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Recent Progress in Atmospheric Observation Research in China

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ABSTRACT

Recent progress in atmospheric observation techniques, observational systems and their application in China are reviewed. According to different observational platforms, the review is presented in three sections, i.e., satellite remote sensing (SRS), ground-based observation technologies and applications, and aircraft/balloon measurements. The section "satellite remote sensing" presents advances in SRS techniques, SRS of clouds and aerosols, and SRS of trace gases and temperature/moisture profiles. The section "ground-based observation technologies and applications" focuses on research such as lidar systems and applications, sun/sky radiometer and broadband radiation observations, weather radar and wind profilers, GPS measurements, and some new concept systems. The section "aircraft/balloon measurements" presents some newly developed aircraft- and balloon-based sounding techniques.

Key words: observation techniques, observation system, application, satellite remote sensing, ground-based observations

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1. Introduction

Modern atmospheric observations, mainly composed of satellite remote sensing and advanced ground-based observation systems, play a very important role in many research fields such as modern atmospheric science, global change and so on. In recent years, atmospheric observations have received much attention and great advances have been made recently in China. In this paper, we will review recent research progresses in the atmospheric observation techniques, observation systems and applications in China. According to different observation platforms, satellite remote sensing, ground-based observation technologies and applications, and aircraft/balloon measurement techniques will be reviewed, respectively.

2. Satellite remote sensing

2.1 *Development and launch of spaceborn instruments*

There has been great progress made in satellite remote sensing technique development for atmospheric observation applications in China in recent years. Both polar orbiting and geostationary meteorology satellites FY-1D and FY-2C were successfully launched in May 2002 and October 2004, respectively. These two satellites operate well and allow China to be in possession of two kinds of meteorology satellites. The huge amount of data from FY-1D and FY-2C has being used in weather surveillance and forecasting, environment monitoring, disaster reduction, and atmospheric science research.

The second generation of polar orbit meteorology satellite, i.e., FY-3, is scheduled to be launched in 2007. FY-3 will orbit at 836 km with 98.75° of inclination angle and a period of 102.3 minutes (see: http//nsmc.cma.gov.cn/item/fy_yanzhi.htm/). The main payloads of FY-3 are MEdium Resolution Spectral Imager (MERSI), Infrared Atmospheric Sounder (IRAS), Microwave Temperature Sounder (MWTS), Microwave Humidity Sounder (MWHS), Total Ozone Unit (TOU), Solar Backscattering Ultraviolet Sounder (SBUS), and Earth Radiation Measurement (ERM).

The MERSI instrument has 20 channels with two spatial resolutions, 250 m and 1000 m, respectively,

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for visible and infrared bands. MERSI has similar features to MODIS, of which the channels are good for retrieving Aerosol Optical Thickness (AOT) over the ocean as well as over land, atmospheric water vapor, dust content, surface albedo, ocean color, and so on. The IRAS scans from 49.5° negative to positive values across the track, and the spatial resolution is 17 km at nadir. Twenty-six channels in the CO_2 absorption 15 μm band, water vapor band, ozone band, and atmospheric window are designed for retrieving atmospheric temperature and humidity profiles. The MWTS scans from 48.3° negative to the same positive degree, and a pixel at nadir stands for about 50 km. While the MWHS scans within 53.35°, with a swath of 2700 km and a resolution of 15 km at nadir. The TOU instrument has 6 channels, ranging from 308 nm to 360 nm, of which five channels are sensitive to ozone absorption, and one insensitive. The spatial resolution is about 50 km at nadir. The SBUS has 12 channels, ranging from 252 nm to 340 nm, and its spatial resolution is about 200 km. The retrieval algorithms for these four kinds of applications are being developed.

2.2 *Satellite remote sensing of aerosols and clouds*

Satellite remote sensing of aerosols and clouds can provide global coverage of optical properties, which is thought to be a unique approach to obtain temporal and spatial distribution of aerosols and clouds with high resolution on a global scale. Aerosols and cloud particles can change the intensity of incoming radiation by scattering and absorbing, so we can get their optical properties by measuring the change of incoming radiation. Aerosols can serve as cloud condensation nuclei (CCN), and its interaction with sunlight and their effect on cloud microphysics form a major uncertainty in predicting climate change.

During the last five years, after the successful launching of the Moderate Resolution Imaging Spectroradiometer (MODIS), Chinese researchers have contributed greatly to remote sensing research of aerosols and clouds from space. The research is summarized in four areas: (1) development of aerosol retrieval algorithms, (2) validation of satellite remote sensing of AOT, (3) application of satellite aerosol products to atmospheric and environmental research, and (4) development of cloud retrieval algorithms and applications.

2.2.1 *Development of aerosol retrieval algorithms*

After the successful launch of MODIS/Terra, several works have been done based on MODIS data. Based on the 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) radiative transfer code, the dense dark vegetation method, and the contrast reduction method are used to retrieve AOT over the land surface from MODIS/Terra data over Beijing and the surrounding area. It is found that the dense dark vegetation method fails to retrieve AOT over urban areas because of bright surface and strongly absorbing urban aerosols. By selecting suitable combinations of the two methods, a reasonable retrieval of AOT can be achieved (Li et al., 2003c). The synergy of MODIS/Terra and MODIS/Aqua data is applied to retrieve AOT and surface reflectance simultaneously, and this method can be used over many kinds of ground types (Tang et al., 2005). Based on MODIS aerosol operational algorithm, an AOT retrieval method with 1 km resolution is developed, and it is used for obtaining the AOT over Hong Kong. Comparing these products with long-term sun photometer observations, it is found that the relative error of the products is about 20%, which indicates that this method applied in Hong Kong has precision enough to capture the urban aerosol distribution (Li et al., 2005a).

LANDSAT/Thematic Mapper 5 (TM5) high spatial resolution images are used to discriminate clouds by their shadows since they are projected on the surface from cloud-free pixels in the visible band. Over a nontransparent cloud shadow, the radiance obtained from satellite measurements is the contribution of the atmospheric path radiance and surface diffuse reflection. Over a bright area surrounding the cloud shadow, besides the contribution of atmospheric radiance and surface diffuse reflection, the surface direct reflection also contributes to the radiance measured from satellite. Based on this theory, the difference between the two radiances and their relationship with the surface reflectance and AOT are analyzed, and a new method to retrieve surface reflectance and AOT simultaneously over land is developed (Duan et al., 2002).

2.2.2 *Validation of satellite remote sensing of AOT*

MODIS AOT-products are compared with ground-based sun photometer observations. The comparison in the Beijing area, presented by Mao et al. (2002), shows the two data fit very well with high correlations. Over eastern Asian, MODIS aerosol retrievals are evaluated by comparison with Aerosol Robotic Network (AERONET) aerosol observations. The preliminary validation results showed a moderate agreement between MODIS and AERONET AOT. Seasonal variation and uncertainties of surface reflection in the northern inland area of eastern Asia produce large random errors in MODIS aerosol retrievals. It is particularly important to improve MODIS aerosol retrieval algorithms in these regions (Xia et al., 2004). But new studies show that on a global scale over land, MODIS/AOT retrievals are overestimated except at a few AERONET sites in Africa and eastern Asia. This is likely due to uncertainty of surface reflectance, but issues with the AERONET cloud screening methodology remain open. More research concerning cloud contamination should be done (Xia, 2006). The validation analysis showed that the performance of MODIS C005 aerosol products had better agreement with ground aerosol measurements than MODIS C004 products. Smaller discrepancies were generally found when the MODIS-assumed surface reflectance was similar to the surface reflectance corrected under clean and clear sky conditions (Mi et al., 2007). Such comparison provided further insight into the possible error sources of satellite retrievals and could potentially help improve aerosol products in the future.

2.2.3 *Applications of satellite observations to atmospheric and environmental research*

Chinese researchers use satellite data to analyze aerosol process and properties. Li et al. (2003a) applies MODIS L1B data to retrieve 1–km resolution AOT products and apply the products to study the aerosol distribution patterns and the air pollution problems over China. Li et al. (2004) also use MODIS AOT-data and aerosol extinction coefficient profiles from MPL lidar to study an aerosol pollution episode in the Pear River Delta on 18–19 June 2003. Using Total Ozone Mapping Spectrometer (TOMS) aerosol index data, Gao et al. (2004) studied the aerosol spatial distribution, its variation trend, and the influence of dust aerosol on solar radiation. Using three MODIS thermal infrared bands, Zhang et al. (2006) investigated a dust event on 7 April 2001 in northern China. The dust optical thickness, its effective radius, and the column-integrated dust content were retrieved. Based on satellite data, Zhang et al. (2007a) also analyzed a dust event in 2006.

2.2.4 *Development of cloud retrieval algorithms and applications*

It is well known that clouds strongly modulate the energy balance of the Earth system through their interaction with solar and terrestrial radiation. Knowledge of cloud properties and their variation in space and time is crucial to the study of global climate change.

In the visible spectral region, cloud reflection function depends mainly on the Cloud Optical Thickness (COT). In the near infrared and middle infrared spectral region, the cloud reflection function depends mainly on cloud particle effective radius. Based on this consideration, an iterative algorithm is developed to retrieve cloud properties from National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) imagery (Zhao et al., 2002). The algorithm is applied to analyze the radiative properties of stratocumulus over the East China Sea.

The Chinese meteorological satellite FY-1C was successfully launched on 10 May 1999. It has ten spectral channels, among which channel 1 (0.58–0.68 μm), channel 4 (10.3–11.3 μm) and channel 6 (1.58–1.64 μm) can be used for cloud particle phase detection. As shown in the study by Liu et al. (2003b), the channel of 1.6 μm can be used to analyze the thermodynamic phase of cloud particles. The FY-1C data were used to retrieve COT and the effective radius of water clouds. The results show that the reflection function of clouds at a non-absorbing band (channel 1) in the visible wavelength region is primarily a function of the cloud optical thickness, while the reflection function at water (or ice) absorbing band (channel 6) in the near infrared is primarily a function of cloud particle size. The COT and the effective particle radius of water clouds can be determined solely from reflection function measurements at channel 1 and channel 6 or from the function measurements at channel 1 and brightness temperature at channel 3 of FY-1C/CHPRT data when COT is larger (Liu et al., 2003a).

2.3 ***Satellite remote sensing of gases***

Much attention has been paid by Chinese researchers to the remote sensing of gases by satellite because of their significance in climate and environment research.

An algorithm for the joint retrieval of air density and ozone in the stratosphere and mesosphere using the limb-scan technique has been developed by Guo and Lü (2006). Using the algorithm, the density profile in the 22–90 km altitude range and the ozone profile in the 20–90 km altitude range can be retrieved with accuracies of 1%–2% and 3%–5%, respectively. Sponsored by a Joint Dragon Program, Chinese scientists work together with European scientists on the spatial and temporal variation of NO_2 over China during 1996–2006 from the analysis of Global Ozone Monitoring Experiment (GOME) and The SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) products (Zhang et al., 2007b). Satellite-borne DOAS (Differential Optical Absorption Spectroscopy) techniques have been applied to measure air pollutants such as O_3, NO_2, SO_2 in the Institute of Atmospheric Physics (IAP), the Chinese Academy of Sciences (CAS). The NO_2 derived from the Ozone Monitoring Instrument (OMI) onboard the AURA satellite was applied to monitor the transport pattern of air pollutants for supporting the air quality assurance for the Beijing 2008 Olympic Games. Some very important features of NO_2 distribution over China such as the high value of NO_2 over northern China were observed.

2.4 *Satellite remote sensing of temperature/moisture profiles*

Retrieval algorithms for satellite remote sensing of atmospheric temperature/moisture profiles were developed. Wu et al. (2005) presented a physical retrieval algorithm retrieving atmospheric temperature and moisture distribution from the Atmospheric InfraRed Sounder (AIRS). The algorithm is applicable for AIRS clear-sky radiance measurements. The algorithm employs a statistical retrieval followed by a subsequent nonlinear physical retrieval. The regression coefficients for the statistical retrieval are derived from a dataset of global radiosonde observations (RAOBs) including atmospheric temperature, moisture, and ozone profiles. Evaluation of the retrieved profiles is performed through comparison with RAOBs from the Atmospheric Radiation Measurement (ARM) Program Cloud And Radiation Testbed (CART) in Oklahoma, USA. Comparisons show that the physically-based AIRS retrievals agree with RAOBs from the ARM CART site with a Root Mean Square error of 1 K on average for temperature profiles above 850 hPa, and approximately 10% on average for relative humidity profiles. In addition, based on the GMS-5 data of 1996–2002, Huang et al. (2004) investigated the average distribution of the upper troposphere water vapor over eastern Asia.

3. Ground-based observation technologies and applications

3.1 *Lidar systems and applications*

Lidar is a powerful means for remote sensing of the atmosphere. Recently, there has been substantial progress in the development of lidar systems and their applications in China. A Differential Absorption lidar (DIAL) and a transportable Raman-Mie lidar system were recently developed in the Anhui Institute of Optics and Fine Mechanics (AIOFM), CAS. In the DIAL system, the fourth harmonic of Nd: YAG laser was used to pump CH_4 and D2 gas cell. The system was applied to measure trace gases such as SO_2, O_3, NO_2 (Hu et al., 2004a). The DIAL measurements of the trace gases were validated by the chemical analyzers. The Raman-Mie lidar system was used to measure profiles of water vapor mixing ratio by Raman scattering as well as the aerosol extinction coefficient by Mie scattering (Xie et al., 2005, 2006). Using the lidar, water vapor mixing ratio was measured over the city of Hefei. The characteristics and the errors of typical water vapor mixing ratio profiles detected by the lidar were analyzed.

Three Doppler lidar systems for wind profile measurements have been developed in China in recent years. The Ocean University of China in Qindao has developed a 550 nm Doppler lidar (Liu et al., 2002), which uses iodine filters for frequency analysis of backscattered light from both aerosols and molecules for tropospheric wind measurements. The system can detect the wind profile up to 15 km at night and 12 km during daytime. AIOFM has constructed a 1064 nm Doppler lidar system for measuring three-dimensional wind profiles in the low troposphere (Sun et al., 2005, 2006; Zhong et al., 2006). The system uses a double-edging technique with Fabry-Perot standard. The lidar wind profiles were compared with those observed by CINRAD/SA Doppler weather radar, Airda 16000 microwave radar, and a Vaisala balloon. Quite good agreements were obtained, suggesting its capability of continuous monitoring the 3-D wind field. This Doppler lidar is able to detect the atmosphere up to 9 km at night. Another Doppler lidar is being developed in the IAP, CAS.

A dual-wavelength lidar for detecting the upper atmosphere was developed in the Wuhan Institute of Physics and Mathematics, CAS (Hu et al., 2004b). The lidar was applied to detect solar activity and disastrous space weather. It is capable of detecting the atmosphere in the range of 30–110 km, including the middle and upper atmosphere and the lower ionosphere. It has become an effective observation method for studying the middle and upper atmosphere and the sun-earth relationship.

The Mie-Rayleigh-Sodium lidar (She et al., 1992) system has been developed at the University of Science and Technology of China in Hefei. The lidar system is applied to measure the vertical profiles of the aerosol extinction coefficient by Mie scattering, temperature by Rayleigh scattering and the density of the Na atom by fluorescence. The reliability of the measured data by lidar was checked by the comparison with the nearby lidar of NIES (National Institute for Environmental Study, Japan) and good agreement was observed.

Mie scattering lidars are very useful in detecting atmospheric aerosols, the planet boundary layer structure, and cloud height and thickness. This kind of lidar was widely used in China to monitor the transport behavior of dust during dust storm events, aerosol extinction coefficient profiles, regional air pollutant transport, and the urban mixed layer (He and Mao, 2005; He et al., 2006a,b). In addition, AIOFM has joined national and international projects on lidar monitoring of the atmosphere (Yuan et al., 2005; Zhou et al., 2006; Hu et al., 2004a). These projects include the AD-Net (Asian Dust lidar observation NETwork) (Murayama et al., 2001), ADEC (Aeolian Dust Experiment on Climate impact) (Mikami et al., 2006), SKYNET (Nakajima et al., 2003), ABC (Atmospheric Brown Cloud), and GALION (GAW Aerosol lidar Observation Network).

3.2 *Sun/sky radiometer and radiation measurements*

Much attention has been paid to the connection between the greenhouse effect brought on by human activity and global climate change. Human activity also results in the emission of large amounts of aerosols, which can significantly influence global climate. The global annually-averaged direct radiative forcing by aerosols at the top of the atmosphere is estimated to be in the range of -0.5 to 0.2 W m^{-2}. Because of the relatively short lifetime of aerosol particles and their large regional variability, instances of strong localized direct forcing can occur (Ramanathan and Crutzen, 2003). On a regional scale, it is suggested that aerosols are already affecting surface forcing, atmospheric heating, and precipitation. The important role that aerosols play in the climate and environment system is widely recognized. However, large uncertainties in the chemical, physical, and optical properties of atmospheric aerosols render the quantitative assessment of aerosol effects on climate and environment problematic (Nakajima et al., 2003; Li et al., 2007). Rapid economic growth and population expansion over the last twenty years has led to a significant increase in AOT over much of China. The average AOT at 750 nm observed at 46 stations in China increased from 0.38 in 1960 to 0.47 in 1990 (Luo et al., 2001). It should be noted that long-term continuous observations of aerosol properties are still very limited in China, so we should maintain the existing observations and make an effort to augment aerosol observations across China (Xia et al., 2007a). A combination of ground-based and satellite remote sensing and the integration and assimilation of all aerosol data available into models are a feasible way to reduce the uncertainties in the effects of aerosols on environment and climate.

Use of the sun photometer is a reliable mean to measure aerosol optical properties, including the AOT. In recent years, three main sun photometer or sun/sky radiometer networks have been established in China and played an important role in measuring aerosol optical properties. One is CSHNET (Chinese Sun Hazemeter Network), using hand-held sun photometers to measure AOT (Xin et al., 2007). Using these measurements, the spatial and temporal distributions of AOT were derived and the MODIS AOTs were assessed (Wang et al., 2007). CSHNNET is a part of Chinese Ecological Research Network (CERN). Along with sun photometers, a set of broadband solar radiometers is installed in CERN stations, the data from which were used to discuss the spatial-temporal variations of solar radiation (Hu et al., 2007). The second is the Chinese sites of AERONET. AERONET (Holben et al., 1998) is a worldwide aerosol monitoring network, initiated in the 1990s and expanded rapidly to hundreds sites across the world. The CIMEL sun/sky radiometers measure direct spectral solar radiation with a 1.2° full-viewing field at 440, 675, 870, 940, and 1020 nm (nominal wavelength) every 15 minutes. These solar extinction measurements are used to derive AOT except for the fourth, which is used to retrieve column water vapor amount. The AOT-accuracy was estimated to be 0.01–0.02. The radiometer also performs sky radiance scans at 440, 675, 870, and 1020 nm (nominal wavelengths) at optical air masses of 4, 3, and 2 in the morning and afternoon, and once per hour in between. Aerosol microphysical properties, including size distribution and a refractive index, are retrieved at solar zenith angles greater than 45 degrees. Aerosol optical quantities such as phase function, asymmetry factor, and single scattering albedo are computed from the retrieved microphysical properties. The third is the CE-318 sun photometer Network established by the China Meteorological Administration (CMA) in 2002. Using the CE-318 sun photometer data, dust aerosol optical properties in the south Tarim Basin were studied (Li et al., 2005b), and the AOT over the urban areas in Urumqi and Beijing were retrieved (Li et al., 2005c, Zhang et al., 2002a). Dust events in northern China were monitored by this network and the data were widely used to improve the numerical model simulations of dust storms (Liu et al., 2004; Wang et al., 2005a).

Based on the aerosol optical property data from the above three aerosol networks as well as other satellite and ground-based measurements, aerosol optical properties in China were actively initiated recently. High aerosol loading over much of China was evident from satellite and ground-based measurements (Li et al., 2003b; Xia et al., 2005; Zhang et al., 2002b). An extremely wide range of aerosol loading, size, and absorption was derived from multi-year AERONET data in Beijing (Xia et al., 2006a; Fan et al., 2006). The increase in aerosol loading was suggested to partly account for a notable decrease of sunshine duration and downward surface solar irradiance (Che et al., 2005a; Liang and Xia, 2005; Xia et al., 2006b).

Heavy aerosol loading and notable temporal and spatial variation over the Beijing and Xianghe sites in spring were revealed by AERONET data in spring 2001. Aerosol loading and size between Beijing and Xianghe, an urban and suburban site in northern China, were highly correlated, illustrating a clear picture of regional air pollution (Xia et al., 2005). The climatologic aspects of aerosol optical properties in Beijing were studied using AERONET data from 2001 to 2004 (Xia et al., 2006a). The AOT increased gradually from January to June, and then decreased gradually to December. However, the surface PM10 concentration showed quite different seasonal variation. Higher PM10 occurred during the spring and the winter and relatively lower values during the summer and autumn. The seasonal variations of the pollution boundary layer height and relative humidity might be responsible for this inconsistency. Aerosol Single Scattering Albedo (SSA) in Beijing was about 0.90 at 440 nm and decreased slightly in the near infrared wavelength. SSA increased notably and the spectral dependence reversed if Beijing was impacted by dust events. Aerosol absorption in Beijing was close to AERONET data in urban regions such as in Mexico City and Kanpur. Using AERONET data, Che et al. (2004, 2005b) studied the aerosol optical characteristics in the Mu Us desert and also compared the aerosol optical and physical characteristics under two different weather conditions, i.e., dust storm and haze.

In September 2004, scientists from China and the United States cooperated to establish a comprehensive radiation site in Xianghe. A set of broadband pyranometers was installed side-by-side with a CIMEL sun photometer. The first objective is to establish a testbed for the validation of satellite estimates of aerosol, clouds, and the energy budget in northern China. Secondly, the effects of aerosols on the energy budget at the surface and at the top of the atmosphere are to be explored based on long-term ground-based and satellite observations (Li et al., 2007). The Xianghe site officially became the new Baseline Surface Radiation Network (BSRN) station by having its data accepted by the BSRN archive in 2005. BSRN is a project of the World Climate Research Programme (WCRP) and the Global Energy and Water Experiment (GEWEX) and as such is aimed at detecting important changes in the earth's radiation filed at the earth's surface and at supporting the validation and confirmation of satellite and computer model estimates of these quantities. It should be pointed out that Xianghe is the only BSRN station in the vast continent of Asia.

Using fifteen months of ground-based broadband and spectral radiation data in Xianghe, aerosol loading and effects on surface solar radiation were analyzed. The mean 500 nm AOT is 0.66, and the standard AOT-deviation is up to 0.67, implying a large day-to-day variation. Approximately 23% of AOT data exceeded 1.0 in spring and winter, and 34% was larger than 1.0 in summer and autumn. About 37% of AOT data were less than 0.15 in winter, but the frequency was only 10% in spring and summer. The aerosol extinction was primarily contributed by fine particles with radii less than 0.6 except a few cases of dust events. The collocated aerosol and surface solar radiation data were utilized to quantitatively estimate the aerosol effects on global shortwave radiation (SWR) and Photosynthetically Active Radiation (PAR). The monthly aerosol direct radiative forcing (ADRF) for SWR at the surface varied from -13 W m^{-2} in January to -45 W m^{-2} in June and then to -15 W m^{-2} in December, which was about 1.73 times ADRF for PAR (Xia et al., 2007b). The normalized ADRF, i.e., the ratio of ADRF to AOT at 500 nm, ranged from -40 W m^{-2} in winter to -72 W m^{-2} in June. The estimates from observations were in good agreement with radiative transfer model simulations.

In the spring of 2005, a sun photometer and a set of broadband pyranometers were installed in Liaozhong, a suburban region in northeast China (Xia et al., 2007c). Aerosol properties derived from sun photometer measurements and aerosol-induced changes in surface irradiances were explored based on four months of data. The results showed that the mean aerosol optical depth (AOT) at 500 nm was 0.63. The day-to-day variation of aerosol optical depth was dramatic, with a maximum daily AOT close to 2.0 and a minimum value close to the background level. Dust activity generally produced heavy aerosol loading characterized by larger particle sizes and less absorption than those observed under normal conditions. The reduction of instantaneous direct shortwave surface irradiance per unit of AOT was 404.5 W m^{-2}. About 63.8% of this reduction was offset by an increase in diffuse irradiance, consequently, one unit increase in AOT led to a decrease in global surface irradiance of 146.3 W m^{-2}. The diurnal aerosol direct radiative forcing efficiency was about -47.4 W m^{-2}. This value is somewhat less than the estimates in Korea and Japan where the efficiency is estimated to be 50–100 W m^{-2} (Nakajima et al., 2003). The difference is partly caused by a large regional difference in AOT and single scattering albedo. AOT and single scattering albedo here are quite large due to the input of a large volume of dust aerosols with weak absorption, both suggesting a relative smaller radiative efficiency at the surface. Overall, aerosols reduced about 30 W m^{-2} of surface net shortwave irradiance in this suburban region.

Trends in surface global radiation, direct horizontal radiation, diffuse radiation, the clearness index, the diffuse fraction and percentage of possible sunshine duration for the period 1961–2000 in China were evaluated. Annual means for all six variables were calculated for each station and for China as a whole. Linear regression analysis was used to characterize long-term annual trends in these variables. Over the latter half of the 20th century, there has been a significant decrease in global radiation (-4.5 W m^{-2} per decade), direct radiation (-6.6 W m^{-2} per decade), the clearness index (-1.1% per decade), and the percentage of possible sunshine duration (-1.28% per decade), but diffuse fractions have increased (1.73% per decade). Although there is some evidence that conditions have improved in the last decade, the consistent spatial and temporal variations of these variables support the implication that increased aerosol loadings were at least partially responsible for the observed decrease in global radiation and direct radiation, the clearness index, and the monthly percentage of possible sunshine duration over much of China.

3.3 *Pyrheliometer/pyranometer measurements of aerosol and cloud optical properties*

There is a denser worldwide network using relatively inexpensive but reliable pyrheliometer and pyranometer instruments for surface-based broadband solar radiation measurements. In China, pyrheliometer and pyranometer measurements started in the 1950s and now there are more than 90 and 40 meteorological observatories performing routine pyranometer and pyrheliometer measurements, respectively. Available yet quantitative methods to derive aerosol and cloud optical properties from these broadband radiation data should be very significant and useful. Propelled by this application, some Chinese authors have contributed considerable effort to develop the methods.

Based on Broadband Diffuse Solar Radiation method (BDRM) for Aerosol Imaginary Part (AIP) retrieval, an improved BRDM for the AIP and 1-μm-wavelength SSA retrievals is proposed by Qiu et al. (2004). The first improvement is to determine diffuse radiation from combined pyrheliometer and pyranometer data. Secondly, available approaches to input parameters demanded for AIP retrievals are presented, including the approach to determine an aerosol extinction coefficient profile from visibility and aerosol optical depth data. This method is used in retrieving AIP and SSA from routine pyrheliometer and pyranometer observation data measured in 1993–2001 over six meteorological observatories in northern China. As shown in the retrieval results, annual mean AIP during 1993–2001 changes from 0.0207 to 0.0301 for the six cities, and the corresponding SSA from 0.851 to 0.803 with a mean value of 0.832. This BDRM is available to retrieve 1-μm-wavelength SSA. Generally, SSA is closely wavelength-dependent. In order to take account into the dependence, Qiu (2006a) developed a new BDRM to retrieve radiation-weighted-mean SSA. As shown in retrieval simulations, if the error of Ångström index is within ± 0.2, the errors of the SSA retrievals are within ± 0.0227 and ± 0.0345 for continental and urban-industrial aerosols, respectively. The larger aerosol optical thickness is, the larger the error of the SSA solution caused by the error of radiation data. Under the condition of 0.55-μm-wavelength aerosol optical thickness being larger than 0.312, the errors of SSA solutions are within ± 0.0149 and ± 0.0317 if radiation data errors are within $\pm 2\%$ and $\pm 4\%$, respectively.

Using the Broadband Extinction Method (BEM) for AOT retrieval (Qiu, 2003), Zong et al. (2005a) compared AOT from BEM with AOT from AERONET at the Beijing site. The results showed that both AOT-data were in good agreement. Furthermore, they developed a method to minimize the effects of clouds on the monthly-average AOT-estimation. The method feasibility is tested through a comparison of the BEM AOT with AERONET AOT. Based on AOT data from BEM, Zong et al. (2005b) also analyzed variation characteristics of monthly/seasonally/yearly mean AOT in 16 sites during 1993–2002. AOT increased over Shenyang and Zhengzhou but a decreasing trends were derived over Harbin, Lanzhou, Guangzhou, and Beijing.

Qiu et al. (2005) developed a method to determine a so-called scaling height of the tropospheric aerosol and the exponent-type aerosol extinction coefficient profile from the pyrheliometer or sun photometer measurements and surface visibility data. Using this method, characteristics of seasonal/yearly mean scaling heights and aerosol extinction profiles over 11 sites in China during 1994–2001 are analyzed. The yearly-mean scaling heights over the 11 sites change between 1.30 km and 2.67 km, and they are quite variable for different seasons, being usually larger in spring. As far as the yearly-mean scaling heights of all 11 sites are concerned, they change between 1.88 km and 2.11 km during 1994–2001, showing an increasing trend.

In addition, Qiu (2006b) developed a method to retrieve COT from global solar radiation detected by a ground-based pyranometer. Based on numerical simulations and comparative tests, the main error factors of COT retrievals are analyzed. COTs ($\tau_{\rm Pyr}$) from pyranometer data at two meteorological observatories are compared with COTs ($\tau_{\rm ISCCP}$) from ISCCP and COTs ($\tau_{\rm MODIS}$) from MODIS. The relative standard deviations between monthly-mean $\tau_{\rm Pyr}$ and $\tau_{\rm MODIS}$, or $\tau_{\rm Pyr}$ and $\tau_{\rm ISCCP}$, are all less than 45.4% for both sites. The agreement among the yearly-mean $\tau_{\rm Pyr}, \tau_{\rm MODIS}$ and $\tau_{\rm ISCCP}$ is satisfactory. The absolute (relative) deviations between the yearly-mean $\tau_{\rm Pyr}$ and $\tau_{\rm MODIS}$ are within ±1.55 (8%) for both sites, and the deviations between the $\tau_{\rm Pyr}$ and $\tau_{\rm ISCCP}$ are within ±1.94 (25%).

3.4 *Weather radar and wind profilers*

CMA plans to deploy 158 sets of new generation Doppler weather radar (CINRAD) over the main continent during eleventh five-year planning periods (2006–2010). Over the last four years, more than half of them have been set up mainly in southern China where heavy rainfall and typhoon events occur frequently. The national and regional mosaics of radar product images are now available on the web sites of national and regional meteorological centers.

To improve the capability of precipitation estimation and hailstorm detection, several X-band and C-band dual-polarization radars have been developed in the IAP and the Institute of Cold and Arid Regions Environmental and Engineering Research in collaboration with radar manufacturers. A theoretical study of estimations of rain and hail rates in mixed-phase areas using dual-polarization radar was carried out by Liu et al. (2002). The results show that the reflectivity of hail measured by a C-band dual-polarization radar decreases with hail rate when the hail rate is very large. The differential phase shift $K_{\rm DP}$ in a hailstorm is related to the shape, orientation, and the size of hail. In the mixture of rain and hail, the major contribution of horizontal polarization radar reflectivity factor $Z_{\rm H}$ is from hail. Raindrops are the main factor to affect $K_{\rm DP}$. Both rain and hail contributions to differential radar reflectivity factor $Z_{\rm DR}$. $Z_{\rm H}$ and $K_{\rm DP}$ in rain have good correlation. A simple yet effective method is proposed to estimate hail and rain rates in a mixed phase area with $Z_{\rm H}, Z_{\rm DR}$, and $K_{\rm DP}$ with error analyses.

For the purpose of obtaining the information of a 3-D wind field, the X-band bistatic Doppler weather radar system is being developed by the Nanjing Research Institute of Electronics Technology in collaboration with the IAP (Li et al., 2005a). Based on the specifications and functions of X-band radar, a slotted wave-guide antenna and GPS timer are used to solve the synchronization problems of space, phase, and time. The system is characterized by the simple structure, cheapness, reliability, and high sensitivity. In addition, the design of the phased array Doppler weather radar is also under way to improve the time resolution of radar observations.

The wind profiler is a powerful tool to measure the vertical wind structure in the troposphere. In recent years, a number of wind profilers both home- and overseas-made have been deployed in many big cities and used in some field experiments. Wang et al. (2005c) conducted a comparison study between the radiosonde and the wind profiler measurements during the 973 heavy rain field campaign held in the summer 2002 in Anhui Province. The wind profiler WPR 1300 was used. Results show that the vertical structure of wind can be well detected by wind profilers during a mesoscale precipitation episode.

3.5 *GPS measurements of water vapor*

Ground-based GPS meteorology focuses on such three main objectives as: (1) measurement of precipitable water vapor in the zenith direction, (2) remote sensing of slant-path water vapor, and (3) retrieval of water vapor three-dimensional structures in the local region (water vapor tomography). Bi et al. (2006) developed a GPS approach to measure 4-D Water Vapor Tomography in the Troposphere, and Li and Mao (2004) presented the concepts of hydrostatic delay and wet delay in remote sensing water vapor with ground-based GPS receivers. The common formula of calculating precipitable water from GPS troposphere delay is inferred based on the refractive index and air state equation expressions. In the approach presented by Bi et al. (2006), a tomographic method was utilized to retrieve the local horizontal and vertical structure of water vapor over a local GPS receiver network using SWV amounts as observables in the tomography. The method of obtaining SWV using ground-based GPS is described first, and then the theory of tomography using GPS is presented. A water vapor tomography experiment was made using a small GPS network in the Beijing region. The tomographic results were analyzed in two ways: (1) a pure GPS method, i.e., only using GPS observables as input to the tomography; (2) combining GPS observables with vertical constraints or a priori information, which is from average radiosonde measurements over three days. It is shown that the vertical structure of water vapor is well resolved with a priori information. Comparisons of profiles between radiosondes and GPS show that the RMS error of the tomography is about 1–2 mm. It is demonstrated that the tomography can monitor the evolution of tropospheric water vapor in space and time. The vertical resolution of the tomography is tested with layer thicknesses of 600 m, 800 m, and 1000 m. Comparisons with radiosondes show that the result from a resolution of 800 m is slightly better than results from the other two resolutions in the experiment. Water vapor amounts recreated from the tomography field agree well with precipitable water vapor (PWV) calculated using GPS delays. Hourly tomographic results are also shown using the resolution of 800 m. Water vapor characteristics under the background of heavy rainfall development are analyzed using these tomographic results. The water vapor spatio-temporal structures derived from the GPS network show a great potential in the investigation of weather disasters.

3.6 *Upper air sounding system*

Over the past five years, new generation upper air sounding systems with L-band radar have been deployed in about one-half of the network of Chinese upper air sounding stations and the other half of the stations with old sounding systems will be gradually replaced in the five years.

The CMA is also planning to use the RS92 radiosondes in some climate monitoring observatories. The Väisälä RS92 radiosonde was introduced by Ma et al. (2005). RS92 adopts digital technology with greatly improved sounding precision and anti-jamming capability in information transmission. The bandwidth of its transmitter is only one-tenth of RS80's. By using GPS frequency-extending technology, RS92 wind data acquirement is greatly enhanced. The sensors of temperature, pressure, and humidity as well as their calibration techniques are also significantly improved. In parallel, the GPS-based radiosonde system has been successfully developed in China (Wang et al., 2004b). The design and performance of the software system for new generation radiosonde are described by Du et al. (2004).

A new pattern of digital atmospheric turbulence detector designed with the adoption of the dipole sensor device is presented by Luo et al. (2004). The analog and digital filters are also optimized. The MA (Moving Average) and the incremental processing algorithms are provided to give a solution to the problem of the high frequency and gusty interference. Both the simulation and experimental results show that the performance of the new pattern is much better than the traditional systems, in sensitivity, data reliability, and noise level.

3.7 *Other systems of atmospheric observations and applications*

Several innovative instruments have been developed in the Laboratory for middle Atmosphere and Global Environment Observations (LAGEO) of the IAP, including the trail-tracked advice for multi-target albedo observation, the scanning infrared all sky thermometer for simultaneously measuring sky and surface IR brightness temperatures (Zhang et al., 2007c), and the visible all sky imager based on an up-looking fisheye camera (Huo and Lü, 2005, 2006).

In order to fill in the data gaps between upper air sounding and the surface meteorological and environmental observation stations, Chen and Zheng (2005) suggested that it is necessary and feasible, along with the advance of transport platform and communication technology, to build up a 3-D mobile system for monitoring the global atmosphere and its environment by using commercial transport platforms such as aircraft, ship, train, and autobus. Some perspectives for atmospheric sounding can be found in Zhang et al. (2003).

To automatically analyze on-line the concentrations of water-soluble ions in ambient particles, a system of rapid collection of fine particles and ion chromatography (RCFP-IC) was developed by combining the system of rapid collection of ambient particles and ion chromatography (Wen et al., 2006). The detection limit of RCFP-IC for SO_2^{-4}, NO^- , NO^- , Cl^- and F^- is below 0.3 μg m^{-3}. The collection efficiency of RCFP-IC increases rapidly with increasing particle size. For particles larger than 300 nm, the collection efficiency approaches 100%. The precision of RCFP-IC is more than 90% over 28 repetitions. The response of RCFP-IC is very sensitive and no obvious cross-pollution is found during measurement. A comparison of RCFP-IC with an integrated filter measurement indicates that the measurement of RCFP-IC is comparable in both laboratory experiments and field observations. The results of the field experiment prove that RCFP-IC is an effective on-line monitoring system and is helpful in source apportionment and pollution episode monitoring.

A study by Si et al. (2006) has shown that the continuous operation of the DOAS system has the capability of profiling atmospheric aerosols. The correlation study using diurnal datasets shows that, on the average, the MEE values vary over a range of 2.6–13.7 m^2 g^{-1}. On the basis of the simulation study, it is likely that high MEE values indicate the dominance of fine particles, while low MEE values suggest the dominance of coarse particles. It is also obvious that MEE changes with the relative humidity. These findings are supported by both the variation of Angstrom coefficient and the relative humidity.

The aircraft observations of the size distributions of particles (0.47–3 μm, 57 channels, including number concentration distribution, surface area concentration distribution and mass concentration distribution) were carried out by Wang et al. (2005b) at an altitude of 2000 m over eastern costal areas of China from Zhuhai, Guangdong to Dallan, Liaoning. The TSI APS-3310A Aerodynamic Particle Sizer was used on aircraft to sample particle size distributions. It consists of the Model 3310A Aerodynamic Particle Sizer Spectrometer (APS) and data analysis system. It uses 57 channels to analyze particles with diameters in the range 0.43–3 μm and gives number size distribution automatically. Air was introduced into the instrument through a Teflon tube and a stainless steel tube at a rate of 5 L min^{-1}. The inside of the tube was treated with glycerin in order to reduce the static charge and to further reduce the loss of particles. The measurements show that the average daily concentrations of PM10 are very high in the cities along the flight leg. These cities are among the most heavily polluted cities in China. The main pollution sources are anthropogenic activities such as wood, coal, and oil burning. The observed size distributions show a broad spectrum and unique multi-peak characteristics, indicating no significant impacts of individual sources from urban areas.

Ozone vertical profiles are retrieved from the Dobson Umkehr observations of Beijing from 1990 to 2002 (Yang et al., 2005). Using the derived profiles combined with the total ozone data measured by the Dobson spectrophotometer, the characteristics and variations of the ozone vertical distributions of Beijing during 1990–2002 are studied. The results show that in the fall of 1992 and the spring of 1993, the seasonal average ozone concentrations in layers 2–4, corresponding to heights of 10.3–23.5 km, were unusually lower than normal, and at the same time, the total ozone underwent a marked decline; During the period 1990-2002, the monthly mean total ozone decreased slightly, but the trends of change of ozone concentrations at different altitudes were different.

Using an aethalometer and a TEOM1400a (Tapered Element Oscillting Microbalance), Lou et al. (2005) measured black carbon (BC) aerosol properties in Peking University. The result indicated that 90% and 82.6% of BC existed, respectively, in PM10 and PM2.5 in the winter aerosol. The average BC mass concentrations in summer and winter of 2003 are 8.80 μg m^{-3} and 11.4 μg m^{-3}, respectively.

4. Airborne/balloon measurements

4.1 *Ozonesonde systems*

The ozonesonde system, an effective technique for direct measurement of vertical ozone structure in the atmosphere, has been developed (Wang et al., 2003, 2004a). This system is a combination of single cell ozone sensor with GPS sonde. Before its application for routine operation, the performance of the system was tested in laboratory and compared with that commonly used in the world ozone monitoring network. The main technical specifications, components, and the performance test results can be found in Wang et al. (2003, 2004b), and Xuan et al. (2004). Ozonesondes launched from Beijing, China, over a 3-year time period (September 2002 to July 2005) have been used to evaluate the performance of ozone profile retrievals in the upper troposphere and lower stratosphere (UTLS) from two new spaceborne instruments, the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua satellite and the Microwave Limb Sounder (MLS) on the NASA Aura satellite (Bian et al., 2007).

4.2 *Aircraft sounding system*

Ma et al. (2004) present a miniature robotic plane meteorological sounding system (RPMSS), which consists of three major subsystems: a miniature robotic plane, an air-borne meteorological sounding and flight control system, and a ground-based system. Take-off and landing of miniature aircraft are guided by radio control and the flight of robotic plane along a pre-designed trajectory is automatically piloted by an onboard navigation system. The observed meteorological data as well as all flight information are sent back in real time to the ground, then displayed and recorded on the ground-based computer. The ground-based subsystem can also emit some instruction signals to the airborne control subsystem. Good system performance has been demonstrated by more than 300 flight hours for atmospheric soundings.

The miniature robot aircraft (MRA) has been innovatively used for weather modification, i.e., precipitation enhancement (Ma et al., 2006). The system is composed of three parts: the miniature aircraft, the mission loading (the airborne seeding device and meteorological measurement device), and the ground monitor control sub-system. Before each launch, the flight path is designed and transferred to the airborne control system. After reaching altitude and receiving the instruction from the remote control terminal, the cloud seeding is conducted. During the course of the flight, the meteorological parameters are measured and transferred in real-time to the ground. Through a number of flight tests, the performance of MRA for weather modification and its capability for meteorological observation have been proven. The MRA can fly up to 6000 m of altitude carrying the seeding materials of 1 kg (silver iodide), and its operation radius can reach 25 km. The operation can be accomplished during severe weather.

4.3 *Airborne microwave radiometer*

An airborne upward-looking microwave radiometer for measuring column super-cooled cloud liquid water path was developed by Lei et al. (2003). The tests of the instrument both in laboratory and on the airplane suggest that under certain conditions the instrument sensibility can be better than or equal to 0.2 K. The calibration methods are also introduced and the measurement uncertainties are discussed in their paper. And the retrieval method is described in Jiang et al. (2004).

4.4 *Tethered balloon*

The tethered balloon sounding system has great applications for meteorological and environmental observations in the boundary layer. A home-made one named XLS-II is introduced by Wang et al. (2004b). The technical specifications of the main components are given as follows: winch weight of 36 kg, motor power of 600 W, maximum pulling force of 175 kg, and a cord of 1500 m. The payload can be meteorological sensors, ozone sensor, aerosol sampler, optical particle counter and so on.

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