Polar Meteorol. Glaciol., **16**, 140–148, 2002

Meteorological observations on Sofiyskiy Glacier, Russian Altai Mountains

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Abstract: Meteorological observations were carried out on Sofiyskiy Glacier from July 7 to 17, 2001. Air temperature, relative humidity, wind direction, wind speed, atmospheric pressure and global radiation were measured with automatic instruments every ten minutes. Snow surface height was measured using a stake installed in the surface snow several times a day. The net gain of snow surface during the observation period was 268 mm. In the first half of the observation period, air temperature exceeded 3°C during the daytime, but air temperature never became positive during the latter half of the observation period. The heat balance was examined from the meteorological data. The values of estimated snowmelt and observed snowmelt correspond almost exactly.

1. Introduction

Glaciological and meteorological investigations were carried out on Sofiyskiy Glacier in the Russian Altai Mountains in a Japanese-Russian joint research project. An automatic weather station was used to collect data on the accumulation area of Sofiyskiy Glacier from July 7 to 17, 2001, in order to observe the local weather conditions on the glacier. Many meteorological observations have been carried out on Himalayan glaciers (*e.g.* Inoue and Yoshida, 1980; Sakai *et al.*, 1998; Takeuchi *et al.*, 2001), however, no meteorological observations have previously been conducted in the Altai Mountains. This paper presents our meteorological observations from the Altai Mountains, including the heat balance estimated from the meteorological data.

2. Observation methods

The meteorological observation site (M) on Sofiyskiy Glacier is shown in Fig. 1. The site, at 3435 m above sea level, is estimated to be located at 49°47′10″N, 87°43′48″ E. Sofiyskiy Glacier was described by Fujii *et al.* (2002)

Measured elements and the instruments used are summarized in Table 1. The air

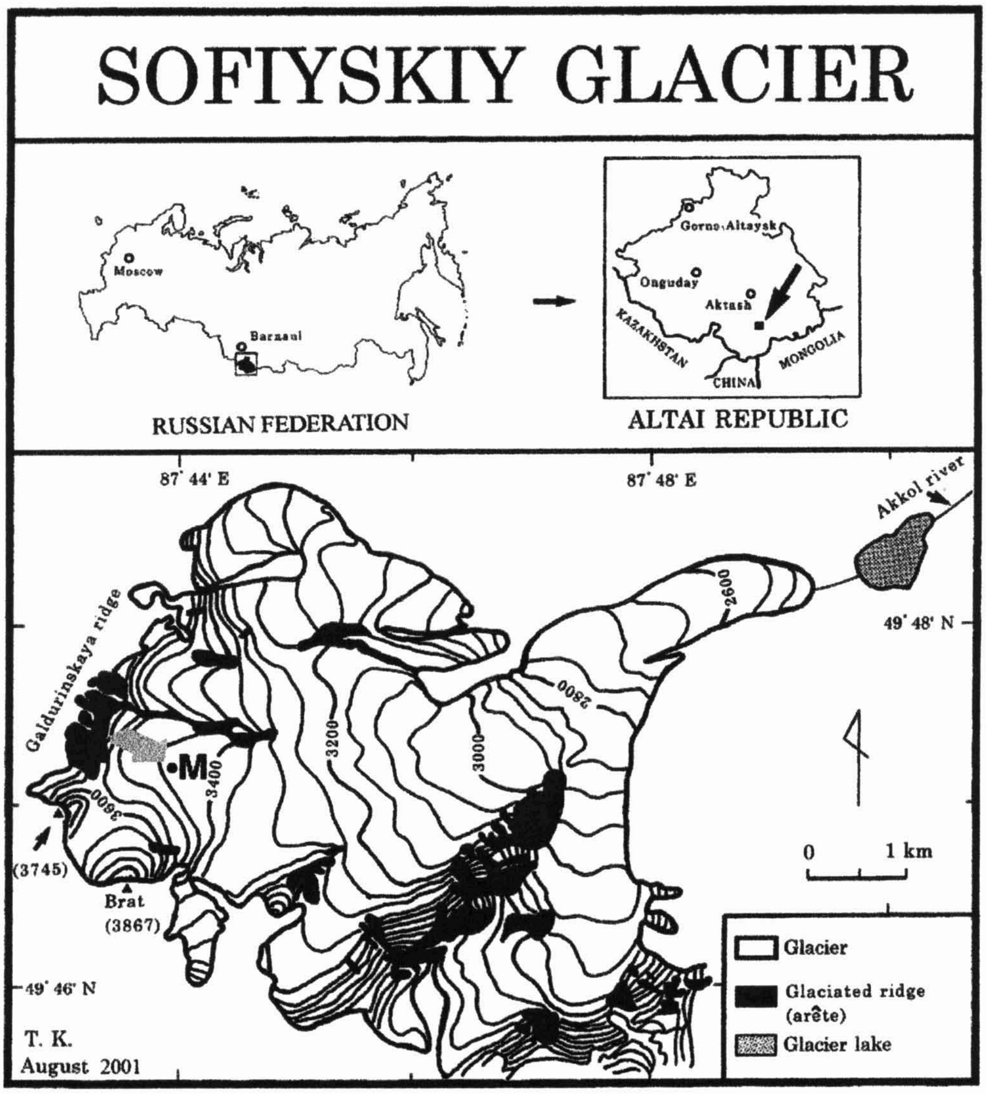

Fig. 1. Map indicating location of meteorological station. Meteorological observation site is designated by "M".

temperature and relative humidity sensors were installed in a white shelter for insulation against solar radiation (Fig. 2). Air temperature, relative humidity, wind direction, wind speed, atmospheric pressure and global radiation were measured with data loggers every ten minutes. Snow surface height was measured several times a day using a stake installed in the surface snow. The following data were not obtained from 0910 LST on July 11 to 1020 LST on July 14: air temperature, relative humidity, wind direction, wind speed and atmospheric pressure, because of instrument trouble.

Table 1. List of measured elements and instruments.

Element	Sensor type	Abbreviation
Air temperature	Thermistor thermometer	T_a
Relative humidity	Hygrophiber	H
Wind spped	3-cup anemometer	U
Wind direction	Potentiometer	WD
Atmospheric pressure	Silicon chip	P
Global radiation	Pyranometer	S_d
Snow surface height	Snow stake	H_s

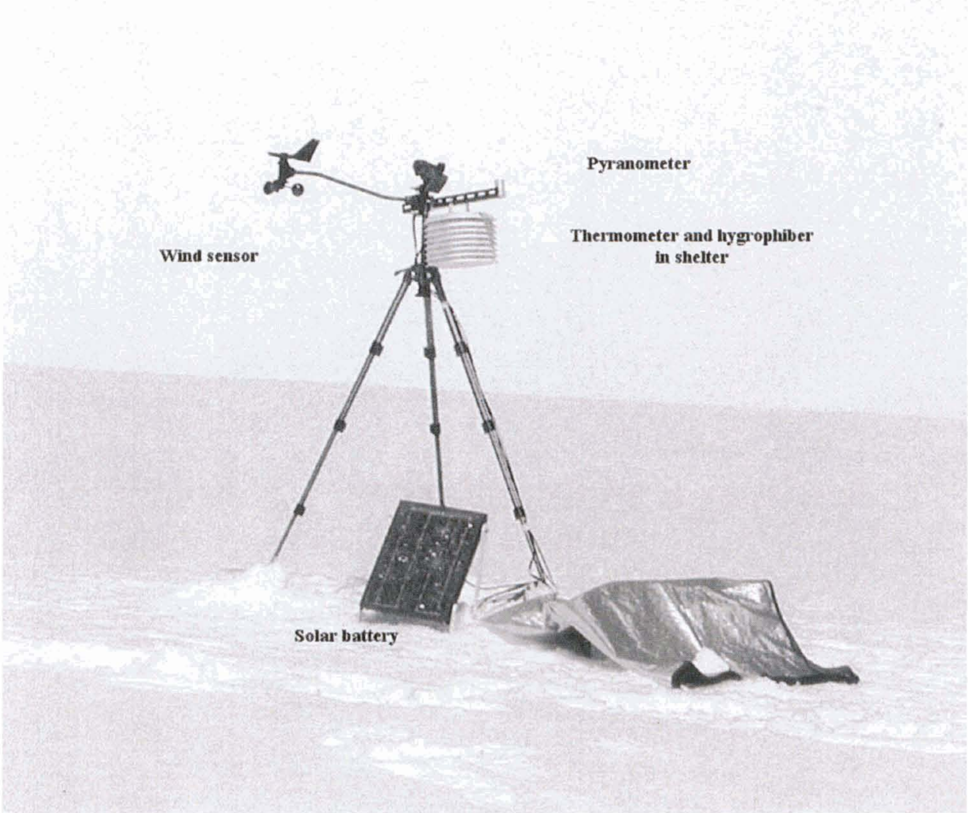

Fig. 2. Meteorological station on Sofiyskiy Glacier. Height of the air temperature sensor is 1 m.

3. Meteorological features

3.1. Global radiation and snow surface height

Fluctuations in global radiation and snow surface height during the observation period are shown in Fig. 3. The snow surface height was taken to be zero at 1200 on July 7 when observation began, and is shown as deviations from the initial height thereafter. The weather was clear almost all day on July 7, 8 and 13; it was cloudy with

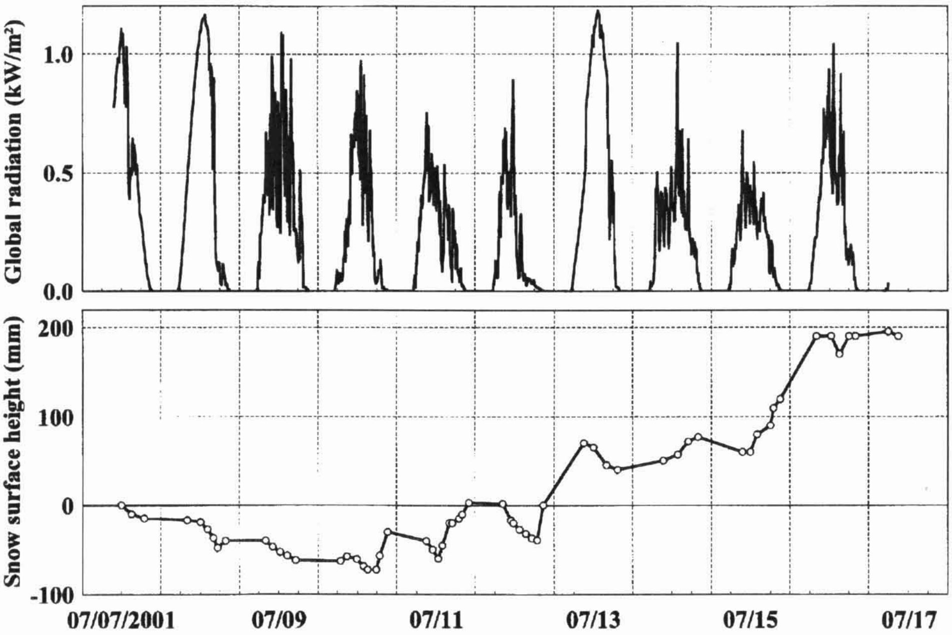

Fig. 3. Fluctuations in global radiation and snow surface height.

intermittent clear weather or snowfall on all other days. Because of these weather conditions, global radiation showed clear daily fluctuations only on July 8 and 13. Global radiation was observed from approximately 0500 on clear weather days and reached its daily maximum value after 1300; it became zero at around 2000. The maximum value of global radiation on fine weather days exceeded 1 kWm^{-2}. Because with the exception of July 7, 8 and 13 it was overcast continually during the observation period, values of global radiation changed intensely in a short period of time. Additionally, there was continuous snowfall on July 15 and the global radiation value for that day was therefore small. There were brief hailstorms around 1800 on July 8, but snow surface height declined smoothly from July 7 to 9 by sublimation and melting. After the evening of July 10, snow fell continuously and snow surface height tended to increase until the morning of July 17 when observation concluded. Snow surface height reached its lowest value of −73 mm at 1800 on July 10; the maximum value was 195 mm, recorded at 0600 on July 17. The net gain of snow surface height during the observation period was 268 mm.

3.2. Air temperature, relative humidity, wind speed and direction, atmospheric pressure, and dew-point temperature

Changes in air temperature, relative humidity, wind speed and direction, and atmospheric pressure are shown in Fig. 4. Because July 7 and 8 had fine weather, air temperature rose during the daytime, reaching 5.1°C on the afternoon of July 8. The relative humidity did not exceed 70% on any day during the observation period; sometimes it dropped to less than 40% during the daytime. From the afternoon of July

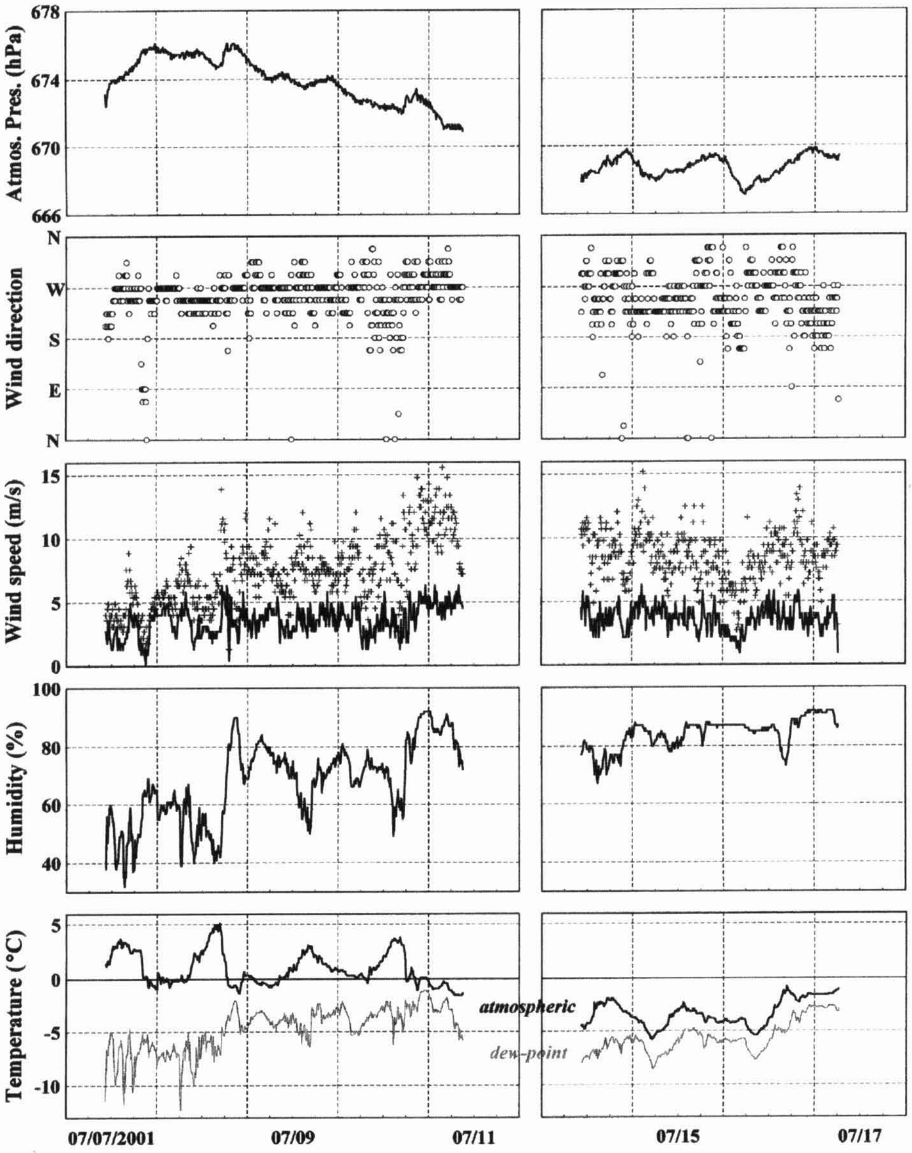

Fig. 4. Changes in air temperature, relative humidity, wind speed (mean and +: maximum instantaneous speed) and direction, and atmospheric pressure.

8, until the afternoon of the 10th, air temperature exceeded 3°C during the daytime, but it fell below the freezing point during the night. During that time, nighttime relative humidity exceeded 80%, falling only to 50% in the daytime. There was snowfall between July 14 and 17 as mentioned above, so air temperature on these days never became positive. Consequently, the relative humidity for these days changed only within a high range of 70–90%.

The wind direction was prevailing from southwest to northwest; the wind was blowing from the upper reaches to the lower reaches of the glacier throughout the observation period. Neither daily fluctuations in wind speed nor fluctuations in wind direction are included in our observations. In wind speed, we experienced variable winds of 2–5 m/s, and maximum instantaneous wind speed data showed occasional winds of more than 15 m/s.

In accordance with the fine weather on July 7 and 8, atmospheric pressure was observed to be about 675–676 hPa, but it fell gradually thereafter beginning on the night of July 8; after July 14, it never exceeded 670 hPa.

Dew-point temperature, which can be obtained from air temperature and relative humidity, is also presented in Fig. 4; note that dew-point temperature fell below -10°C on July 7 and 8.

4. Estimation of heat balance on the snow surface

Based on the observed meteorological data, we estimated the heat balance on the snow surface. Observations of meteorological elements were performed every ten minutes, and heat balance estimates were carried out hourly. By averaging the 10-min interval data for each meteorological element, 1-hour data were obtained. First, the radiation balance was determined using the following formula to calculate net radiation (R_n):

$$R_n = (1-A)S_d + L_d - L_u, \tag{1}$$

where A is albedo of snow, S_d is global radiation, and L_d and L_u are downward and upward longwave radiation, respectively.

Here, the only value determined by direct observation is global radiation (S_d); the other values were established by the following methods.

Albedo (A) was set at 0.75, which was the typical value for wet fresh snow. Upward longwave radiation (L_u) can be determined by the following formula:

$$L_u = \varepsilon \sigma T_s^4, \tag{2}$$

where T_s is snow-surface temperature, σ is Stefan-Boltzmann's constant (5.67×10^{-8} $\mathrm{Wm^{-2}K^{-4}}$) and ε is emissivity of snow. We adopted the value of 0.97 as the emissivity (Kondo and Yamazawa, 1986). The snow-surface temperature was obtained from air temperature by the following assumption:

$$T_s = 273.15\mathrm{K}, \quad (T_a \geqq 273.15\mathrm{K}) \tag{3}$$

$$T_s = T_a. \quad (T_a < 273.15\mathrm{K}) \tag{4}$$

Nakagawa (1977) and Nakagawa and Kayane (1979) suggested the following formulae to find downward longwave radiation (L_d) from air temperature:

$$L_d = 0.70\sigma T_a^4, \quad \text{(clear skies)} \tag{5}$$

$$L_d = 0.85\sigma T_a^4. \quad \text{(cloudy skies)} \tag{6}$$

Changes in net radiation obtained by the method described above are shown in Fig. 5. Note that the net radiation values for both day and night were significantly higher

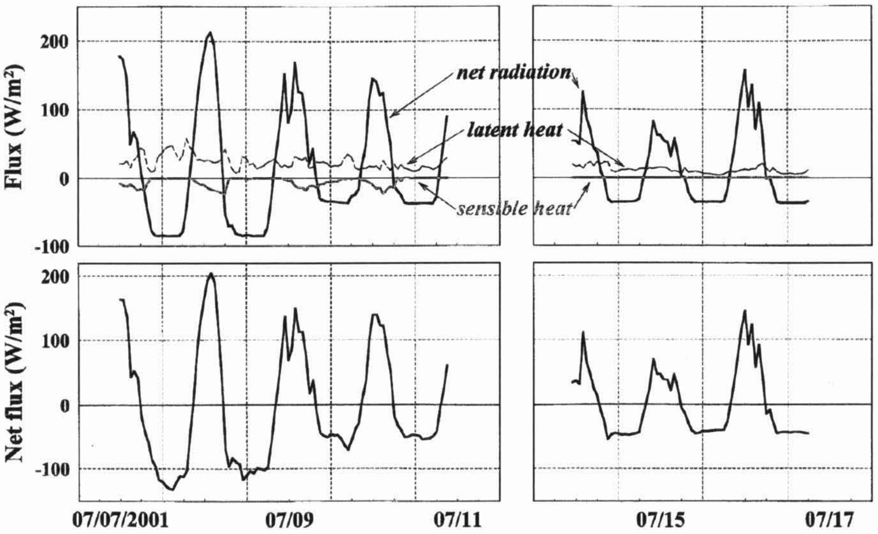

Fig. 5. Changes in net radiation, sensible and latent heat flux, and net flux.

on July 8 than on other days; this is because this was the only date on which the weather was fair for almost the full day.

Next, we calculated sensible heat flux (H) and latent heat flux (iE) by applying the following formulae, respectively, with the appropriate bulk transfer coefficients (Yamazaki, 1998):

$$H = C_p \rho C_H U (T_s - T_a), \tag{7}$$

$$iE = i \rho C_E U (q_{sat} - q), \tag{8}$$

where C_p is specific heat at constant pressure, ρ is density of air, C_H is the bulk transfer coefficient for sensible heat, U is wind speed, C_E is the bulk transfer coefficient for water vapor, i is heat of vaporization of water, q is specific humidity and q_{sat} is saturated specific humidity. Here, the bulk transfer coefficient for sensible heat (C_H) and that for water vapor (C_E) were taken to be $C_H = 0.002$ and $C_E = 0.0021$, respectively (Kondo and Yamazawa, 1986).

The sensible and latent hear flux data obtained by calculation are shown in Fig. 5. Because air temperature was positive in the daytime from July 7 to 10, sensible heat flux was negative as well. Latent heat flux, however, was positive throughout the whole observation period; this indicates that evaporation occurred from the snow surface throughout the observation period.

The net flux (Q), shown in Fig. 5, was found from net radiation, sensible heat flux, and latent heat flux using the following formula:

$$Q = R_n - H - iE. \tag{9}$$

It is assumed that, throughout the observation period, heat was supplied to the snow surface and snow melting occurred during the daytime, and cooling occurred on the snow surface during the nighttime.

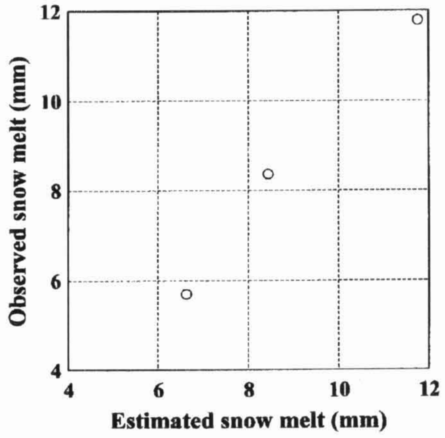

Fig. 6. The relationship between the estimated snowmelt and observed snowmelt.

In order to validate our heat balance estimate, we calculated the amount of snowmelt from July 8 and 10, when snow surface height fell during the daytime. First, observed snowmelt was calculated by determining the amount of meltwater by multiplying the decrease in snow surface height for each of these three days by snow density. Next, the estimated snowmelt was calculated by dividing the time integrated net flux for time, revealing the decrease in snow surface height by heat of fusion. The results of these calculations are presented in Fig. 6. Although the estimated snowmelt value was slightly larger than that of observed snowmelt on July 10, the values of estimated snowmelt and observed snowmelt correspond almost exactly on July 8 and 9.

5. Conclusions

Meteorological investigations were carried out on Sofiyskiy Glacier in the Russian Altai Mountains from July 7 to 17 of 2001 in order to observe the local weather conditions on the glacier. The maximum value of global radiation on fine weather days exceeded 1 kWm^{-2}. Snow surface height reached its lowest value of -73 mm at 1800 on July 10; the maximum value was 195 mm, recorded at 0600 on July 17. The net gain of snow surface height during the observation period was 268 mm. For the first half of the observation period, air temperature exceeded 3°C during the daytime, but it fell below the freezing point during the night. There was snowfall for the latter half of the observation period, so air temperature on these days never became positive. The wind was blowing from the upper reaches to the lower reaches of the glacier throughout the observation period. We experienced variable winds of 2–5 m/s; and maximum instantaneous wind speed data showed occasional winds of more than 15 m/s.

Based on the observed meteorological data, we estimated the heat balance on the snow surface. The net radiation values for both day and night were significantly higher on July 8 than on other days; this is because this was the only date on which the weather was fair for almost the full day. Because air temperature was positive in the daytime from July 7 to 10, sensible heat flux was negative as well. Latent heat flux, however, was positive throughout the whole observation period; this indicates that evaporation occurred from the snow surface throughout the observation period.

Although the estimated snowmelt value was slightly larger than that of observed snowmelt on July 10, the values of estimated snowmelt and observed snowmelt corresponded almost exactly on July 8 and 9.

Acknowledgments

These observations were supported by a Grant-in-Aid of the International Scientific Research Program of the Ministry of Education, Culture, Sports, Science and Technology, Japan (Principal investigator: Prof. K. Kamiyama of NIPR, 11208202).

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(Received February 21, 2002; Revised manuscript accepted June 6, 2002)