Abstract

A feasibility study has been undertaken to improve air support for the Japanese Antarctic Research Expedition (JARE) by establishing hard-surface runways near JARE stations and introducing an intercontinental air operation. Historical meteorological observations for JARE stations have been reviewed. Two major parameters, prevailing wind direction and maximum temperature, have been examined because they have a dominant influence on snow-ice runway construction. The glaciological conditions near Syowa Station, Asuka Station and in Yamato Mountains were considered to identify the favorable sites for hard-surface runway construction. The analysis shows that the Syowa area is suitable for construction and operation of runways on both compacted snow and blue ice. Construction techniques and logistic facilities for snow-ice runway construction are briefly outlined. The general characteristics of aircraft that are of practical interest in Antarctica are summarized.

1. Introduction

Four Japanese scientific stations are established in East Antarctica: Syowa Station (69°00'S, 39°35'E), Mizuho Station (70°42'S, 44°20'E), Asuka Station (71°32'S, 24°08'E) and Dome Fuji Station (77°22'S, 39°37'E). Two of these, Syowa and Dome Fuji, are currently operated as year-round stations. Asuka and Mizuho are used to support seasonal projects. The total area of the Japanese Antarctic Research Expedition (JARE) activity covers the sector in East Antarctic from 15° E to 55° E as shown in Fig. 1. Operating in this area, JARE traditionally interacts and collaborates with the national Antarctic programs of Russia, Australia and others, which have their own stations nearby.

Traditionally JARE has used fixed-wing aircraft and helicopters to provide inter-station flights, field camp support and ship-to-shore operations. Currently two Sikorsky S-61A helicopters and one Hughes OH-6D helicopter are based on board RV "SHIRASE". Two fixed-wing single-engine aircraft, Pilatus Porter PC-6/B2-H4 and Cessna A-185F, periodically winter at Syowa Station.

To date, JARE has not conducted intercontinental air operations. However, it is now considering the use of heavy wheeled aircraft, which would provide numerous benefits:

• It would allow the transport of personnel and high-priority cargo to Antarctica much earlier in the season than is currently possible, faster and over much larger areas.

• An air bridge between the other southern continents and the Antarctic also would maximize research productivity by facilitating personnel exchange and reducing travel time.

• It would allow short-term visits to Antarctic projects and greatly enhance the quality of the JARE research program.

A feasibility study has been undertaken at NIPR to find a practical way to improve air support for JARE through an intercontinental air operations. Two main issues were considered. The first, to identify a favorable site for constructing a hard surface snow-ice runway close to Syowa Station as well as alternative runway sites near other coastal JARE stations. The second, to formulate a concept by which JARE can take part in the international East Antarctic Air Network (EAAN), creating a link between the outer continents (Australia, Africa) and the Antarctic stations of many nations.

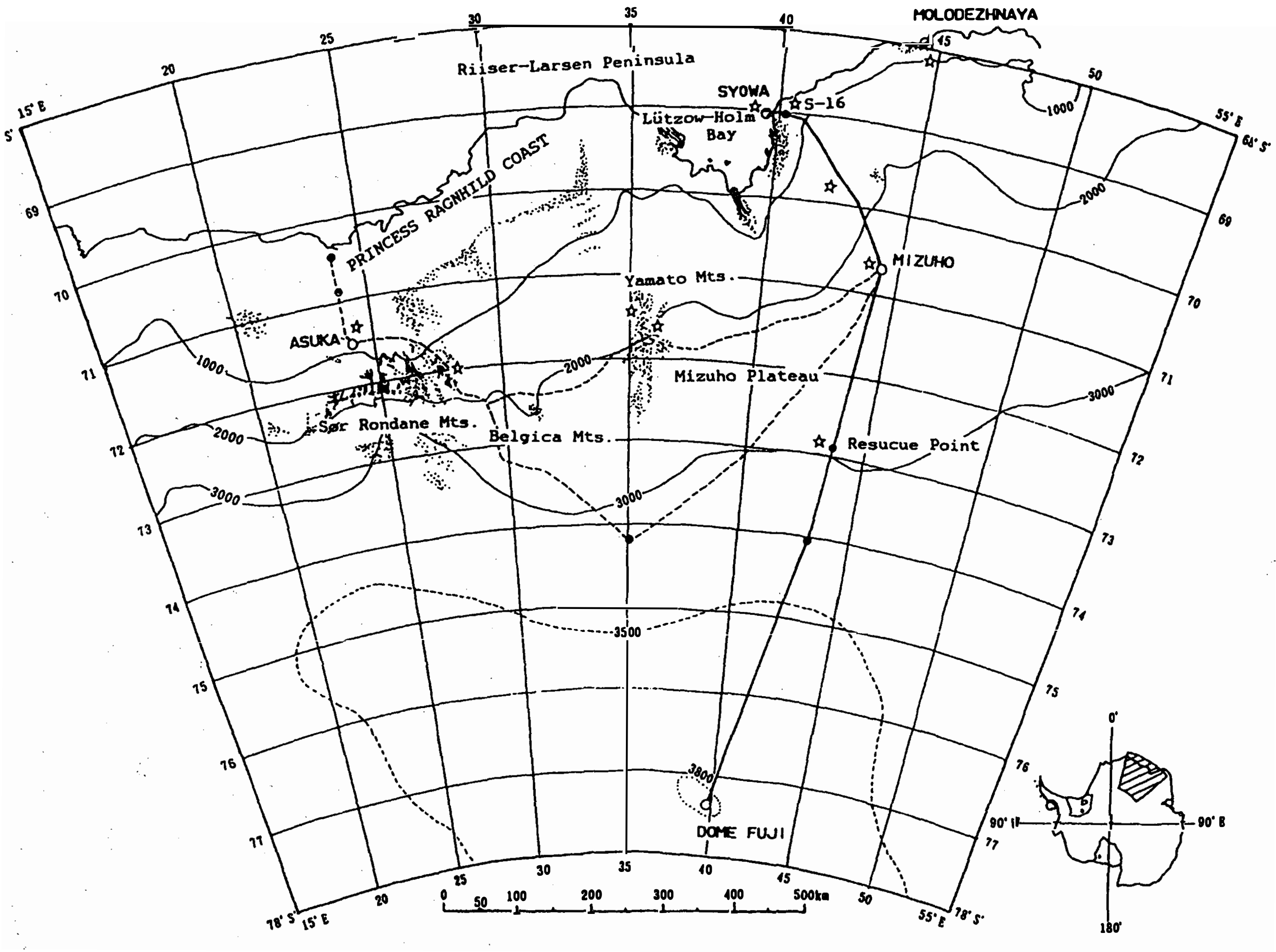


Fig. 1. Location of JARE stations. Stars indicate landing sites by small aircraft of JARE, and dotted areas show blue-ice fields.

2. Selection of Potential Runways Sites

By the term "hard-surface runway" we mean a runway that is capable of receiving heavy wheeled aircraft. There is no doubt that the most easiest site to establish a hard-surface runway is on the blue-ice fields (*e.g.* SWITHINBANK, 1991).

However, the easiest site for construction is not always the best location for other factors such as transportation of personnel, fuel, machinery and so on. Thus remote runways would be difficult to be maintained. At the present time, it is recognized that a hard-surface runway could be created at practically any location in Antarctica either in the coastal areas or inland. There are both tested construction techniques and sufficient construction experience to build a runway practically anywhere on the Antarctic ice sheet (AVER'ANOV and KLOKOV, 1975). However, to undertake construction of a hard-surface runway at any arbitrarily designated point would require tremendous construction effort and much heavy machinery because cold, dry and deep snow, typically tens of meters thick, covers most of Antarctica.

There are no sites near Syowa Station where a gravel runway for heavy wheeled aircraft could be easily constructed. UMEMURA and HANNUKI (1993) showed the possibility of the construction of a gravel runway at the East Ongul Island where Syowa Station is located. However, it is only suitable for single- or twin-engined light aircraft. The topography is rather rough at coastal outcrops located near the station (Ongul Islands, Langhovde, Skarvsnes) in Lützow-Holm Bay. Sites of bare rock or coarse glacial till that are sufficiently level exist in the inland parts of Queen Maud Land on the west side of the Sør Rondane Mountains and in the Yamato Mountains. These sites, however, are located quite far (200–300 km) from the shore and farther still from Syowa Station. To construct and maintain a conventional runway at any of these sites would require a great deal of work and a significant investment that would severely strain the resource of JARE. Therefore, the only alternative is to construct a runway using locally available and accessible materials such as snow and ice. In choosing how and where a hard-surface snow or ice airstrip might be constructed, three options are considered:

- fast sea ice,
- compacted snow runways on deep snow,
- snow-free glacier ice.

The three options require the use of different techniques and methods of snow and ice processing. To make the best choice of runway location and construction method, four prospective sites should be considered in the area of JARE activity.

3. Meteorological Summaries for JARE Stations

Historical standard meteorological data for JARE stations, published by the Japan Meteorological Agency, have been compiled. Climatological summaries of the meteorological parameters for Syowa Station, based on observations from 1955 to 1995, and for Asuka Station, based on observations from 1987 to 1991 are shown in Tables 1 and 2, respectively (Fig. 2). Limited data, obtained by an automatic weather station in 1988, are available for the S-16 site located on the ice sheet 20 km east of Syowa Station (Fig. 3) (MATSUBARA *et al.*, 1990). Unfortunately, no systematic meteorological data are available for the Yamato Mountains.

Table 1. Monthly summaries of surface meteorological data at Syowa Station, 1955–1995.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Pressure (station)(hPa)	991.4	988.4	985.8	986.1	989.1	989.3	986.1	984.5	982.7	983.0	985.6	989.8
Mean temperature(°C)	−0.6	−3.1	−6.3	−9.9	−13.3	−15.8	−17.8	−19.7	−17.9	−13.4	−6.4	−1.5
Mean max. temperature(°C)	2.3	−0.6	−4.1	−7.4	−10.5	−12.8	−14.5	−16.2	−14.6	−10.3	−3.5	1.5
Mean min. temperature(°C)	−3.7	−5.8	−9.0	−12.9	−16.5	−19.2	−21.3	−23.6	−21.9	−17.3	−10.0	−4.8
Mean wind speed(m/s)	3.9	6.1	7.9	8.7	7.8	6.7	6.7	6.0	6.0	6.2	6.2	4.5
Max. gust wind speed(m/s)	50.2	50.8	49.9	49.1	59.2	53.5	51.0	52.7	55.8	49.0	48.7	48.4
Max. wind direction (1993)(16 s)	NE	NE	NE	ENE	ENE	NE	NE	ENE	NE	NE	NE	NE
Mean cloud amout(tenths)	5.9	7.2	7.8	7.5	6.6	6.6	6.5	6.5	6.3	6.8	6.6	5.7

Table 2. Monthly summaries of surface meteorological data at Asuka Station, 1987–1991.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Mean temperature(°C)	−8.3	−11.9	−16.1	−20.6	−23.7	−22.3	−23.3	−25.6	−25.7	−20.2	−14.0	−8.5
Mean max. temperature(°C)	0.5	0.0	−1.7	−8.8	−7.0	−7.8	−9.2	−12.9	−12.3	−6.6	−2.8	−0.3
Mean min. temperature(°C)	−18.8	−24.4	−33.8	−38.1	−42.9	−44.6	−42.0	−48.7	−45.7	−37.0	−32.9	19.0
Mean wind speed(m/s)	10.8	13.4	13.7	12.1	11.4	13.9	14.4	13.7	12.9	12.7	12.5	9.6
Max. gust wind speed(m/s)	36.1	40.4	38.5	32.7	39.1	45.2	37.1	39.5	38.1	42.8	32.1	27.8
Max. wind direction (1991)(16 s)	E	ESE	ESE	SE	ESE	SE	ESE	ESE	SE	ESE	ESE	

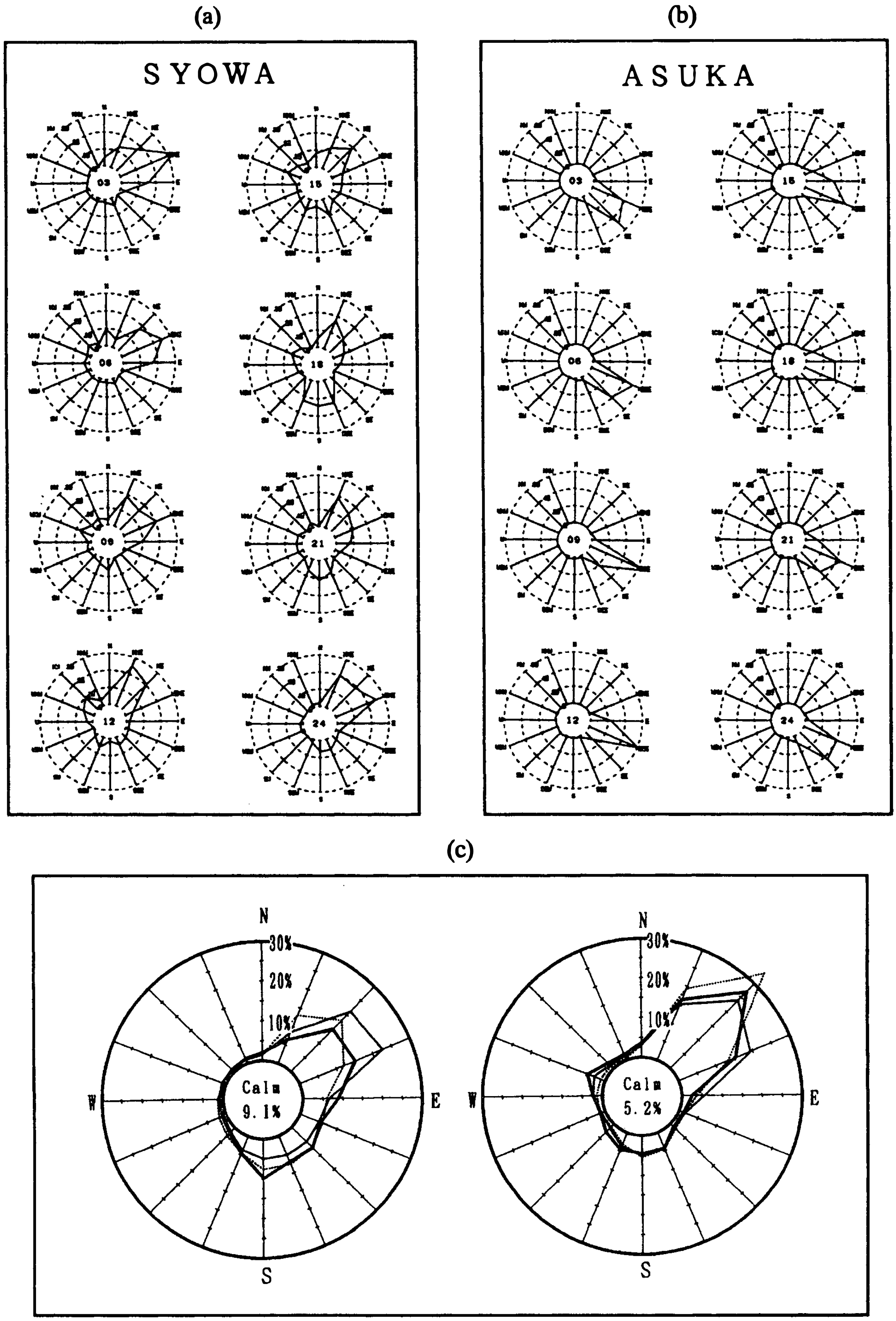


Fig. 2. Wind roses at Syowa and Asuka Stations: 3-hourly wind roses on clear days in summer (December, January, February) at (a) Syowa Station and (b) Asuka Station (KANETO et al., 1994), (c) three annual (1993, 1994, 1995) wind roses at Syowa Station in winter (June, July, August) on the left and in summer (December, January, February) on the right.

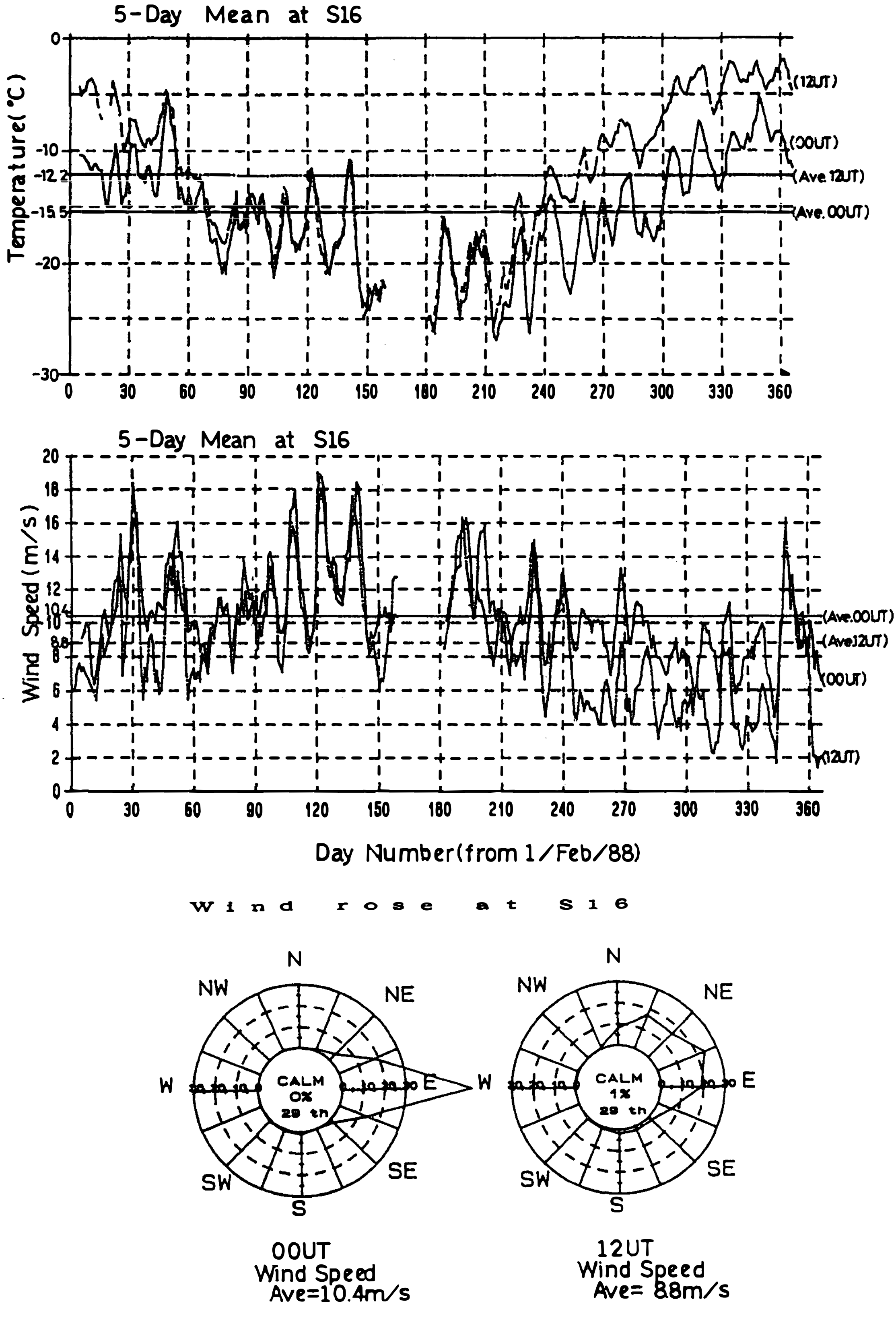


Fig. 3. Variations of meteorological parameters at S-16 from AWS records in 1988 (MATSUBARA et al., 1990).

Two major meteorological parameters, maximum temperature and prevailing wind direction, have been examined because they have a dominant influence on snow/ice runway construction methods and maintenance procedures. The maximum temperature is a very sensitive factor that must be considered to any snow/ice runway project. On the one hand, a maximum temperature around 0°C, causing minor melting, is favorable for the construction and maintenance of a compacted snow runway because the optimal temperature of snow for effective compression is in the range –5° to 0°C (KLOKOV, 1979). On the other hand, melting is a negative factor for ice runway construction on a blue-ice field because melt cavities could develop.

The data on the seasonal variation of monthly means of daily maximum air temperature at Syowa Station, the S-16 site, and Asuka Station show that temperature values are considered to be roughly proportional to the altitude. The temperature conditions at Syowa Station are typical for most coastal stations in East Antarctica located close to sea level. The mean maximum temperature is in the range +1.5 to +2.3°C. This mean that substantial melting occurs in the Syowa Station area in summer.

Lying at an altitude of 554 m, the S-16 site has a temperature regime that appears suitable for constructing a compacted snow runway. The maximum temperature from December to January is about 0°C (Fig. 3). Therefore, we assume that at S-16 the melting process affects the winter snow accumulation to a degree adequate for effective compression. In general, the summer climate at this location is similar to that at Molodezhnaya Station where Russian Expeditions had been constructed a runway for heavy wheeled aircraft.

At Asuka Station, lying at an altitude of 930 m, the maximum temperature is below 0°C during the summer. This means that melting would not occur on the snow surface near Asuka Station. However, melting could occur in the blue-ice fields in this area because ice is a much less reflective material than snow. Therefore, the high solar radiation could occasionally cause minor melting in the blue-ice fields that lie 100–150 m below the station. On the other hand, it is clear that melting never occurs in the blue-ice fields in the Yamato Mountains because they lie at altitudes of 1600–2000 m.

The wind regime is one of the most important factors for both runway construction and aviation operations. A knowledge of strong-wind direction is needed to align the runway along the strongest wind direction or as close as possible to it. Wind records can also reveal how often sudden strong winds occur that can cause problems when aircraft are parked for a relatively long time.

Wind speed and direction at Syowa and Asuka Stations have been analyzed by KANETO *et al.* (1994). According to him, wind speed shows large diurnal variations at both stations on clear summer days. At Syowa, daily peak wind speed in summer is greater than in winter, but at Asuka, summer daily peak winds are slightly less than winter winds. Figure 2 shows wind roses for Syowa and Asuka Stations for every three hours on clear days in summer. The prevailing wind direction at Syowa changes during the day; it is ENE in the morning and NNE in the afternoon. At Asuka, the prevailing wind direction is SE in the morning and ESE in the afternoon. On the other hand, from wind direction statistics the strongest wind is quite constant in direction at both stations: NE at Syowa and ESE at Asuka. The historical data for Syowa Station (see Table 1) show that very strong winds (around 50 m/s) can occur throughout the year. The speed of the strong winds at Asuka Station is generally less than at Syowa Station and the maximum wind in summer is less than 30 m/s (Table 2).

There are few data on the local wind regime at the S-16 site. Figure 3 shows the data collected by AWS during one year. Wind roses for 00 UT and 12 UT demonstrate that the prevailing wind direction at S-16 is substantially different from that at Syowa Station. Therefore wind observations will be required at this particular out station runway site to complement the long-term wind database collected at Syowa Station.

In general, the above information on the wind regime at JARE stations suggests the following runway placements to align with local prevailing winds: Syowa-NE, Asuka-ESE, S-16-ENE. In the Yamato Mountains area, wind directions are very much affected by the local topography, though SE winds predominate.

4. Glaciological Conditions at Prospective Runway Sites

4.1. Fast sea ice near Syowa Station

Level sea ice is an attractive platform for runway construction for wheeled aircraft. In Antarctic seas large areas of fairly thick fast ice are encountered. Some fragments of thick multi-year sea ice remain stable for several years. Such ice plates exist in the Syowa Station area. The thickness of second-year or multi-year ice in Lützow-Holm Bay increases towards the west from 160 cm to 300 cm (YOSHIDA and MORIWAKI, 1983). One of these multi-year ice fields is attached to the East Ongul Island and was used semi-permanently as an airstrip from the time the station was set up in 1957 until it finally broke up in 1980.

Sea ice thickness and depth of snow cover on the sea ice were measured in Lützow-Holm Bay in 1990–1992 (KAWAMURA *et al.*, 1995). Sixteen stations were established on three observation lines south-west of the Syowa Station. The location of the stations are shown in Fig. 4. The data for snow depth and sea ice thickness are

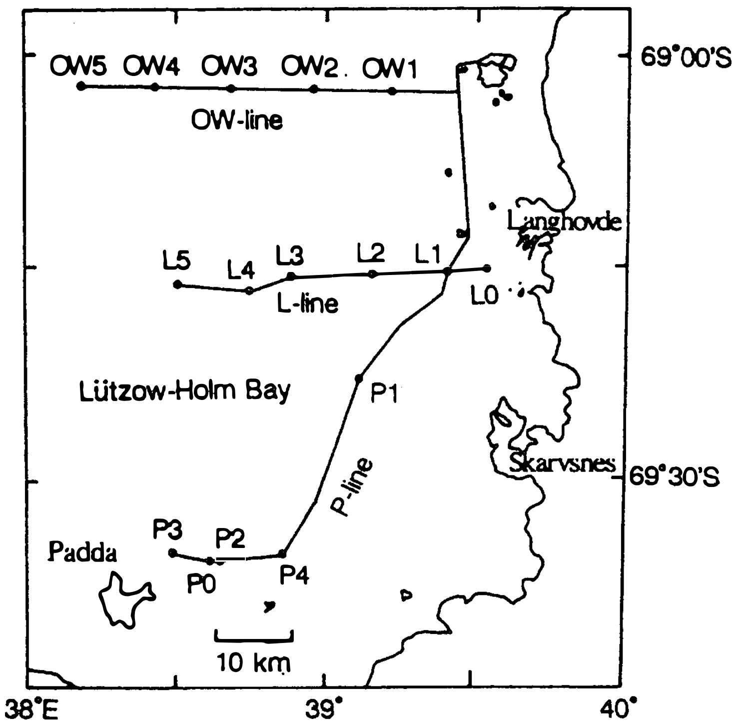


Fig. 4. Location of 16 observation stations in the Lützow-Holm Bay, 1990–1992 (KAWAMURA et al., 1995).

Table 3. Snow depth (Zs) and sea ice thickness (Zi) in meters on the observation stations in the Lützow-Holm Bay, 1990–1992.

	OW1		OW2		OW3		OW4		OW5	
	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi
May 1990	0.33	1.60	0.47	1.90	0.46	1.28				
Aug. 1990	0.53	2.00	0.98	2.11	0.72	1.70	1.30	2.31	1.13	3.02
Oct. 1990	0.55	2.01	1.17	2.19	1.02	2.26	1.21	2.85	1.64	2.77
Aug. 1991	0.48	2.45	1.04	2.83	1.09	1.77	1.40	3.38		
Oct. 1991	0.64	2.39	1.10	2.73	1.16	2.05	1.54	3.30		

	L0		L1		L2		L3		L4		L5	
	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi
May 1990			0.11	1.44	0.39	2.20	0.63	2.15	0.72	2.20		
Aug. 1990			0.15	1.70	0.70	2.50	0.97	2.13	1.20	2.13	1.40	2.13
Oct. 1990			0.29	1.98	1.05	2.22	1.39	2.24	1.59	2.37	1.65	2.12
Apr. 1991	0.05	0.72	0.05	1.45	0.10	2.10	0.35	3.03	0.58	3.16	0.47	2.88
Aug. 1991	0.20	1.34	0.22	1.74	0.36	2.15	0.86	3.25	0.92	2.81	1.12	2.97
Oct. 1991	0.15	1.60	0.20	2.04	0.53	2.36	0.98	3.25	1.13	2.86	1.42	2.80
Jan. 1992							0.53	3.38				

	P0		P1		P2		P3		P4	
	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi	Zs	Zi
Jan. 1990	0.26	2.38								
Apr. 1990			0.27	1.89	0.65	2.35	0.60	2.05	0.56	2.08
Aug. 1990			0.72	2.08	1.35	2.25	1.35	2.10	1.04	2.08
Oct. 1990			0.86	1.90	1.52	2.45	1.45	2.15	1.25	2.10
Jan. 1991	0.67	2.71								
Jan. 1992	0.88	3.32								

given in Table 3. In Table 3, sea ice thickness is in the range 1.28–3.38 m. In fact, just three points give values more than 3 m (OW4, L3, PO). All of these maximums represent multi-year ice. Sea ice cores were collected at the stations to assess structure, temperature, salinity and oxygen isotope concentration. Results of the analyses at the station that had maximum ice thickness are shown in Fig. 5. Values of investigated parameters and thin section photomicrographs appear to indicate that this fast sea ice is strong. It is highly probable that such a sea ice plate has a high enough bearing capacity for landing of large aircraft. However, the natural snow cover is very thick, reaching 1.2–1.5 m at many points (Table 3). Therefore, a great deal of plowing will be needed to remove snow from the runway.

The possibility of having a sea ice plate thickened by flooding with sea water for constructing an airstrip in the vicinity of Syowa Station has been examined by NAKAWO (1982). Using monthly mean values of meteorological data at Syowa Station he calculated that generation of artificial ice is possible between March and September. Taking the value of −10°C as the average ice temperature in the construction period, it was estimated that the maximum thickness of built-up ice might be 3.8 m. However, the period available for construction would be shorter because of snow storms and the time needed to remove the deposited snow. Consequently, a more realistic estimation of the possible thickness of the artificial ice platform would be smaller, perhaps about 3 m.

These considerations demonstrate that sea ice, natural or built up by flooding, could be used to create a runway in the Syowa Station area. However, in many

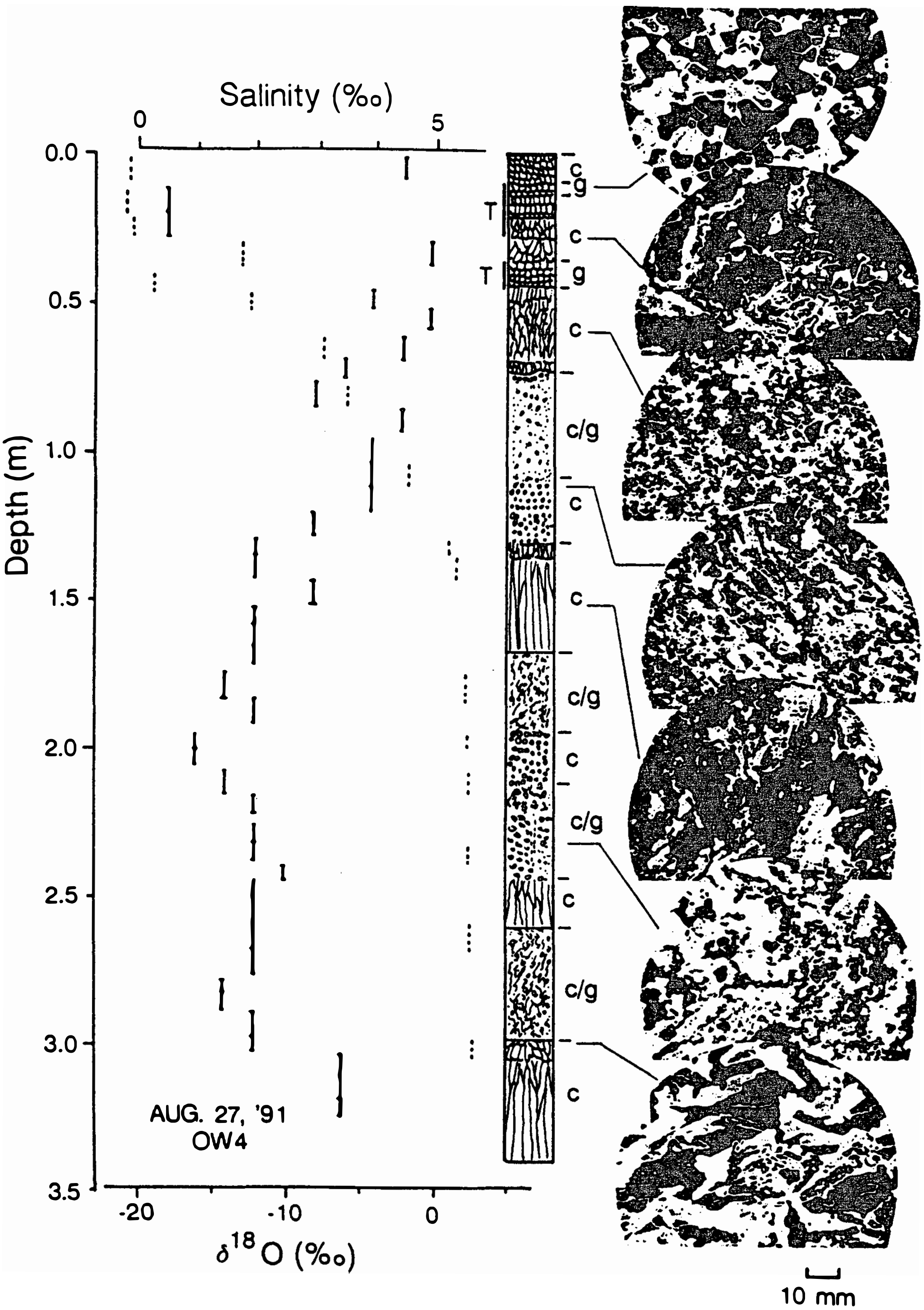


Fig. 5. Salinity (solid line) and oxygen isotope concentration (dashed line) profiles, vertical structure sections and photomicrographs of horizontal thin sections of sea ice. Lützow-Holm Bay, Station OW4, August 27, 1991 (KAWAMURA et al., 1995).

respects, it is not a simple task to construct and maintain a runway on sea ice. Special techniques and methods are needed to prepare the runway. A significant amount of machinery must be provided for construction, such as bulldozers, snow-blowers, powerful water pumps and so forth.

Also, there is a substantial problem in constructing and maintaining a runway on multi-year sea ice at the same site year after year. During the construction phase, a great deal of snow must be cleared. On multi-year ice this is several years' accumulation. Upon completion, the snow must be removed constantly during the maintenance phase. As a result of this, huge (up to several meters high) snow banks are formed along the sides of the runway, depressing and cracking the ice, which would eventually break up.

And finally, a runway constructed on sea ice can be broken up or completely destroyed by natural causes at an unpredictable moment. From this point of view, a runway built on sea ice should not be considered as a long-term installation.

4.2. Coastal area around S16

The S16 site (69°02'S, 40°03'E) is located on the ice sheet 20 km east of Syowa Station at an altitude of 554 m. This location is used as the starting point for JARE inland traverses. There are two routes connecting Syowa Station and S16: a northern one named Tottuki Route and a southern one named Mukai Route. Both routes go up a rather steep slope of the ice sheet and cross a few crevassed areas. However, there are no reports of crevassing in the S16 area. Also, according to numerous descriptions of the S16 area, the site is reasonably level and surface gradients at this elevation do not exceed 0.02. Therefore, there is little concern that finding a possible runway site in this area with grades specified for airfield standards would be problem.

The location of S16 is just above the firn line, though the position of the boundary of the permanent snow cover varies from year to year. The results of a stratigraphic study made by WATANABE (1978) along the inland traverse route are shown in Fig. 6. The type of snow/ice structure found at S16 can be characterized as multiple firn layers alternating with ice lenses and vertical ice inclusions. Thus it is reasonable to infer that bulk melting occurs annually in this area. This type of stratigraphy is typical for the infiltration zone that usually exists at the transition between areas of net accumulation and net ablation. In accordance with existing glaciological records, the relation between volume of ice inclusions and annual snow accumulation in S16 area varies year to year from 30 to 100%.

Historical information concerning the rate of snow accumulation in the S16 area is relatively comprehensive. During the period from 1972 to 1994 the snow accumulation was measured at a 36-stake farm located near S16. Mean values of snow accumulation varied significantly from year to year (Table 4). According to JARE Data reports, the average value of snow accumulation at the 36-stake farm is roughly 10–15 cm per year. Occasionally the mass balance was negative, and superimposed ice was exposed at the surface. Data on snow density collected at the same site are shown in Table 5.

The above data show that the S16 site is not favorable for building a hard sur-

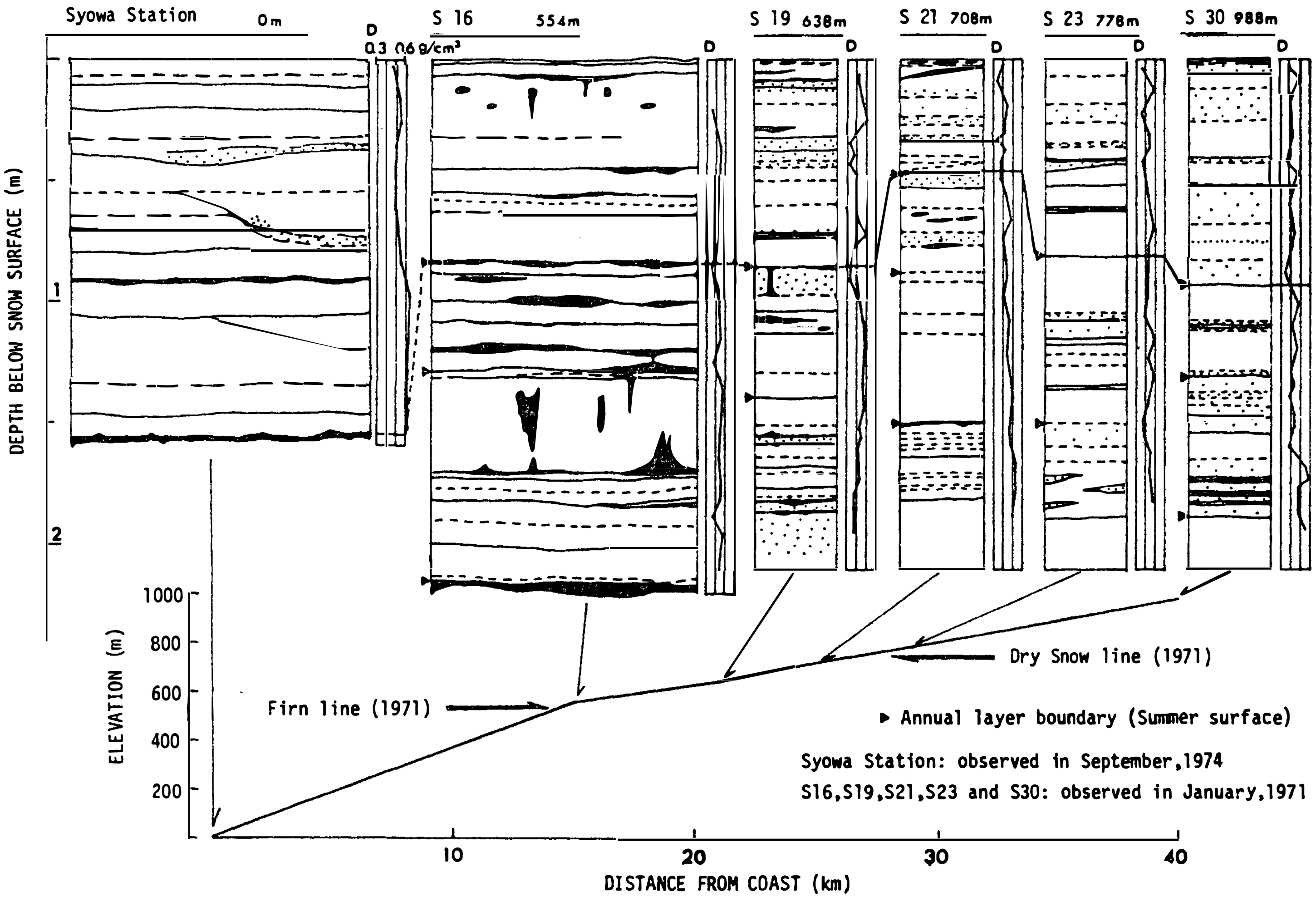


Fig. 6. Stratigraphy of the upper snow layers inland of Syowa Station (WATANABE, 1978).

Table 4. Net accumulation of snow(cm) at the ice sheet surface in S16 arera (mean values at the 36-stake farm).

Period	2.06.1972 ~29.01.73	29.01.73 ~26.04.74	26.04.74 ~11.02.75	7.01.81 ~13.01.82	27.12.83 ~14.01.85	14.01.85 ~30.09.86
Accumulation(+)	+0.4	+20.2		+59.8	+4.6	+19.9
Ablation(−)			−7.0			

Period	30.09.86 ~19.01.87	19.01.87 ~7.01.88	7.01.88 ~1.01.89	03.02.92 ~31.01.93	31.01.93 ~28.01.94	28.01.94 ~29.12.94
Accumulation(+)	+22.3	+0.8		+14.7	+18.3	+7.3
Ablation(−)			−0.1			

Table 5. Snow density (g/cm³) in 2-m pit at S16.

Depth(cm)	20	38	50	60	73	87	95	104	112
Snow density	0.39	0.45	0.45	0.57	0.45	0.38	0.41	0.42	0.45

Depth(cm)	125	137	165	178	181	187	197	207
Snow density	0.39	0.47	0.44	0.45	0.45	0.38	0.47	0.45

face runway by compacting snow. It is possible that a compacted snow runway could be constructed in an area inland of S16, somewhere between S16 and S18 (Fig. 7), where the snow accumulation rate is about 70–80 cm (YAMADA and WATANABE, 1978). It seems that at elevations of about 600 m glaciological conditions are quite similar to the runway site at Molodezhnaya. With tested construction techniques and past construction experience, a hard-surface runway could be built at this location. However, as the runway construction at Molodezhnaya showed, a tremendous construction effort and a number of heavy machines would be required (AVER'ANOV and KLOKOV, 1975). Moreover, the construction procedure would need to be (partly or wholly) repeated annually to maintain the runway because of the high snow accumulation. Also,.unlike the Molodezhnaya runway site, no rock outcrop exists in or near the area between S16 and S18 at which to set up ground facilities and machinery to protect them from heavy snow drifts. It is an additional negative factor for this potential site, because the absence of any rocky elevation in the area will substantially increase the magnitude of logistic support as well as the cost of airfield construction and maintenance between S16 and S18.

A reasonable alternative to establishing a compacted snow runway inland from Syowa Station might be to build a runway on the snow-free ice fields south of the Langhovde hills. A vast area of blue ice is located between the Langhovde Glacier and the Honnor Glacier drainage basins (Fig. 7). This area appears to be a stable part of the ice sheet on the Sôya Coast. Also, there are more or less flat spots on the ice slope between the 400 m and 600 m elevations. Using a 1:100000 map, we estimate that within this altitude interval the general slope gradient is roughly 0.02. After all, there is a rock outcrop in the area, the Langhovde hills, where a runway infrastructure could be set up. These natural conditions make this area very attractive as a potential site for a blue-ice runway. However, field investigations should be carried out in the area to examine the surface topography, melting conditions and extent and location of any crevassing.

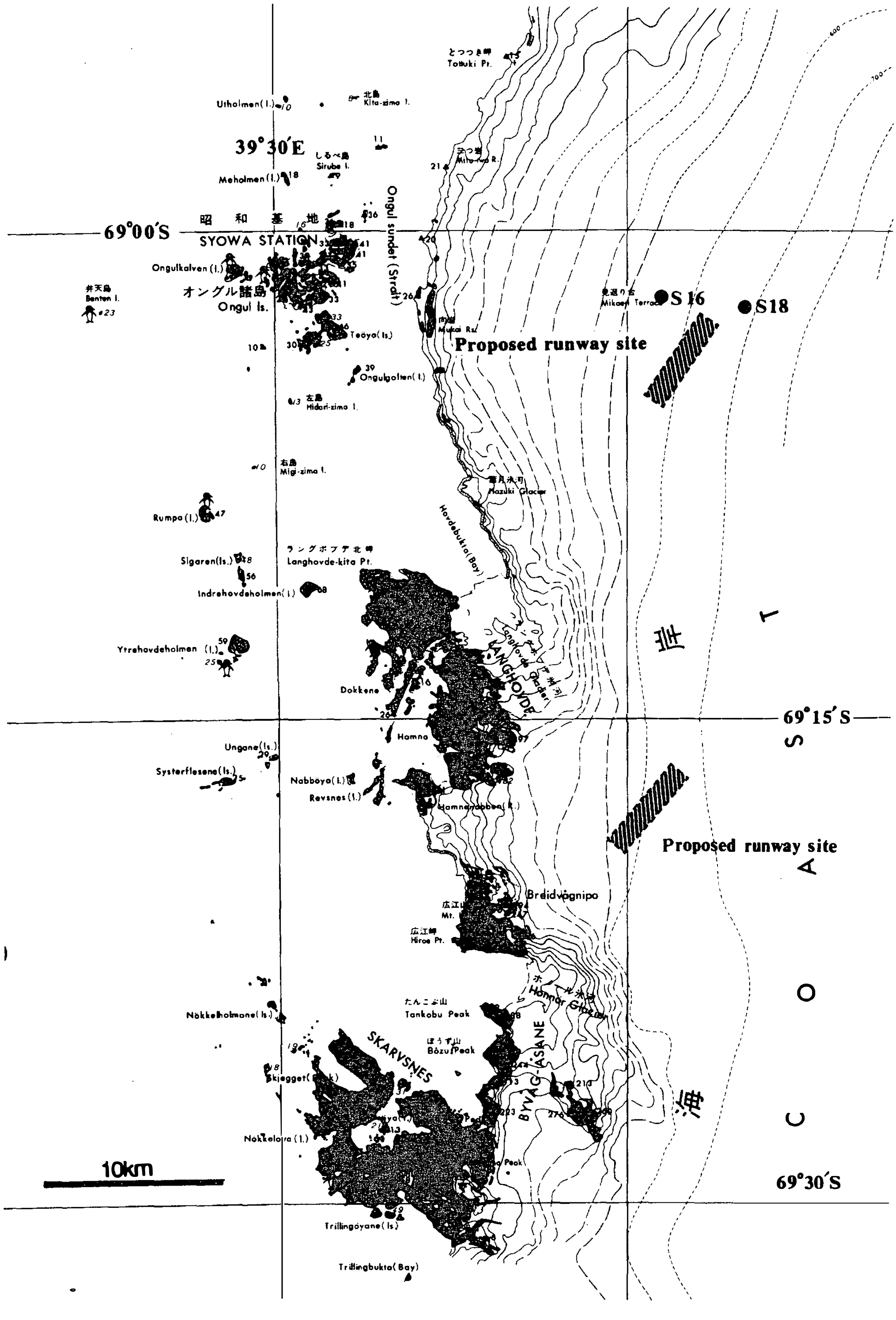


Fig. 7. Proposed runway sites in the coastal area east of Syowa Station. Base map by Geographical Survey Institute, Japan.

4.3. Asuka Station area

The JARE year-round station, Asuka (71°32'S; 24°08'E), was established in 1987 and operated until 1992. The station is located at a point 30 km north of the western part of the Sør Rondane Mountains at 930 m altitude, 120 km from the coast. The route connecting Asuka Station and the ship unloading area in Braid Bay is quite straight (Fig. 1). A groomed skiway was prepared and supported near the station during the summer seasons (Figs. 8, 9).

The area around the station appears as a low gradient slope of the ice sheet with a rather smooth snow surface. The snow accumulation was measured at a snow stake farm near Asuka Station from 1986 to 1991. Mean values of snow accumulation are shown in Table 6. The data show that a compacted snow runway could be built at Asuka Station, though significant construction and maintenance would be required because of the rather high snow accumulation .

Table 6. Snow accumulation at Asuka Station 1985–1987 and 1989–1991.
(Mean values, cm in depth)

Period	27.12.1985 ~29.01.1986	29.01.1985 ~25.01.1987	11.06.1987 ~25.12.1987	20.11.1989 ~22.12.1990	22.12.1990 ~21.11.1991
Accumulation(+)		+16.1		+42.4	+39.1
Ablation(−)	−5.3		−8.2		

The gradient of the ice sheet surface increases abruptly starting a few kilometers north-west of Asuka Station. The steep part of the slope is quite short, about 5–10 km. Farther north the ice sheet surface again becomes flatter. Three rock outcrops lie at the change in slope in this area: Mt. Romnoesfjellet, Mt. Vesthaugen and Seal Rock (Fig. 10). In this topography, the katabatic winds blowing down the slope increase their speed with increasing slope inclination and erode the snow cover, leaving bare ice. Blue-ice fields are thus developed leeward of the rock outcrops which act as an obstruction to the katabatic winds. A small blue-ice field about 4.5 km long exists leeward of Seal Rock, which rises about 100 m above the ice sheet surface. The length of the blue-ice fields behind Mt.Vesthaugen, with 300 m relief, is about 15 km and behind Mt. Romnoesfjellet, with 500 m relief, about 50 km. The mechanism of formation of bare ice fields in this area was discussed by TAKAHASHI et al. (1992).

As determined by meteorological observations, the temperature almost never rises above 0°C at Asuka Station. Therefore, we assume that no melting occurs at the blue-ice fields behind Mt. Vesthaugen and Mt. Romnoesfjellet. Corresponding with previous studies (KLOKOV, 1995), these fields qualify as "cold blue-ice fields". At such sites a runway can be built with minimal construction effort. In emergencies, such sites can be used for occasional landing of conventional wheeled aircraft without a preliminary ice surface treatment.

Mass balance observations were carried out on the blue-ice field leeward of Seal Rock by the snow stake method in 1989–1990. Snow stakes were placed along a 1-km line across the blue-ice field as shown in Fig. 11. The surface mass balance was calculated using the data of surface level change and the densities of ice (0.92 kg/m^3)

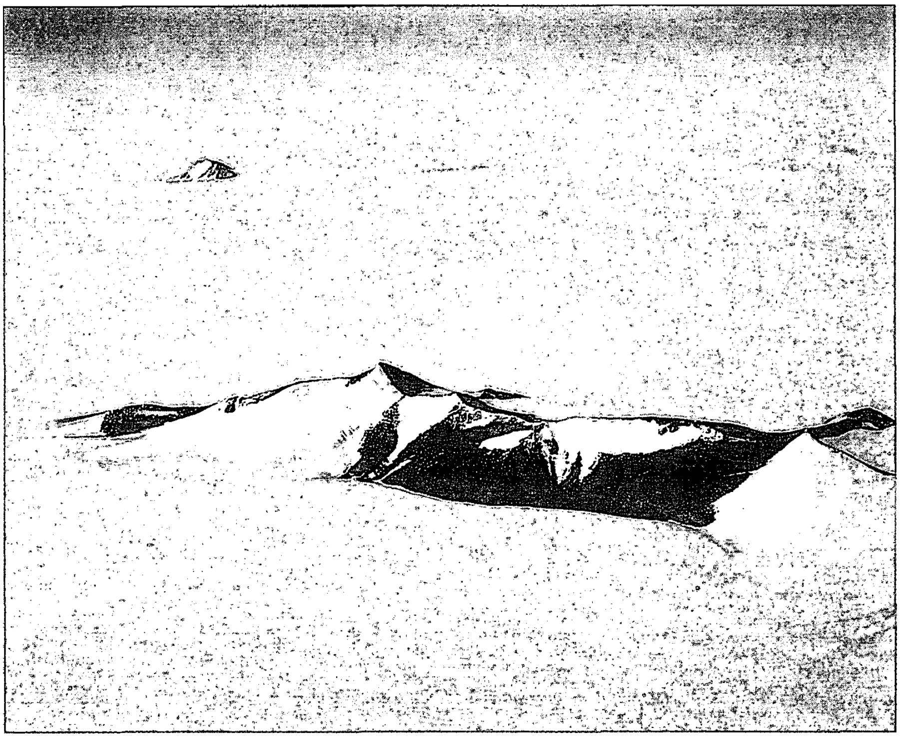


Fig. 8. The proposed blue-ice airfield (foreground) at Mt. Vesthaugen, Sør Rondane Mountains area. Background are Mt. Romnoesfjellet (left) and, barely visible, Seal Rock (right). Asuka Station is 2 km east of Seal Rock (JARE photo, 4/197, December 1986).

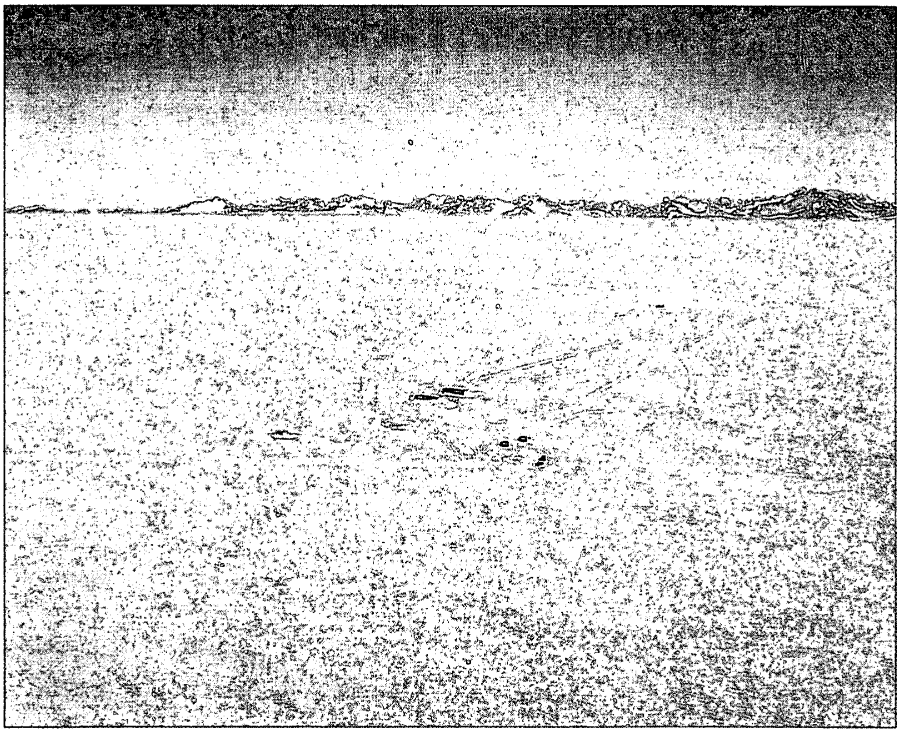


Fig. 9. Asuka Station, looking south-east (JARE photo, 4/205, December 1986).

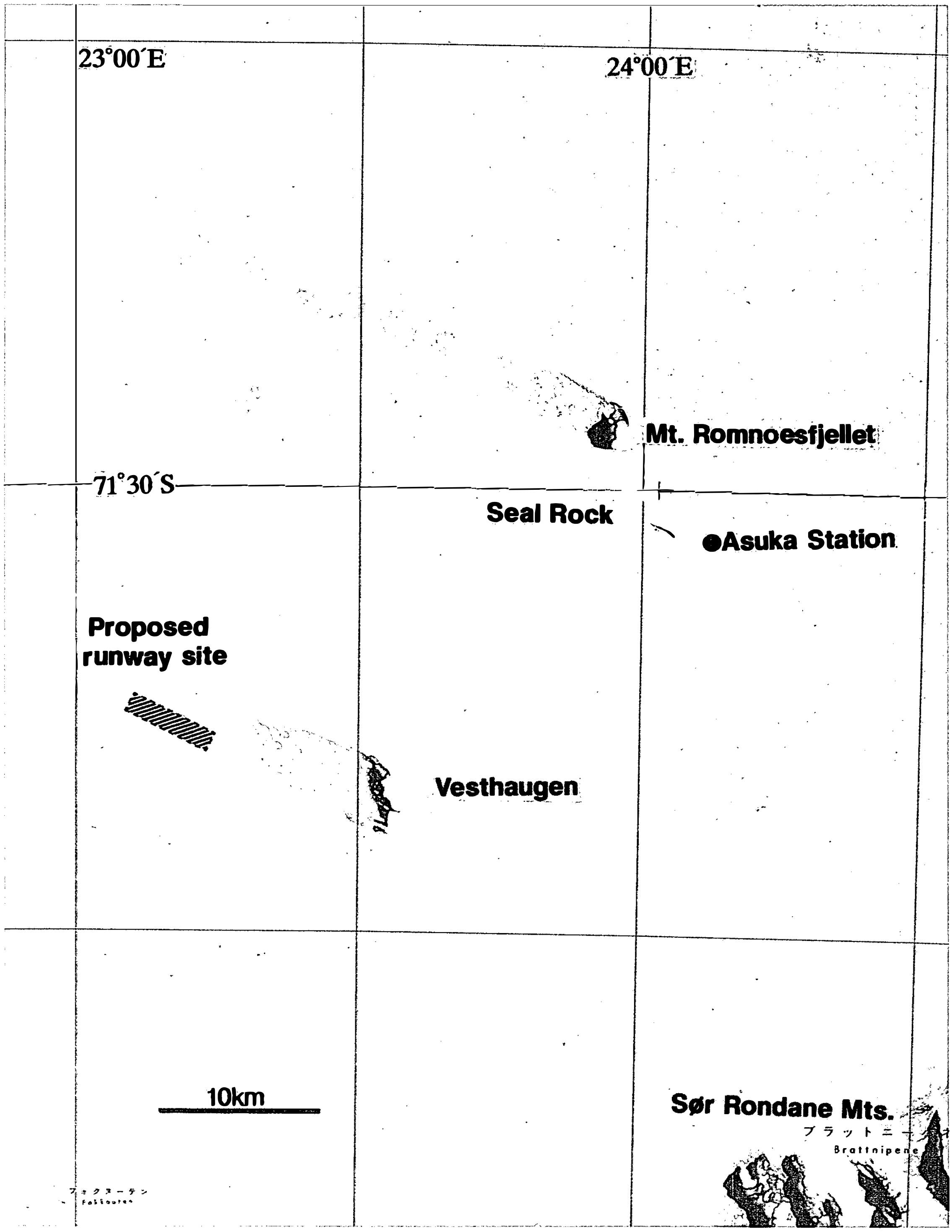
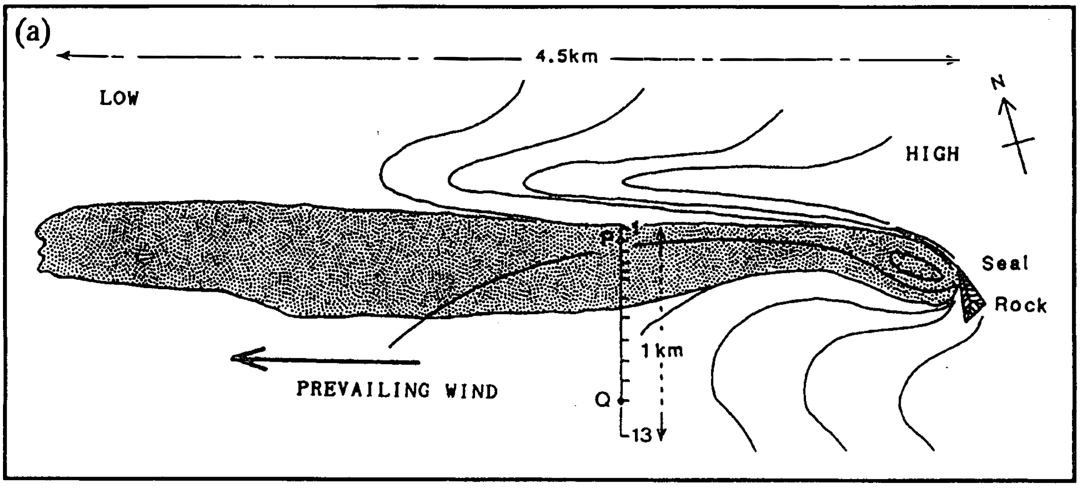


Fig. 10. Location map of the Asuka Station area. The prospective site for a blue-ice runway is shown by hatches.



(b)

Snow stake number	1	2	3	4	5	6	7	8	9	10	11	12	13
Distance from the stake No.1 (m)	0	50	100	150	200	250	350	450	550	600	750	850	1050
Surface level change (cm) from 07.01.89 to 30.01.90	-33	-26	-25	-24	-15	-8	1	0	13	41	42	42	15
Net mass balance (mm) from 07.01.89 to 30.01.90	-285	-224	-216	-207	-129	-64	4	0	49	154	158	158	56

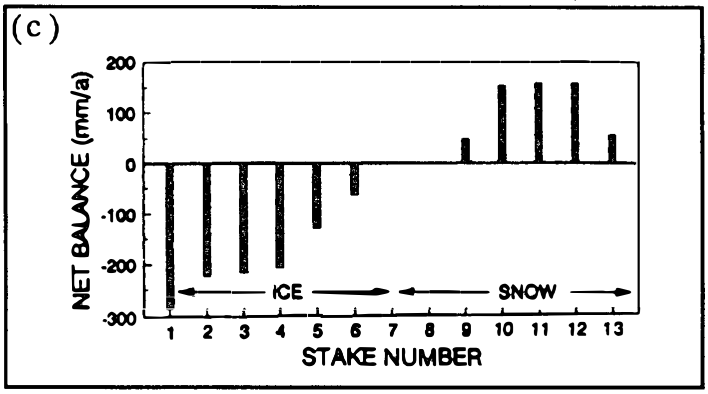


Fig. 11. Sketch map showing (a) snow stake positions on the blue-ice field at Seal Rock, (b) mass balance observations and (c) net surface mass balance from January 1989 to January 1990 (TAKAHASHI et al., 1992).

and snow (0.40 kg/m^3). Negative mass balance was observed on the bare ice surface with sublimation values in the range from 200 mm to 280 mm in water equivalent. The bare glacier ice had a typical cuspate surface, with regularly spaced pits about the size of a saucer. Such surface texture occurs if melting is absent and ablation occurs directly by sublimation. The snow depth in the area surrounding the blue-ice field was about 40 cm (150 mm in water equivalent).

Two blue ice fields among the three mentioned above are attractive as prospective runway sites: Mt. Vesthaugen and Mt. Romnoesfjellet. The blue-ice field leeward of Mt. Vesthaugen is the best location in the Asuka Station area for a natural, hard-surface ice runway. The bare ice area behind Seal Rock is too small for a runway.

From study of the topography of the two blue-ice fields, we determined that the climb-out path would meet aircraft take-off standards if the runways were oriented close to the prevailing wind (ESE) at the far leeward end of the blue-ice fields behind Mt. Vesthaugen and Mt. Romnoesfjellet. Although Mt.Vesthaugen has a relief of about 300 m, the climb-out profile heading into the prevailing winds (ESE) would be less than 1/60 if the runway were positioned at the north-west edge of the blue-ice field (Fig. 10). However, there is some concern that turbulence may occur leeward of the mountains, which would adversely affect aircraft in the climb.

4.4. Blue ice fields in the Yamato Mountains

Remarkably extensive blue-ice fields exist on the ice sheet slope in the Yamato Mountains. Two related factors produced this large area of bare ice: the steepness of the local topography and the acceleration of katabatic winds with increasing inclination. Under these conditions the snow drifting increases, eroding the snow and leaving bare ice. As a result, a huge cluster of blue-ice fields, with a total area of more than 800 km^2, extends in the sector 71°10'S–72°30'S and 34°30'E–37°00'E.

Photographs and records of aerial observations of blue-ice peculiarities in the area were made during JARE geological surveys in the Yamato Mountains in 1973, 1979 and 1980 by K. SHIRAISHI. It was recognized that the blue ice here is generally affected by crevassing but a few sites are crevasse-free. According to a surface reconnaissance, a vast blue-ice field lying west of Massif B and Massif C appears to be the best location for establishing a runway (Fig. 12). It has a flat surface and no crevassing. Local topography would allow a runway heading into prevailing winds (ESE) that would meet aircraft take-off standards if the runway lays at the south edge of the blue-ice field. A fuel depot could be set up on the moraine bordering the rock outcrops. Thus, this site could be used for occasional landing of conventional wheeled aircraft without preliminary ice surface treatment.

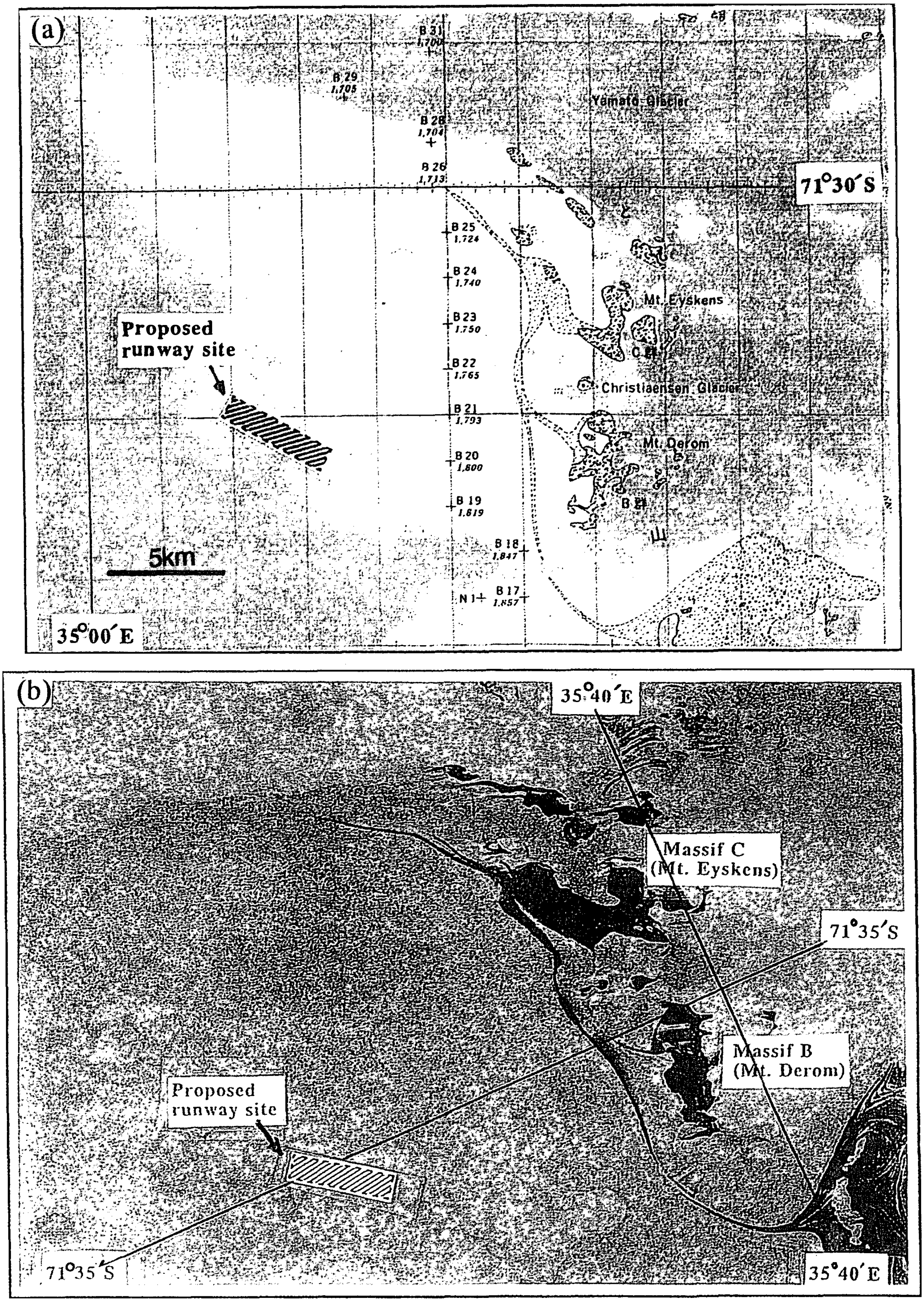


Fig. 12. Location of the proposed runway site in the Yamato Mountains: (a) JARE 1 : 200,000 scale map of the area; (b) satellite image of the area. The prospective site for a blue-ice runway is shown by hatches.

5. Construction Techniques for Establishing of a Hard-surface Runway on the Snow and on the Ice

Establishing a hard-surface runway on deep snow would seem to be a difficult task considering that a strong pavement has to be created on a thick and weak snow/firn basement. However, a fairly simple procedure has been developed (AVER'ANOV and KLOKOV, 1975) and the first compacted snow runway was built in 1981 at 10 km east of Molodezhnaya station (Fig. 13). The runway dimensions were 2540×42 m and the operating headings were 140° and 320°. The construction technique used at Molodezhnaya entailed three main methods of snow processing: disaggregating the snow with disk harrows, leveling with a grader, and compacting with a multiple-tire roller (Fig. 14). The maintenance procedure includes the same methods of snow processing, although it is less labor-intensive. The runway at Molodezhnaya was operated until November 1994.

In the 1989–1990 summer season a 3-km long compacted-snow runway was constructed near Casey Station. The Australians used the same construction technique at Casey as the Russians in Molodezhnaya. Though the runway has not been used for landing aircraft, the comprehensive testing program and a proof rolling showed that the runway pavement was strong enough to support wheeled C-130 aircraft (RUSSELL-HEAD and BUDD, 1991).

Any runway, whether on ice or on snow, designed for wheeled aircraft has to be hard enough to resist rutting formed by the wheels and strong enough to support the maximum take-off weight of the aircraft. The major input parameters to design an adequate pavement for a snow/ice runway are the aircraft wheel tire pressure and the maximum take-off weight. A pavement of adequate thickness and strength has to be designed using the specifications of the particular aircraft to be used. The value of the required thickness and strength for different types of aircraft are given in Table 7.

Table 7. Required parameters of snow pavements for wheeled aircraft use in Antarctica.

Aircraft	Max take-off weight (kg)	Tire pressure (MPa)	Pavement thickness (m)	Upper layer hardness (Mpa)
C-130H	79380	0.7	0.5	0.8
Ilyushin Il-76TD	90000	0.5-0.7	0.7	0.8
Dornier 228-100	5700	0.3-0.5	0.25	0.5
DHC-6 Twin Otter	5670	0.3-0.5	0.25	0.5

Fig. 13. Ilyushin Il-76TD on the compacted snow runway at Molodezhnaya.

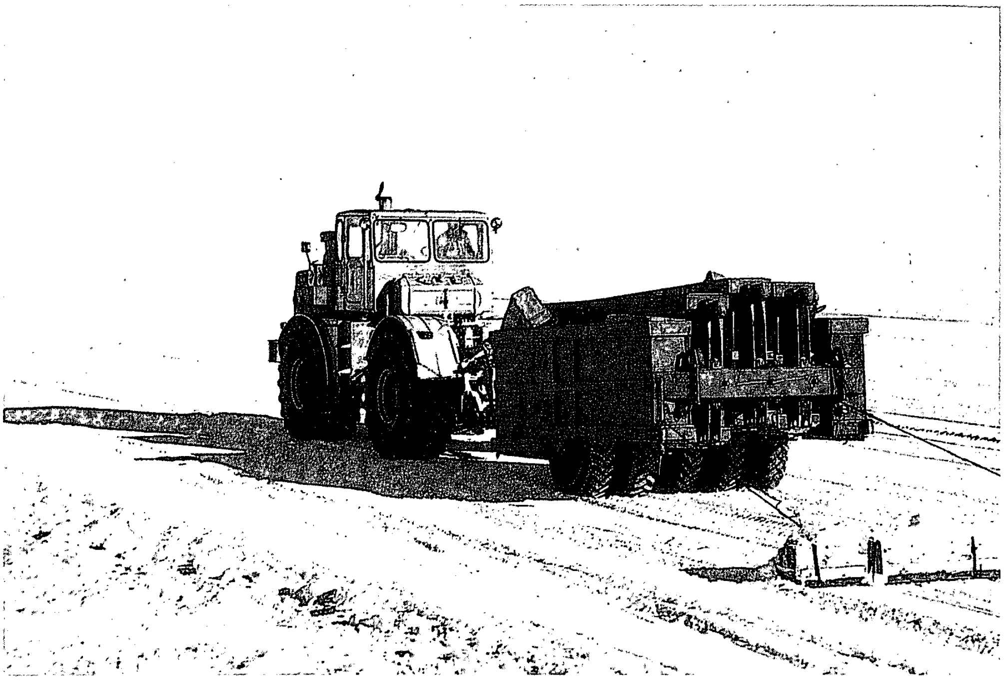


Fig. 14. Multiple-tired compaction roller used at Molodezhnaya.

Basically, it is easier to build a conventional runway on blue-ice than in areas of net snow accumulation. Even without substantial treatment, snow-free glacier ice can be used by wheeled aircraft for air operations. However, several factors must be taken into account. First, a blue-ice field is rarely smooth, either on a micro or macro scale. Second, cavities or crevasses must be absent in an area the size of a runway. Third, the duration and degree of any melting in a blue-ice area must be known. In areas affected by melting, to operate from a blue-ice runway in summer a protective snow cover should be created on the ice surface before the melting. Such a snow cover will protect the runway from melting and also improve the friction parameters of the runway surface. The first full scale ice runway was built in 1982 15 km south of the Novolazarevskaya Station and was operated as an alternate to the runway at Molodezhnaya until 1994.

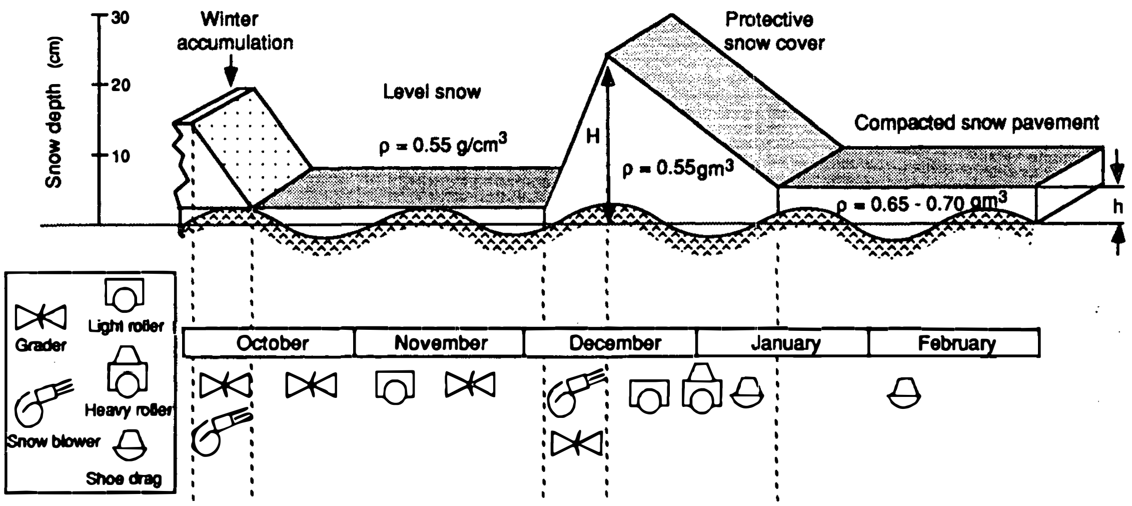


Fig. 15. Schematic outline of protective snow pavement construction on a blue-ice runway affected by melting.

Both the initial and annual procedures of runway preparation on bare ice include planing the ice, using a heavy grader or rotary ice chipper, and periodic compaction of the snow if a protective snow cover is needed. A typical procedure for ice runway construction was described earlier (KLOKOV and DIEMAND, 1995). The construction and maintenance procedures for making a protective snow pavement on an ice runway involves a simple and inexpensive technique (Fig. 15). The main ingredient of a protective snow pavement on a blue-ice runway is the natural snow that accumulates on the ice surface during the winter or is brought in from elsewhere and spread on the runway surface by snowblower. The idea is to make a snow pavement that is thicker than the rate of snow melting but not so thick that needs to be removal snow at the end of the season. Also, leaving a final thin snow pavement gives a comfortable reserve and a buffer against extremely strong melting.

The required equipment and logistic facilities for establishing a snow/ice runway are listed in Table 8. The infrastructure requirements in the table assume the runway site is located distant from a permanent station. If the snow or ice runway is close to the station, support for runway construction can be mostly based on existing infrastructure. In any case, temporary field camp facilities should be established at the runway site during the operating period.

Table 8. Required infrastructure for establishing of a snow/ice runway.

	Compacted-snow airfield		Airfield on snow-free ice	
	Heavy wheeled aircraft	Small (light) wheeled aircraft	Heavy wheeled aircraft	Small(light) wheeled aircraft
Personnel (full time)	6–8	3–4	3–4	2–3
Camp modules (accommodation, workshop, power unit, store)	4–5	2–3	3–4	1–2
Fuel tanks (l) and refueling gears	70000	5000	70000	5000
Machinery:				
Tractor	3–4	2–3	2–3	2
Multi-tired roller	2–3	1	1	
Snow miller (multi-disk harrow)	1–2	1	-	-
Grader on skis	1–2	1	-	-
Drag-planer	1	-	-	-
Snow-blower	1–2	1	1–2	1
Radio/Nav aids	HF, VHF, UHF, Beacon, GPS, Satcom			
Medical and fire care	+	+	+	+

6. Aircraft for Intercontinental and Intracontinental Flights

Table 9 summarizes the general characteristics of aircraft that are of practical interest for use in Antarctica.

The selection of aircraft for flights to and from Antarctica should be made with many parameters of the aircraft in mind. But above all, the aircraft must meet three major requirement:

• They must have sufficient range to reach, if needed, an alternate airport in the limited air network of Antarctica or be able to return to the point of departure;

• They should be multi-engined, STOL (short take-off and landing) type with high-flotation main landing gear and high wing;

• They should be equipped with airborne ramp, winch, telpher and reasonable facilities for passengers.

Table 9. Characteristics of aircraft with potential for Antarctic use.

Type	Ski/wheeled	Wing span	Length	Height	Max. take-off weight	Take-off run	Max. payload	Max. range with max payload	Ferry range
		m	m	m	kg	m	kg	km	km
Lockheed LC-130R	Wheeled	10.4	29.8	11.6	70310	1090	19685	2435	7871
Lockheed C-130J	Wheeled	40.4	29.8	11.6	79380	890	20181	2978	8654
Ilyushin 76TD	Wheeled	50.5	46.6	14.8	190000	1500	50000	3650	10580
Dornier 228 Polar	Ski/wheeled	17.0	16.6	4.9	5700	450	2201	870	2440
DHC Twin Otter	Ski/wheeled	19.8	15.8	5.7	5670	260	2350	690	2030

The Ilyushin Il-76TD and two versions of the Lockheed C-130 meet these requirements. The Ilyushin is a large and fast aircraft with very short take-off and landing distances. The aircraft has sixteen large-diameter, low-pressure tires to avoid rutting the surface of the snow runway. Uneconomical turbojet engines, however, are a serious negative feature of the Ilyushin Il-76TD.

For the past three decades the most practical aircraft for long-range operation in Antarctica has been the ski-wheel Lockheed C-130 Hercules. Recently, since hard surface runways were built at Pegasus and King George Island, some countries (Argentina, Chile, Italy, New Zealand and USA) are beginning to fly to Antarctica using the conventional C-130 on wheels. Wheeled take-off allows about 3600 kg of extra cargo and fuel over the ski-wheeled counterpart. The next-generation Hercules-designated C-130J by Lockheed-has new engines and digital avionics. Performance improvements of the C-130J over the current Hercules include 35% additional range and a 22% reduction in take-off run.

Much of inland air transportation is carried out by fixed-wing ski-wheeled aircraft that are capable of landing on short runways. The current choice includes the DHC-6 Twin Otter and Dornier 228 Polar (Table 9). Both these aircraft are capable of limited over-ocean journeys but are too large to be transported by ship to Antarctica. Therefore, the operating cost of these aircraft is rather high. A reasonable way to reduce their operating cost is to share the cost between several partner operators.

Helicopters are traditionally used for short distance ship-base-ship operations. However, at the present time some Antarctic operators use heavy helicopters to transport personnel and cargo between stations and field bases. Such long range flights are normally performed adequately by twin-engined helicopters, although fuel depots need to be established along unusually long routes. The technical parameters of twin-engined helicopters that are in use are presented in Table 10. The Sikorsky helicopters have proven to be the most capable.

Table 10. Technical parameters of two-engine helicopters proposed for operation in Antarctica.

Type	Max range with IFR km	Cruising speed km/h	Cabin volume m^3	Max. take-off weight kg	Max. payload kg
Mil MI-8	760	220	12.5	12000	4000
Sikorsky S-62	473	268	10.9	9185	3630
Sikorsky S-76	533	269	5.8	5307	2300
Sikorsky S-92	741	259	16.9	10079	3750

7. Conclusions

During last decade Antarctic aviation has been getting more international attention than never ever before. National Antarctic programs are taking practical steps to improve efficiency and safety of air operations. A logical extension of this trend in international collaboration would be establishing a wide network of hard-surface runways. In particularly, such a joint air network would be beneficial and productive in East Antarctica where many countries operate. The effort to establish an airlink is formally called the East Antarctic Air Network (EAAN) project.

This feasibility study undertaken by two prospective partners in the EAAN, JARE and RAE, provides information on the meteorological regime and glaciological conditions in prospective runway sites near JARE stations. The Syowa area demonstrate a good opportunity for provision and operation both a compacted snow runway and blue-ice runway. A field reconnaissance should be done in the area to identify the most favorable scheme to construct a semi-permanent hard surface runway. At Asuka Station a runway can be built on a nearby blue-ice field with minimal construction effort. Extensive blue-ice fields on the ice sheet slope in the Yamato Mountains can be used by conventional wheeled aircraft without preliminary ice surface treatment, so are suitable in emergencies.

A general scheme and principal components of the EAAN is given in Fig. 16. The EAAN includes: two trans-ocean air bridges with gateway airports in Australia (Hobart) and Africa (Cape Town) associated with the local network of hard-surface runway in the East Antarctic. Considering provided information on natural conditions near permanent station in the sector from 60°E to 120°E (KLOKOV, 1996) we conclude that three hard-surface runways could be constructed at low cost near Casey, Larsemann Hills and Novolazarevskaya. Results of this feasibility study show that Syowa Station area has also very favorable potential for snow or ice runway construction.

The knowledge base and technical capabilities for runway establishment already exist. A realistic solution for joint air operations could be found in commercial charter of a conventional C-130J aircraft. To mitigate financial difficulties, a mechanism for cost sharing should be formulated. However, to create such a significant intercontinental airlink as the EAAN, an agreement between potential partners (Australia, China, Japan and Russia) should be negotiated.

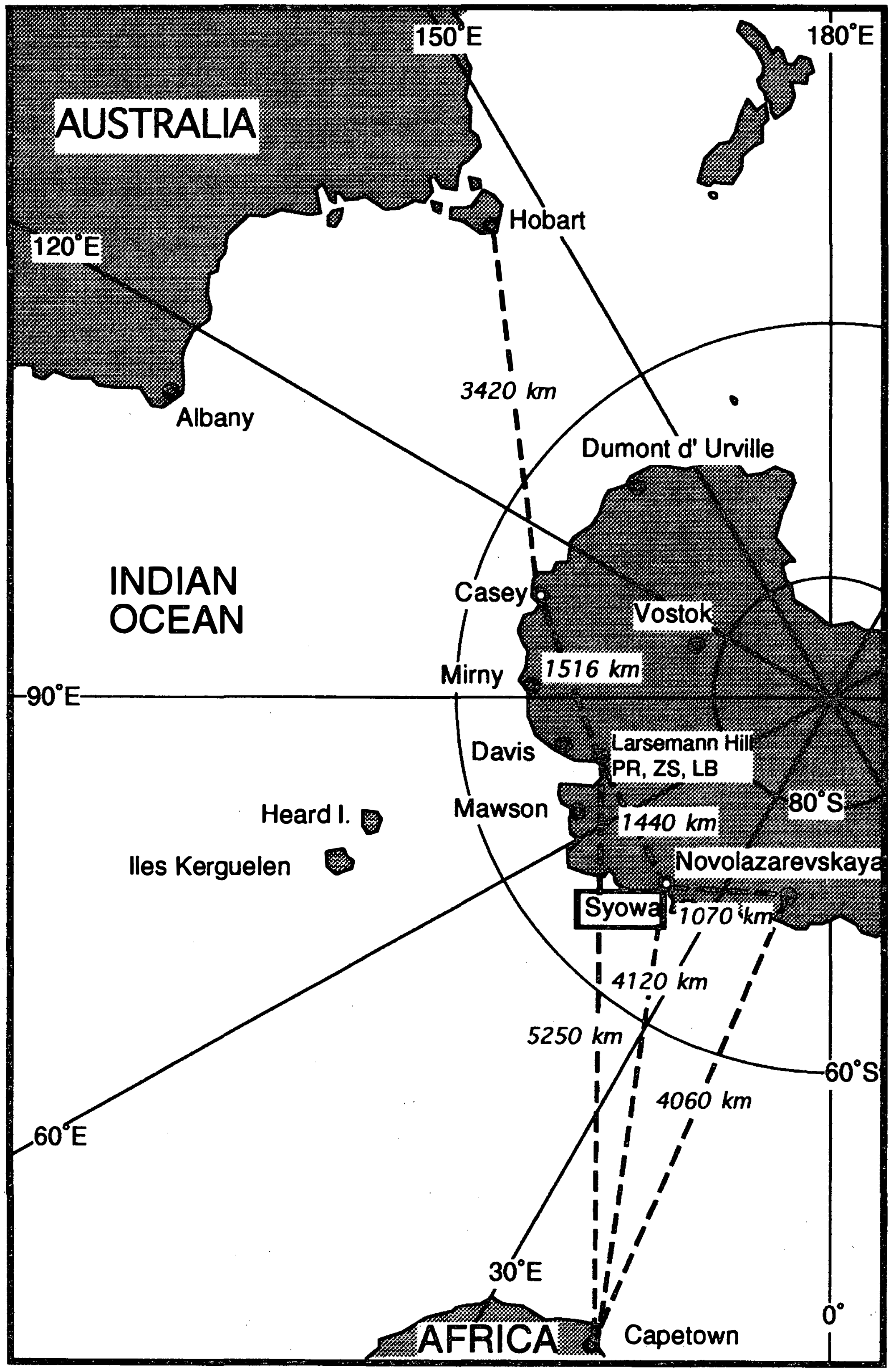


Fig. 16. Gateway airports in Australia and Africa and potential stations in the East Antarctic Air Network.

Acknowledgments

Valery KLOKOV is grateful to JSPS for their invitation to Japan. He wishes to extends thanks to Prof. Takeo HIRASAWA, Director-General, National Institute of Polar Research for his hospitality during stay in Tokyo. The authors were benefited by discussion with Prof. Okitsugu WATANABE of NIPR, Prof. Emeritus Akira HIGASHI of Hokkaido University, Mr. Masashi SANO and colleagues at NIPR and the Low Temperature Institute of Hokkaido University. Dr. Tom FRISCH of the Geological Survey of Canada was kind enough to read the draft and make correction English.

References

AVER'ANOV, V. and KLOKOV, V. (1975): Engineering and glaciological considerations and construction technology for snow runways in Antarctica. Tr. Sov. Antarkt. Eksped., **65**, 177–203 (in Russian).

KANETO, S., IGARASHI, H. and MATSUHARA, K. (1994): Wind varitaion features of Syowa and Asuka Stations, East Antarctica. Proc. NIPR Symp. Polar Meteorol. Glaciol., **8**, 46–52.

KAWAMURA, T., TAKIZAWA, T., OHSHIMA, K.I. and USHIO, S. (1995): Data of sea-ice cores obtained in Lützow-Holm Bay from 1990 to 1992 (JARE-31, -32) in period of Japanese Antarctic Climate Research. JARE Data Rep., **204** (Glaciology 24), 1–16.

KLOKOV, V. (1979): Melting and surface runoff on the Antarctic Ice Sheet. Leningrad, Gidrometeoizdat, 167p.

KLOKOV, V. (1995): Technique and logistic considerations for establishing snow and ice airstrips. Proceedings of the Workshop on Antarctic Air Transport Networks, Washington.

KLOKOV, V. (1996): Feasibility of establishing a snow/ice runway in the 60°E–120°E sector of the Antarctic coast. ANARE Spec. Rep., 53 p.

KLOKOV, V. and DIEMAND, D. (1995): Glaciology of the McMurdo Ice Shelf in the area of air operations. Contributions to Antarctic Research IV, ed. by D.H. ELLIOT. Washington, D.C., Am. Geophys. Union, 175–195 (Antarct. Res. Ser., Vol. 67).

MATSUBARA, K., DOI, M., UEKUBO, T. and OKADA, K. (1990): Meteorological observations at Syowa Station in 1988 by the 29th Japanese Antarctic Research Expedition. Nankyoku Shiryô (Antarct. Rec.), **34**, 175–215 (in Japanese with English abstract).

NAKAWO, M. (1982): On the possible thickness of artificial ice built up for airstrip at Syowa Station, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **24**, 274 – 282.

RUSSELL-HEAD, D.S. and BUDD, W.F. (1991): The development of compressed snow runway for wheeled aircraft near Casey. MUPAS Report, **72**.

SHIRAISHI, K. (1995): Present status and considerations of East Antarctic Air Network. Nankyoku Shiryô (Antarct. Rec.), **39**, 170–188 (in Japanese with English abstract).

SWITHINBANK, C. (1991): Potential airfield sites in Antarctica for wheeled aircraft. CRREL Spec. Rep., **91-24.**

TAKAHASHI, S., ENDOH, T., AZUMA, N. and MESHIDA, S. (1992): Bare ice fields developed in the inland part of Antarctica. Proc. NIPR Symp. Polar Meteorol. Glaciol., **5**, 128–139.

UMEMURA, T. and HANNUKI, T. (1993): On a trial estimation of construction work for the ground runway at East Ongul Island in Antarctica. Nankyoku Shiryô (Antarct. Rec.), **37**, 176–195 (in Japanese with English abstract).

WATANABE, O. (1978): Stratigraphic studies of the snow cover in Mizuho Plateau. Mem. Natl Inst. Polar. Res., Spec. Issue, **7**, 154–181.

YAMADA, T. and WATANABE, O. (1978): Estimation of mass input in the Shirase and Sôya drainage basins in Muzuho Plateau. Mem. Natl Inst. Polar. Res., Spec. Issue, **7**, 182–197.

YOSHIDA, Y. and MORIWAKI, K. (1983): Sea ice condition around Syowa Station, Lützow-Holm Bay, in 1981. Mem. Natl Inst. Polar. Res., Spec. Issue, **29**, 217.

(Received July 25, 1997; Revised manuscript accepted September 25, 1997)