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Satellite observation of melting and break-up of fast ice in Lützow-Holm Bay, East Antarctica

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Abstract: Lützow-Holm Bay, East Antarctica is covered entirely by multi-year fast ice, almost every year, but this fast ice breaks up periodically, with several years between break up events. A large break-up started in March 1997, and reached its maximum at the end of March 1998. Two thirds of the fast ice in the bay was blown out. Melting features in the fast ice and surrounding ice sheet slope were observed by high resolution ADEOS AVNIR visible data in 1997.

Since there are periodic break ups of the fast ice in Lützow-Holm Bay, warmer climate conditions and an increase in melting are investigated and compared with the occurrences of fast ice break up. The interannual variation of melting in the coastal zone was estimated by using the passive microwave brightness temperature. The gradient ratio of horizontal channels of 18/19 GHz to 37 GHz of SMMR and SSM/I was used to detect the melting duration of each summer from 1978/79 to 1998/99. A long melting period was estimated to have occurred in summer 1996/97 before the large break up; similar relationships were observed in the previous break-ups. The fast ice area has large variability in the number of melting days compared to the ice sheet slope zone, and it will be sensitive to the air temperature change in the coastal zone.

1. Introduction

Break up of huge shelf ice has been reported in Antarctica (Doake and Vaugham, 1991; Skvarca, 1994; Rott *et al*., 1996; Keys *et al*., 1998; Yamanouchi and Seko, 1992). The climatological relationships and changes in mechanical strength were investigated by Rott *et al.* (1998). The coastal zone of Antarctica can be sensitive to global warming through melting, as the summer air-temperature range is around the melting point of ice. Thus, ice shelves and fast ice areas are sensitive to changes of air temperature.

This study focuses on a multi-year fast ice area in Lützow-Holm Bay, East Antarctica. The fast ice in this bay is multi-year fast ice, however, it is not stable as it has been broken and blown out of the bay every few years. Thus, the ice thickness is few metres. Although annual growth of new ice formation is about 1 m in the first year, there are unique ice growth processes in summer and the thickness can increase several tenth centimeters in summer (Kawamura *et al*., 1997). This is due to heavy snow cover in this region. Although ice shelves are formed near most large glaciers in

East Antarctica, no shelf ice is formed in Lützow-Holm Bay. One of the fastest glaciers in Antarctica, Shirase Glacier (Fujii, 1981; Nakawo *et al*., 1990), flows into this bay and the floating glacier terminus tends to disintegrate when the fast ice is blown out (Nishio, 1990). Thus, the fast ice condition is an important factor for the ice margin change along the coast.

Warm air-temperatures and increased melting are considered to cause weakening of the fast ice cover. There have been large break ups of fast ice. In the case of the break up in March 1980, the influx of large swell into this bay was examined as the cause of the break (Higashi *et al*., 1982). The break up in 1980 occurred in autumn. The climatological condition for the break up is the object of the present study. This study investigates especially possible ice conditions of the previous summer.

Kawamura *et al.* (1997) found evidence of snow melt over the fast ice in Lützow-Holm Bay. From ice core analysis, they pointed out the possibility of upward ice growth processes of fast ice due to the snow ice formation and refreezing of the melt water of snow over ice. The interannual variation of this process and any trends are strong concern for the climatological approach to coastal ice change investigation. This study attempts to observe the occurrence of melting using satellite data and then describes its interannual variations.

There have been some previous studies of melting distribution over the ice shelf, ice sheet and sea ice. Phillips (1998) used satellite images with high spatial resolution to show the melt distribution over Amery Ice Shelf. Melting of sea ice around Antarctica was studied by Drinkwater *et al.* (2000) using active microwave sensors. They obtained valuable data on temporal and spatial variation of sea ice melting. Surface melting of snow cover on sea ice increases the liquid water content, which then influences microwave signals from the sea ice. Drinkwater and Lytle (1997) discussed influences of flooded water over the sea ice in summer, as the ice became porous due to ice temperature rise in summer. Kawamura *et al.* (1997) noted that both upward percolation of seawater through sea ice, which produces so-called snow-ice, and meltwater of snow on sea ice can exist and increase the liquid water content of snow on sea ice with much snow cover.

First, visible satellite data are used to identify possible melting features in the Lützow-Holm Bay area. Then, this study attempts to detect melting over fast ice using passive microwave data. There are some techniques of observation for ice sheet melting. Zwally and Fiegles (1994) analyzed melting patterns in Antarctica using Nimbus-7 SMMR data and found a large interannual variation in 1978–87. A significant increase in brightness temperature was used to detect melting. Steffen *et al.* (1993) analyzed melting patterns in Greenland with a melting index calculated from the gradient ratio of two passive microwave channels, 19 GHz (V) and 37 GHz (H). These techniques were used for ice sheets, but the present study attempt to apply similar technique of passive microwave analysis to a large fast ice area. In addition, open water signal from the passive microwave data provides evidence of fast ice break up. The present study uses the gradient ratio as a melt-index and compares it with observational data at Syowa Station (69°00′S, 39°35′E).

Since satellite observations of microwave brightness temperature have coarse spatial resolution, individual melting patterns cannot be observed, but only an areal mean melting signal is available. However, it is still useful for observing a large melt area over fast ice or an ice sheet. An advantage of using passive microwave data is the long observation record, as the passive microwave data by SMMR and SSM/I cover a twenty-year period. A long-term record of break ups is available in the study area. This study utilizes the snow depth data from Syowa Station. This study considered the timing of melting/freezing, which is shared in common with the surrounding area, and then this study compared the satellite estimation with snow depth decrease in summer as measured by the snow-stake farm near Syowa Station.

2. Satellite and field data

This study used satellite observation data sets from optical sensors, AVHRR (Advanced Very High Resolution Radiometer) and AVNIR (Advanced Visible and Near Infrared Radiometer), and passive microwave sensors, SMMR (Scanning Multichannel Microwave Radiometer), SSM/I (Special Sensor Microwave/Imager). Figure 1 shows the map of Lützow-Holm Bay and the AVNIR, SMMR and SSM/I observation area used in this study.

Two field data sets are available in this study. Air and snow/ice interface temperature data, which were recorded hourly in 1993/94 summer by an automatic weather station set in the fast ice area 1 km north-east of Syowa Station. When the snow temperature sensor was recovered at the end of observations (31 January, 1994), the sensor was placed at the bottom of the 0.5 m snow cover on the ice surface. As Syowa Station is located on the Ongul Islands and surrounded by the multi-year fast ice, the air and snow temperature and snow observation sites are set in this fast ice area.

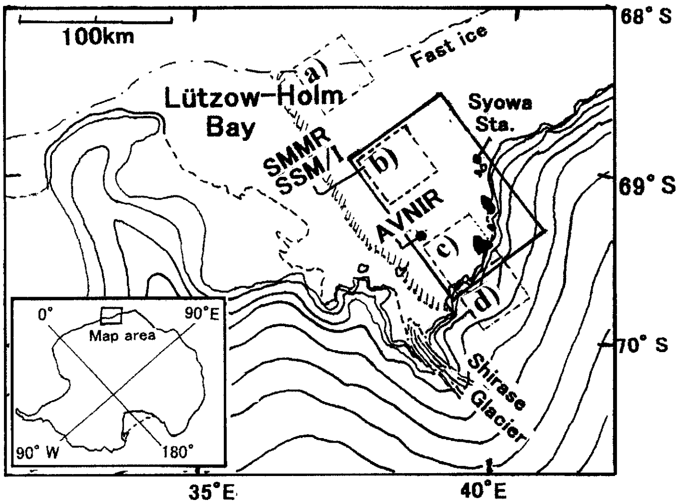

Fig. 1. Map of Lützow-Holm Bay and observation area of AVNIR, and approximate observation pixel of SMMR and SSM/I for a) fast ice edge, b) fast ice near Syowa Station, c) coastal zone and d) slope. Break-up of 1997–98, in the eastern part of the bay, is indicated by dotted line.

Snow depth was observed every 10 day from 1978 to 1998 by Japanese Meteorological Agency personnel at the snow stake farm (10×10 stakes at 10 m intervals) set on the fast ice near Syowa Station. This snow stake farm was displaced periodically after a few years, but fixed after 1989. Thus the snow depth could be affected by different local wind conditions in different years; however, the significant decrease of snow depth in the melting period is considered to occur concurrently over the broad fast ice in Lützow-Holm Bay. Although the observations are limited in a small area, the data are useful to verify the satellite estimation of the start of melting.

Monthly mean air temperature observed at Syowa Station was used in this study. Summer mean air-temperature was obtained from data November to February and compared with the melting.

3. Melting features

A high resolution visible and near infrared radiometer (AVNIR) were used to describe the variability of the conditions in Lützow-Holm Bay (Fig. 2). The satellite images were acquired on 31 January and 4 February 1997. Puddles are distributed along the coastal zone (Fig. 2a). On the coastal slope of the ice sheet (areas A and B in Fig. 2a), melting features were evident. Figure 2b shows a pond at the lower edge of a snow patch in the bare ice field on the coastal slope of the ice sheet. There are signs of outlet streams from the pond. Figure 2c shows streams of water in the snowfield on the ice sheet. These images show that the fast ice and the coastal slope of the ice sheet were affected by melting in summer. There was continuous melting, more than one month, in summer 2000/2001 on the neighboring glacier surface (Nishimura, personal communication).

The large break started in March 1997 and reached its maximum in March 1998. Approximately 10^4 km of ice area disappeared. Figures 3a and b show the sea ice coverage in the Lützow-Holm Bay area observed on 9 August 1997 and 23 March 1998 by NOAA AVHRR. These images show an occurrence of break up of the fast ice before winter in 1997 and blown-out of ice in summer 1997/1998. It is the largest such event in the observation record of the Japanese Antarctic Research Expedition since 1957.

4. Detection of melting

In order to detect the occurrence of snow melting from space, this study utilized the gradient ratio (GR) of the horizontal polarization channels of 18 and 37 GHz for SMMR and 19 and 37 GHz for SSM/I. Brightness temperature (*TB*) of snow increases when the liquid water content of snow increases. Therefore, by observing the abrupt rise of *TB,* snow melt can be detected (Zwally and Fiegles, 1994). This signal became more significant in the changes at 19 GHz than 37 GHz; thus, by differentiating TBs (ΔTB) at the two frequencies, the melt signal became more stable (Steffen *et al*., 1993). To reduce the influence of temperature change of snow on TB, ΔTB was divided by the sum of *TB*s. Since the horizontal channel of *TB* shows higher variability in summer, this study applied GR to horizontal channels. Steffen *et al.* (1993) used

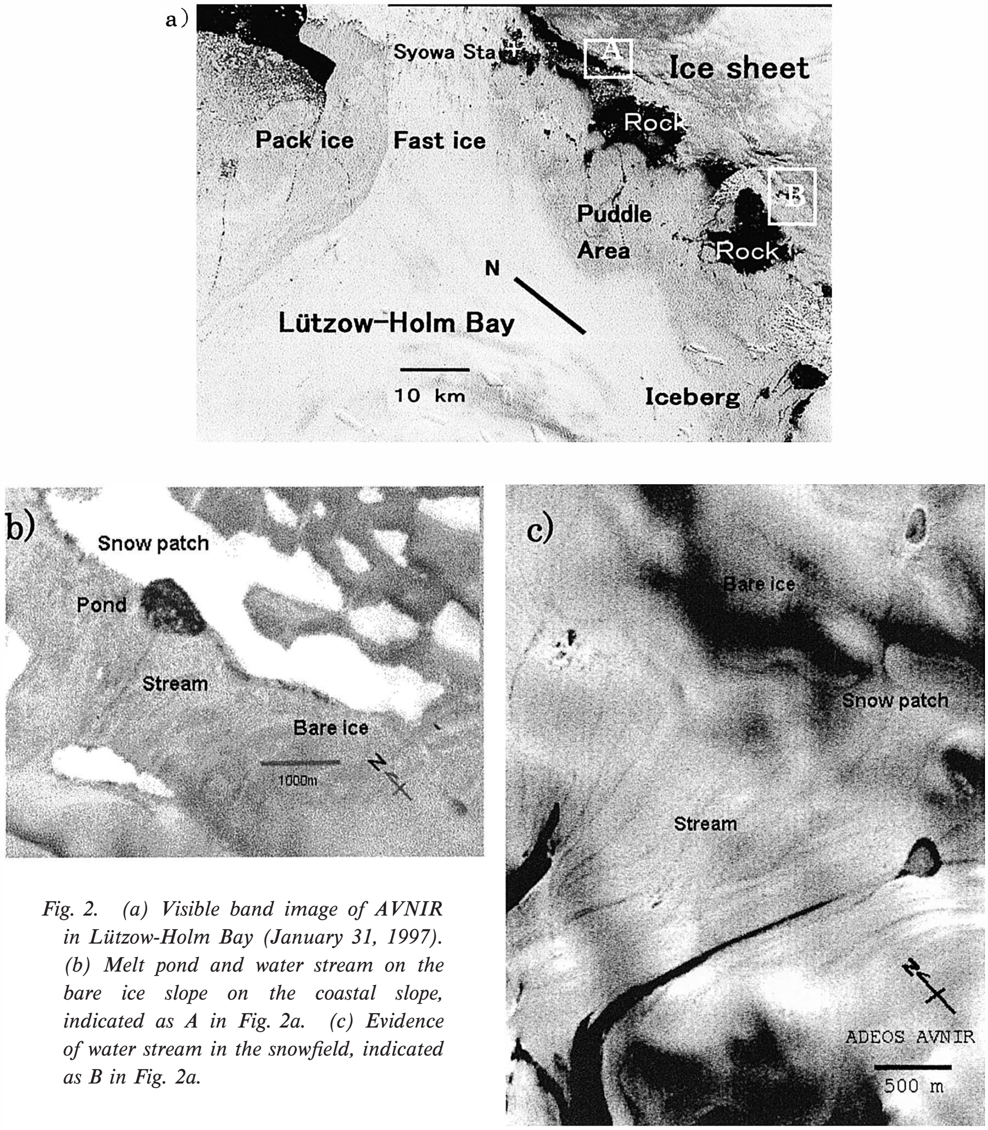

Fig. 2. (a) Visible band image of AVNIR in Lützow-Holm Bay (January 31, 1997). (b) Melt pond and water stream on the bare ice slope on the coastal slope, indicated as A in Fig. 2a. (c) Evidence of water stream in the snowfield, indicated as B in Fig. 2a.

cross GR using the horizontal 37 GHz channel and the vertical 19 GHz channel and applied on the ablation zone in the Greenland. These GR analysis seems be useful on a bare ice field. This study used the horizontal channels for both bands. There is little difference in the analysis of the fast ice of Lützow-Holm bay.

GR was compared with air temperature and snow/ice interface temperatures in summer 1993/94 (Fig. 4). Snow/ice interface temperature increased gradually prior to 21 December 1993, then increased more rapidly until it reached 0°C on 25 December (Fig. 4a), due to meltwater percolation through the snow. The snow/ice interface temperature was 0°C during the refreezing of meltwater on the sea ice surface.

On 29 December, snow/ice interface temperature quickly dropped to -1.5°C and

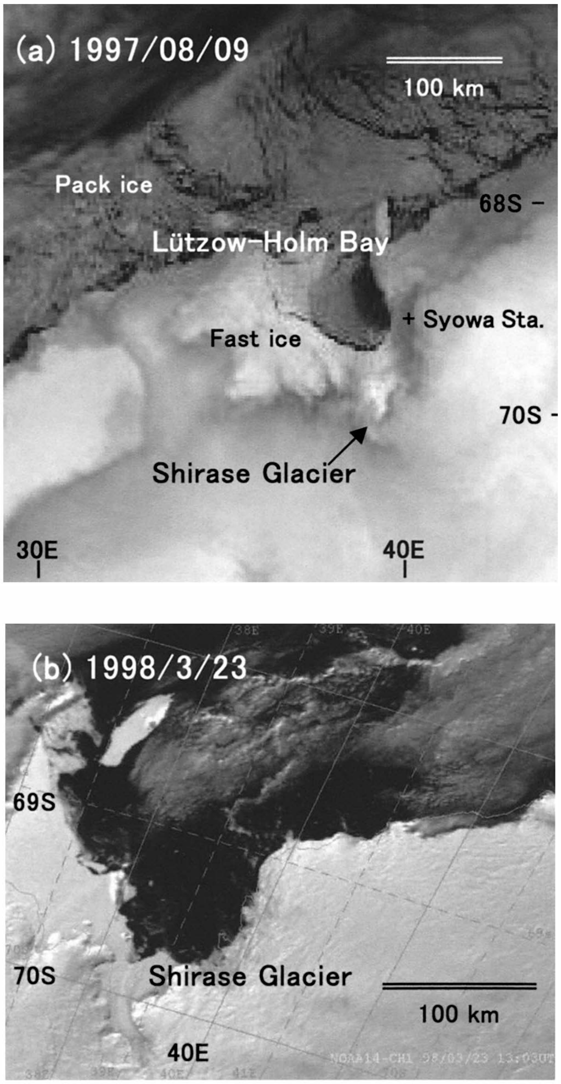

Fig. 3. NOAA AVHRR image of Lützow-Holm Bay on (a) 9 August 1997 (Thermal infrared band) and on (b) 23 March 1998 (Visible band).

showed little fluctuation for a week. This could be due to the upward percolation of seawater through the ice. Sea ice has permeability of sea water above -5°C (Drinkwater *et al.*, 2000). In such case, the snow ice can be formed at the bottom of snow cover. The snow/ice temperature increased gradually in January to 0°C. The TB of snow increases when the liquid water content of snow increased slightly—as much as few percent.

Figure 4b shows the variations of *TB*. The TBs began to increase in December but decreased after 20 December. GR became larger after 20 December and decreased in February. This is because *TB* of 37 GHz decreased significantly more than which *TB*

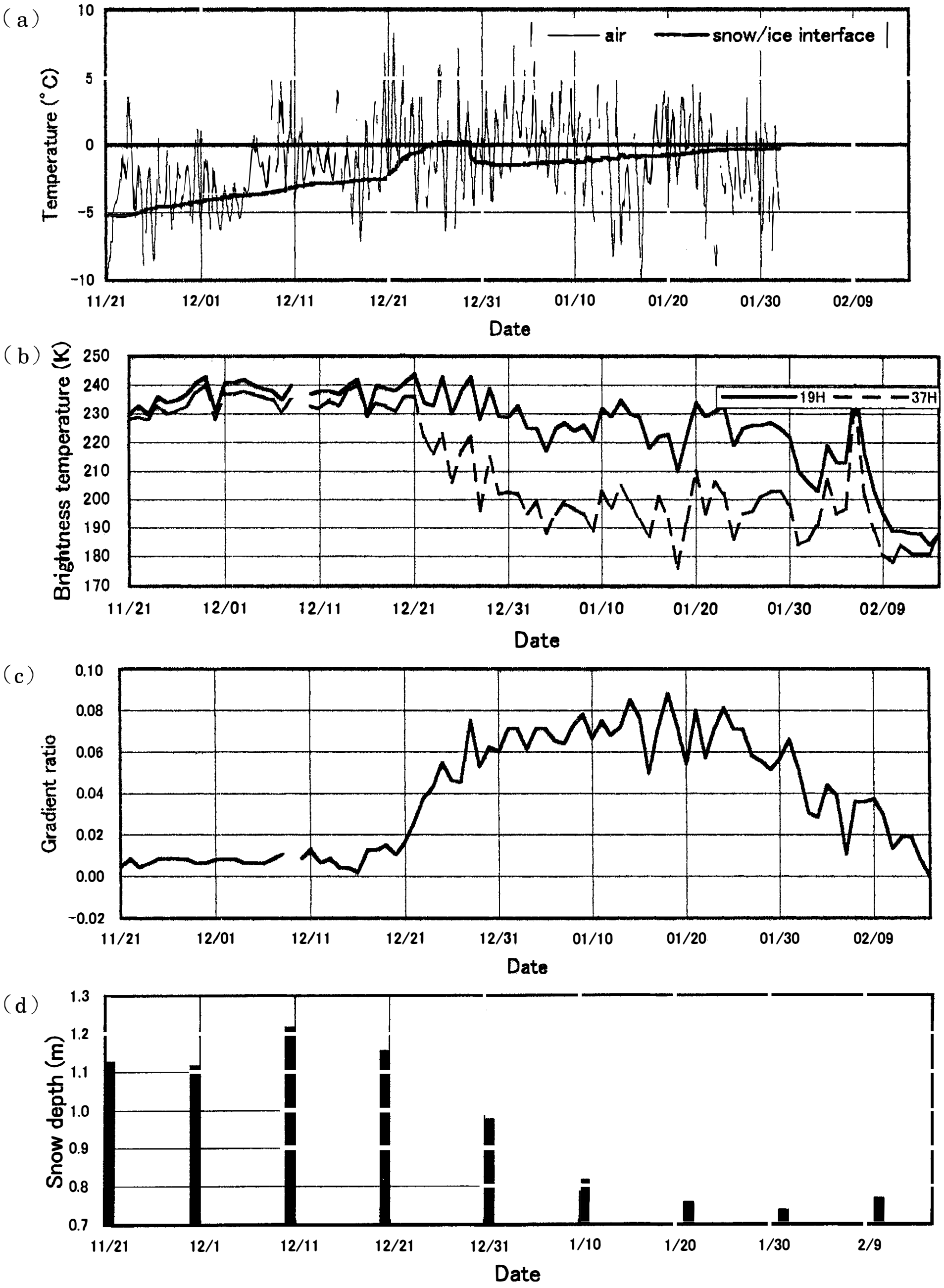

Fig. 4. (a) Air and snow/ice interface temperatures hourly observed at the automatic weather station on the fast ice near Syowa Station (69°00′S, 39°35′E) for the period 21 November 1993 to 31 January 1994. (b) Daily variations of brightness temperatures of 19 GHz (H) and 37 GHz (H) Station from 21 November 1993 to 15 Febrauary 1994. (c) Variance of melt index expressed as the gradient ratio of 19 GHz and 37 GHz channel of SSM/I data for the fast ice near Syowa. (d) Snow depth data near Syowa Station by JARE.

of 19 GHz decreases. Increase of *TB* has been used as the indicator of melting in a snow field; however, it seems to be not useful in this fast ice area. Water surface such as pond on sea ice or open water and snow with much water causes falling *TB* since water has low emissivity for the microwave. On the other hand, as GR has different sign for melting and open water, the GR is useful for melting and it indicates steady signals of melting of fast ice area.

Figure 4c shows a significant rise of GR obtained at the data pixel of the fast ice area near Syowa Station for the melting period as indicated in Fig. 4a. GR rises in summer and decreases when the snow cover cools off. Based on the steep increase of GR, the melting was identified. Snow stake data near the Syowa Station are shown in Fig. 4d. This snow stake data shows that snow depth started to decrease between 11 and 20 December, and a significant decrease occurred after 21 December. At the end of January, air temperature fell below 0°C and the snow depth showed little change. Thus, this period was the end of melting season. At the beginning of February, the snow depth started increasing and high GR period ended in 10 February. For detecting melting, GR value was used and its threshold value was chosen to be 0.02 from these steep shifts of GR.

A steep increase of GR indicates a melting signal, and daily variation of GR was small; thus the dates of start and end of melting period were utilized. The start and end dates of melting were determined from the first and last days when GR exceeded the threshold. Although there were increases of GR in winter, this is not due to melting but possibly due to colder surface temperature and larger snow depth. Thus, the melt was estimated for the five summer months, November to March.

When the open water expands, GR becomes negative (*i.e.* 37 GHz (H) > 19 GHz (H)), corresponding to the TB range of the open water. Thus, break ups can be identified when GR decreases greatly.

5. Interannual variability of melting

The passive microwave data of SMMR and SSM/I cover more than twenty years since 1978. Figure 5 shows variations of GR obtained for the fast ice in 1978–1998. Figure 5a shows the variation at the edge zone of fast ice (Fig. 1) and Fig. 5b shows that in the interior of the fast ice, near Syowa Station (b in Fig. 1). GR was obtained every 2 days from SMMR data and every day from SSM/I. There were no data in December 1987 when the data of two sensors in the pixels of Lützow-Holm Bay are missing. There are large decreases of GR below -0.05. This negative GR indicates open water in the Bay, indicating that there were break-ups and expanding open water. Figure 5 a shows break ups of fast ice almost every year. On the other hand, Fig. 5b can indicate mainly occurrences of large break ups. Sea ice conditions were reported in the JARE wintering reports. Occurrences of break up are indicated with solid circles in Fig. 5. In 1988, there was a large break up but ice was not blown out from the bay (Yamanouchi and Seko, 1992). In such case, the observations of break up were limited.

From these GR data in the Lützow-Holm Bay, the melting dates were identified for each year. Numbers of melting days were estimated in the fast ice area near Syowa

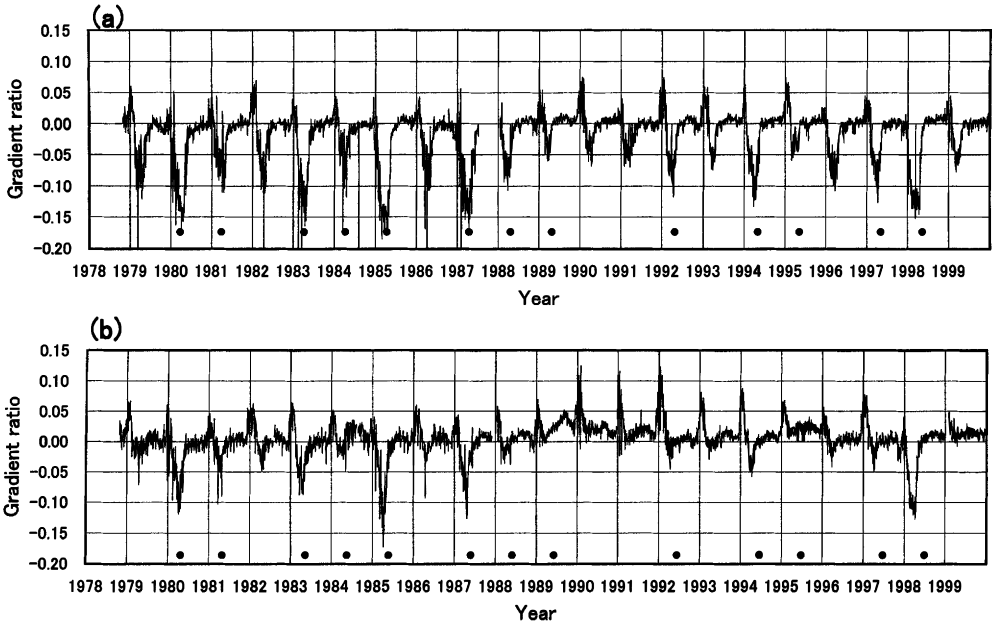

Fig. 5. Twenty years (1978–1998) of gradient ratio (GR) of (a) fast ice edge zone and (b) fast ice area near Syowa Station. GR is almost zero for sea ice in the cold period. The summer peaks indicate occurrence of melting. The great decreases of GR indicate open water due to break up of the fast ice. Recorded break ups were indicated with dots. The melting period is identified when GR exceed 0.02. As sea ice cooling in winter shows a similar value, the melt signal was identified from the summer months (November to March).

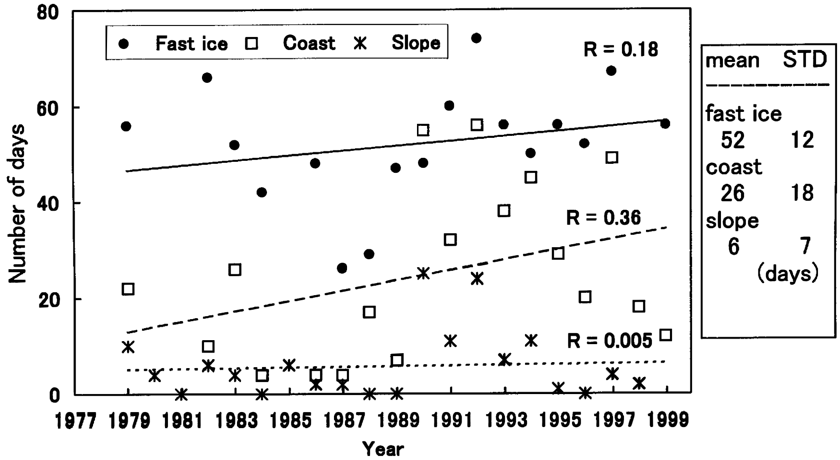

Fig. 6. Number of melting day estimated by GR for fast ice near Syowa Station, coast and slope area.

Station, coastal and on the slope (approximate positions are indicated as c and d in Fig. 1). The fast ice area shows large number of melting day, while the slope region shows a small number of melting day. The mean number of melting day and its standard deviations are shown in Fig. 6. The fast ice area shows large interannual variability of melting days. Fast ice and coast showed increasing tendency but the slope area showed little trend. In 1980, 81, 85 and 1998, the melt signal was not obtained sufficiently in the fast ice area and coastal zone of ice sheet. TB data from ice was not obtained because the fast ice was broken and removed in summer. The absence of these data affects the calculation of the trend. There are uncertainty in the trend in the fast ice and coast area.

The melting start, end and duration (end date minus start date) for the fast ice area in Lützow-Holm Bay are shown in Fig. 7, with the summer mean air temperatures (November, December, January and February). The duration was obtained in the fast ice area. The duration was not obtained at the coast and slope areas, since the melting was not observed continuously on the slope area. The melt duration on the fast ice was

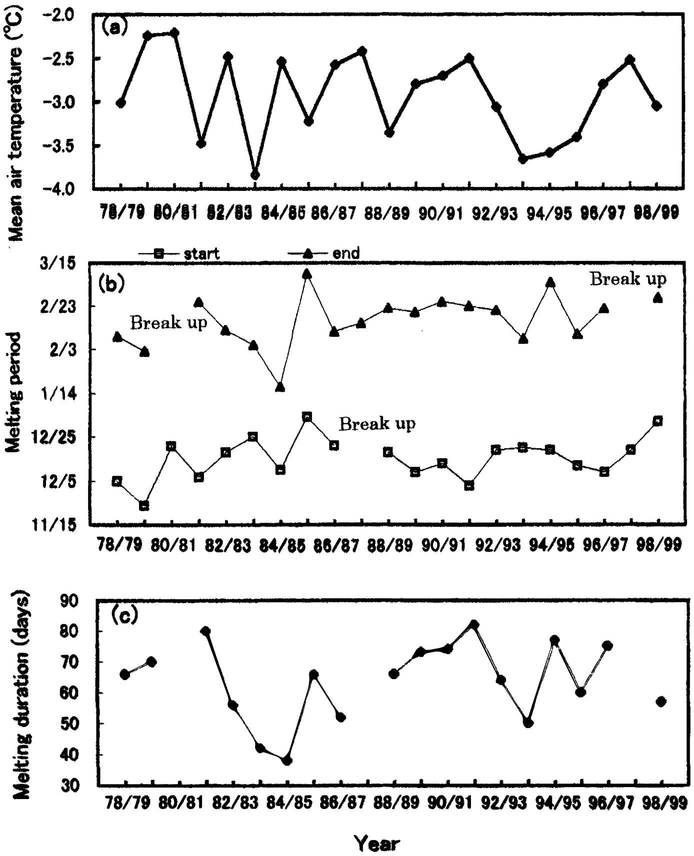

Fig. 7. Interannual variations of (a) summer (November–February) air temperature, (b) the date of start and end of melting period and (c) melting duration in the fast ice.

estimated to be 64 days on average, and varied from 38 days to 82 days. The standard deviation was 13 days. There were large interannual variability and the melting duration was correlated with the summer mean air temperature. Since the summer mean air-temperature fluctuated over a 4–5 year period, large break ups of the fast ice occurred with similar frequency. The air temperature data before the break up 1997 shows relatively high in November 1996. It may have been the trigger for an early melting in this summer in 1996. The date of melt-start shows a slight tendency of delay through the analzed period (Fig. 7b). The date of melt-end has large variability (Fig. 7b) and it affected the melting duration (Fig. 7c).

6. Discussion

6.1. *Melt duration and trends*

This study estimated melt-duration of 64 days on average in the Lützow-Holm Bay. The number is large compared to the data over the ice sheet (Zwally and Fiegles, 1994) and over the pack ice (Drinkwater *et al.*, 2000), and similar to the data over the ice shelf (Torinesi, personal communication). We estimated the melting duration on the coastal slope near the terminus of Shirase Glacier. It showed the concurrent fluctuations with those of fast ice but the length of melt duration was 20 days shorter on average.

From 1978 to 1998, there has been a slight tendency toward increased melting duration in Lützow-Holm Bay. Zwally and Fiegles (1994) showed a tendency toward decreasing melting in East Antarctica, Dronning Maud Land and Amery Ice Shelf sectors, during the period 1978–1987. Torinesi (personal communication) showned a tendency toward increasing melt duration on the ice shelves on the Antarctic Peninsula. Ice shelves and fast ice in Lützow-Holm Bay show a longer melt period than over the ice sheet, and increasing trend. Since there are large variations in the melt period data, the trend estimated for Lützow-Holm Bay is not significant statistically. However, the fast ice and shelf ice showed different tendency from the tendency known for the ice sheet.

6.2. *Snow depth change*

The estimated melt period was compared with the snow depth data obtained from the snow stake farm (Fig. 8) near Syowa Station. Snow depth data indicate rapid decrease in the melting season (Fig. 8a). The melt period derived from passive microwave data corresponds well to the period of decrease of snow depth.

Figure 8b compares the date of melting start estimated by the GR and snow depth data observed every 10-day. Using the snow depth data, start of the melting was identified by observing the change of decreasing rate of snow depth, as twice larger than the change of the previous interval. As there are uncertainties of observation interval for identifying the exact timing of surface lowing, thus the start of melting was indicated with a bar of 10 days-long started from the previous observation date. When little snow was recorded, the snow depth data was not used for this comparison. In this case, strong local conditions were expected. Consequently, 14-years cases were compared between 1978–1997. The correlation coefficient was 0.72 (significant with 1% confidence level) when the relative variations were compared, however, the correlation coefficient decreased to 0.50 when the absolute dates were compared. The satellite

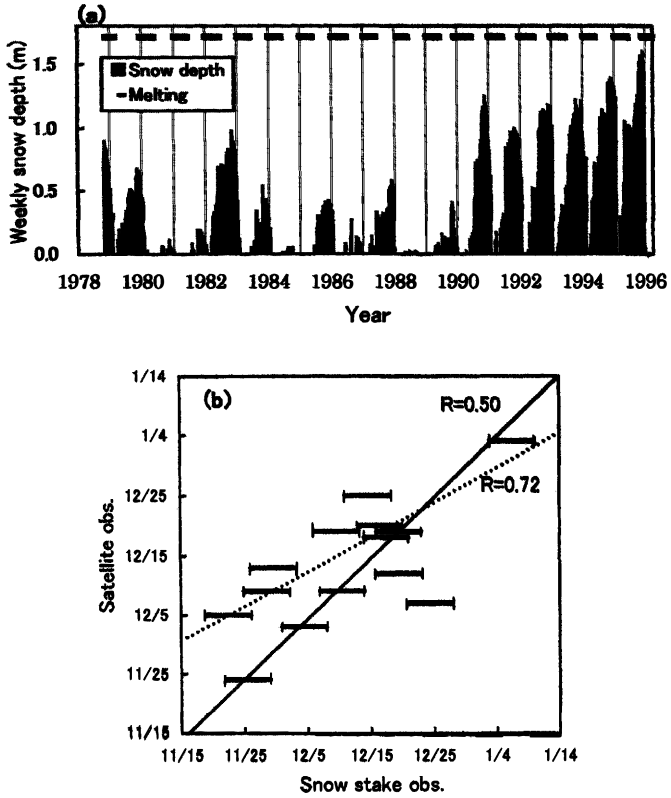

Fig. 8. (a) Comparison of snow depth near Syowa Station and melting period described by the melting index (GR). (b) Comparison of the start date of melting estimated from snow depth data and satellite observation.

estimation of melt start tends to be later. Surface lowering started before the snow melt in spring. The standard deviation between the two melt-start data, the satellite and snow stake estimation, was 6.9 days.

There were interannual variations of snow depth, with an especially significant increase after 1990. However, the snow depth might be affected by different local wind conditions as the observation sites were displaced before 1988. Using the maximum snow depth data after 1989, the maximum snow depth and the start of melting were compared. There is a slight tendency of late melt start in the year of heavy snow. However, the relationships are not clear.

6.3. *Break up of fast ice*

The fast ice in this area has been broken after only a few years growth, thus variation of ice thickness may not be an essential factor in the ice break up. Higashi *et al.* (1982) analyzed the breaking mechanism of fast ice by swells with various periods. Thick fast ice can be broken by a swell with longer period but thin fast ice might not be broken by same swell. This could be a cause of break up of fast ice after growth in a few years.

On the other hand, the present study shows warmer air-temperature and longer melting period in the preceding summer, possibility a case of climatological preconditioning for a large break up. Higher air-temperature in summer increases meltwater supply and also warms sea ice, then increases upwelling of water through ice. It could affect on the mechanical strength of ice. These changes in water content might be important factors in initiating the break up. The combination of the preconditioning by warmer air-temperature in summer and following swell in autumn might affect the break up of fast ice.

Field observation on vertical motion of ice and wave condition off the Lützow-Holm Bay will be needed for further study. SAR data on wave and surface melting will be effective for further study.

7. Conclusions

Melting duration was analyzed for the period 1978–1998 in Lützow-Holm Bay, where fast ice has broken up periodically at intervals of about 5 years. The gradient ratio of microwave brightness temperature is used to derive a melt index as an indicator of interannual change. The melting duration estimated by this analysis was 64 days on average over 1978–1999.

The interannual variations of melt duration were obtained and the results show that melting duration was longer before the large break up events. A large break up of fast ice in Lützow-Holm Bay started in March 1997 and became its maximum in the end of March 1998. This break up started after a longer melting period in the previous summer; *i.e.* the 1996/97 summer.

We used the passive microwave sensors as they provide a long-term data useful for climatological discussions. The fast ice area has large number of melting days and high variability. Data pixels for the fast ice and ice shelf could be sensitive to the air-temperature change. On the other hand, for the ice sheet slope zone, the spatial resolutions of passive microwave sensors are too coarse for observe the relatively narrow coastal regions where ice melting can occur. Since the temperate zone in the Antarctica may be great concern for the ice margin change, observations of the coastal zone, by improved sensors, might be required.

Acknowledgments

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