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Study of Influence on Global Warming by Aerosols
— Present Investigation and Remaining Issues —

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3.1 Introduction

The concept where human activities increase the amount of greenhouse gases in the atmosphere, thereby having a long-term impact on the global climate is becoming well known across the world. Greenhouse gases consist primarily of carbon dioxide (CO_2), along with methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbon (PFC) and sulfur hexafluoride (SF_6).[1] As climate modeling incorporating the effects of these greenhouse gases becomes more elaborated, variations in the simulation results derived from a number of forecasting models for temperature increases are becoming less distinct – i.e., the impact of greenhouse gases on global warming is being proved scientifically. Based on the accumulation of such efforts in quantifying global warming effects, the Intergovernmental Panel on Climate Change (IPCC) has prepared evaluation reports, forecasting increases in CO_2 concentrations and mean temperatures over the next century; it has released its first, second and third reports [1]-[3] so far.

In response to the efforts of IPCC in accumulating scientific findings on the global warming phenomenon, the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (COP) began discussing numerical targets and other related issues in 1995 for reducing greenhouse gases. In the COP7, which was held in 2001, political agreement was finally reached on the "rule book" for the implementation of the Kyoto Protocol; each country has been gearing up for the upcoming enforcement of the protocol. If enforced, Japan will be obliged to reduce greenhouse gas emissions by 6% from the 1990 level during the first commitment period, namely from 2008 to 2012. [4], [5] In response to this, the Japanese government set the "Guideline for Measures to Prevent Global Warming" [4] in 2002, presenting specific measures against global warming that are being promoted nationwide.

However, greenhouse gases are not the only causes of global warming. Fine particles in the atmosphere have a significant impact on global temperatures. For instance, volcanic ash in the atmosphere reflects sunlight, thereby decreasing temperatures. Fine particles (measuring 0.001~10 micrometer in diameter) emitted into the atmosphere by the combustion of fossil fuels and the eruption of volcanoes are generally called "aerosols." The effects of aerosols in promoting or suppressing global warming, [6], [7], [8] as well as the effects of clouds in decreasing the range between maximum temperatures and minimum temperatures [9] — a phenomenon that is difficult to certify — have yet to be proved scientifically. A variety of studies are thus going on to collect scientific findings in these areas.

This report addresses the three study fields designed to secure the scientific credibility of the impact assessment of aerosols – i.e., observations and monitoring of substances causing global warming; analysis of climate-model-based mechanisms; and forecasts based on global simulation models. Chapter 3-2 classifies the study of global warming and interrelates the three study fields with one another. Chapter 3-3 reports on the present status of observations/monitoring of phenomena centered on aerosols. Chapter 3-4 discusses the ideal collaboration between the study of observations /monitoring and that of mechanisms. Chapter 3-5 suggests approaches to promote the study of forecasts. And Chapter 3-6 summarizes challenges to be addressed in the study of global warming in relation to aerosols.

3.2 Classification of the study of global warming and the interrelation between each study field

In the international framework for global warming, scientific findings serving as the basis of IPCC's scientific assessments are summarized by START (Global Change System for Analysis, Research and Training), which is being promoted jointly by the following three international research projects: WCRP (World Climate Research Programme, which analyzes the global climate system); IGBP (International Geosphere-Biosphere Programme, which accumulates scientific findings in biological and chemical processes regarding global climate changes); and IHDP (International Human Dimensions Programme on Global Environmental Change, which addresses the human dimensions of global environmental changes.

The accumulation of scientific assessments by IPCC is correlated with political decisions to be made within the international framework set by UNFCCC. The results of those assessments are closely related to policy trends regarding: (1) observations and monitoring of substances causing global warming; (2) analysis of climate-model-based mechanisms; (3) forecasts based on global simulations; (4) assessments of the impact on the natural and the living environments; and (5) development of measures against global warming. Specifically, scientific approaches constitute the major part of (1), (2) and (3), covering most of the studies regarding the impact assessment of aerosols.

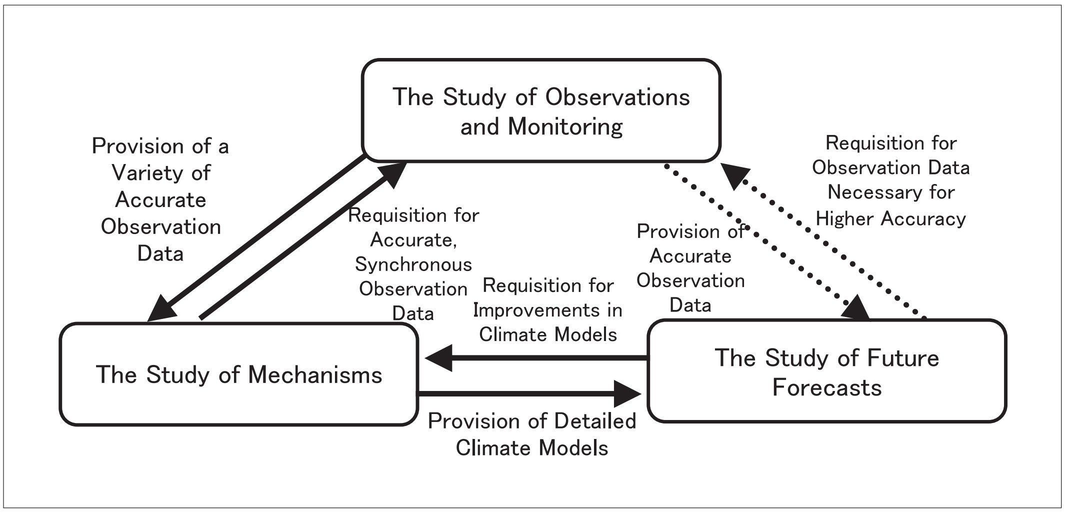
The scientific studies of aerosols can be categorized into (1), (2) and (3) mentioned above, with each category correlated with one another as shown in Figure. 1. In general, climate-model researchers may be able to improve the accuracy of climate models by applying a set of high-precision data (obtained through multiple observation/monitoring methods) to the models. In other words, this relationship between provision and requisition is necessary to improve the scientific studies.

It should be noted that there is no data set observed globally at one time. Moreover, the credibility of simulation models to be used for forecasts has yet to be established. The present situation is such that models are verified by confirming the reproducibility of climate changes that took place in the past.

3.3 The present status of the study of observations and monitoring

There are many observation and monitoring methods involved in global warming problem, according to principles/models to be adopted, as well as the target, location, time and frequency of observations. Aerosols are made up of sulfate, soot,

Figure 1: Correlation between the three study fields comprised primarily of scientific approaches



and mineral dust such as Asian dust (called Kosa in Japan, and which means "yellow sand") and volcanic ash. Several methods for observing/monitoring these substances have been established for the scientific studies.

3.3.1 Significance of aerosol observations

Coupled with greenhouse gases, substances such as ozone and aerosols also contribute to the global warming. "Radiative Forcing*1" is a physical value that indicates the effects of various substances on global warming and cooling; a positive radiative forcing means a warming effect, while a negative one indicates a cooling effect.The radiative forcing of various substances causing global warming has been evaluated based on the scientific findings accumulated by IPCC. [2], [3], [6], [7] Figure. 2 shows the estimates of radiative forcing released through the IPCC Third Assessment Report. IPCC evaluates the scientific credibility of each estimate subjectively. In evaluating the scientific credibility, meanwhile, assumptions required for evaluating radiative forcing, the level of understanding regarding physical and chemical mechanisms determining radiative forcing, and uncertainties (the margin of error) associated with the quantitative estimate of radiative forcing are taken into account. While the credibility with respect to greenhouse gases and ozone is relatively high (with low uncertainties), that of aerosols remains at low levels. In particular, uncertainties associated with tropospheric aerosols are extremely high – scientific findings in aerosols have yet to be established.

The complexity of the mechanism of aerosol generation as well as the difficulty in figuring out their amount on a global scale makes it difficult to evaluate the amount of aerosol radiative forcing.As far as the movement of aerosols in the atmosphere is concerned, understanding their large-scale distribution is also difficult because of the effects of rainfall on them. Due in large part to the complexity of their chemical and physical characteristics, moreover, how much the atmosphere containing aerosols reflects or absorbs the sunlight can hardly be estimated – a fact that makes the estimate of large-scale distribution through observations all the more difficult. For these reasons, most of the existing climate models incorporate simplified versions of

Figure 2: Evaluation results of the radiative forcing of various substances

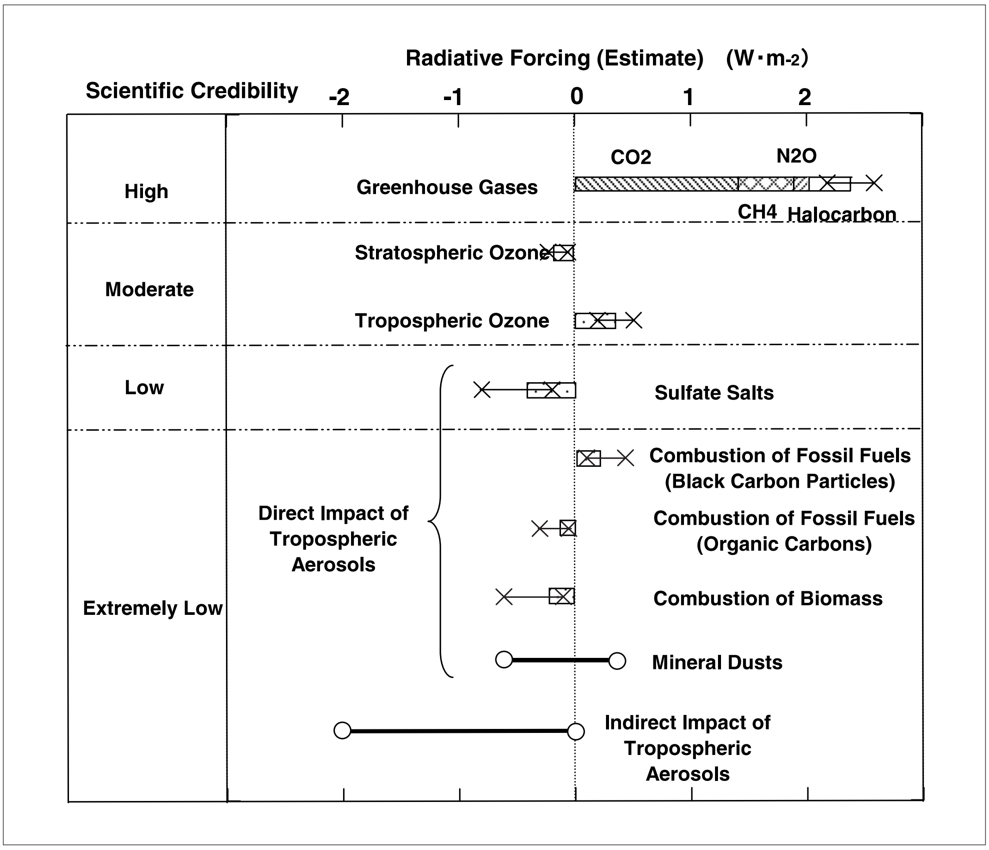


Table 1: Classification of aerosol observation technology

Observation Equipment	Observation Method	Physical Value to be Estimated	Installation (Satellite)
Radiometer (Imager and Spectrometer)	(1) Analyze radiation from the cloud, earth and ocean (2) Analyze the sunlight reflected from the cloud and earth	(1) Diameter and type of particles (2) Horizontal distribution of particle density (3) Physical value (4) Characteristics and distribution of the cloud	(1) Satellite - Advanced high-performance microwave radiometer / AMSR-E (Aqua) - Advanced high-resolution radiometer / AVHRR radiometer (NOAA series)
Scatterometer	Analyze the reflection of light and microwave emitted	(1) Wind velocity on the water (speed of aerosol transportation) (2) Wind direction (direction of aerosol transportation)	(1) Satellite Conical scan scattering meter / SeaWinds (QuickSCAT)
Cloud Radar	Analyze the reflection of microwave emitted	(1) Conditions of cloud particles in the troposphere	(1) Earth (2) Aircrafts
LIDAR	Analyze the scattering light of laser emitted	Vertical and horizontal distribution of the following in the troposphere and stratosphere: (1) Particle density (2) Particle diameter (3) Substances	(1) Earth (2) Aircrafts (3) Vessels (4) Space Shuttle (experimental)

the chemical and physical characteristics regarding aerosols. The mechanism of climate change attributable to aerosols has yet to be fully resolved. It is thus indispensable that scientific knowledges on aerosols be accumulated.

3.3.2 The present status of aerosol observation technology

The primary purpose of observing aerosols is to identify their chemical and physical characteristics; observations are conducted from the ground, at sea and in the air, using several types of equipment. High-precision data are becoming available thanks to increased observation stations on the ground and to satellites equipped with high-performance observation equipment (observation area at a time is expanding).

Hand in hand with advances in information technology, moreover, research and observation institutes across the world are improving the quality and accessibility of their observation data. For researches, therefore, observation data at a given time are becoming more and more accessible.

(1) Observation technology for physical characteristics

Observation technology for the physical characteristics of aerosols can be classified in terms of mode (active or passive), wavelength range, and subject and method of observations. Table 1 shows the classification of observation technology, based on common aerosol-observation equipment.

In creating models in the study of mechanisms, it is indispensable that the physical characteristics of aerosols (e.g., the three-dimensional distribution of the density and diameter of particles) be observed. "LIDAR" (Light Detection and Ranging) [10] is an observation system that can meet this particular requirement. LIDAR is made up of a short-pulse laser oscillator and a detector sensing the scattering light from aerosols. The principle: short-pulse laser beam that is emitted up into the air scatters in all directions in accordance with the physical characteristics of target aerosols, which can be diagnosed by the light scattered back to the laser side; various physical characteristics can be diagnosed by selecting the wavelength of the laser beam. In addition, an intense laser beam accommodates observations of aerosols in the stratosphere. Because of these advantages, expectations are large for LIDAR. As the achievements of avid studies conducted so far, (1) a compact low-power LIDAR for observing urban aerosols, Asian dust and aerosols in the troposphere and stratosphere, and (2) a scanning LIDAR for observing the movement of clouds (where the three-dimensional images of observation targets are obtained by sweeping a laser beam) have been developed and established for use in observations from the ground, at sea (vessels) and in the air (aircrafts). Moreover, other studies are underway to develop a LIDAR system that can measure the distribution of temperatures and wind speeds by means of changes in the wavelength of scattered light, though they are still in the stage of demonstrating their principle.

Although full-scale observations using satellites equipped with LIDAR have yet to be conducted, there has been the LITE experiment, in which the vertical distribution of aerosols was observed through LIDAR aboard the Space Shuttle. On the other hand, institutes in and outside Japan are pushing ahead with observations from the ground and aircrafts. The Japan Meteorological Agency, for instance, set up an atmospheric environment observatory in Iwate prefecture (Ryori, Ofunato-shi); the station is using LIDAR to observe the vertical distribution of Asian dust (few hundred meters to 10km or 5km to 35km above the ground) and its temporal variations on a regular basis, while exchanging observation data with other countries including China.[11] Using a relatively compact LIDAR system, the Atmospheric Environment Division of the National Institute for Environmental Studies conducted round-the-clock observations of Asian dust in the atmosphere up to 3km above the ground, and succeeded in obtaining temporally accurate data on its vertical distribution.[12] The division is also accumulating data on the horizontal distribution by setting observation points at other locations such as Tsukuba, Nagasaki, Amami Oshima and Beijing. A number of universities including Chiba University are likewise conducting observations using LIDAR. LIDAR can be considered an established technology.

(2) Observation technology for chemical characteristics

Observations to obtain data on the chemical characteristics of aerosols are conducted primarily through aircrafts. Specifically, the types of aerosols are identified and their chemical characteristics are determined by analyzing the air introduced into an aircraft or by analyzing substances filtered out. The technology for identifying the types and chemical makeup of aerosols, the structures of which are relatively simple, has been established, and a large amount of data has been collected so far through observations using analyzers aboard aircrafts and vessels. In addition, a broad database of chemical reactions associated with those aerosols is available, which is utilized for creating models necessary for forecasting changes in the atmospheric constituents. However, quite a few factors have yet to be elucidated – e.g., the rate constant of chemical reactions of aerosols, and the chemical characteristics of compounds made up of aerosols and other chemical substances such as sulfides (for example, soil particle with SO_4, soot with H_2SO_4, etc.). Equipment for analyzing these compounds is still in the development stage.

3.4 Collaboration between the study of observations/ monitoring and the study of mechanisms

The first step in the study of aerosol mechanisms is to create models that can simulate climate changes at a given period of time based on observation data collected through satellites and observatories on the ground. Aerosol radiative forcing can be evaluated by using models simulating climate changes that took place in the past.[13] In this particular case, it is very important to unify the times (or periods) and targets of observations to ensure the time consistency of data. In conducting aerosol observations on a global basis, therefore, relevant research institutes across the world need to collaborate and cooperate with one another in unifying observation methods, exchanging/sharing observation data and analyzing observation results.

Based on several frameworks, research activities are ongoing at a number of institutes conducting aerosol observations, each of which is engaged in forecasts. [14] As an organization responsible for meteorological observations, the Japan Meteorological Agency is creating relevant databases including those of aerosols in line with the GAW (Global Atmosphere Watch) Programme initiated by WMO (the World Meteorological Organization) in 1989. [11] The atmospheric environment observatory in Ryori, which was mentioned in Section 3-3-2, is registered with

WMO as a local observatory conducting aerosol observations. In addition, the Japan Meteorological Agency established a group responsible for observations, monitoring and modeling within its organization, with the Meteorological Research Institute taking the initiative. The agency is addressing the study of forecasts in an integrated manner.

Aside from the framework of the GAW Programme, researchers at research institutes (the National Institute for Environment Studies, etc.) and universities in Japan are developing observation equipment, collecting observation data and creating models with a view to more accurate study of aerosols. For instance, the National Institute for Environment Studies has organized a group dedicated to these particular efforts. From the standpoint of public facilities, meanwhile, the Center for Climate System Research, the University of Tokyo is pushing ahead with a series of studies centered on modeling, while obtaining part of the required data through its own observations.

3.5 Measures to promote the study of forecasts

The IPCC Fourth Assessment Report is expected to place particular emphasis on the studies for some part of atmospheric constituents – a subject that was not addressed in the Third Assessment Report. Specifically, the studies in short-lived substances (aerosols, tropospheric ozone, etc.) will be emphasized and evaluated rather than those in long-lived greenhouse gases, the scientific studies of which are considered sufficient in amount. Of these short-lived substances, suppressing anthropogenic aerosols is considered one of the important measures against global warming. Aerosols are short-lived because they readily combine with water vapor in the atmosphere, thereby falling to the ground with rain, and are chemically unstable, properties of which change through a variety of chemical reactions. In estimating the effects of aerosols on global warming, there is a need to address changes in their chemical properties during their lifetime, using a function of particle densities and locations, the calculations of which could be enormous. In conducting the study of forecasts in consideration of the effects of aerosols, therefore, it is indispensable that calculations based on an enormous amount of data be carried out in a short period.

While simulations using supercomputers have been the mainstream of the study of forecasts, a global simulator has been developed as a new science tool.[15] With the use of this global simulator, the study of forecasting the effects of atmospheric constituents (aerosols, the tropospheric ozone attributable to exhaust gases, etc.) on climate changes is expected to make a great leap forward.

As far as the study of aerosols based on the global simulator is concerned, the development of a "chemical meteorological chart" (where unknown chemical properties mentioned in Section 3-3-2 are evaluated in detail and temporal changes in the distribution of aerosols are mapped out) as well as the forecast of global changes in climate and carbon circulation due to temporal changes in the distribution of aerosols are expected to emerge as important subjects. In forecasting global warming using the global simulator, a mesh (10km square or smaller) that serves as a point of calculations can be set, the range of which is capable of incorporating the behavior of clouds. In other words, the generation of clouds attributable to aerosols as well as their extinction can be incorporated into the global warming forecast.This development is expected to shed light on the effects of clouds on global warming, which have been considered too complicated a process that exceeds the capacity of supercomputers.

With the conventional supercomputers replaced by the global simulator, the performance of calculations has improved dramatically: the size of a grid, which was one hundred to several hundred kilometers square, has been downsized to 10km square or smaller. This enables models to incorporate the lifecycle of clouds, namely the process of their generation, development and extinction. The major challenge, however, is to prepare a data set of the default value of each smaller size grid. Although observation/monitoring equipment such as LIDAR is now available, the amount of global observation data on aerosols is far from being sufficient. When using given observation/monitoring data as default values, moreover, the data set must have time consistency. Under the present situation, preparing such data set is extremely difficult even if the observation area is limited to East Asia centered on China. To improve the study of forecasts, therefore, it is indispensable that the time consistency of data be ensured. Specifically, there is a need to establish a partnership between organizations engaged in observations/monitoring and those preparing data set for forecasts out of observation/monitoring results. In other words, a partnership in the three study fields shown in Figure. 1 should be established between relevant organizations in and outside Japan, and a mechanism where models are elaborated and observation/monitoring data are improved should be in use.

3.6 Challenges in promoting the study of aerosols

Since aerosols have yet to be fully addressed in the study of global warming, there is a need to push ahead with observation/monitoring efforts and elucidate their mechanisms, the achievements of which will be used for promoting the study of highly credible forecasts. However, there is no specific framework for addressing these efforts – scores of challenges remain untapped.

First of all, the present study of mechanisms is too primitive to create models that can accommodate quantitative assessments – the amount of observation data is insufficient for creating any substantial models. Despite the efforts of a number of research institutes, observation data showing the detailed distribution of aerosols in the atmosphere above Japan have yet to be collected. Under the present situation where observations and monitoring through satellites are not feasible, year-round observations extending over a wide area should be conducted through aircrafts. Since there are not many observatories that can observe the distribution of aerosols near the earth's surface, there is also a need to establish an on-the-ground observation network that would improve the accuracy of models. As far as the Asian region is concerned, moreover, Japan should take the initiative in improving the regional data - the amount of data on the vertical distribution of aerosols remains insufficient in many areas including China.

Secondly, researchers well versed in several study fields are hard to find in Japan, and so are modeling researchers who have sufficient physical and chemical knowledge. While universities are the major source of researchers engaged in the study of global warming, study of the climate system (including aerosol observations) is underway at only a handful of research centers and laboratories in Kyoto University, Chiba University, University of Tokyo, Tokyo University of Mercantile Marine, etc. Naturally, there is a limit to the number of researchers who can be trained by these institutes. Discussions about measures against global warming to be adopted after the expiration of the first commitment period under the Kyoto Protocol are expected to start in the near future - there is not much time left, but only a limited number of researches are likely to become full-fledged in such a short period of time. If Japan is to contribute to accumulating scientific findings in the future, those limited number of junior researchers should be trained so that they can take an active part in the study of both observations/monitoring and modeling, or for that matter, participate in the study of forecasts. What is needed above all is the framework for an inter-organizational relationship where researchers can play an active role in various study fields.

Lastly, it should be pointed out that Japan-originated quality findings are not well communicated to other countries as far as the studies of observations/monitoring and mechanisms are concerned. Since most of the research papers concerned are written in Japanese, only a few of them have been referred to in the IPCC Third Assessment Report and other overseas documents. Underlying this regrettable situation is the absence of a system where relevant institutes and research groups in Japan can communicate their findings in various study fields to other countries in a comprehensive and effective manner. Top-notch researches in Japan should thus take part in a number of international projects including IPCC in the future; they must take the leadership in those projects, while acting as a go-between to build a partnership between domestic research groups and promote the transmission of information.

Acknowledgements

We appreciate deeply the informative lecture, which is held at the National Institute of Science and Technology Policy and informed us recent international and domestic trends on the global warming research, by Professor Nobuo MIMURA at the Center for Water Environment Studies of Ibaraki University.

The authors also would like to acknowledge the following scientists for fruitful discussions and valuable information: Professor Mikio KASAHARA, Dean of the Graduate School of Energy Science, Kyoto University; Professor Teruyuki NAKAJIMA, the Center for Climate System Research, University of Tokyo; Mr. Hideo HARASAWA, the head of the Environmental Planning Section, Social Environment System Department, National Institute for Environmental Studies; Mr. Nobuo SUGIMOTO, the head of Atmospheric Remote Sensing Section, Atmospheric Environment Division; Mr. Yukio MAKINO, the head of the Atmospheric Environment Division, Observations Department, Japan Meteorological Agency; Mr. Toru SASAKI, Senior Coordinator for Global Atmosphere Watch; Mr. Tomohiro NAGAI, chief researcher at the Third Research Laboratory, Meteorological Satellite and Observation System Research Department, Meteorological Research Institute; Mr. Hajime AKIMOTO, Program Director of the Atmospheric Composition Research Program, Frontier Research System for Global Change; and Professor Fumihiko NISHIO, the Database Research Section, Center for Environmental Remote Sensing, Chiba University.

Glossary

* 1 Radiative Forcing

An index for measuring the force of one given factor to change the energy balance of the atmosphere, or an amount that indicates the probability of changing climate.

References

[1] IPCC Third Report on Global Warming, IPCC, Chuohoki Publishers (2002).

[2] IPCC94: Climate Change 1994 — Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios, Cambridge University Press (1994).

[3] IPCC95: Climate Change 1996 — The Science of Climate Change, Cambridge University Press (1996).

[4] The Global Warming Prevention Headquarters' website, http://www.kantei.go.jp/jp/singi/ondanka/index.html.

[5] Kazuaki Miyamoto, "Trends in the Development of Measures Against Global Warming Centered on CO_2 Underground Storage", Science & Technology Trends – Quarterly Review, No. 5 (Jan. 2003)

[6] IPCC Third Report on Global Warming, IPCC, Chuohoki Publishers, p. 15 (2002).

[7] Teruyuki Nakajima, "Jin'i Kigen Earozoru to Kiko Hendo (Manmade Aerosols and Climate Changes)," Science, Iwanami Shoten, Vol. 69, pp. 838-845 (1999).

[8] Sym-Bio Community, "Asu no Enerugi to Kankyo (The Energy and Environment of Tomorrow)," Nikko Forum, Chapter 4, pp. 141-172 (1998).

[9] D. J. Travis et al., "Contrails reduce daily temperature range," Nature, No. 6898, Vol. 418, 601 (2002).

[10] "Nihon Kogaku Gatsukai shi (Japan Optical Academy Journal)", "Kogaku (Optics)," "Chikyu Kankyo Rimoto Senshing no Tenbo (Prospects for Global Environment Remote Sensing)," No. 9, Vol. 29, pp. 532-553 (2002).

[11] "Report on the Atmosphere and Marine Environment," Vol. 2, Observation Results for Fiscal 2000, the Meteorological Agency (March 2002).

[12] T. Murayama et al., "Ground-based network observation of Asian dust events of April 1998 in East Asia," J. Geophys. Res., Vol. 106, No. D16, 18,345-18,359 (2001).

[13] For instance, Nakajima, T. et al., A possible correlation between satellite-derived cloud and aerosol microphysical parameters, Geophys. Res. Lett., 28, 1171-1174 (2001).

[14] For instance, "Report on the Basic Research on Global Warming - Review of Climate Scenarios," the Ministry of Land, Infrastructure and Transport (March 2002).

[15] Science & Technology Trends, No. 10, the National Institute of Science and Technology Policy, p. 5 (2001) (http://www.nistep.go.jp/index-j.html).

(Original Japanese version: published in November 2002)