LAND/SEA BREEZE CIRCULATION SYSTEMS

OF CHURCHILL, MANITOBA

BY

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ABSTRACT

This research details the presence of the land/sea breeze circulation system near Churchill, Manitoba. Data collected from June 6 to August 13, 1987 were analyzed with respect to wind direction, temperature and vapour pressure to determine the effects of the system on the climate.
Results indicate that there is a seasonal progression in wind frequency from dominantly onshore (42% of the time) to dominantly mixed winds (75% of the time). The frequency of the land/sea breeze increases across the season. Smaller wind velocities, colder temperatures and larger vapour pressures are associated with onshore winds, while offshore winds have greater velocities, higher temperatures, and smaller vapour pressures. Offshore winds are 5 - 7°C warmer than onshore winds. The sea breeze is larger than the land breeze by a 3:2 ratio.

ACKNOWLEDGEMENTS

I am sincerely grateful to Dr. W. R. Rouse for his guidance and supervision in this research project. His help and comments were invaluable throughout the year. I would also like to thank Ted Weick for allowing me to use his data and for his help in the preliminary stages of this project. Both were greatly appreciated.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

There have been many studies investigating land-sea breeze circulation systems around the world. They are common mesoscale features that are found in coastal regions (Kozo, 1982). The land-sea breezes may differ considerably in character from one area to another, varying in direction, intensity and time according to local conditions (Flohn, 1969). They are not often associated with Arctic environments, but two land/sea breeze studies have been conducted in the north. Until 1982, the farthest north a sea breeze study had been conducted was on the shores of the Baltic Sea at 60° N near Ilmala, Finland (Rossi, 1957). Kozo (1982) studied the sea breeze at the Alaskan Beaufort Sea coast, at latitude 70°N. The evidence from both these studies indicates that the sea breeze also exists in northern latitudes.

Other evidence also supports the presence of the land/sea breeze system in northern latitudes. Research conducted in the Churchill, Manitoba area shows that wind direction does change over time from onshore to offshore directions (Rouse and Bello, 1985; Rouse et al, 1986). The purpose of this present research is to investigate the land/sea breeze system and its thermal effects in the

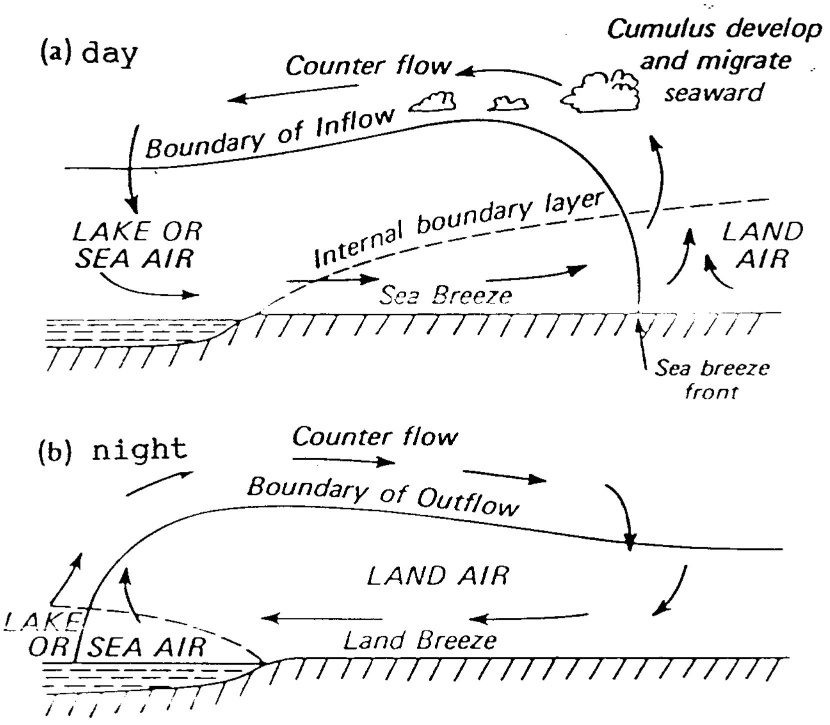
Churchill area.

1.2 FORMATION OF THE SEA BREEZE

The land-sea breeze system is a mesoscale response of the atmosphere to the horizontal variations in surface heating (Walsh, 1974). For equal amounts of incoming radiation, most systems show that the surface temperature of the water is less than that for the land due to the greater amount of radiation going into evaporation of the water (Kozo, 1982). In the subarctic, the majority (60%) of the net radiation is used to heat the cold polar sea, while only 35% is used for evaporation (Silis et al, 1989). Both leave less heat available for heating the atmosphere over the water. A smaller vertical temperature gradient, $\Delta T/\Delta z$, exists over the water as a result of the water body's greater heat capacity and slower warming. The land, however warms up quickly, leaving more radiation available for heating the atmosphere.

Kozo (1982) further explains that the warming of the coastal lands in the morning cause an increase in the thickness of the isobaric layers over the land and the upper pressure surface rises (Figure 1.1). As the upper pressure surface is higher over the land, a downward, seaward sloping horizontal pressure gradient is formed. The air accelerates

FIGURE 1.1 - LAND/SEA BREEZE CIRCULATION



(Oke, 1978)

down the gradient towards the sea at some height above the earth's surface. There is an excess of mass created offshore at sea level and a deficit of mass on land, leading to a reversed horizontal pressure gradient at the surface. This gradient slopes downward from the water to the land to form the sea breeze part of the circulation. As the air over the land is warmer than the sea breeze, the sea breeze wedges under the warmer air and forces it to rise. The warm air rises, cools and then once again accelerates down the pressure gradient. This system reverses at night when the water is warmer than the land (Kozo, 1982). $\Delta T/\Delta z$ also reverses to an inversion profile at night.

The onshore sea breeze usually forms within two hours after sunrise (Walsh, 1974) if conditions are optimal. Favourable conditions include light winds, clear skies (Keen and Lyons, 1978) and a stable atmosphere (Walsh, 1974). If conditions are both calm and stable, then there is a more rapid inland propagation of the sea breeze (Walsh, 1974).

1.3 PROPERTIES OF THE LAND-SEA BREEZE

The extent of the land-sea breeze varies according to location and land-sea temperature contrasts. In the mid-latitudes, the sea breeze penetrates for 30 to 50 km inland (Estoque, 1961) and extends 1 to 2 km in height (Kozo, 1982). There have been very large penetrations recorded.

Marshall (1950) studied a sea breeze in England that penetrated 150 km up the Thames valley. Johnson and O'Brien (1973) found a penetration of more than 60 km on the central Oregon coast.

In the tropics, the sea breeze usually extends 100 to 200 km inland at a height of 1 to 2 km (Estoque, 1961). Kozo (1982) found that the sea breeze extended inland for 40 km at a height of 500 m near the Alaskan Beaufort Sea. The Arctic sea breeze is more limited in its extent due to the extreme stability and small eddy thermal diffusivity of the strong ground based inversion. Because of this, the sea breeze is often limited to a height of less than 400 m (Kozo, 1982). The effects of the very stable atmosphere are partly compensated by the much larger land-sea temperature difference inland. The temperature can reach 25 °C inland, as compared to 14°C on the coast in the Arctic (Kozo, 1982). As the circulation system is driven by temperature differences, the sea breeze is stronger when the temperature difference is greater. Extreme temperature differences like these are not seen in the mid-latitudes.

The land breeze component is smaller in extent and weaker in intensity due to the greater stability of the night atmosphere (Estoque, 1961). The differences in sea and land breezes are due to diurnal variation of atmospheric stratification (Mak and Walsh, 1976). The magnitude of the land-sea breeze depends on the magnitude of the land-sea temperature differences (Mathews, 1982) and since the temperature differences are smaller during the nighttime, the land breeze is also smaller. The daytime breeze is usually stronger than the nighttime breeze by a factor of 3:2 (Mak and Walsh, 1976).

The land breeze is not always present. Estoque (1961) found that the land breeze can be suppressed where the sea temperatures are sufficiently low. Kozo (1982) found that the surface winds on the Beaufort Coast cannot exhibit a 360^{o} turning because the land remains warmer than the water during the short Arctic night. This led to an absence of the land breeze at this site.

The wind speeds also vary with the land and sea breezes. The winds are strongest when the stability is weakest (ie during the daytime). The land breeze shows slower wind speeds due to greater atmospheric stability (Walsh, 1974).

1.4 EFFECTS OF THE SEA BREEZE ON CLIMATE

The wind direction along the Churchill coast has a great influence on the coastal energy balance because the offshore sea ice persists until August (Rouse et al, 1987). A strong correlation between the summer concentration of sea ice on Hudson Bay and cold summer temperatures and increased wind chilling has been found. These conditions are especially associated with onshore winds (Rouse and Bello, 1985). With onshore winds, the temperatures on the land are approximately 7 ^{o}C colder than for offshore winds. The components of energy balance have a major effect on climate and are also affected by wind direction. Smaller ground heat and evaporative fluxes and a larger sensible heat flux have also been associated with onshore winds (Rouse et al, 1987). These effects extend well inland (Rouse and Bello, 1985).

CHAPTER 2
STUDY SITE AND METHODOLOGY

2.1 STUDY AREA

Churchill, Manitoba is located on Hudson Bay at approximately 59°N, 94°W (Figure 2.1). The study area falls within the Hudson Bay Lowlands and the topography is typical of the wetlands that characterize the coastal tundra regions of the Lowlands. There is little local relief in the area and few distinct drainage features. The underlying rock is the Canadian Shield and this is occasionally visible around the area. There are raised beaches near the coastline and glacially deposited features inland. There are many shallow lakes which range from 1 to 2 m in depth. Vegetation consists mainly of open spruce woodland in the few fairly well-drained areas and peat bogs, palsa and sedge meadows in poorly-drained areas. Elevation change is approximately 22 m above mean high tide across the measurement sites and has a mean slope of 0.17% (E.J. Weick, personal communication).

2.2 STUDY SITES

Four individual sites were located on a transect running inland from Hudson Bay (Figure 2.2). All sites were considered homogeneously wet and representative of the surrounding terrain.

Site 1 was located on the coastline of Hudson Bay

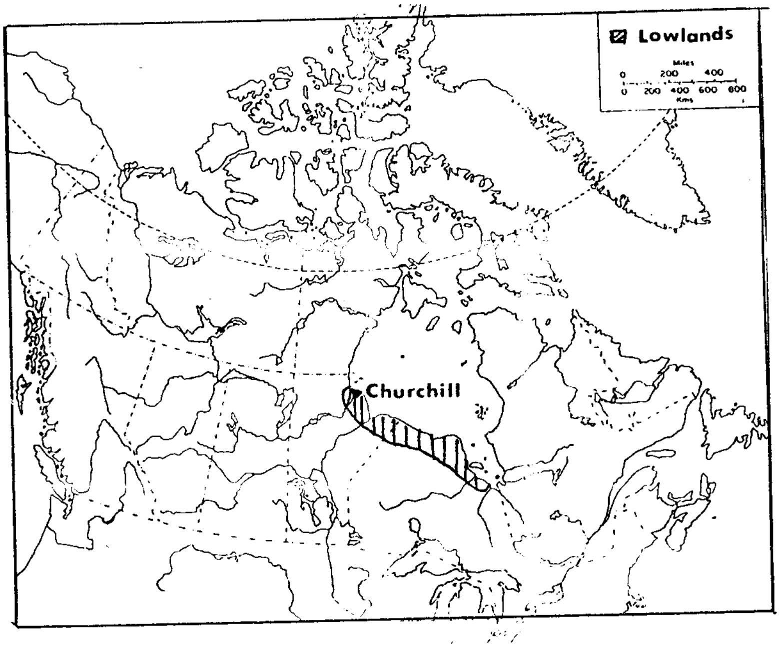
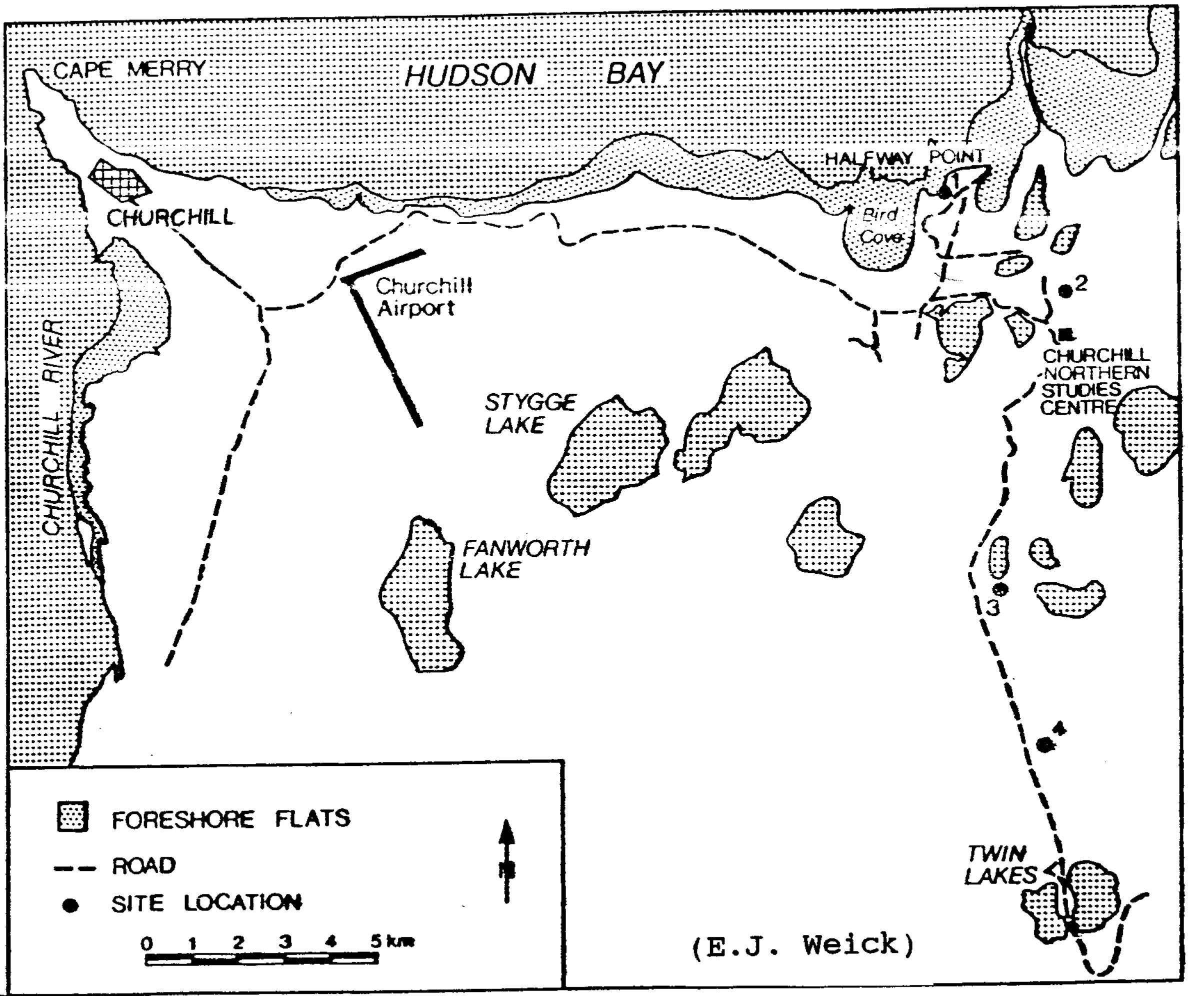


FIGURE 2.1 - LOCATION OF CHURCHILL, MANITOBA WITHIN THE HUDSON BAY LOWLANDS

FIGURE 2.2 - SITE LOCATIONS



east of Bird Cove and just above the high tide line. A tidal flat extending from 250 to 400 m was present during low tide during the ice-free season. Surrounding vegetation consisted of Elymus arearius, Stellaria humafusa, and Hippurus tetraphulum.

Site 2 was located 3 km further inland at an elevation of 6 m above mean high tide. Vegetation mainly consisted of Carex spp. Many small lakes were located to the north, south and east of the site.

Sites 3 and 4 were physically very similar and were located at 9.8 km and 12.4 km inland from the coast. Site 3 has a few small lakes located 50 to 100 m to the north and east of the site. Surrounding vegetation consisted of Scirpus ceaspitous and Carex spp. (E.J. Weick, personal communication).

2.3 FIELD METHODS

The data were collected by E.J. Weick during the summer of 1987. Net radiation (Q^*) was recorded at all sites at heights between 2.5 and 3m using Middleton pyrradiometers. Incoming solar radiation ($K\downarrow$) was measured at sites 1, 2 and 4 using upward facing Epply black and white pyranometers. Temperature and vapour pressure measurements were recorded at four heights using an aspirated pyschrometer system.

Wind direction was measured at all four sites using wind vanes. Gill 3 cup anemometers were used to measure wind speeds at four heights. Heights at site 1 were increased twice during the season to clear the growing vegetation. All data used in this analysis was taken from the 2m level on the instrument masts.

Measurements at the four sites were recorded every ten seconds and then integrated over ten minute intervals using Campbell Scientific data loggers. Data reduction was completed in the field. Results from equipment testing before and after the field season indicated that the sensors functioned properly over the full measurement period.

2.4 ANALYSIS

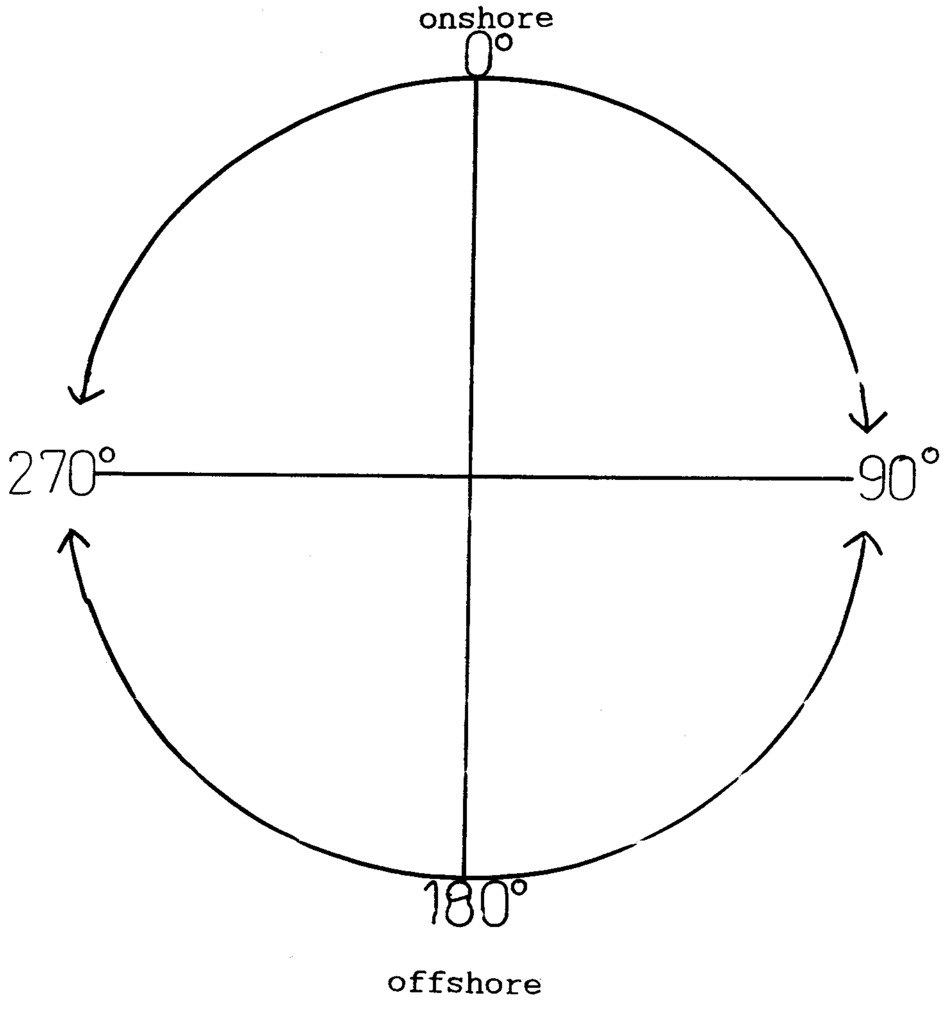
The ten minute averaged data were reduced to hourly averaged values for manageability and selected data days were chosen from the measurement period between June 6 to August 13. Sample selection for this study was based primarily on wind direction. A second criterion was that all days showed similar net radiation characteristics.

Days in June, July and August were selected for analysis. The land/sea breeze system was best developed in July. Hourly wind speed vectors were graphed for whole days for each individual site. The wind speed and direction measurements for all four sites were used to calculate the resultant wind vector. This vector was plotted to show the overall daily wind pattern. The resultant vectors were calculated using basic trigonometric functions, as illustrated in Appendix 1. Figure 2.3 shows the compass bearings used throughout the analysis to denote onshore and offshore wind directions.

Temperature measurements were also examined on a site by site basis to show the effect of the wind direction. Temperature data were also plotted against time. Horizontal temperature gradients between sites were calculated in °C/km. Twelve hour average temperatures were used to represent the daytime and nighttime periods, where "daytime" encompassed the twelve hours from 0700 to 1800 and "nighttime" encompassed the twelve hours from 1900 to 600.

Vapour pressure measurements were analyzed in the same way as the temperature measurements and horizontal vapour pressure gradients were calculated between sites. Horizontal wind speed gradients were calculated in the same manner.

FIGURE 2.3 - WIND DIRECTION NOTATION



CHAPTER 3
RESULTS AND DISCUSSION

3.1 GENERAL CLIMATIC CONDITIONS

Table 3.1 lists the general climatic conditions for the days under investigation. Bright hours of sunshine and precipitation data are from the Atmospheric Environment Service weather station at Churchill airport. Total net radiation data are from Site 1 and average, maximum and minimum temperatures are from Site 4. Site 4 was chosen for this data as the data are least influenced by Hudson Bay and more likely to illustrate seasonal rather than day to day variations.

Precipitation, temperatures and bright sunshine hours were all within the range of the normals for the summer (monthly climatological summary, 1987). The only unusual weather in the study days was a brief period of hail on August 13. Shorefast ice was evident on the bay until June 12, when it broke up into ice floes. The last of the ice floe disappeared on July 20 (E.J. Weick, personal communication).

3.2 WIND DIRECTION

Table 3.2 shows the frequency of the wind direction over the field season. The wind direction has been broken up into four classes, where onshore indicates winds blowing

TABLE 3.1 - GENERAL CLIMATIC CONDITIONS

Day	Condition	Q* (MJ/m2)	Max Hourly Q* (W/m2)	Ave T (°C)	Max T (°C)	Min T (°C)	Ppt (mm)	Bright Sun Hours
June 8	land/sea	13.59	469	10.8	16.8	.61	0	16.5
June 12	offshore	9.8	448	3.84	9.05	.07	.6	5.2
June 26	onshore	15.03	469	7.66	10.5	3.98	0	15.3
July 5	offshore	13.44	481	14.1	19.9	5.61	0	16.5
July 10	onshore	10.06	448	9.17	12.9	4.6	0	7.6
July 12	land/sea	13.07	476	9.36	15.2	.55	0	15.6
July 13	land/sea	12.26	462	14.3	19.8	4.48	0	15.3
July 14	land/sea	12.71	455	17.6	23.9	8.24	0	16.4
August 3	land/sea	10.46	409	11	16.4	3.33	0	13.4
August 13	offshore	8.52	357	9.84	13	5.15	* 5	10.4

* - hail (brief)

TABLE 3.2 - WIND DIRECTION FREQUENCY (%)

Month	Onshore	Offshore	Mixed	Land/sea
June	42	29	25	4
July	16	13	55	16
August *	0	17	75	8

* - August 3 to 13

from Hudson Bay and offshore indicates winds blowing from inland. "Mixed" indicates that no single one wind direction was dominant in the day, while "land/sea" indicates the presence of the land/sea breeze. There is a definite seasonal progression in the wind direction from June to August. As the season progressed, the wind direction became predominantly mixed. The frequency of the land/sea breeze increased and its magnitude decreased.

During June, the dominant wind direction was onshore, as was expected for this time of the year. The ice on Hudson Bay exerts a major effect on the wind direction. The surface of Hudson Bay remains cold throughout the day and night, setting up horizontal temperature and pressure gradients that favour an onshore wind flow.

There is only one occurrence of a land/sea breeze event in June. This is not a perfect example of the land/sea breeze system because the land breeze is not maintained at night. The wind blew onshore for two hours during the night. Large scale synoptic conditions may have overidden the mesoscale regime to disrupt the land breeze for this period.

The greatest frequency of the land/sea breeze occurred in July. The temperature differences between the land and sea for all hours of the day are at a maximum at this time of the year, which promotes strong pressure gradients and stimulates the land/sea breeze system.

The breakup of the sea ice was also important with respect to the land breeze. Open water was available for absorbing solar radiation during the day and warming the surface at night, thereby driving the nocturnal land breeze. Figure 3.1 illustrates the daily pattern of the land and sea breezes on a hourly basis for July 12, 13 and 14. The length of the arrow represents the wind speed in m/s. The wind blew offshore from 1800 to 0800 hours and onshore from 0900 to 1700 hours. The daytime onshore winds generally have greater velocities due to the lower atmospheric instability. At night, more stability is present and wind speeds decrease.

The land/sea breeze in August was slightly smaller in magnitude due to the gradual warming of Hudson Bay. The temperature difference between the land and sea surfaces was smaller as the bay warmed, and this resulted in a smaller land/sea breeze (Figure 3.2).

The changeover period between times of onshore and offshore winds grew earlier in the morning and later in the evening as the season progressed. Figure 3.3 shows that the changeover period in June at Site 1 was at 0800 in the morning and 1800 in the evening. Figures 3.4 to 3.6 for July 12, 13, and 14 also show that the changeover period at site 1 was at 0800 and 1800 hours. However, for August 3 (Figure 3.2), the changeover period was at 0600 and 2000 hours. The greater number of daylight hours and therefore

FIGURE 3.1 - JULY LAND/SEA BREEZE WIND VECTORS

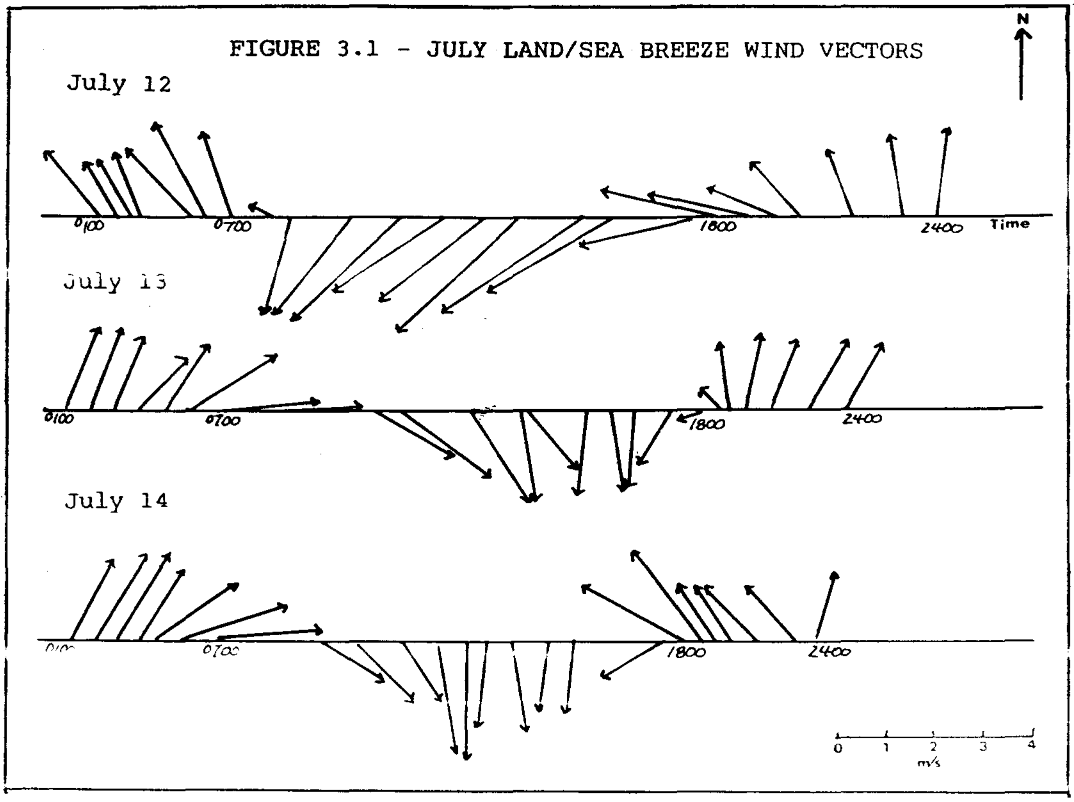


FIGURE 3.4 - WIND VECTORS FOR SITES 1 TO 4

JULY 12, 1987

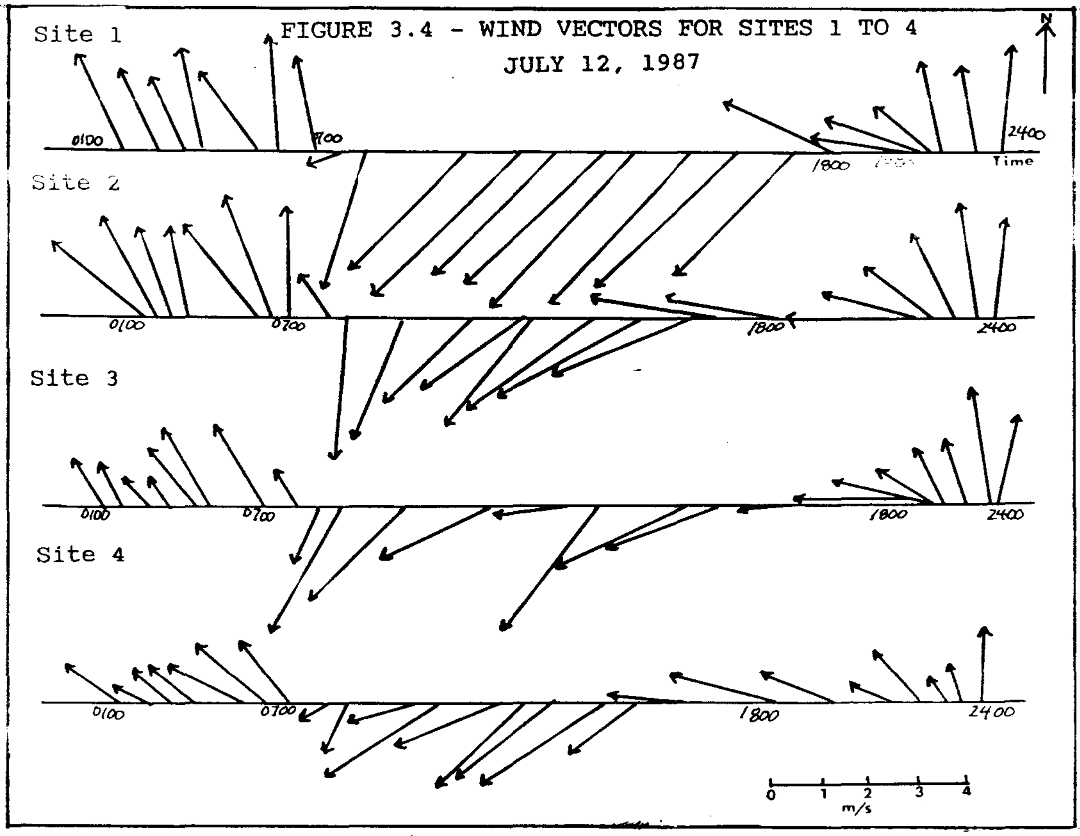
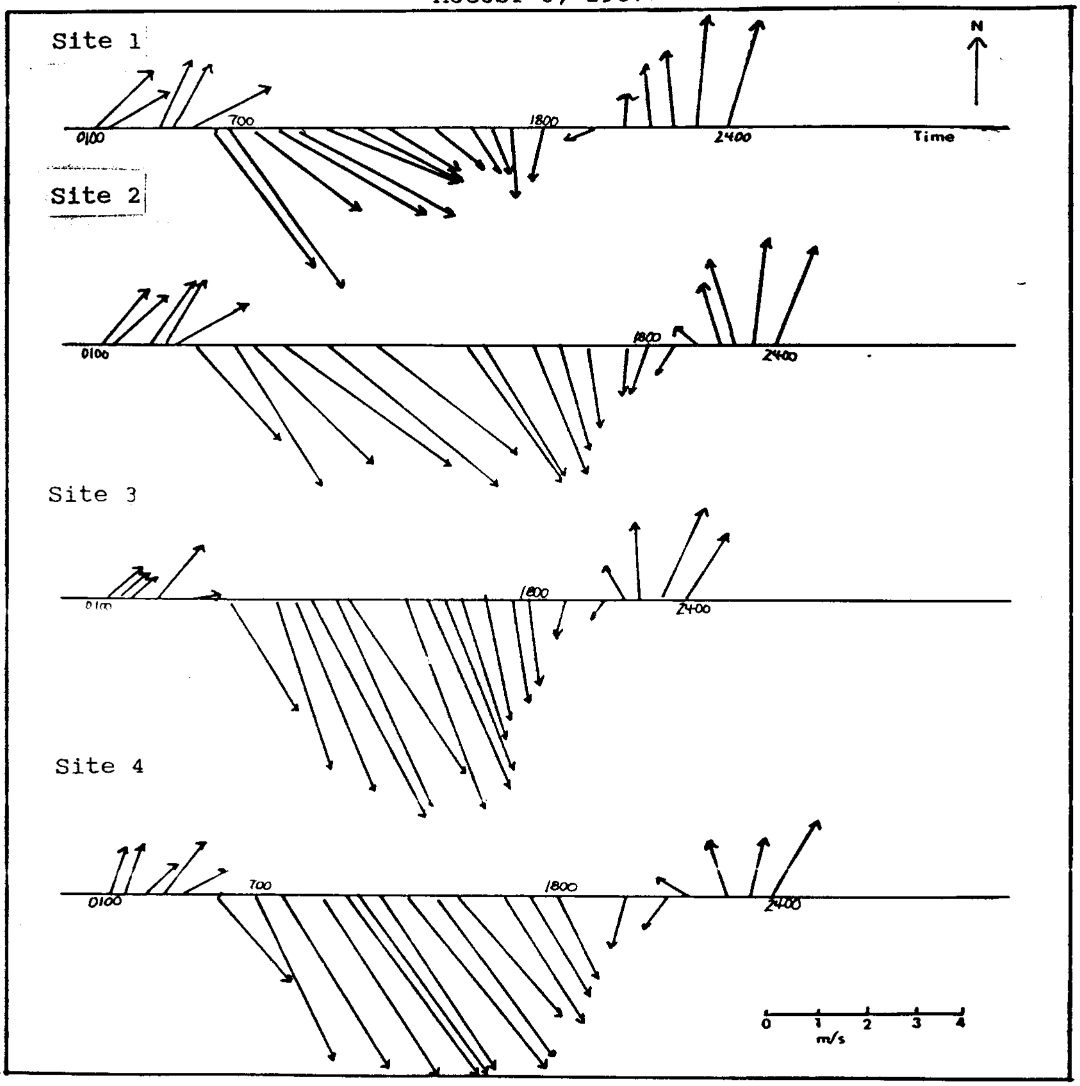


FIGURE 3.2 - WIND VECTORS FOR SITES 1 TO 4
AUGUST 3, 1987



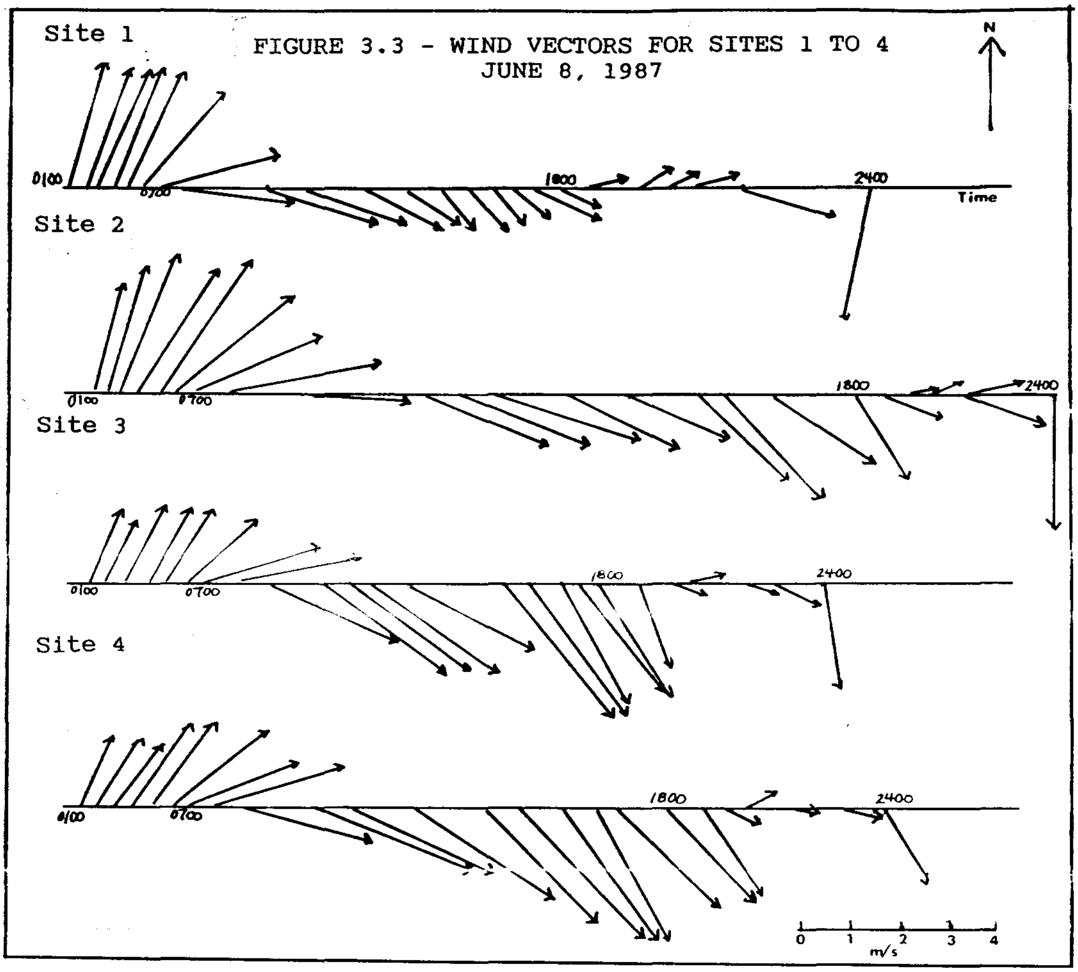


FIGURE 3.3 - WIND VECTORS FOR SITES 1 TO 4
JUNE 8, 1987

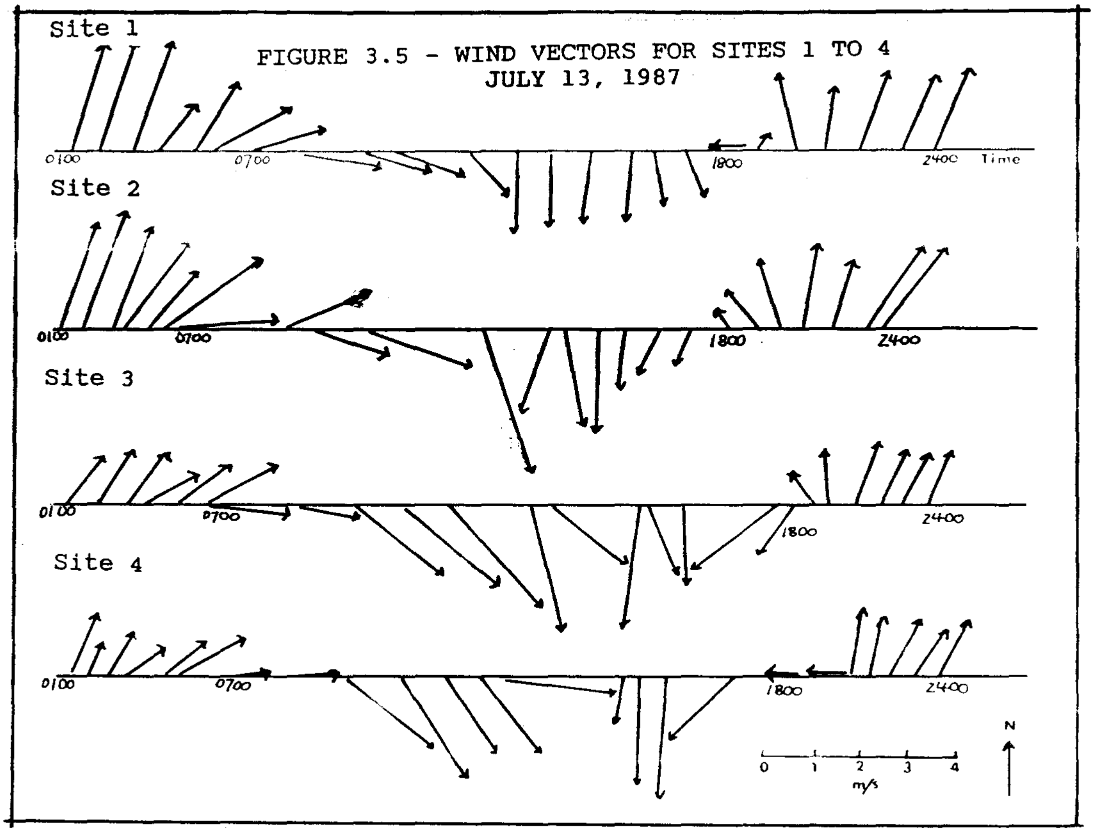


FIGURE 3.5 - WIND VECTORS FOR SITES 1 TO 4
JULY 13, 1987

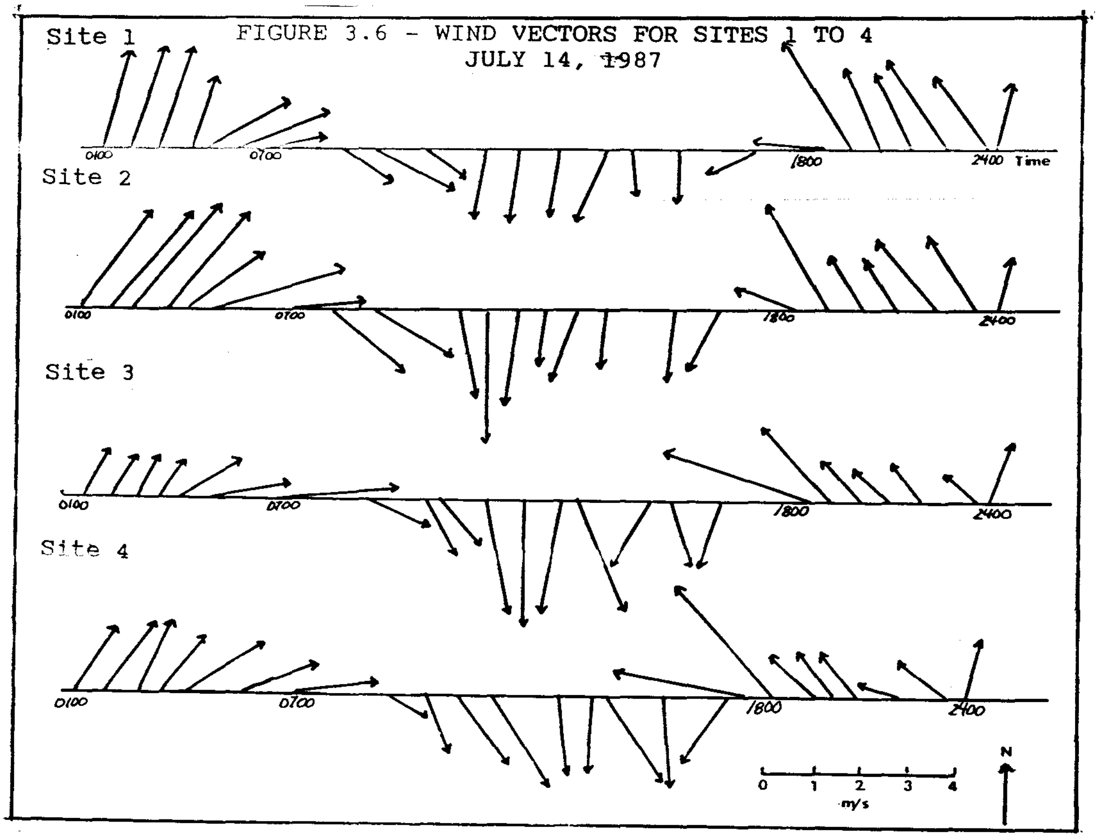


FIGURE 3.6 - WIND VECTORS FOR SITES 1 TO 4
JULY 14, 1987

more time required to heat the atmosphere was the probable cause for the earlier and later changeover hours.

The changeover period is a good indicator of the inland progression of the sea breeze. This period can be easily distinguished as the wind direction is usually close to parallel to the coast. This can be seen especially clearly in Figure 3.5. No single dominant wind direction can be established at all sites during the changeover period. For example, Figure 3.4 for July 12 indicates that the wind is onshore at Site 1 at 0800, offshore at Sites 2 and 3, and onshore at Site 4. By 0900, all the sites experience onshore winds. The sea breeze has penetrated inland to Site 4 by 0900, whereas it was only found at Site 1 at 0800. At night, the land breeze is first evident at Site 4 at 1700. The wind is still onshore at Site 1 at this time. At 1800, all sites show offshore winds occurring. The wind vectors for the remaining sample days are in Appendix 2.

Site 3 tends to deviate from the general behaviour of all four sites. Its location near a 2m deep lake may be the cause of the discrepancies whereby the lake sets up its own local circulation system which perturbs the land and sea breezes.

3.3 EFFECTS OF OFFSHORE WINDS

Offshore winds promote greater wind velocities, warmer temperatures and smaller vapour pressures than do onshore winds. The average wind speed, calculated for 12 hour periods, is higher for offshore days (Table 3.3).

Table 3.4 shows the acceleration/deceleration of the wind as it travels across the land to the coast or further inland. The land/sea breeze days have been broken up in their 12 hour periods to classify the periods as onshore or offshore. Offshore winds tend to accelerate towards the coast and onshore winds accelerate inland. This horizontal divergence at the surface must be combined with vertical convergence from above. The source of the vertical convergence is not known due to the limited amount of data. The actual wind speed gradients, $\Delta u/ \Delta x$, are found in Table 3.5. A negative number indicates that the wind speed is faster at Site 1 (the coast), while a positive number indicates that the wind speed is faster at Site 4.

Offshore winds produced warmer air temperatures than did onshore winds. Temperatures at Site 1 were about 5 to 7 °C warmer for onshore winds. The average temperature at Site 1 on July 5 for offshore wind conditions was 14.76 °C, while July 10th (onshore winds) had an average temperature of 7.55°C at Site 1. Figures 3.12 (d) and (e) illustrate four-hour averaged temperatures for July 5 and July 10. August 13 (Figure 3.12(j)) also showed depressed temperatures, with a daily average of 10.15°C at Site 1. Twelve hour averaged temperatures for all four sites may be

TABLE 3.3 - AVERAGE WIND SPEED FOR SITES 1 AND 4

Day	Condition	Ave daytime Site 1 m/s	Ave daytime Site 4 m/s	Ave nighttime Site 1 m/s	Ave nighttime Site 4 m/s
June 8	land/sea	2.79	2.96	2.23	1.79
June 12	offshore	5.87	4.64	5.16	4.14
June 26	onshore	3.2	5.03	3.2	2.14
July 5	offshore	4.24	4.25	4.04	3.42
July 10	onshore	2.88	2.96	2.97	1.96
July 12	land/sea	3.37	2.2	2.15	1.37
July 13	land/sea	1.46	2.02	1.83	1.25
July 14	land/sea	1.52	2.21	2.17	1.61
August 3	land/sea	2.28	3.9	1.71	1.28
August 13	offshore	4.86	4.91	4.02	3.37

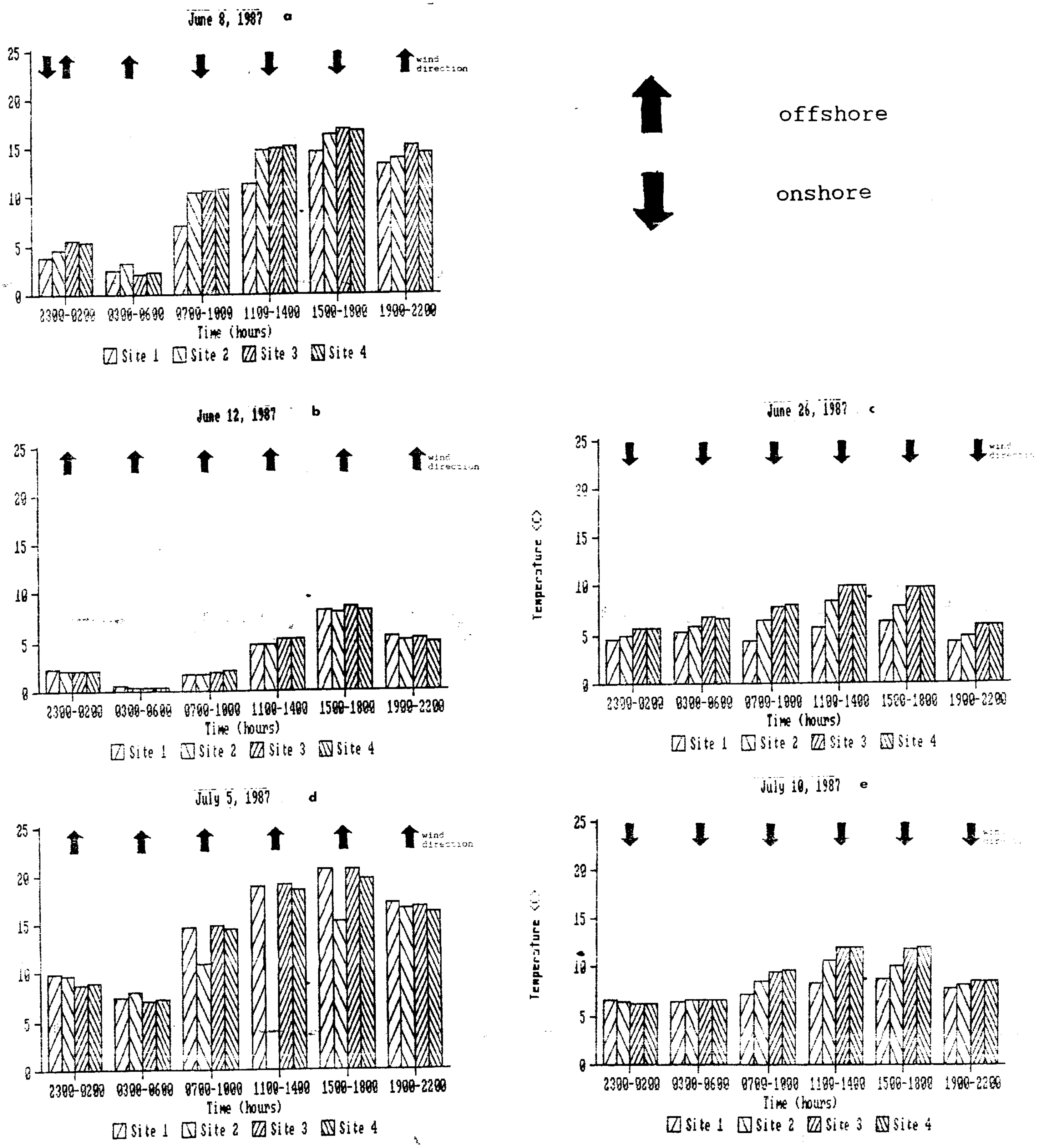
TABLE 3.4 - FREQUENCY OF ACCELERATION OR DECELERATION(%)

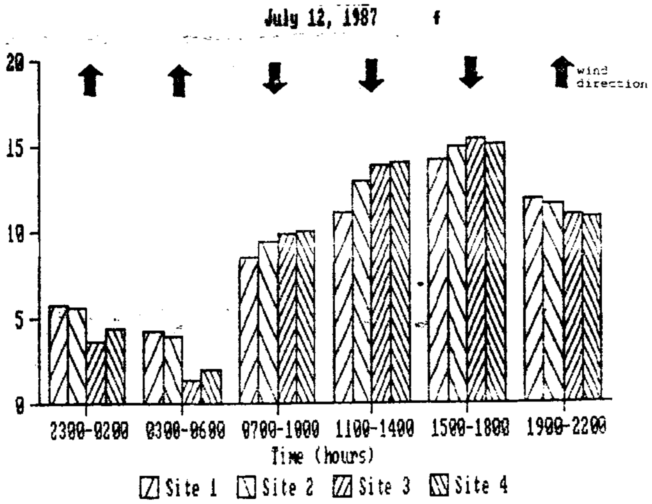
Wind	Accel *	Decel **
offshore	82	18
onshore	66	33

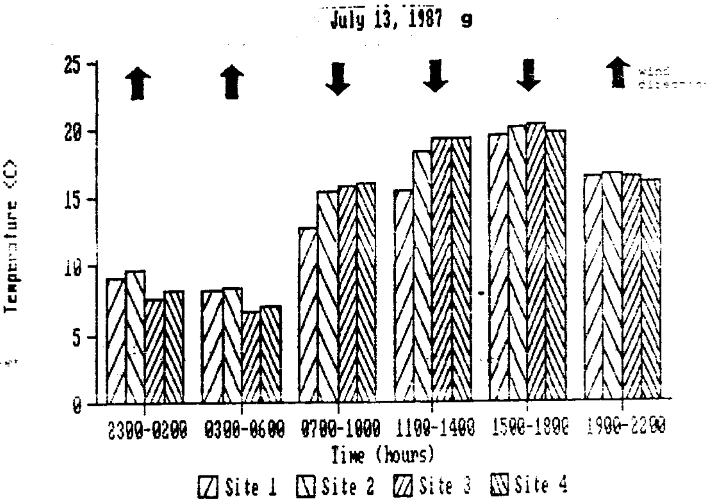
* acceleration of the wind from site 4 to site 1 on offshore days or acceleration of the wind from site 1 to site 4 on onshore days

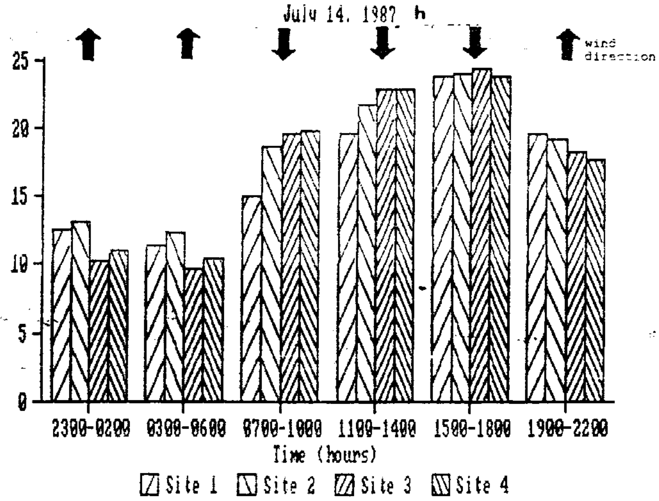
** deceleration of the wind from site 4 to site 1 on offshore days or acceleration of the wind from site 1 to site 4 on onshore days

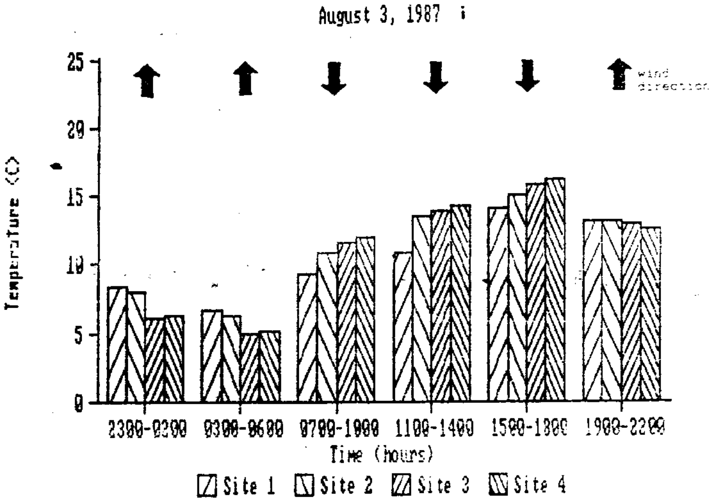
DIURNAL PATTERNS OF TEMPERATURE
Figure 3.12




July 12, 1987 f
wind direction
0
5
10
15
20
2300-0200
0300-0600
0700-1000
1100-1400
1500-1800
1900-2200
Time (hours)
Site 1
Site 2
Site 3
Site 4


July 13, 1987 g
Temperature (C)
0
5
10
15
20
25
2300-0200
0300-0600
0700-1000
1100-1400
1500-1800
1900-2200
Time (hours)
Site 1
Site 2
Site 3
Site 4


July 14, 1987 h
wind direction
0
5
10
15
20
25
2300-0200
0300-0600
0700-1000
1100-1400
1500-1800
1900-2200
Time (hours)
Site 1
Site 2
Site 3
Site 4


August 3, 1987 i
Temperature (C)
0
5
10
15
20
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2300-0200
0300-0600
0700-1000
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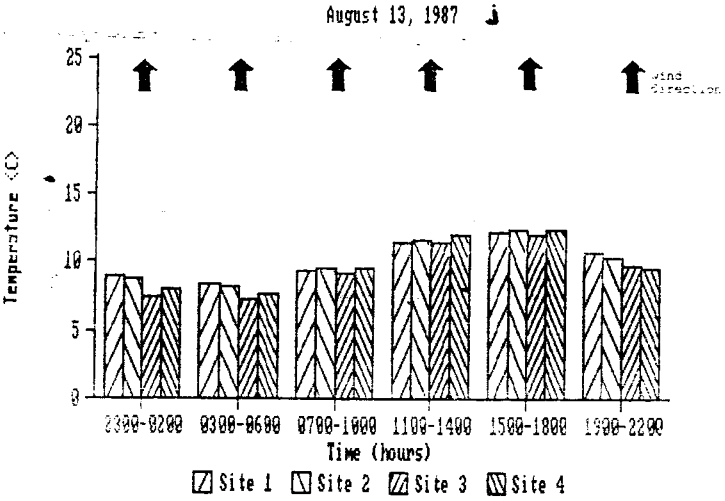
Time (hours)
Site 1
Site 2
Site 3
Site 4


August 13, 1987 j
Temperature (C)
0
5
10
15
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2300-0200
0300-0600
0700-1000
1100-1400
1500-1800
1900-2200
Time (hours)
Site 1
Site 2
Site 3
Site 4

found in Appendix 3. The daytime average for Site 2 on July 5 has not been calculated due to an equipment malfunction that resulted in the loss of data from 1000 to 1600. It is not possible to compare the onshore and offshore days in June (Figures 3.12(a) and (c)). Too much time elapsed between them and the annual temperature cycle masked the temperature effect due to wind direction.

Temperature also varied with distance from the coast. The temperature was consistently warmer at the coast for offshore winds. This is illustrated in Figure 3.12. Site 3 tends to be cooler or warmer than expected some days and this can be attributed to the moderating effect the small lakes to the north have on the site. Site 1 is cooler than expected some nights and this could be due to two things. The tidal cycle has an effect on air temperatures such that air temperatures are colder when the tide is in and warmer when the tide is out. The incoming tide tends to decrease the temperature at Site 1 by 2 °C.

The temperature at Site 1 may also be affected by air converging from above. As mentioned previously, vertical convergence of air from above is necessary to balance the horizontal divergence of air at the surface. The source of the converging air is unknown, but can be inferred from the temperatures at Site 1. Cooler temperatures at night at Site 1 would indicate that air flow originated over Hudson Bay, while warmer temperatures would indicate a terrestrial origin.

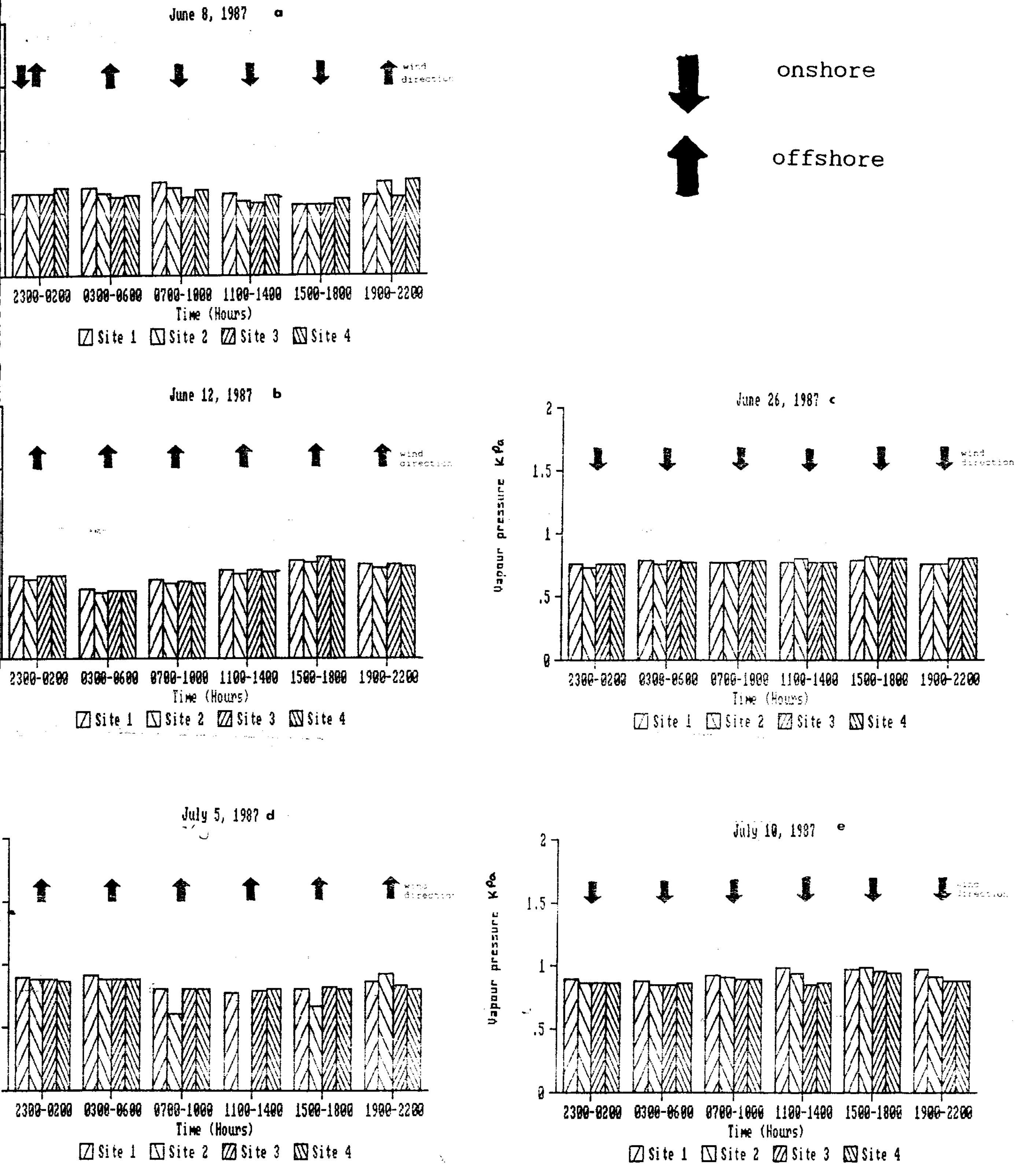
The horizontal temperature gradients between sites in Table 3.5 indicate that the temperature gradients are stronger during the day. Negative values indicate that the temperature is cooler inland and positive values indicate that the temperature is warmer inland. The gradients are weakest for offshore conditions.

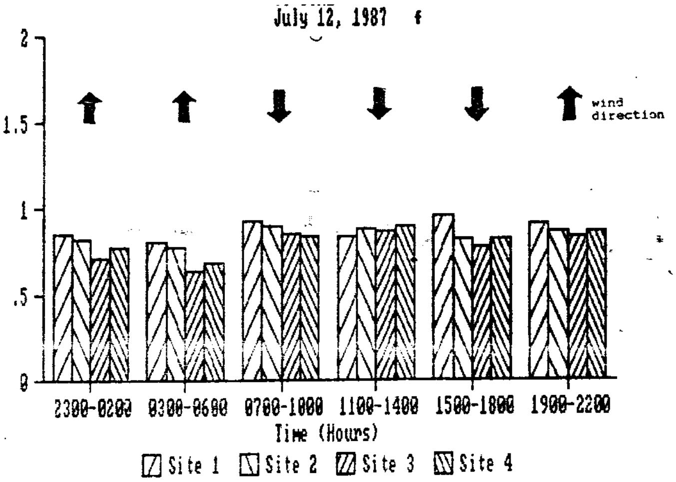
The behaviour of the vapour pressure corresponds to that of the temperatures. Vapour pressure increases over the season as the air warms up and is generally smaller for offshore winds than for onshore winds. Figures 3.13(d) and (e), (July 5 and 10th) illustrate that vapour pressure is smaller for offshore winds during the daytime period and is approximately equal for the nighttime periods.

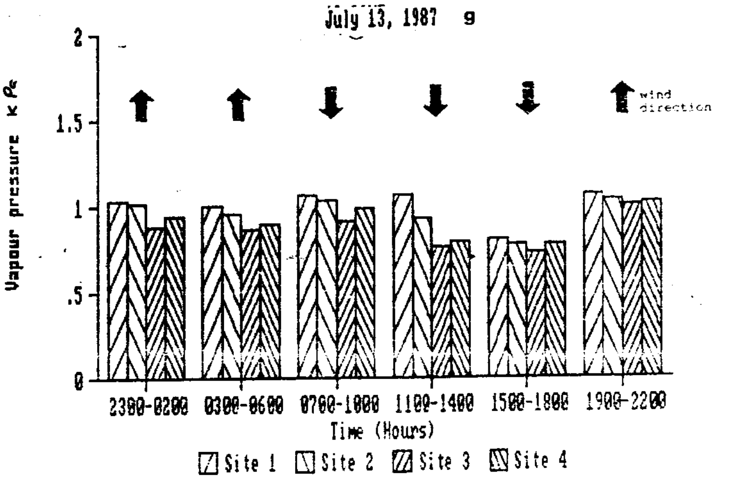
Figure 3.13 and Table 3.5 show that the vapour pressure varies little between sites. A negative number indicates that the vapour pressure is higher at the coast and a positive number indicates that the pressure is higher inland. The vapour pressure gradients are small for most of the time, with the magnitude of the gradient increasing over the summer. Although the vapour pressure shows little variation between sites, it is usually higher at Site 1. This is probably due to the proximity of the site to a large body of water.

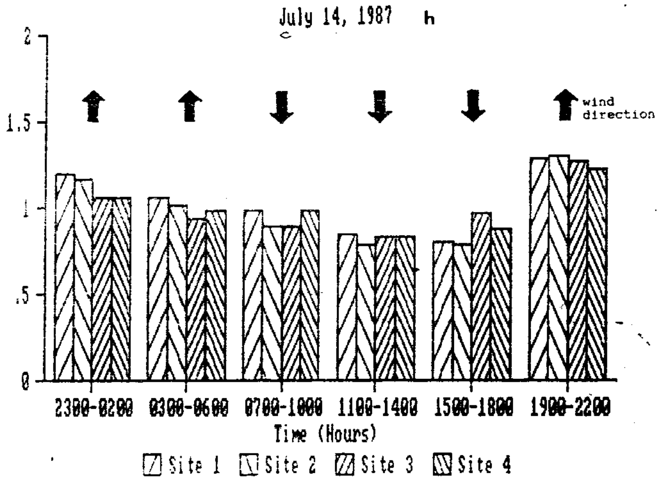
The loss or gain of water vapour at the surface must be supplemented with moisture from above. Moisture must be

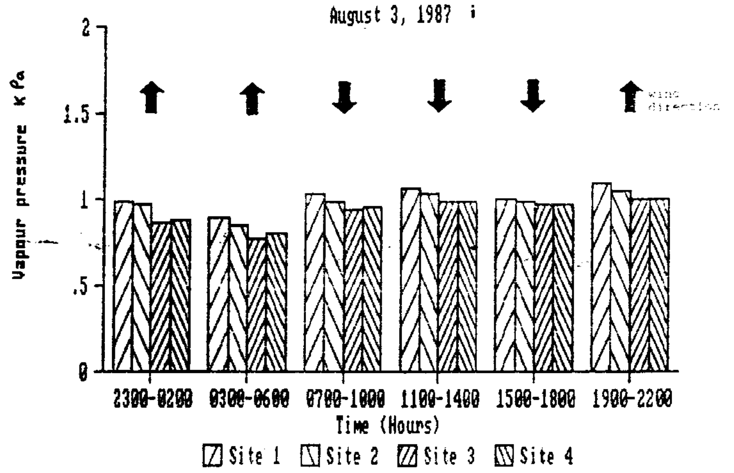
IURNAL PATTERNS OF VAPOUR PRESSURE
Figure 3.13




July 12, 1987 f
2
1.5
1
.5
0
wind direction
2300-0200 0300-0600 0700-1000 1100-1400 1500-1800 1900-2200
Time (Hours)
Site 1 Site 2 Site 3 Site 4


July 13, 1987 g
Vapour pressure kPa
2
1.5
1
.5
0
wind direction
2300-0200 0300-0600 0700-1000 1100-1400 1500-1800 1900-2200
Time (Hours)
Site 1 Site 2 Site 3 Site 4


July 14, 1987 h
2
1.5
1
.5
0
wind direction
2300-0200 0300-0600 0700-1000 1100-1400 1500-1800 1900-2200
Time (Hours)
Site 1 Site 2 Site 3 Site 4


August 3, 1987 i
Vapour pressure kPa
2
1.5
1
.5
0
2300-0200 0300-0600 0700-1000 1100-1400 1500-1800 1900-2200
Time (Hours)
Site 1 Site 2 Site 3 Site 4

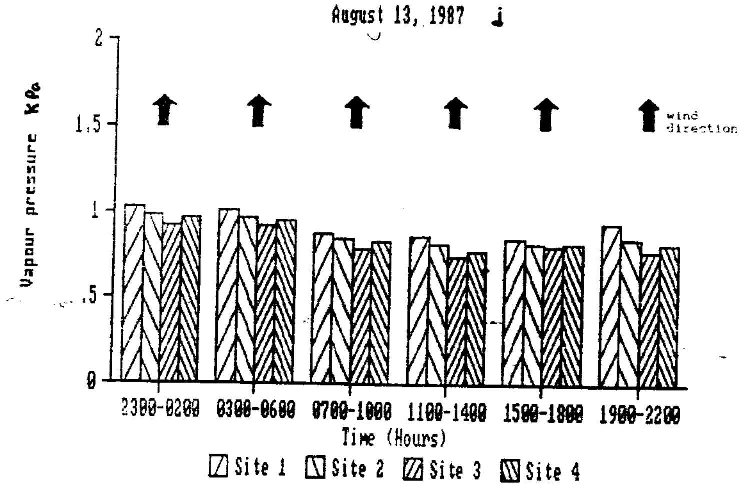

August 13, 1987 j
Vapour pressure kPa
2
1.5
1
.5
0
wind direction
2300-0200 0300-0600 0700-1000 1100-1400 1500-1800 1900-2200
Time (Hours)
Site 1 Site 2 Site 3 Site 4

TABLE 3.5 - HORIZONTAL WIND SPEED ($\Delta u/\Delta x$), TEMPERATURE ($\Delta T/\Delta x$) AND VAPOUR PRESSURE ($\Delta e/\Delta x$) GRADIENTS *

Day	Condition	$\Delta u/\Delta x$ day	$\Delta u/\Delta x$ night	$\Delta T/\Delta x$ day	$\Delta T/\Delta x$ night	$\Delta e/\Delta x$ day	$\Delta e/\Delta x$ night
		m/s/km		°C/km		kP/km	
June 8	land/sea	.17	-.44	.26	.07	-.001	.002
June 12	offshore	-1.23	-1.02	.02	-.02	-.001	-.001
June 26	onshore	1.83	-.06	.31	.11	.001	.001
July 5	offshore	.01	-.62	-.04	-.06	.001	-.003
July 10	onshore	.08	-1.01	.25	.29	-.005	-.003
July 12	land/sea	-1.17	-.78	.13	-.13	-.004	-.007
July 13	land/sea	.56	-.58	.2	-.06	-.1	-.007
July 14	land/sea	.69	-.56	.21	-.11	.001	-.007
August 3	land/sea	1.62	-.43	.22	-.11	-.006	-.008
August 13	offshore	.05	-.65	.03	-.08	-.005	-.007

* positive sign indicates that wind speeds, temperatures and vapour pressures are highest at Site 4, negative that they are highest at Site 1.

Δx = 12.4 km

supplied to the surface from aloft when there is a water loss at the surface. This process probably occurs during the daytime on June 8. The sea breeze is accelerating inland and diverging, and there is a decrease in vapour pressure from Site 1 to Site 4. The converging winds from above would bring in more moisture to the surface. Twelve hour averaged vapour pressures for all four sites are in Appendix 4.

3.4 EFFECTS OF ONSHORE WINDS

Smaller wind velocities, colder temperatures and higher vapour pressures exist under onshore wind conditions. Table 3.4 shows that onshore winds accelerate inland 66% of the time and decelerate inland for 33% of the time. The temperature was 5 - 7 °C colder for onshore winds at Site 1 and was consistently warmer inland. The horizontal temperature gradient, $\Delta T/\Delta x$, was stronger for the onshore winds. Figure 3.13 illustrates that higher vapour pressures are found for onshore days.

3.5 EFFECTS OF LAND/SEA BREEZE

For the land/sea breeze days, the sea breeze is stronger than the land breeze by a factor of 3:2. This was also found by Mak and Walsh (1976). July 13 has day and night wind speed gradients that are equal in magnitude. The opposite signs indicate that the direction of the gradient is inland during the day and towards the coast at night. June 8 has a much stronger nighttime gradient. The tendency of these gradients to deviate from the overall trend is probably due to the presence of a regional wind system that would augment the nighttime wind speed and oppose the daytime wind speed.

The strength of the land/sea breeze temperature gradients varied little as the season progressed. The land breeze of June 8 had a small temperature gradient of 0.7 °C/km. This gradient is small due to the small temperature difference between land and sea surfaces at this time of the night and year. The ice on Hudson Bay does not allow the sea to experience a higher nighttime temperature and acts as a suppressant for the land breeze. The temperature gradient of the land/sea breeze of August 13 was comparable in magnitude to those of July 12, 13, and 14, and did not show the large expected decrease in magnitude. It is anticipated that the magnitude of the land/sea breeze temperature gradient would decrease in late August and early September as Hudson Bay warmed up. The heat storage of Hudson Bay would lessen the temperature difference and thus the land/sea breeze temperature gradient and magnitude. This effect was not seen as the data covers only the period to August 13.

The vapour pressure gradients show the greatest diurnal change on the land/sea breeze days as the winds shift from onshore to offshore (Table 3.5). The vapour pressure is higher for the onshore winds during the day, and lower for the offshore winds during the night.

3.6 EXTENT OF THE SEA BREEZE

Although the wind frequencies, temperatures and vapour pressures were only measured 13 km inland, it is anticipated that the sea breeze effects extend further inland. Rouse et al (1987) found that the effects of the onshore wind extended to 65 km inland. The height of the circulation cell is greater than 350m. Weather balloons sent up to this height did not pick up the counterflow of air within the first 350m of the atmosphere (E.J. Weick, personal communication).

CHAPTER 4
CONCLUSIONS

The presence of the land/sea breeze circulation system at Churchill, Manitoba is well-developed. Onshore winds from the north are present during the day and offshore winds from the south persist during the night. The sea breeze is stronger than the land breeze, particularly when the temperature differences are largest.

The land/sea breeze was present in June, July and August, although the land/sea breeze in June was not a perfect example of the phenomenon. There was a definite seasonal progression of the wind from predominantly onshore conditions (42% of the time) in June to mixed wind directions in July and August (75% of the time). The frequency of the land/sea breeze increased as the season progressed. The land/sea breeze was best developed in July when both daytime and nighttime land and sea temperature differences were large. Onshore winds accelerated inland 66% of the time and offshore winds accelerated towards the coast 82% of the time.

The land/sea breeze changeover periods showed a seasonal and site by site progression. Over the season, the changeover was progressively earlier in the morning and later in the evening. In the morning, the sea breeze was first evident at Site 1 and penetrated inland. At night, the land breeze was first evident at Site 4 and moved towards the coast.

The thermal and moisture effects of the land/sea breeze were found to correspond to studies by Rouse et al (1987) and Rouse and Bello (1985). Temperatures were 5 to 7°C colder for onshore winds than for offshore winds. Rouse et al (1987) found a temperature difference of 7°C. The vapour pressure was smaller for offshore winds than for onshore winds.

The effects of the sea breeze were measured to a distance of 13 km inland. Site 1 was consistently colder than Site 4 for onshore winds. These positions were reversed for offshore winds. Vapour pressure showed little variation from site to site. The full extent of the land/sea breeze circulation system is not known as its effects extend beyond the study area.

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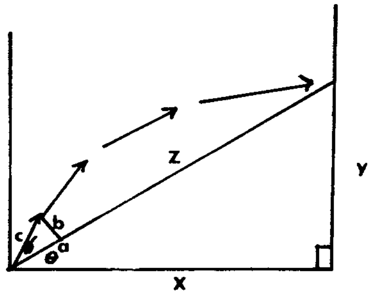
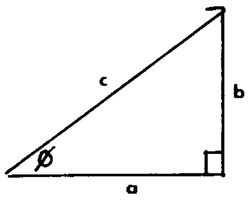
APPENDIX 1 - METHOD FOR CALCULATING RESULTANT WIND VECTORS



θ - resultant direction
z - resultant wind speed
c - individual site wind speed
Ø - individual site wind direction



$$x = \Sigma \cos \phi \,.\, c$$
$$y = \Sigma \sin \phi \,.\, c$$

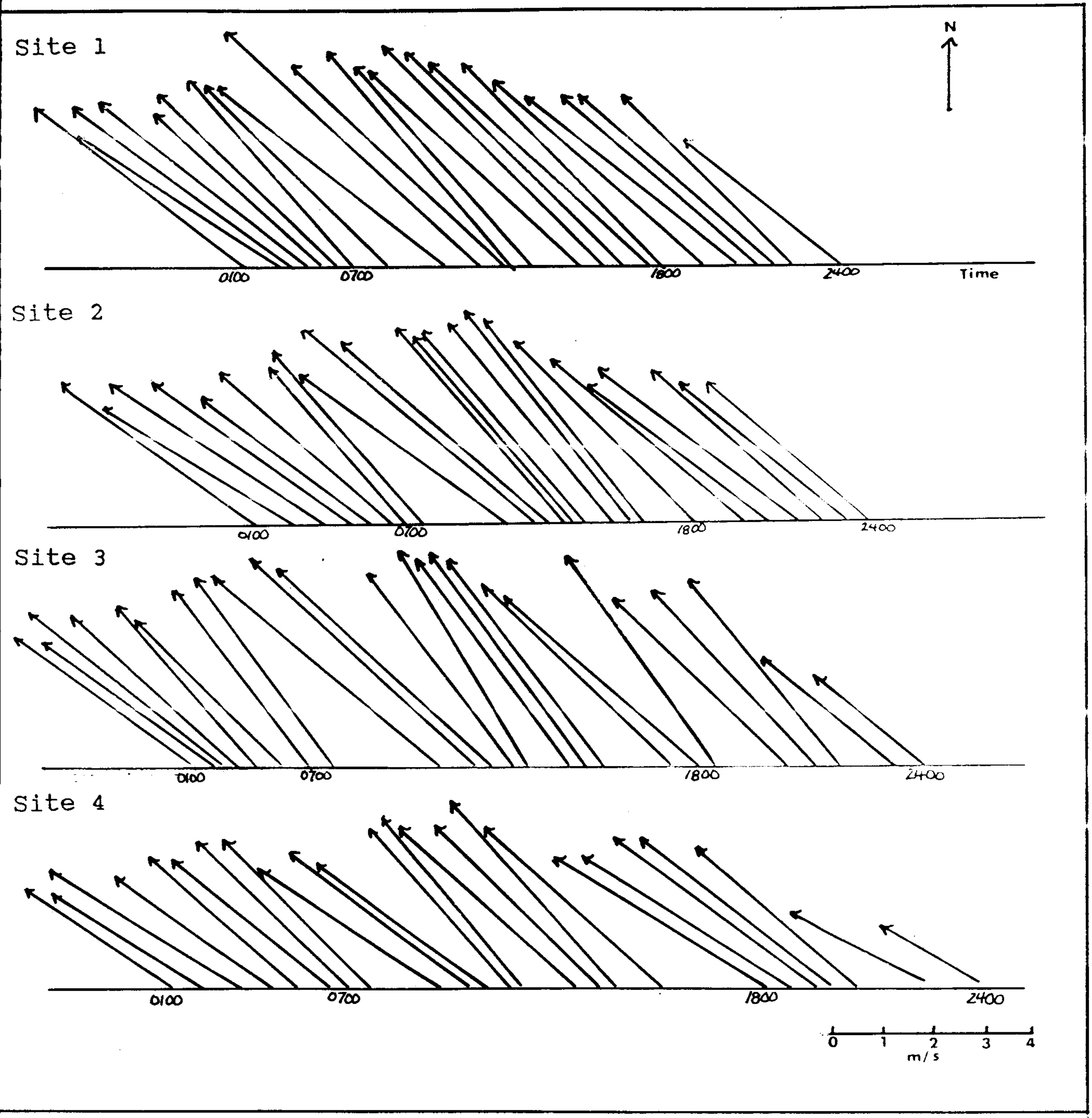
$$\because z^2 = x^2 + y^2$$

$$\therefore z = \sqrt{x^2 + y^2}$$

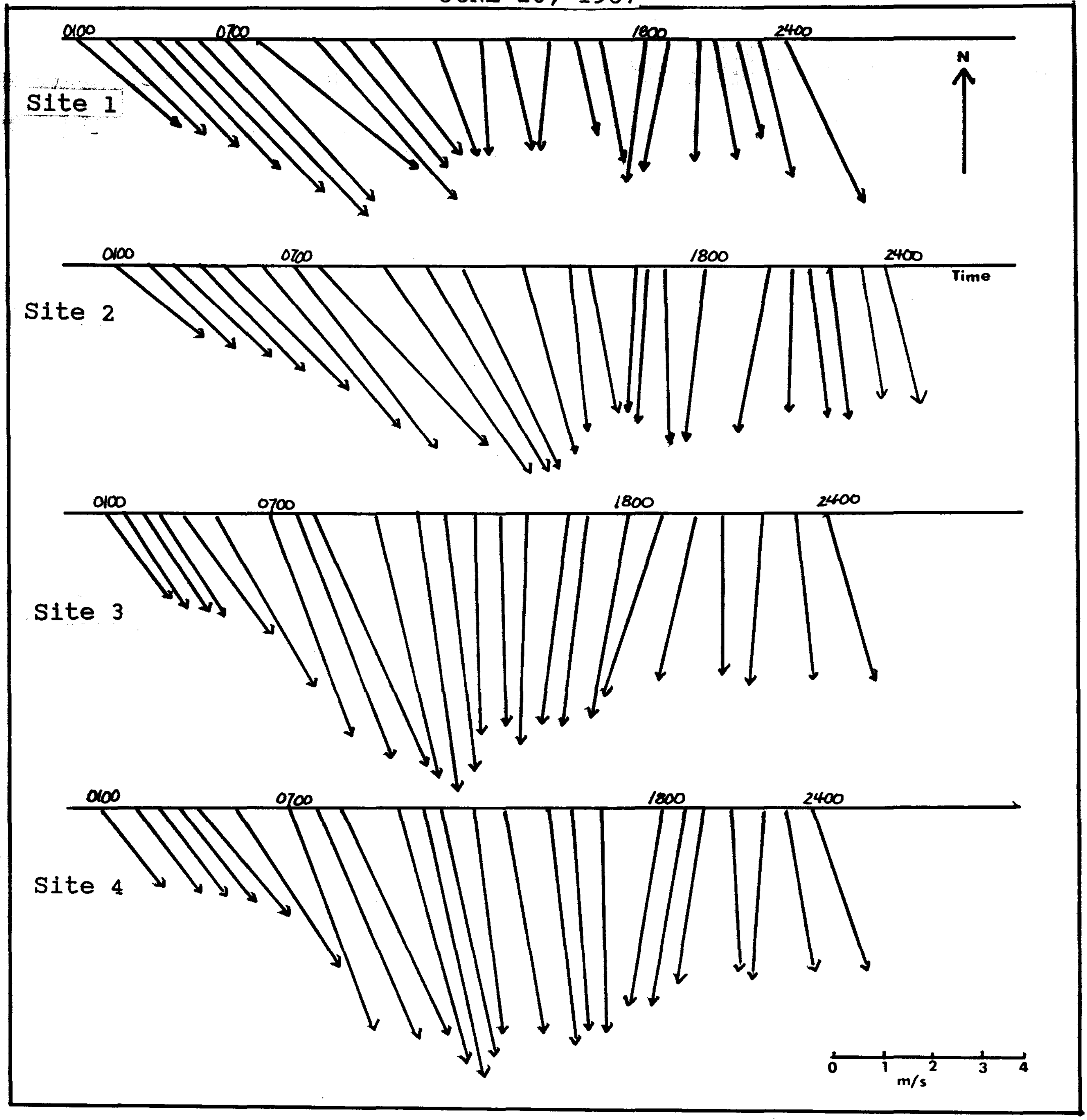
$$\theta = \arctan x^2 \,,\ \arctan y^2$$

APPENDIX 2 - WIND VECTORS

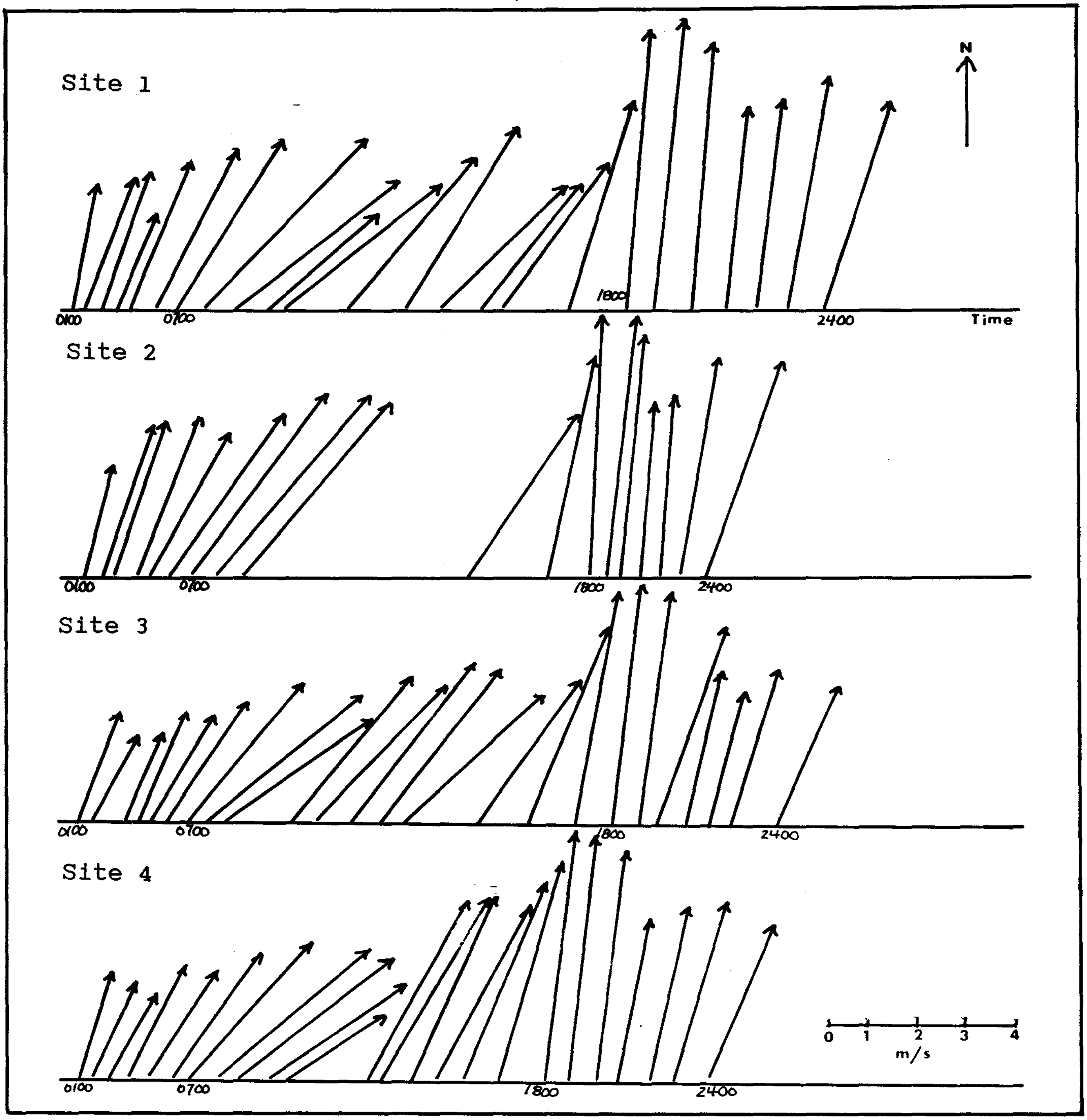
WIND VECTORS FOR SITES 1 TO 4
JUNE 12, 1987

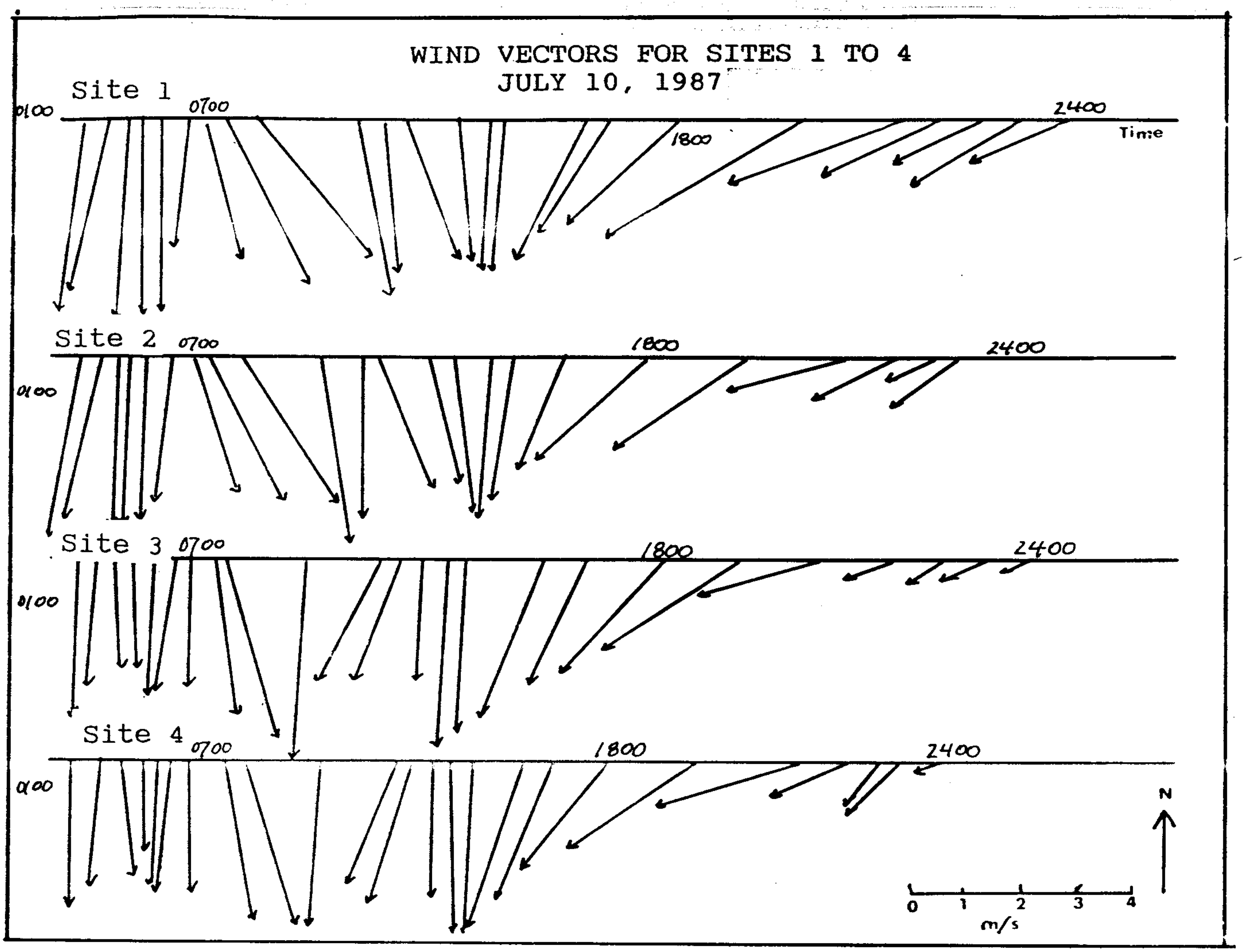


WIND VECTORS FOR SITES 1 TO 4
JUNE 26, 1987

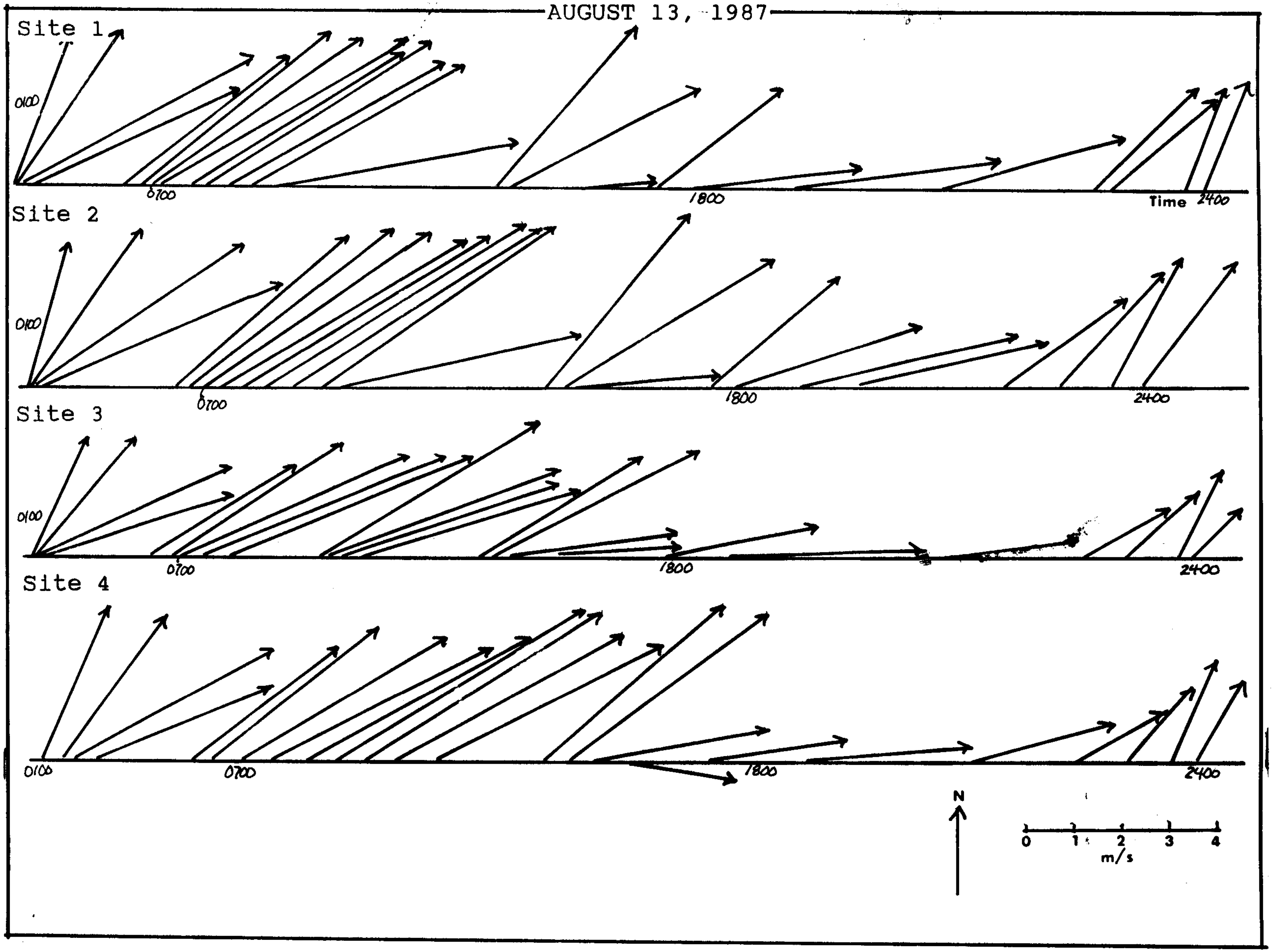


WIND VECTORS FOR SITES 1 TO 4
JULY 5, 1987




WIND VECTORS FOR SITES 1 TO 4
JULY 10, 1987
Site 1
0100
0700
1800
2400
Time
Site 2
0100
0700
1800
2400
Site 3
0100
0700
1800
2400
Site 4
0100
0700
1800
2400
N
0
1
2
3
4
m/s

WIND VECTORS FOR SITES 1 TO 4
AUGUST 13, 1987



APPENDIX 3

AVERAGE TEMPERATURES FOR ALL SITES

Day	Conditions	Average Day Temp 7:00 - 18:00 (C) Site 1	Site 2	Site 3	Site 4
July 5	offshore	18.02	17.38	18.07	17.52
July 10	onshore	8.09	9.81	11.11	11.22
July 12	land/sea	11.31	12.39	13	12.98
July 13	land/sea	15.83	17.87	18.34	18.25
July 14	land/sea	19.45	21.41	22.29	22.11
June 8	land/sea	11.05	13.86	14.23	14.22
June 12	offshore	4.87	4.83	5.29	5.17
June 26	onshore	5.42	7.53	9.17	9.22
August 3	land/sea	11.41	13.11	13.8	14.11
August 13	offshore	10.96	11.21	10.87	11.29

Day	Conditions	Average Night Temp 1:00 - 6:00, 19:00 - 24:00 (C) Site 1	Site 2	Site 3	Site 4
July 5	offshore	11.51	11.42	10.8	10.77
July 10	onshore	7.01	7.06	7.08	10.57
July 12	land/sea	7.31	7.07	5.34	5.75
July 13	land/sea	11.17	11.52	10.14	10.39
July 14	land/sea	14.49	14.91	12.73	13.07
June 8	land/sea	6.57	7.2	7.57	7.38
June 12	offshore	2.76	2.49	2.64	2.5
June 26	onshore	4.69	5.14	6.16	6.1
August 3	land/sea	9.37	9.18	8	7.97
August 13	offshore	9.34	9.11	8.16	8.4

APPENDIX 4

AVERAGE VAPOUR PRESSURES FOR ALL SITES (kPa)

Day	Conditions	Average Vapour Pressure 7:00 - 18:00			
		Site 1	Site 2	Site 3	Site 4
July 5	offshore	.793		.804	.805
July 10	onshore	.965	.95	.906	.906
July 12	land/sea	.906	.865	.834	.852
July 13	land/sea	.98	.908	.802	.85
July 14	land/sea	.884	.829	.902	.902
June 8	land/sea	.655	.616	.587	.642
June 12	offshore	.694	.676	.702	.688
June 26	onshore	.781	.799	.79	.789
August 3	land/sea	1.041	1.003	.965	.971
August 13	offshore	.867	.833	.782	.808

Day	Conditions	Average Vapour Pressure 1:00 - 6:00, 19:00 - 24:00			
		Site 1	Site 2	Site 3	Site 4
July 5	offshore	.893	.899	.871	.855
July 10	onshore	.918	.817	.866	.875
July 12	land/sea	.858	.821	.732	.774
July 13	land/sea	1.033	1.006	.92	.952
July 14	land/sea	1.188	1.167	1.095	1.096
June 8	land/sea	.668	.686	.632	.699
June 12	offshore	.649	.619	.643	.638
June 26	onshore	.775	.754	.785	.784
August 3	land/sea	.994	.954	.882	.897
August 13	offshore	.996	.938	.881	.914