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A PROPOSAL FOR OBSERVATION OF ATMOSPHERIC CIRCULATION AND TRANSPORT PROCESSES IN THE TROPOSPHERE AND LOWER STRATOSPHERE OVER ANTARCTICA WITH A NETWORK OF WIND PROFILERS

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Abstract: The wind profiler is a powerful tool to study atmospheric circulation and transport processes because it can measure not only horizontal components but also the vertical component of wind. A wind profiler developed originally by the U.S. NOAA/Environmental Research Laboratories/Wave Propagation Laboratory can measure winds from 0.5–17 km above the surface with an altitude resolution of 250 m and time resolution under 1 hour. The profiler uses a 400 MHz UHF band, and the area of the antenna is about 170 m^2. Observations with a network of the wind profilers at several sites over Antarctica will give useful information on meridional circulation in the Antarctic troposphere and lower stratosphere, on vertical motion around the tropopause whose altitude over Antarctica is around 10 km, and on disturbances such as convection, gravity waves, baroclinic waves, and so on. Observations are also useful for understanding how, when, and how much ozone, water vapor, and other materials are transported from the stratosphere to the troposphere, and then to the Antarctic surface or the middle latitude troposphere. Problems to be overcome for realizing the project are also briefly discussed.

1. Introduction

The atmospheric circulation and transport processes in the troposphere and the stratosphere over Antarctica remain to be studied. The vertical motion is a key factor in the maintenance of moderate temperature during the polar night, and it has a bearing on dynamical aspects of the Antarctic ozone hole: downward motion is considered to maintain the polar night temperature through adiabatic compression heating against radiative cooling, and vertical motion at the tropopause is a critical parameter for controlling ozone distribution. However, until recently no technique had yet been devised to directly measure the vertical motion. The vertical motion has, hitherto, been indirectly calculated from data on the horizontal components of the wind, geopotential height, temperature, and pressure on the basis of the basic equations controlling the atmospheric motion and temperature. Now an instrument has been developed which can directly measure the vertical component of wind. The instrument is called a wind profiler. The wind profiler is a Doppler radar for the measurement of horizontal components and the vertical component of wind. The principle of the wind profiler is common to the MU radar of Kyoto University at Shigaraki as well as other MST (mesosphere-stratosphere–troposphere) radars when they measure the motion of the neutral atmosphere (*e.g.*, GAGE and BALSLEY, 1984). This paper presents a proposal for observation of atmospheric circulation and transport processes in the troposphere and the lower stratosphere over Antarctica using a network of wind profilers.

2. The Wind Profiler as an Instrument

The wind profiler is a type of MST radar or clear-air Doppler radar, and as such uses UHF or VHF bands and detects echoes from atmospheric turbulence moving with a background wind (*e.g.*, BALSLEY and GAGE, 1982). A large system such as the MU radar of Kyoto University at Shigaraki (*e.g.*, KATO, 1986) is necessary to observe the stratosphere and mesosphere, whereas a smaller system can be useful for a Doppler measurement in the troposphere.

An outstanding characteristic of the wind profiler is its ability to measure directly the vertical component of wind (*e.g.*, NASTROM *et al.*, 1985; FUKAO *et al.*, 1988; BALSLEY *et al.*, 1988; SATO, 1990). While the vertical component of wind is a quantity important in general for meteorology, no instrument for directly measuring it in the whole troposphere has been developed so far: There are balloon borne wind instruments to measure the vertical component, but the lifetime of balloons is normally too short for continuous observation required for the purposes described in Section 3.

A 400 MHz (UHF) wind profiler has been developed by the U. S. NOAA/Environmental Research Laboratory (ERL)/Wave Propagation Laboratory (WPL): this wind profiler is designed to cover the troposphere and the lower stratosphere, and it is smaller in size than the MST radars (*e.g.*, STRAUCH *et al.*, 1987; VAN DE KAMP, 1988; WEBER *et al.*, 1990). Wind profilers of this type are now being distributed in the U. S. A. within the framework of the Wind Profiler Demonstration Network Project of the U. S. NOAA (see the PROFILER FORUM and/or FSL FORUM series). The National Weather Service of NOAA is now assessing the utility of the network in an operational setting: This network is expected to be the precursor of a national network in the U. S. A. The same type of UHF wind profiler has been installed and is now operated in the Meteorological Research Institute of Japan (*e.g.*, NAGAI *et al.*, 1988). A network of 50 MHz (VHF) wind profilers is being installed by a group of the NOAA/ERL/Aeronomy Laboratory (AL) on several islands over the equatorial Pacific for ocean-atmosphere interaction and global environmental studies, and the results of observation were found to be significant (*e.g.*, BALSLEY *et al.*, 1988; GAGE *et al.*, 1988). Moreover, a smaller wind profiler intended only for the atmospheric boundary layer has been developed by the NOAA/ERL/AL group using 915 MHz (UHF) radar (ECKLUND *et al.*, 1988), and is being developed also by other groups.

Since the wind profiler developed by the U. S. NOAA/ERL/WPL is considered to be an almost complete instrument commercially available from Unisys Defense Systems, Inc., it is reasonable to conceive of the wind profiler today as the instrument for the present project. Specifications of the wind profilers that Unisys has built for NOAA are shown in Table 1. The radio wave frequency is 404.37 MHz in the UHF band (the wavelength is 0.75 m). The antenna area is about 170 m^2 (13 m $\times$ 13 m). A field layout of the profiler is shown in Fig. 1. The measurement items include

Table 1. System primary specifications of the wind profiler. From a Unisys Defense Systems brochure on the wind profiler which is being utilized by NOAA for the Wind Profiler Demonstration Network.

Performance requirements		
Maximum height (above ground level)	16.25 km	
Minimum height (above ground level)	0.50 km	
Vertical resolution	250 m	
Time to complete measurement cycle	6 min	
Measurement accuracy: Wind speed	±1 m/s	
Wind direction	±3°	
Operation	Unattended	
Mean-time-between-failures	6 months	
Environmental requirements		
Surface winds (max)	63 m/s	
Gusts (max)	83 m/s	
Temperature	−40°C to +50°C	
Ice build-up (max)	7.6 cm	
Snow depth (max)	1.2 m	
Radar parameters		
	Low mode (0.5–9.25 km)	High mode (7.5–16.25 km)
Frequency	404.37 MHz	404.37 MHz
Band width	1 MHz	1 MHz
Peak power	16 kW	16 kW
Pulse widths		
Uncompressed	3.3 μs	20.0 μs
Compressed	1.6 μs	6.6 μs
Pulse repetition frequency	10 kHz	6.7 kHz
Average power	0.5 kW	2.2 kW
System features		
Transmitter type	Solid state	
Antenna type	Coaxial collinear	
Aperture dimensions	13 m × 13 m	
Number of beam positions	3 (vertical, east, north)	
Beam width	4° nominal	
Side lobe levels	−40 dB 0–5°	
	−25 dB 5–45°	
	−20 dB above 45°	
Processing	Hardwired FFT, Micro Vax II	
Software	FORTRAN 77/PASCAL	
Remote maintenance monitoring	200 parameters	
Communications interface	RS-232C	
Satellite telecommunication	GOES* transmission (401 MHz)	
SARSAT** protection	Automatic	

* GOES: Geostationary Operational Environmental Statellite
** SARSAT: Search and Rescue Satellite-Aided Tracking

three components of wind (eastward, northward, and upward winds) using three radar beams. The altitude region 0.5–17 km is covered with an altitude resolution of 250 m. The time resolution is 6 min. The accuracy of the measurement is about 1 m/s for the time resolution of 6 min. Because of the potential for interfering with

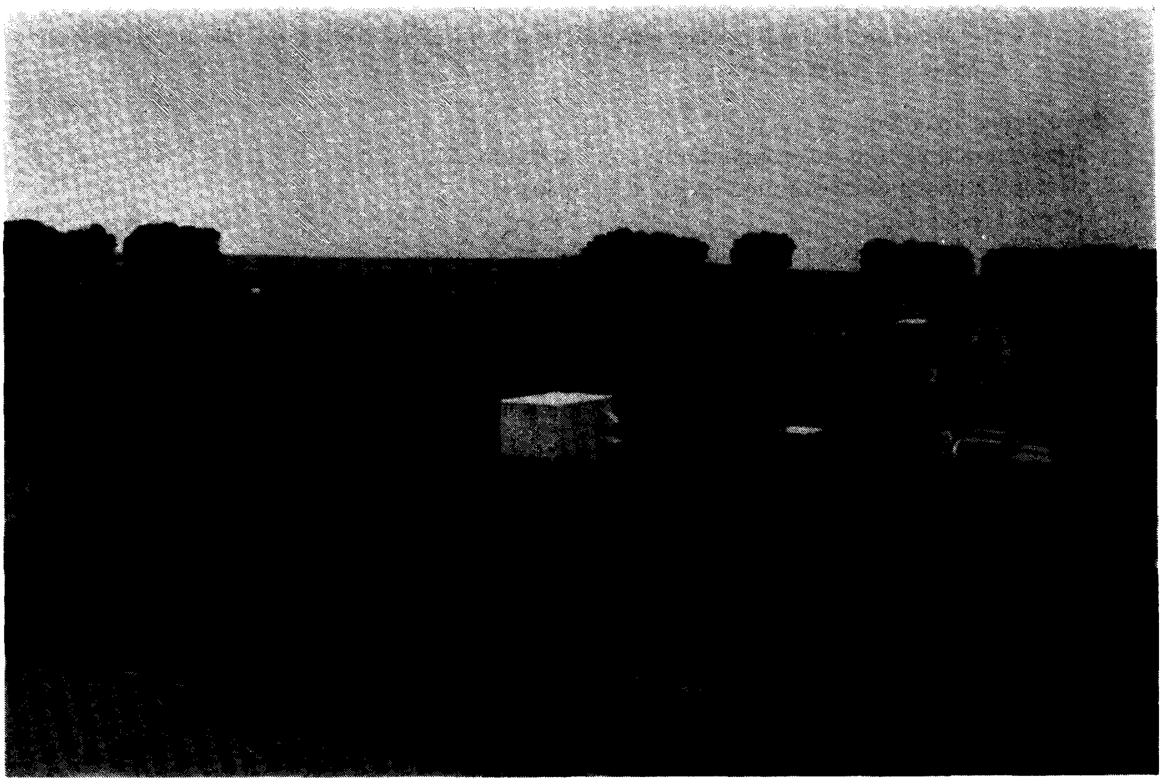

Fig. 1. Picture of the wind profiler at the NOAA test site in Platteville, Colorado. A white cabin in the center of the photograph is an equipment shelter, and antenna array is seen in front of the shelter. Photographed by Unisys Defense Systems, Inc.

Search and Rescue Satellites (SARSATs), NOAA is in the process of obtaining a new frequency for wind profilers. Indications are that the new frequency will be 449 MHz.

Moreover, there is a Radio Acoustic Sounding System (RASS) which is a technique for remotely measuring temperature profiles by combining radar and acoustic techniques. The RASS is now being developed by the NOAA/ERL/WPL group (*e.g.*, MAY *et al.*, 1988, 1989, 1990) and other groups (*e.g.*, MATUURA *et al.*, 1986; TSUDA *et al.*, 1989). The radar detects back-scattered radiation from fluctuations in the refractive index of the air induced by a sound wave. The Doppler shift of the back-scattered signal gives an estimate of the speed of sound and therefore temperature. The wind profiler can be easily adapted to the RASS technique. At present, the altitude coverage attained by the RASS technique of the NOAA group using the 400 MHz wind profiler radar is from 0.5 km up to 2–3 km (MAY *et al.*, 1988), but it is now being extended up to 3–5 km (FSL FORUM, 1991). A RASS of the NOAA group using a 50 MHz radar is able to measure temperature up to 5–7 km (MAY *et al.*, 1990). The RASS using the Kyoto MU radar of 50 MHz covers the upper troposphere from 5 km up to 11 km (TSUDA *et al.*, 1989), and up to 22 km in the lower stratosphere under good conditions of weak tropospheric jet in summer (MATUURA *et al.*, 1986). The RASS technology is now developing.

3. Observation Plan

I propose a plan for installing the wind profilers at several points over Antarctica about 5 years from now (1991). Especially, the main target of the measurement is the vertical wind. The observation will be useful for understanding not only atmospheric circulation itself but also material circulation in the atmosphere (KANZAWA, 1989). Here the problem of the "material circulation in the atmosphere" is defined as follows: When and how are materials in the atmosphere (say, ozone) generated (chemical production) or how are they taken into the atmosphere from the earth's surface or the top of the atmosphere; how are they transported by atmospheric motion (mean meridional circulation, planetary waves, gravity waves, convection, turbulence, etc.), and what metamorphoses occur during the transportation (chemical reaction); where and how do they disappear in the atmosphere (chemical loss) or how they are taken into the earth's surface (destruction over the surface) or the top of the atmosphere?

Purposes of observations using the wind profilers are as follows:

(1) Mean meridional circulation

Figure 2 illustrates observations to measure meridional circulation over Ant-

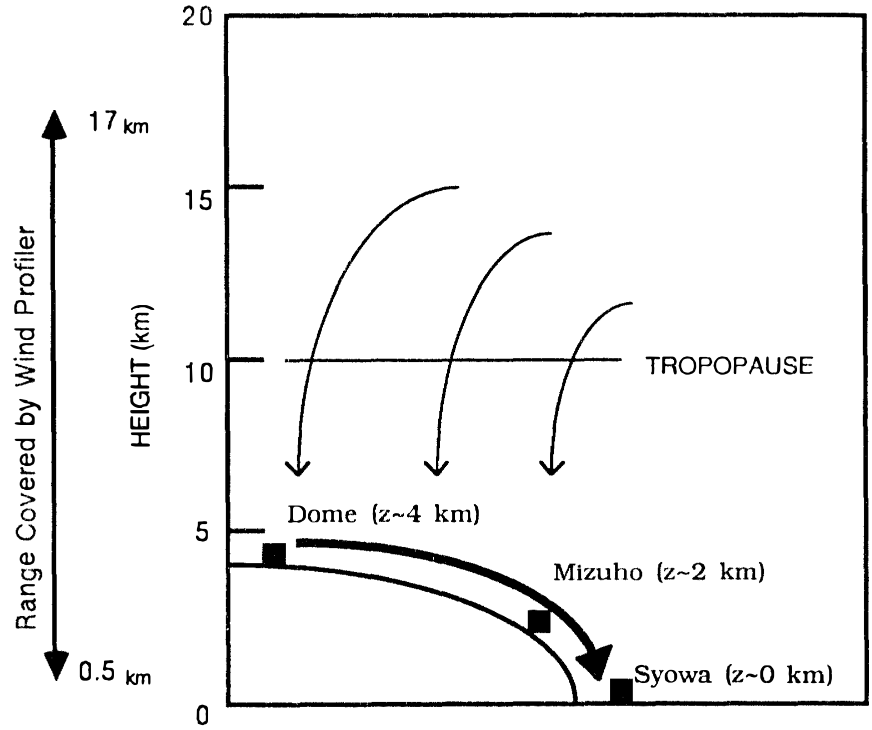

Fig. 2. Schematic illustration of the observational plan using the wind profilers. It has been supposed that the wind profilers are installed at several points along the meridional direction over Antarctica. Three sites, Syowa (69°S, 40°E), Mizuho (71°S, 44°E), and Dome in East Antarctica (around 77°S, 35°E), are tentatively drawn in the figure. The thick arrow in the figure designates katabatic wind and the thin arrow shows meridional circulation imagined to be measured by the wind profilers. The measurement height range covered by the wind profiler shown on the left side of the figure is applied to Syowa Station. As for Dome, the upper level may be about 21 km (4 km+17 km).

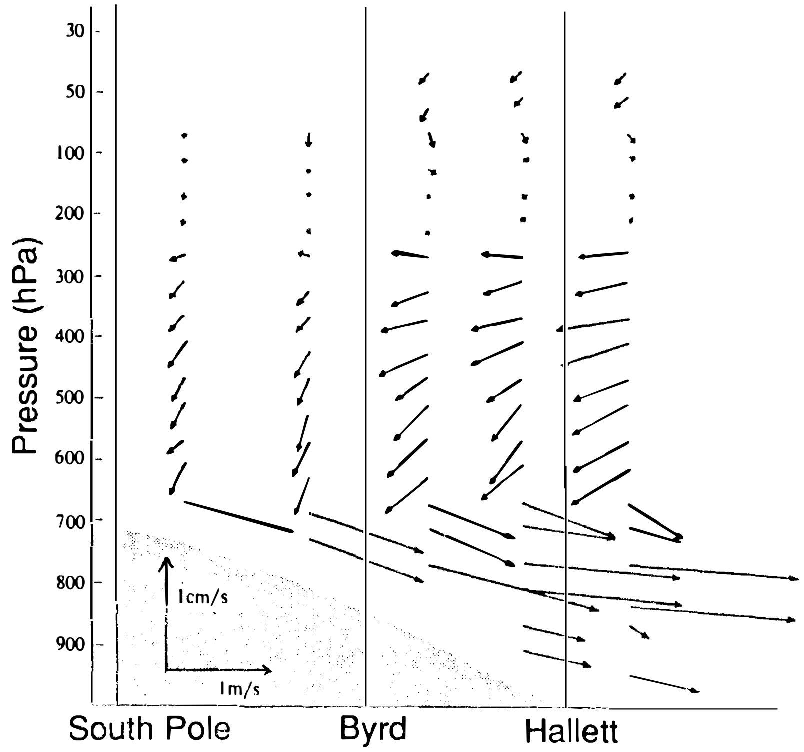

Fig. 3. Average meridional circulation in winter estimated from radiative cooling data. The vertical wind speed is estimated by the difference between time change of temperature and infrared radiative cooling on the basis of the thermodynamic equation. The radiative cooling rate is estimated from long wave radiation sonde observation carried out in June–July, 1959–1963 at South Pole (90°S), Byrd (80°S, 120°E) and Hallett (72°S, 170°E). The meridional wind speed is estimated from the vertical wind distribution to satisfy the mass continuity equation. The scale of wind velocity is added to the original figure by WHITE and BRYSON (1967). This figure has been reproduced from Figure 3.15 of NATIONAL INSTITUTE OF POLAR RESEARCH (1988).

arctica (three points, Syowa, Mizuho, and Dome in East Antarctica, are tentatively drawn in the figure). It is anticipated that adiabatic compression heating by downward motion balances strong radiative cooling of the atmosphere over Antarctica to maintain moderate temperature, especially during the polar night. However, direct measurements of the vertical wind have not been carried out so far. Figure 3 is an example where meridional circulation is estimated from the postulate that the circulation balances radiative cooling measured by long wave radiation sonde data in the Antarctic winter. This procedure leaves considerable imprecision in the estimates. Of course, the resulting figure has a meaning as it is the first attempt to draw a figure of this kind. In fact, the present observational plan came to my mind when I saw the figure. A trial to directly measure the flow is one of the motivations of the present proposal. In the Antarctic area where flow is comparatively uniform with respect to longitude, the measured wind under this project will represent zonally averaged meridional circulation on a climatological time scale.

Katabatic winds flow near the earth's surface as shown in Figs. 2 and 3, generated by strong radiative cooling. It is an interesting problem to determine how deep in the troposphere the effect of the katabatic winds permeate. The katabatic wind flows in the boundary layer from the ground to about the 300 m altitude level. The katabatic wind, therefore, cannot be observed by the wind profiler which measures winds above the 500 m (0.5 km) level (see Table 1). The other type of wind profiler for the boundary layer described in Section 2 becomes necessary for observing the katabatic wind itself.

Before carrying out the observations, we need to estimate meridional circulation over Antarctica using conventional aerological sonde data obtained at many Antarctic stations and objective analysis grid point data, *e.g.*, of JMA, ECMWF, and NMC. This estimate has a value of its own, and it will contribute to making up the observational plan using the wind profilers.

(2) Stratosphere–troposphere exchange and material circulation

The altitude of the tropopause is about 10 km in the polar region. The present observation will give us a clearer picture of the air exchange processes between the stratosphere and the troposphere, since the wind profiler can measure vertical motion up to about 17 km above the ground. It is thought that air parcels enter the stratosphere from the troposphere through the equatorial tropopause, move poleward, and come back to the troposphere in the area of tropopause folding in middle latitudes and/or through the polar tropopause. How much vertical (downward) motion is observed through the tropopause over Antarctica is the problem at hand. Comparison of the vertical motion in winter (when the existence of the tropopause becomes vague) with that in other seasons will be of special interest. The development of the RASS technique described in Section 2 shows considerable promise when applied to determine the tropopause height and look at vertical profiles of temperature.

This observation will contribute to understanding of not only atmospheric circulation but also material circulation, for example, circulation of ozone, water, and other materials. If we observe ozone and water vapor using lidar and radar simultaneously with winds using the wind profiler, our understanding of circulation of these two important materials will increase.

(3) Disturbances

The above two items deal mainly with climatological aspects. However, the wind profiler can also become useful for observing atmospheric phenomena on time scales of several hours to days, for example, convection, gravity waves, baroclinic waves, and so on, because it can measure vertical wind, which is a critical parameter in understanding these phenomena. Moreover, it will also contribute to the evaluation of material transport by the motions on these scales.

4. Problems to be Overcome

There are several problematic issues to be overcome, with respect to the condition of the instrument itself, the logistics of installing it over Antarctica, and others.

In principle, the wind profiler can measure vertical wind. However, in practice, this is not always the case. The magnitude of vertical wind is thought to be very small, *e.g.*, on the order of 1 mm/s, as shown in Fig. 3. If a "vertical" beam is not precisely radiated vertically from the wind profiler owing to poor installation of the antenna, the horizontal component of wind velocity will mix with the Doppler shift signal of the "vertical" beam of the profiler, and vertical velocity cannot be precisely measured: thus we must develop techniques so as keep the antenna array horizontal on the ice sheet when we install the wind profiler in the interior. Moreover, there is a problem as to how much data should be integrated in time for obtaining vertical velocity with reasonable precision since the anticipated magnitude of the mean vertical velocity is on the order of 1 mm/s, while precision of the wind profiler measurement is 1 m/s for 6 minutes integration of the data (see Table 1). Furthermore, the wind profiler has to be able to work under severe cold conditions in the interior (remember that the coldest temperature at the Dome is considered to be about −90°C, and that the present wind profiler is designed to work at temperature above −40°C as shown in Table 1).

Logistic problems are as follows. How much will the wind profiler disturb other observational instruments at Syowa Station due to large electric power of emitted radio waves of the profiler (peak power is 16 kW while average power is 2.2 kW as shown in Table 1) when the profiler is installed at the Station? How is the wind profiler to be transported to the interior once it is installed (remember, for example, that a computer for processing the data must be transported to the profiler site, and computers are generally sensitive to vibrations caused by the rough transport during its passage by overland snow vehicle)?

To realize the project of observations using the wind profilers in the interior over Antarctica and to distribute many wind profilers to organize a wind profiler network over Antarctica if possible, international cooperation as well as domestic cooperation will be required. This raises the question of the composition of a research team (domestic and/or international), discussing the purposes of observation multilaterally, developing software for analyzing the data, and carrying out the actual observations. An example of a topic that has to be addressed is whether or not we will use a satellite for data acquisition as the Wind Profiler Demonstration Network Project of NOAA uses the Geostationary Operational Environmental Satellite (GOES). There are many other problems to be overcome.

The first attempt may be to install the wind profiler at Syowa Station to observe the winds in the coastal area, and to test its performance and work out some of the logistic problems.

5. Concluding Remarks

The present paper is meant to introduce a concept which can be worked up more thoroughly in the coming years. Hopefully it can lead to substantial progress after about five years in cooperation with scientists whose interest are in atmosphere circulation, those who think about material transport in the atmosphere through measuring a variety of atmospheric minor constituents, and those who investigate the integrated theme of material circulation.

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