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Climatology and implications for perennial lake ice occurrence at Bunger Hills Oasis, East Antarctica

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Abstract: The Bunger Hills Oasis (66°15'S; 100°45'E), a large ice-free expanse on the coast of East Antarctica, contains many lakes, only a few of which maintain an ice cover all year. To understand the environmental conditions that allow for persistent ice cover we established an automatic meteorological station on White Smoke Lake, a perennially ice-covered lake in contact with the Apfel Glacier. The data were collected from January 1992–July 1993. The mean annual solar flux during this period was 115 W m^{-2}, the mean wind speed 4.6 m s^{-1}, and the mean air temperature -11.2°C. Summer degree-days above freezing (71 °C-days) are similar to regions of the Antarctic (the McMurdo Dry Valleys - 78°45'S; 163°00'E) with thick perennial lake ice but the winter freezing degree days (3987 °C-Days) are much smaller and are closer to regions with seasonal ice covers (e.g. the high Arctic). The Bunger Hills Oasis seems to be in a marginal climatic region for the persistence of thick lake ice. Therefore, the extent of glacier ice contact becomes the controlling factor in maintaining an ice cover all year. We propose that this is either through the heat sink the glacier offers, and/or the positive feedback for ice growth provided by the high albedo of the adjacent glacier.

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Introduction

The Bunger Hills Oasis (66°15'S; 100°45'E) is an ice-free area in East Antarctica, approximately 350 km east of the Russian research base Mirny. Its 950 km^2 extent makes this oasis one of the largest ice-free areas on the Antarctic continent, yet it is one of the least studied. The oasis is comprised of low-lying, rocky rolling hills and fault valleys ranging from sea level to 172 m a.s.l. The oasis is bounded by the Shackleton Ice Shelf to the north, the continental ice sheet to the east, the Apfel outlet glacier to the south, and the Edisto outlet glacier to the west (Fig. 1). Deglaciation of this area is estimated to have commenced before 9.0 ka BP (Bolshiyanov *et al.* 1993, Colhoun & Adamson 1989, Verkulich & Hiller 1994).

One of the more striking features of the Bunger Hills is its hundreds of lakes and ponds ranging from tens of square metres in surface area to >14 km^2 (Lake Figurnoe) that have formed in topographical depressions and fault valleys. The majority of lakes are in the centre of the oasis and are observed to become ice-free in the summer months, while the lakes at the edge of the oasis in contact with glacier ice mostly retain their lake ice covers year-round.

In the McMurdo Dry Valleys of Antarctica (78°45'S; 163°00'E), thick perennial ice covers are found on all lakes. The ice thickness of 2.8–5.5 metres (Wharton *et al.* 1992) depends on the mean annual temperature and the summer ablation (McKay *et al.* 1985). In the high Arctic, lakes generally thaw completely in the summer even for locations at which the mean annual temperature is close to that of the Dry Valleys. The key difference is the degrees days above freezing in the summer — Arctic values can be 5–10 times the Dry Valley levels (Doran *et al.* in press).

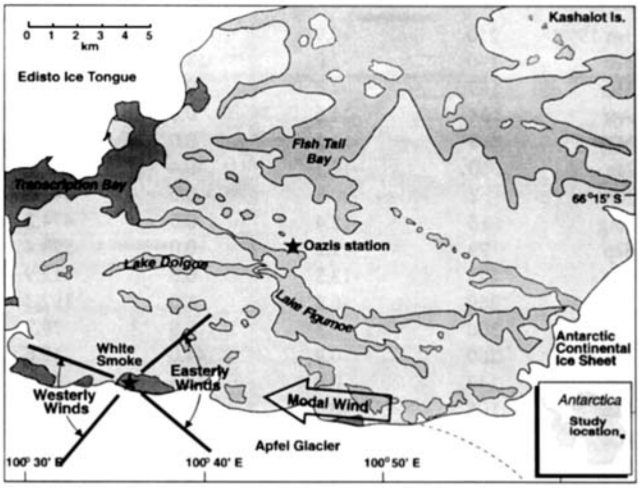

Fig. 1. Map showing location of Bunger Hills Oasis. The main meteorological station was on White Smoke Lake, and comparison data for 30 days was obtained at Oasis base (shown by stars). White is glacier ice, light grey is land, medium grey marks seasonally ice-covered water, dark shading indicates perennially ice-covered water bodies.

To explain why the ice covers persist in some, but not all, of the lakes in the Bunger Hills Oasis, a year-round meteorological record and a model of the ice cover thermodynamics are needed. In this paper we report on ~1.5 years of meteorological observations relayed via satellite from a small island on White Smoke Lake – a perennially ice-covered lake in Bunger Hills. We use this data set to explore the conditions that allow for perennial ice covers at the edge of the oasis, comparing the meteorological conditions at White Smoke Lake with those at the nearby seasonally ice-free lakes in the Bunger Hills as well as other ice-covered lakes in the Antarctic and the Arctic.

We compare our data to those collected by previous expeditions to the Bunger Hills Oasis. Gregorczuk (1980) reports on two years of Russian meteorological observations between October 1956 and November 1958. These data were collected year-round by occupants of Oazis station (Fig. 1). Streten & Nairn (1986) summarize the Russian data as well and make some preliminary comparisons with the climate of Vestvold Hills, another oasis ~1000 km to the west of Bunger Hills.

Instrumentation

Two automatic meteorological stations were established for this study. The White Smoke Lake station (hereafter referred to as the lake station) was deployed on an island towards the southwestern end of the lake (Fig. 1). The base of this station was approximately 5 m above the lake surface which is close to sea level. The lake station operated for 539 days. The second station (hereafter referred to as the central station) was located near Russia's Oazis station on the shore of Lake Figurnoe in the middle of the Bunger Hills Oasis (Fig. 1). This station was ~8.5 km from the lake station, at an elevation of 40 m a.s.l. The central station operated for just over a month (6 February–15 March 1992). Both stations measured wind speed and direction, solar flux, relative humidity, air temperature, and soil temperature at 0.25 and 1.0 m depth. In addition the lake station collected barometric pressure.

The meteorological sensors (with the exception of the pressure sensor) were mounted on a guyed metal mast. Model 05013 RM Young wind monitors (wind speed and direction), and Licor LI200SZ pyranometers (solar flux) were fixed to the mast at ~2.5 m above the ground, and a model 207 Phys-Chem relative humidity/temperature sensor contained in a radiation shield was positioned at ~2.2 m height. Campbell Scientific 107B soil thermistors were buried at depths of 25 cm and 1 m. The Vaisala model PTA427 barometric pressure sensor, data loggers, interfaces, and batteries were housed in an insulated container.

The wind monitors were a propeller type with a stated accuracy of 2% wind speed up to 60 m s^{-1}. The lowest speed which will start the propeller is stated as 0.9 m s^{-1}, yet speeds

Table I. Climate summary for White Smoke Lake Station, January 1992–July 1993.

	Solar flux (W m^{-2})	Air temperature (°C)	Thawing degree days	Freezing degree days	RH (%)	Water vapour density (g m^{-3}) x 100	Wind speed (m s^{-1})	Wind direction (degrees)	Barometric pressure (kPa)
Jan 1992[a]	210	-0.9	4.2	10.9	70.2	320.9	4.0	148.9	98.31
Feb	170	-2.0	13.7	72.6	67.8	287.6	5.2	140.2	98.94
Mar	117	-7.8	0.7	219.4	68.8	199.7	3.1	172.1	98.29
Apr	34	-14.6	0.0	440.4	72.3	140.4	4.4	136.9	98.05
May	5	-19.1	0.0	590.0	69.8	100.9	3.9	127.3	99.03
Jun	0	-14.5	0.4	438.0	69.4	147.8	6.3	135.4	98.94
Jul	2	-20.8	0.0	642.0	69.5	99.1	3.6	149.0	98.12
Aug	18	-15.4	0.0	474.2	74.8	138.9	5.6	134.0	97.77
Sep	79	-19.2	0.0	579.4	64.9	91.1	5.0	151.8	97.24
Oct	175	-13.3	0.0	412.9	63.2	126.1	4.4	155.7	98.13
Nov	260	-6.3	1.0	192.3	70.0	226.4	5.6	133.1	97.88
Dec	300	-2.3	8.8	79.7	69.4	289.2	3.8	171.9	98.33
Jan 1993	260	0.9	44.0	15.6	66.3	343.0	4.8	140.0	98.90
Feb	147	-0.8	17.1	39.4	72.4	332.9	4.3	122.6	97.81
Mar	105	-8.6	0.2	266.2	64.8	181.0	4.0	138.9	98.23
Apr	34	-12.6	0.0	375.6	67.9	144.3	3.1	133.8	98.02
May	4	-20.3	0.0	629.0	71.6	91.1	4.3	155.2	97.58
Jun	0	-19.4	0.0	584.5	69.0	95.8	6.5	129.8	98.04
Jul[b]	1	-21.1	0.0	275.6	75.1	117.3	3.4	158.9	97.56
Annual means[c]	115	-11.2	71.1	3988.6	68.8	183.5	4.6	142.6	98.17

[a]Incomplete month: values based on 23–31 January
[b]Incomplete month: values based on 1–14 July
[c]Thawing degree day value is sum for 1992–93 summer only
Freezing degree day value is sum for 1992 winter only (1 March–31 November)
All other mean values are the mean of all 365 day running-window averages that fit within the data.

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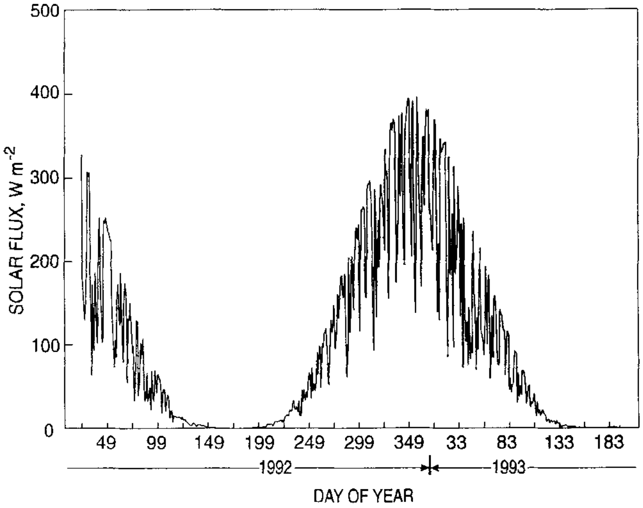

Fig. 2. Mean daily solar flux at White Smoke Lake.

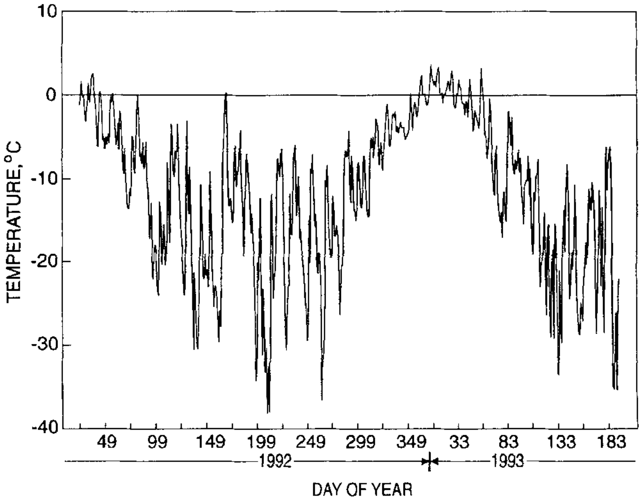

Fig. 3. Mean daily temperature at White Smoke Lake. Note the above freezing temperatures during a mid-winter katabatic wind storm.

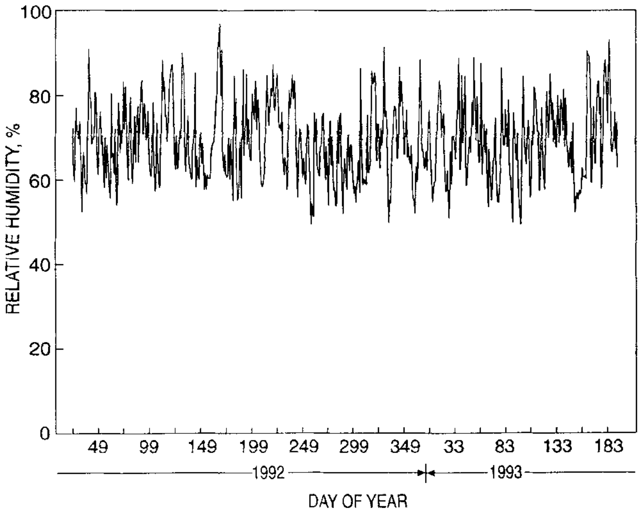

Fig. 4. Mean daily relative humidity at White Smoke Lake.

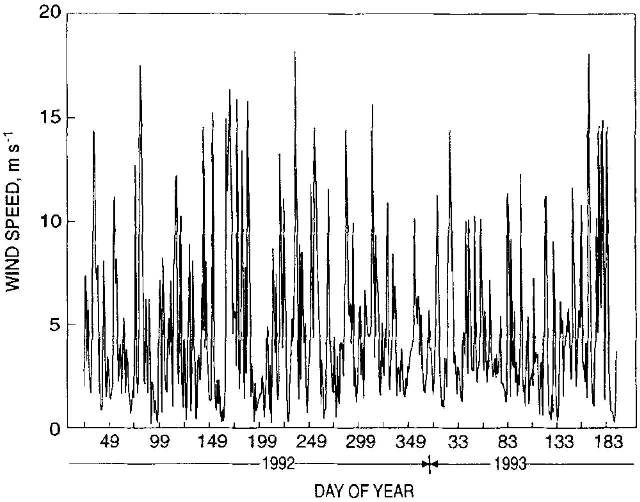

Fig. 5. Mean daily wind speed at White Smoke Lake.

lower than this have been noted turning the propeller in the field. The uncertainty in the wind direction is less than 5°.

The air and soil thermistors were Fenwal Electronics type UUT51J1. The accuracy of these thermistors is a combination of Fenwal's interchangeability specification, the precision of the bridge resistors, and the polynomial error, which becomes significant below -35°C. To correct for the polynomial error the fitting equation was converted from the polynomial supplied by Campbell Scientific, to the Steinhart-Hart equation (Steinhart & Hart 1968). Applied to the Fenwal thermistors, the Steinhart-Hart equation results in a fit that is ± 0.02°C over -40 to +60°C (G.D. Clow personal communication 1992).

The humidity sensor accuracy is a combination of the relative humidity sensor, the thermistor accuracy (since temperature is used to calculate relative humidity), and a polynomial error. Combined, these errors provide for a relative humidity accuracy of ± 5% (at 25°C) over the humidity range 12–100%.

The light sensors were cosine-corrected silicon photodiodes with a spectral response that is proportional to the solar energy received by a horizontal surface. A typical response curve is very low at 400 nm, increases nearly linearly to a peak at ~950 nm, and decreases nearly linearly to a cut-off near to 1200 nm. The Licor measurement has an absolute error of ±5% maximum, typically ±3% for angles less than 80°. Drift of the sensor is < 2% yr^{-1}.

The barometric pressure sensor uses Vaisala's patented silicon capacitive system. A linear output of 0-5 VDC is proportional to pressure within the range 800–1060 mb. The transmitter is temperature compensated over the range of -40°C to +60°C. Stated accuracy is ± 0.4 mb @ 20°C.

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Stability of the sensor is ± 0.2 mb yr⁻¹

At the lake station, data were collected using a Campbell Scientific CR10 data logger and transmitted to ARGOS Data Collection and Location System (DCLS) packages onboard two simultaneous polar-orbiting NOAA satellites using a Telonics Platform Transmitter Terminal (PTT). Using an antennae mounted at the top of the mast, the PTT transmitted the contents of the transmit buffer every 200 seconds for the duration of operation. Data were stored onboard the satellites until they could be transmitted to one of three ground stations. After being routed through NESDIS and Service Argos, we received the data on a daily basis by electronic mail. The environmental sensors were controlled by the data logger, programmed to initiate measurements every 30 seconds. During the first two months of operation at the lake station, averaging was variable (2 h, 12 h, and 6 h) as quality of satellite receipt was being determined. Six hour averaging was set as the practical maximum data volume which could be transmitted while guaranteeing at least triplicate satellite receipt of the same data package for the purpose of error checking (i.e. the transmit buffer was updated with new averages every 6 h to be transmitted every 200 seconds).

Data collection at the central station was similar to that of the lake station, with the exception that averaging was consistently every 2 h for the duration of operation, and data were down-loaded from the Campbell 21X data logger to computer in the field rather than being transmitted to satellite.

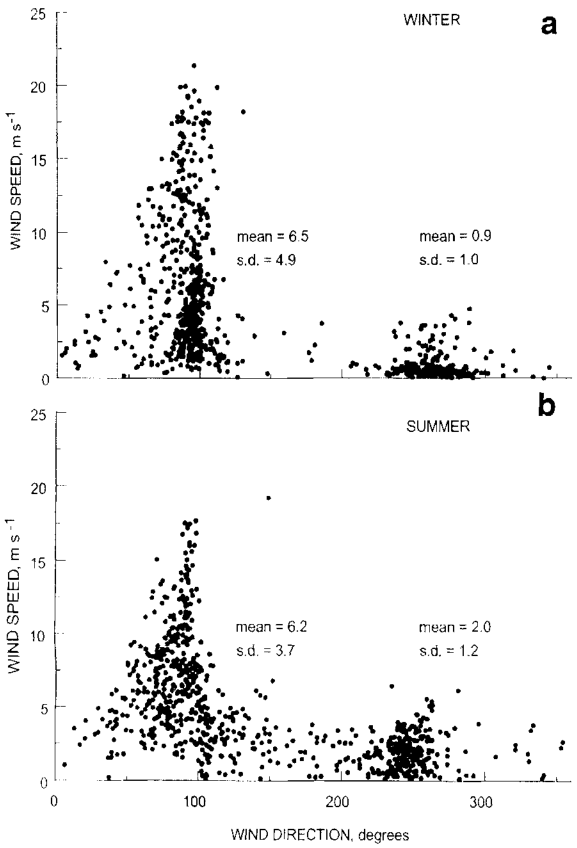

Fig. 6. Wind speed vs. wind direction for **a.** winter and **b.** summer. Strong easterly (90–120 degree) katabatic winds occur both in winter and summer.

Meteorological observations

The principal climatic factors at the White Smoke Lake station are summarized as monthly and annual averages and totals in Table I for the period January 1992–July 1993, while the daily averages for key parameters of this 539-day period are plotted in Figs 2–5.

The measured mean-annual solar flux at this site is 115 W m^{-2}, with measurable light during all months but June (White Smoke Lake is ~17 km north of the Antarctic Circle; 66°30'S). The day-to-day variation in solar flux (Fig. 2) is a result of solar angle and cloudiness. Lack of northern exposure at this site results in low winter radiation values for this latitude.

The temperature regime at Bunger Hills is strongly controlled by sun and wind in the summer, and wind in the winter. The mean annual temperature at the lake station was -11.2°C for the period of record, more than 2°C lower than values reported by Gregorczuk (1980) for two years of manned observations at Oazis station (the site of our central station). The minimum instantaneous temperature for the lake site was -49.6°C (17 May 1993), and the maximum was 6.9°C (27 January 1993). Soil temperature at 25 cm depth

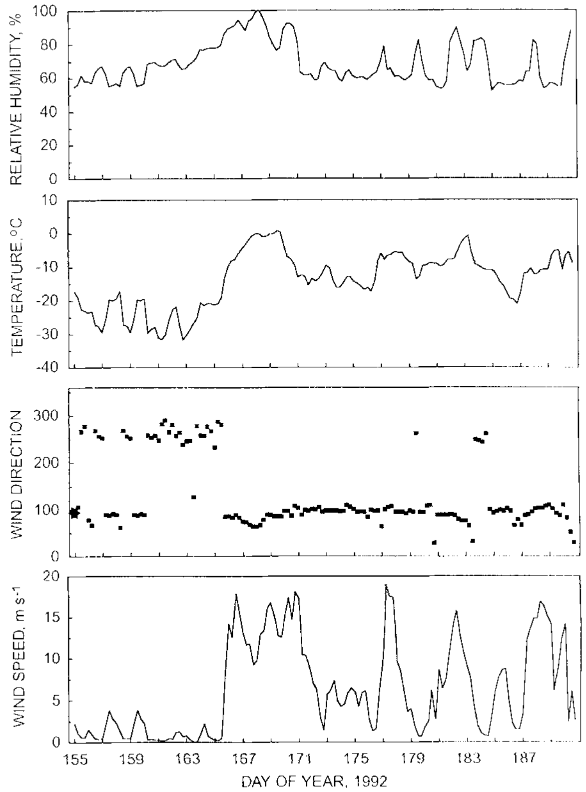

Fig. 7. Wind speed, wind direction, temperature, and relative humidity during a winter katabatic wind event. The onset of the katabatic wind occurs at day 165 (13 June 1992).

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ranged from -23.7°–7.6°C, and -18.8°–2.7°C at 1 m depth. The mean soil temperatures were -8.8°C and -8.4°C at 25 cm and 1 m depth, respectively. Relative humidity at our lake site ranged from 42–100%, with an average of 68.8%, considerably higher than other Antarctic ice-free areas. Wind speeds averaged 4.6 m s^{-1} over the period of record. This is considerably windier than reported for the McMurdo Dry Valleys (3.3 m s^{-1}; Clow *et al.* 1988) and less windy than records from Oazis station (6.8 m s^{-1}; Gregorczuk 1980), although the latter measurements were made at 10 metres height. We measured a maximum wind speed of 32 m s^{-1} at the lake station, but it should be borne in mind that this is the maximum value for the 30 second sampling interval. Gregorczuk (1980) reported a maximum instantaneous wind speed of 56 m s^{-1}. Mean barometric pressure was 982 hPa and ranged from 947–1016 hPa.

Winter vs summer

Clow *et al.* (1988) have shown that in the McMurdo Dry Valleys there is a significantly different wind regime in the summer than in the winter. In the Dry Valleys, the winter is characterized by strong dry down-valley winds while in summer the winds are often up-valley from the direction of McMurdo Sound. Although there are some notable and significant differences between winter and summer wind regimes in the Bunger Hills, the differences are not as marked as in the Dry Valleys. One difference in the Bunger Hills wind regime is that during the winter, winds are strongly bimodal when compared to the summer. Also, westerly winds are significantly (P<0.001) stronger in summer than in winter (Fig. 6).

Katabatic winds occur both in summer and winter, but owing to the lack of solar radiation, they are the dominant control of climate in winter. Such events can be seen in Fig. 7. Strong winds descend from the polar plateau via the Apfel Glacier to the east. As they descend they warm adiabatically. As seen in Fig. 6 the strong katabatic winds are easterly (90–120° direction) and are expected to be warm and dry after descending the ~2 km altitude difference between the polar plateau and the Bunger Hills Oasis (essentially at sea level). For example, if air on the plateau is at -40°C and 100% relative humidity then after a 2 km descent it will be at -20°C and 15% humidity, following a dry adiabatic lapse rate. However, the relative humidity observed during katabatic winds was not this low (Fig. 8) suggesting that the descending air remains in contact with a moisture source. During winter this moisture source must be ice, since the closest open water is thousands of kilometres to the north. We propose that the increased wind speeds and associated turbulence combine to ablate the ice sheet until the air mass is at saturation.

As seen in Fig. 7, during a katabatic wind event the air temperature can rise 30°C, as the wind reaches average speeds of 15 m s^{-1} from the east. However, as noted above, the relative humidity does not drop and in fact reaches high levels (top panel Fig. 7), supporting the hypothesis that these strong winds and the associated turbulence are more efficient at ablating ice and picking up moisture. In fact, this point was clearly demonstrated when we observed Lake Figurnoe, with ice cover thick enough to walk on, be stripped of its ice cover in places of concentrated wind, in just one day during an early winter wind storm.

The other major wind mode in both summer and winter, westerly winds, typically have speeds of less than 5 m s^{-1}. During the winter, humidity is independent of wind direction, while in summer westerly winds are significantly (P<0.001) more humid than easterly winds (Fig. 8), presumably from traversing more open water. During winter, pervasive frozen ice surfaces occur in all directions while during the summer, open water exists in the Davis Sea, and in the numerous melt ponds on the Shackleton Ice Shelf to the west.

In summer, the influence of diurnal solar variation becomes an important component of Bunger Hills climate. Even at summer solstice there is a marked decrease in solar flux in the evening, driving temperature fluctuations as high as 8°C. Diurnal fluctuations are also apparent in nearly all other observed meteorological parameters in summer (Fig. 9). Radiative heating of the ground surface during the day

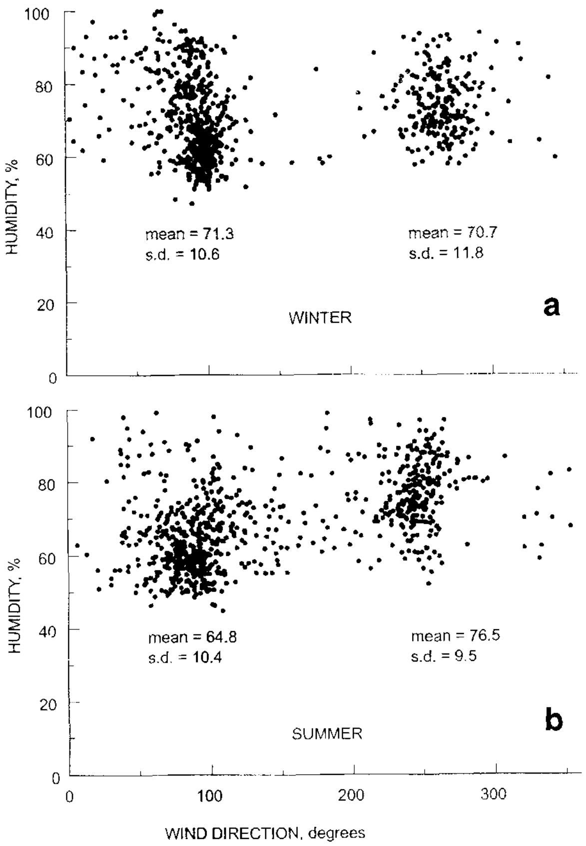

Fig. 8. Relative humidity vs. wind direction for **a.** winter and **b.** summer. Humidity is independent of wind direction in the winter while westerly winds are slightly more humid than easterly in summer.

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Table II Mean values for the principal climate variables at the two sites (6 February–15 March 1992).

	Solar flux (W m^{-2})	Temperature (°C)	Thawing degree days	Freezing degree days	RH (%)	Wind speed (m s^{-1})
Central Oasis	152	-3.1	12.6	130.7	57.8	4.6
White Smoke Lake	154	-4.8	7.5	187.2	68.9	3.5

warms the surface air causing it to rise upslope. The resultant westerly anabatic wind – a reversal of the normal easterly, down-slope wind component – occurs on some summer days, typically strengthening towards the afternoon (Fig. 10). A similar effect has been reported in the McMurdo Dry Valleys (Clow *et al.* 1988).

Oasis edge vs centre

Mean values for principal climate variables for the 38 days of comparison between the lake and central stations are shown in Table II. It is clear from these values that the central site is warmer, windier, and drier than the lake site. This effect is seen in Fig. 11. At night when the solar input is effectively zero the lake site cools by radiative emission much more effectively than the central site. During these times the energy balance at the surface is between loss by radiative cooling and the return of heat from the subsurface. If the heat capacity of the two surfaces are approximately equal – which is to be expected – then the return of heat from the subsurface is determined by the thermal conductivity. If the thermal conductivity is low, then the surface will cool more effectively. The data are consistent with a lower thermal conductivity at the lake site, possibly the result of fractured, porous ice on the surface of the lake. The temperature drop from noon to midnight at the lake site can be more than a factor of two larger than at the central site. Temperature differences are largest when the absorption and emission of thermal radiation are the dominant terms in the surface energy balance. Figure 12 shows that with increasing wind, and hence advective energy, the temperature difference between the two stations is reduced. Although not demonstrable with our data, we would expect that this same effect would result in colder winter temperatures at the lake site than the central site during those periods when the wind is calm and the surface temperature is determined by radiative cooling to space (see *e.g.* Clow *et al.* 1988).

The more windy nature of the central station is explained by its slightly higher elevation and more exposed location. During periods of light wind there is no apparent difference

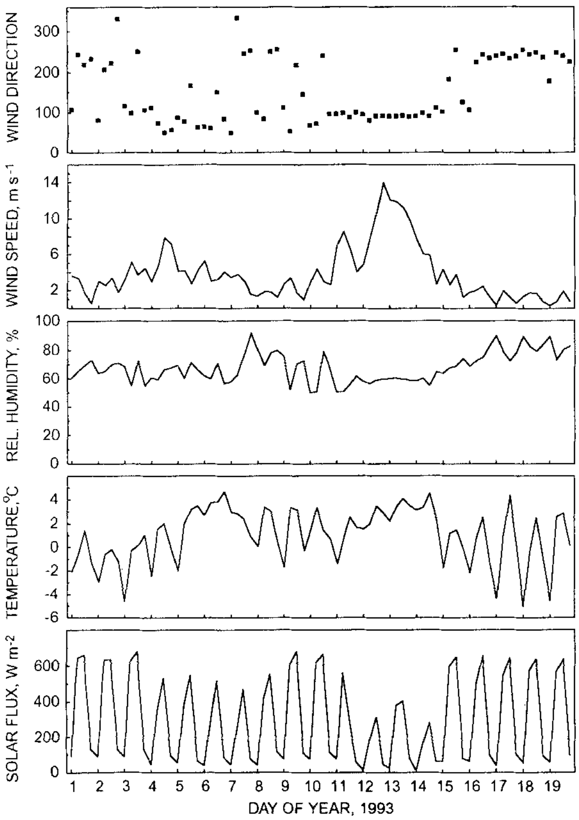

Fig. 9. Diurnal variations in summer (January 1993). Solar incidence angle in summer cause corresponding diurnal changes in temperature, relative humidity, and wind speed.

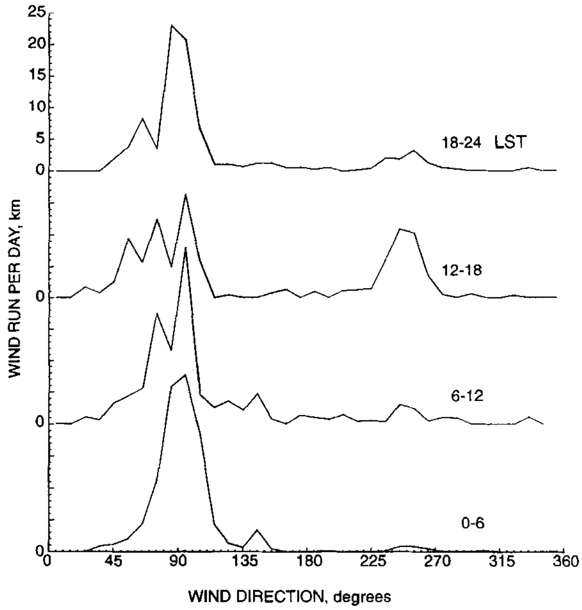

Fig. 10. Total wind run in a day as a function of time of day during the summer. The easterly winds dominate throughout the day with westerly winds intensifying in the afternoon.

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between the two sites. Above ~5 m s^{-1} the central site is almost always windier. The stronger the wind speed over ~5 m s^{-1}, the greater the difference between the two sites (Fig. 13).

Perennial lake ice in the Bunger Hills Oasis

The only known perennial lake ice covers in the Bunger Hills Oasis occur along the glacier-ice margin at the edge of the southern end of the oasis (see Fig. 1). Many of these lakes are tidal in nature (unpublished data) with a large daily flux of cold water. However, the perennial ice covers are not unique to these "epishelf" lakes. All perennially ice-covered lakes in Bunger Hills Oasis have substantial contact with glacial ice (Fig. 1). Some lakes with minor glacier ice contact are not perennially ice covered.

Our observations show that the Bunger Hills area is warm by coastal Antarctic standards. Mean annual temperature is -11.2°C compared to -17.3°C in the McMurdo Dry Valleys. The relatively warm nature of this area is in agreement with the observations of Gregorczuk (1980). His temperature data refer to the central oasis site (Oazis station). Comparison of his mean monthly temperatures and those from our data indicate the broad similarity between the two sites over the course of the year (Fig. 14).

Key variables that correlate with the persistence of ice cover are freezing and thawing degree-days (e.g. Aston 1983, Barnes 1960). Annual thawing degree-days in the Bunger Hills (71 °C-days) is comparable to the values obtained in the McMurdo Dry Valleys (45–90 °C-days; Clow *et al.* 1988).

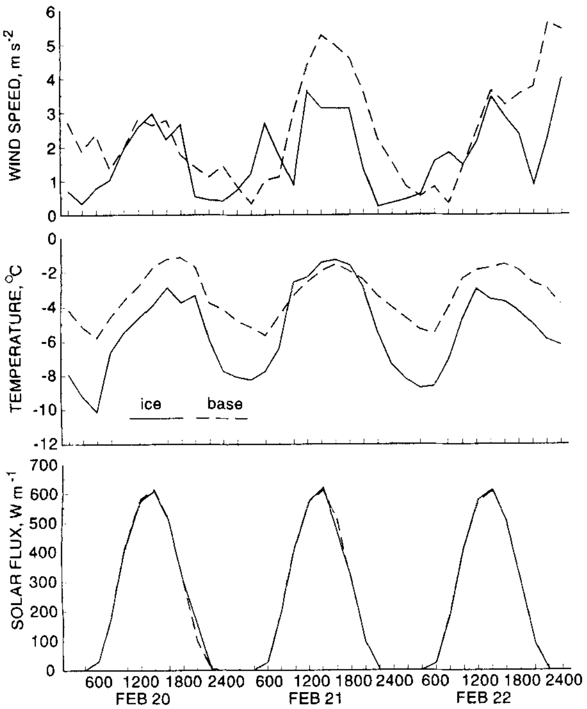

Fig. 11. Comparison between White Smoke Lake and Oasis Base with respect to solar flux, temperature, and wind speed, during three days in summer (February 1992).

The summer months (November through February) are similar at the two locations, while the winters (March through October) are quite different. The freezing degree-days at Bunger Hills (3967 °C-days) is much less than the value in the McMurdo Dry Valleys (6200 °C-days). Thus while the same amount of ice melts in the summer, much less ice forms in the winter on Bunger Hills lakes. If ice thickness is roughly proportional to the square root of the freezing degree-days, then ice growth in Bunger Hills would be 0.8 times that in the McMurdo Dry Valleys. Apparently this difference is sufficient to allow many Bunger Hills lakes to become ice-free. If this were the only factor involved, then all Bunger Hills lakes should behave similarly. This is not the case. All the lakes in Bunger Hills with perennial ice cover have at least 50% of their shoreline as glacier ice. We suggest that the climatic conditions for maintaining an ice cover in

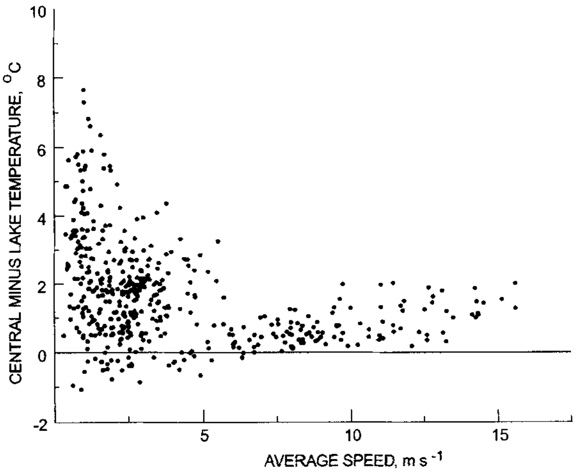

Fig. 12. Difference between Oasis base and White Smoke Lake air temperatures vs the average wind speed of the two sites.

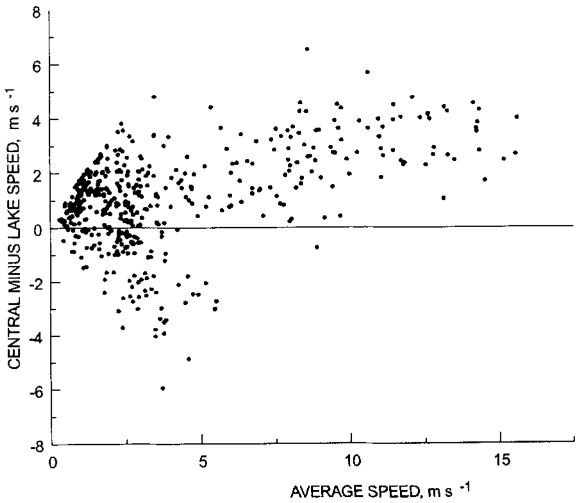

Fig. 13. Difference between central oasis and White Smoke Lake wind speeds vs the average wind speed of the two sites.

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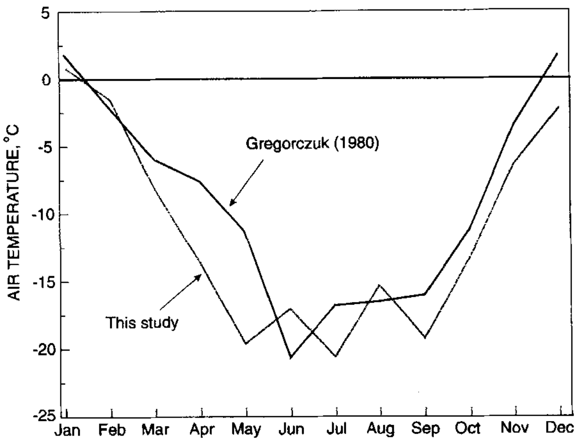

Fig. 14. Mean monthly temperature comparison between White Smoke station (1992–1993) and data (1956–1958) presented by Gregorczuk (1980).

Bunger Hills are marginal. The additional heat sink of glacial contact is enough to stabilize a perennial ice cover. It is also possible that a thick ice cover tends to be self stabilizing in that it reflects incoming solar radiation; that is, the reduced solar energy flow into the water column and increased albedo are positive feedbacks for maintaining ice. Thus significant glacier contact promotes a perennial lake ice environment.

The effect of a glacier on maintaining the ice cover can be illustrated by considering what would happen if White Smoke Lake were to instantly lose its ice cover. Using a modified Stefan equation (Barnes 1960) and our value for freezing degree days (~4000), we can calculate that the following winter, a layer of ice would form uniform across the lake at a thickness of 2.2 m. The next summer, melting would begin with a moat near the shore and the ice would begin to deteriorate as it does with other lakes in the region. However, the ice that is edged by the glacier would be likely to remain frozen, possibly forming an apron of ice attached to the glacier. In subsequent years this apron of perennial ice would thicken and grow in area eventually becoming the thick perennial ice cover. Clearly for this mechanism to be effective, the glacier must contact a substantial fraction of the lake's perimeter, as is the case in the Bunger Hills perennially ice-covered lakes.

Conclusions

Conditions for perennial lake ice growth in the Bunger Hills Oasis are marginal. Seasonally ice-free lakes in the centre of the oasis are in contrast to the perennially-ice covered lakes occurring at the oasis edge. The difference appears to be degree of ice contact between the lake and glacier. Without sufficient glacial contact, the thermodynamics of the oasis lakes is insufficient to sustain a persistent ice cover. With the addition of glacier ice into the lake basin, the heat budget is offset enough to form a thick lake ice cover. We propose that this is either through the heat sink the glacier presents, and/or the positive feedback for ice growth provided by the high glacial albedo. Once an ice cover is formed, it is protected by the cold glacier edge, and no moat along this edge forms, thereby preserving the ice cover in these climatologically marginal conditions.

Note: The meteorological datasets from the lake and central station sites are available from the authors on disk (requester pays price of disk), or by electronic transfer.

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