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LODEWAVE
(Long-Duration Balloon Experiment of Gravity WAVE over Antarctica)

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Atmospheric gravity waves transport momentum in the atmosphere and play an important role in determining temperature and wind distributions through driving the meridional circulation in the middle atmosphere. However, they have wide spatial and temporal scales, which make it difficult to capture the whole feature of gravity waves with any of the latest observations and models. The first Mesosphere-Stratosphere-Troposphere (MST)/ Incoherent Scatter (IS) radar in the Antarctic, PANSY, which was installed at Syowa Station (69.0S, 39.6E) in 2011, can directly estimate the momentum flux of gravity waves in all frequency bands by observing 3-dimensional winds with high precision and high resolution. On the other hand, the super pressure (SP) balloon observation can also estimate momentum transport due to gravity waves in all frequency bands, and its horizontal distribution is also clarified. In order to carry out this SP balloon observation in the Antarctic where the observational constraint on the momentum transport due to gravity waves is especially insufficient, we proposed the LOng-Duration balloon Experiment of gravity WAVE over Antarctica (LODEWAVE). By combining it with the PANSY observation, observational constraints on the momentum transport due to gravity waves in climate models are acquired, which contributes to the improvement of the future prediction by the climate models.

Key Words: Antarctic, Super Pressure Balloon, Gravity Wave, PANSY Radar

1. Introduction

Atmospheric gravity waves are atmospheric waves with buoyancy as a restoring force. They drive a global meridional circulation by remotely transporting momentum, and play an important role in determining wind, temperature, and material distribution in the middle atmosphere. However, their spatial scales range from several kilometers to several thousand kilometers, and their time scales range from minutes to tens of hours. It is not easy to capture the entire processes of excitation, propagation, and dissipation of gravity waves, and to quantitatively evaluate and reproduce their roles in driving the meridional circulation in any of the latest observations and models.[1,2)] Therefore, it is essential to conduct high-resolution observations in both the spatial and temporal in order to quantitatively examine the effects of gravity waves. It is also important to examine the intermittency of gravity waves. It has been found that gravity waves have intermittency due to the source and the fluctuation of background winds on the propagation path. Even if the time or spatial average of momentum flux is the same, the driving force of the meridional circulation caused by gravity waves with high/low intermittency is induced at lower/higher altitudes.[3)] Therefore, it is necessary to consider not only the average picture of the amplitude and momentum flux of gravity waves but also its spatial and temporal non-uniformity.

Recent climate models with high spatial and temporal resolutions can explicitly express long-period and long-wavelength gravity waves to some extent. On the other hand, the effect of momentum transport due to gravity waves on a scale smaller than the horizontal resolution of the model has been taken into account by gravity wave drag parameterization, which assumes theoretical and empirical sources of gravity waves in the model and considers only their vertical propagation. However, there are large differences between models in the Antarctic region where there is a particular lack of observations to impose constraints on gravity wave parameters.[4)] In addition, studies using high-resolution models have indicated that gravity waves represented explicitly in the model propagate horizontally over long distances.[5)] The assumption of vertical propagation alone used in many gravity wave drag parameterizations is considered to be one of the causes of the cold temperature bias in the winter polar stratosphere and the uncertainty in the prediction of ozone depletion.[6,7] It suggests that the future prediction of climate models cannot solve the above-mentioned problems unless the effects of gravity waves including horizontal propagation are properly incorporated into the model.

Thus, quantitative understanding of the role of gravity waves in the formation of meteorological fields in the middle atmosphere and improving the expression of gravity wave effects in the model are important issues for improving the accuracy of future predictions by the model. It is necessary to carry out observations that cover all the wide wavelength bands and period bands of gravity waves and capture the temporal and spatial non-uniformity of momentum flux due to gravity waves. As observational techniques that cover all the period bands of gravity waves and can estimate their momentum flux, there are observations of three-dimensional wind velocity by a large atmospheric radar and observations of atmospheric pressure and two-dimensional wind velocity by a super pressure (SP) balloon that floats on a constant density surface for a long time.

During the 1980's and 90's, observations by large atmospheric radars located mainly in mid-latitudes revealed that momentum transport due to gravity waves played an important role in determining wind velocity and driving the meridional circulation in the mesosphere and lower stratosphere.[8,9] In addition, a group including the authors (PI: Kaoru Sato) installed the PANSY (Program of the Antarctic Syowa MST/IS radar) radar, which is the first and only large atmospheric radar over Antarctica. They are conducting continuous observations of gravity waves in the troposphere, stratosphere, and mesosphere over Antarctica.[10] Analyses of radiosonde observation data at several Antarctic stations confirmed that the characteristics of gravity waves over Syowa Station (69.0S, 39.6E) are highly representative of gravity waves over Antarctica.[11] Based on the long-term continuous observation data of PANSY radar, the frequency spectrum of gravity waves in the Antarctic troposphere and lower stratosphere and the altitude dependence and seasonal dependence of intermittency were clarified for the first time.[12]

Since the SP balloon flies on a constant density surface for more than one month, it is possible not only to observe the momentum transport due to gravity waves in the entire period band, but also to capture their horizontal distribution (i.e., note that it is not a snapshot). In the Antarctic region, two campaigns using SP balloons were carried out by an international joint research group led by France in 2005 and 2010.[13,14] Not only was the spatial distribution of gravity waves in the lower stratosphere clarified, but also their momentum flux was shown to have large intermittency depending on the location.[3,15] However, these observations were difficult to carry out continuously due to technical and budgetary reasons. In addition, the PANSY radar observation which captures the same height region in a Eulerian frame has not yet been conducted at that time.

The PANSY radar can obtain the time and altitude profiles of gravity waves above Syowa Station, while the SP balloon observation can obtain the horizontal distributions of gravity waves at a single altitude. These are only independent data without combining them. On the other hand, the latest meteorological reanalysis data can qualitatively represent the horizontal distribution of momentum flux due to long-period and long-wavelength gravity waves.[16] In addition, it is known that the gravity wave spectra theoretically follow the power law.[17] So it is possible to estimate the three-dimensional distribution of momentum transport due to gravity waves in the Antarctic troposphere and lower stratosphere by quantitatively constraining the gravity wave spectra based on the PANSY radar and SP balloon data and by assuming their horizontal and vertical distributions based on the meteorological reanalysis, PANSY radar, and SP balloon data. Thus, we designed the super pressure balloon observation project of atmospheric gravity waves in the Antarctic region (LOng-Duration balloon Experiment of gravity WAVE over Antarctica: LODEWAVE). The required accuracy of the observed quantities necessary to capture gravity waves in the whole period band and estimate their momentum fluxes is described in Section 2. Section 3 gives details of the observation at Syowa Station. Section 4 briefly describes a specification of SP balloon to be used. Section 5 describes details of the on-board equipment. Section 6 gives the balloon release condition at Syowa Station and monitoring system. Section 7 gives the conclusion. This article is partly based on a study[18] first reported in the JAXA Research and Development Report in Japanese.

2. Required Measurement Accuracy

In this SP balloon observation, temperature, horizontal wind velocity and atmospheric pressure are measured at 30 second intervals to derive momentum flux and amplitude of horizontal wind disturbance in the whole period band of gravity waves (about 5 minutes to more than 10 hours) in the lower stratosphere of the Antarctic region. These are basically the same as the physical quantities obtained by meteorological radiosonde observation (except for the absence of relative humidity). On the other hand, this observation differs greatly from the radiosonde observation in that gravity waves can be observed in a Lagrangian frame because the balloon is floating on a constant density surface. It enables estimate of the momentum flux due to gravity waves. In the actual analysis, wavelet transform is applied to the time series data of horizontal wind and pressure, and for each frequency component obtained, the momentum flux is estimated using the dispersion relation of gravity waves.[19] The measurement accuracy required for each physical quantity is as follows.

2.1. Horizontal wind

The PANSY radar, which performs cooperative observation, has a measurement accuracy of 0.1 ms^{-1} for line-of-sight wind velocity and 0.5 ms^{-1} for horizontal wind velocity.[10] To detect all the gravity waves captured by the PANSY radar, our SP balloon observation requires a measurement accuracy equal to or higher than that of the PANSY radar. In SP balloon observation, the horizontal wind velocity is derived from the difference in the position information of the balloon obtained by GPS every 30 seconds on the assumption that the balloon is drifted by the in-situ wind. Assuming that the horizontal position accuracy of GPS is σ_h (m), the estimated accuracy of horizontal wind velocity σ_w (ms^{-1}) is $\sigma_w = \sqrt{2}\sigma_h/30$. Therefore, the required horizontal position accuracy is about 10 m.

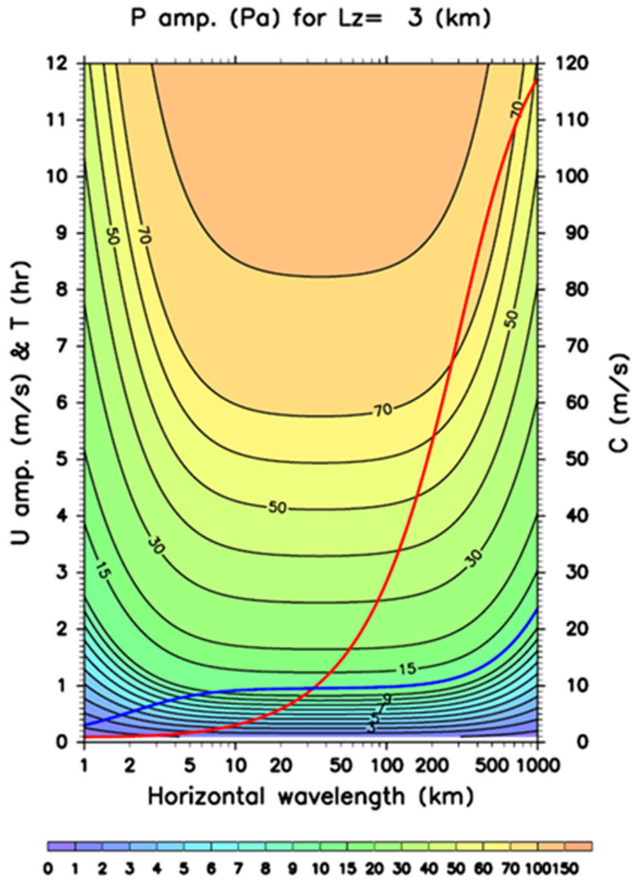

Fig. 1. Pressure amplitude (Pa) of gravity wave as a function of horizontal wavelength and horizontal wind amplitude, assuming a vertical wavelength of 3 km and a pressure level of around 60 hPa. Red and blue lines represent intrinsic period (hr) and intrinsic phase velocity (ms^{-1}) of gravity wave, respectively.

2.2. Temperature

In estimating the momentum flux of gravity waves, temperature data is used only for estimating the background density obtained by removing the gravity wave component with a low-pass filter, so the required accuracy is not high. On the other hand, when estimating the potential energy of gravity waves, it is necessary to have an accuracy of about 0.3 K to obtain an accuracy equivalent to the kinetic energy estimated from the horizontal wind velocity disturbance. In the lower stratosphere of Antarctica, temperatures may fall to -70 ℃ in summer and -90 ℃ in winter, so it is necessary to be able to measure temperatures in the range of -90 to 40 ℃.

2.3. Pressure

Pressure measurement is required to estimate the momentum flux due to gravity waves.[19] Figure 1 shows the amplitude of the gravity wave pressure disturbance observed by the SP balloon around 60 hPa pressure level as a function of the horizontal wavelength and the amplitude of the horizontal wind disturbance.[19] Since the required accuracy of horizontal wind velocity in this observation is 0.5 ms^{-1}, assuming a horizontal wind amplitude of 1.5 ms^{-1}, which is about three times that, the corresponding pressure amplitude is about 15 Pa. In other words, if the measurement accuracy is about 5 Pa, the momentum flux due to the gravity wave detectable by the PANSY radar can be obtained by the SP balloon observation.

3. Flight Level, Season, and Location of Observation

Studies using the PANSY radar have reported that in the stratosphere over Syowa Station in the austral summer, upward-propagating (i.e., group velocity is upward) gravity waves excited by topography, meteorological disturbances in the troposphere, jet streams near the tropopause, etc. are predominant.[20] Therefore, it is expected that the characteristics of gravity waves which are responsible for momentum transport to the Antarctic stratosphere and mesosphere in austral summer are captured by the observation at one height in the stratosphere to some extent. On the other hand, for the coordination of PANSY radar and SP balloon observation, the SP balloon observation needs to be performed below 20 km, since gravity waves in the troposphere and stratosphere are observed by PANSY radar at altitudes up to about 20 km. In addition, from the viewpoint of aviation safety, observations at altitudes of 18 km (60,000 ft) or higher are not restricted by the Civil Aeronautics Act. In the past SP balloon observation of gravity waves (i.e., Vorcore/Concordiasi campaigns conducted in 2005/2010),[13,14] observations at altitudes of 19 km were conducted because of the latter reason. Therefore, it is desirable to conduct observations at altitudes of 19 km for comparison of the results. Furthermore, at Syowa Station in the Antarctic, the surface weather conditions during summer are good and sufficient number of workers can be secured. For these reasons, SP balloon observation will be conducted at altitudes of 19 km during the austral summer season (from January to February).

In order to obtain the horizontal distribution of the momentum flux due to gravity waves, it is desirable to carry out as many SP balloon observations as possible so that the Antarctic region can be widely covered. However, due to the constraints of the budget and the period for balloon launch, three SP balloon observations was carried out in January-February 2022.

4. Super Pressure (SP) Balloon

In this project, a SP balloon with a volume of 180 m^3, pressure resistance of 1200 Pa or more, and low gas permeability is used to suspend a payload of up to 3 kg at an altitude of 18-19 km for 10 days or more. Since it flies along the constant density surface, it is possible to observe the movement of the air mass in situ (i.e., Lagrangian). The specifications of the SP balloon required to realize this project are as follows.

1) Since the difference between day and night gas temperature is assumed to be about 10%, the absolute pressure of gas inside the balloon during the day is expected to be 600 Pa higher than that at night at an atmospheric pressure level of 60 hPa. So the SP balloon should have a pressure resistance of 1200 Pa, which is twice as high as the differential

pressure.

2) As a result of trajectory analysis in austral summer (see Fig. 5), the SP balloon is considered to remain in the polar region (i.e., south of 60S) for about 10 days. So low gas permeability to keep a positive differential pressure for 10 days (= 240 hr) or more is required.
3) It has weight / volume ratio which can reach the altitude of 19 km with 3 kg payload.
4) The experiment can be terminated by quickly destroying the balloon upon request.
5) The degradation of material strength is sufficiently small in the ultraviolet irradiation environment for 10 days.

SP balloons have been developed mainly in France, the United States and Japan by the Institute of Space and Astronautical Science (hereafter referred to as ISAS) since the second half of the 1990's. Although the SP balloons have not been put into practical use in Japan, we have succeeded in its developing by making the following two technical improvements. By covering a polyethylene film balloon with a vectran net, the pressure resistance performance has been improved,[21] and by adopting a double-layered structure in which a rubber balloon is placed inside a polyethylene film balloon, the gas permeability performance has been improved,[22,23] making it possible to produce a small SP balloon for use in this project (Fig. 2).

Fig. 2. Super pressure balloon in full inflation.

5. Gondola

The balloon equipment used in this project is suspended on the SP balloon. It collects the three-dimensional position information and in-situ pressure and temperature every 30 seconds and transfers the data through the Iridium satellite once every 7.5 or 10 minutes. It also receives commands from ground operators through the Iridium satellite and destroys the balloon and turns the heater ON/OFF. The total weight of the equipment is 2.70 kg, and the system is designed with the policy to mitigate the aviation safety constraint by making a system which can be handled as a light balloon according to the rule of ICAO (International Civil Aviation Organization). The environmental temperature is assumed to be -90 to 40 °C and the atmospheric pressure is assumed to be 50 to 1100 hPa. The outline is shown below.

5.1. Data collection and processing system

The system consists of a baseboard that communicates with a data acquisition and processing board (hereafter referred to as an option board) equipped with a CPU. The latter is a newly developed board that uses RS232C serial communication for signals from a GPS receiver, SPI serial communication for output from pressure and temperature sensors. The CPU generates telemetry packets every 7.5 minutes and transmits them to the baseboard through RS232C serial communication. The baseboard uses hardware developed by the ISAS Scientific Balloon Group (hereafter referred to as the ISAS Balloon Group) for communication with the Iridium satellite [24] and newly developed firmware. This board enables the Iridium short burst communication by using the SBD9602N chip. When a packet is received on this board, data is transmitted through the Iridium satellite and can be received as an e-mail on the ground. Conversely, it is also possible to send a command from the ground by sending an e-mail to the corresponding address. The e-mail received on the baseboard is sent to the option board, which interprets the command and performs ON/OFF control of the heater and balloon destruction. The circuit for balloon destruction, which is based on the circuit developed by the ISAS Balloon Group, is equipped with two independent systems. One is driven by the above command, and the other is a timer cutter which can be reset by a command. The power consumption of the whole system is 0.9 W, and the power is supplied by the primary battery. The temperature of the baseboard, option board and battery is measured by using thermistors. The minimum operating temperature of the system is -40 °C, and a heater is provided to prevent low temperature.

5.2. Sensor system

5.2.1. Barometers

As shown in Section 2.3, the atmospheric pressure measurement in this observation requires absolute accuracy of 5 Pa at 19 km (atmospheric pressure of 65 hPa). We are using the MEMS small atmospheric pressure sensor (XPA2326-0311A-R made by Murata Manufacturing Co., Ltd.) used by Meisei Electric Co., Ltd. for radiosonde. This is an on-board chip using MEMS technology. When the performance at 65 hPa was evaluated, it was confirmed that the accuracy of about 4 Pa could be achieved by over-sampling and average operation of three sensors. Although there were problems such as the need for calibration of individual sensors and the temperature dependence required for calibration, the required accuracy can be achieved with these sensors by performing the necessary calibration.

5.2.2. Thermometers

As indicated in Section 2.2, the required specification for temperature observation is to measure temperatures in the range of -90 to 40 °C with an absolute accuracy of 0.3 K. This accuracy can be achieved by over-sampling with temperature sensors on commercial radiosondes and averaging for 30 seconds. We use temperature sensors (glass-chip thermistors) and readout circuits (resistance-to-frequency converters) for radiosondes. To prevent heat from the gondola, the sensor is suspended 1 m below the gondola.

5.2.3. GPS receiver / antenna

As shown in Section 2.1, the required accuracy for horizontal wind observation is a horizontal position accuracy of 10 m. We use an antenna integrated chip (GSU-121B made by Position Co., Ltd.) and a GPS-based receiver that has been used for radiosondes, because they have a horizontal position accuracy of 7.5 m.

5.3. Transmit / Receive system

We use the communication board with the Iridium satellite (SBD-BASE-2011 made by Embedded Technology Co., Ltd.) developed by the ISAS Balloon Group and the newly developed firmware. Data measurement is performed once every 30 seconds. It is possible to transmit 340 bytes of Iridium short burst data in one transmission. The command is received at the time of data transmission every 7.5 or 10 minutes, which includes permission and execution of balloon destruction, heater ON/OFF, etc.

5.4. Mechanical design

The equipment is exposed to a low temperature environment of -90 ℃. It is designed to keep the temperature of the gondola at -40 ℃ or higher. As a result, the structure is formed of styrene foam having a thickness of 35 mm. Figure 3 shows the whole arrangement. Boards are placed on 11 batteries (BCX85 made by ElectroChem Co., Ltd.). The size is 285 mm x 140 mm x 210 mm, and the current mass is 2700 g.

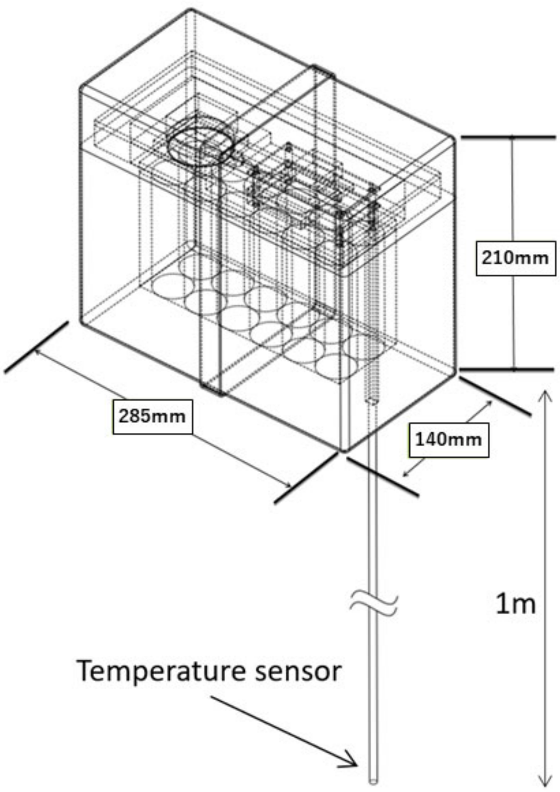

Fig. 3. Overview of balloon-borne instrument. Cylinders inside are batteries. The housing consists of an upper lid and a lower body.

5.5. Thermal design

The trade-off of the surface material of the gondola was examined from the viewpoint of the thermo-optic characteristics as shown in Table 1. The case (lid) is covered by weatherproof coating (white) because aluminum-metallized film cannot be used due to transmission/reception of GPS and Iridium radio wave. Aluminum-metallized film is attached to the inner wall of the battery compartment to suppress heat radiation. Table 1 shows estimate of heat budget of the gondola for different coating methods of side walls. In case that the side walls are coated by aluminum-metalized film on one side, both of infrared radiation from the side walls and absorption of solar radiation at the side walls are adequately suppressed. This result suggests that the coating of side walls by aluminum-metallized film on one side is suitable for summer operation.

Since the observation period (i.e., January-February) corresponds to a white night, the power consumption was examined under the assumption that the heater is turned on / off so that the temperature inside the gondola becomes -40 ℃ or higher. The heat release from the gondola is mainly by radiation rather than by thermal convection at 60 hPa. It was found that the heater is unnecessary under the white night and the operation for 52 days is possible. On the other hand, the heater is required under the polar night in winter, which will reduce the possible operation duration.

Table 1. Estimate of thermal characteristics of the gondola.

Coating of side walls	weatherproof coating (white)	Aluminum-metallized film on two sides	Aluminum-metallized film on one side
Solar absorption rate (α)	0.2	0.11	0.35
Infrared emissivity (ε_H)	0.8	0.05	0.65
α/ε_H	0.25	2.2	0.54
Evaluation	Since ε_H is large, heat radiation is excessive regardless of sunlight condition.	Since ε_H is small, heat radiation can be suppressed. Temperature becomes high under solar radiation because of $\alpha > \varepsilon_H$. ⇒ Suitable under the polar night	Since ε_H is small compared to weatherproof coating, heat radiation can be suppressed. Since $\alpha < \varepsilon_H$, temperature rise can be suppressed under solar radiation. ⇒ Suitable except for the polar night

6. Preparation for Launch

6.1. Surface wind condition for balloon launch

Figure 4 shows the probability of the surface wind speed being 3 ms^{-1} or less as a function of month and local time at Syowa Station during April 2016 to March 2019. The probability in the local afternoon in January is more than 50%, indicating that the summer afternoon is in a suitable condition for balloon launch.

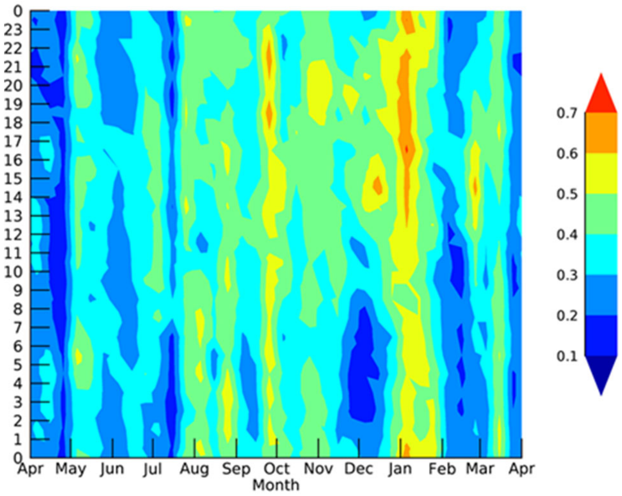

Fig. 4. Probability of the surface wind speed being 3 ms^{-1} or less as a function of month and local time at Syowa Station during April 2016 to March 2019.

6.2. SP balloon trajectory

To predict the forward trajectory of a SP balloon, a forward trajectory program on a constant density surface was developed by modifying the NITRAM model of the National Institute of Polar Research.[25] A trajectory calculation in January 2019 was carried out using meteorological reanalysis data[26] (Fig. 5). Although it is in austral summer, the lower stratosphere over Antarctica is basically covered by the westerly wind, and the air mass is advected eastward over Antarctica. However, since it is not a stable strong westerly wind like the polar-night jet in winter, it can be seen that air masses often leave Antarctica and fly over South America. In order to secure aviation safety, we have discussed with the Air Operations Expert Group of COMNAP (Council of Managers of National Antarctic Programs), and decided to terminate the observation before the balloon reached a latitude north of 60S.

6.3. SPB watch system

Observation data such as temperature, pressure and GPS position measured by the SP balloon on-board equipment is transmitted as an attachment file to a specified e-mail address through the Iridium short burst data service. When the termination condition of the SP balloon observation is satisfied (i.e., the SP balloon goes north of 60S, the battery is exhausted, etc.), a cutter command must be immediately sent to the balloon. Therefore, it is necessary to monitor the balloon position and housekeeping data of the SP balloon on a 24-hour basis. For this purpose, a Quick Look (QL) system with the following functions was built on our web server.

- The attachment file of the received data is extracted from the e-mail and stored on the web server.
- After discussions with COMNAP, it was decided to register the balloon's location in COMNAP Asset Tracking System (CATS: https://apps.aad.gov.au/comnap/ (accessed March 4, 2023)) during its flight. To register the location information of the SP balloon to CATS, a file in GeoJSON format that describes the latitude and longitude of the balloon is created and stored on our web server every 10 min.
- Position information and trajectory of the SP balloon during flight are displayed on our web server in real time.
- A 10 day forward trajectory on a constant density surface from the latest position of the balloon is computed using Global Forecast System (GFS: https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast (accessed August 24, 2022)) data and displayed on our web server. It is updated every 1 min.

In addition, 10 day forward trajectories starting from Syowa Station 0-5 days later are also computed and displayed on our web server every day to determine the date of balloon launch.

Based on this QL system, a 24-hour monitoring system is established by Japanese Antarctic Research Expedition members staying at Syowa Station and domestic support members.

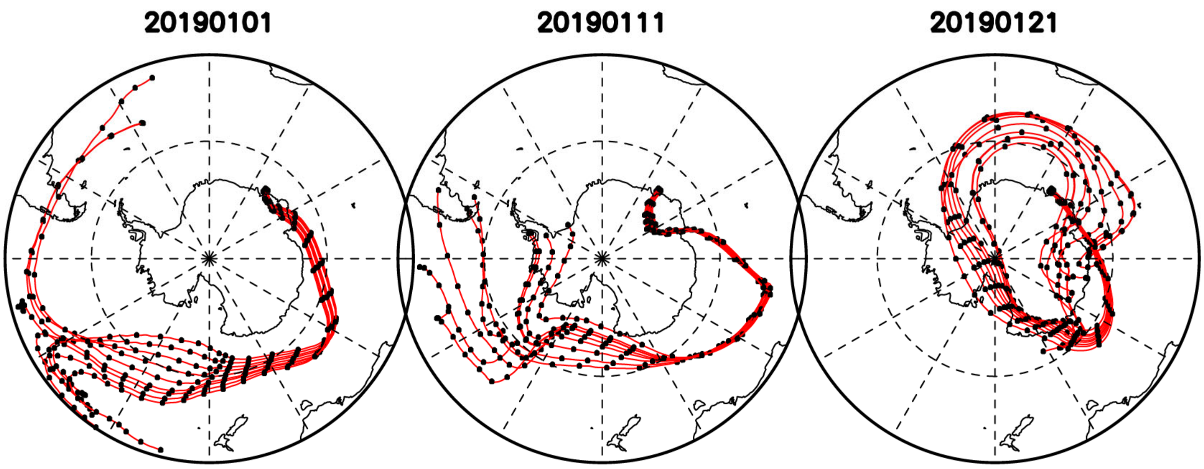

Fig. 5. 30day forward trajectories on a constant density surface starting at 65 hPa from Syowa Station. Initial 9 air parcels are put at (39.6E±1.0 deg, 69.0S±0.5 deg) on 1, 11, and 21 Jan. 2019. Dots are plotted every 1 day.

7. Conclusion

One of the major uncertainties in the current climate model is that it is not possible to accurately express the momentum transport due to gravity waves in the atmosphere. Since gravity waves have a wide range of periods and horizontal wavelengths, there are limited methods to observe the whole gravity waves. Our SP balloon observation project (LODEWAVE) was designed so that the horizontal distribution of the gravity wave momentum transport in the whole period band can be obtained in the Antarctic region where the gravity wave activity is high compared with other regions. In addition, the horizontal distribution of the gravity wave momentum transport obtained from the SP balloon observation and the vertical distribution obtained from the PANSY radar observation will be used to impose constraints on the momentum flux due to gravity waves in the latest climate models. Thus, the qualitative and quantitative problems of the expression of the gravity wave effect in the model will be clarified.

In addition, another purpose of this project is to reduce the size of the SP balloon by reducing the weight of the observation equipment, and to develop a balloon that is easy to handle. This will enable non-experts to carry out SP balloon observations and will serve as a first step for the establishment of a regular observation basis in the future. If meteorological data such as temperature and wind speed at various locations over the Antarctic region can be provided in a near-real-time and continuous manner through regular SP balloon observations, numerical weather forecasts in the Antarctic region will be greatly improved.

The first campaign observation of this project was carried out at Syowa Station in Antarctica in January-February 2022, which was the summer period of the southern hemisphere. Its details and scientific result will be reported soon in another paper.

Acknowledgments

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