Statistical analysis based on meteorological data factors related to ozone hole generation in Antarctica

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南極のオゾンホール発生に係わる気象データ因子に基づく統計的解析

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Abstract : Electric insulators and similar materials are often used in outdoor environments and exposed to ultraviolet rays. Electric cables are installed around Syowa Station in Antarctica as well. It is concerned that these cables may be affected by short wavelength ultraviolet rays due to the presence of ozone holes. Concerns are raised that ultraviolet rays may exert its influence not only in the polar areas but also in middle latitude areas. Using the observation data of the Japan Meteorological Agency and the National Institute for Environmental Studies, the authors conducted statistical analysis based on meteorological data factors of midair ozone concentration at Syowa Station. The concentrations of organic chlorine/bromine such as chlorofluorocarbons (CFCs) and halons in the Antarctic midair were shown to have the highest correlation with reduced ozone concentration. In addition, the ozone concentration in the Antarctic midair was also statistically confirmed to be correlated with midair temperature and the amount of solar radiation energy reaching the stratosphere. However, the ozone concentration in the midair at Syowa Station located inside the polar vortex was found to have no correlation with wind velocity in the midair. On the basis of the observation data, analysis was performed assuming multiple regression models. When statistical analysis was performed using three meteorological data factors such as the concentration of combined CFCs and halons, temperature, and solar radiation energy in the midair against the daily representative value of total amount of ozone in Antarctica, the adjusted coefficient of determination was 0.878, which is the highest correlation.

Keyword : ozone hole; Antarctica; Ultraviolet rays; chlorofluorocarbons; Statistical analysis; Syowa Station

1. Introduction

Since the 1980s, large-scale destruction of the ozone layer has occurred during October, which corresponds to spring in Antarctica's midair. The ozone hole phenomenon, which is a remarkable decrease in ozone concentration, is thought to be caused by special meteorological conditions of Antarctica and chlorine atoms released from chlorofluorocarbons (CFCs)[1)-3)]. The measures adopted under the Montreal Protocol aim to restore the ozone layer to that measured in 1980 by reducing the amounts of ozone-depleting substances in the atmosphere that are subject to regulations[4)]. In fact, the levels of chlorine- and bromine-containing compounds produced by decomposition of ozone-depleting substances have decreased in the stratosphere[4)]. Several numerical models have been employed to predict the effects of CFCs on the ozone layer[5)-6)]. However, the destruction of the ozone layer is thought to depend not only on the effects of regulations on CFCs but also on the strength of the polar vortex and the degree of sustained low temperature inside it.

The destruction of the ozone layer enables ultraviolet rays with short wavelengths to easily reach the ground. These rays damage important biological substances such as nucleic acid and have serious influence on human health such as increase in skin cancer and cataracts as well as immunosuppression. Moreover, various adverse effects may be extended to terrestrial and aquatic ecosystems. Electric insulators and similar materials are often used in outdoor environments and exposed to ultraviolet rays. Electric cables are installed around Syowa Station in Antarctica as well. It is concerned that these cables may be affected by short wavelength ultraviolet rays due to the presence of ozone holes. Concerns are raised that ultraviolet rays may exert its influence not only in the polar areas but also in middle latitude areas.

One of the authors (Tetsuya Takahashi) was a member of a Japanese Antarctic Research Expedition to study UV-cutting fibers in the Antarctica. This study used the data observed by the Japan Meteorological Agency and the National Institute for Environmental Studies to examine the relationship between meteorological data, such as airborne CFC concentration and air temperature, and the daily representative value of the total amount of ozone in Antarctica. Statistical analysis was performed on the meteorological data, and correlation coefficients for each factor were obtained. Some of the interesting findings are discussed in this paper.

2. Observation equipment

2.1 Observation of total ozone amount (observation by Japan Meteorological Agency)

The total amount of ozone near the ground surface to the upper end of the atmosphere was observed by using a Dobson ozone spectrophotometer (Beck Corp.). The total amount existing in the midair at Syowa Station was obtained and is expressed as the daily representative value of the total amount of ozone. All ozone existing in all layers from the upper to lower regions of the atmosphere was gathered near the ground surface as a unit. The volume was converted to 0°C and 1 atm; its thickness is expressed by m atm-cm. The daily representative value describes the observation value with the highest observation accuracy among all the observations made on a particular day[7)].

2.2 Upper-air observation with radiosonde (observation by Japan Meteorological Agency)

Atmospheric conditions including pressure, temperature, and humidity from the ground up to an altitude of about 30 km were obtained by using a radiosonde weather observatory instrument equipped with sensors measuring weather elements such as atmospheric pressure and temperature and a radio transmitter suspended from a rubber balloon for sending measurement information. Wind direction and wind velocity were measured by calculations based on data recorded by the balloon. The radiosonde observation data in this study were obtained at 09:00 Japan Standard Time (15:00 local time) from the midair at an atmospheric pressure of 70 hPa equivalent to 16,500–18,500 m in altitude[7)].

2.3 Observation of solar radiation in ultraviolet region classified by wavelength (observation by Japan Meteorological Agency)

Ultraviolet rays of different wavelengths were observed by using a Brewer spectrophotometer (SCI-TEC Brewer MKII Spectrophotometer) and were spectrally separated with a diffraction grating or similar instrument. The intensities of the respective wavelengths were measured by using a photomultiplier tube; the intensities of ultraviolet rays reaching the ground were determined on the basis of this information. The wavelength range measured was 290–325 nm, and the ultraviolet intensity in 0.5 nm wavelength intervals was measured every hour between sunrise and sunset[7].

3. Results and discussions

3.1 Interannual changes in ozone and CFCs concentrations in Antarctic midair

The ozone concentrations in Antarctic midair have changed since the discovery of the ozone hole in Antarctica more than 30 years ago; thus, the levels should be re-examined. Therefore, observation data of Japan Meteorological Agency were used to determine the daily representative value of the total amount of ozone in the midair over Syowa Station since 1974, as shown in Fig. 1.

In 1974 and 1977, this value was above 220 m atm-cm. In 1982, however, the daily representative value of the total amount of ozone decreased to 203 m atm-cm around October (Fig. 1). In 1984, the world's first report of a low value of total ozone amount was made by the group of Shigeru Chubachi, who participated in the Japanese Antarctic Research Expedition. This information was subsequently later observed by the Japan Meteorological Agency. In 1985, British Farman et al. announced a reduction in the total ozone value in Nature, and in 1986, Stolarski et al. of the National Aeronautics and Space Administration (NASA) confirmed the reduced ozone value in the Antarctica midair via satellite imagery. Soon afterward, a sudden decrease in ozone concentration in the Antarctic midair, termed "ozone hole," was reported worldwide.

In 1987, 2005, and 2014, the daily representative value of the total amount of ozone in the midair over Syowa Station was significantly lower than 220 m atm-cm during September and November, which is the spring season in Antarctica (Fig. 1). The CFCs in the Antarctic midair gradually decreased after peaking during the first half of the 1990s. Unfortunately, however, significant recovery of the ozone concentration could not be confirmed from the chart of the daily representative value of the total amount of ozone at Syowa Station shown in Fig. 1.

Figure 2 shows interannual changes in the concentrations of total organic chlorine (CCly) and that with 60 times the total organic bromine (CCly + 60CBry) in the Antarctic midair according to the data from Eiji Akiyoshi at the National Institute for Environmental Studies[8)-9)]. These data are accompanied by predicted values up to 2100 obtained by using a high-frequency automatic volatile organic compound (VOC) continuous measurement system developed independently by the National Institute for Environmental Studies. CCly includes concentrations such as CFCs, and CCly + 60CBry includes halons. The figure also shows the minimum values of the daily representative value of the total amount of ozone for each year based on data of the Japan Meteorological Agency recorded in the period from 1978 to 2014.

The concentrations of both CCly and CCly + 60CBry increased around 1978 when the observation began and peaked in the mid-1990s. Although these values slowly declined afterward, they are higher than the levels measured in 1978 at the start of the observation and those recorded in 2016. However, a smooth decline in CFCs is expected in the future such that by 2050, CCly and CCly + 60CBry will be reduced to about 1,500 pptv and 2,500 pptv, respectively. By 2100, further reductions of about

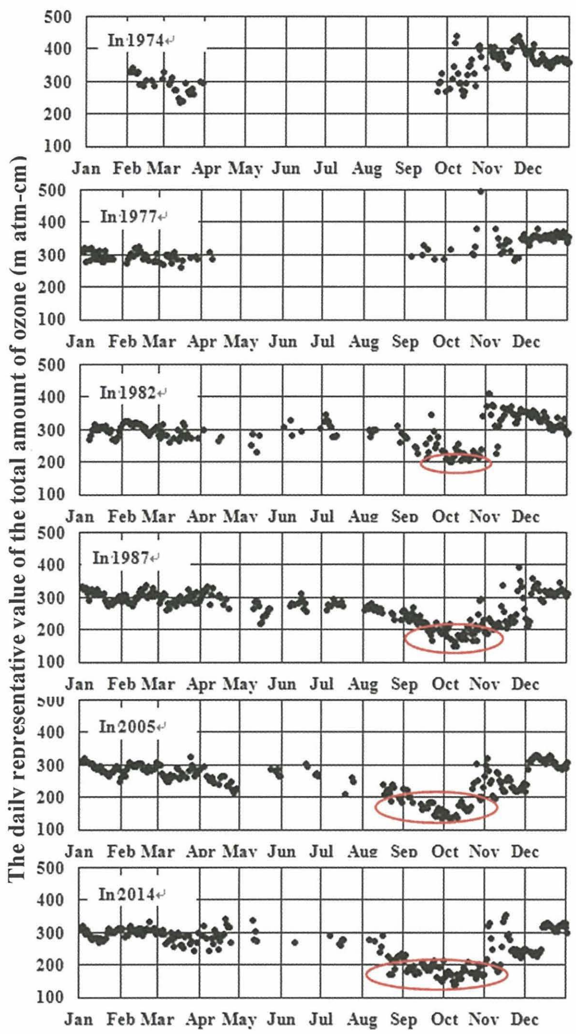

Fig. 1　Interannual changes in ozone concentration in the midair at Syowa Station.
Circled parts indicate the period during which the daily representative value of the total amount of ozone dropped to 220 m atm-cm or below.
図１　昭和基地上空のオゾン濃度の経年変化

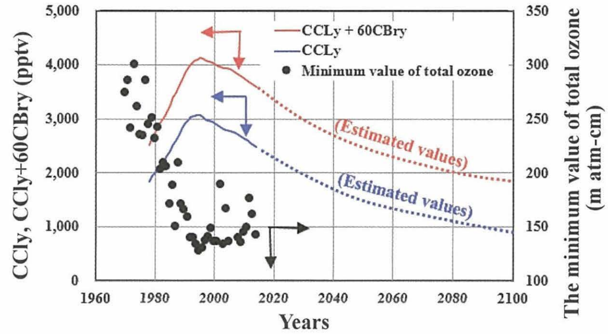

Fig. 2　Estimated values of CFC concentration (CCly, CCly + 60CBry) and the minimum daily representative value of the total amount of ozone for each year.
図２　フロンガス濃度の予測値（CCly, CCly + 60CBry）と、年毎のオゾン全量日代表値の最小値

1,000 pptv and 1,800 pptv in CCly and CCly + 60CBry, respectively, are expected.

On the contrary, the lowest daily representative value of the total amount of ozone measured annually, which was about 250–300 m atm-cm in the 1970s, declined rapidly and dropped sharply to about 130 m atm-cm after the 1990s. These changes correspond to increases in CCly as CFCs and in CCly + 60CBry as (CFCs + halons). That is, a sharp increase in CFC concentration in the midair led to significant decreases in the daily representative value of total amount of ozone.

Figure 3 shows the relationship between the lowest daily representative value of total amount of ozone of the year at Syowa Station and CFC and (CFCs + halons) concentrations in the midair. Figure 3, shows a linear relationship between CFCs and (CFCs + halons) concentrations and the daily representative value of the total amount of ozone; the relational expressions can be obtained from each straight line. That is, it was confirmed that both the concentrations of CCly and CCly + 60CBry in the midair are in good agreement with the ozone concentration in the midair.

3.2 Meteorological conditions affecting ozone concentration

As previously mentioned a decrease in the concentration of ozone in the Antarctic midair is largely related to the CFC concentration in the midair. However, because this ozone decomposition is a photochemical reaction[2], it may also correlate to the solar radiation energy reaching the stratosphere[2], which greatly depends on the sun altitude. Figure 4 shows the changes in solar altitude at noon at Syowa Station during one year. At this station, “polar night” occurs from the end of May until the middle of July, when the sun is not visible from the ground, and “white night,” when the sun does not set, occurs for about 60 days from around November 20 until around

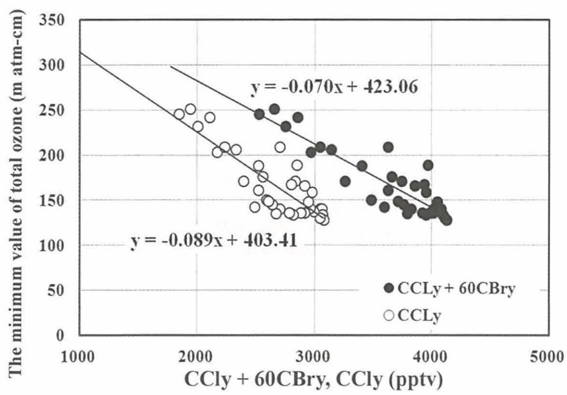

Fig. 3 Relationship between CFC concentration (CCly, CCly + 60CBry) and the minimum daily representative value of total amount of ozone for each year of 1978 – 2014.

図 3 フロンガス（CCly + 60CBry, CCly）濃度と、年毎のオゾン全量日代表値の最小値の関係（1978 年～2014 年）

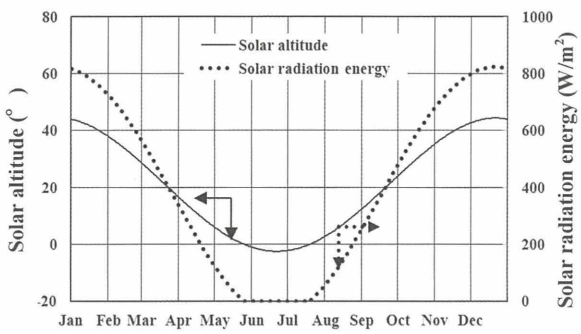

Fig. 4 One-year changes in solar altitude and solar radiation energy measured at noon at Syowa Station (69 00' 28"S , 39 34'13"E).

図 4 昭和基地における正午の太陽高度と太陽放射エネルギーの 1 年間の変化（南緯 69 度 00 分 22 秒，東経 39 度 35 分 24 秒）

January 20 the following year. On the contrary, the solar altitude reaches a peak of 20.1° around December 22, which is the summer solstice in the Southern Hemisphere.

The amount of solar radiation energy in the stratosphere from this solar altitude θ at noon was calculated by the following calculation formula assuming an average solar extraterrestrial solar radiation constant (J_0) of 1,366 W/m^2. These values are also shown in Fig. 4.

Solar radiation energy $J_D = J_0 \times \sin\theta$

When J_D is 0 or less, the value is set to 0.

The results show that even in the Antarctic midair, solar radiation energy reaches 400 W/m^2 in summer.

Figure 5 shows the relationship between solar radiation energy at noon and the daily representative value of the total amount of ozone. Here, the colors of the displayed marks varied monthly. In 1972, prior to identification of the ozone hole, the relationship between solar radiation energy and the daily representative value of the total amount of ozone was linear with some fluctuation. That is, a higher (lower) daily solar radiation energy relates to a higher (lower) daily representative value of the total amount of ozone. Conversely, after the ozone hole was discovered around 1982, clear differences began to appear in the data recorded in September–November from that recorded during the rest of the year, particularly in 1987 and 2014. Moreover, this relationship changed to resemble a counterclockwise circle with the passage of time during the year. Thus, between 1974 and 1987/2014, the relationship between solar radiation energy and the daily representative value of the total amount of ozone changed significantly.

During winter to spring in Antarctica, a strong west wind known as the polar vortex covers the Antarctic midair. Inside this vortex, the wind is relatively weak, the temperature is very low, and the exchange of air from the outside is minimal. In addition, the very low winter temperature of -78°C or below creates a polar stratospheric cloud (PSC), which is an aerosol composed mainly of nitric acid and ice. When sunlight is present in Antarctica in spring, Cl_2 and HOCl decompose to generate chlorine atoms, which destroy ozone. That is, the formerly inactivate chlorine compound is converted into an active form capable of breaking ozone in a chain-reaction manner. Therefore, it is conceivable that the destruction of the ozone layer is largely affected by air temperature and wind velocity in the midair. Therefore, this study investigates the relationship between ozone destruction and the temperature and wind velocity in

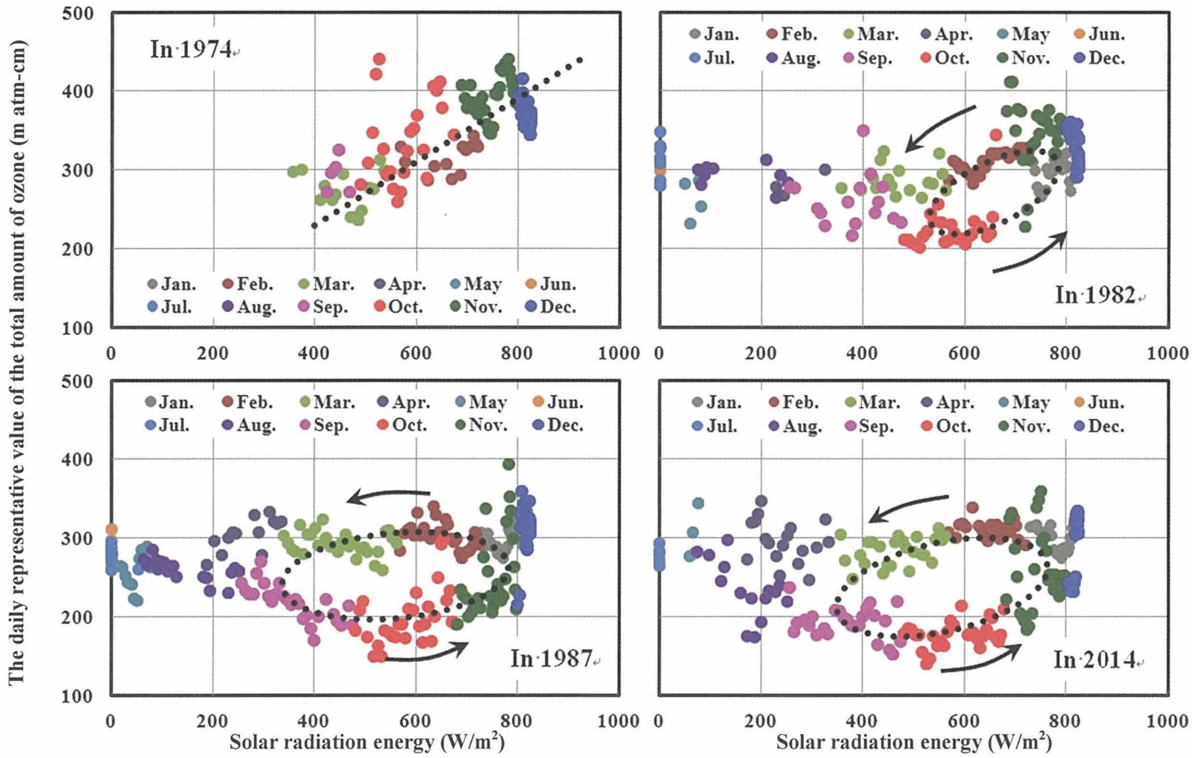

Fig. 5　Relationship between ozone concentration in the midair and solar radiation energy measured at noon at Showa Station for each year of 1974 – 2014

図５　昭和基地上空のオゾン濃度と正午の太陽放射エネルギーの関係（1974 年～2014 年）

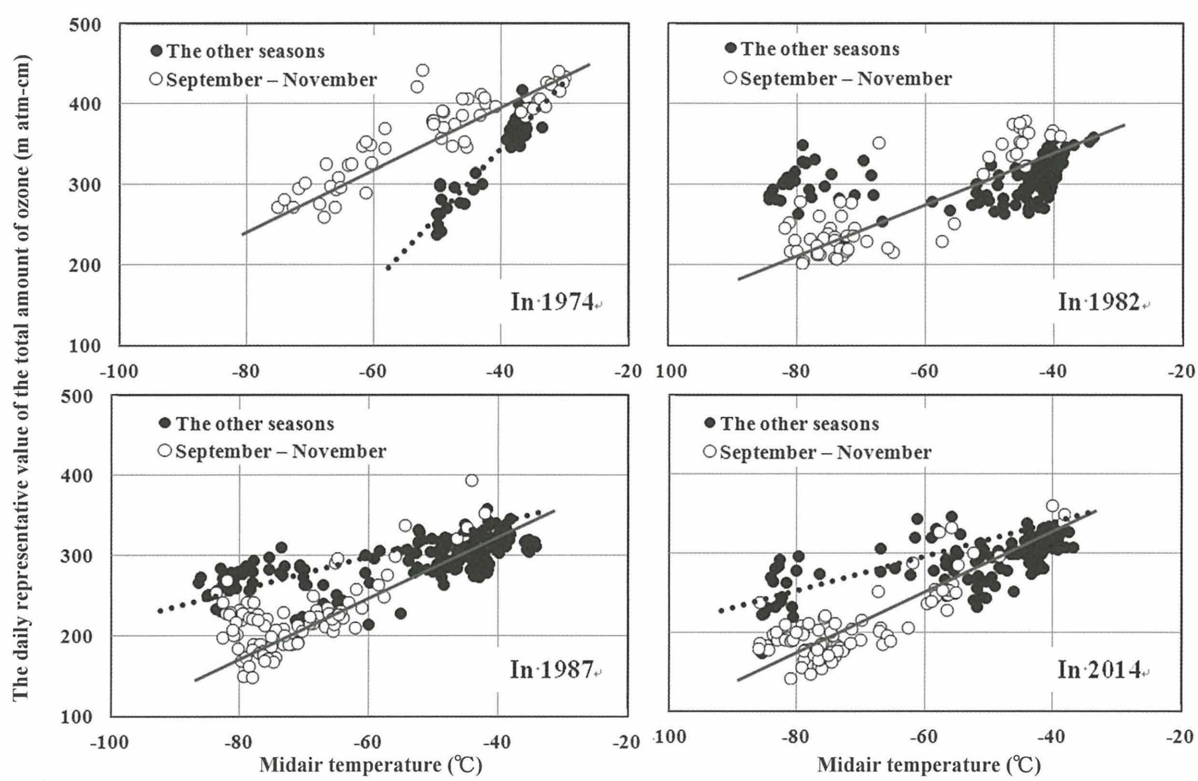

Fig. 6　Relationship between air temperature and ozone concentration in the midair at Syowa Station (70 hPa). Comparison of the season of ozone hole generation (September–November) and other seasons.

図６　昭和基地上空（70 hPa）の気温とオゾン濃度の関係，オゾンホール発生時期（９月～11 月）とそれ以外の時期の比較

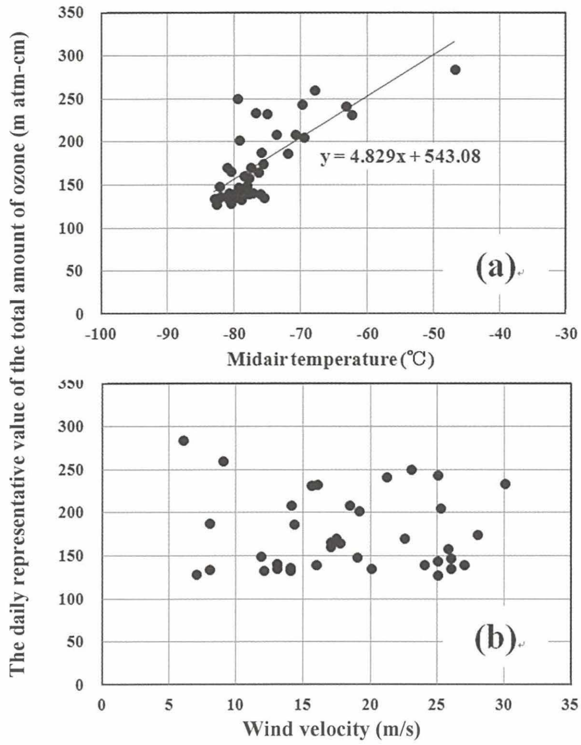

Fig. 7 Relationship between the minimum daily representative value of the total amount of ozone for each year and air temperature–wind velocity in the midair at Syowa Station (70 hPa) for each year of 1974 – 2014; (a) Air temperature; (b) wind velocity

図 7 年毎のオゾン全量日代表値の最小値と、昭和基地上空（70 hPa）の気温，風速の関係（1974 年～2014 年）；(a) 気温，(b) 風速

the midair observed by radiosonde.

Figure 6 shows the relationship between the temperature in the midair over Syowa Station and the daily representative value of the total amount of ozone. The data of the period from September to November are shown by open circles, and those of the period in which the ozone hole was not generated are shown by closed circles. The label “Air temperature in the midair” indicates the air temperature at about 70 hPa over Syowa Station, or the stratospheric temperature at about 16,500–18,500 m in altitude. The daily representative value of the total amount of ozone tended to become lower as the air temperature decreased. In 1987 and 2014, the daily representative value of the total amount of ozone revealed separate linear relationships between September–November and other seasons. That is, although the midair temperature was about the same, the daily representative value of the total amount of ozone was clearly lower in the September–November season.

As previously mentioned, polar stratospheric clouds promote ozone layer destruction. As the stratospheric temperature decreases, polar stratospheric clouds composed of fine particles tend to form. When the amount of solar radiation energy increases in the stratosphere of Antarctic midair in spring, the light causes the inactive chlorine molecules accumulated in winter melt to become active chlorine atoms, which is thought to act as a catalyst in destroying ozone layer[2)-3)]. Therefore, the relationship between the ozone concentration and the air temperature and wind velocity in the midair at Syowa Station was investigated (Fig. 7). For each year, the relationship between the value of the day with the lowest daily representative value of the total amount of ozone and the midair temperature of that day is shown in Fig. 7a. In addition, the relationship between the value of the day in which the daily representative value of the total amount of ozone became the lowest of the year and the midair wind velocity of that day is shown in Fig. 7b.

A clear correlation was revealed between the lowest daily representative value of the total amount of ozone and the midair temperature of that year (Fig. 7 a), i.e., as the midair temperature decreased, the minimum daily representative value of the total amount of ozone decreased. The relationship of these meteorological data is indicated by a straight line in Fig. 7a.

Initially, it was predicted that when the midair wind velocity is weak, the ozone hole likely occurs owing to the lack of air exchange the outside air. In addition, the flow of CFCs existing in the stratosphere is minimal, which encourages ozone hole formation. However, no correlation was found between the midair wind velocity over Syowa Station and the daily representative value of the total amount of ozone (Fig. 7b). This may have occurred because Syowa Station is located inside the polar vortex, where the daily representative value of the total amount of ozone is not dependent on wind velocity.

3.3 Statistical analysis of ozone concentration and arrival of short-wavelength ultraviolet rays on the ground

On the basis of the meteorological data discussed thus far, the relationship between the meteorological data factors and the daily representative value of the total amount of ozone was examined (Table 1). The following meteorological factors affect the daily representative value of the total amount of ozone: (1) CCly + 60CBry existing in the midair, (2) air temperature of that day, and (3) solar radiation energy present in the midair of that day. Thus, the relationship between these meteorological factors and the daily representative value of the total amount of ozone was analyzed. The observation data used in this statistical analysis cover the data of 1978 before the discovery of

Table 1　Relationship between CFC concentration and meteorological conditions in the midair at Syowa Station

表１　昭和基地上空のフロンガス濃度と気象条件の関係

Date in which the daily representative value of the total amount of ozone became the lowest	Minimum daily representative value of total amount of ozone for each year	CFC concentration of the day CCly + 60CBry (pptv)	Midair temperature (70hPa) of the day (°C)	Solar radiation energy of the day (W/m^2)
1978/10/15	245	2524	-69.8	147
1979/9/13	251	2654	-79.5	-108
1980/11/5	232	2751	-62.4	286
1981/11/13	242	2848	-63.3	327
1982/10/5	203	2961	-79.3	72
1983/10/18	209	3042	-73.7	169
1984/10/22	206	3139	-69.6	198
1985/10/10	171	3252	-77.5	110
1986/10/16	188	3398	-72	155
1987/10/8	150	3479	-78.2	95
1988/10/6	209	3625	-70.8	80
1989/9/30	171	3738	-81.1	35
1990/9/28	166	3851	-76.4	20
1991/9/30	159	3948	-77.9	35
1992/10/4	140	4013	-76.1	65
1993/10/11	140	4078	-77.9	118
1994/9/27	134	4094	-79	11
1995/10/6	128	4126	-82.7	80
1996/10/8	130	4110	-80.5	95
1997/10/12	137	4078	-82.2	125
1998/10/27	141	4061	-77.3	231
1999/10/10	148	4045	-79.4	110
2000/9/28	136	4013	-75.6	20
2001/9/30	136	3981	-79.6	35
2002/9/26	189	3964	-76	2
2003/10/6	134	3948	-80.9	80
2004/9/18	167	3932	-80.6	-67
2005/10/4	136	3916	-79.4	65
2008/10/16	140	3819	-80.1	155
2009/10/13	135	3786	-83	133
2010/10/6	145	3754	-79.1	80
2011/9/21	149	3706	-82.3	-41
2012/9/23	176	3657	-75.7	-24
2013/9/25	161	3625	-78.6	-6
2014/10/7	142	3592	-80.9	88

(Note) Ozone hole was identified after 1982

the ozone hole until 2014, which is close to the present.

On the basis of these metrological data, a statistical analysis of ozone concentration in the midair at Syowa Station was conducted assuming multiple regression models. First, analysis was conducted by using a simple regression model with each meteorological factor alone as an independent variable. As a result, the coefficient of determination was 0.797 when only CFCs (CCly + 60CBry) were used against the daily representative value of the total amount of ozone as a dependent variable. On the contrary, when the influence of the number of independent variables was removed and the apparent goodness of fit was subtracted, the adjusted coefficient of determination was 0.790. This value is clearly higher than that obtained when other meteorological factors were used. The simple regression model for this case is $Y = -0.070X_1 + 422.85$.

On the contrary, when only the midair temperature factor of that day was used as an independent variable against the daily representative value of the total amount of ozone, the coefficient of determination of the simple regression model was 0.528, and its adjusted coefficient of determination was 0.513. When only solar radiation energy was used as a factor, the coefficient of determination was 0.053, and its adjusted coefficient of determination was 0.025.

Analysis was then conducted on the basis of a multiple regression model in which two meteorological factors including CFCs (CCly + 60CBry) and air temperature of that day were used as independent variables against the daily representative value of the total amount of ozone. In this case, the coefficient of determination was 0.845, and its adjusted coefficient of determination was 0.836. This result means that the correlation obviously increased over that in which only CFCs was used as an independent variable. The multiple regression model in this case is $Y = -0.057X_1 + 2.066X_2 + 532.20$.

Additional multiple regression analysis was conducted by using three meteorological factors including CFCs (CCly + 60CBry), midair temperature of that day, and solar radiation energy of that day as independent variables against the daily representative value of the total amount of ozone. As a result, the coefficient of determination of the multiple regression model was 0.888, and its adjusted coefficient of determination was 0.878. This result means that the correlation further increased. In this case, the multiple regression model is $Y = -0.055X_1 + 3.346X_2 - 0.104X_3 + 632.40$. Because the adjusted coefficient of determination showed a high value of 0.878, it has been proved via statistical analysis that the three factors of CFCs concentration, midair temperature, and solar radiation energy have high correlation with the ozone concentrations in the Antarctic midair.

When the midair ozone layer is destroyed, short-wavelength ultraviolet rays can easily reach the ground. Therefore, the intensity of ultraviolet rays reaching the ground from January to December was examined for each wavelength. Figure 8 shows the data of 2014 as an example. In every wavelength of ultraviolet rays, a curve can be drawn in which the ultraviolet intensity shows the highest values in January or December in summer, and ultraviolet intensity shows the minimum values around June in midwinter. It should be noted that ultraviolet rays of 290–295 nm, which have shorter wavelengths, reached the ground in spring likely owing to the generation of

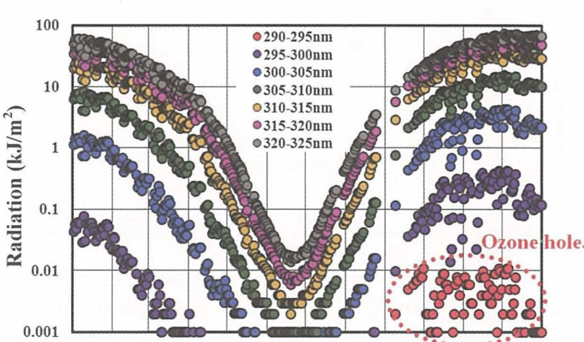

Fig. 8 One-year changes in ultraviolet ray amount for each wavelength that reached Syowa Station in 2014

図 8 2014 年に昭和基地に到達した波長別紫外線量の 1 年間の変化

the ozone hole. Even under the same solar altitude, short-wavelength ultraviolet rays of 290–295 nm did not reach the ground at all during February and April of autumn. The Meteorological Agency does not measure ultraviolet rays with wavelengths shorter than 290 nm. Therefore, during September and November, which is spring season, ultraviolet rays with wavelengths shorter than 290 nm could have reached the ground.

For each year, the relationship was examined between the daily representative value of the total amount of ozone on the day of lowest ozone level and the value of ultraviolet intensity with wavelengths of 290 –295 nm on the highest ozone day of with wavelengths of 290 –295 nm on the highest ozone day of that year. Figure 9 shows the results between 1993 and 2014. During years in which the ultraviolet intensity of short wavelengths increased, the daily representative value of the total amount of ozone was higher. That is, during years in which the midair ozone concentration showed lower values, the shorter-wavelength ultraviolet rays reached the ground without being absorbed by the stratosphere. These relationships can be indicated by an exponential approximation curve.

During 1993–2014, when the daily representative value of the total amount of ozone showed the lowest

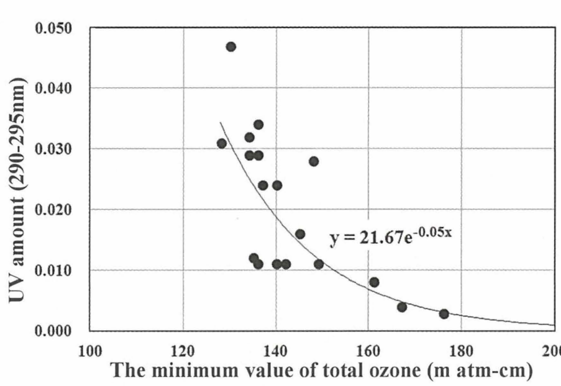

Fig. 9　Relationship between the maximum value of UV amount (290–295 nm) and the minimum daily representative value of the total amount of ozone for each year of 1993 – 2014

図９　年毎のUV量（290-295nm）の最大値と、オゾン全量日代表値の最小値の関係（1993年～2014年）

value of the year, the observation value, solar radiation energy, and ultraviolet intensity at wavelengths of 290–295 nm reaching the ground were summarized for that day. In addition, when the ultraviolet intensity at wavelengths of 290–295 nm reaching the ground showed the highest value in the year, the observation value, daily representative value of the total amount of ozone, and solar radiation energy were also summarized for that day. These results are shown in Table 2.

The days in which the short-wavelength ultraviolet intensity became the highest were delayed about one to two months from those in which the daily representative value of the total amount of ozone became the lowest. For example, in the case of 2014, the day in which the daily representative value of the total amount of ozone became the lowest was October 7, whereas that in which the short-wavelength ultraviolet intensity reaching the ground became the highest was December 4. That is, a time lag of 58 days occurred between the day in which the ozone concentration became the lowest and that in which the short-wavelength ultraviolet intensity became high.

Furthermore, the ozone concentration had already recovered by December 4, when the short-wavelength ultraviolet rays became the highest. This means that although the midair ozone concentration was already rising, the intensity of ultraviolet rays reaching the stratosphere increased as summer approached. As a result, the short-wavelength ultraviolet rays easily reached the ground 58 days after the ozone concentration became the lowest. In fact, as time elapsed from October 7 to December 4, the solar altitude increased, and the solar radiation energy reaching the stratosphere increased to 308 W/m^2. As a result, the ultraviolet intensity of 290–295 nm reaching the ground increased to 0.009 kJ/m^2. The same trends appeared during other years in which the ozone hole was present. That is, a time lag of about one to two months occurred between the day in which the ozone concentration became the lowest and that in

Table 2 Ozone concentration in the midair at Syowa Station and the amount of short-wavelength ultraviolet radiation reaching the ground

表 2 昭和基地上空のオゾン濃度と地上に届く短波長紫外線量

Year	Day, month*1)	Time-lag (days)*2)	Total ozone (m atm-cm)		Solar radiation energy reaching the stratosphere (W/m^2)		Amount of ultraviolet radiation reaching the ground (at 290-295nm) (kJ/m^2)	
			Minimum value of the year (Upper row)	Amount of change*2)	The value of the day	Amount of change*2)	Maximum value of the year (Lower row)	Amount of change*2)
1993	11-Oct 14-Nov	34	**140** (177)	+37	118 332	+214	(0.014) **0.024**	+0.010
1994	27-Sep 27-Oct	30	**134** (140)	+6	11 231	+220	(0.008) **0.032**	+0.024
1995	6-Oct 7-Dec	62	**128** (201)	+73	80 401	+321	(0.014) **0.032**	+0.018
1996	8-Oct 30-Oct	22	130 (131)	+1	95 250	+155	(0.012) **0.047**	+0.035
1997	12-Oct 23-Oct	11	**137** (152)	+15	125 205	+79	(0.020) **0.024**	+0.004
1999	10-Oct 11-Nov	32	**148** (169)	+21	110 317	+207	(0.007) **0.028**	+0.021
2000	28-Sep 16-Nov	49	**136** (189)	+53	20 341	+321	(0.010) **0.034**	+0.024
2001	30-Sep 20-Nov	51	**136** (174)	+38	35 357	+322	(0.001) **0.029**	+0.028
2003	6-Oct 19-Nov	44	**134** (219)	+85	80 176	+97	(0.001) **0.029**	+0.028
2005	4-Oct 4-Dec	61	**136** (324)	+188	65 396	+331	(0.002) **0.011**	+0.009
2008	16-Oct 3-Dec	48	**140** (207)	+67	155 394	+239	(0.006) **0.011**	+0.005
2009	13-Oct 13-Oct	0	**135** (135)	0	133 133	0	(0.012) **0.012**	0.000
2010	6-Oct 5-Dec	60	**145** (192)	+47	80 397	+317	(0.003) **0.016**	+0.013
2011	21-Sep 1-Nov	41	**149** (163)	+14	0 263	+263	(0.000) **0.011**	+0.011
2014	7-Oct 4-Dec	58	**142** (243)	+101	88 396	+308	(0.002) **0.011**	+0.009

*1) Upper row shows the date in which the daily representative value of the total amount of ozone became the lowest of the year. Lower row shows the date in which the amount of ultraviolet radiation (Wavelength: 290-295nm) reaching the ground became the maximum of the year.

*2) Elapsed time from the day in which the ozone concentration of the year became the lowest until that in which when the amount of short-wavelength ultraviolet rays (Wavelength: 290-295nm) reaching the ground became the maximum of the year (Value obtained by subtracting the value of upper row from that of lower row).

which short-wavelength ultraviolet rays likely reached the ground. This fact suggests that when ozone hole generation period drags on in spring, the ozone hole is exposed to the sun at high altitude in summer, which triggers an increase in the danger of short wavelength ultraviolet rays.

4. Conclusions

Using the observation data of the Japan Meteorological Agency and the National Institute for

Environmental Studies, the authors conducted statistical analysis based on meteorological data factors of midair ozone concentration at Syowa Station.

(1) The concentrations of organic chlorine/bromine such as chlorofluorocarbons (CFCs) and halons in the Antarctic midair were shown to have the highest correlation with reduced ozone concentration.

(2) The daily representative value of the total amount of ozone at Syowa Station correlated with the solar altitude such that greater amounts of solar radiation energy reaching the stratosphere related to lower ozone concentration. The midair ozone concentration at Syowa Station also correlated with the midair temperature. On the contrary, the midair ozone concentration at Syowa Station showed no correlation with the midair wind velocity.

(3) Statistical analysis was performed by assuming a multiple regression model based on metrological data. For the cases in which only CFCs (CCly + 60CBry) were used as a factor, CFCs and midair temperature were used as factors, and solar radiation energy was also added to the above as a factor, the adjusted coefficients of determination were 0.790, 0.836, and 0.878, respectively. That is, when three meteorological factors—midair CFCs concentrations, midair temperature, and solar radiation energy reaching the midair—were considered as factors, the highest correlation appeared. With this adjusted coefficient of determination of 0.836, considerably high correlation has been confirmed.

(4) In the 1980s, the phenomenon of low ozone concentration appeared during September and November. However, the day in which the highest levels of short-wavelength ultraviolet rays reached the ground was delayed by about one to two months. This fact suggests that although the ozone concentration became higher as summer approached, the intensity of short-wavelength ultraviolet rays reaching the ground increased because the solar radiation energy reaching the stratosphere increased.

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