RADIATION AND OZONE

Catalysts for Advancing International Atmospheric Science Programs for over Half a Century

BY G. OHRING, R. D. BOJKOV, H.-J. BOLLE, R. D. HUDSON, AND H. VOLKERT

A pivotal joint meeting of radiation and ozone pioneers 50 years ago at Oxford presaged the increasingly close relationship of these two specialties with each other and with subsequent developments in atmospheric science.

The authors dedicate this article to the memory of our colleague and friend, Julius (Julie) London, who died in his sleep on February 25, 2009, just one month shy of his 92nd birthday. Julie made major contributions to both radiation and ozone science and served as president of the International Radiation Commission from 1971 to 1979.

During a very warm, sunny July week, in 1959, some 110 scientists from throughout the world assembled in the historic university town of Oxford, United Kingdom, to discuss their latest results in radiation and ozone research. The meeting, organized by the International Radiation Commission and the International Ozone Commission, marked the first—and, to this date, the only—time the two bodies sponsored such a joint event. It took place just after the conclusion of the world's first international global observing program in the Earth sciences: the International Geophysical Year of 1957/58, which had been organized by the Commissions' parent organization, the International Council of Scientific Unions (ICSU). The meeting occurred at a time when simple representations of ozone photochemistry and radiative transfer were being replaced by complex models that were solvable only by high-speed computers, when measurements by individual investigators at a small number of locations were giving way to coordinated worldwide observational networks (including a global space-based observing system), and, most significantly, when the fields of ozone and radiation, which had had limited interaction with other atmospheric science disciplines, started to emerge as central elements of global weather and climate programs. The Radiation and Ozone Commissions played major roles in promoting these developments, which are seen today in the constellation of environmental satellites circling the Earth, the Montreal Protocol's phasing out of the production of ozone-destroying chemicals, the basic physics of global warming models, and improved weather prediction through satellite observations and data assimilation.

AFFILIATIONS: OHRING—College Park, Maryland; BOJKOV—Radebeul, Germany; BOLLE—Munich, Germany; HUDSON—University of Maryland, College Park, College Park, Maryland; VOLKERT—Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany
CORRESPONDING AUTHOR: G. Ohring, Westchester Park Dr., College Park, MD 20740
george.ohring@noaa.gov

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/2009BAMS2766.1

In final form 19 May 2009

Radiation is the driving force for the general circulation of the atmosphere and controls the Earth's climate. Ozone is responsible for the warm stratosphere and protects life on Earth from harmful solar ultraviolet radiation. We take this opportunity on the occasion of the 50th anniversary of the Oxford meeting to present a brief account of the Radiation and Ozone Commissions and how they worked to advance the science over the last century. It is based largely on a report on the history of the Radiation

Commission (Bolle 2008), prepared for the International Association of Meteorology and Atmospheric Sciences (IAMAS), and a paper on the history of the Ozone Commission (Bojkov 2009), presented at the Quadrennial Ozone Symposium in Tromso, Norway, in 2008. The commissions are part of the international structure for scientific research; we begin by describing this framework and how it initiates, facilitates, and coordinates international science activities.

FACILITATION AND COORDINATION OF ATMOSPHERIC RESEARCH ON THE INTERNATIONAL LEVEL. Starting in the eighteenth century, meteorology focused either on a synoptic view of measurements over larger areas or detailed time series at single stations; it combined physical measurements with seemingly dry statistical analysis and empirical findings. Atmospheric physics, on the other hand, concentrated on often intricate processes, for example, the absorption of light by gases, such as carbon dioxide and ozone, and the scattering of light by aerosols. Only in the twentieth century did experimental methods, increasingly sophisticated models, global observational networks, and good international cooperation lead to a sufficiently unified scientific approach.

The IAMAS, whose precursors date back to 1922, coordinates and facilitates meteorological and atmospheric research. Within the international science structure, IAMAS is one of eight associations of the International Union of Geodesy and Geophysics (IUGG), which itself is one of 25 unions within the ICSU. Many atmospheric scientists have participated in IUGG/IAMAS symposia at their interleafed biennial scientific assemblies, but few really know what takes place behind the scenes and how IAMAS works to advance atmospheric research.

IAMAS is composed of 10 international commissions whose memberships consist of leading scientists from around the world. Among the oldest of these are the Radiation and Ozone Commissions, which were formed as parts of the International Association of Meteorology [IAM; later the International Association of Meteorology and Atmospheric Physics (IAMAP), and the IAMAS]. In addition to planning scientific symposia, the commissions facilitate and advance cooperative international projects and programs by providing the scientific guidance for these efforts. They conduct focused planning workshops, often with other international scientific bodies, participate on project/program scientific steering committees, facilitate support of international efforts by funding agencies, and organize meetings to discuss and exchange scientific results.

Progress in the intrinsically difficult problems of increasing understanding, diminishing uncertainties, and enhancing predictive capabilities for the Earth's atmosphere is most rapid when visionary scientists cooperate on an international level and are supported by global institutions such as the World Meteorological Organization (WMO) and the national funding agencies. IAMAS has made significant contributions to the success of the International Geophysical Year (IGY; 1957/58), the International Quiet Sun Year (IQSY; 1964/65), and the Global Atmospheric Research Program (GARP; 1968–80), as well as to ongoing initiatives such as the WMO/ICSU World Climate Research Program (WCRP; online at http://wcrp.wmo.int) and the International Geosphere–Biosphere Programme (IGBP; online at www.igbp.net).

How international programs are developed and the role of the international science bodies are further explored in the sidebar "Advancing international programs."

THE ROOTS OF THE RADIATION AND OZONE COMMISSIONS. Recognizing that the energy driving atmospheric processes derives ultimately from the incoming solar radiation and that consistent measurements were necessary to characterize this radiation, in 1896 the International Meteorological Organization (IMO; today's World Meteorological Organization), established a Special Commission for Radiation and Insolation to make "recommendations for standardized radiation instruments and methods of solar and sky radiation measurements." A parallel group, the Solar Radiation Commission, of the International Union of Geodesy and Geophysics, was organized at the IUGG General Assembly in Madrid, Spain, in 1924, to bring together active research scientists involved in observational and theoretical studies of the distribution of solar radiation at the ground and in the atmosphere. Realizing the importance of the radiative effects of atmospheric ozone, the Solar Radiation Commission, at its first meeting, in Stockholm, Sweden, in 1930, recommended that a Subcommission for Atmospheric Ozone be formed. This was formally done by IUGG in Lisbon, Portugal (in 1933), which charged the group with obtaining a better understanding of the stratosphere. At the IUGG Assembly in Oslo, Norway (in 1948), both radiation groups were combined into a single International Radiation Commission (IRC), and in recognition of the importance of ozone monitoring and research, a separate International Ozone Commission (IOC) was established.

During the first half of the twentieth century, the radiation groups focused on measurements of solar radiation at the Earth's surface, attempts to estimate the "solar constant" from ground-based observations, schemes for calculating atmospheric radiative transfer, and the problems of measurement standards. One of the issues with which the International Radiation Commission struggled for decades was the systematic difference of about 5% between solar radiation scales of the two major instruments: the Ångström pyrheliometer and the silver disc pyrheliometer. This was finally resolved in 1956, when the International Pyrheliometric Scale was adopted. Other activities pursued by the International Radiation Commission up to the time of the Oxford meeting included an intercomparison of longwave radiation instruments, the first measurements of the ultraviolet radiation of the sun and sky, techniques for radiation measurements in the free atmosphere, and the technical application of solar energy.

Early ozone research focused on measurements to ascertain the major features of the atmospheric ozone distribution. In the 1920s, G. M. B. Dobson theorized that the warm stratosphere was caused by the absorption of solar ultraviolet radiation by ozone. Following the principle established in 1920 by Fabry and Buisson, he built a spectrograph to measure this absorption and to determine the ozone amount. His measurements at Oxford in 1925 revealed a spring maximum and fall minimum. He distributed instruments to take year-long observations at a dozen places around the world, which provided the first data points of the meridional and seasonal ozone distribution. The global network now consists of more than 120 stations; the double-quartz spectrophotometer designed by Dobson in 1931 remains the standard instrument, and the units used to measure the amount of ozone [matm-cm] are informally called Dobson units.

Activities promoted by the International Ozone Commission in its early decades included the theory of the production and destruction of ozone, highlighted by Sidney Chapman's work on the oxygen

ADVANCING INTERNATIONAL PROGRAMS

The International Association of Meteorology and Atmospheric Sciences has had a long history of collaboration with the World Meteorological Organization. Such a partnership is a natural one: IAMAS, through its commissions, provides scientific guidance, and the WMO, comprising all the governments of the world with weather services, facilitates the implementation of global observing programs.

From an idea to an international program. In many cases, international programs grow from the idea of one, or a few, individuals. For example, someone has a bright idea for a global program in atmospheric science. He (she) discusses the idea with colleagues, perhaps at a coffee break of an American Meteorological Society (AMS) or American Geophysical Union (AGU) conference, or during the business meeting of one of the IAMAS commissions at an international symposium. The idea is elevated to ICSU, which organizes experts' workshops to develop a program proposal. ICSU approves the proposal and forms a partnership with WMO and/or with other international bodies to develop a program plan. The program plan is briefed back to national institutions for funding support, national agencies commit to responsibilities for parts of the program, joint working groups and steering committees are formed, and an international program is born.

The Global Atmospheric Research Program, the forerunner of today's World Climate Research Program, is an illuminating and perhaps unique example (Phillips 1995; Houghton 1985). In 1961, Massachusetts Institute of Technology (MIT) Professor Jule Charney initiated a series of discussions among atmospheric scientists on methods to advance international cooperation. He was responding to a request from Jerome B. Wiesner, President John F. Kennedy's special assistant for science and technology, who had been asked by Kennedy for suggestions to promote the peaceful uses of outer space. The Charney group came up with a proposal for improving weather prediction using observations from satellites. President Kennedy, in his September 1961 speech at the United Nations (UN; *New York Times*, 26 September 1961) proposed "cooperative effort between all the nations in weather prediction . . ." UN Resolutions 1721 and 1802 followed, requesting that the World Meteorological Organization and the International Council of Scientific Unions develop plans for such a program, which emerged in 1967 as GARP. Some of the contributions of the IRC to GARP and WCRP are included in this article in the section, "Increasing importance of radiation and ozone research in the second half of the twentieth century."

An interesting account of how the International Geophysical Year grew out of conversation at a dinner party hosted by James van Allen for Sidney Chapman is given by Korsmo (2007).

The International Ozone Commission and the Agreement to Protect the Ozone Layer. In the mid-1970s, members of the IOC raised concerns about the potential destruction of the stratospheric ozone layer by manmade chlorofluorocarbons (CFCs). They drafted a warning about the geophysical consequences of ozone destruction that the WMO executive body accepted as the first intergovernmental statement of concern for the future of the ozone layer (WMO 1976). This initiated an international process in which the WMO and the United Nations Environment Program played major roles in addressing these concerns. Governments of the world endorsed the Vienna convention on the protection of the ozone layer, which led to the 1987 Montreal Protocol to phase out the production of ozone-depleting substances (ODS).

The IOC took an active role in the preparation of the scientific background for negotiations leading to the Vienna convention and its Montreal Protocol. Almost all of its members are involved in the periodic international ozone assessments organized by the WMO, which serve as a base for assessing the implementation of the protocol and justifying necessary amendments.

photochemistry of ozone, ground-based measurements of the vertical distribution of ozone based on the "Umkehr effect," balloon spectrograph proof that the ozone maximum was at ~22 km, and development of optical ozonesondes.

The surface-based measurements of the total amount and vertical distribution of atmospheric ozone carried out by the Dobson instruments were possibly the first examples of the use of remote sensing in meteorology.

THE JOINT MEETING OF THE OZONE AND RADIATION COMMISSIONS IN 1959.

Researchers in atmospheric ozone and radiation from all parts of the world assembled in Oxford during the week of 20 June 1959 (the lists of participants are given in the appendix). Their images are captured for posterity in the accompanying group photo (see a discussion of the photograph and information on some of the key figures in the sidebar "A Stunning Photograph").

The radiation symposium. Forty-seven papers were presented at the radiation symposium (IUGG-4 1960). The traditional topics included surface instrumentation for radiation measurements, observation and computation of terrestrial radiation (now, more usually referred to as longwave radiation), transmission of solar radiation in the atmosphere, and spectroscopic methods. However, in 1957 and 1958, a major international program had taken place—the IGY. The IGY was the first in a grand series of cooperative international projects in which the ozone and radiation communities would play major roles. Organized by the ICSU, the parent organization of IAMAS, following a suggestion by Lloyd Berkner, a member of the U.S. National Academy of Sciences, and Sidney Chapman, developer of the theory of the ozone layer, its goal was to observe geophysical phenomena and to secure data from all parts of the world, and to conduct this effort on a coordinated basis by fields, and in space and time, so that results could be collated in a meaningful manner. At the request of the IUGG committee for the IGY, the International Radiation Commission had prepared a program of radiation measurements and detailed instructions for conducting these observations. Radiation measurements were conducted at about 700 stations throughout the world, including observations of solar and net radiation in the Antarctic. An entire session of the Oxford meeting was devoted to the results of these measurements.

The future development of the field was anticipated in a small session on satellite and rocket programs. Recall that the first weather satellite was still two years away from being launched. In a prescient paper, S. Fritz, the first director of what was to become the National Oceanic and Atmospheric Administration's (NOAA's) National Environmental Satellite, Data and Information Service, stated that "Meteorology deals with world-wide phenomena and for the first time the artificial satellite will make it possible to obtain observations from all over the world. In addition, satellite observations will provide types of measurements which have never been made." Another important application of space-based measurements was presaged by F. E. Stuart, C. E. Sheldon, E. P. Tood, and P. R. Gast, who used observations from a rocket to determine the solar constant to be 1333–1389 W m^{-2}.

Interestingly, another transitional development in the field, the use of digital computers, was noted by Fritz Möller, president of the IRC, in his opening address. "For 6 months of the year 1955, we have calculated the short and long wave radiation fluxes at 100 European stations, *4 months of them by use of modern electronic computers.*"

The ozone symposium. Fifty papers were presented at the ozone symposium (IUGG-3 1960). The usual topics were covered, such as the accuracy of and improvements in ground-based measurements of the total ozone and its vertical distribution. However, as in the radiation area, the IGY had energized the study of atmospheric ozone.

The IOC had been instrumental in increasing the small number of stations measuring ozone into a 50-station network, including a few in Antarctica, whose continuous measurements led to the discovery of the Antarctic ozone hole in 1985. The first results of these IGY ozone observations were reported at the meeting. The ability to obtain vertical ozone soundings from balloons was demonstrated in several papers using different techniques, including several types of ozonesondes.

Previous studies of the relationship between ozone and meteorology had focused on ties to weather conditions and synoptic patterns in the troposphere. The Oxford symposium included, for the first time, a number of papers on the fundamental relationships between ozone and meteorological conditions in the stratosphere.

Studying the ozone distribution and the stratospheric circulation in the Northern Hemisphere winter and summer, K. R. Ramanathan, in an attempt to explain the disagreement between the observed ozone distribution and that predicted by photochemical theory, invoked the need for the existence of meridional and vertical transport mechanisms. His idea was further developed in the now-well-known Dobson–Brewer circulation scheme. R. J. Murgatroyd reported that measurements by aircraft up to 15 km from the equator to 70°N indicate rapid ozone increase and humidity decrease in the stratosphere immediately above the tropopause. The evidence of moist air rising in the upper part of the equatorial troposphere and spreading poleward between 12 and 15 km, with considerable subsidence over the subtropics, was important for understanding the overall ozone transport within the atmospheric circulation, as suggested by Ramanathan.

INCREASING IMPORTANCE OF RADIATION AND OZONE RESEARCH IN THE SECOND HALF OF THE TWENTIETH CENTURY. *Radiation.* After the Oxford meeting, the IRC expanded its radius of activity thematically and structurally by organizing working groups, initiating research and projects to solve critical scientific problems, and establishing close working relationships with other international bodies. Radiation science became critical to our understanding of global warming, our ability to observe the Earth remotely from satellites, and our capacity to forecast weather and climate. And, the IRC played significant roles in two of ICSU's most successful programs: the GARP and the WCRP.

Through its working groups, the IRC strived to document and standardize terminology (Raschke 1978), computations (Lenoble 1985), and measurements (Fröhlich and London 1986) of radiative transfer. It also developed a standard radiation atmosphere that, for the first time, included trace gas concentrations and aerosol models (WCRP/IAMAP/IRC 1986). Observations of the solar spectrum and the longwave atmospheric sky radiation, supported by laboratory measurements, provided a new foundation for calculating atmospheric radiative transfer. The IRC stimulated the construction of accurate transmission functions based on spectral line data, which also accounted for the nonlocal thermal equilibrium conditions in the upper atmosphere.

The advent of satellites offered new perspectives to assess state quantities of the Earth's atmosphere and surface. The IRC organized working groups and collaborated with the ICSU's Committee on Space Research (COSPAR) and other bodies to exploit these new capabilities. IRC scientists provided scientific guidance at a seminal meeting of the ICSU's COSPAR in Geneva, Switzerland, in 1967. The meeting developed the concept of a constellation of five geostationary satellites ringing the Earth's equator as part of the Global Observing System for GARP. This initiative was embraced by the international satellite agencies and continues to this day as part of the WMO's World Weather Watch, providing crucial observations for nowcasting, short- and long-term weather predication, environmental hazards (fires, floods, volcanic ash), and climate applications.

In 1981, the IRC formed an International Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Working Group (ITWG) on the use of TIROS Operational Vertical Sounder data on NOAA's polar-orbiting satellites. The ITWG organized its first conference in 1983, and it continues to organize study conferences every 18–24 months to advance methods for extracting information on temperature, moisture, and composition from satellite soundings, assimilating the data in numerical weather prediction models, and applying the information in climate studies.

Global climate change motivated the development of accurate techniques for calculating radiation in climate models, understanding the role of clouds in climate, and measuring the Earth's radiation budget. Together with the Joint Scientific Committee of the WCRP, in 1991 the IRC initiated a program on the Intercomparison of Radiation Codes in Climate Models (ICRCCM) to evaluate and to improve solar and longwave radiation calculations in climate models. IRC scientists participated in the GARP's Oxford 1978 study conference on the parameterization of extended cloudiness and radiation for climate models (Joint Planning Staff for GARP 1978). Following up on the recommendations of this meeting, the IRC cosponsored an experts' workshop in Balatonalmadi, Hungary, that laid down the specifications for the International Satellite Cloud Climatology Project (ISCCP), the first project of the World Climate Research Program. And, in 1986, the IRC cosponsored a workshop on surface radiation budget for climate applications in Columbia, Maryland (Suttles and Ohring 1986), that subsequently led to the WCRP's Baseline Surface Radiation Network (BSRN) and satellite-based Surface Radiation Budget (SRB) program. The improved accuracy of radiative transfer models and the increased knowledge of cloud–radiation interactions resulting from these programs permit the effects of greenhouse gases, clouds, and aerosols to be treated with ever-increasing reliability in predicting climate change.

During the early 1970s, the IRC engaged in identifying and resolving differences between observa-

A STUNNING PHOTOGRAPH

During the 1959 meeting, the attendees of the symposiums on radiation and ozone were guided in a well-choreographed manner onto a high stand in front of the Deneke Building, Lady Margaret Hall, Oxford, for their photo opportunity. The stunning photograph (Fig. 1), contains a number of intertwined narratives: i) the attendance from many countries and several generations implies a well-established group spirit; ii) the large number of eminent (and to be) names reveals the attractive power of the existing informal network; iii) the mixture of light summer dressing with some formal elegance reflects good working relations in important scientific fields; and iv) the family-type atmosphere with spouses and even some children underscores a spirit of friendship.

Among the carefully arranged grouping with numerous key figures in atmospheric research over the last century are the following (the identification numbers of the following attendees are included after their name or dates and correspond to Fig. 1):

Anders Angström (1888–1981; #78), president of the IMO Radiation Commission 1935–46, of the IUGG Solar Commission 1930–51, and of the IRC 1948–51, and inventor of the Angström compensation pyrheliometer on which the Angström pyrheliometric scale was based;

Alan Brewer (1915–2007; #119), inventor of the Brewer ozonesonde and ozone spectrophotometer, and developer, with G. M. Dobson, of the Brewer–Dobson circulation to explain why tropical latitudes have less ozone than polar latitudes;

Mikhail Budyko (1920–2001, #69), author of *Heat Balance of the Earth's Surface,* which changed climatology from a purely descriptive/qualitative science to a physical/quantitative one, and developed the first climate model;

Gordon Dobson (1889–1976; #79), inventor of the "Dobson" instrument, still used today at 120 stations worldwide to measure ozone, and organized the first measurements to define seasonal and latitudinal ozone distributions;

Hans Ulrich Dütsch (1917–2003; #90), secretary and president of the IOC, calculated photochemical equilibrium vertical profiles of ozone, conducted long series of total ozone and ozone profile (Umkehr) observations at Arosa, and led numerous ozonesonde intercomparisons;

Joe Farman, (1976–; #70) head of the Stratosphere Section, British Antarctic Survey Headquarters, Cambridge, and led a team that discovered the Antarctic ozone hole;

Sigmund Fritz 1914–; #42) appointed first director of NOAA's weather satellite unit in 1958, calculated the Earth's albedo, and studied solar radiation and weather satellite measurements;

Warren L. Godson (1920–2001; #43), secretary and president of IAMAP for 20 yr, and promoted Canadian atmospheric research, including ozone stations and new instruments;

John Houghton (1931–; #108), director general, Met Office, 1983–91, lead editor of first three IPCC reports, and author of acclaimed textbook *Physics of Atmospheres;*

Kirill Ya. Kondratiev (1920–2006; #104), rector, University of Leningrad, 1964–70, member, Russian Academy of Sciences, IRC president, 1967–71, and generated a wide spectrum of radiation research contributions and a prolific author of books;

Julius London (1917–2009; #91), president of IRC, 1975–79, made important contributions to both ozone and radiation research, and performed seminal work on cloud climatology and atmospheric heat balance;

Fritz Möller (1906–83; #64), president of IRC, 1957–67, led the commission into the space age and developed jointly with S. Manabe the first radiation code for general circulation models;

Walter Mörikofer (1892–1976; #94), director of the Physikalisch-Meteorologische Obsesrvatorium Davos, 1929–66, president of IRC, 1951–57, promoted the intercomparison of radiation instruments, and studied the bioclimatic impact of radiation;

Sir Charles Normand (1889–1982; #62), director-general of Indian Met Service, secretary of the IOC, 1948–58, and developed the modern measurements of ozone with the double wavelength (A-D) method, eliminating the need for aerosol corrections;

Kalpathi R. Ramanathan (1893–1984; #46), director-general, Indian Met Service and Ahmedabad Physical Laboratory, president of IUGG, IAMAP, and Ozone Commission, proposed the concept for meridional transport of ozone, trained numerous scientists, and advanced ozone research in India;

Jacques van Mieghem (1905–1980; #80), director, Institut Royal Meteorologique de Belgique, and planned the WMO program for IGY; and

Arlette (#121) and Etienne Vassy (dates unknown; #45), conducted pioneering laboratory and field measurements of ozone and oxygen absorption coefficients.

tions of the solar constant, more correctly, solar irradiance, obtained from the ground, aircraft, and rockets. However, satellites provided the capability of measuring the solar irradiance and the Earth's radiation budget (ERB) components at the top of the atmosphere. Members of the IRC were invited by COSPAR to an experts meeting in Alpbach, Austria, in 1978 to develop plans for an internationally coordinated Earth radiation budget satellite observing system (ICSU-COSPAR 1978). The report of this meeting motivated the National Aeronautics and Space Administration (NASA) series of ERB missions.

In 1983, the IRC and COSPAR organized the International Satellite Land Surface Climatology Project (ISLSCP) under the United Nation's environmental program to assess long-term albedo and land use changes and to promote the use of satellite data for the global land surface datasets needed for climate studies. Since 1992, ISLSCP has been part of the WCRP.

Another branch of remote sensing was implemented by the IRC in 1983—the International Coordination Group on Laser Atmospheric Studies, which advanced the possibility of assessing cloud and aerosol properties from the ground, from aircraft, and, eventually, from space.

Since 1948, research results have been presented and exchanged at 56 international radiation symposia with up to several hundred participants, as well as at numerous separate special meetings of working groups.

Ozone. The IOC evolved from a highly specialized group of scientists with a common interest in the measurement techniques of atmospheric ozone to the present body representing an expanded scope of diverse scientific interests. This includes *meteorology, atmospheric chemistry and physics, air pollution, laboratory chemistry, statistics, and environmental sciences in general, as well as promoting and participating in international programs*.

In the first four decades of its existence, the International Ozone Committee, and later the commission, were preoccupied with improving measurement techniques and enlarging the network of stations from less than a dozen before 1950 to more than 50 in 1958, an effort led by G. M. B. Dobson and Sir C. Normand. A second period started in the 1970s with the explosive increase of ozone studies related to NOx exhaust into the stratosphere from planned supersonic aircraft and to the discovery that anthropogenic emissions of chlorofluorocarbons were providing chlorine. Chlorine is the precursor material for destroying the ozone layer, and creating an ozone hole—an abrupt and almost complete disappearance of the lower-stratosphere ozone over Antarctica during each Southern Hemisphere spring.

Fig. 1. Participants of the 1959 Oxford symposiums on atmospheric radiation and ozone. Please see the Appendix for more detailed information on this photo.

#102, Hans-Gerhard MÜLLER, 1962-72 erster IPA-Direktor

Members of the IOC took an active part in these studies and three of them—P. J. Crutzen, F. S. Rowland, and M. J. Molina—were awarded the Nobel Prize for Chemistry in 1995. In the last decade, relationships between ozone and climate change, air pollution, and the launching of more sophisticated satellites initiated a third period of activities.

Since its inception, the IOC has gathered and distributed information mainly through its Quadrennial Ozone Symposia and small working groups on particular issues. For the first three decades (1929–59), only 222 papers were presented at these meetings. For the next three decades (1978–2008) the Quadrennial Ozone Symposia on four occasions exceeded 400 presentations, with close to 700 in 2004. All together the IOC has organized more than 30 international symposia at which more than 3,800 papers were presented and published.

Motivated largely by the worldwide destruction of stratospheric ozone, the second period also coincided with the initiation of a number of global research programs with direct participation of the IOC in planning activities and its members as initiators and project leaders [e.g., Middle Atmosphere Program (MAP), International Global Atmospheric Chemistry (IGAC); Network for Detection of Stratospheric Changes (NDSC); Stratospheric Processes and their Role in Climate (SPARC); and organizing and contributing to WMO Global Ozone Research Project and Scientific Assessments of Ozone Change (from 1981 until present)].

Global ozone coverage became a reality with the launches of satellite instruments by NASA in the 1970s. In 1978, NASA launched the Total Ozone Mapping Spectrometer (TOMS) instrument to measure the total column of ozone in the atmosphere, and two ozone profile instruments, the Solar Backscatter Ultraviolet Spectrometer (SBUV) and Limb Infrared Monitor of the Stratosphere (LIMS) on board the *Nimbus-7* spacecraft. IOC members were involved in all aspects of this mission, from instrument design to the analysis of the data. Since then, IOC members have participated in the development of a series of satellite missions to investigate the composition of the stratosphere and to monitor the total column of ozone, under the auspices of NASA and NOAA, the European Space Agency (ESA), Japanese Aerospace Exploration Agency (JAXA), European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and China Meteorological Administration (CMA). The same time period saw a rapid increase in the complexity of two- and three-dimensional models.

In 1988, IAMAS defined the role of the IOC as follows: "To provide scientific expertise for the improvement of the Global Ozone Observing System (GO_3OS), to clarify questions of ozone variability by rigorous review of measurements and photochemical models as inputs to WMO Ozone Assessments and to development of global control measures." The commission took an active role in the preparation of the scientific background for the negotiations leading up to the Vienna Convention for Protection of the Ozone Layer and its Montreal Protocol for phasing out chlorofluorocarbon emissions, and members have been actively involved in the periodic international ozone assessments.

FUTURE RESEARCH CHALLENGES. *Radiation.* Atmospheric radiation research now covers the full spectral range from the ultraviolet to the microwave and deals with a wide range of theoretical and observational investigations ranging from the molecular scale to the entire Earth system and the sun. Its actual front line can be marked by the following challenges:

- Theoretical challenges:
  - three-dimensional radiative transfer models for cloudy, precipitating, and aerosol laden atmospheres;
  - fast, accurate atmospheric radiative transfer models based on improved molecular spectroscopy for real-time applications, such as NWP;
  - radiation processes at the surface–atmosphere interface; and
  - radiative transfer under conditions where local thermodynamic equilibrium breaks down, such as in the upper atmosphere.
- Observational challenges:
  - development of algorithms for the application of advanced technological tools, such as interferometry, lasers, radars, and hyperspectral instruments to measure atmospheric and surface properties and composition by remote sensing from the ground and from space;
  - accurate long-term measurements of the extraterrestrial solar flux and of the Earth's radiation budget, including the surface budget; and
  - satellite sensors with high absolute accuracy traceable to international system (SI) units and a well-calibrated and intercalibrated global Earth observing system.

Advances on the above topics will contribute to improved understanding, monitoring, and prediction of weather and climate. Satellite observations

THE DISCOVERY OF THE HOLE IN THE OZONE LAYER

As is often the case with scientific discoveries, several investigators arrived at the same result at about the same time. At the International Ozone Commission's Quadrennial Ozone Symposium Ozone in 1984, a Japanese scientist, Shigeru Chubachi, presented a paper (Chubachi 1984) on some unusual observations at his country's station at Syowa, Antarctica. In September and October—the first two months of the Antarctic spring—of 1982, Chubachi reported that Syowa had recorded extremely low ozones values (~200 Dobson units, more than one-third lower than typical values). The comparison with normal spring readings was made possible only because a few of the stations established in Antarctica for the International Geophysical Year in 1957 had become permanent observation posts.

In the same year that Chubachi presented his paper, NASA Goddard Space Flight Center scientists analyzing observations from the TOMS satellite, which had been launched in 1979, noticed that extremely low ozone values had occurred over Antarctica during October 1983; they reported on this phenomenon at the International Association of Geomagnetism and Aeronomy Assembly in August 1985.

At the same time, Joe Farman and his colleagues at the British Antarctic Survey (BAS) observed that in October the total ozone over their BAS Halley Bay Station had decreased by ~40% since 1976. This result was published in 1985 (Farman et al. 1985). In this paper the authors suggested that manmade CFCs were the reason for the unusual spring decline. This was the first article on the ozone hole to be published in a peer-reviewed journal, and Farman and his colleagues have received credit for the discovery of the ozone hole.

Since 1985, spring Antarctic total ozone has declined to values of 50%–60% below pre–ozone hole years, at times to less than 100 Dobson units, with the 14–22-km stratospheric layer almost devoid of ozone (see Fig. 2 for a depiction of the dramatic ozone losses in this layer). The last 10 yr have seen the six strongest thinnings, with the spring of 2006 registering the largest area (>28×10^6 km^2) and lowest values ever observed. Eventually, however, the Antarctic spring ozone layer is expected to recover by the last half of the century as a result of the phase out of CFCs specified in the Montreal Protocol of 1987.

The building stones for explaining the ozone decline can be found in a few unconnected publications. Stolarski and Cicerone (1974) established that chlorine in the stratosphere could catalytically decompose ozone molecules, but a source of chlorine was not obvious except in the exhaust of solid booster rockets. At the same time, Molina and Rowland (1974) determined that CFCs could not be destroyed in the troposphere, but when they reached the stratosphere they could decompose and release enough chlorine atoms to catalytically destroy ozone molecules at ~40 km. While this could explain the observed worldwide depletion of stratospheric ozone at a rate of a few percent per decade, it could not account for the huge Antarctic spring decreases, which, furthermore, were occurring lower down in the stratosphere. Solomon et al. (1986) proposed that in the Antarctic spring, a heterogeneous reaction between two major sinks for chlorine, hydrochloric acid, and chlorine nitrate, on aerosol surfaces [polar stratospheric clouds (PSCs)] could produce atomic chlorine. These clouds are known to exist in the extremely cold Antarctic lower stratosphere, especially at temperatures below −78°C, which are common within the circumpolar stratospheric vortex for that time of the year. This explanation was further developed by Crutzen and Arnold (1986), who discovered the role of type-1 PSCs, and Molina and Molina (1987), who introduced the most efficient catalytic cycle for the destruction of ozone. Most of these scientists were members of the International Ozone Commission. Detailed discussions of the Antarctic depletion can be found in the series of International Ozone Assessments published as WMO Ozone Project Reports 18, 20, 37, and 44.

A final note: The term "ozone hole" to signify these Antarctic events was coined by Nobel Prize winner Sherwood Rowland in a seminar he gave at the Chemistry Department at the University of Maryland on 6 November 1985.

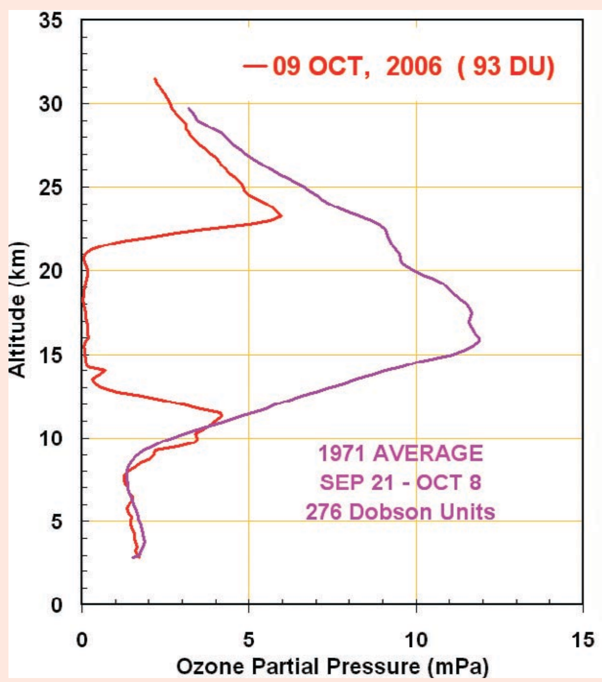

Fig. 2. Vertical profiles of ozone at South Pole: average 21 Sep–8 Oct values in 1971, a typical year prior to the development of Antarctic ozone holes (purple); and at time of maximum ozone hole in 2006, typical of recent decades (red; South Pole ozone profile data provided by the NOAA Earth System Research Laboratory, Global Monitoring Division).

have contributed to the dramatic increases in weather forecast accuracies over the past few decades; additional improvements will result from the assimilation of observations in cloudy and precipitating regions, exploitation of the full range of hyperspectral observations through rapid, accurate radiative transfer calculations, and the measurement of the three-dimensional wind field with lidar instruments.

Climate science will benefit from improved monitoring of global climate change (temperature, precipitation, and other climate variables), climate forcings (solar, greenhouse gases, aerosols, and land use), and climate feedbacks (clouds, water vapor, snow/ice, and biosphere). Better radiative transfer models will lead to more realistic depictions of radiative processes in climate models that will result in more reliable predictions of the future climate.

Ozone. It is now firmly established from both model calculations and measurements that the observed ozone depletion of the past three decades is mainly due to anthropogenic halogen compounds. The controls on ozone-depleting substances imposed by the Montreal Protocol have certainly reduced this effect. However, to determine how stratospheric ozone and surface UV type B (UVB) will behave in the future, one has to also consider factors other than ODS. For example, it has been shown that about one-third of the ozone decrease seen at midlatitudes between 1979 and 1991 was due to a northern movement of the upper-tropospheric fronts, which, in turn, was driven by the increase in the greenhouse gases in the tropics.

Generally, the chemistry of polar stratospheric ozone loss is well understood. Although current models project that the Antarctic ozone hole will disappear in the later part of twenty-first century, there are uncertainties in this projection. The temperature in the Antarctic stratosphere determines the amount and composition of the polar stratospheric clouds. This temperature depends not only on the amount of ozone but also on the dynamics of the formation of the polar vortex, which could also be affected by changing climate.

It is now clear that there are multiple interactions between changes in ozone, UV radiation, aerosols, increased tropospheric photochemical pollution, and the changing climate. The focus of research in the future will be on understanding the relationship between atmospheric ozone and the changing climate of the twenty-first century.

SUMMARY. Atmospheric radiation and ozone have been the subjects of research studies for well over a century. Formal international collaboration in radiation studies date back to 1896 when the International Meteorological Organization (IMO), today's World Meteorological Organization, established a Special Commission for Radiation and Insolation to make "recommendations for standardized radiation instruments and methods of solar and sky radiation measurements." Realizing the importance of the radiative effects of atmospheric ozone and the necessity to improve understanding of the stratosphere, the IUGG, in 1933, formed a body to advance ozone studies. These groups were the forerunners of the International Radiation and Ozone Commissions, which have guided research and promoted international programs in these disciplines for more than half a century.

The commissions advance international scientific programs in the following three general ways:

1) Commission meetings provide an opportunity for scientists to develop, discuss, and implement new ideas for international activities. If the proposals require broader scientific participation, they are channeled through IAMAS up to the higher levels of the scientific and intergovernmental hierarchy, where they can be implemented into international programs. Mechanisms of this type performed an important function during the Cold War period: without them scientific exchange between the East and West would have ceased.
2) International programs rely on the expertise accumulated in the commissions to develop subprograms and to provide advice for solving specific scientific and technical problems. Commissions also have experience in establishing and standardizing the observations of global measurement networks, such as the solar radiation and ozone measuring network, on which global programs rely. The commissions also provide a reservoir of experts who are consulted and appointed as members of advisory and planning committees for international programs.
3) Commission symposia contribute to a thorough topical evaluation of the results obtained during international activities, which may lead to mid-course corrections in multiyear programs.

The results of more than 50 years of these activities can be seen in today's improved monitoring, better understanding, and more reliable predictions of weather and climate change. With global warming a continuing and growing threat to the planet, and the recovery of the ozone layer from its depleted state still of concern, the International Radiation and Ozone Commissions will continue to face and meet major challenges in the future.

ACKNOWLEDGMENTS. Jeff Rosenfeld, chief editor of BAMS, provided an insightful critique of an early version of the manuscript. John Barnett (Oxford) energetically supported the process of identification concerning location and individuals of the group photograph, while Aharon Eviatar (Tel Aviv), Joe Farman (Cambridge), Claus Fröhlich (Davos), John Le Marshall (Melbourne), Jacqueline Lenoble

(Grenoble), Zev Levin (Tel Eviv), Manfred Reinhardt (Oberpfaffenhofen), and Desmond Walshaw (Oxford) added valuable information. Steve Jebson (Met Office) provided the information on weather conditions during the week of the Oxford meeting. All of this assistance is acknowledged with gratitude.

APPENDIX: PARTICIPANTS AT THE 1959 OXFORD MEETING. A group photograph can be regarded as a visual dataset. Its value is much enhanced, if full name and geographical context (country of work) of every person is known. Often these auxiliary data are not collected when a picture is taken. The *post-festum* identification of the persons on the Oxford group photograph (Fig. 1) was aided by lists of participants for both commission meetings. They are given here together with the number code of all identified persons to aid further identification.

Participants at the International Ozone Commission session, Oxford, July 1959.					
Identification No.	**Full name, country**	**Identification No.**	**Full name, country**	**Identification No.**	**Full name, country**
58	M. Alaka, Switzerland	68	Hans Hinzpeter, Germany	46	Kalpathi R. Ramanathan, India
39	Arthur D. Belmont, United States		R. H. Ray, United Kingdom		
122	Wouter Bleeker, Netherlands	104	Kyrill Ya. Kondratyev, Russia	17	Ichtiaque Rasool, France
119	Alan W. Brewer, United Kingdom		Mr. Langham, United Kingdom	106	Victor Regener, United States
	F. Brown, United Kingdom	77	Kaare Langlo, Norway (WMO)		W. T. Roach, United Kingdom
69	Mikhail Budyko, Russia		S. H. H. Larsen, Netherlands	92	George D. Robinson, United Kingdom
	G. Cena, Italy	91	Julius London, United States	109	Zdenek Sekera, United States
79	Gordon M. B. Dobson, United Kingdom	25	Joe MacDowell, United Kingdom	118	Peter A. Sheppard, United Kingdom
1	Robert Dogniaux, Belgium		D. B. McMullen, Ghana	26	S. Desmond Smith, United Kingdom
90	Hans-Ulrich Dütsch, Switzerland	103	Marcel Migeotte, Belgium		Dieter Stranz, Germany (Belgian Congo)
116	Alfred Ehmert, Germany		F. Morgan, United Kingdom	61	Reginald Sutcliffe, United Kingdom
70	Joe C. Farman, United Kingdom	73	Robert J. Murgatroyd, United Kingdom	71	William Swinbank, Austria
3	G. Fea, Italy	28	Morris Neiberger, United States	83	John B. Tyldesley, United Kingdom
	Mme. E. Fesenkova, Russia	62	Sir Charles Normand, United Kingdom	80	Jacques van Mieghem, Belgium
42	Sigmund Fritz, United States	57	George Ohring, United States	121	Arlette Vassy, France
43	Warren L. Godson, Canada	59	Hans-Karl Paetzold, Germany	45	Etienne Vassy, France
6	M. Grigg, United Kingdom	18	R. Pastiels, Belgium	87	Ernest Vigroux, France
60	J. Vern Hales, United States		A. Perlat, (unknown)	33	Desmond Walshaw, United Kingom
2	F. R. Harrison, United Kingdom		Perrin de Brichambaut, France		G. F. Wlaton, United Kingdom

Participants at the International Radiation Commission session, Oxford, July 1959.

Identification No.	Full name, country	Identification No.	Full name, country	Identification No.	Full name, country
58	M. Alaska, Switzerland	27	Herfried Hoinkes, Austria		D. Z. Robinson, United Kingdom
	R. Anderson, United States	108	John T. Houghton, United Kingdom	92	George D. Robinson, United Kingdom
78	Ånders Ångström, Sweden		L. Jacobs, United Kingdom	101	Nathan Robinson, Israel
107	Dov Ashbel, Israel		W. S. Keeler, (unknown)	76	Fuad Saïedy, United Kingdom
82	Paul Bener, Switzerland	104	Kyrill Ya. Kondratyev, Russia		Miss R. Salvador, Senegal
19	Hans-Jürgen Bolle, Germany	65	Günter Korb, Germany		F. Sauberer, (unknown)
	H. J. de Boer, Netherlands		S. H. H. Larsen, Norway	81	Herfinn Schieldrup-Paulsen, Norway
	T. A. Bosua, South Africa	93	Jacqueline Lenoble, France		
72	F. A. Brooks, United States		O. Lönnqvist, Sweden	53	Rudolf Schulze, Germany
69	Mikhail Budyko, Russia	29	Reinhold Marchgraber, United States		J. Seeley, United Kingdom
85	Kurt Bullrich, Germany	98	Henri Masson, Senegal	109	Zdenek Sekera, United States
	G. Cena, Italy		B. W. McMullen, United Kingdom	118	Peter A. Sheppard, United Kingdom
114	Geoff J. Day, United Kingdom	56	W. E. K. Middleton, Canada	26	S. Desmond Smith, United Kingdom
5	Diran Deirmendjian, United States		W. Möller (UNESCO)	20	Gunnar Spinnager, (unknown)
1	Robert Dogniaux, (unknown)	64	Fritz Möller, Germany	115	V. J. Stakutis, United States
22	Andrew Drummond, United States	94	Walter Mörikofer, Switzerland		K. H. Stewart, United Kingdom
	Mme. E. Fesenkova, Russia	102	Hans-Gerhard Müller, Germany	49	J. C. Thams, Switzerland
42	Sigmund Fritz, United States	24	David G. Murcray, United States		E. Theisen, (unknown)
	F. Froiland, United States	73	Robert J. Murgatroyd, United Kingdom	55	Peter Valko, Switzerland
100	P. R. Gast, United States	28	M. Neiberger, United States		D. O. Vickers, Nigeria
30	David M. Gates, United States		B. C. V. Oddie, United Kingdom	87	Ernest Vigroux, France
43	Warren L. Godson, Canada		A. Perlat, (unknown)	80	Jacques van Mieghem, Belgium
84	Kurt Gräfe, Germany		Perrin de Brichambaut, France	66	Hugo Wierzejewski, Switzerland
60	J. Vern Hales, United States	46	Kalpathi R. Ramanathan, India		H. Wörner, Germany
68	Hans Hinzpeter, Germany		W. T. Roach, United Kingdom	120	Giichi Yamamoto, Japan

REFERENCES

Bojkov, R. D., 2009: History of the international ozone commission. *Proc. Acad. Athens,* in press.

Bolle, H.-J., 2008: *International Radiation Commissions 1896 to 2008: Research into Atmospheric Radiation from IMO to IAMAS.* IAMAS Publication Series, Vol. 1, International Association of Meteorology and Atmospheric Sciences, iv + 141 pp.

Chubachi, S., 1984: A special ozone observation at Syowa station, Antarctica from February 1982 to January 1983. *Atmospheric Ozone,* C. S. Zerefos and A. Ghasi, Eds., Reidel, 285–289.

Crutzen, P. J., and F. Arnold, 1986: Nitric acid cloud formation in the cold Antarctic stratosphere: A major cause for the springtime "ozone hole." *Nature,* **324,** 651–655.

Farman, J. C., B. G. Gardiner, and J. D. Shanklin, 1985: Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interactions. *Nature,* **315,** 207–210.

Fröhlich, C., and J. London, Eds., 1986: Revised instruction manual on radiation instruments and measurements. WCRP Publication 7, WMO/TD 149, 140 pp.

Houghton, J. T., Ed., 1985: *The Global Climate.* Cambridge University Press, 256 pp.

ICSU-COSPAR, 1978: Toward an internationally coordinated Earth Radiation Budget Satellite observing system: Scientific uses and system considerations. Report to ICSU and to JOC for GARP, 76 pp.

IUGG-3, 1960: *Proceedings of the Symposium on Atmospheric Ozone. IUGG Monogr. 3,* International Union of Geodesy and Geophysics, 37 pp.

IUGG-4, 1960: *Proceedings of Symposium on Radiation. IUGG Monogr., 4,* International Union of Geodesy and Geophysics, 43 pp.

Joint Planning Staff for GARP, 1978: *Report of JOC Study Conference on Parameterization of Extended Cloudiness and Radiation for Climate Models.* ICSU/WMO, 146 pp.

Korsmo, F. L., 2007: The genesis of the International Geophysical Year. *Phys. Today,* **60,** 38–43.

Lenoble, J., Ed., 1985: *Radiative Transfer in Scattering and Absorbing Atmospheres: Standard Computational Procedures.* A. Deepak, 300 pp.

Molina, L. T., and M. J. Molina, 1987: Production of Cl_2O_2 from the self-reaction of the ClO radical. *J. Phys. Chem.,* **91,** 433–436.

Molina, M. J., and Rowland, F. S., 1974: Stratospheric sink for chlorofluoromethanes: Chlorine atom-catalyzed destruction of ozone. *Nature,* **249,** 810–812.

New York Times, 1961: Text of President Kennedy's address to the United Nations General Assembly, 26 September.

Phillips, N. A., 1995: Jule Gregory Charney: January 1, 1917–June 16, 1981. *Biographical Memoirs,* No. 66, National Academies Press, 81–113. [Available online at www.nap.edu/html/biomems/jcharney.html.]

Raschke, E., Ed., 1978: Terminology and units of radiation quantities and measurements. IAMAP Radiation Commission, 17 pp.

Solomon, S., R. R. Garcia, F. S. Rowland, and D. J. Wuebbles, 1986: On the depletion of Antarctic zone. *Nature,* **321,** 755.

Stolarski, R. S., and R. J. Cicerone, 1974: Stratospheric chlorine: Possible sink for ozone. *Can. J. Chem.,* **52,** 1610–1615.

Suttles, J. T., and G. Ohring, 1986: Surface radiation budget for climate applications. NASA Reference Publication 1169, 132 pp.

WCRP/IAMAP/IRC, 1986: A preliminary cloudless standard atmosphere for radiation computation. WCP 112, WMO/TD 24, 53 pp.

WMO, 1976: Annex 1. *Proc. WMO Executive Council 28th Session,* Geneva, Switzerland.

——, 1989: Report of the International Ozone Trends Panel: 1988. Global Ozone Research and Monitoring Project Rep. 18, Geneva, Switzerland.

——, 1990: Scientific Assessment of Stratospheric Ozone: 1989. Global Ozone Research and Monitoring Project Rep. 20, Geneva, Switzerland.

——, 1995: Scientific Assessment of Ozone Depletion: 1994. Global Ozone Research and Monitoring Project Rep. 37, Geneva, Switzerland.

——, 1999: Scientific Assessment of Ozone Depletion: 1998. Global Ozone Research and Monitoring Project Rep. 44, Geneva, Switzerland.