A Plan for Observation of the Antarctic Ozone Hole in 1991 under the Polar Patrol Balloon (PPB) Project

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ポーラー・パトロール・バルーンによる 1991 年のオゾンホール観測計画

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要旨: 第 32 次南極地域観測隊によって実施される三つのポーラー・パトロール・バルーン (PPB) 実験のうちの一つとして，昭和基地 (69°S, 40°E) から 1991 年 9 月に，南極オゾンホールとして知られる南極大陸上空のオゾン層の破壊現象を観測するための気球が放球される．オゾン，エアロゾル，温度のその場 (*in situ*) での観測を，南極大陸上空 50 hPa (約 18 km) を浮遊する気球の軌跡に沿って，約 10 日間行う．この観測の動機は以下の通りである: 極域成層圏雲 (PSCs) は冷たい極域下部成層圏で形成されるエアロゾルから成ること; 冬の後期あるいは春の初期のオゾンの減少 (南極オゾンホールの一側面) が，PSCs 表面で起こる不均一系化学反応過程によると考えられていること．オゾン減少は 50 hPa の高度で顕著であり，PPB はこの高度を浮遊して，ラグランジュ型の観測を行うことができる．従って，PPB によるオゾン観測は，オゾンの化学的ソース/シンクの大きさを，ほかの型の観測に比べてより直接的に測ることができるという利点を持つ．エアロゾル観測器は，エアロゾルの粒径分布を，0.4–10 μm の間を 7 分割して測るので，PSCs の微物理および化学についての詳細な情報を与える．データ取得および気球位置決定は ARGOS システムを使用して行う．ゼロプレッシャー気球の高度は，オートバラストシステムによってほぼ一定高度に維持される．

Abstract: Among the three Polar Patrol Balloon (PPB) experiments planned in the course of the 32nd Japanese Antarctic Research Expedition, one balloon will be launched from Syowa Station (69°S, 40°E) in September 1991 to observe depletion of the ozone layer over Antarctica —the so-called Antarctic ozone hole. *In situ* measurements will be made of ozone, aerosol, and temperature along the track of the balloon around the 50 hPa level (∼18 km) for about 10 days. The motivation for this exercise is as follows: Polar Stratospheric Clouds (PSCs) consist of aerosols which are formed in the cold polar lower stratosphere; the decrease of ozone in the Antarctic lower stratosphere in late winter and early spring, which is an aspect of the Antarctic ozone hole, is believed to be due to heterogeneous chemical processes occurring on the surface of PSCs. The PPB observation is a Lagrangian type observation, and it will be held around the 50 hPa level where the ozone decreases most. Consequently, the ozone concentration measurement has the advantage that it will be able to detect the *in situ* chemical budget of ozone more directly than other types of observation. The aerosol instrument measures aerosol concentrations in the diameter range of 0.4–10 micron meters, devided into 7 classes to give detailed information on the microphysics and chemistry of PSCs. Data acquisition and balloon positioning will utilize the ARGOS system.

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The almost constant altitude of the zero-pressure balloon will be regulated with the help of an auto-ballast system.

1. Introduction

The Polar Patrol Balloon (hereafter referred to as PPB) project is to execute a long duration circumpolar balloon experiment in the Antarctic using a zero-pressure balloon with an auto-ballast control to keep the balloon at an almost constant pressure level in the stratosphere. The PPB project aims at placing several moving stations at a balloon altitude during long periods (about 10–20 days) over the Antarctic region for geophysical and astrophysical observations. The concept and feasibility of the project has been reviewed by the Institute of Space and Astronautical Science (ISAS). The project was proposed by ISAS to the National Institute of Polar Research (NIPR) that is responsible for the annual Japanese Antarctic Research Expedition (JARE). Since 1984, NIPR, ISAS, and a nation-wide network of collaborating scientists have carried out the PPB program, and balloon technology for the long duration flights has been developed (NISHIMURA *et al.*, 1984; KODAMA and FUKUNISHI, 1984; NISHIMURA *et al.*, 1985; NAGATA *et al.*, 1985). Two test flights launched from Syowa Station (69°S, 40°E) were carried out by the 28th Japanese Antarctic Research Expedition (JARE-28) in 1987 (MIYAOKA *et al.*, 1988), and a test flight was carried out by JARE-30 in 1990 (KADOKURA *et al.*, 1991). These test flights carried out during two austral summers have convinced us that PPB will be a good tool for scientific observations (*e.g.*, EJIRI *et al.*, 1990).

On the basis of the foregoing developments described above, scientific observations using the PPB have been planned (FUJII *et al.*, 1989; EJIRI *et al.*, 1990). Three PPB experiments had been planned for JARE-32; one of these is devoted to observation of the Antarctic ozone hole, *i.e.*, *in situ* measurements of ozone, aerosol, and temperature around the 50 hPa (about 18 km) level. The present paper describes the plan of the ozone hole observation using the PPB scheduled for September 1991. Two earlier PPB flights, for auroral observations, were incorporated in JARE-32: Successfully carried out already in December 1990–January 1991, their results are being reported on elsewhere by other authors.

2. Participants of the Ozone Hole PPB Project

A team of eleven persons, including ourselves, is involved in the plan of the ozone hole PPB observation. Some are responsible for carrying out the experiment at Syowa Station, others will analyze the resulting data. The role division of the participants is as follows:

KANZAWA, Hiroshi (National Institute of Polar Research): Management of the ozone hole PPB experiment as a whole; Feasibility study of the PPB experiment from a meteorological perspective; Investigation of the significance of atmospheric dynamics.

KONDO, Yutaka (Solar-Terrestrial Environment Laboratory, Nagoya University): Management of the ozone hole PPB experiment as a whole; Development of the observational instruments for ozone and aerosol measurements; Investigation of the significance of atmospheric chemistry.

FUJII, Ryoichi (National Institute of Polar Research): Chief of the PPB experiment of JARE-32 at Syowa Station.

HAYASHI, Masahiko (Solar-Terrestrial Environment Laboratory, Nagoya University): Operation of the aerosol instrument at Syowa Station.

MURATA, Isao (Faculty of Science, University of Tokyo): Operation of the ozone instrument at Syowa Station.

IWASAKA, Yasunobu (Solar-Terrestrial Environment Laboratory, Nagoya University): Advice on the development of the aerosol instrument; Investigation of the significance of atmospheric chemistry.

MAKINO, Yukio (Meteorological Research Institute): Advice on the development of the ozone instrument; Investigation of the significance of atmospheric chemistry.

OGAWA, Toshihiro (Faculty of Science, University of Tokyo): Advice on the development of the ozone instrument; Investigation of the significance of atmospheric chemistry.

YAMANAKA, Manabu D. (Radio Atmospheric Science Center, Kyoto University): Feasibility study of the PPB experiment from a meteorological perspective; Investigation of the significance of atmospheric dynamics.

YAMAZAKI, Koji (Meteorological Research Institute): Investigation of the significance of atmospheric dynamics. Trajectory analysis of air parcels.

YAMANOUCHI, Takashi (National Institute of Polar Research): Feasibility study of the PPB experiment from a meteorological perspective; Management of other ozone-related observations of JARE-32.

The ozone hole PPB project has been planned and developed following discussions in the PPB Working Group (chair: N. YAJIMA, ISAS) under the auspices of the Advisory Board on the Japanese Antarctic Observation of Upper Atmosphere and Space Physics at NIPR, and on the basis of cooperation involving various people in addition to those described above, *e.g.*, members of the upper atmosphere physics group of NIPR, members of the balloon technology group of ISAS, and members of the atmospheric environment group of the Solar-Terrestrial Environment Laboratory of Nagoya University.

3. Purpose of the Experiment

3.1. Characterization of the PPB as a tool of observation

One of the advantages of observations on board PPB is that the PPB observation is a Lagrangian type observation, *i.e.*, an observation following the motion of an air parcel. The equation for the Lagrangian type observation is schematically written as follows:

Lagrangian (D/Dt):

$$D\chi/Dt = \text{chemical source/sink},$$

where χ is mixing ratio of species in the atmosphere (*e.g.*, ozone). This is contrary to the most commonly used method, which is Eulerian, *i.e.*, an observation at a fixed point:

Eulerian ($\partial/\partial t$):

$$\partial\chi/\partial t = \text{advection } (-v\nabla\chi) + \text{chemical source/sink.}$$

The Lagrangian type observation has the advantage that it can directly measure chemical source/sink of species (*e.g.*, ozone), since it measures time change of the species for the same air parcel ($D\chi/Dt$). The Eulerian type, in contrast, cannot directly measure chemical source/sink of the species, since it measures time change of the species at a fixed point ($\partial\chi/\partial t$): Usually the advection by atmospheric motion ($-v\nabla\chi$) makes the analysis of the chemical budget more complex.

In principle, PPB observation is a Lagrangian type observation. However, in practice, this need not to be the case. Ideally for the Lagrangian observation, PPB should be controlled to fly on a constant potential temperature surface since potential temperature is approximately conserved following air parcel motion for a time scale of about ten days. The real PPB, however, is regulated to fly not on a constant potential temperature surface but on a constant pressure surface. Moreover, the PPB, whose altitude is controlled by an auto-ballast system (see Section 4), does not necessarily fly on a constant pressure surface; rather, the altitude will vary in the order of a few km range during the overall flight (*e.g.*, KADOKURA *et al.*, 1991). In addition, there is small scale mixing of the species by turbulent motion whose time scale is too short for the PPB to appreciate. Analyses of the original PPB data will, however, with help of meteorological maps, give a Lagrangian type information.

3.2. Observation purpose

Generally it will be useful to use the PPB as a tool of Lagrangian observation. There are two reasons for this:

(a) Dynamical study: Observation of trajectories for transport.

(b) Chemical study: Observation of atmospheric minor constituents along the trajectories.

The period and the altitude level should be chosen depending on each special aim. The following are examples.

(a) The Antarctic lower stratosphere (around 15–20 km) where ozone depletion is strong in late winter or spring when the Antarctic ozone hole is developing, maturing, and breaking down. The period here can be divided into two parts, one is the period when the polar vortex which contributes to the conditions responsible for the ozone hole is stable, and the other is the period when the polar vortex breaks down and the dilution effect is strong.

(b) The other periods and other levels of altitude. Observations in this case reveal the characteristics of the undisturbed Antarctic stratosphere as background.

The trajectories of the PPBs, irrespective of the period and altitude, will provide useful information on the dynamics of the stratosphere (YAMANAKA *et al.*, 1988). What is the difference between the PPB trajectory and the trajectory calculated on the basis of wind data of synoptic scale (*e.g.*, objective analysis data of JMA, NMC, and ECMWF)? Does the trajectory show signs of gravity wave motion? What strong undulation does the trajectory show, and does the balloon move irreversibly toward a latitudinal direction rather than a circumpolar direction? These are some of the pertinent questions.

Formation of the Antarctic ozone hole is, at present, the most interesting problem for chemistry of the polar stratosphere. The existence of Polar Stratospheric Clouds (PSCs) is considered to be critical for the formation of the Antarctic ozone hole through heterogeneous chemical processes. However, the microphysics and chemistry of PSCs have not been well understood. Observation of the aerosol in the same air parcel will give important information on the mechanisms of the formation of PSCs. Observation of ozone using PPB provides information on chemical source/sink characteristics of ozone since PPB observation is a Lagrangian type observation as described above. If both aerosol and ozone instruments are mounted simultaneously on the PPB, a contribution will be made to clarifying the chemical relationship between ozone and aerosol (PSCs). Since reactive nitrogen and chlorine species are believed to control chemical loss of ozone, measurements of these species on board PPB should be considered in future.

For an overview of the state of the art in present day understanding of the Antarctic ozone hole, see, for example, WMO (1990), SOLOMON (1990), and KANZAWA (1991). In a previous work one of us has discussed the significance of the ozone hole PPB observation in terms of the global budget of minor constituents in the polar atmosphere (KANZAWA, 1989).

4. Observation Plan of JARE-32 in 1991

An ozone hole PPB observation of JARE-32 in 1991 was planned on the basis of the discussion in Section 3. The plan is summarized in Table 1. This section concretely describes Table 1.

4.1. *Outline of the experiment*

The PPB will be launched from Syowa Station (69°S, 40°E) in September when it is anticipated that the polar vortex is stable and the Antarctic ozone hole is developing. The balloon will be floated around the 50 hPa (about 18 km) altitude level where ozone concentration should decrease most when the Antarctic ozone hole develops. The lifetime of the balloon will be about 10 days; this will allow it to circulate twice or three times over Antarctica in September (YAMANAKA *et al.*, 1988).

4.2. *Balloon*

A zero-pressure balloon with auto-ballast control of the altitude level has been adopted for the PPB project since a super-pressure balloon (*e.g.*, OHTA and ITO, 1970) is not strong enough to carry heavy payloads (a few hundred kg) at high altitude levels in the stratosphere (NISHIMURA *et al.*, 1984). An auto-ballast system has been developed to keep the floating pressure level of the zero-pressure balloon almost constant (KOMA, 1984; OHTA, 1988). The total weight of the payload (300 kg; shown below) and the float level of the balloon (50 hPa) require the size of the balloon to be B_3 (about 3500 m^3). The weight of the balloon is about 45 kg.

4.3. *Observational items*

The horizontal position of the balloon is determined by positioning data using the ARGOS system (see Subsection 4.4). The vertical position of the balloon is determined by data from a pressure sensor (variable capacitance ceramic sensor).

Table 1. Summary of the plan for the ozone hole PPB observation by JARE-32 in 1991.

Outline of experiment
Site of the balloon launch: Syowa Station (69°S, 40°E)
Period of the PPB flight: September 1991
Level of the balloon: 50 hPa (~18 km)
Lifetime of the PPB: ~10 days
Balloon
Type: Zero-pressure balloon
Volume: B_3 (~3500 m^3)
Weight: ~45 kg
Observational items
Horizontal position of the balloon: ARGOS system
Vertical position of the balloon: Pressure (variable capacitance ceramic sensor)
Ozone concentration: Ultraviolet photometer (Dasibi type); ~12 W; ~28 kg (main body, ~10 kg; battery, ~18 kg)
Aerosol (PSCs) concentration: Counter of optical Mie scattering; Size distribution, 0.4 μm~10 μm (7 classes); ~22 W; ~42 kg (main body, ~14 kg; battery, ~28 kg)
Temperature: Thermistor thermometer
Data acquisition: ARGOS system
Positioning (horizontal): ~20 times a day; accuracy, 10–20 km
Other data: ~25–30 times a day (~10–15 min for 1 time) Data sampling using multi-ID ARGOS (6 IDs) and CPU: 4 min normal ARGOS (1 ID); real time telemetry, 1.6 GHz
Weight of the payload: ~300 kg (total)
Observation instruments (ozone and aerosol) with their battery: ~70 kg
Others (gondola frame, ARGOS transmitters, auto-ballast system, CPU, balloon accessories, etc.): ~80 kg
Ballast: ~150 kg

In situ observational items are ozone concentration, size distribution of aerosol (PSCs) concentration, and temperature. The instruments used in the observation are briefly described as follows:

(1) Ozone instrument (ultraviolet photometer): The ultraviolet photometer is an *in situ* instrument that determines ozone concentrations by measuring the absorption at the 253.65 nm mercury line near the ultraviolet ozone peak, *i.e.*, in the Hartley absorption band (*e.g.*, GRANT, 1989). Essentially, the instrument is a modified version of the Dasibi ozone monitor often used at ground level pollution monitoring stations. This instrument uses a mercury lamp as the spectral source, and a pump to pull air through the sample volume. For half of the measurement time, an ozone scrubber removes the ozone to provide an ozone-free reference air. This ozone instrument mounted on the PPB will work for about 10 days or longer. The electric power consumption of the instrument is about 12 W. Its weight without battery is about 10 kg, and the weight of the battery to operate it for about 10 days is about 18 kg including the battery box (the battery itself is 13 kg).

(2) Aerosol instrument (counter of optical Mie scattering): The aerosol instrument is an *in situ* instrument that determines size distribution of aerosol by measuring optical Mie scattering (*e.g.*, HOFMANN *et al.*, 1975; MORITA and TAKAGI, 1983). This

instrument uses a Tungsten lamp emitting 2850 K blackbody radiation as the light source, and a pump to pull air through the sample volume. Two photo-multiplier tubes (PMTs) detect light scattered by aerosols. The concentration of aerosol is measured from the number of the pulses detected by the PMTs. Size distribution (concentration for each size range) of aerosol is measured by using the fact that pulse intensity of the scattered light depends on the size of aerosol. The aerosol instrument measures size distribution for 7 classes in the range of 0.4–10 μm diameter. The aerosol instrument mounted on the PPB is designed to work for about 10 days or longer. The electric power consumption of the instrument is about 22 W. Its weight without battery is about 14 kg, and the weight of the battery for operating it about 10 days is about 28 kg including the battery box (the battery itself is 22 kg).

(3) Temperature: Ambient temperature is measured by a thermistor thermometer.

4.4. Data acquisition

We use the ARGOS system for data acquisition. The ARGOS system offers capabilities for the satellite-based location of fixed and moving platforms, and the collection of environmental data. The system comprises three distinct segments: fixed and mobile data collection platforms, carrying independently transmitting "platform transmitter terminals" (PTTs); two NOAA satellites which receive the messages transmitted by the PTTs and retransmit them to the ground; ground stations which recover and sort the data before sending them to the ARGOS data processing center for processing and distribution to users. Each platform carries a PTT to transmit encoded messages at regular intervals on 400 MHz. Messages transmitted by the various platforms within the range of satellite visibility (*i.e.*, 10–15 min) are selected for processing on a random access basis. Separation of messages is also performed by the satellite-borne instrument. Platform location can then be determined by computing the Doppler effect on the received frequency.

The frequency of the positioning data of PPB obtained through the ARGOS location system by the two NOAA satellites now in operation is about 20 times a day. The accuracy of the horizontal positioning is about 10–20 km.

The data from the instruments on board the PPB are received about 25–30 times a day by the two NOAA satellite through the ARGOS data collection system. The data acquisition system common to all the PPB experiments of JARE-32 using a CPU and multi-ID ARGOS (Ejiri *et al.*, 1990) was developed especially by R. Fujii: The CPU controls interfaces with sensors, stores input data into memories, processes the data, and sends them to the multi-ID ARGOS transmitter. The number of the ID for the ozone hole PPB experiment in 1991 is 6. The CPU data control and multi-ID (6 IDs) ARGOS systems enable us to obtain continuously large amounts of data: sampling time of the ozone and aerosol measurements is 4 min.

A normal ARGOS transmitter with only one ID, which transfers only 32 Byte (256 bit) of data per one encounter with a NOAA satellite, is also taken on board the PPB to send a minimum amount of data. To get a vertical profile of aerosol, ozone, and temperature, the data are also telemetered immediately to Syowa Station using a carrier frequency of 1.6 GHz radio wave when the balloon is within the range of the station just after the launch. Details of the data acquisition are described in Ejiri *et al.* (1990).

4.5. *Weight of the payload*

The total weight of the observational instruments of ozone and aerosol, each with their battery, is about 70 kg. The weight of other payloads including the gondola frame, the ARGOS transmitters, the auto-ballast system, the CPU data control system, balloon accessories, etc., is about 80 kg. Total weight of the whole gondola except for the ballast is, thus, about 150 kg. The period (about 10 days) for keeping the weight for observation (150 kg) at the level (50 hPa) requires a ballast weight of about 150 kg. Thus the total weight of the payload is about 300 kg.

4.6. *Decision-making of the period of launch*

The time window of the launch of the ozone hole PPB experiment is scheduled to be set at September 10$\pm$5 days. The PPB should fly inside of the polar vortex, that is, inside of the ozone hole to achieve our purpose. Consequently the PPB should be launched when Syowa Station is inside of the polar vortex. To decide the launch date of the PPB, and to watch the stratospheric meteorological fields under which the PPB flies, we will try to obtain the following two items of information on a real time scale: This will be done for a period from the beginning of September to the end of the PPB lifetime (perhaps the end of September), and the information will be taken from records relayed by facsimile via NIPR to Syowa Station. One item of information consists of objective analysis and forecast maps of geopotential height and temperature on a 50 hPa level of the southern hemisphere. This will be processed at the Japan Meteorological Agency (JMA) using the JMA objective analysis and forecast scheme. The other item consists of total ozone maps of the southern hemisphere. This will be obtained from Nimbus 7/TOMS (Total Ozone Mapping Spectrometer) data on a daily basis, processed at NASA/GSFC (Goddard Space Flight Center). Data of total ozone, ozone sonde, and aerological sonde at Syowa Station will be used to confirm the launch timing decided upon using the two global items of information.

5. Concluding Remarks

The main objective of the experiment is to investigate the heterogeneous processes which are believed to cause the Antarctic ozone hole. The magnitude of chemical source/sink of ozone can be evaluated directly by measuring ozone in a Lagrangian mode. Detailed processes of the growth and dissipation of PSCs are expected to be observed by measuring aerosol. In addition, the role of PSCs in the formation of the Antarctic ozone hole can be evaluated by measuring aerosol and ozone simultaneously. It is significant that the PPB measurements will be performed in both sunlit and dark regions since ultraviolet solar radiation is required for catalytic destruction of ozone by active chlorine produced through heterogeneous reactions. Observation of ozone and aerosol is but a first step which may be followed by measurements of reactive nitrogen and chlorine species, turbulence, and so on using the PPB. Thus the PPB experiment opens up an important approach to empirical study of interaction between chemistry and dynamics in the Antarctic stratosphere, where the formation of the Antarctic ozone hole is a typical example of a process requiring further study.

Pursuing this line of reseaech it is useful, especially from the viewpoint of dynamics and transport in the Antarctic stratosphere, to launch a large number of super-pressure balloons with light payloads (*e.g.*, only an ARGOS transmitter, and temperature and pressure sensors) from Syowa Station and/or other sites in the Antarctic, as for example has been done in the case of tropospheric meteorology in the southern hemisphere (*e.g.*, LALLY and LICHFIELD, 1969; MOREL and BANDEEN, 1973; THE TWERLE TEAM, 1977). Since the super-pressure balloon flies on a constant density surface without ballast, its lifetime is generally longer (say 3–6 months) than that of the PPB. This is an important fact to be taken into consideration.

HOLTZWORTH (1983) has successfully investigated the electrodynamics of the stratosphere using super-pressure balloons. Moreover, a French group is now planning to carry out "STRATEOLE" project (SADOURNY *et al.*, 1991), which is an extended version of the EOLE experiment in the troposphere (MOREL and BANDEEN, 1973). It is planned to start in 1993. In the "STRATEOLE" project, a large number of super-pressure balloons lifting from launch bases, such as Tierra de Fuego near 55°S, will fly at 50 hPa or 70 hPa with a lifetime expectancy of 3 months. The balloon will be able to carry a payload of 5 to 10 kg, and on its trajectory it will measure position, pressure, temperature, and column amount of aerosols, NO_2, and O_3 above the balloon level using a Total-Direct-Diffuse Radiometer.

Our PPB, which is able to carry a heavy payload, has the advantage of permitting us to carry out *in situ* observations. Both types of observation—using zero-pressure and super-pressure balloons—will contribute to understanding interaction between chemistry and dynamics in the Antarctic stratosphere.

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