized Sichuan Basin has been attributed to the influence of exceptional aerosol concentrations. There are very few studies on the aerosol indirect effect in China, although the effect could be substantial, especially with regard to suppression of precipitation. Xu (1993, 1997) argued, based on a statistical analysis, that the aerosol increase is responsible for the increasing "northern drought and southern flood" pattern (Fig. 4), which seems to corroborate model simulation results (Geng et al., 1997). If so, aerosols have a significant impact on the hydrological cycle and on the monsoon regime that governs summer weather and climate across China. However, these arguments are essentially hypotheses that are yet to be substantiated with more sound physical mechanisms following rigorous scientific investigations.

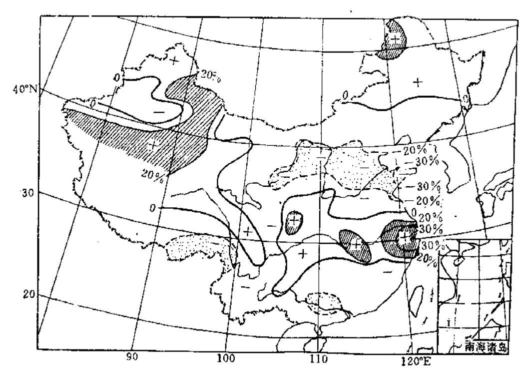

Fig. 4. Rainfall anomaly in 1980-1993 relative to long-term mean (1951-1980) (Xu, 1997)

Of course, the impact of pollution is more far-reaching than just climate. Air pollution in China is likely to reduce crop yield by 5-30% due to reduced photosynthetically active radiation (PAR) reaching the surface, according to a model study by Chameides et al. (1999). On the other hand, aerosol increases diffuse solar radiation that may enhance photosynthesis of a canopy and thus boosts productivity. There is also a significant linkage between pollution and mortality. It is widely acknowledged that today more people die from pollution than cancer in China.

3. OUTSTANDING ISSUES

3.1 Ground-based Observation

Despite numerous studies as discussed, the knowledge of Chinese aerosol characteristics and their climate effects remain very much uncertain for the following reasons. First, many of the instruments used in aforementioned studies are outdated with little knowledge of their accuracies. They were only deployed for a short period of time over few locations. There have existed nearly no operational aerosol observation stations equipped with rigorously calibrated instruments, although China recently purchased some 30 Cimel sunphotometers mainly for monitoring dust storms. The lack of long-term seasonal and large-scale measurements of aerosol microphysical and radiative properties means there is no baseline against which to gauge changes in aerosol loading and climate impacts in the future. Yet, aerosols in the region are unique, so that measurements and information acquired over other source regions cannot be substituted to fill the gap. Given the major advances in ground-based observation techniques and analysis methods, it is highly desirable to establish a long-term routine aerosol observation network equipped with advanced instruments such as those used in the Aerosol Robotic Network (AERONET). At present, there exists a big gap in the coverage of AERONET in China. In situ aerosol measurements are badly wanting to validate ground-based aerosol retrievals and to properly characterize the physical and chemical properties of major aerosol types found in the region.

3.2 Remote Sensing

Few attempts have been made in China to utilize satellite data to quantify the spatial and temporal variations of aerosols. Increasingly, remote sensing is playing an indispensable role in observing and understanding aerosols and their effects, especially in the era of the Earth Observing System (EOS) (King et al., 1999; Kaufman et al., 2001). In China, only a handful of attempts were made to use satellite data to monitor aerosols (Zhao et al., 1986). Most studies have been limited to qualitatively browsing imagery for major aerosol episodes, such as dust storms (Zhou et al., 1994). A quantitative investigation was made recently to retrieve aerosol optical thickness over major lakes across China using the GMS-5 and MODIS satellite data (Liu, 1999; Mao et al., 2000). Lack and inaccessibility of ground truth information in the region have hindered investigations by scientists outside China. There are some major challenges in the retrieval of aerosol properties in China where a large portion of the country has rather bright surfaces. The majority of aerosol remote sensing studies are restricted to dark surfaces (e.g. Kaufman et al., 1997). A combination of bright surfaces and absorbing aerosols that are often encountered in China makes the retrieval of aerosol optical thickness particularly cumbersome. New retrieval methods need to be developed with the aid of AERONET observations.

3.3 Modeling

The enhanced observation capability and rich information obtained will facilitate aerosol modeling. Models are useful to assess the environmental-climate impact of the anthropogenic and natural aerosols produced in East Asia. Aerosol modeling hinges heavily on ground-based and space-borne observations. The former can offer aerosol composition and properties in limited temporal and spatial domains, while the latter provides extensive temporal and spatial coverage but falls short on measurable quantities. Models can integrate the observations from various platforms on different time scales and quantitatively assess the large-scale impact and the future change of climate forcing due to anthropogenic and natural aerosols (Kinne et al., 2001). In recent years, several regional- to global-scale models have been developed to simulate major types of tropospheric aerosols using available emission inventories for aerosols and their precursors and/or by parameterizing the emission as a function of environmental conditions (e. g., wind speed). However, the inventory data used are prone to large uncertainties in this region.

A major piece of missing information is the composition of pollution aerosols. The largest uncertainty is probably linked to the source of carbonaceous aerosols. Model-calculated black carbon concentrations were nearly a factor of 5 lower than aircraft measurements throughout the measured altitude range, an underestimation whose consequence can be serious. Although its contribution to total optical thickness is relatively small, the black carbon level may be the determining factor in the sign, whether positive or negative, of aerosol radiative forcing and the degree of aerosol atmospheric heating. Again, direct observations from the source locations are needed to understand the discrepancies. Inventories of BC are difficult even under the best conditions, and uncertainties in inventories of BC in China are no exception. Recent analyses of data from the Indian Ocean and the US (Chen et al., 2001; Dickerson et al., 2002) indicate that using two different techniques gives answers for BC emissions in India that differ by a factor of 2 to 3. Since China, with its many small coal-fired sources is likely quite different from both the US and India, there is reason to expect that an inventory must be developed specifically for China.

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References (omitted due to space limitation, available upon request).