Ice velocity from static GPS observations along the transect from Zhongshan station to Dome A, East Antarctica

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ABSTRACT. Dome A, the highest point on the Antarctic ice sheet at just over 4000 m a.s.l., is located near the centre of East Antarctica. Chinese National Antarctic Research Expeditions have studied ice-sheet dynamics and mass balance along a traverse route from Zhongshan station to Dome A during the austral summers from 1996/97 to 2004/05. Nineteen GPS sites were occupied on at least two occasions at approximately 50 km intervals. The purpose of the surveys was to provide accurate ice-dynamics data. A dual-frequency GPS receiver was used and each site was occupied for 1–12 hours. GPS data were processed using GAMIT/GLOBK software, and horizontal accuracies were within 0.1 m. Repeat GPS measurements provided ice velocities. The horizontal surface ice velocities increase from the summit of the ice sheet to the coast. In the Dome A area, the velocities are <10 m a^{-1}; in the plateau area, velocities range from 8 to 24 m a^{-1} and reach about 98.2 m a^{-1} at a site (LT980) near the coast. The flow directions are roughly perpendicular to the ice-sheet surface elevation contours, primarily toward the Lambert Glacier basin.

INTRODUCTION

Ice sheets play a major role in studies of global climate change and sea-level rise. The Antarctic ice sheet stores the majority of the Earth's fresh water, and the mass balance of the Antarctic ice sheet is an important climatic variable since any significant deviation from a balanced state will have an effect on global sea level (Meier, 1993; Alley and others, 2005). Mass-balance and other glaciological studies require knowledge of ice velocity, surface elevation, ice thickness and snow accumulation either from direct field measurements or via remote-sensing methods (Paterson, 1994). There are very few geodetic measurements of the above parameters in the interior of the East Antarctic ice sheet. Considering the difficulties of accessibility, the hostile environment and the logistic problems in Antarctica, the global positioning system (GPS) has become a standard tool for field measurement of ice kinematics and surface topography in Antarctica (Tabacco and others, 1998; Capra and others, 2000; King and others, 2000, 2007; Gudmundsson, 2006).

Dome A, the highest ice feature in Antarctica, is just over 4000 m a.s.l., located near the center of East Antarctica and approximately midway between the head of Lambert Glacier and the South Pole. In the framework of the International Trans-Antarctic Scientific Expedition (ITASE), the Chinese National Antarctic Research Expedition's (CHINARE) glaciological research program has concentrated on the traverse route between Zhongshan station and Dome A during the austral summers from 1996/97 to 2004/05 (Qin and others, 2000, 2004; Xiao and others, 2001, 2004; Zhang and others, 2002; Ren and others, 2004). The program has included studies of mass balance and ice temperature, meteorological measurements including automatic weather station installations, glacio-chemical studies of surface snow and shallow ice cores, and stratigraphy in snow pits and snow/firn cores.

Along the traverse route, GPS sites were established at approximately 50 km intervals. This paper describes the results of GPS surveys, which provide information on ice velocities along the transect from the coast to Dome A.

FIELD EXPEDITIONS AND DATA PROCESSING

The first expedition south from Zhongshan station extended to site DT001 (Fig. 1), 296 km inland, during the 1996/97 austral summer. Two GPS sites were set up at DT001. The

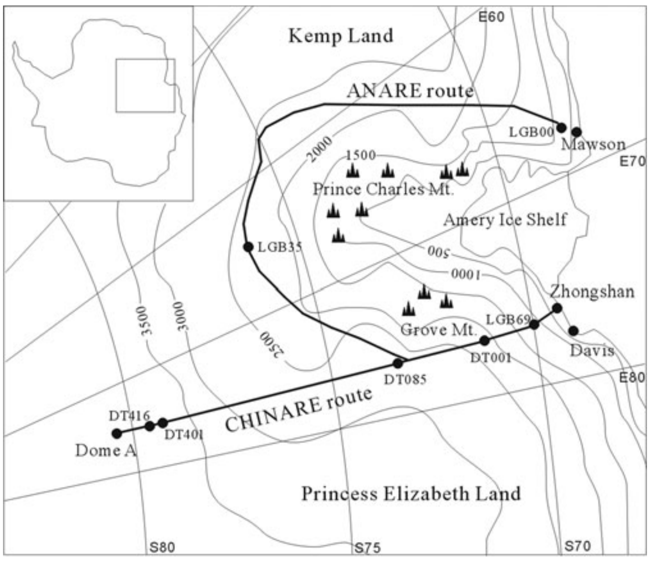

Fig. 1. Sketch map showing the route of the Chinese Antarctic inland traverse.

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Table 1. GPS observation information from 1996/97 to 2004/05 along the traverse route

Site	Distance from Zhongshan km	Epoch	Year	Year	Year	Year	Year	Year
DT001	300	1	1996/97					
DT002	300	1	1996/97					
LH9605	9	1						2004/05
LH406	29	1					2002/03	
LH400	39	1						2004/05
LT980	92	4		1997/98	1998/99	1999/00	2002/03	
LT975	102	1						2004/05
LT944	164	1						2004/05
LT940	172	2		1997/98	1998/99			
LT934	184	1			1998/99			
LT921	211	1						2004/05
LT918	217	4		1997/98	1998/99	1999/00	2002/03	
LT907	239	1			1998/99			
LT887	280	1						2004/05
DT008	310	4		1997/98	1998/99	1999/00	2002/03	
DT028	350	1						2004/05
DT038	370	4		1997/98	1998/99	1999/00	2002/03	
DT058	410	1						2004/05
DT063	420	4		1997/98	1998/99	1999/00	2002/03	
DT085	464	5		1997/98	1998/99	1999/00	2002/03	2004/05
DT118	528	2			1998/99			2004/05
DT132	556	2			1998/99			2004/05
DT150	592	1						2004/05
DT158	608	2			1998/99			2004/05
DT177	647	2			1998/99			2004/05
DT200	693	2			1998/99			2004/05
DT217	728	2			1998/99			2004/05
DT233	760	2			1998/99			2004/05
DT256	806	1						2004/05
DT263	820	2			1998/99			2004/05
DT278	850	1			1998/99			
DT280	854	1						2004/05
DT294	882	1			1998/99			
DT313	920	2			1998/99			2004/05
DT338	970	2			1998/99			2004/05
DT364	1022	2			1998/99			2004/05
DT381	1057	1						2004/05
DT401	1098	2			1998/99			2004/05
DT416	1128	1						2004/05
DT04551	1178	1						2004/05
DT04564	1204	1						2004/05

traverse was extended further southwards to site DT085, 464 km from Zhongshan station, during the 1997/98 field season. Seven GPS sites were set up along this section of the traverse. At each site, stainless-steel poles 3 cm in diameter and 3 m long were penetrated (vertically) into the snow to at least 1 m depth. The position was measured overnight using a dual-frequency GPS receiver. The satellite cut-off angle was set to 15° and the sample interval was 15 s. During the 1998/99 field season the traverse was extended further south to site DT416, 1128 km from Zhongshan station. The seven GPS sites set up in 1997/98 were reoccupied and 16 new GPS sites were established. During the 1999/2000 and 2002/03 field seasons, CHINARE carried out two expeditions to the Grove Mountains (Fig. 1); the traverse route was from Zhongshan station to DT085 and then turned west to the Grove Mountains (Dongchen and others, 2004, 2005). Along the traverse route, six GPS sites were reoccupied for several hours.

During the 2004/05 austral summer, the traverse was extended to the summit of Dome A, 1228 km from Zhongshan station. Snow accumulation rate and ice temperature were measured, and snow/firn ice cores were collected. Radio-echo sounding measurements and meteorological studies were conducted along the traverse route and at the summit of Dome A (Hou and others, 2007; Xu and others, 2007). The surface topography around the summit of Dome A, over an area of 60 km^2, was measured using real-time kinematic GPS techniques (Zhang and others, 2007). Individual measurements of surface mass balance were made on bamboo poles spaced at 2 km intervals along the whole traverse route. The coordinates of the poles were recorded by a hand-held GPS navigator. The surface elevation profile of the traverse route was constructed from the GPS navigation data (Fig. 2). The topographic profile of the traverse indicates three sectors: an area extending about 200 km from Zhongshan station (slope area) with a steep

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Table 2. Horizontal velocities at GPS sites along the traverse route from Zhongshan station to Dome A

Site	Distance from Zhongshan km	Lat. (S)	Long. (E)	Ellipsoidal height m	Time	Velocity $m\,a^{-1}$	Azimuth
LT980	92	70°07′49″	76°35′31″	1291	1997/98–2002/03	98.2	306
LT940	172	70°50′07″	77°04′37″	1870	1997/98–1998/99	17.5	324
LT918	217	71°13′18″	77°23′42″	2095	1997/98–2002/03	13.3	300
DT008	310	72°00′50″	77°55′27″	2373	1997/98–2002/03	24.5	296
DT038	370	72°32′30″	77°35′06″	2433	1997/98–2002/03	21.6	306
DT063	420	72°58′51″	77°17′22″	2546	1997/98–2002/03	8.9	310
DT085	464	73°22′05″	77°00′42″	2561	1997/98–2004/05	9.4	268
DT118	528	73°56′06″	76°59′18″	2643	1998/99–2004/05	17.7	277
DT132	556	74°10′41″	77°00′36″	2675	1998/99–2004/05	18.2	283
DT158	608	74°39′34″	77°00′20″	2738	1998/99–2004/05	10.7	291
DT177	647	74°59′42″	76°58′03″	2786	1998/99–2004/05	10.4	275
DT200	693	75°24′58″	76°55′00″	2806	1998/99–2004/05	10.0	278
DT217	728	75°43′05″	76°50′11″	2811	1998/99–2004/05	12.8	270
DT233	760	76°00′20″	76°56′18″	2793	1998/99–2004/05	15.8	277
DT263	820	76°32′28″	77°01′28″	2824	1998/99–2004/05	17.1	316
DT313	920	77°25′43″	76°59′45″	3026	1998/99–2004/05	18.5	325
DT338	970	77°52′16″	77°08′21″	3154	1998/99–2004/05	7.6	316
DT364	1022	78°20′15″	77°00′04″	3373	1998/99–2004/05	3.0	36
DT401	1098	79°00′48″	76°59′56″	3736	1998/99–2004/05	1.3	9

slope and height up to 2000 m; a second area (plateau area) extending up to about 950 km with a gentle slope and height ranging from 2000 to 3100 m; and the dome area in the last 300 km with height up to 4093 m. The accuracy of elevation data during the 2004/05 traverse is higher than that of 1998/99, because the GPS navigation accuracy improved significantly once 'selective availability' was terminated on 1 May 2000 (Leick, 2004). This topographic profile is similar to the topographic profile from Terra Nova Bay to Dome C (slope area up to 250 km, plateau area up to 900 km, and dome area up to 1150 km) (Frezzotti and others, 2002, 2005).

Along the 2004/05 traverse route, 28 GPS sites were measured including 13 repeated sites and 15 new sites. Along the first part of the traverse route from Zhongshan station to DT085, because the poles at the old GPS sites (at which ice velocities had previously been measured) were all buried, eight new sites were established. Along the second part of the traverse route from DT085 to Dome A, most of the old sites were remeasured; some of them were occupied overnight, and others occupied for 1–2 hours during short stops. There are 19 sites along the route that have been occupied on at least two occasions. GPS observation information from 1996/97 to 2004/05 is shown in Table 1.

The GPS data were processed using GAMIT/GLOBK software (King, 2002). During the data processing, (1) International GNSS Service (IGS) precise ephemerides were used; (2) several IGS stations around Antarctica (e.g. CAS1, DAV1, MAW1, MCM4, PALM, SYOG and VESL) were tightly constrained (within 1 cm) at their ITRF2000 values, while the site along the traverse was loosely constrained (within 100 m); (3) an elevation cut-off angle of 15° was set; (4) antenna-phase centre variation corrections were applied; (5) the ionospheric-free linear combination of the L1 and L2 frequencies was used; (6) corrections were applied for both the solid-Earth and frequency-dependent tides; (7) the dry component of the zenith tropospheric delay was estimated by the Saastamoinen model; and (8) the wet component was estimated during the inversion, with zenith-delay adjustments every 2 hours. The GAMIT solutions were then combined using GLOBK software.

RESULTS AND DISCUSSION

Horizontal velocities at each of the 19 sites were extracted from the GAMIT/GLOBK solution. Horizontal uncertainties at the 19 sites were within 10 cm. Elevation change in the region was also determined but will be reported elsewhere. Table 2 summarizes the velocity results of the 19 sites on the traverse. The surface ice-velocity vectors map is shown in Figure 3.

The horizontal surface velocity values are close to zero at the summit of Dome A and increase with distance from the summit. At Dome C, the ice surface at the poles closest to the summit moves horizontally by up to a few mm a^{-1}, while velocities 25 km from the summit are up to 0.211 $m\,a^{-1}$ (Vittuari and others, 2004). At Dome F the surface ice-flow rate is <10 $m\,a^{-1}$ in the inland region above 3000 m (Takahashi and others, 2003).

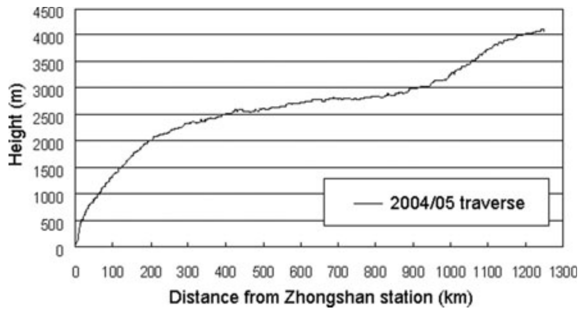

Fig. 2. Surface elevation profile of the traverse route from the coast to Dome A.

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Table 3. Horizontal velocities at GPS sites along the CHINARE and ANARE routes

Site	Distance from Zhongshan km	Lat. (S)	Long. (E)	Ellipsoidal height m	Time	Velocity m a^{-1}	Azimuth	Surveyor
LGB72	68	69°55′15″	76°29′36″	1056	1993/94–1994/95	52.9	306	ANARE
LT980	92	70°07′49″	76°35′31″	1291	1997/98–1998/99	98.1	306	CHINARE
					1998/99–1999/2000	98.4	306	
					1999/2000–2002/03	98.2	306	
LGB71	106	70°15′32″	76°40′59″	1406	1993/94–1994/95	62.6	318	ANARE
LGB70	142	70°34′33″	76°51′59″	1669	1993/94–1994/95	25.5	331	ANARE
LT940*	172	70°50′07″	77°04′37″	1870	1997/98–1998/99	17.5	324	CHINARE
LGB69*		70°50′07″	77°04′40″	1871	1993/94–1994/95	17.7	323	ANARE
LGB68	202	71°05′43″	77°17′19″	2013	1993/94–1994/95	14.1	310	ANARE
LT918	217	71°13′18″	77°23′42″	2095	1997/98–1998/99	13.7	300	CHINARE
					1998/99–1999/2000	13.7	300	
					1999/2000–2002/03	13.7	300	
LGB67	232	71°21′38″	77°30′40″	2152	1993/94–1994/95	14.8	287	ANARE
LGB66	262	71°37′14″	77°43′50″	2230	1993/94–1994/95	22.6	292	ANARE
LGB65	292	71°52′51″	77°57′03″	2341	1993/94–1994/95	22.5	295	ANARE
DT008	310	72°00′50″	77°55′27″	2373	1997/98–1998/99	24.5	296	CHINARE
					1998/99–1999/2000	24.4	296	
					1999/2000–2002/03	24.5	296	
LGB64	324	72°09′02″	77°56′58″	2367	1993/94–1994/95	24.2	297	ANARE
LGB63	354	72°24′38″	77°43′23″	2439	1993/94–1994/95	21.0	304	ANARE
DT038	370	72°32′30″	77°35′06″	2433	1997/98–1998/99	21.6	306	CHINARE
					1998/99–1999/2000	21.5	306	
					1999/2000–2002/03	21.6	306	
LGB62	384	72°40′16″	77°29′37″	2483	1993/94–1994/95	21.3	306	ANARE
LGB61	412	72°55′52″	77°15′47″	2525	1993/94–1994/95	8.6	310	ANARE
DT063	420	72°58′51″	77°17′22″	2546	1997/98–1998/99	8.7	310	CHINARE
					1998/99–1999/2000	9.0	310	
					1999/2000–2002/03	9.0	310	
LGB60	442	73°11′29″	77°01′37″	2595	1993/94–1994/95	7.6	265	ANARE
DT085	464	73°22′05″	77°00′42″	2561	1997/98–1998/99	9.4	268	CHINARE
					1998/99–1999/2000	9.3	268	
					1999/2000–2002/03	9.5	268	
					2002/03–2004/05	9.4	268	
LGB59	475	73°27′07″	76°47′16″	2549	1993/94–1994/95	10.6	276	ANARE

*Site LT940 and site LGB69 are the same site.

The velocity increases from 1.3 m a^{-1} at site DT401 (150 km from the summit of Dome A) to 3.0 m a^{-1} at site DT364 (~230 km from the summit of Dome A). The velocity at site DT338 (3154 m a.s.l.; 280 km from the summit) is 7.6 m a^{-1}, while it reaches 18.5 m a^{-1} at DT313 (3026 m a.s.l.; 330 km from the summit). So the velocity in the dome region, which is above 3100 m and within about 300 km of the summit, is <10 m a^{-1}. The flow directions at these sites are consistent with downslope (perpendicular to the elevation contours) motion of the ice sheet. In forthcoming field seasons, we plan to establish a strain network in the Dome A region for the study of ice dynamics, which will provide fiducial control for synthetic aperture radar (SAR) interferometry and balance-velocity computation, and will be an important pre-site survey for deep ice drilling.

In the plateau area of the traverse route, the velocities range from 8 to 24 m a^{-1}, and ice flows towards the Lambert Glacier basin (LGB). The first part of the route from Zhongshan station to DT085 is partly coincident with the Australian National Antarctic Research Expeditions (ANARE) traverse route surrounding the LGB during the early 1990s (Fig. 1). The ice-flow velocities along the ANARE traverse line varied between 10 and 25 m a^{-1} (Manson and others, 2000; Kiernan, 2001), agreeing with our results (Table 3). The velocity differences during the three periods (1997/98–1998/99, 1998/99–1999/2000 and 1999/2000–2002/03) at the six sites (LT980, LT918, DT008, DT038, DT063 and DT085) are very small (within 0.3 m a^{-1}) and the flow directions are the same. The velocity difference between 1993/94–1994/95 and 1997/98–1998/99 at LT940 and LGB69 is 0.2 m a^{-1}. Considering the calculation uncertainty,

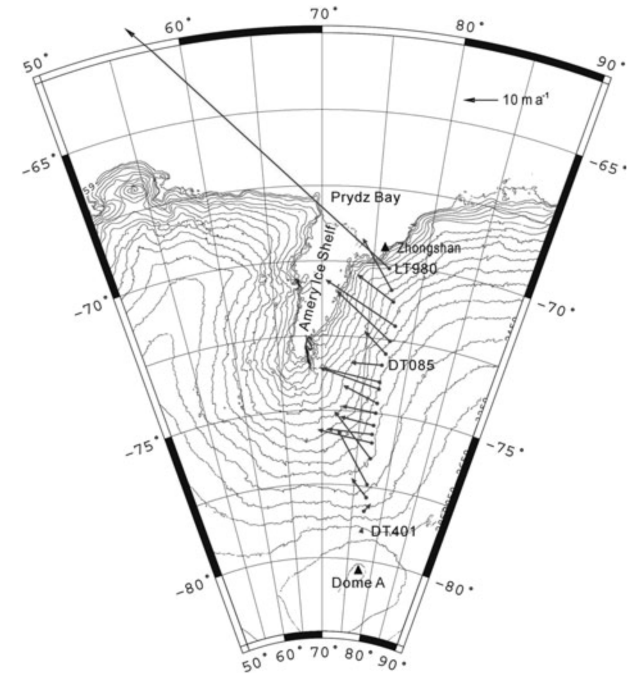

Fig. 3. Vector map of surface ice flow along the traverse from Zhongshan station to Dome A. (Elevation contours derived from the RAMP DEM.)

the eastern edge of the LGB is considered to have been in balance since the 1990s. Similar ice-flow measurements have been performed over other glacier basins in Antarctica. For instance, the surface flow velocity is $\sim$20 m a^{-1} in the middle part of the Shirase Glacier drainage basin at about 2500 m a.s.l. in the Dronning Maud Land ice sheet (Takahashi and others, 2003).

The maximum ice velocity was found in the coastal ice-sheet regions where the velocity reaches 98.2 m a^{-1} at site LT980 (92 km from Zhongshan station). The velocities at sites LGB72 and LGB71 on the steep coastal slopes of the eastern side of the LGB are respectively 52.9 and 62.6 m a^{-1}.

CONCLUSION

We have detailed the measurement of ice-surface movement along the traverse route from Zhongshan station to Dome A, the highest point on the Antarctic ice sheet. The horizontal ice-surface velocities increase from near zero at the summit to several tens of m a^{-1} near the coast. The flow directions are roughly perpendicular to the surface elevation contours, most of the vectors indicating flow towards the LGB. Our measurements are in good agreement with the ANARE measurements in the lower section of the CHINARE traverse, where the two sets overlap (see Fig. 4). In addition, the measurements show similar characteristics to those in other Antarctic glacier drainage basins.

The ice surface velocity measurements in this region will provide fiducial control for remote-sensing analysis. Future repeat GPS measurements will be used to validate the present ice-flow conditions. Radio-echo sounding was also carried out along the traverse route; results will be published elsewhere. Ice thickness and bedrock topography will provide further explanation for the ice-velocity variation along the transect. Combining the data of ice velocity, ice thickness and snow accumulation will be helpful in the study of ice dynamics, and so will be useful in mass-balance assessment of the ice sheet.

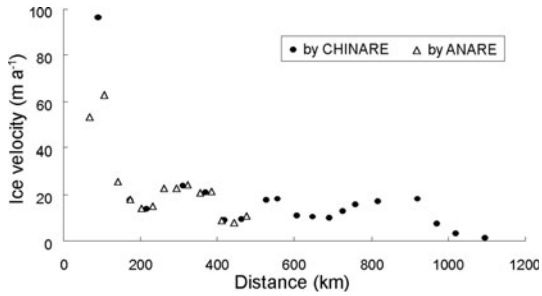

Fig. 4. Surface ice velocity along both CHINARE and ANARE traverses.

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