NOTE AND CORRESPONDENCE

An Analysis of Seasonal and Decadal-long Variations of Aerosols over the Asian Pacific Region using NOAA/AVHRR Data

Akira SOBAJIMA¹, Shoji ASANO, and Hironobu IWABUCHI²

Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Sendai, Japan

(Manuscript received 25 March 2004, in final form 6 July 2004)

Abstract

Seasonal and decadal-long variations of aerosols in the Asia Pacific region, over the seas east off the Asian continent, have been analyzed using AVHRR data from NOAA-11 and NOAA-14 satellites. The aerosol optical thickness at wavelength 0.5 μm and Ångström exponent were retrieved by means of the so-called two-channel algorithm for the period of about 12 years, between November 1988 and January 2001. Evident seasonal variation was found in the geographical distributions of aerosols over the region. Excepting the interval of strong influence by the Pinatubo volcanic eruptions, the aerosol optical thickness has gradually increased almost all over the region during the analyzed period. The present results verified the fact that the Asian Pacific region is under significant influence of natural and anthropogenic aerosols from the Asian continent.

1. Introduction

As a result of growing trends of population and industrialization, East Asia is said to be one of the strongest source regions of anthropogenic aerosols (IPCC 2001). Additionally, the East Asian region is subject to substantial loadings of such natural aerosols as dusts from the Asian deserts, known as *Kosa* (yellow sand), particularly in spring seasons (e.g., Arao and Aoki 2001; Yoshino 2002), and particulate matters caused by extensive biomass burning. Aerosols downwind of the Asian continent are

complex mixtures of anthropogenic and natural sources (e.g., Okada et al. 1990; Chen et al. 1997; Kaneyasu et al. 2000; Sugimoto et al. 2002). Recently, various effort has been undertaken to investigate the behavior and radiative effects of Asian aerosols in several intensive campaigns, such as ACE-Asia (Asian Pacific Region Aerosol Characterization Experiment; see, e.g., Huebert et al. 2003), APEX (Asian Atmospheric Particle Environmental Studies; see, e.g., Nakajima et al. 2003), and ADEC (Aeolian Dust Experiment on Climate impact; Mikami et al. 2002). However, the long-term trend of aerosol loadings in the East Asian region is still poorly understood. A main purpose of the present study is to survey, from space, long-term variations of aerosols in the Asian Pacific region.

It is convenient to use satellite data to monitor a long-term variation of aerosol distributions in wide areas. Data from the Advanced Very High Resolution Radiometer (AVHRR), onboard the NOAA (National Oceanic and At-

---

Corresponding author: Shoji Asano, Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Sendai, 980-8578, Japan.

E-mail: asano@caos-a.geophys.tohoku.ac.jp

1 Present affiliation: Kanazawa Local Meteorological Observatory, Japan Meteorological Agency Kanazawa, 920-0024, Japan.

2 Present affiliation: Japan Agency for Marine-Earth Science and Technology, Yokohama, 236-0001, Japan.

© 2004, Meteorological Society of Japan

mospheric Administration) polar-orbiters, have been widely used to retrieve global aerosol distributions by means of one-channel algorithm (e.g., Husar et al. 1997; Stowe et al. 1997) or two-channel algorithm (e.g., Higurashi and Nakajima 1999; Higurashi et al. 2000; Mishchenko et al. 1999). We have developed a retrieval algorithm to infer aerosol optical properties over the seas by using NOAA/AVHRR multi-spectral data (Iwabuchi et al. 2001). The aerosol optical thickness and Ångström exponent can be retrieved, following the two-channel algorithm developed by Higurashi and Nakajima (1999), from the AVHRR data in the visible channel (ch.-1) and near-infrared channel (ch.-2). Data from every other channel were used to screen cloudy pixels out. With the retrieval algorithm, we have analyzed a decadal-long aerosol variation during about 12 years, from November 1988 to January 2001, from the AVHRR data of NOAA-11 and NOAA-14 satellites. For such a long-term analysis, it is crucially important to monitor and correct the sensitivity degradation of AVHRR sensors. Iwabuchi (2003) has developed a method to determine the calibration coefficients for the AVHRR ch.-1 and ch.-2 of NOAA-11 and -14 satellites. With the calibration coefficients, reliable and consistent aerosol analysis became possible over a decadal-long period from the AVHRR data. In this short note, we present the analyzed results for seasonal and decadal-long variations of aerosol distributions over the Asian Pacific region. In Section 2, the used data are briefly described. In Section 3, we shortly review the retrieval algorithm and its performance for aerosol retrieval. In Section 4, the analyzed results are discussed for the seasonal and decadal-long variations of aerosol distributions. Conclusions follow in Section 5.

2. Data

The AVHRR data used in the present study were processed from the High Resolution Picture Transmission (HRPT) data, with the geometrical correction and nonlinear radiometric correction (Kawamura et al. 1993a); the HRPT data are being archived at Tohoku University, Sendai, Japan, since 1988 (Kawamura et al. 1993b). The AVHRR is a scanning radiometer with a nominal spatial resolution of 1.1 km at nadir, and it has five spectral bands: ch.-1

(0.58–0.68 μm), ch.-2 (0.725–1.10 μm), ch.-3 (3.55–3.93 μm), ch.-4 (10.3–11.3 μm), and ch.-5 (11.5–12.5 μm). We have analyzed the AVHRR data for a decadal-long period of about 12 years, from November 1988 to October 1994 collected from the NOAA-11 satellite, and from February 1995 to January 2001 collected from the NOAA-14 satellite. It is well known that the gains of the AVHRR solar bands (ch.-1 and ch.-2) suffer from sensitivity degradation during the lifetime of the radiometers in its orbit. We applied the sensor calibration for the two channels following the formulae developed by Iwabuchi (2003), where the calibration used solar reflection from clear-sky ocean surfaces and stratiform clouds. The calibration coefficients could assure us a consistent long-term analysis of the AVHRR data from the different satellites (see Fig. 8 of Iwabuchi 2003).

The target region of the present analysis is the Asian Pacific region, east off the Asian continent, including the East China Sea, the Sea of Japan, and the Sea of Okhotsk, as well as the western North Pacific Ocean. The region was divided into 10 sub-areas as shown in Fig. 1. In the aerosol retrieval, climatic monthly-mean values of precipitable water vapor, total ozone

Fig. 1. Geographical locations of the target region (dotted-line) and sub-areas (solid-lines). For the northern three areas, the analysis was made only in summer seasons from June to September.

amount, and sea-surface wind velocity were prescribed for each area and each month: precipitable water was adopted from the re-analysis data (Kalnay et al. 1996) of the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research), the total ozone was taken from the database retrieved from TOMS (Total Ozone Mapping Spectrometer; Todaro et al. 2001), and the wind velocity data came from the database by da Silva et al. (1994). For the northern areas of Sakhalin, the Sea of Okhotsk, and South-east of Kamchatskaya, the analysis was carried out only in summer seasons (from June through September), because in the other seasons the solar elevations are too low, and the unfavorable sun-glint effects increase. In addition, the coastal areas within 7 pixels from the coastlines were omitted from the analysis, in order to avoid possible disagreement in the geometrical correction, as well as effects of contaminated coastal waters.

3. Method

3.1 Retrieval algorithm

Here, we only briefly review the retrieval algorithm to estimate aerosol parameters from the AVHRR multi-channel data, since the algorithm has already been described in detail in Iwabuchi et al. (2001). The retrieved aerosol parameters are aerosol optical thickness τ_a at wavelength $0.5 \mu\text{m}$ and Ångström exponent α . The Ångström exponent is a measure of a mean size of dispersive aerosol particles; a larger α value corresponds to a smaller mean size, and vice versa. The aerosol parameters are approximately related to aerosol optical thickness $\tau(\lambda)$ at wavelength λ through Ångström's law (Ångström 1961),

$$\tau(\lambda) = \tau_a (\lambda/\lambda_0)^{-\alpha}, \quad (1)$$

where τ_a is the aerosol optical thickness at a reference wavelength λ_0 . In this study, following Higurashi et al. (2000), we adopt $\lambda_0 = 0.5 \mu\text{m}$, so as to be able to compare the retrieved τ_a with aerosol optical thicknesses measured by widely used sun-photometers with the WMO (World Meteorological Organization) standard channels at $\lambda = 0.5 \mu\text{m}$.

The present algorithm to infer the aerosol parameters (τ_a and α) in clear-sky pixel is, in

essence, the same as the two-channel algorithm developed by Higurashi and Nakajima (1999), using ch.-1 and ch.-2 AVHRR data. The other channel data were used to screen out cloudy and cloud-contaminated pixels. We have developed a precise cloud screening scheme by utilizing an advantage of high spatial resolution ($\sim 1.1 \text{ km}$ at nadir) of the AVHRR data (Iwabuchi et al. 2001), instead of $\sim 4 \text{ km}$ resolution used in the previous studies (e.g., Husar et al. 1997; Stowe et al. 1997; Higurashi and Nakajima 1999; Higurashi et al. 2000). Cloudy pixels were screened out by a threshold technique, using multi-channel signals and signal-differences between the infrared channels (ch.-4 and ch.-5, and ch.-3 and ch.-4), as well as by a textural analysis using local variance and deviation of the visible ch.-1 data. Cloud-neighboring pixels were also excluded from aerosol retrieval to avoid such three-dimensional radiative effects near the clouds as, cloud-shadowing and side-illumination (Iwabuchi and Hayasaka 2002; Iwabuchi 2003).

After the cloud screening, the aerosol parameters for clear-sky pixels can be inferred by comparing the AVHRR-observed reflection-functions at ch.-1 and ch.-2 with the corresponding reflection-functions computed for various combinations of τ_a and α . For the comparison, the relationship between the reflection-functions at ch.-1 and ch.-2 and the aerosol parameters (τ_a and α) were theoretically calculated in a form of look-up-tables for various observational conditions, such as precipitable water vapor, ozone, and sea-surface wind velocity, as well as for different sun-satellite configurations. The look-up-tables were constructed by employing almost the same radiative transfer code and aerosol models used in Higurashi and Nakajima (1999) and Higurashi et al. (2000). A bimodal volume size distribution function was assumed for aerosol size distribution in the form,

$$\frac{dV}{d \ln r} = \sum_{n=1}^2 C_n \exp \left[-\frac{1}{2} \left\{ \frac{\ln(r/r_{mn})}{\ln s_n} \right\}^2 \right], \quad (2)$$

where V is the volume of aerosol particles, r_{mn} and s_n are the n -th mode radius and standard deviation, respectively, with suffix n denoting size mode, $n = 1$ for fine-mode and $n = 2$ for coarse-mode. We assumed that $r_{m1} = 0.17 \mu\text{m}$,

$r_{m2} = 3.4 \mu\text{m}$, $s_1 = 2.0$, and $s_2 = 3.4$. When the mode radii and widths of the bimodal distribution are given, it is known that Ångström exponent α exhibits a one-to-one relationship with the ratio, C_1/C_2 , of unknown mode-peak coefficients C_n (Higurashi and Nakajima 1999; Iwabuchi et al. 2001). In the look-up-tables, Ångström exponent α were obtained by a regression fitting of Eq. (1) to the spectral optical thicknesses $\tau_a(\lambda)$ calculated from Mie theory for the size distribution Eq. (2) with various C_1/C_2 values at 10 wavelengths between $0.5 \mu\text{m}$ and $1.0 \mu\text{m}$, which cover the wavelength range of ch.-1 and ch.-2. In the Mie scattering calculation, we assumed a constant value of $1.50 - 0.005i$ for the complex refractive index of aerosols, both in ch.-1 and ch.-2. Although the size distribution and complex refractive index of real aerosols could be considerably variable with season and place (e.g., Nishizawa et al. 2004), we fixed these values throughout the present analysis. Further, we ignored scattering effects by particulate matters suspended in the ocean in the radiative transfer calculations. So, the retrieved aerosol parameters should be regarded as “equivalent” values, effective under the assumptions adopted in this study.

3.2 Performance tests

We have tested performance of the present retrieval algorithm for possible ranges of such variables as precipitable water, total ozone, wind velocity, and aerosol refractive index, as well as for different vertical distributions of water vapor and aerosols (Figs. 3–5 of Iwabuchi et al. 2001). The test suggested that these variables may bring significant errors in daily estimates of the aerosol parameters, especially, of Ångström exponent (e.g., Ignatov et al. 1998), when the climatic or fixed values are used, instead of daily changing values, for these variables. From the test, the maximum relative error of $\pm 25\%$ was estimated for the optical thickness retrieval. On the other hand, for the retrieval of Ångström exponent α , the accuracy was worse with the maximum errors of ± 0.7 and ± 0.5 , when $\alpha = 0.5$ and $\alpha = 1.0$, respectively. However, the errors can be greatly diminished for the statistical values of monthly-mean aerosol parameters discussed in the present study. We also compared the aerosol parameters retrieved by the present algorithm

with those obtained from the ground-based sun-photometer measurements at Minamitorishima (24.30°N , 153.96°E) and Yonagunijima (24.46°N , 123.02°E) by the Japan Meteorological Agency. The comparison revealed a good agreement between the retrieved and sun-photometer-measured aerosol optical thicknesses, with a root-mean-squares (RMS) error of 0.004; while, for Ångström exponent, the agreement was less satisfactory with a larger RMS error of 0.053. We compared the retrieved aerosol parameters with other estimates using AVHRR data by Husar et al. (1997) and by Higurashi et al. (2000) for the region around Japan, and the comparison proved reasonably good agreement among them, especially for τ_a . The performance tests assured that the present retrieval algorithm is capable of reliable estimates of monthly-mean aerosol parameters, at least of τ_a , over the Asian Pacific region for the decadal-long period.

4. Results

4.1 Seasonal variations

Figure 2 displays the geographical distributions of the monthly-mean aerosol parameters (τ_a and α), averaged over 9 years from 1988 to 2001, excepting an interval between June 1991 and the end of 1993, to avoid the effects of volcanic eruptions in June 1991 of Mt. Pinatubo (15.14°N , 120.35°E). The monthly-mean values of τ_a and α , averaged over each area shown in Fig. 1, are summarized in Table 1. The spatial distributions of τ_a and α in the Asian Pacific region exhibit, in general, similar features to those of Fig. 10 of Higurashi et al. (2000), analyzed for the year 1990, with similar seasonal variations.

At a glance, the western parts of the region, the areas closer to the Asian continent, are more turbid (larger τ_a), with relatively large α , through out the year. This suggests that in these areas the dominant aerosols are fine-mode particles, originated from the Asian continent and caused mainly by gas-to-particle (G-P) conversion and accumulation processes. On the other hand, the southeast part of the region is the most clean (smallest τ_a) area with rather small α ; the dominant aerosols there may be coarse-mode particles originated from sea salts. There seems to be a boundary of clean and turbid air-masses between the lat-

Fig. 2. Geographical distributions of monthly-mean values of the aerosol optical thickness at wavelength 0.5 μm (*left column*) and Ångström exponent (*right column*) for the months of January, April, July, and October. The values were averaged over 9 years of the analyzed period, excepting the Pinatubo period.

Table 1. Monthly-mean and area-averaged values of (a) aerosol optical thickness at wavelength 0.5 μm and (b) Ångström exponent. The values were averaged over the analyzed period from November 1989 to January 2001, excluding the Pinatubo period between June 1991 and the end of 1993.

(a)

Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Western East China Sea	0.47	0.45	0.37	0.47	0.42	0.36	0.19	0.17	0.25	0.40	0.25	0.44	0.35
Eastern East China Sea	0.22	0.25	0.33	0.34	0.36	0.28	0.16	0.15	0.19	0.26	0.21	0.21	0.25
Sea of Japan	0.17	0.21	0.28	0.31	0.27	0.23	0.19	0.17	0.17	0.17	0.18	0.18	0.21
South coast of Japan	0.17	0.23	0.28	0.29	0.23	0.17	0.16	0.17	0.16	0.18	0.17	0.16	0.20
East far from Japan	0.15	0.19	0.22	0.25	0.24	0.13	0.12	0.11	0.11	0.13	0.13	0.12	0.16
South far from Japan	0.12	0.12	0.15	0.13	0.10	0.07	0.09	0.09	0.08	0.10	0.11	0.10	0.11
Sakhalin	—	—	—	—	—	0.16	0.20	0.16	0.15	—	—	—	—
Sea of Okhotsk	—	—	—	—	—	0.15	0.13	0.14	0.14	—	—	—	—
South east of Kamchatkaya	—	—	—	—	—	0.16	0.15	0.13	0.14	—	—	—	—
Around Japan	0.17	0.22	0.28	0.30	0.27	0.20	0.18	0.16	0.17	0.18	0.18	0.17	0.21

(b)

Area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Western East China Sea	0.87	0.97	0.88	0.96	1.12	1.26	1.03	1.00	0.98	0.88	0.76	1.08	0.98
Eastern East China Sea	0.59	0.72	0.78	0.94	1.02	1.15	0.93	0.84	0.93	0.72	0.61	0.84	0.84
Sea of Japan	0.55	0.70	0.63	0.89	0.87	0.95	0.97	0.88	0.62	0.60	0.70	0.61	0.75
South coast of Japan	0.54	0.55	0.64	0.85	0.97	0.95	0.90	0.92	0.80	0.63	0.60	0.69	0.75
East far from Japan	0.47	0.52	0.61	0.79	0.88	0.86	0.79	0.80	0.71	0.66	0.59	0.68	0.70
South far from Japan	0.41	0.43	0.58	0.56	0.52	0.52	0.50	0.56	0.51	0.62	0.51	0.62	0.53
Sakhalin	—	—	—	—	—	1.11	0.98	0.84	0.75	—	—	—	—
Sea of Okhotsk	—	—	—	—	—	1.22	1.13	0.94	0.85	—	—	—	—
South east of Kamchatkaya	—	—	—	—	—	1.05	1.00	0.78	0.76	—	—	—	—
Around Japan	0.54	0.67	0.62	0.86	0.93	0.95	0.96	0.88	0.66	0.60	0.67	0.66	0.75

itudes of 20°N and 30°N, running from southwest to northeast: the northern turbid air-mass is substantially affected by aerosols originated from the Asian continent. In summer, the air-mass boundary goes up toward north, resulting in smaller τ_a , even in the East China Sea area. In the areas around Japan, the largest τ_a appears in spring; this may be partly contributed

by soil dusts (*Kosa*), frequently transported from the desert areas in China (e.g., Arao and Aoki 2001; Yoshino 2002), adding to prevailing anthropogenic aerosols from the Asian continent in the seasons (e.g., Chen et al. 1997; Sugimoto et al. 2002). It is worth noting that in spring in mid-latitudes a zone of large τ_a is extending eastward, at least, to 170°E. It is in-

Fig. 3. Latitude-time plots of the zonal-mean aerosol optical thickness at wavelength 0.5 μm (*top*) and Ångström exponent (*bottom*).

teresting that in summer the northern areas are predominated by small particles of fine-mode, with moderately large τ_a and quite large α . The aerosols might be caused by the G-P conversion from activated emission of DMS (dimethylsulfide) from the sea, as well as by extensive biomass burning in Siberia (e.g., Kasischke et al. 1999; Tanimoto et al. 2000).

4.2 Long-term variations

Figure 3 shows the latitude-year plots of the monthly-mean aerosol parameters (τ_a and α), averaged over the longitude range (zonal-mean) in the analyzed region. The figure indicates that the most prominent event that affected the aerosol variations in the first half of 1990s, was the eruptions of Mt. Pinatubo, which resulted in the great enhancement of τ_a with moderate α values almost all over the region, particularly in the winters of 1991–92 and 1992–93. The feature was caused by Pinatubo volcanic aerosols, having a mode radius of about $0.6 \mu\text{m}$ between the typical fine-mode and coarse-mode radii (e.g., Asano et al. 1993). Compared with the period before the Pinatubo eruptions, the aerosol optical thickness was significantly increased nearly all over the latitude range during the second half of the 1990s through 2001, particularly, in springs of the mid-latitude areas between 25°N and 45°N , as well as in summers of the higher latitude areas ($> 40^\circ\text{N}$). The former case could be caused by an increased emission of sulfate particles in Asia (Streets et al. 2000), and partly due to frequent *Kosa* events, particularly, occurred in 1996 and 2000 (Arao and Aoki 2001). While the latter case might be due to extensive forest-fires in Siberia, particularly in the 1998 summer (Kasischke et al. 1999; Tanimoto et al. 2000).

The increase of τ_a in the recent years after the Pinatubo period can be recognized even as annual-mean values in the analyzed region, excepting the area south far from Japan. Figure 4 shows variations of the annual-mean and area-averaged aerosol parameters (τ_a and α) for the selected areas. Particularly in the latest few years, a rapid growth of the annual-mean τ_a , with an increase of α , can be seen, more evidently for the areas closer to the Asian continent and even in the area east far from Japan. For example, when compared with the 2-yr-mean τ_a values averaged over 1989 and

Fig. 4. Variations of the annual-mean and area-averaged values of the aerosol optical thickness at wavelength $0.5 \mu\text{m}$ (top) and Ångström exponent (bottom) for the selected areas.

1990, the (1999–2000)-mean τ_a values increased by 0.16, 0.08, 0.06, and 0.03, respectively, in the eastern East China Sea, Sea of Japan, the area east far from Japan, and the area south far from Japan. This feature might be caused by an increasing emission of anthropogenic aerosols of fine-mode particles, and their precursor gases in the Asian continent.

5. Conclusions

We have investigated the seasonal and decadal-long variations of aerosols in the Asian Pacific region, over the seas east off the Asian continent, using NOAA/AVHRR multi-spectral data. We have developed the aerosol retrieval algorithm with precise cloud-screening and corrections for the degradation of AVHRR sensors (Iwabuchi et al. 2001; Iwabuchi 2003). The aerosol optical thickness τ_a at wavelength $0.5 \mu\text{m}$, and Ångström exponent α were retrieved

by the two-channel algorithm using ch.-1 and ch.-2 AVHRR data: data from every other channel were used to screen cloudy pixels out. After performance tests of the algorithm, we have analyzed variations of the monthly-mean aerosol parameters (τ_a and α) during the period of about 12 years from November 1988 to January 2001 using the AVHRR data from NOAA-11 and NOAA-14 satellites.

We found evident seasonal variations of aerosol distributions in the Asian Pacific region. In most areas, the aerosol optical thickness takes the maximum value in spring and the minimum value in summer. The variations could be caused by seasonal changes of dominant aerosol sources and dominant wind directions for long-range aerosol transport, as well as by seasonal cycles of the G-P conversion activities. The Asian Pacific region north of about 25°N is significantly affected by aerosols from the Asian continent. Excepting the period of strong Pinatubo effects, the aerosol optical thickness has gradually increased, with year-to-year fluctuations, in the almost all areas during the 12 years. We found a rapid increase of fine-mode aerosols in the recent few years; this verifies a growing emission of anthropogenic aerosols in the Asian continent (Streets et al. 2000; IPCC 2001).

Acknowledgements

The authors are grateful to Prof. H. Kawarura and Prof. J. Kudoh of Tohoku University for their kind assistance in processing the AVHRR data. The sun-photometer data were kindly provided by JMA. This work was partly supported by JST/CREST within APEX.

References

- Ångström, A., 1961: Techniques of determining the turbidity of the atmosphere, *Tellus*, **13**, 214–223.
- Arao, K. and K. Aoki, 2001: A review of yellow sand events at Nagasaki in recent five years: 1996–2000. *Proceedings of Joint Workshop of APEX and RIHN (Kyoto, Sep. 26–28, 2001)*.
- Asano, S., A. Uchiyama, and M. Shiobara, 1993: Spectral optical thickness and size distribution of the Pinatubo volcanic aerosols as estimated by ground-based sunphotometry, *J. Meteor. Soc. Japan*, **71**, 165–173.
- Chen, L.L., G.R. Carmichael, M.S. Hong, H. Ueda, S. Shim, C.H. Song, Y.P. Kim, R. Arimoto, J. Prospero, D. Savoie, K. Murano, J.K. Park, H. Lee, and C. Kang, 1997: Influence of continental outflow events on the aerosol composition at Cheju Island, South Korea. *J. Geophys. Res.*, **102**, 28551–28574.
- Higurashi, A. and T. Nakajima, 1999: Development of a two-channel aerosol retrieval algorithm on a global scale using NOAA AVHRR. *J. Atmos. Soc.*, **56**, 924–941.
- , B.N. Holben, A. Smirnov, R. Frouin, and B. Chatenat, 2000: A study of global aerosol optical climatology with two-channel AVHRR remote sensing. *J. Climate*, **13**, 2011–2027.
- Huebert, B.J., T. Bates, P.B. Russell, G. Shi, Y.J. Kim, K. Kawamura, G. Carmichael, and T. Nakajima, 2003: An overview of ACE-Asia: Strategies for quantifying the relationship between Asian aerosols and their climatic impacts, *J. Geophys. Res.*, **108**(D23), 8633, doi:10.1029/2003JD003550.
- Husar, R.B., J.M. Prospero, and L.L. Stowe, 1997: Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution spectrometer optical thickness operational product. *J. Geophys. Res.*, **102**, 16889–16909.
- Ignatov, A., L. Stowe, and R. Singh, 1998: Sensitivity study of the Ångström exponent derived from AVHRR over oceans. *Adv. Space Res.*, **21**, 439–442.
- IPCC (Intergovernmental Panel on Climate Change), 2001: Climate Change 2001: The Scientific Basis. Cambridge University Press, 944 pp.
- Iwabuchi, H., A. Sobajima, J. Kudoh, and S. Asano, 2001: Remote sensing of aerosol properties using NOAA AVHRR data over north-eastern Asian seas: Development of retrieval system. *Northeast Asian Studies (Tohoku Univ.)*, **6**, 143–155. (PDF copy is available from http://homepage.mac.com/h_iwabuchi/cloud/Publications/).
- and T. Hayasaka, 2002: Effects of cloud horizontal inhomogeneity on the optical thickness retrieved from moderate resolution satellite data, *J. Atmos. Sci.*, **59**, 2227–2242.
- , 2003: Calibration of the visible and near-infrared channels of NOAA-11 and -14 AVHRRs by using reflections from molecular atmosphere and stratus cloud. *Int. J. Remote Sensing*, **20**, 5367–5378.
- Kalney, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelloah, W. Ebisuzali, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Raynolds, R. Jenne, and D. Josheph, 1996: The

- NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kaneyasu, N., K. Takeuchi, M. Hayashi, S. Fujita, I. Uno, and H. Sasaki, 2000: Outflow pattern of pollutants from East Asia to the North Pacific in the winter monsoon, *J. Geophys. Res.*, **105**, 17361–17377.
- Kasischke, E.S., K. Bergen, R. Fennimore, F. Sotelo, G. Stephens, A. Janetos, and H.H. Shugart, 1999: Satellite imagery gives clear picture of Russia's boreal forest fires. *EOS Trans. Amer. Geophys. Union*, **80**, 141–152.
- Kawamura, H., F. Sakaida, and S. Kizu, 1993a: The AVHRR data processing system in the Center for Atmospheric and Oceanic Studies in the Tohoku University, *Tohoku Geophys. J. (Sci. Rep. Tohoku Univ., Series 5)*, **34**, 103–114.
- , S. Kizu, F. Sakaida, and Y. Toba, 1993b: The NOAA-HRPT data receiving system in the Center for Atmospheric and Oceanic Studies in the Tohoku University, *Tohoku Geophys. J. (Sci. Rep. Tohoku Univ., Series 5)*, **34**, 89–102.
- Mikami, M., et al., 2002: The impact of aeolian dust on climate: Sino-Japanese cooperative project ADEC, *J. Arid Land Studies*, **11**, 211–222.
- Mishchenko, M.I., I. Geogdzhayev, B. Cairns, W.B. Rossow, and A.A. Lacis, 1999: Aerosol retrievals over the ocean by use of channels 1 and 2 AVHRR data: sensitivity analysis and preliminary results, *Appl. Opt.*, **38**, 7325–7341.
- Nakajima, T., M. Sekiguchi, T. Takemura, I. Uno, A. Higurashi, D. Kim, B.J. Sohn, S.-N. Oh, T.Y. Nakajima, S. Ohta, I. Okada, T. Takamura, and K. Kawamoto, 2003: Significance of direct and indirect radiative forcings of aerosols in the East China Sea region, *J. Geophys. Res.*, **108**(D23), 8658, doi:10.1029/2002JD003261.
- Nishizawa, T., S. Asano, A. Uchiyama, and A. Yamazaki, 2004: Seasonal variation of aerosol direct radiative forcing and optical properties estimated from ground-based solar radiative measurements, *J. Atmos. Sci.*, **61**, 57–72.
- Okada, K., H. Naruse, T. Tanaka, O. Nemoto, Y. Iwasaka, P. Wu, A. Ono, R.A. Duce, M. Uematsu, J.T. Merrill, and K. Arao, 1990: X-ray spectrometry of individual Asian dust-storm particles over the Japanese Islands and the North Pacific Ocean, *Atmos. Environ.*, **24A**, 1369–1378.
- da Silva, A., A.C. Young, and S. Levitus, 1994: Atlas of surface marine data 1994, Volume 1: Algorithms and procedures. *NOAA Atlas NESDIS*, **6**, U.S. Department of Commerce, Washington, D.C..
- Stowe, L.L., A.M. Ignatov, and R.R. Singh, 1997: Development, validation, and potential enhancement to the second-generation operational aerosol product at the National Environmental Satellite, Data, and Information service of the National Oceanic and Atmosphere Administration. *J. Geophys. Res.*, **102**, 16923–16934.
- Streets, D.G., N.Y. Tsai, H. Akimoto, and K. Oka, 2000: Sulfur dioxide emissions in Asia in the period 1985–1997. *Atmos. Environ.*, **34**, 4413–4424.
- Sugimoto, N., I. Matsui, A. Shimizu, I. Uno, K. Asai, T. Endo, and T. Nakajima, 2002: Observation of dust and anthropogenic aerosol plumes in the Northwest Pacific with a two-wavelength polarization lidar on board the research vessel Mirai. *Geophys. Res. Lett.*, **29**(19), doi:10.1029/2002GL015112.
- Tanimoto, H., Y. Kajii, J. Hirokawa, and H. Akimoto, 2000: The atmospheric impact of boreal forest fires in far eastern Siberia on the seasonal variation of carbon monoxide: Observations at Rishiri, a northern remote island in Japan. *Geophys. Res. Lett.*, **27**, 4073–4076.
- Todaro, R.M., P.A. Newman, G. Morris, B. Gage, D.J. Sunday, A. Aikin, W. Heaps, M.F. Crum, D. Larko, E. Celarier, Ms.S. Hollandsworth, E. Cordero, C. Weaver, E. Fleming, E. Hilsenrath, R. Stolarski, S.M. Hollandsworth, M.D. Binder, and D. Considine, 2001: Stratospheric Ozone: An Electronic Textbook. NASA's Goddard Space Flight Center, Atmospheric Chemistry and Dynamics Branch (Code 916). URL: <http://hyperion.gsfc.nasa.gov/>
- Yoshino, M., 2002: Climatology of Yellow sand (Asian sand, Asian dust or Kosa) in East Asia. *Sci. China Ser. D*, **45**, 59–70.