Polar Meteorol. Glaciol., **12**, 10–18, 1998

OBSERVATIONS OF LIQUID WATER, WATER VAPOR, AND DOWNWARD FLUX OF INFRARED RADIATION IN THE ARCTIC REGION WITH A MICROWAVE RADIOMETER AND A PYRGEOMETER

Haruma ISHIDA[1], Tadahiro HAYASAKA[1], Masahiro KAJIKAWA[2], Katsuhiro KIKUCHI[3], Hiroshi UYEDA[3], Yoshio ASUMA[3] and Yusuke INOUE[4]

[1]*Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Aoba-ku, Sendai 980-8578*
[2]*Department of Earth Sciences, Faculty of Education, Akita University, Tegatagakuen-machi, Akita 010-0852*
[3]*Division of Earth and Planetary Sciences, Graduate School of Science, Hokkaido University, Kita-10, Nishi-8, Kita-ku, Sapporo 060-0810*
[4]*Japan Weather Association, Higashi-Ikebukuro 3-chome, Toshima-ku, Tokyo 170-6054*

Abstract: Observations of cloud liquid water path, columnar water vapor amount, and downward flux of infrared radiation in the Arctic region Inuvik, Canada and Kiruna, Sweden, during winter were carried out with a microwave radiometer and a pyrgeometer. The algorithm used in this study for the retrieval of liquid water path and columnar water vapor amount from measured intensity of microwave radiation requires the atmospheric temperature profile and the cloud temperature, which were obtained from radiosonde measurements. It was shown from microwave radiometer measurements that the columnar water vapor amount changed between 1–13 kgm^{-2} during about a month in both observation points, and supercooled liquid water existed on several days. At Inuvik liquid water path reached about 0.25 kgm^{-2} at most; this is comparable to a typical value of summer clouds in mid-latitude. It was also shown that the downward flux of infrared radiation on the ground surface changed between 130 Wm^{-2}~300 Wm^{-2}. Finally, the downward flux of infrared radiation was calculated using the liquid water path retrieved from the microwave radiometer and water vapor and temperature profiles obtained from radiosonde observations. A comparison between the calculated and the measured values shows that both are in good agreement and the downward flux of infrared radiation in the Arctic region is primarily dependent on the water vapor amounts and temperature profile.

1. Introduction

Variations of water amounts in the atmosphere (liquid as well as vapor) and their relations to radiation on the ground surface in the Arctic region during winter are not well understood, because only few *in situ* observations have been carried out in this season, compared with other seasons (*e.g.*, CURRY *et al.*, 1996; LUBIN and SIMPSON, 1997). For example, YAMANOUCHI and ØRBÆK (1995) measured the downward flux of infrared radiation through a year at Ny-Ålesund, Svalbard and found that infrared radiation had large variability in winter, but water amounts such as water vapor and liquid water paths were not observed simultaneously.

For more detailed studies of the relationship between atmospheric conditions and radiation during the Arctic winter, we performed the WANTS (Water vapor, Aerosol and Nuclei Transportation and Snow crystals) Arctic Experiment in Inuvik, Canada and Kiruna, Sweden during winter. In the present paper, we show the results of liquid water path and columnar water vapor amount obtained with a microwave radiometer and also the downward flux of infrared radiation measured with a pyrgeometer on the ground surface.

2. Observations

As part of the WANTS-Arctic Experiment, two observations were carried out at Inuvik (68.32°N, 133.50°W) from 14 December 1995 to 16 January 1996, and at Kiruna (67.88°N, 20.25°E) from 26 December 1996 to 15 January 1997. Inuvik, about 100 km from the Beaufort Sea, is located within the Mackenzie Delta, with the Richardson Mountains to the southwest. Kiruna is located in a mountainous area of Scandinavia. During the observations at both sites the sun never rose above the horizon. Locations of both observation sites are illustrated in Fig. 1a and 1b, respectively. In this paper the results obtained with a microwave radiometer and a pyrgeometer are mainly introduced although many instruments had been set up during the experiment.

A microwave radiometer was used in order to retrieve liquid water path and columnar water vapor amount. The radiometer measures radiative intensity at frequencies 23.8 GHz (absorption band of water vapor) and 31.4 GHz (window region) in terms of brightness temperature. The radiometer was calibrated by applying the TIP-curve Method. At both observation points, the radiometer was set up to measure the radiative intensities from the zenith direction at about 1-min measurement intervals.

The algorithm to retrieve liquid water path and columnar water vapor amount from brightness temperatures measured by the radiometer is briefly described as fol-

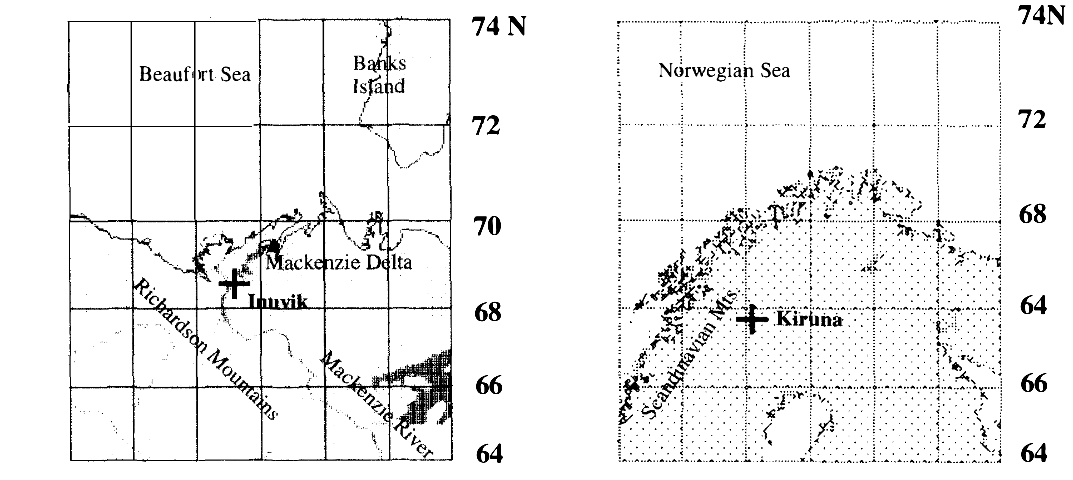

Fig. 1. Location of both observation sites: (a) Inuvik, and (b) Kiruna, Sweden.

lows. Optical thickness of each frequency is calculated by assuming columnar water vapor amount and liquid water path as initial values, then the calculations of optical thicknesses are iterated, changing columnar water vapor amount and liquid water path until optical thicknesses are consistent with the measured brightness temperatures. In this calculation, absorption coefficients of water vapor and liquid water particles are calculated with the parameterizations of LIEBE (1989) and the Mie theory (*e.g.* VAN DE HULST, 1957), respectively, with an assumption that cloud cover is thin and single layer. Figure 2 illustrates the flow chart of the retrieval.

The scattering effect of microwave radiation by particles in the atmosphere is not taken into account in the calculation of radiation. In this algorithm, since the change in atmospheric temperature profile, particularly the cloud temperature, gives rise to non-negligible errors to calculated values, cloud temperature (or cloud height) is necessary to calculate the absorption coefficients of water vapor and liquid water particles. At Inuvik, radiosonde data measured near the microwave observation point at 0000 and 1200 UTC were available, so that atmospheric profile data were given from the radiosonde measurement. Cloud temperature was also estimated from radiosonde measurements with an assumption that the larger of humidity over 80% was a cloud layer. At Kiruna, on the other hand, radiosonde data were obtained only on a few days, so that the atmospheric parameters during the entire observation period are assumed referred to the radiosonde data at Kiruna as follows. Surface temperature was

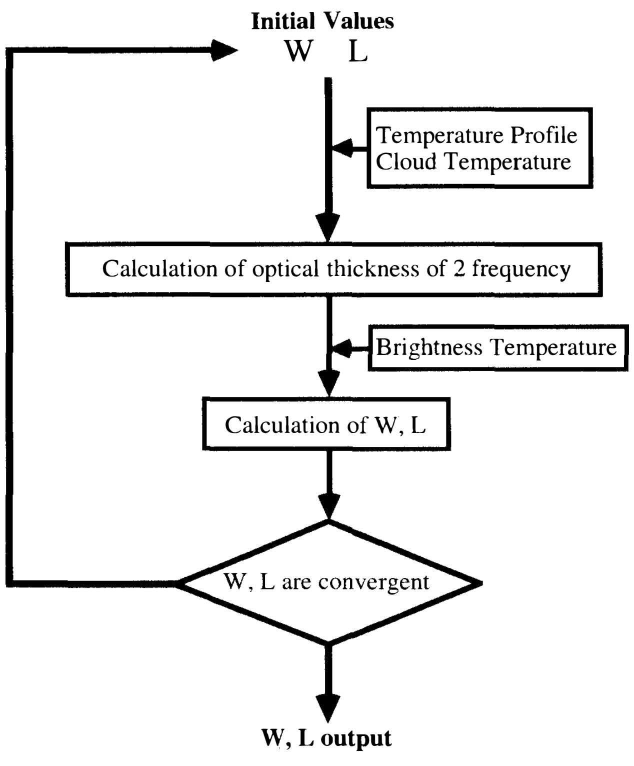

Fig. 2. The flow chart of the retrieval algorithm. W and L denote columnar water vapor amount and liquid water path, respectively.

243.2 K, atmospheric temperature lapse rate in troposphere was 4.5 K km^{-1} and cloud temperature was 241 K. Furthermore, we considered that water vapor content decreases exponentially with increase of height from the surface.

At both observation sites, a pyrgeometer was also set up in order to measure the downward flux of infrared radiation at the surface at 1-min intervals. This pyrgeometer measures the radiation in the wavelength region of 3–50 μm. When the pyrgeometer was covered with snow it was removed rapidly to avoid errors.

3. Results and Discussion

3.1. Liquid water path and columnar water vapor amount

Figure 3 shows columnar water vapor amount and liquid water path observed at Inuvik. At Inuvik, columnar water vapor amount was found to change in a range from about 1 to 12 kgm^{-2}, and reached maximum values on 24 and 27 December 1995, while for five days from 14 December 1995 and for three days from 9 January 1996 the water vapor amount was quite small near 1 kgm^{-2}. Compared with the radiosonde data, shown in Fig. 3 by squares, both values were in good agreement. Liquid water was observed on 18 days during the observation period; all of it was supercooled. The maximum value of about 0.25 kgm^{-2} occurred on 28 December 1995; this is comparable to the value of summer cloud in mid-latitude (GREENWALD *et al.*, 1993). Early in the morning of this day the liquid water path decreased and heavy snowfall was observed (INOUE, 1997). This phenomenon might be caused by liquid water droplets in cloud condensing to ice crystals and falling.

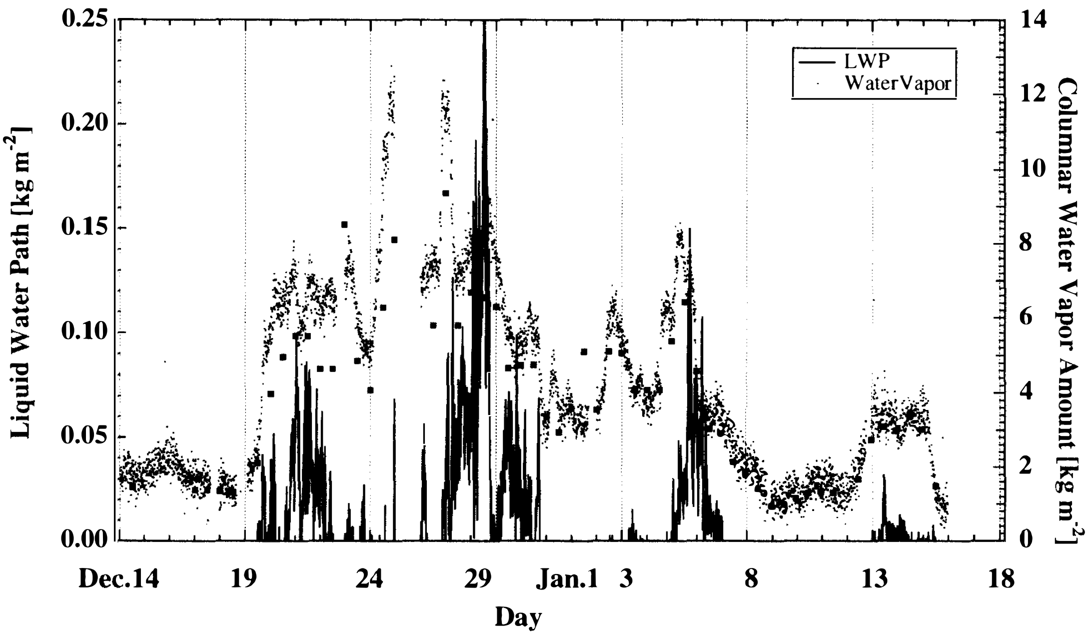

Fig. 3. Liquid water path (solid line) and columnar water vapor amount (dots) at Inuvik. Columnar water vapor amount obtained from radiosonde data are also presented by squares.

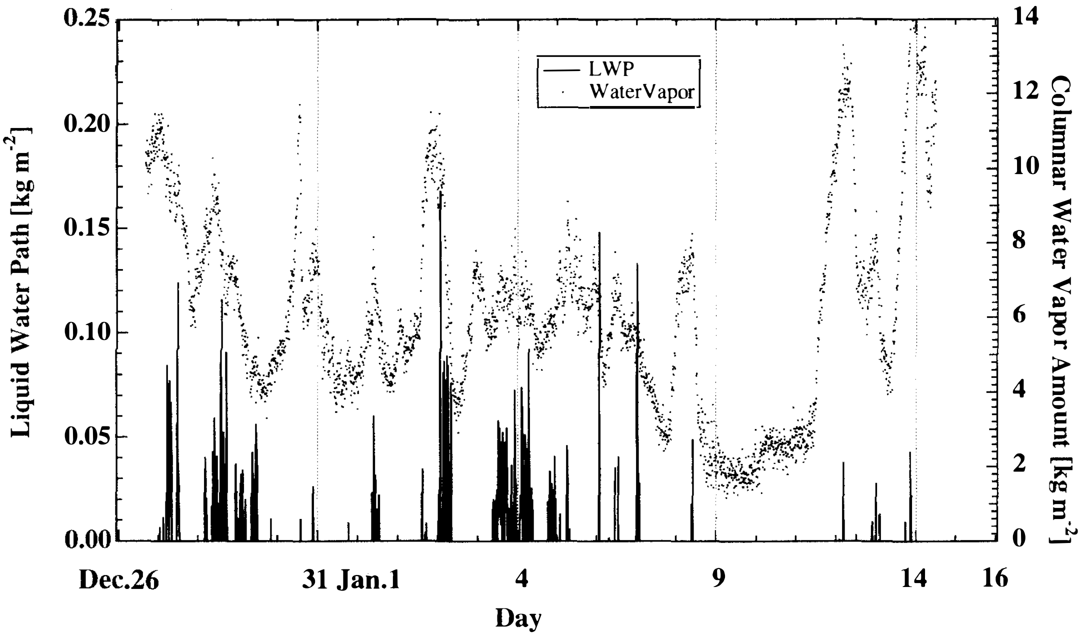

Fig. 4. Liquid water path (solid line) and columnar water vapor amount (dots) at Kiruna.

Columnar water vapor amount and liquid water path observed at Kiruna are shown in Fig. 4. Columnar water vapor amount varied in a range from 1 to 13 kgm^{-2}, which was comparable to that value at Inuvik. The maximum values near 13 kgm^{-2} were observed on 13 and 15 January 1997, while on 10 January 1997 the observed value was slightly larger than 1 kgm^{-2}. The liquid water path reached about 0.2 kgm^{-2} for the maximum value on 3 January 1997, but liquid water was not observed continuously longer than several hours.

With respect to the retrieval of liquid water path at Kiruna, errors might have occurred because of lack of accurate temperature profile data. For example, on 3 January 1997, an increase of 10 K in the assumed cloud temperature value made the retrieved liquid water path increase about 0.05 kgm^{-2}, while columnar water vapor amount showed little difference. In order to retrieve the liquid water path more precisely, it is necessary to obtain cloud temperature with other instruments.

The remarkable difference of liquid water path fluctuation between Inuvik and Kiruna is persistence of the liquid water path. At Inuvik, the liquid water path was observed continuously all day long in several cases, which suggests that cloud develops more frequently at Inuvik than at Kiruna. The reason for this difference might be that moisture and warm air can be transported from the Gulf of Alaska to Inuvik to develop cloud, whereas Kiruna is located near mountains which block moist air transported from the Gulf Stream. More observations, especially to the west of the Scandinavia Mountains are needed to elucidate the difference of water transportation mechanism.

3.2. Downward flux of infrared radiation

Figure 5 shows the downward flux of infrared radiation at the surface measured at Inuvik by a solid line. Measured values are averaged 10 min before and after 0000 and 1200 UTC on each day. Downward flux variation ranged from 130 to 260 Wm^{-2} during about a month, reaching around 260 Wm^{-2} on 27 December 1995 and 5 January 1996.

To investigate the primary cause of infrared flux variation, theoretical calculations with a radiative transfer scheme were carried out and compared with measured values. We used the NAKAJIMA and TANAKA (1988) radiative transfer scheme, which is based on the discrete ordinate method assuming a plane parallel atmosphere and the k-distribution method was used for calculation of gaseous absorption. Temperature and water vapor amount in each atmospheric layer were referred to radiosonde data. It was assumed that cloud existed at heights with humidity over 80% and cloud contained only liquid water droplets with droplet size spectra following the log-normal distribution. Although liquid water path was referred to the value retrieved with the microwave radiometer and the effective radius of cloud particles was assumed to be 4 μm, the change in liquid water path or effective radius causes quite small error.

The calculated downward flux at 0000 and 1200 UTC on each day is also shown in Fig. 5 by dots. In the comparison, measured and calculated values are consistent, and the largest difference between calculated and measured values was about 30 Wm^{-2} at 0000 on 25 December 1995, which suggests that the variation of downward flux of infrared radiation in winter could be ascribed to the changes in atmospheric temperature, water vapor profile, and the existence of cloud.

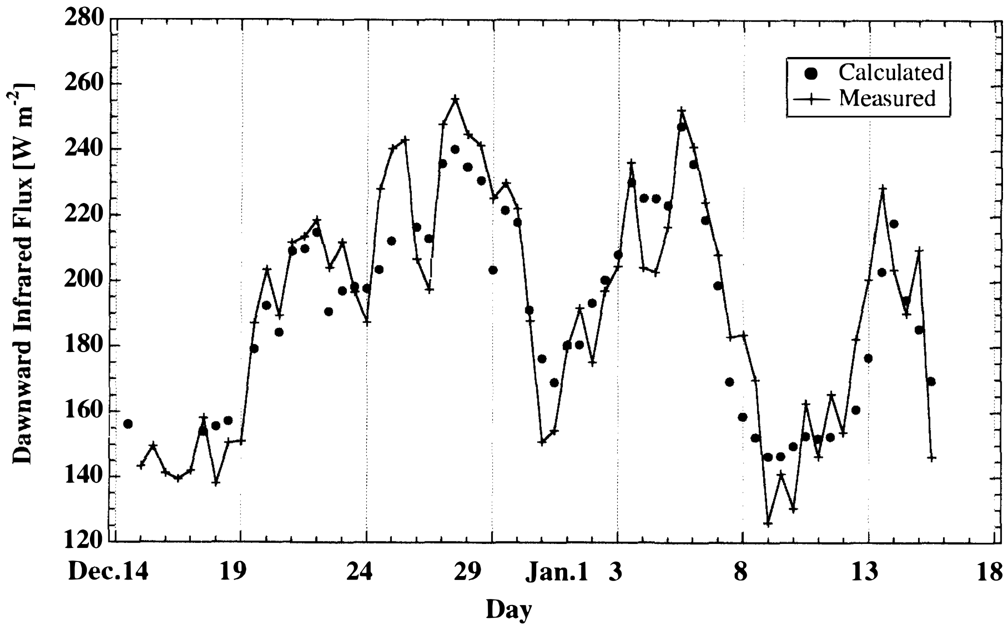

Fig. 5. Measured (line with plus mark) and calculated (dots) downward flux of infrared radiation at Inuvik. Values are averaged 10 min before and after 0000 and 1200 UTC on each day.

Downward flux of infrared radiation at Kiruna is also presented in Fig. 6, averaged with the same procedure as at Inuvik. The value ranged from 140 Wm^{-2} to 300 Wm^{-2}, comparable to the range at Inuvik.

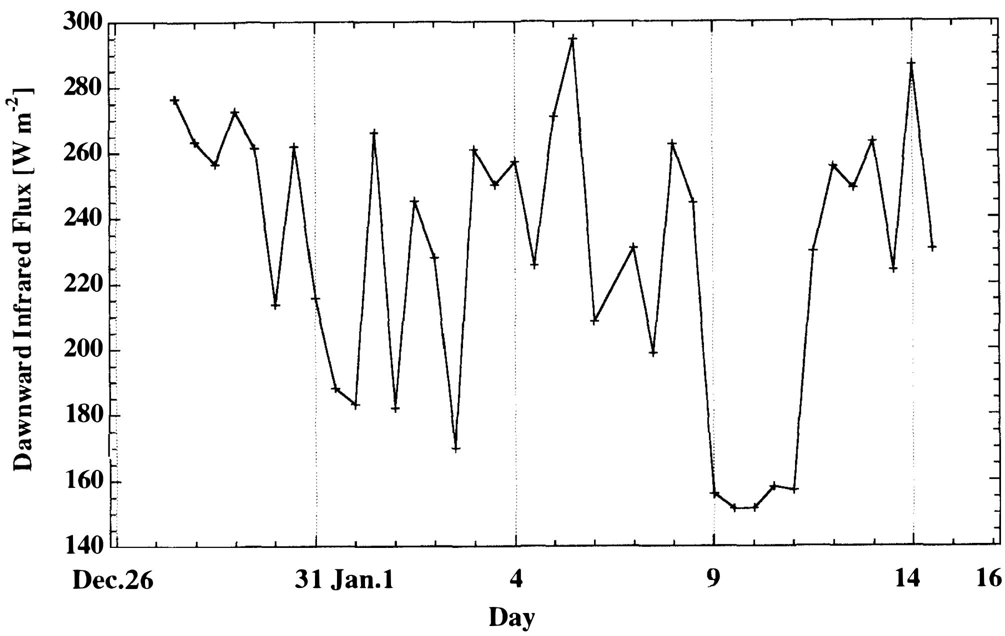

Fig. 6. Measured downward flux of infrared radiation at Kiruna. Values are averaged 10 min before and after of 0000 and 1200 UTC on each day.

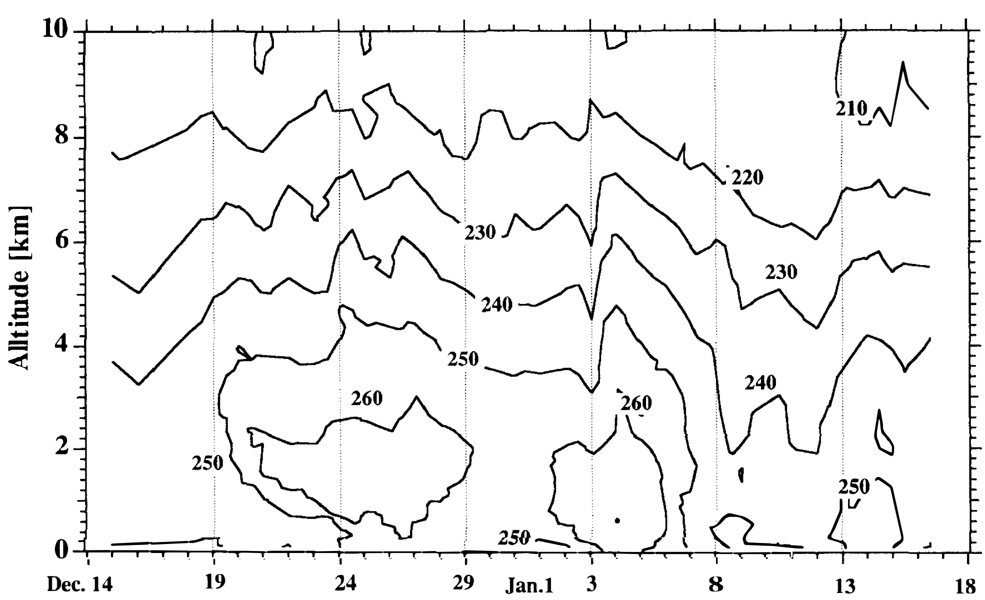

Fig. 7. Temperature profile obtained from radiosonde data at Inuvik. Temperature is presented in K.

To investigate more details of the relation between infrared radiation and atmospheric condition at Inuvik, a time-height cross section of atmospheric temperature derived from radiosonde data at Inuvik during the observation is shown in Fig. 7. A comparison between Fig. 5 and Fig. 7 suggests that the downward flux of infrared radiation was small with low columnar water vapor amount when temperature was relatively low, *e.g.* around 15 December 1995 or around 10 January 1996. This relationship between downward flux of infrared radiation and columnar water vapor amount also appeared at Kiruna *e.g.* around 10 January 1997. On the other hand, water vapor variation affects infrared radiation as well as the temperature profile when the atmosphere contains a warm air. For example, the temperature of the atmosphere on 4 January 1996 was higher in all layer of atmosphere than on the days after 4 January 1996, while downward flux on 4 January 1996 was lower, which means that the difference of downward flux occurred due to the difference of water vapor amount shown in Fig. 3. It is considered that a warm air mass has large variability of water vapor content relative to a cold air mass. In addition, radiative transfer calculations showed that the change in downward flux of infrared radiation due to the cloud cover was about 20 Wm^{-2} for any day during the observation. It is therefore concluded that the change in downward flux of infrared radiation at the surface in the Arctic winter is caused by the exchange of an airmass which has distinctive water vapor amount and temperature profile. In contrast, according to in situ observations in mid-latitude, downward infrared flux is affected primarily by cloud.

4. Conclusions

The observations with a microwave radiometer and a pyrgeometer revealed characteristics of mid-winter atmosphere and radiation on the ground surface in two Arctic regions, Inuvik and Kiruna. The results obtained in this study are summarized as follows:

1) Columnar water vapor amount ranged from 1 kgm^{-2} to 13 kgm^{-2}.
2) Supercooled liquid water was observed on several days and the maximum value of liquid water path was comparable to the typical value of summer cloud in mid-latitude.
3) Liquid water path was sometimes observed continuously for one day at Inuvik, but only sporadically at Kiruna. This difference may be caused by the different mechanism of water transportation.
4) Downward flux of infrared radiation at the surface ranged from 130 Wm^{-2} to 300 Wm^{-2}. This variation was primarily due to the exchange of air masses of different atmospheric temperature profiles and water vapor amounts.

Further observations are needed in order to clarify the detailed mechanism of water transport and to find other factors which affect the radiation budget in the Arctic winter.

Acknowledgments

The radiative transfer code used in this study was provided by Prof. T. NAKAJIMA.

This study was supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Science, Sports, and Culture of Japan.

References

CURRY, J. A., ROSSOW, W. B., RANDALL, D. and SCHRAMM, J. L. (1996): Overview of Arctic cloud and radiation characteristics. J. Clim., **9**, 1731–1764.

GREENWALD, T. J., STEPHENS, G. L., VONDER HAAR, T. H. and JACKSON, D. L. (1993): A physical retrieval of cloud liquid water over the global oceans using Special Sensor Microwave/Imager (SSM/I) observations. J. Geophys. Res., **98**, 18471–18488.

INOUE, Y. (1997): The formation of ice particles and water transportation in the Canadian Arctic during midwinter. Master's Thesis of Hokkaido Univ. (in Japanese).

LIEBE, H. J. (1989): MPM-AN atmospheric millimeter-wave propagation model. Int. J. Infrared Millimeter Waves, **10**, 631–650.

LUBIN, D. and SIMPSON, A. S. (1997): Measurement of surface radiation fluxes and cloud optical properties during the 1994 Arctic Ocean Section. J. Geophys. Res., **102**, 4275–4286.

NAKAJIMA, T. and TANAKA, M. (1988): Argorithms for radiative intensity calculation in moderately thick atmospheres using a truncation approximation. J. Quant. Spectrosc. Radiat. Transfer, **40**, 51–69.

VAN DE HULST, H. C. (1957): Light Scattering by Small Particles. New York, Wiley, 470 p.

YAMANOUCHI, T. and ØRBÆK, J. B. (1995): Comparative study of the surface radiation budget at Ny-Ålesund, Svalvard and Syowa Station, Antarctica, 1987. Proc. NIPR Symp. Polar Meteorol. Glaciol., **9**, 118–132.

(Received December 25, 1997; Revised manuscript accepted March 16, 1998)