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Article

Different Climate Regimes Over the Coastal Regions of the Eastern Antarctic Ice Sheet

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Abstract : For ten firn cores, from both the eastern and the western side of Lambert Glacier basin (LGB), snow accumulation rate and isotopic temperature were measured for the recent 50 years. Results show that snow accumulation for five cores over the eastern side of LGB (GC30, GD03, GD15, DT001, and DT085) at Wilks Land and Princess Elizabeth Land increases, whereas it decreases at the western side (Core E, DML05, W200, LGB16, and MGA) at Dronning Maud Land, Mizuho Plateau and Kamp Land. For the past decades, the increasing rate was 0.34-2.36 kg m^{-2} a^{-1} at the eastern side and the decreasing rate was –0.01-–2.36 kg m^{-2} a^{-1} at the western side. Temperatures at the eastern LGB were also increased with the rate of 0.02‰ a^{-1}. At the western LGB it was difficult to see clear trends, which were confirmed by instrumental temperature records at coastal stations. Although statistic analysis and modeling results display that both surface temperature and accumulation rate has increased trends in Antarctic ice sheet during 1950-2000, the regional distributions were much more different for different geographic areas. We believe that ice-core records at Wilks Land and Princess Elizabeth Land reflect the real variations of SST and moisture change in the southern India Ocean. For the Kamp Land and Dronning Maud Land, however, circulation pattern was different, by which the climate was more complicated. The International Trans-Antarctic Scientific Expedition (ITASE) aimed to reveal an overall spatial pattern of climate change over Antarctic ice sheet for the past 200 years. This study points the importance of continental to regional circulation to annual-decadal scale climate change in Antarctica.

Key words : antarctic ice sheet, Lambert Glacier basin (LGB), climate change, firn core.

1. Introduction

Dramatic warming of both hemispheres during the past century has been highlighted by both observation and simulations (Wu *et al.* 1999; Fyfe *et al.* 1999). The overall impact of global warming on Antarctic mass balance would be enhancing ocean evaporation and thus increasing the surface accumulation. Since the margin calving and ice flow is not accelerated, the mass of Antarctic ice sheet will increase, leading to lowering the sea level. Despite the general increasing trends of both temperature and accumulation rate for the past century, temperature and accumulation rate recorded in the ice cores at different sites on Antarctic ice sheet are much different. For instance, although increasing accumulation rates have been reported from previous studies (Peel and Mulvaney 1988; Morgan *et al.* 1991; Pourchet *et al.* 1983; Mosley-Thompson *et al.* 1995), others showed opposite trend (Kameda *et al.* 1990; Graf *et al.* 1990; Bindschadler *et al.* 1993; Ren *et al.* 1999; Isaksson and Karlén 1994). A similar pattern is apparent for the isotope temperature records (Isaksson *et al.* 1996; Ren *et al.* 1999; Xiao *et al.* 2001).

The complexity of climate history in Antarctica has been observed not only by ice cores, but also by the

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instrumental records at meteorological stations all over the continent (Jones 1995). Following reasons may cause the mechanism for the complexity. First, there is a lack of high latitude/low latitude link particularly due to the nature of the Southern Hemisphere atmospheric circulation. It does not favor strong north-south energy exchange, due to the relatively small meridional amplitude of the long waves and to the strong circum polar circulation around Antarctic continent. Secondly, the air-sea-ice interactions over different sectors of the Southern Ocean divide different climatic regimes corresponding to the sectors of the Antarctic continent. This may be relevant to an important factor that was called Antarctic Circum-polar Wave (ACW). In this paper, we will show climatic conditions are different between the eastern and western sides of Lambert Glacier basin (LGB), based on the firn-core records that temporally cover the past half centuries.

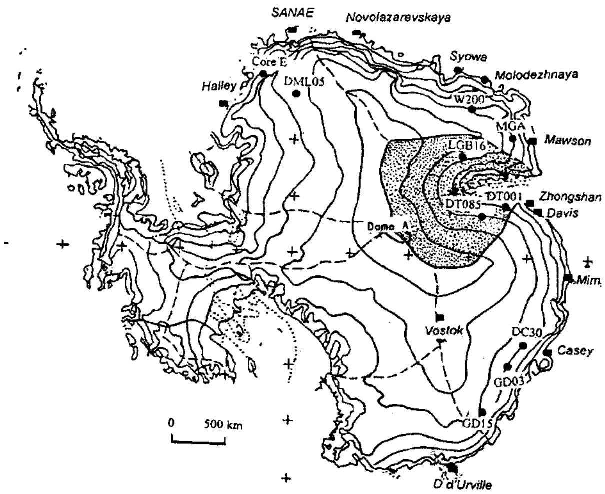

Fig. 1. Location map of the firn cores (dots) and meteorological stations (squares) discussed in this study. The gray-shading area is Lambert Glacier basin.

2. Data resources and restrictions

The Lambert Glacier basin, with area 1320×10^3 km^2, and an overall accumulation 87 kg m^{-2} a^{-1}, is one of the largest glaciers in East Antarctica, drainaging approximately 10% of the east Antarctic ice sheet (Higham and Craven 1997). It is flanked by the Princes Charles Mountains and discharge into Prydz Bay via the Amery Ice Shelf (Fig. 1). Several shallow cores (within 100 m in length) have been retrieved from the two wings (eastern and western) of LGB during the past 10 years, of which results provide a possibility for differentiating the climatic regime of the drainage area (Xiao *et al.* 2001).

Ice cores have been extracted at the sites of DT001, DT085, LGB16, MGA and DC30 by Chinese scientists together with Australian scientists. DT001, DT085 and LGB16 are within LGB, which is close to MGA (Kamp Land). Cores of DC30, GD03 and GD15 at Wilks Land, as well as Core E, DML05 and W200 at Dronning Maud Land were selected for comparison (Table 1). The five (LGB16, MGA, W200, DML05 and Core E) of ten cores are located at the western side to the central axis of the LGB, while DT001, DT085, DC30, GD03 and GD15 are located at the eastern side. All cores were taken in the coastal regions in East Antarctica, of which elevation is below about 3000 m a.s.l.

Cores within LGB and at Kamp Land

During 1996/97 and 1997/98 austral summers, two firn cores were drilled in Princess Elizabeth Land: DT001 (71°51'S, 77°55'E; 2325 m a.s.l.) and DT085 (73°22'S, 77°01'E; 2570 m a.s.l.). The length of core was 50 m and 52 m, respectively. Stable isotope ($\delta^{18}O$) and soluble ions (Cl^-, Na^+, and NO_3^-) contents were used to cross check. The analysis precision was estimated to be within ±2

Table 1. Locations of the firn cores discussed in this study and the periods covered by these cores.

Site	Location	Elevation (m a.s.l.)	Period covered	Sources
GC30	69°21'S, 110°51'E	2307	1950-1981	This study
GD03	69°00'S, 110°30'E	1835	1940-1985	Goodwin 1991
GD15	69°00'S, 110°48'E	2155	1940-1985	Goodwin 1991
DT001	71°53'S, 12°26'E	2325	1940-1996	This study
DT085	73°22'S, 77°01'E	2577	1940-1997	This study
Core E	73°36'S, 12°26'W	700	1940-1991	Isaksson *et al.* 1996
DML05	75°00'S, 0°01'E	2892	1940-1996	Oerter *et al.* 1999
W200	69°35'S, 48°50'E	2165	1940-1980	Satow and Watanabe 1990
LGB16	72°49'S, 57°20'E	2689	1940-1993	This study
MGA	68°39'S, 60°15'E	1830	1940-1992	This study

years for the upper 20 meters (Qin *et al.* 2000). Only upper parts of the two cores were used in order to match roughly the time periods corresponding to the other cores discussed below.

During 1992/93 Australian/Chinese joint traverse on the western side of LGB, two firn cores were drilled at Kamp Land: MGA (68°39'S, 60°15'E; 1830 m a.s.l.) and LGB16 (72°49'S, 57°20'E; 2689 m a.s.l.). The length of core was 27 m and 15.2 m, respectively. The age of cores were estimated by the isotopic profiles, electrical conductivity measurements (ECMs) and visible stratigraphy. Snow accumulation rate was also used as a reference. A series of firn cores were drilled adjacent to the two sites to validate the precision of dating (Ren *et al.* 1999).

Cores at Wilks Land

In 1984, a 20.1 m firn core was drilled at GC30 (69°21'S, 110°51'E; 2307 m a.s.l.), Wilks Land. The core was dated using $\delta^{18}O$ profiles and β activities. The stake measurement during 10-20 years prior to the drilling operation confirmed that the error of dating was within 1-2 years (Qin and Wang 1990).

Other two cores were drilled at Wilks Land: GD03 (69°00'S, 115°30'E; 1835 m a.s.l.) and GD15 (69°00'S, 130°48'E; 2155 m a.s.l.). The depths of cores were 31 m and 30 m, respectively. The annual accumulation layers were identified using a firn-stratigraphic model along with seasonal oxygen-isotopic ratios (Goodwin 1991).

Cores at the Dronning Maud Land (DML)

Three firn-core records from DML will be compared with results of our study. These cores were selected because of their similar geographical settings (altitudes and distances from the coast). The core of W200 (69°35'S, 48°50'E; 2165 m a.s.l.) was taken in 1980 and its length was around 34 m. The core was dated using $\delta^{18}O$ profiles, depth hoar level, density and stratigraphy (Satow and Watanabe 1990). Core E (73°36'S, 12°26'E; 700 m a.s.l.) was drilled down to a depth of 30 m during 1988/89 austral summer. Annual dating was obtained by counting the summer peaks of oxygen isotope stratigraphy, which shows pronounced annual cycles. The ECM record gave additional control for the dating (Isaksson *et al.* 1996). The core at DML05 (75°00'S, 0°00'E; 2892 m a.s.l.) was drilled down to a depth of 11.2 m in 1996/97 austral summer. The core was dated using seasonal stratigraphy of stable isotopes, electrical properties and absolute time markers produced by volcanic events or the fallout of isotopic radio from nuclear weapon tests (Oerter *et al.* 1999).

Meteorological data from coastal stations

Instrumental temperature records were chosen for Davis, Mirny, Casey, and D d'Urville stations. These stations were close to the drilling sites and relatively long-term records are available. We took records at Vostok, inland of the ice sheet, as a reference, since above four stations are all located at the eastern coast of LGB. For the western LGB, records from Halley Bay, SANAE, Novolazarevskaya, Molodezhnaya and Mawson were used to verify the firn-core records. Because most stations have no precipitation data due to the difficulty of measurement, only instrumental temperature records were used to investigate the firn core records in this study.

3. Discussion

Accumulation history and trends derived from firn cores

The discussion below is restricted to the upper part of the cores, covering the period from 1940 A.D. to the time of drilling. Accumulation records for 5 firn/ice cores at the eastern LGB were compared with 5 at the western LGB. All cores at the eastern LGB show an increasing trend in accumulation rates since 1940s (Fig. 2). Although the core of DC30 includes 35 annual layers, only 32 annual layers from 1950 to 1981 have been retrieved because the surface 0.87 m was lost. The average accumulation rate for the 30 years is 306.1 kg m^{-2} a^{-1}. An overall increasing rate of accumulation was estimated to be +2.36 kg m^{-2} a^{-1}, with large change from year to year. For instance, the maximum rate is 516.0 kg m^{-2} a^{-1} in 1976, which is 3.1

Table 2. The rate of change in accumulation and $\delta^{18}O$ records in the firn cores collected in the coastal regions in East Antarctica during each period from 1940 up to the time that the cores were drilled.

Site of the core	Duration (years)	Rate of change in accumulation rate (kg a^{-1})	Rate of change in $\delta^{18}O$ (‰ a^{-1})
GC30	31	+2.36	+0.02
GD03	55	+1.61	+0.02
GD15	50	+1.17	+0.02
DT001	56	+0.34	+0.02
DT085	57	+1.21	+0.02
Core E	51	−0.01	+0.04
DML05	56	−0.02	+0.03
W200	40	−1.66	−0.03(Max line), −0.06(Min line)
LGB16	53	−0.73	−0.01
MGA	52	−2.36	~0

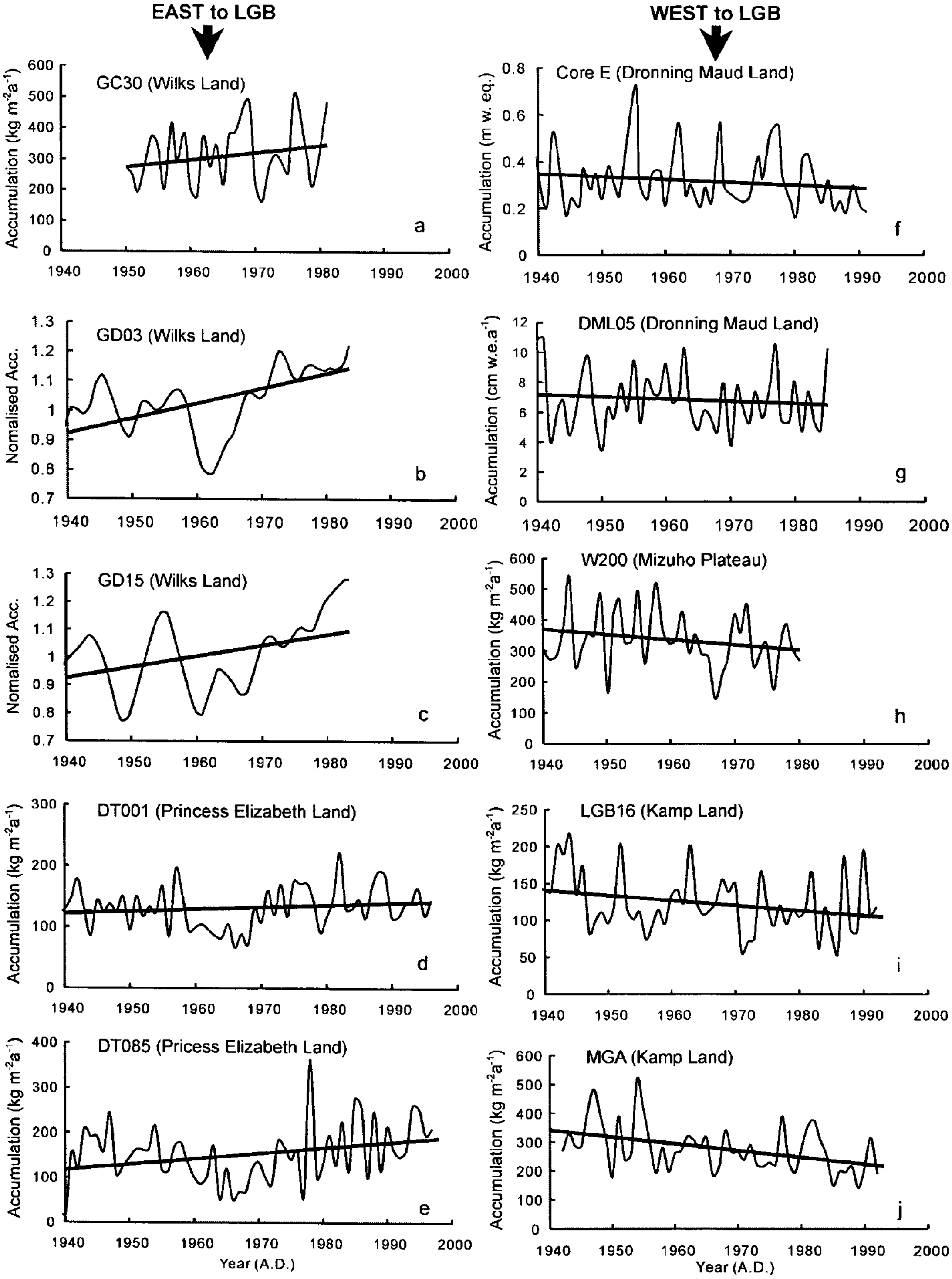

Fig. 2. Accumulation rates deduced from the upper parts of the firn cores extracted from the eastern (a-e) and western (f-j) LGB. The linear couplings show the trends of the variations. Data resources are shown in Table 1.

times as much as the minimum rate of 165.5 kg $m^{-2} a^{-1}$ in 1971.

The increasing rates of accumulation at GD03 and GD15 since 1940 are 1.61 and 1.17 kg $m^{-2} a^{-1}$, respectively.

The annual accumulation has increased by 25% from 1960 to 1985, resulting in the highest accumulation rates during 1930-1985. Goodwin (1991) suggested that the increase in accumulation in Wilks Land was attributed to changes in the general atmospheric circulation pattern, which have produced a higher precipitation rates. The relatively higher accumulation rate during 1975-85 is probably due to greater regional precipitation caused by stronger cyclonic activities. Such an increase in cyclonic activity could result from an easterly shift or intensification of the quasi-stationary cyclones in the circumpolar low-pressure trough (Bromwich 1988), which is centered near 100°-110°E, north of Casey station.

Increase in accumulation rate for the past half centuries is also obvious at DT001 and DT085 in Princess Elizabeth Land. There is also decreasing trend observed during 1960s, with deviation of −70% at DT001 and −38.8% at DT085 from the average accumulation. The highest accumulation rate was observed during 1980-90s, with the deviation of +19.3% at DT001 and 21.0% at DT085 from the average.

On the contrary, all the five cores from western LGB show decreasing trends in accumulation rate, with the maximum decreasing rate of -2.36 kg m^{-2} a^{-1} at MGA. Increasing in recent accumulation rate at Dronning Maud Land has been identified in a series of shallow firn cores (Isaksson and Karlén 1994). Their decreasing rate is −1.4-−2.1 cm water equivalent per year during 1970-1990s. Isaksson and Karlén (1994) found an excellent correlation between the mean annual accumulation rate in the west Dronning Maud Land and the temperature record at Halley.

Converse to the history of the eastern wing of LGB, the largest deviations of accumulation from the average in firn cores at MGA and LGB16 occur during 1980-90s. They are −11.2% and −13.7%, respectively. The decrease in accumulation at Kamp Land may be due to a permanent cyclone centered at ~62°S, 85°E (Bromwich 1988). The cyclone has caused an equatorward moisture flux at the western LGB (Slonaker and Van Woert 1999).

Temperature history and trends derived from firn cores

Temporal variations of temperature at the ten sites, which derived from stable isotopic ratios ($\delta^{18}O$) in the ice cores, are shown in Fig. 3. We found an increasing trend in temperature for the past decades over a large area of east LGB, including Princess Elizabeth Land and Wilks Land. The five cores at east LGB (Fig. 3a'-e') are characterized by lower $\delta^{18}O$ values during 1960s. Using the formula developed by Lorius and Merlivat (1977):

$$\delta D = 8\delta^{18}O + 10,$$

Qin and Wang (1990) obtain

$$\delta D = 6.04T - 51.$$

From the above relationship, the mean annual temperature at GC30 for 32 years is −33.45°C, which is close to the temperature of 10 m-depth firn measured in 1984 (−33.60 °C). Using the formula we developed at the Princess Elizabeth Land:

$$\delta^{18}O = 0.84T - 10.60,$$

the $\delta^{18}O$ increases in DT001 and DT085 firn cores since 1940 result in temperature increase of about 1.1°C and 1.4°C, respectively. This warming trend over the Princess Elizabeth Land is very similar to that of Wilks Land as deduced in the cores of GC30, GD03, and GD15.

The variation of isotopic temperature over the west LGB is much more complex compared with those at the east LGB. The most remarkable feature is that the increasing rate at western DML was similar to those at the east LGB, while decreasing or constant trends in temperature were found at Kamp Land and Mizuho Plateau. The stable isotope records from Core E show an increasing trend of 0.036‰ a^{-1} from about 1932 to the present, which is significant at 99% confidence level. Based on the change of 1.16‰/°C for this area (Isaksson and Karlén 1994), the increase in $\delta^{18}O$ would correspond to temperature increase by about 3.6°C since 1932. The increasing rate of 0.018‰ a^{-1} in $\delta^{18}O$ and about 1.8°C in temperature can be obtained during 1930-1996 at DML05. These increasing trends were well recorded in the adjacent stations such as Halley. The oxygen isotope records in Core E and DML05 indicate that temperature increase and accumulation decrease were contemporaneous. A similar trend between temperature and accumulation rate was observed in the Antarctic Peninsula by Jones *et al.* (1993). It was attributed to either layer thinning at depth due to ice compaction or to change in moisture source. Isaksson and others (1996) pointed out that the inverse relationship between temperature and accumulation rate was possibly due to the uncertainty in accumulation measurement, seasonality of snowfall and stable isotopes, or change in meteorological condition such as trajectories of the cyclones along the coast.

At Kamp Land and Mizuho Land, however, decrease in accumulation was accompanied with decrease in isotopic temperature. Using a formula of δ-T relationship as

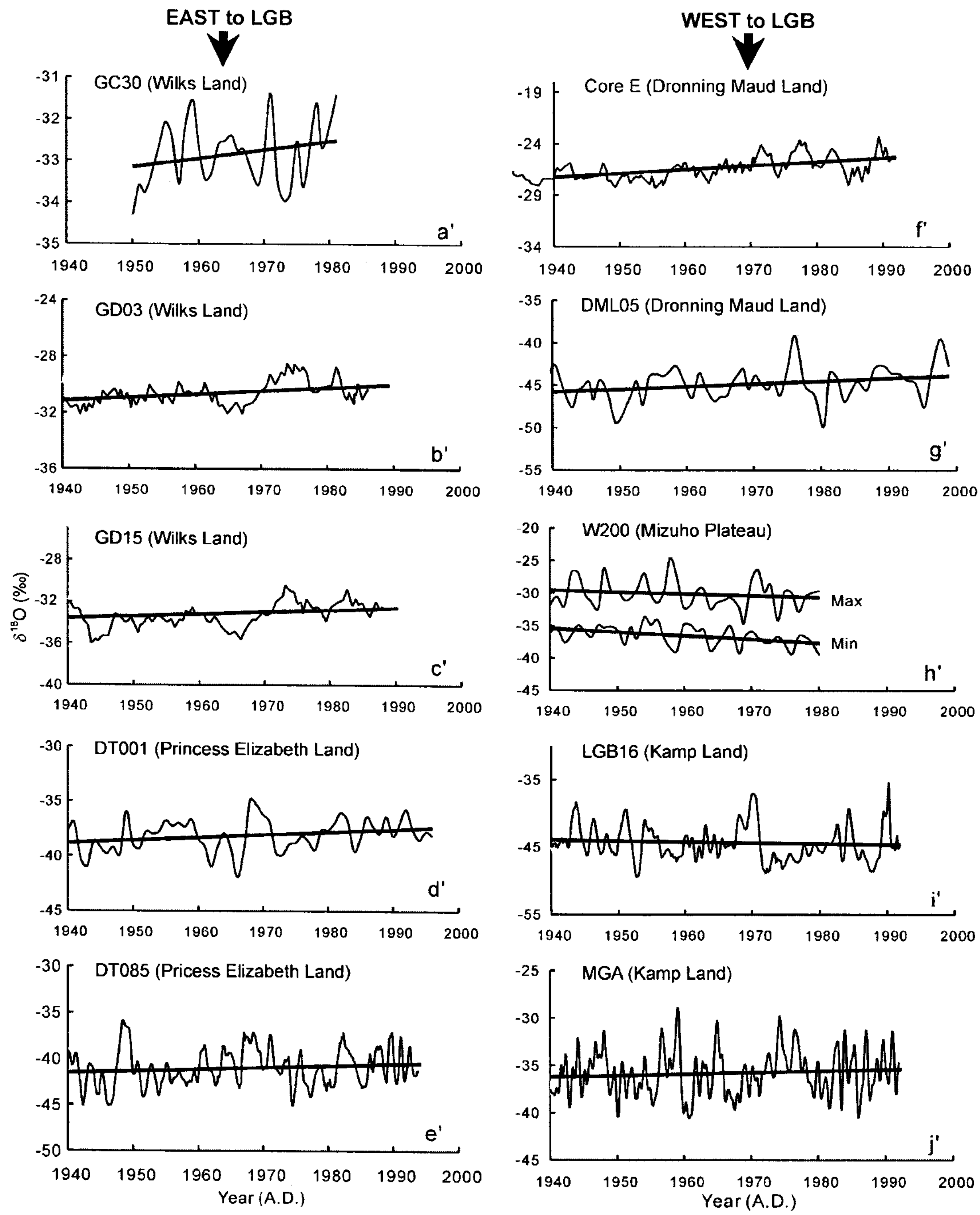

Fig. 3. Isotopic temperature change in the upper parts of the firn cores extracted from the eastern (a'-e') and western (f'-j') LGB. The linear couplings show the trends of the variation. Data resources are shown in Table 1.

$$\delta^{18}O = 0.60T - 15.08$$

developed at the west, we found decreasing tend of temperature at MGA and LGB16 since 1940A.D., ~0°C and −2.9°C, respectively. At W200, both the annual minimum and maximum of $\delta^{18}O$ clearly show decreasing tends since 1940 (Satow and Watanabe 1990).

The Kamp Land seems to differ from other regions in East Antarctica with showing decrease in both temperature and surface accumulation rate. We can suggest several

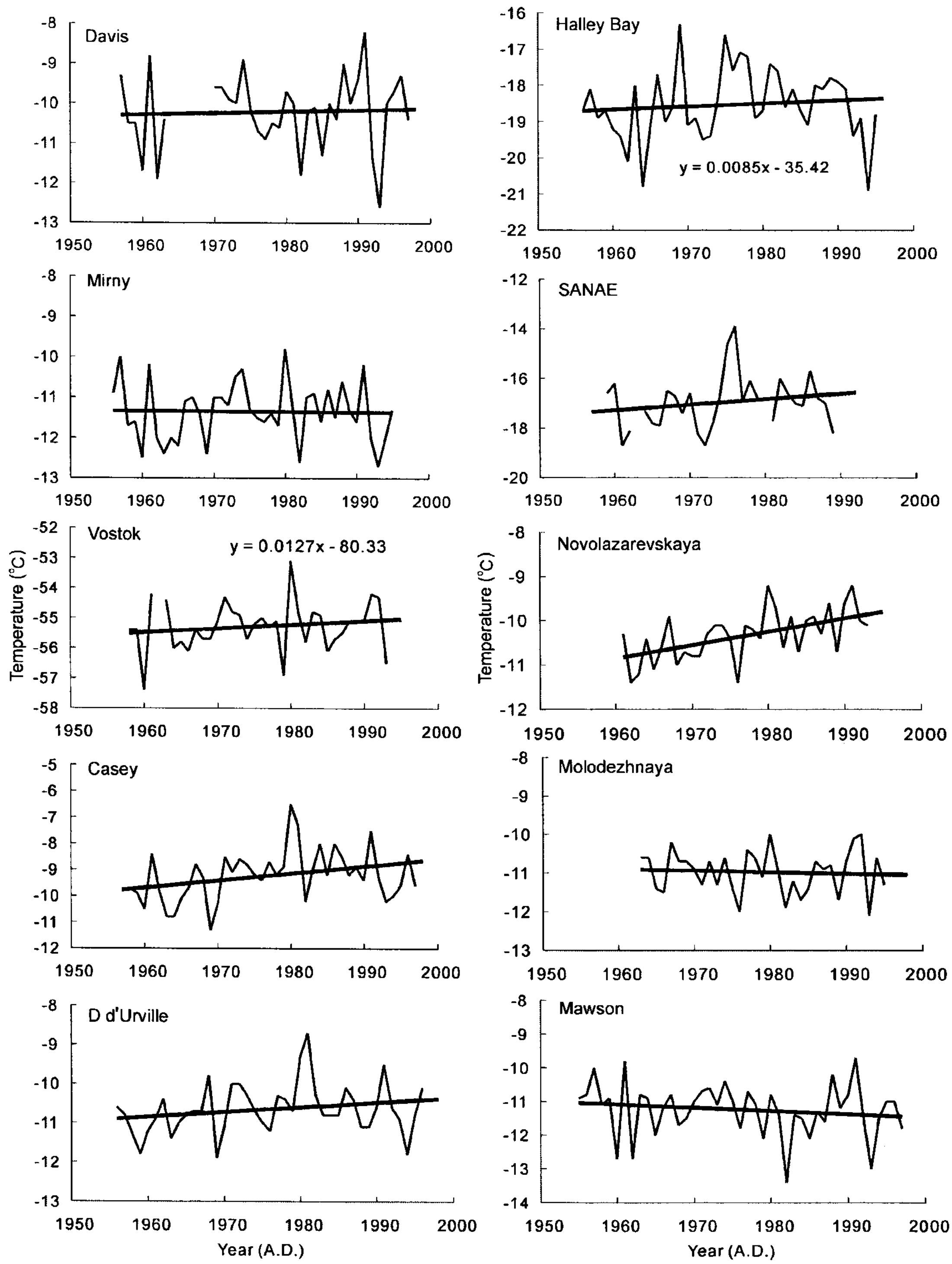

Fig. 4. Temperature changes recorded at the stations in the Antarctic coastal regions, with the record at Vostok, inland of the ice sheet, as a reference. The linear couplings give the trends of the variations. Data description is given in Table 3.

interpretations. First, the cyclone located at 62°S, 85°E may have reduced the poleward moisture flux at west LGB. Secondly, enhanced wind speed, which was obvious in head regions of LGB since 1950s, may have reduced

$\delta^{18}O$ via the post-depositional fractionation, leading to decreasing isotopic temperature since 1940s. Thirdly, enhanced clockwise circulation covering the coastal LGB during the past decades would have increased accumulation and temperature at the eastern LGB, but decreased at the western LGB. This is because the eastern LGB is under the direct influence of south Indian Ocean that is known to be warm in recent decades (Jacka and Budd 1998), whereas the western LGB is mostly affected by air masses from interior regions.

Temperature trends from instrumental records

The stations at the coast of Dronning Maud Land, Kamp Land, Princess Elizabeth Land, and Wilks Land were chosen to clarify temperature records from firn-cores of adjacent sites. Stations with relatively long-term records were selected. These stations are adjacent to the drilling sites, which helps to establish correlations between instrumental and proxy records of temperature. No precipitation measurements are available at most stations. At the east of LGB, including Davis, Mirny, Casey, and D d'Urville, the overall warming trends are obvious since 1950s, which is consistent with records at Vostok, an inland station of the ice sheet. The instrumental records confirm the findings in the firn cores at Wilks Land and Princess Elizabeth Land. This warming trend of this sector is probably related to the warming of Australian region in the Southern Ocean, even though SST was found to be increasing in recent decades (Jacka and Budd 1998).

Similarly, temperatures measured at the coast of DML, Halley, SANAE, and Novolazavoskaya slightly increased, which is in accordance with firn core records at Core E and DML05. Also, decreasing or quasi-stable temperature variations at stations Mawson and Molodezhnaya coincide well with records in W200, MGA, and LGB16 firn cores. Table 3 lists the rate of change in temperature at these stations.

4. Conclusions

Using results from our study in conjunction with others, we investigated climate variability of the coastal regions in the eastern Antarctic ice sheet for the past 50 years (Fig. 5). There was a distinct difference in accumulation rate between the two sides of LGB for the past half centuries: increase in the eastern LGB (Princess Elizabeth Land and Wilks Land), and decrease in the western LGB (Kamp Land and Dronning Maud Land). Variations in isotopic temperature also differ between the two sides, with more complicated pattern at western side. While an overall warming took place at the east of LGB, the warming was detected only at the western DML in the western LGB. It is not clear at the eastern part of DML.

The climate change of the coastal region shown in Fig. 5 is in good agreement with model calculations (Smith *et al.* 1998). They run a climate model using the historical sea surface temperature (SSTs) to examine Antarctic accumulation rates and their relationship to temperature changes during 1950-91. Model results were consistent with evidence from firn cores for much of East Antarctica. This suggests that climate change over the coastal regions in East Antarctica could be intimately coupled with climate variation over the Southern Ocean.

Variability on Southern Ocean over a wide range of time scales was well reflected in the pattern of the ACW, where anomalies in sea ice extent, SST, sea level pressure, and meridional wind stress propagate eastwardly (White

Table 3. The rate of change in temperature recorded at meteorological stations in the coastal regions in East Antarctica, except for Vostok station that is located inland.

Station	Period covered	Rate of change in temperature (°C a^{-1})	Remarks
Davis	1957-1997	0.004	Interrupted during November 1964 to February 1969
Mirny	1956-1996	0.00	
Vostok	1958-1995	0.013	Interrupted in 1962 and 1994
Casey	1957-1997	0.027	
D d'Urville	1956-1996	0.012	
Halley Bay	1956-1996	0.009	
SANAE	1957-1992	0.023	
Novolazarevskaya	1961-1996	0.030	
Molodezhnaya	1963-1996	−0.004	
Mawson	1954-1997	−0.010	

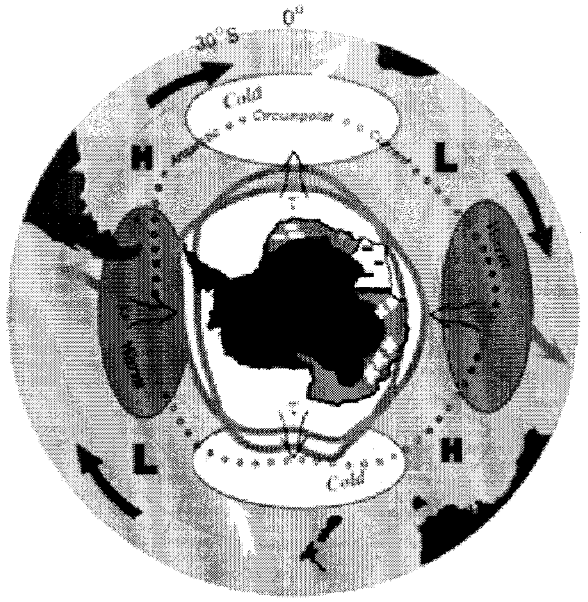

Fig. 5. The spatial pattern of the climate changes over the Antarctic coastal regions, as deduced from the firn-core and the instrumental records. The black and the gray shadings over the east Antarctic ice sheet are divided by the 3000 m contour line. The darker areas of the coastal Antarctic ice sheet indicate the warming and the lighter one indicate the cooling areas. The map is based on the study of White and Peterson (1996).

et al. 1996) The interannual variations in sea surface temperature may have triggered the spatial patterns of temperature and accumulation over the coastal Antarctic ice sheet. However, the pattern became more complicated by topographic effect by large drainage basin such as LGB, in contrast to the pattern over the Southern Ocean.

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